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BIOLOGICAL CONSIDERATIONS OF NONNUCLEAR INCIDENTS INVOLVING NUCLEAR WARHEADS

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Foreword

The material in this document was assembled in a period of approximately four weeks in response to an urgent programmatic directive by the AEC's Division of Military Application. The following people responded to hurried requests for information and, in some cases, for written contributions to the text:

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In the rush to meet the imposed time schedule, credit for individual contributions was completely forgotten or ignored. In many instances, those making contributions did not have the opportunity to see the final report and what was done with their individual efforts; I must assume the responsibility, therefore, for any interpretation and philosophy not in keeping with the principles and intent of the various contributors.

The original document was classified. It was the feeling of some of us, however, that a major part of the material was unclassified and could be made available to a larger audience who may have occasion to consider the problems of large-area contamination from the accidental spread of plutonium and the other potentially toxic materials either from non-critical detonation of nuclear warheads or from other types of accidents in which plutonium particularly might be involved.

Mr. James F. Becker of the Lawrence Radiation Laboratory has been kind enough to edit the original document and to coordinate the necessary changes and reviews resulting in this unclassified version. I am sure many of the shortcomings resulting from the hurried assembly of the earlier version still persist. This, of course, is not Mr. Becker's fault but, rather, a result of the difficulties inherent in getting the report critically reviewed and the many sections revised by the various contributors.

As the person who took the responsibility for assembling the original draft I wish to thank the various contributors, and I am particularly grateful to James Becker and Walter Bennett, who felt strongly enough about the need for wider distribution of the unclassified information that they took the responsibility for issuing this version as a LRL document.

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BIOLOGICAL CONSIDERATIONS OF NONNUCLEAR INCIDENTS INVOLVING NUCLEAR WARHEADS

Abstract

Materials frequently used in nuclear warheads are recognized to be toxic. In the event of a nonnuclear incident involving a warhead, some of these materials may be released. Pertinent physical, chemical, and radiological properties of these materials are presented. Prediction of exposure and contamination levels and an evaluation of biological consequences of such an incident are summarized.

Introduction

In general, nuclear warheads contain ^{239}Pu, ^{235}U, natural or depleted uranium, and beryllium; if thermonuclear, the warhead also contains ^{3}H (tritium). Plutonium and tritium are highly radioactive and, if taken into the human body in sufficient quantity, impose a critical internal radiation hazard. Natural uranium and ^{235}U have such low specific activities that they would be more significant as a chemical toxin to the kidneys rather than a radiation hazard. The rather large intake of uranium required to produce kidney damage and the low intake rate of uranium into the body under conditions of noncritical weapons incidents are such that it can be eliminated from consideration as a hazard in such incidents. Beryllium is nonradioactive, but inhalation of relatively small amounts of beryllium compounds (predominantly the oxide) may produce a lung disease known as berylliosis.

Associated with nuclear warheads as a part of the nuclear detonating system is a quantity of high explosive. Although it is possible to construct the warhead so that inadvertent detonation of the high explosive will not initiate a nuclear reaction, it has not been possible to assure against inadvertent burning or detonation of the high explosive. Such an unplanned burning or detonation of the high explosive can result in the release of potentially hazardcus materials of the warhead into the immediate environs. The extent of contamination of the environment in such situations is dependent on many factors. The most important factors affecting the distribution and concentration of the hazardous materials after a release are (1) the total amount of each hazardous material that was in the warhead; (2) the energy release of the high explosive detonation and/or fire; (3) the detailed local meteorology (wind velocity and shear, stability conditions, etc.) at the time of the incident; and (4) the amount and nature of any material immediately surrounding the warhead when the incident occurs (e.g., a bunker, a silo, the wreckage of

a plane or truck crash, or open air). Atmospheric dispersal of these materials creates two types of potential hazards to people in the immediate vicinity of the incident: (a) inhalation of significant amounts of the materials during passage of the contaminated cloud or smoke plume, and (b) the ingestion over a long time of products contaminated by the settling and deposition of the hazardous materials from the cloud during passage over the area and long-term inhalation of particles resuspended from contaminated surfaces.

This report summarizes the pertinent physical, chemical, radiological properties and the physiological and toxicological effects of ^{239}Pu, tritium, and beryllium.

Relevant Properties of Toxic Materials

The properties relevant to the potential hazards associated with noncritical destruction of nuclear warheads are (1) the physical, chemical, and radiological properties of the toxic materials they contain; (2) their physiological properties (i.e. the amounts that enter the body, routes of entry, distribution in tissues and organs, and rates of elimination); and (3) their toxicity (i.e., the nature of the undesirable effects produced and the amount of the materials required to produce them).

PLUTONIUM-239

Physical, Chemical, and Radiological Properties

Plutonium is a member of the actinide series of elements, all of which have certain similar chemical properties. Chemically, plutonium resembles thorium, an element that has been known for over 100 years. The plutonium in nuclear warheads is in the form of the metal. The metal has a melting point of 640°C and oxidizes quite readily in air, particularly in the presence of moisture, exhibiting pyrophoric properties at temperatures of 300 to 350°C depending on specific surface. The predominant oxide formed is PuO_2. The properties of PuO_2 are more relevant to the problem under consideration than are the properties of the metal, since the metal is quite likely to be converted all or in part to the oxide by the prevailing conditions of the incident. Plutonium oxide has a high density (~11 g/cm^3), is quite friable, and is extremely insoluble in water and dilute acids. Its maximum solubility in water at room temperature is only about 20 μg/liter. At a pH above neutral (e.g., the pH of the small bowel), plutonium forms hydroxides or hydrous oxides that are notoriously insoluble; the solubility product of $Pu(OH)_4$ is 7×10^{-56}.

Plutonium-239 undergoes radioactive decay by alpha particle emission (half-life approximately 24,000 years). The average alpha particle energy is 5.15 MeV, and 1 μg (1 millionth of a gram) gives off 140,000 alpha disintegrations per minute (specific activity ~0.062 Ci/g). Some soft x rays (17 to 22 and 60 keV) are given off by impurities or decay products, but these x rays do not contribute significantly to the radiation dose (considerably less than 0.01 percent of the total energy emitted).

Physiological Properties of Plutonium

The physiological properties of plutonium were reviewed extensively by Thompson.[1] Only those properties most relevant to the problem are summarized in this report.

The relevant physiological properties are those governing the entry, deposition, distribution, and retention of the material in the body. It is, after all, the amount of material in the body, its distribution among the various tissues, and the time it remains there that determine the exposure. The most likely routes of intake of any substance into the body are (a) absorption through the intact or broken skin; (b) ingestion and subsequent absorption from the gut; and (c) deposition in the absorption from the lung. Plutonium has its own specific intake, deposition, distribution, and elimination characteristics. In the case of plutonium particularly, the route of entry into the body has a significant effect on tissue deposition and distribution.

Skin Absorption and Subsequent Deposition and Retention

The intact skin is a very effective barrier to absorption of plutonium in nearly every form apt to be encountered. This is particularly true of the highly insoluble oxides. Absorption of a soluble plutonium compound through the unbroken skin of the hand has been observed and appeared to be no more than 0.00002 percent of the quantity initially present even though considerable plutonium contamination remained on the hand for at least a week. For all practical purposes, absorption through the intact skin can be dismissed as a route of entry of plutonium into the body under the prevailing conditions associated with nuclear warhead incidents. In experimental animals, complexing agents and strong acids applied to the skin enhance skin absorption to some degree. Under these enhanced conditions, exposure to plutonium of several days duration resulted in 2 percent absorption through the skin of rats. These conditions, however, do not exist in connection with the problem under consideration.

Rather large amounts of PuO_2 rubbed into abrasion-type lesions in the skin of experimental animals failed to show measurable amounts of absorption into the systemic circulation. The particles of PuO_2 were entrained in the exuded tissue fluid that formed the escar (scab). When the escar detached, the PuO_2 remained with it. Puncture wounds and lacerations of a few millimeters width and depth within an area of generalized skin contamination in rats did not increase the absorption above that observed for the intact skin. Introduction of pluontium in various forms by intradermal or intramuscular injections results in slow translocation of the plutonium to other sites, probably largely through the lymph rather than the blood. PuO_2 introduced at depth in tissue elicits a fibrotic response resulting in its becoming encapsulated and remaining largely at the site of introduction where it can produce undesirable local effects. For this reason, such local deposits are usually excised if known to exist. Their removal also alleviates the possibility of absorption or translocation of the plutonium.

Unless complexed, plutonium ions have a strong tendency to hydrate, especially at or above neutral pH, and associate into polymeric or colloidal forms. The form of the plutonium in the blood influences greatly its deposition in the various tissues.

The monomeric form deposits predominantly on bone surfaces. Polymeric plutonium is selectively taken up by the reticuloendothelial system, particularly in the liver and spleen. After 30 days or so, the bone and liver contain most of the retained plutonium. Since the degree of polymerization influences distribution, the partitioning of plutonium between bone and liver is influenced by the route of entry to the extent that the route favors entry of monomeric or polymeric plutonium. Plutonium absorbed through the unbroken skin deposits predominantly in bone. Plutonium entering from sites of intradermal or intramuscular injections (or administration) results in increased deposition in the liver.

Regardless of the route of entry, once plutonium has become fixed in the bone and liver its rate of elimination is exceedingly slow. The half-time of elimination of plutonium from the human skeleton appears to be in excess of 100 years. The elimination half-time from the liver in beagles is between 5 and 10 years and may be even longer for man.

Gastrointestinal Absorption and Deposition

Absorption from the gastrointestinal tract of plutonium administered in various forms has been studied extensively in experimental animals. One of the most relevant studies involved chronic feeding of $Pu(NO_3)_4$ to rats in concentrations below or approaching the maximum permissible level specified by the National Commission on Radiation Protection for drinking water. The average absorption and retention under these conditions were 0.003 percent of the total amount ingested. The fraction absorbed was independent of the amount administered. The administration of $Pu(NO_3)_4$ solutions to pigs gave quite comparable results (0.002 percent absorption). Absorption of plutonium from the gut can be enhanced by complexing it so that it remains soluble at the prevailing pH of the duodenum or by administering it in the hexavalent state or in strong acid solution. These are not conditions, however, that would prevail in nuclear weapons incidents where the plutonium would be in the form of insoluble PuO_2. The age of the animal has been observed to significantly influence gut absorption of $Pu(NO_3)_4$ administered to rats. One-day-old animals absorbed 0.25 percent of the amount administered. Absorption dropped rapidly with increasing age until, at 33 days (approximately weaning age), absorption was the same as for the adult animal (0.003 percent).

All observations to date strongly support the conclusion that the gut mucosa is a very effective barrier to plutonium absorption under the more usually encountered conditions of exposure (particularly those associated with nuclear weapons incidents) except perhaps in the case of the infant whose diet would be expected to be much lower in plutonium than that of children and adults. The plutonium concentration in the milk is only about 2.5 percent of the concentration in the blood plasma of the lactating animal. Plutonium passes through the gut mucosa largely in monomeric form and is deposited preferentially in bone from which its elimination rate ($T/2 > 100$ years) is, for practical purposes, negligible.

Inhalation and Deposition

The physiology of inhaled toxic materials is exceedingly complex, and many important factors related to the disposition of inhaled materials are either unknown or semiquantitatively known at best. The complexity of the problem stems from the multitude of interacting physical, chemical, and biological factors and the extreme difficulties inherent in their experimental study. Deposition, distribution, retention, absorption and translocation are all influenced by particle size distribution, chemical form, solubility, density, and respiratory values such as respiration rate and tidal volume, to mention only a few.

The current approach to the problem of physiology and toxicology of inhaled materials is by the construction of deposition and retention models that generally take into consideration all applicable experimental data. Hopefully, the models may then be adjusted to apply to specific substances or classes of substances under the prevailing conditions of exposure. The most recent and thorough lung model is that of the Task Group on Lung Dynamics for Committee II of the International Commission on Radiological Protection.[2] The Task Group consider PuO_2 a class Y material (avid retention, cleared slowly over a matter of years), and some animal experimental data are available, both from laboratory and field studies, that show it is indeed cleared very slowly from the lung. The lung model divides the respiratory tract into three compartments: nasopharynx, tracheobronchial (the trachea and the bronchial tree down to and including the terminal bronchioles), and pulmonary (the functional area or exchange space). Deposition levels of inhaled substances in each of these compartments may be calculated on the basis of particle size distribution, tidal volume, and physical properties of the material. The particle size distributions of PuO_2 from noncritical detonations have been determined in experiments at the Nevada Test Site. Using these data, the lung model predicts deposition levels in the nasopharynx of 70 percent, tracheobronchial compartment of 8 percent, and respiratory compartment of 15 percent. These values are percent of the total amount inhaled. A small amount (~7 percent in this case) is exhaled before it is deposited on the compartmental surfaces. The model assigns absorption, elimination, and translocation rates to the material in each compartment that are generally in agreement with experimentally observed values.

It then is possible to calculate the amount of material remaining in each compartment or transferred to other structures of the lung or to the bloodstream as a function of time after exposure. The principal potential hazard associated with noncritical destruction of nuclear weapons containing plutonium is the 15 percent of the inhaled plutonium that is deposited in the respiratory compartment. Animal exposures to PuO_2 aerosols both in the laboratory (dogs, rats) and in the field (dogs, burros, sheep) show that material deposited in the nasopharynx and tracheobronchial compartments is cleared rather rapidly. A part of the material in the respiratory compartment is slowly eliminated via the tracheobronchial tree ($T/2 \sim 500$ days), a part is translocated to the lymph nodes where it tends to remain indefinitely, and a small part both from

the lymph nodes and the respiratory compartment (1 to 10 percent) is transferred to the blood (T/2 ~ 500 days) and subsequently deposited in the bone and liver. These studies suggest also that the plutonium entering the blood from the respiratory tract may be in polymeric form and the concentration in the liver may be from 1 to 5 times the concentration in bone. The deposition and retention model takes all of these factors into account in deriving the exposures of various tissues from inhaled $^{239}PuO_2$. Table 1 shows the calculated plutonium burden remaining in the lungs and in the pulmonary lymph nodes, and that transferred to the blood and subsequently deposited in bone and liver at 0, 500, 1000, and 1500 days after exposure to a PuO_2 aerosol comparable to that which might be expected from a one-point detonation of high explosive in a nuclear warhead. The values given are percent of the total amount in the body at the specified time.

Table I. Distribution of retained plutonium as a function of time after inhalation of a PuO_2 aerosol from a nonnuclear detonation.

Time since exposure (days)	Percent of retained dose		
	Lung	Liver plus bone[a] via blood	Pulmonary lymph nodes
0	99.5	0.5	0
500	66	17	17
1000	42	25	33
1500	25	32	43

[a]Animal data suggested that from a single inhalation exposure the plutonium entering the blood during the first 30 days is about equally distributed between bone and liver. Beyond 1500 days after exposure, the liver-to-bone distribution ratio may be 2 to 3.

A crude comparison of the calculated values with animal experimental data collected in the field and in the laboratory suggests that the calculation may tend to overestimate the amounts transferred to the blood and lymph nodes at later times and to underestimate the amounts remaining in the respiratory compartment of the lung. Experimental data are fragmentary, however, and it seems reasonable to conclude that the calculated values are as good as can be done at the present time.

General Ecological and Environmental Uptake Considerations

One other aspect of the problem of noncritical detonation of warheads containing plutonium seems relevant—that of general ecological and environmental uptake. Direct uptake of plutonium by animals indigenous to weapons test areas and by experimental animals kept for long periods in heavily contaminated areas has been studied. The uptake of plutonium was surprisingly small. Plutonium uptake by plants from soil and growth media has been investigated in both the field and the laboratory and under a variety of conditions. The concentration of plutonium in plants on a dry weight basis was never more than 10^{-3} times that in the growth medium and was only about 10^{-4} times that in the soil. The fraction of plutonium absorbed from the gastrointestinal tract of animals grazing on contaminated vegetation is apt to be less than 10^{-4}, and measurements of plutonium transfer from plasma to milk suggest a further reduction in plutonium concentration by another factor of 10 at least. Consumption of animal products by man will introduce another reduction factor of at least 10^{-4} in the plutonium concentration entering the systemic circulation, except in the very young infant where the factor may approach 10^{-2}. It seems apparent that the significant passage of plutonium from

soil to man by way of a food chain is hardly to be anticipated. This conclusion is supported by the extremely low plutonium levels that have been measured in tissues of persons exposed to fallout from past nuclear weapons tests, which have resulted in production and dispersal of about 500 kCi of plutonium. These measurements indicate a maximum plutonium concentration of 3×10^{-14} Ci/g in pulmonary lymph nodes. The highest concentration found in the lung was 5×10^{-15} Ci/g. These values attest to the very low bodily intake via inhalation of the atmosphere of a slightly contaminated environment. In addition, follow-up studies in Palomares, Spain, following the nuclear weapons incident of January 17, 1966, have failed to reveal any consistently measurable plutonium concentration levels in people or produce from the area even though plutonium surface contamination levels approaching 500 $\mu g/m^2$ were plowed into the soil and, in some areas, the plutonium could not be plowed under because of the mountainous rocky terrain.

Toxicological Properties of Plutonium

The previous sections give details of the physical, chemical, radiological, and physiological characteristics of ^{239}Pu as a basis for discussion of its toxicological properties under conditions that might be expected from nonnuclear detonation of nuclear warheads containing plutonium. The toxicological problem is one of radiation effects produced in people in the immediate vicinity of the incident from exposure to $^{239}PuO_2$. The radiation delivered to tissue from plutonium and the effects of this radiation on the individual differ significantly from that of many other radioactive materials and from what seems to be the public concept of radiation and radiation effects. It is important to understand these differences and their impact on the assessment of potential hazard in the event of an incident. Hazard, in this connection, is defined as the possibility of producing harmful effects on individuals exposed to the material.

Effects from Skin Deposition and Absorption

The only radiations of any consequence emitted by plutonium are alpha particles. Some x rays are produced, but these contribute considerably less than 0.01 percent of the energy emitted and, thus, of the radiation dose. Alpha particles differ from the more familiar x rays or gamma rays in that they will not pass through much material. They are stopped completely by a thickness less than the normal sheet of paper. Since the skin has a protective layer of dead cells thick enough to absorb all of the alpha particles, radiation from plutonium outside of the body will not penetrate to the living cells. Further, since these cells are already dead and are constantly being renewed by sloughing and replacement from cells underneath, there can be no effect of the alpha particles in this layer. Thus, any quantity of plutonium outside of the body, even if spread directly on the skin, cannot cause harm. This situation is quite different from the case where radioactive materials which emit beta or gamma radiations are present or are handled since these other radiations can penetrate the dead layer of the skin and reach living tissue. It can then be seen that the release of a quantity of plutonium to the environment

constitutes a completely different problem than the release of more penetrating radioactive materials such as can occur from a postulated accident in a reactor or from the early fallout field of a nuclear detonation.

Why then does plutonium have the reputation of being a highly dangerous material? This is because it can be taken into the body, where the alpha radiation can gain access to the tissue without the protective layer to shield the radiation. In this sense, the potential problem is more akin to chemical poisons which must be taken into the body to produce any effect.

From the information given in the section on physiological properties of plutonium, it seems quite certain that the possibility of absorption of an effective amount of plutonium into the body through the skin under conditions characteristic of warhead incidents is remote indeed. Even scratches, cuts, and abrasions of contaminated skin appear to have little or no effect on the amount absorbed.

Effects from Ingestion and Absorption from the Gut

On the basis of the information given on page 4, ingestion or eating of plutonium oxide would hardly appear to be of any consequence. As the plutonium passes through the gastrointestinal tract, it is associated with a relatively large mass of material, and there is a fluid layer between the bulk contents of the gut and the gut mucosa. These two factors combine to stop the poorly penetrating alpha particles so that the radiation dose to the living tissue of the gastrointestinal tract is quite low as the nonabsorbable plutonium passes through the body. Suspensions of $^{239}PuO_2$ were administrated to rats by stomach tube at doses as high as 230 mCi/kg body weight (3.9 g/kg) without gross evidence of toxicity. Histological effects on the gut mucosa, studied after plutonium doses of 155 mCi/kg of body weight, were limited to mild inflammation of neutrophils in the surface of the epithelium and lamina propria of the cecum and colon at 3 days but not at 6 days after administration of the plutonium.

Absorption of PuO_2 from the gut is so low (probably <0.003 percent) that it would be necessary to eat 10^5 to 10^6 times the plutonium required to produce an effect for ingestion to have any biological significance. The possibility of ingesting such large amounts of plutonium would appear practically nonexistent under the prevailing conditions of noncritical warhead destruction.

Effects from Inhalation, Lung Deposition, and Translocation

The above considerations leave the toxicological effects of inhalation, lung deposition, and translocation as the principal concern, particularly under conditions inherent in noncritical detonation of nuclear warheads containing plutonium. As pointed out on p. 5, $^{239}PuO_2$ as well as any other solid can be dispersed in the atmosphere in particles small enough that they can be inhaled and deposited in segments of the respiratory tract. For the conditions under consideration, about 70 percent of the inspired material from a noncritical detonation may be deposited in the nasopharyngeal region and about 8 percent in the tracheobronchial region and clearance is rather rapid from both.

About 15 percent, however, is deposited in the respiratory or exchange space of the lung from which clearance is slow and significant translocation to other organs and tissues occurs. The chief concern, therefore, with inhaled PuO_2 is essentially with that portion deposited deep in the lung where rapid removal mechanisms are not operative and translocation to other tissues occurs more or less in keeping with the lung model predictions given in Table 1.

The actual radiation dose delivered to the various organs and tissues from plutonium alpha-particle emission is a function of the amount of plutonium present and its rate of removal either by elimination from the body or translocation to other tissues and organs. The organs or tissues of primary interest, because they are subjected to the highest radiation doses as a result of high levels of plutonium accumulation and slow elimination rates, are lung, lymph nodes, liver, and bone. The radiation dose to these structures may be estimated from the physical properties of the PuO_2 aerosol inhaled and the pertinent parameters of the deposition and retention model described on p. 5. Hopefully, some evaluation of the expected biological effects or consequences of inhalation of plutonium aerosols from nonnuclear weapons detonations may be derived by comparison with animal experiments and experience accumulated from humans who have received plutonium doses to these organs from other radiation sources.

The following subsections summarize some of the experimental observations in animals that appear pertinent to the effects of plutonium alpha radiation in the skeleton, lung, lymph nodes, and liver. Also included is a section summarizing some of the human experiences believed relevant to the problem of biological consequences of $^{239}PuO_2$ dispersal from nonnuclear destruction of nuclear weapons.

Effects in the Skeleton — Over the past 25 years numerous animal experiments have demonstrated that injection of plutonium and its subsequent localization in the skeleton result in the occurrence of spontaneous fractures and osteogenic sarcoma. These findings were not unanticipated in view of the experiences of radium workers and iatrogenic radium cases. These radium cases constitute the greatest single source of human information on the skeletal effects of radioactive isotopes that selectively concentrate in bone.

In 1951, a program was initiated on beagles at the University of Utah Medical School for the primary purpose of establishing the relative effectiveness of radium, plutonium, and other bone-seeking radioactive isotopes for production of bone disease on the basis of equivalent dose to the skeleton. The results of this program to date are summarized in Table 2. Plutonium was surprisingly more effective at producing skeletal disease than had been anticipated. All animals in the four highest dose levels died with bone sarcoma or (in the highest dose group) with complications associated with their plutonium burdens. This situation necessitated the introduction of lower-dose-level groups into the experiment. These lower-dose groups have not been on experiment long enough to yield definitive information on biological effects at these lower dose levels. The results to date, however, have produced considerable information relevant to the problem under consideration.

Table II. Osteosarcomas in the Utah beagles as of March 1968.[3]

Injected dose (μCi/kg of body weight)[a]	Osteosarcomas	Average exposure times and skeletal doses resulting in sarcoma	
		Time (yr)	Skeletal dose (rads)[b]
^{239}Pu			
2.88	7[c]	4.05	4930
0.909	12[c]	3.61	1310
0.296	12[c]	4.52	602
0.0951	10[c]	7.15	313
0.0477	8	8.14	183
0.0157	4	9.92	78
^{226}Ra			
10.4	9[c]	3.04	10900
3.21	12[c]	4.36	4530
1.07	11[c]	6.28	1940
0.339	5[c]	10.28	824
0.116	1	11.25	458
0.062	0		

[a]Twelve animals in each group except at the highest level.

[b]One year prior to death to allow for tumor induction time.

[c]All injected dogs at these levels have died.

Pathological bone fractures were a common occurrence in beagles receiving injected doses of 1 μCi Pu/kg of body weight and above. At the higher levels, nearly all beagles showed multiple fractures which were most common in the ribs and thoracic vertebrae. Histological examinations of bone specimens showed extensive microscopic damage to bone elements. Spontaneous healing of these fractures was a common occurrence.

The most serious and dramatic effect, however, of plutonium deposited in the bone was the production of osteogenic sarcoma. Four of the twelve animals that received only 0.0157 μCi of Pu/kg of body weight (the lowest dose level at which the beagles have lived out the majority of their life span) have died of bone tumors. The average skeletal radiation dose to these 4 animals was only 78 rads mean skeletal dose. Dose, in this case, was determined by measuring the skeletal plutonium content at death and averaging over the entire skeletal mass. Because of the nonhomogeneous distribution pattern of plutonium in bone, specific regions or portions of the organ may have received doses at least 100 times the organ mean dose. To date, the lowest skeletal mean dose to have produced a bone sarcoma was 60 rads. Whether serious osteogenic sarcoma will show up in the lower-dose groups at lower average skeletal doses

remains to be seen and makes the Utah beagle experiment of extreme interest and value for the future. There appears, however, to be a relationship between dose rate and latent period for tumor induction. The beagle's life span (average about 12 years) will not be long enough for the lower-dose groups to demonstrate unequivocally that an average skeletal dose of less than 60 rads for a lifetime will not produce an occasional osteogenic sarcoma during an exposure time approaching the normal life span of man.

Comparing the information to date on the relative tumor-producing properties of plutonium and radium shows that plutonium is from 5 to 10 times as effective as radium on the basis of an equal mean dose to the organ. The relatively greater effectiveness of plutonium over radium is attributable to their differences in distribution pattern in bone. These differences in distribution are such that more of the radiation dose from plutonium is confined to the more sensitive areas for tumor formation. This ratio provides an empirical means of relating the toxicity of radium in the human cases with the anticipated toxicity of plutonium in the human. While this procedure of comparing effects on animals with effects on man has uncertainty, it does have the merit of being a measurement of biological response in relation to the well studied effects of radium in humans. Although a species difference may enter into the final result, it should not be as important a factor in establishing the ratio as is the direct scoring of the response itself.

The leukemogenic effects of highly penetrating radiation are well known and publicized. Leukemia, however, has not been a particularly significant finding either in the human radium cases or in the beagles injected with plutonium.

Many other animal experiments (usually in rats and mice) on the tumorigenic effects of plutonium and other bone-seeking radioactive materials have been carried out. These observations are not reviewed here, but the results are not inconsistent with those shown in Table 2. In general, they indicate that plutonium is highly tumorigenic and that the doses required to produce bone tumors in these species are quite a bit higher than for the beagle. This species difference could be largely related to the interrelationships of dose, tumor induction time, and life span.

Effects in the Lung—The effects of radiation in the lung are primarily pneumonitis, fibrosis, and induction of lung tumors. Introduction of various isotopes into the lungs of experimental animals in a variety of forms and via a variety of methods has demonstrated that radiations emanating from radioactive material in the lung indeed will produce deleterious effects, including neoplasia. Human experience has likewise demonstrated such effects in man. Animal experiments most relevant to the problem under consideration are those conducted at the Hanford Pacific Northwest Laboratory (Battelle-Northwest) during the past 9 years.[4] About 100 beagles and several hundred rats and mice have been exposed via inhalation to PuO_2 aerosols. PuO_2 depositions of more than 0.1 μCi/g of lung tissue resulted in the death of all animals within about 1 year due to respiratory insufficiency brought about by extensive fibrosis and pneumonitis. This observation is not

surprising, since a concentration of 0.1 μCi/g results in an alpha radiation dose of about 25 rads/day which, at the observed elimination rate of the material from the lung (T/2 = 1000 to 1500 days), would deliver an average dose to the entire lung of 6000 to 9000 rads in the first year. Long-term or delayed effects were observed in 40 beagles subjected to a single inhalation exposure to $^{239}PuO_2$ aerosol with a count median diameter (CMD) of 0.25 to 0.5 μ and having much lower pulmonary retention levels than 0.1 μCi/g. All but 9 of these animals have died or have been sacrificed (~3 to 9 years after exposure). Some died (or were sacrified when death was eminent) of pulmonary insufficiency, some from lung tumors, and some showed pulmonary insufficiency plus lung tumors. The experimentalists[5] combined the animals in both the high- and low-exposure groups dying of pulmonary insufficiency and established a function for survival time versus plutonium lung concentration at death. By extrapolation to the maximum life expectancy of the beagle (15 years), they concluded that a retained pulmonary deposition of 0.002 μCi/g of bloodless lung would result in no life shortening from pulmonary insufficiency. They stressed, however, this level of pulmonary retention may cause life shortening due to pulmonary carcinogenesis.

Thirteen of the 40 animals in the lower exposure group have shown primary pulmonary neoplasms at autopsy. The tumors appeared multicentric in origin, and metastases were evident in 10 of the animals. Tumors were classified as bronchiolo-alveolar carcinomas, bronchiolar adenocarcinomas, and bronchial carcinomas. In addition, 2 animals showed a lymphangiosarcoma in a mediastinal lymph node, and 2 others showed neoplasia of the lung vasculature. Of the 9 animals still alive, 5 show radiographically confirmed tumors and 3 more are suspect.[6] This suggests a lung tumor incidence (histologically confirmed plus radiographically identified or suspected) in these animals of 52 percent. Had the other animals not died earlier from pulmonary insufficiency or been sacrificed, the incidence might be expected to approach 100 percent. The average organ mean dose for the animals with histologically confirmed lung tumors at autopsy was 7300 rads. The lowest dose resulting in a tumor was 3100 rads. These doses were calculated on the basis of the weight of the blood-free lung, which is about 60 percent of the functioning lung weight. This would change the previous dose values to 4400 and 1900 rads, respectively, on the basis of the functioning lung with its normal blood content. Furthermore, the tumors produced appear to be quite slow growing. Some animals were sacrificed or died when the tumor was just beginning, and others lived as much as 2 years after the tumor was initiated. The data are wholly inadequate to support other than a guess that the organ mean dose required to initiate the tumor surely was less than the doses estimated at time of death or sacrifice by as little as a few percent in some cases, and it may have been less by as much as 50 percent in others. The animal showing a tumor at the lowest terminal plutonium lung content (0.05 μCi in the total lung) lived 8.5 years. The radiation dose averaged over the whole lung was 4400 rads.

These and all the other animal data are inadequate to support even a crude dose-response relationship for the pulmonary tumorigenicity of $^{239}PuO_2$ deposited in the deep lung. As a basis for intuitive judgment, they suggest that mean organ dose levels in the vicinity of 2000 rads are tumorigenic and that doses in the vicinity of 4000 rads may produce a tumor incidence of at least 50 percent, which may approach 100 percent in a longer lived species if death does not result from pulmonary insufficiency. Furthermore, because of uncertainties in the dose levels observed to produce tumors and the levels required for tumor initiation, these levels of effect well may occur at one-half the stated doses (i.e., 1000 and 2000 rads).

Effects in the Lymph Nodes—According to the deposition and retention model discussed on p. 5, after respiratory deposition of an insoluble aerosol, the concentration of particles in the respiratory lymph nodes builds up slowly with time after inhalation until, at 1500 days, about 43 percent of the retained total body burden is in the lymph nodes compared to about 25 percent in the functional area of the lung. The beagle experiments at Hanford Battelle-Northwest suggest about 35 percent in the lymph nodes and about 35 percent in the deep lung. The difference lies in the different values for the amount transferred to the blood and subsequently deposited in the liver and bone. Net translocation of insoluble particles from the lung to the lymph nodes has been observed for several materials and in several animal species, including man. These observations are not surprising, since the movement of particles through the lymphatic system into the respiratory lymph nodes is one of nature's protective mechanisms for removing them from the lung and preventing their entering the systemic circulation. While the translocation rate to the lymph nodes is relatively slow (T/2 = ~500 days), the rate of elimination from these structures is slower still and a large fraction of the accumulated particulates may be retained indefinitely. These factors result in concentration ratios between lymph node and lung that increase with time after exposure. Furthermore, the lymph nodes are extremely small (total mass of the respiratory lymph nodes in man is 15 to 30 g) compared to the total lung (1000 g). Using the observed deposition ratios in the beagles and the relative masses of the human respiratory lymph nodes and lungs, the expected average concentration of PuO_2 in the lymph nodes at 1500 days after exposure would be about 23 to 46 times that in the lung. Since the average radiation dose rate is strictly dependent on concentration, the organ average dose rate to the pulmonary lymph nodes at 1500 days would be 23 to 46 times that to the lung. In addition, the much slower elimination rate from the lymph nodes than from the lung will result in an even larger life-time accumulated dose ratio between lymph nodes and lung.

Deaths in the 100 beagles and several hundred rats and mice studied at the Hanford Battelle-Northwest Laboratory were attributed primarily to pulmonary insufficiency resulting from fibrosis, pneumonitis, and lung tumors. In the animals dying, the lymph nodes were almost completely destroyed and were composed of up to 3 times their original mass of dense sclerotic or collagenous tissue devoid of lymphoid elements. Of the

beagles exposed in the lower deposition range, 2 animals showed lymphangiosarcoma which appeared to originate in the capsule of a mediastinal lymph node. Ten animals showed metastases of their primary lung tumors to the lymph nodes.

As the lymph nodes are small organs, the dose rate they receive is very high from even a small quantity of plutonium. Irradiation of the pulmonary lymph nodes, however, involves only a small volume of tissue. Experiments with animals to date have indicated that the primary effect at the dose rates studied are in the lung rather than in the lymph node. Where effects have been noted, they have been complete destruction of the lymph node with encapsulation of the plutonium in collagenous or fibrotic tissue or damage to the surrounding tissue which receives a high radiation dose due to its proximity to the lymph node. Present data suggest that lymph nodes are rather insensitive to radiation-induced malignant change and that effects in the lung are apt to be far more serious than effects in the lymph nodes themselves, despite the much higher doses delivered to the latter. This speculation, however, is questionable since long-term experiments in which the amount of plutonium deposited in the lung is small enough to permit observation of effects of a long-continued insult to viable lymphoid tissue have not been performed. It is conceivable that such experiments might result in primary lymph node malignancy when continued on a long-term basis, but this should be a second-order effect in terms of probability of occurrence since lung cancer has been shown to be more easily induced. However, this must remain an uncertainty and at this time is subject only to speculation.

Effects in the Liver—As mentioned on p. 5, a fraction of the plutonium deposited in the lung is translocated to the blood and subsequently deposited in the liver and bone, where it is tenaciously fixed. The beagle experiments at Hanford Battelle-Northwest Laboratory suggest that, beyond 1500 days after exposure, the liver-to-bone deposition ratio may be about 2. Since the mass of the skeleton is about 4 times that of the liver, the mean organ dose rate to the latter at these late times may be 8 times that to the bone. Taking into consideration the relative plutonium concentration in the liver and functional lungs of these animals and the comparable rate of liver build-up (~500 days) and lung clearance (~500 days), the mean organ dose to the livers of animals dying from pulmonary insufficiency and lung tumors would have been about 1/8th of the mean organ dose to the lung, or about 500 rads. None of these animals was reported as having liver tumors or significant liver involvement. Of 72 beagles in the Utah study injected in the higher-dose groups with plutonium citrate and now dead or reaching the end of their normal life span, 53 (74 percent) died of bone sarcoma, 2 had carcinoma of the bile duct, and 2 in the highest dose group died of hepatic failure. The initial diffuse distribution of plutonium in the liver persisted in some animals for as long as a year, but redistribution tended with time toward irregular deposition with concentration in sinusoidal reticuloendothelial cells and heavy periportal concentration. There

were no well defined cholangiomas and no malignant primary hepatic tumors. Because the plutonium was given as citrate complex, which favors bone deposition over liver deposition, the average dose to the livers was estimated to be approximately that to the bone. Lack of malignant liver tumors at this time in these animals is in striking contrast to the high incidence of osteosarcoma. The 2 bile duct carcinomas, however, occurred in animals whose bone doses were estimated at 91 and 200 rads. Although the liver would appear to be relatively insensitive to radiation-induced malignant change, it is not possible to say whether liver tumors might not be a possibility at very long times in animals with bone doses too small to produce death from osteogenic sarcoma.

Relevant Human Experience

From the previous discussion it is quite clear that animal experimentation cannot provide statistically valid dose-response relationships relating dose from inhalation of $^{239}PuO_2$ to tumor incidence or other deleterious effects in the lung, lymph nodes, bone, and liver. Even if it were possible to establish such relationships in animals, the problem of proper extrapolation to man would still exist. It would appear, therefore, that judgment as to the possible biological consequences of plutonium exposure from nonnuclear destruction of nuclear warheads should rely heavily on relevant human experience to date, although radiation type and exposure conditions in some cases may be quite different from those inherent in the problem under consideration. Although the degree of relevancy may be questioned in a strictly quantitative sense because of differences in conditions and the uncertainties of identifying and assessing the significant parameters, considerable relevancy pertains in that these experiences involve the human species. Relating different types of experiences to a specific problem requires a common denominator or point of reference.

Usually in predicting the outcome of a given radiation exposure, the radiation dose in rads (energy absorbed per unit mass of tissue) or the dose equivalent in rems (energy absorbed in the tissue weighted by a factor to allow for differences in the effectiveness of the radiation in producing damage as a function of radiation quality) are used. The radiation dose, however, is not a biological unit which bears, in itself, meaningful information as to the nature of the insult to the tissue. It is, instead, a very useful physical unit which undoubtedly bears a relation to the damage, but at the present state of knowledge this relation must be an empirical one for the conditions of irradiation under consideration. Further, the radiation dose is a measure of the "concentration" of energy liberated in the tissue with wide variations possible from point to point, depending upon the character of the radiation and distribution of the source or sources. In relating dose and effect, three different bases are commonly used for expressing dose. It is imperative to clearly specify the basis on which dose is expressed in deriving, discussing, and comparing dose-response relationships. Three methods of expressing dose are in common usage: (1) specific tissue dose; (2) hot-spot dose; and (3) average or mean organ dose. Each of these methods has its specific advantages, disadvantages, and proponents. The average or mean

to relate pertinent human data to the problem under consideration. The organ mean dose is the total energy absorbed by the total organ divided by the mass of the total organ. It has the advantage that it is readily determinable, and the assumptions as to anatomical features or the existence and location of specific types of tissues which may be more sensitive than the average are greatly minimized. It has the obvious disadvantage that, in very nonuniform distributions where sensitive cells may exist, extrapolations can lead to erroneous answers—either too high or too low depending upon the specifics of distribution with respect to the more sensitive tissue. It is, however, the method of choice in the present situation, since much of the human experience with tumorigenic effects of radiation is with materials that grossly, at least, involve the same target organs as does plutonium. Hopefully, differences in effect resulting from more subtle differences in conditions of deposition and exposure are minimized by empirical relationships derived from comparative animal studies.

The most pertinent human experiences are the radium cases reported by Evans,[7,8] and Finkel, Miller, and Hasterlik,[9] the epidemiological studies of uranium miners,[10-16] thorotrast cases reported by Marinelli,[17] and observations to date on plutonium workers with measurable body burdens. The relevancy of these observations to the problem of biological consequences of $^{239}PuO_2$ exposure from nonnuclear destruction of nuclear warheads resides in the fact that, like $^{239}PuO_2$ under the anticipated conditions, (1) they involve the human species; (2) they involve gross irradiation of the same organs and not generalized whole-body exposure; (3) the radiation dose is predominantly alpha rays with no necessity for assumptions as to quality factor or relative biological effectiveness; (4) they involve nonuniform spatial distribution of absorbed alpha-ray energy within the organ; (5) they involve chronic irradiation distributed over many years; and (6) they involve dose rates that are initially high and decrease with time.

No attempt is made to reevaluate these human experiences or to present the numerous claims and counterclaims as to their accuracy and the validity of the various authors' interpretations which usually involve the question of type of dose-response relationship (threshold versus nonthreshold). These issues are discussed at length in the above cited references. All that is attempted here is to relate empirically the mean organ doses suggested to have produced minimum morbidity in human experience to plutonium mean organ doses that may be expected to produce the same level of morbidity.

Bone Tumors in the Radium Cases—During the past 34 years, the group at the Massachusetts Institute of Technology has carefully studied 496 people with significant body burdens of radium and mesothorium.[7,8] Of these, 90 had accumulated skeletal average organ doses between 1200 and 50,000 rads and 406 had accumulated average skeletal doses below 1200 rads. These doses were accumulated over periods of from 10 to 50 years. Of the 90 cases with skeletal average organ doses above 1200 rads, 28 developed osteogenic sarcoma and 9 developed paranasal or mastoid carcinoma, giving a total tumor

carcinomas were observed in the cases with skeletal average doses of less than 1200 rads. Graphic presentation and statistical analysis of these observations led to a threshold dose-response interpretation with a constant 29 ± 6 percent incidence of tumors at skeletal average organ doses of 1000 to 1200 rads and above and dropping essentially to zero at or slightly below a dose of 1000 rads. Linear nonthreshold relations which would give the observed number of tumors were shown by statistical evaulation to be strongly rejected.

The Argonne Cancer Hosital[9] observed 218 subjects with current or preterminal measurable body burdens of radium ranging from 0.01 to 31.6 μCi. Of these, 18 had developed bone sarcomas, 12 had developed tumors of other types, and 3 had developed leukemias and other blood dyscrasias. Although they chose not to express their observations on the basis of skeletal average organ dose as did the MIT group but, rather, on the basis of estimated maximum radium burden, the two sets of observations appear to be in good general agreement with one highly questionable exception. Microscopic examination of the soft tissue around a tooth that was extracted from one of these cases who had a current radium burden of 0.13 μCi suggested carcinoma of the maxillary epithelium. On reexamination of the tissue, general pathologists continue to classify the lesion as squamous carcinoma. Oral pathologists, however, almost unanimously agree that it is not a malignant lesion.

As pointed out earlier, however, the Utah beagle studies indicate that these the plutonium problem in that these studies show plutonium is 5 to 10 times as effective as radium for production of bone tumors on the basis of an equivalent skeletal mean dose. Introduction of this relative effectiveness ratio indicates that an average skeletal organ dose of 100 to 200 rads from plutonium would have biological consequences equivalent to a dose of 1000 rads from radium (the threshold dose predicted from human experience). Acceptance of a threshold response, of course, suggests that the biological consequences increase disproportionately at doses greater than the threshold value. The minimum plutonium skeletal average organ dose to have resulted in bone sarcoma in the beagle studies was 60 rads. The average dose that produced sarcoma in 4 of 12 beagles (33 percent) was 78 rads. When these observations are considered along with the predicted threshold values of 100 to 200 rads from human radium experience, one is inclined to judge that accumulated skeletal average doses of 50 to 100 rads from bone-deposited plutonium may be approaching the level where biological consequences may be expected. Obviously, the above statement is only a matter of judgment and not amenable to statistical verification.

Bone Doses in the Thorotrast Cases— Intravenous injection of 25 to 50 ml of colloidal thorium dioxide, known as thorotrast, was practiced several years ago for diagnostic radiography of the circulatory system and the liver. Marinelli[17] has carried out detailed dosimetric estimations applicable to over 2000 thorotrast injection cases who have

carried their thorium burdens for 20 to 25 years. These estimates indicate skeletal average organ doses in these people of 30 to 80 rads. No osteogenic tumors have been observed in this group. The initial deposition pattern of the small amount of thorium that escapes the liver and deposits in calcified bone is, in general, quite similar to that of plutonium. Translocation of its first daughter, ^{228}Ra (T/2 = 5.8 years), from liver (where most of the thorium deposits initially) to bone would result in a bone distribution similar to but perhaps more uniform than that in the ^{226}Ra poisoning cases. Further decay of ^{228}Ra to ^{228}Th (T/2 = 1.9 years) probably would result in little translocation back to a pattern resembling that of plutonium. It might be expected, therefore, that the distribution of bone dose in the thorotrast cases would be more comparable to ^{226}Ra than to ^{239}Pu, even though ^{228}Th and its daughters contribute most of the dose. It would appear necessary, therefore to introduce the relative Pu/Ra toxicity ratio observed in the Utah beagle experiments, even though these experiments also show that ^{228}Th is 8 times as effective as ^{226}Ra and at least as effective as ^{239}Pu. The lack of bone sarcomas in the over 2000 thorotrast cases whose skeletal average doses from migrated thorium series alpha-ray emitters are in the range of 3 to 16 rad equivalents of plutonium provides the basis for a rather strong judgment that skeletal average doses from plutonium in this range, delivered over 20 to 25 years, is below the level expected to have biological consequences.

Lung Doses in the Thorotrast Cases— Lung exposure of the 2000 or so thorotrast cases, primarily from exhalation of thoron and its daughter products, also was estimated by Marinelli.[17] He estimated the lung average organ dose rate from a 50-ml injection to be 12.7 rads/year. With exposure times of 20 to 25 years, this would correspond to an accumulated lung average dose of 250 to 320 rads for a 50-ml injection and half that (125 to 160 rads) for a 25-ml injection. No lung tumors have been observed in over 2000 cases. Dose distribution to the lung in these cases would be expected to be more uniform than from deposited $^{239}PuO_2$, and there would be no translocation to the respiratory lymph nodes. These observations are relevant, however, in that they suggest that average lung doses of below 125 rads of uniformly distributed alpha-particle irradiation accumulated over a period of 20 to 25 years may not be expected to have biological consequences.

Lung Tumors in the Uranium Miners— Increased incidence of lung cancers in uranium miners was clearly established in the late 1920's. Cancer induction in miners is attributable, in part, to alpha-particle irradiation of the lung tissues from inhalation of radon and its short-lived daughter products in mine atmospheres. The unit of exposure in mine atmospheres is the working level (W.L.) and is related to the short-lived daughters of radon in 1 liter of air which will result in ultimate emission of 1.3×10^5 MeV of alpha radiation. The lung average organ dose associated with one working level month (W.L.M., taken to be exposure to one working level for 170 hours) is estimated at 0.1 rad.[16] Under the conditions of exposure, the highest dose is delivered

to the bronchial epithelium, which is considered by many investigators to be the critical tissue. Estimates of specific tissue doses to the bronchial epithelium from one W.L.M. range from ~30 to 70 times (3 to 7 rads) the average organ dose to the lung.[12]

The most extensive study of lung cancer in uranium miners is that of the U. S. Public Health Service started in 1950 which included 5000 underground uranium miners. This study has been reviewed extensively by a number of individuals and groups[11-16] in an attempt to provide a reasonable limitation of future exposures. A great deal of controversy and differences of opinion have resulted from interpretation of the data from the lower-exposure categories. Qualified radiobiologists, epidemiologists, and others who have studied the data carefully agree that, at high exposures (above ~1000 W.L.M.), the gross lung cancer rates increase significantly with increasing exposure from ~1000 to 7000 W.L.M. According to Evans,[16] above 900 ± 100 W.L.M., the incidence of lung cancer deaths increases at about the 1.5 power of exposure in W.L.M. Below this level, the cancer incidence in miners appears to be independent of exposure level but is a factor of ~4 higher than the incidence expected from a nonmining control population from the same general area. This observation indicates that there are other etiological factors associated with lung cancer in uranium miners than radiation exposure. For exposures below ~1000 W.L.M., individual feelings on interpretation of the data are divided roughly into three categories: (1) some feel that no interpretation can be made; (2) others feel that the data are consistent with a practical threshold at ~1000 W. L. M. with negligible risk at small exposures; and (3) others feel that, although present data suggest a threshold, there are sufficient inaccuracies so that additional data and other treatments may support a linear nonthreshold interpretation. Therefore, no definitive opinion seems possible at this time on the probable tumorigenic effects or biological consequences of exposures below 900 ± 100 W.L.M., which corresponds to an average dose to the lung of 80 to 100 rads.

The distribution of alpha-ray doses in the total mass of the lung from $^{239}PuO_2$ deposition and from inhalation of mine atmospheres are undoubtedly different; they are similar, however, in that some areas receive more than the organ average dose while others receive less. In the case of mine atmosphere inhalation, the highest dose is delivered to the bronchial epithelium which may receive 30 to 70 times the lung average dose (i.e., for 1000 W.L.M., 3000 to 7000 rads specific tissue dose). For $^{239}PuO_2$ deposition, the majority of the dose is delivered to the lymph nodes and to the pulmonary compartment (respiratory bronchioles, alveolar ducts, atria, alveoli, and alveolar sacs) which makes up a large fraction of the total lung. In the case of $^{239}PuO_2$ in the lung, there is no reason to assume in the comparison with mine atmospheres a greater effectiveness of the plutonium alpha radiation as is indicated by the comparison of radiation effects of ^{239}Pu and ^{226}Ra in bone. Some consider the bronchial epithelium to be a more radiosensitive tissue for induction of malignancy than pulmonary and lymphoid tissue.

The above considerations suggest that accumulated lung average doses of below 80 to 100 rads from $^{239}PuO_2$ deposited in the pulmonary tissues may not exceed the level where biological consequences may be expected.

Liver Tumors in the Thorotrast Cases — The primary site of colloidal ThO_2 deposition when injected into the blood is the reticulo-endothelial system. Therefore, the highest radiation doses from the deposited material are to the liver and spleen. Among the more than 2000 thorotrast injection cases studied in Portugal, Denmark, Sweden, and Japan, at least 57 malignant tumors of the liver have been reported.[18] Even though the dose rate to the spleen is greater than to the liver, no tumors of the spleen have been reported although splenic fibrosis has been seen. The usual dose of thorotrast administered was 25 ml which, according to Marinelli,[17] would result in a maximum alpha-radiation dose rate to the liver of approximately 75 rads/year. Self-absorption, because of the aggregation of the deposits in the liver, would reduce the dose rate to about 30 percent of the maximum or to about 22 rads/year. The majority of thorotrast cases were injected 20 to 25 years prior to observation, which would indicate an accumulated average organ dose to the liver of 450 to 550 rads. Both carcinomas and sarcomas were observed, the most common being hemangioendothelioma. The incidence of possible thorotrast-related deaths in the Portugese cases was 14 percent. The incidence of malignant neoplasms of the liver was approximately 5 percent. The latent period for development of tumors of the liver in these cases was 15 to 20 years, and additional tumors are expected to occur. It would appear that average liver doses of 450 to 550 rads are definitely associated with biological consequences. As mentioned previously, two bile duct carcinomas were observed following plutonium injection in the Utah beagle experiments: one at a dose level of 90 rads and the other at 200 rads. Strictly as a matter of judgment, it would appear that an average organ dose to the liver in the vicinity of 100 rads may be approaching the level of biological consequences.

Human Experience with Plutonium — Since the advent of the atomic energy program, a number of people working with plutonium have systemically accumulated quantities of the material measurable by urinary excretion. Urinary excretion measures only the quantity that has entered the systemic circulation and subsequently deposited in the bone and liver. Animal experiments show that about half of the plutonium entering the body from the lung and from puncture wounds (most common routes of exposure) is deposited in the liver and about half in bone. From the measured systemic burden of these subjects, it is possible to estimate the liver and skeletal average organ doses accumulated since their exposure which, in some cases, is as long as 24 years. It is possible also, on the basis of the lung deposition and retention model discussed on p. 5, to make a crude estimate of the accumulated average organ dose to the lung for those cases exposed via inhalation. In the latter cases, of course, considerable uncertainty in the doses is introduced both by uncer-

tainties in the lung model and because the specific chemical form of the material inhaled was not usually known. Such estimates of accumulated average organ doses for 37 individuals who had estimated systemic burdens in excess of the NCRP established maximum permissible level (0.04 μCi) are given in Table 3, which shows also the years since exposure and the route of exposure, whether via inhalation (I) or via absorption from a wound (W).

These are people who were exposed during the original Manhattan Project or in subsequent operations in facilities of the AEC operated by contractors. Others have received exposures approaching or

Table 3. Estimated accumulated average organ doses for plutonium exposure cases.

Time since exposure (yr)	Route of exposure[a]	Estimated exposure (MPL)[b]	Accumulated average organ dose		
			Bone (rads)	Liver (rads)	Lung (rads)
24	I	1.4	6.7	37	80
24	I	1.4	6.7	37	80
24	I	1.6	7.6	42	90
24	I	1.8	8.6	47	100
24	I	2.0	9.6	53	110
24	I	2.3	11.0	61	130
24	I	2.5	12.0	66	140
24	I	3.3	16.0	87	190
24	I	3.4	16.0	90	190
24	I	3.6	17.0	95	200
23	I	1.1	5.0	28	63
23	I	1.1	5.0	28	63
17	W	1.5	5.0	28	—
16	I	2.7	8.6	48	150
14	I	1.2	3.4	19	68
14	I	2.9	8.1	45	170
13	I	1.2	3.1	17	68
13	I	1.7	4.4	24	100
13	W	2.1	5.3	29	—
13	I	13.5	35.0	180	770
12	W	1.5	3.6	20	—
12	I,W	3.0	7.2	4	170?
12	I,W	10.0	20.0	130	570?
9	I	1.0	1.8	10	57
9	I	1.6	2.9	16	90
9	I	2.4	4.2	23	130
8	W	1.2	1.9	11	—
8	I	4.6	7.4	40	260
7	I	1.6	2.2	12	90
7	I	1.7	2.3	13	100
7	W	3.2	4.5	25	—
6	I,W	10.0	12.0	66	570?
5	I	1.0	1.0	5.5	57
5	W	2.5	2.5	14	—
5	W	3.0	3.0	16	—
5	W	8.0	8.0	44	—
4	W	3.0	2.4	13	—

[a] I, exposure via inhalation; W, exposure via absorption from a wound.

[b] One maximum permissible level (MPL) = 0.04 μCi.

greater than one MPL during licensee operations; these would be relatively few and of more recent origin. A number of workers have been similarly exposed in England and undoubtedly in other nuclear power countries. There have been no reports of any cases of lung, lymph node, liver, or bone morbidity attributable to plutonium inhalation or deposition. The 12 cases with exposures of 23 and 24 years duration have been kept under surveillance and subjected to occasional careful and thorough medical examinations. They have experienced no changes in their physical conditions not attributable to the natural aging process. Obviously, the number of cases is too few to support any elaborate extrapolations to the biological consequences of plutonium contamination from nonnuclear destruction of nuclear weapons systems. They are, however, human experience of the most relevant kind for guidance of value judgments where inadequate data exist on which to base detailed risk evaluations.

TRITIUM (^3H)

Physical, Chemical, and Radiological Properties

Tritium (^3H) is an isotope of ordinary hydrogen and in the elemental form, like hydrogen, is a gas at normal temperatures. It is readily oxidized to tritium oxide (water) in air by burning, and mixtures of hydrogen (and supposedly tritium) in air above 4% can deflagrate if a low ignition source is present. As with plutonium, the physical and chemical properties of the oxide are more relevant than are the properties of the element. The physical and chemical properties of tritium oxide may be considered as essentially the same as those of ordinary water insofar as the problem under consideration is concerned.

Tritium is highly radioactive and undergoes radioactive decay by beta particle emission. Its half-life is 12.26 years, and 1 μg gives off 2.2×10^{10} beta particles per minute (specific activity $\sim 10^4$ Ci/g). The energy of the beta particles, however, is quite low (E_{max} = 0.018 MeV).

Physiological Properties of Tritium

Under the conditions accompanying nonnuclear destruction of nuclear warheads, the tritium will probably be converted to tritium oxide (water). The physiological properties of tritium oxide are, in most respects, better known than for any other radioactive substance because the physiology of tritium oxide is the physiology of ordinary water and its behavior in the body is the same as body water.

Skin Absorption and Subsequent Distribution

Tritium water is absorbed through the skin to a surprising degree. The rate of absorption is a function of the difference in partial vapor pressure of the tritium water in the atmosphere and in the skin barrier. The absorption process involves exchange with moisture in the avascular layer of the skin and subsequent diffusion to the vascular bed with absorption into the bloodstream. The higher the skin temperature, the more rapid is the pick-up into the blood. Exposure of the bare skin of man to an atmosphere saturated with tritium water vapor at 24°C for periods of 15 minutes and longer indicated that an average of 0.018 mg/cm^2/min of water was absorbed into the body. In

practical terms, this would indicate that exposure of the total skin surface to an atmosphere containing tritium water vapor would result in a body intake that would be approximately the same as that from inhaling the same atmosphere at the normal breathing rate. Skin protection by ordinary clothing does not decrease the rate of uptake through the skin when exposure times are long enough to allow equilibration of atmospheric water vapor through the clothing material. For short exposure such as might occur during contaminated cloud passage, clothing would prevent equilibration and provide a high degree of protection from skin absorption.

Once tritium water enters the bloodstream, regardless of its route of entry, it equilibrates with the total body water reservoir in 45 to 90 minutes and becomes, for all practical purposes, uniformly distributed throughout the body. The body consists of approximately 65 percent water. Some tissues, fat, and bone have less than the average water content and some (the blood, for example) have more. These differences are not sufficiently great, however, to materially influence calculation of radiation dose.

The rate of excretion of tritium water is strictly a function of the rate of replacement of the total body water and is governed by the rate of fluid intake. The half time of replacement of body water (and, thus, the half-time of tritium water elimination) is approximately 12 days. Normal half-times as short as 7 days and as long as 17 days have been observed.

Ingestion and Absorption from the Gut

Essentially 100 percent of an ingested amount of tritium water is absorbed from the small intestine into the blood and equilibrated with the total body water within 90 minutes. Since excretion of tritium water is entirely a function of rate of body water turnover and is not influenced by the route of entry, the average elimination half-time of tritium water absorbed from the gut is 12 days.

Inhalation and Absorption from the Lung

Controlled experiments on human subjects show that 99 percent of tritium water inhaled exchanges with the moisture on the pulmonary surfaces and is absorbed into the bloodstream within minutes. Within 45 to 90 minutes, the tritium water in the bloodstream is equilibrated with the total body fluids. As with tritium water absorbed through the skin and from the gut, once equilibrated with the total body fluids the average excretion half time is 12 days. Exchange of tritium ions in the body water with the ordinary hydrogen ions (protium) in tissue resulting in slower elimination rates of a fraction of the tritium has been observed. The fraction of the tritium ions undergoing such exchange is so exceedingly small that it has no bearing on the problem.

Toxicological Properties of Tritium

The toxicological properties of tritium oxide are due entirely to the tritium beta radiation. Because tritium water distributes more or less uniformly throughout the body, the irradiation effects would be expected to resemble quite closely total-body radiation with high-energy x or gamma rays delivered at the same dose rate. The radiation dose from tritium water, however, would not be delivered instantaneously but would be delivered at a changing dose rate paralleling the rate of turnover of body water (T/2 = 12 days).

A tritium body burden of 1 mCi (assuming T/2 = 12 days) will deliver an infinite radiation dose of 120 mrads, half of which will be delivered in the first 12 days. Animal experiments have indicated that the beta rays of tritium are about 1.7 times more effective per rad for the production of certain effects than are x or gamma rays, which suggests a quality factor (QF) of 1.7 for the conversion of tritium beta-ray dose in rads to dose equivalents in rem. A QF of 1.7 for tritium beta rays is being questioned, and some radiobiologists feel the value should be near unity. Using a QF of 1.7, a body burden of 1 mCi of tritium would deliver a dose equivalent of 200 mrem. The promptly delivered dose of high-energy x or gamma rays required to produce a 50 percent chance of early death in man is estimated at about 300 rads (300 rem assuming a QF of 1). If delivered at a changing dose rate of T/2 = 12 days, the LD_{50} might be about 600 rem. On this basis, the LD_{50} intake for tritium would be about 3 Ci.

An exposure of 400 rem (2 Ci) might be associated with a 5 to 10 percent probability of producing death without forced-fluid therapy. The usually considered late or delayed effects of whole-body radiation exposure are actuarial life shortening and increased incidence of leukemia and other neoplastic disease. The actuarial life shortening risk associated with whole-body exposure is not known for man, but informed estimates range from 1 to 10 days per rem, depending on exposure rate. Leukemia risk is estimated at 1 to 2 per 10^6 man-years/rem. The risk from all other malignancies is believed to be approximately equal to that from leukemia. The possibility of genetic effects receives considerable attention also; however, the significance of radiation-induced mutations depends on the exposure of a very large population, which would not occur as a result of a nonnuclear weapons incident.

BERYLLIUM

Physical and Chemical Properties

Beryllium is a silvery-white, brittle element similar in appearance to magnesium With an atomic weight of 9 and a density of 1.85, it is one of the lightest elements. Beryllium metal surfaces, when exposed to air, rapidly become coated with a thin transparent layer of oxide which protects the surface against further oxidation. In the presence of water, particularly if it contains a trace of chloride ions, oxidation proceeds with moderate rapidity, creating a white surface coating of oxide and hydroxide. Beryllium metal melts at 1285°C (2340°F). Beryllium oxide (BeO) is a white crystalline compound melting at 2550°C (4620°F). The oxide (density 3.01) can be formed by heating or burning beryllium metal, but it is usually prepared by igniting the hydroxide or the sulfate at temperatures between 800 and 1400°C. BeO is not as friable as PuO_2 and melts at about 2500°C. The vapor pressure of BeO is low even at high temperatures but is increased significantly in the presence of water vapor. The particle size of the oxide formed by ignition is dependent both on the ignition temperature and on the particular compound ignited. It is smaller at lower ignition temperatures.

Chemically, beryllium is an amphoteric element and, hence, reacts with acids to form beryllium salts and with alkali to

form beryllates. In consequence, all beryllium compounds are readily hydrolyzed by water. BeO is very stable, but its reaction with other materials is strongly influenced by its state of subdivision. It readily forms beryllium hydroxide when heated with water, and the solubility of BeO in water at room temperature is about 200 μg/liter.

The greatest practical stimulus for the production of beryllium has been its application in the field of atomic energy. Its low atomic weight and low thermal neutron absorption cross section give it good moderating and reflecting properties for use in nuclear reactors and weapons. Normal beryllium is nonradioactive.

Physiological Properties

Both beryllium metal and beryllium oxide are apparently very insoluble and unreactive in the pH range found in the body. However, due to its amphoteric nature, it may slowly dissolve and more soluble beryllium compounds may hydrolyze and precipitate. In extremely dilute solutions, the mode of existence of neutral beryllium is probably a colloidally hydrated form. Because hydrolyzed beryllium salts are highly acidic, they produce strong local reactions with tissue. Because of its similarity to magnesium in electronic configuration, it may replace that element in certain physiologic reactions, particularly enzyme systems where magnesium is a key element. For example, beryllium is a powerful inhibitor of alkaline phosphatase, and this inhibition is measurable at extremely low beryllium concentrations. It appears that the entire biological activity of inhaled beryllium in the mammalian lung is not now attributable to a single well defined property or reaction.

Toxicological Properties

Inhalation of beryllium and its compounds may produce two types of disease acute and chronic. Acute disease may result from relatively brief exposure to high concentrations of beryllium oxide or other beryllium compounds. The results may be a pneumonitis where exposure is to the metal or oxide. Nasal pharyngitis or tracheobronchitis is more likely from highly soluble compounds. The pneumonitis may be fulminating following massive exposure, or less severe with gradual onset from lesser exposures.

The chronic disease may result from varying lengths of exposure to a wide range of concentrations, including quite low concentrations. In some cases there is a prompt onset of symptoms, while in others there may be a delay of many months or years between the last exposure and onset of symptoms. Although respiratory symptoms are most prominent and usually occur first, the chronic disease is considered by many to be a systemic disease which may involve other organs. This is consistent with the slow release of beryllium from its original site of pulmonary deposition. Chronic berylliosis is a progressive wasting disease which may be arrested but not cured by medical treatment. It is marked by dramatic weight loss and a great loss of pulmonary function capacity.

Accidental implantation of beryllium or its compounds beneath the skin may cause necrosis of adjacent tissue with the forma-

tion of an ulcer. Implantation of comparatively insoluble compounds may produce a granuloma. Exposure of the eye to beryllium compounds in air can provoke conjunctivitis. No harmful clinical effects have been reported from ingestion of beryllium-containing materials.

While there undoubtedly are some differences in biological effect between different beryllium compounds, all beryllium compounds with the exception of beryl have been found toxic when animals or humans have been exposed. There is no basis on which a quantitative difference of toxic effect can be established with the exception of beryl. The latter seems inert under conditions of known exposure.

Acute beryllium disease has been produced by an estimated intake of 45 μg of beryllium in a normal healthy worker, and intakes as low as 5 μg might certainly cause acute illness in persons of unusual susceptibility or in children or in individuals with respiratory disease. Lung deposition of less than 1 μg would possibly produce no acute effect. Progression from acute to chronic berylliosis is rare (but not unknown) and, hence, chronic berylliosis does not seem to be a serious risk from a single exposure, as in cloud passage. The U. S. Public Health Service has suggested 75 $\mu g\text{-}min/m^3$ as an acceptable limit for offsite exposure to a beryllium rocket fuel exhaust cloud. Assuming a ventilation rate of 20 liters/min, this is a total intake of 1.5 μg, which is consistent with the previous estimate.

It is extremely difficult to predict the toxicity of beryllium under conditions of continuous occupancy of an area contaminated with beryllium in toxic form. An air concentration of 0.01 $\mu g/m^3$ is used as a limit for offsite air contamination by a beryllium-using facility. Assuming a contamination level of 1 mg/m^2 and a resuspension factor of 10^{-6}, this amounts to an air concentration of 0.001 $\mu g/m^3$ for what might be considered average conditions. Conditions might be anticipated where the air concentrations may be greater or smaller by at least a factor of 10. Normal occupancy of an area can, within itself, produce the most diverse conditions of exposure.

In the case of beryllium, individual susceptibility is more variable than with most materials, and a sensitivity response is postulated by some authorities. This makes it impossible to predict the degree of risk associated with normal occupancy of a beryllium-contaminated area. Beryllium concentrations in the lungs of persons with no known beryllium exposure are highly variable; values from 0 to 3900 μg per 1000 g of tissue have been reported. These probably reflect differences in beryllium content of the soil and in coal being burned in the area. Workers having a definite beryllium exposure usually show concentrations in the higher portion of the above range, but there seems to be little relation between lung concentration and incidence of beryllium disease.

Predicted $^{239}PuO_2$ Exposures from Continuous Occupancy of a Contaminated Area

Since the lung offers the only significant route of entry into the body for highly dilute $^{239}PuO_2$ aerosols, the principal problems in evaluation of the hazard from continuous occupancy of a region contaminated with surface deposition from a cloud or plume are estimations of the fraction of material resuspended and the duration of the hazard. In order to obtain entry into the lungs, the $^{239}PuO_2$ must be in very fine "respirable" particles [i.e., less than 10 μ in activity median aerodynamic diameter (AMAD)]. These particles are rare and short-lived in the deposition field. Such fine particles are not deposited efficiently from the initial cloud and tend to be blown to long distances and are consequently highly diluted. They are carried down into the soil and fixed or cemented to larger particles by the action of water, and those which remain on the surface are comparatively difficult to resuspend because of their high threshold drag velocity.[19] Thus, their appearance as a respirable aerosol is primarily a result of secondary processes.[20] Their regeneration and suspension are by collision of or with larger, saltating particles, the latter being mostly in the 100-μ size range. These processes will be highly sensitive to local micrometeorological conditions, and significant concentrations will result only when the wind velocity is fairly high (i.e., greater than 10 miles/hour[19]). Thus, a calculation of exposure from first principles is virtually impossible, and the best approach seems to be reliance on the air concentrations as measured in the field as a function of time.

The first factor of importance is the resuspension factor k, defined as the ratio of the air concentration in m^{-3} to the ground concentration in m^{-2} (thus, k has the dimensions of m^{-1} and can be regarded as the quotient of the fraction K resuspended by the effective height h through which the resuspended material is dispersed: $k = K/h$). Many people have looked at the problem of resuspension from both the theoretical and experimental point of view with the objective of selecting generally useful values of k for industrial and military situations. All admit that the wide variety of possible meteorological and environmental conditions make any one value subject to possible large errors for a specific situation. However, by choosing pessimistic conditions (e.g., dry, unvegetated desert), it is believed that most of the error is on the side of safety.

Mishima[21] has summarized several dozen values of k and notes that many of them lie in the range 10^{-5} to 10^{-7} for Nevada Test Site conditions. We shall use $k = 10^{-6}\ m^{-1}$, a value proposed by Stewart at the International Symposium on Surface Contamination,[22] with the expectation that the value for inhabited vegetated areas will be much smaller. [Note: Fine dust on a smooth (e.g., paved) surface is very difficult to resuspend and is very easy to flush into drains and sewers.]

The other factor necessary to estimate the chronic hazard is the change of air

concentration with time. Here again, experimental field data seem the most useful, and results at NTS[23] based on air concentration measurements for 20 weeks near the 10, 100, and 1000 $\mu g/m^2$ contours indicate an exponential decline with a half-time of about 35 days. This is probably a pessimistic value because of the absence of moisture, a potent agent both for transport of small particles downward into the soil by percolation and for cementing particles into larger units; in more humid climates than the Nevada desert, the rate of immobilization should be higher.

The physiological model for inhalation, accumulation, and elimination of a plutonium-bearing aerosol by the lung is the one discussed on p. 5. Because of the extended duration of the exposure, the significant portion of the lung dose in the chronic case will result only from the long-lived (500-day) component.

The rate of change of the lung burden with time is given by

$$dq_L/dt = -\lambda_B q_L + RFC \qquad (1)$$

where

q_L = the lung burden in microcuries at time t

λ_B = the rate of elimination from the lung per day = (ln 2)/500 d

R = the respiration rate = 24 m^3/day (17 liter/min)

F = the fraction of the inhaled plutonium which is retained in the 500-day pulmonary compartment = 0.25 × 0.60 = 0.15

C = the air concentration at time t in $\mu Ci/m^3$ and is given by

$$C = C_0 e^{-\lambda_A t}$$

where

λ_A = the rate constant for air clearance = (ln 2)/35 d and

C_0 = the air concentration at zero time.

[Equation (1) is formally analogous to the equation for the daughter product in a radioactivity decay series[24] with the difference that the rate of transfer of material to the lung is RF instead of λ_A, the rate of disappearance from the air.]

Equation (1) can be integrated to give,

$$q_L = C_0 \frac{RF}{\lambda_B - \lambda_A}\left(e^{-\lambda_A t} - e^{-\lambda_B t}\right) \qquad (2)$$

$$q_L = 194 C_0 \left(e^{-0.0014t} - e^{-0.020t}\right) \qquad (3)$$

[If it is desired to consider models with more than one clearance time from the lung, then the equation for total lung burden is just the sum of terms of the form of Eq. (2), each term having the appropriate value of F and λ_B for the corresponding compartment. In the current model, only the 500-day compartment is significant in the present context.]

The value of q_L/C_0 (in units of m^3) is plotted as a function of exposure time in Fig. 1, as calculated from Eq. (3). An important feature of this curve is the long time scale; the maximum lung burden is reached only after 143 days and 30 days are required to accumulate half the maximum burden. Beyond 143 days, the curve becomes exponential with a 500-day half-time, and the burden has fallen to half the maximum at about 2 years. The time available for clean-up operations is determined by the air clearance time of 35 days; clean-up must be accomplished in the first

few weeks in order to significantly reduce the total burden. Alternatively, evacuation of the higher areas for a few months would have the same effect.

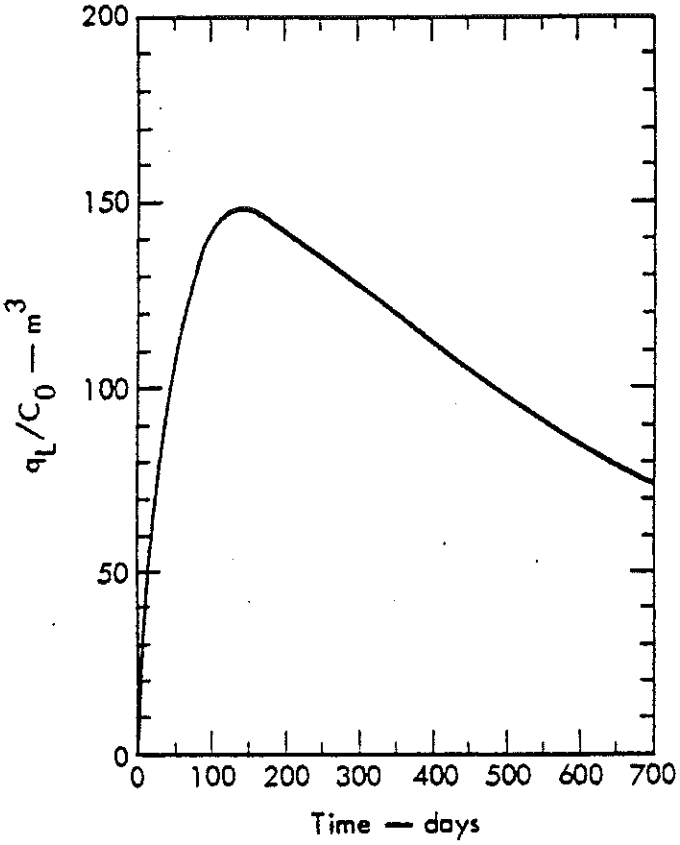

Fig. 1. Pu lung burden as a function of time of exposure in a contaminated area.

(If different values of λ_A were assumed, the peak value of the lung burden would scale approximately as the air clearance time; thus, if the latter were 100 days, instead of 35 days, q_{max} would be $350C_0$ and would be reached at 290 days.)

In order to deduce the total lifetime dose in μCi-days, Eq. (3) is integrated from $t = 0$ to ∞ with the result,

$$\int_0^\infty q(t)\,dt = 1.3 \times 10^5\, C_0.$$

If the resuspension factor is 10^{-6} and S_0 is the initial surface concentration in $\mu g/m^2$ (15 $\mu g/\mu Ci$), this becomes

$$q(t)\,dt = 0.009S_0.$$

Finally, since 1 μCi-day of exposure to the lung is 0.27 rad, the integrated life-time dose D in rads with S_0 in $\mu g/m^2$ is:

$$D = 0.0023S_0 . \qquad (4)$$

In the case of other possibly critical organs, only the liver and bone need be considered. Again using the model given on p. 5, some of the material in the pulmonary compartment is assumed to move to the blood: 5 percent of it directly and 1.5 percent via the lymph, for a total of 6.5 percent. We will assume that half of this goes to the liver and half to bone and that both fractions have negligible excretion (infinite half-times). The total amount of plutonium passing through the pulmonary compartment is subject to this translocation, and this amount is $180C_0$ (rather than the $148C_0$ which is the maximum amount there at any time). The maximum plutonium burden in μCi of each of these two organs (reached about 3 years after exposure) is, therefore, $0.032 \times 180C_0$ (C_0 in $\mu Ci/m^3$) or $3.8 \times 10^{-7}S_0$ (S_0 in $\mu g/m^3$ and a resuspension factor of 10^{-6}). If the plutonium is assumed to remain for a lifetime in these organs, then a 70-year exposure is indicated (2.56×10^4 days), and the exposure in μCi-days becomes $0.01S_0$ for both organs. Because of larger organ size, rad/μCi-day is smaller for the liver than for the lung; for a 10-kg skeleton the factor is 0.027 rad/μCi-day and for a 1.7-kg liver the factor is 0.157. The lifetime dose in rads calculated from a given initial surface contamination is $2.7 \times 10^{-4}S_0$ for the bone and $1.6 \times 10^{-3}S_0$ for the liver compared with the lung value of $2.3 \times 10^{-3}S_0$. (Note that the lung dose is delivered in a few years while the other two require 70 years.)

These conversion factors lead to the results given in Table 4 for the life-time dose to each organ as a function of initial ground concentration S_0. These values may be considered as reasonable for average local conditions and circumstances. They are highly sensitive to conditions affecting the resuspension factor k. One can imagine situations where the values conceivably might be low or high by at least a factor of 10.

Table 4. Accumulated organ average doses from lifetime occupancy of an area contaminated with $^{239}PuO_2$.

Initial surface contamination level, S_0 ($\mu g/m^2$)	Lifetime accumulated organ average dose		
	Lung (rads)[a]	Liver (rads)	Bone (rads)
100	0.23	0.16	0.027
1000	2.3	1.6	0.27
10,000	23	16	2.7

[a]Calculated on the basis of the parameters of the lung model given on p. 5.

Considerations of Biological Consequences from Plutonium Exposures

The radiotoxicological properties of ^{239}Pu, as indicated by animal investigations and comparison with human experience with other radiotoxicological materials, have been considered in some detail on pp. 7-20. This information is summarized in Table 5 and its footnotes. These data are inadequate to provide a basis for sophisticated statistical approaches to dose-response relationships from which to make probabilistic risk assessments in situations involving plutonium exposure from nonnuclear destruction of nuclear warheads. It would appear necessary, therefore, to offer a completely empirical judgment as to the levels at or above which biological consequences may ensue. One such judgment is offered in the summary table. Even if this judgment is accepted, its application to the problem under consideration is subject to the uncertainties introduced by the fact that the observations on which the judgment is based involve small populations of limited distribution. Again, empirical judgment is necessary. One approach might be to adopt the practice of the NCRP and other committees and lower the values by a factor of 10 to generally cover these uncertainties when applying guides to uncontrolled population groups. This practice would lower the levels of possible biological consequences to 10, 5, and 10 rads for lung, bone, and liver, respectively.

This approach implies that the nature of the dose-response relationship and the broader heterogeneity of the population are taken care of within the factor of 10. Another approach might be to assume that the judgment values given in Table 5 apply to the size and nature of the population studied (12-2000, mean about 1000) and the relatively greater heterogeneity in a normal population of this size might be allowed for by evoking the rule of thumb assumption that limits of 1/3 and 3 times the mean, in general, encompass most of the variability encountered in biological phenomena. This approach would give 33, 17, and 33 rads as limiting values for lung, bone, and liver, respectively, when

Table 5. Summary of accumulated average organ doses from plutonium where biological consequences may ensue.

Basis for judgment	Accumulated average organ dose		
	Lung (rads)	Bone (rads)	Liver (rads)
Human experience			
Radium poisoning cases	—	100[a]	—
Thorotrast cases	>125[b]	>~5[c]	<450-500[d]
Uranium miners	80-100[e]	—	—
Plutonium exposure cases	>120[f]	>10[f]	>60[f]
Animal (dogs) investigations			
Plutonium injections	—	<78[g]	<150[h]
Plutonium inhalation	<~2000[i]	—	—
Judgment[j]	100	50	100

[a]No effect expected in 400 cases below this level; 29 percent bone tumors in 90 cases above 120 rads when compared to ^{226}Ra, assuming that the effectiveness ratio of $^{239}Pu/^{226}Ra$ is 10 (10 to 50 years).

[b]No effect in 2000 cases with exposures below this level, assuming that the effectiveness ratio of $^{239}Pu/^{232}Th$ plus its descendants is unity (20 to 25 years).

[c]No effect in 2000 cases, assuming that the effectiveness ratio of ^{239}Pu/migrated descendants of ^{232}Th is 5 to 10 (20 to 25 years).

[d]Five percent liver tumors in 733 cases, assuming that the effectiveness ratio of $^{239}Pu/0.3$ of total energy release from ^{232}Th plus its descendants is unity (20 to 25 years).

[e]Questionable or no effects in 1300 cases exposed below this level, assuming that the effectiveness ratio of $^{239}Pu/Rn$ plus its descendants is unity; increasing tumor incidence in accordance with 1.5 power of dose in approximately 700 cases above this level (10 years).

[f]No effects observed at these average levels in 12 cases (23 to 24 years).

[g]Bone tumors in 4 to 12 beagles (33 percent) at this average level (10 years).

[h]Two bile duct carcinomas in 12 beagles (11 years).

[i]Average level (corrected for tumor initiation time) producing 50 percent tumor incidence in 40 beagles; incidence might have approached 100 percent had other animals not been sacrificed or died from pulmonary fibrosis.

[j]Completely empirical judgment as to levels at or above which biological consequences may ensue in a small population of limited distribution.

applied to a normal population group of up to 1000. Arbitrarily, the limiting values could be additionally reduced by a factor of 2 for each 10-fold increase in population. The limiting values under these assumptions are shown in Table 6. This

Table 6. Dose limit adjustment for size and nature of the population.

Population	Dose limit[a] from plutonium: Lung (rads)	Bone (rads)	Liver (rads)
Sample (12-2000, mean 1000)	100	50	100
Uncontrolled population up to 10^{-3}	33	17	33
Uncontrolled population up to 10^{-4}	17	8	17
Uncontrolled population up to 10^{-5}	8	4	8

[a] If a comparison is to be made with NCRP maximum permissible exposure guides, rads × 10 = exposure equivalent in rems.

philosophy makes adjustments, to some degree, for the lack of information on the true dose-response relationship while simultaneously making some allowance for the heterogeneity of the exposed population.

It should be emphasized that these values are not proposed as maximum permissible levels in the usual sense but are guides for the anticipation of once-in-a-lifetime emergency situations with a low probability of occurrence. In any accidental situation, maximum permissible levels of exposure are of little practical value because the source is not under control.

Feasibility of Plutonium Decontamination

Experience has shown that most plutonium-contaminated surfaces can be restored and returned to normal use through the application of appropriate decontamination methods by properly trained personnel. Accidents involving plutonium contamination[25-30] and controlled experiments during Operation Plumbbob[31,32] have illustrated the effectiveness of several plutonium decontamination methods. Additional information is contained in a number of publications[33,34] concerning general decontamination procedures.

The selection of an appropriate decontamination method will depend on the contamination levels involved, surface characteristics, environmental conditions, economic considerations, and the intended future use of the area. Thus, no single decontamination method is suitable for all situations, and, under most conditions, several methods would probably be utilized. Some of the methods that have been tested and corresponding decontamination efficiencies for various surfaces are listed below.

HARD SURFACES

Decontamination of hard surfaces may be accomplished by the following methods.

Water Methods

A water truck capable of producing a water stream at a pressure of 200 to 400 pounds/in.^{2} is used for (1) plain water hosing, (2) water hosing and scrubbing, (3) hosing with 1 percent (by weight) commercial detergent and water solution, or (4) detergent-solution hosing followed by scrubbing and rinse.

Sandblasting

The surface is removed in this operation, and it should only be used when other methods are unsuccessful. The loose residue must be collected by some suitable means, such as vacuum cleaning.

Vacuum Cleaning

Vacuuming is suitable for situations where the use of water would not be practical. Suitable filters are placed over the

exhaust to prevent resuspension of the contaminant blowing through the cleaner.

Steam Cleaning

Greasy or oily surfaces may best be cleaned by the use of steam cleaners. Decontamination efficiencies for these methods on various surfaces are listed in Table 7.

LAND AREAS[31,32]

Methods for fixation and/or decontamination of land areas include the following.

Plowing

Plowing to a depth of 12 in. to ensure adequate mixing and burial of the contaminant.

Table 7. Percent efficiencies for various hard surface decontamination methods.

	Method (% efficiency)						
Material	Vacuum	High pressure water	High pressure water with scrub	High pressure water and detergent	High pressure water and detergent with scrub	Sand blasting	Steam cleaning
Glass	98	99	97	100	99	100	97
Stucco	48	97	95	95	99	100	27
Painted wood	99	98	96	99	99	100	91
Unpainted wood	36	85	93	99	95	99	85
Aluminum	89	99	97	99	100	98	84
Plate steel	93	97	94	100	98	99	91
Asbestos shingles	61	99	98	96	99	100	63
Unpainted wood shingles	61	97	90	95	97	99	71
Brick	29	99	99	99	99	99	97
Tar paper	55	98	95	95	96	99	52
Corrugated galvanized roofing	69	99	97	99	99	100	85
Highway asphalt	32	99	96	99	99	99	44
Highway asphalt (10 ft^2)	72	92	94	98	96	92	22
Sealed asphalt	71	98	90	100	99	99	84
Sealed asphalt (10 ft^2)	64	90	82	96	97	90	48
Steel trowel concrete	74	98	—	96	99	100	—
Steel trowel concrete (10 ft^2)	—	78	97	—	98	98	27
Wood float concrete	—	98	92	100	97	100	65
Wood float concrete (10 ft^2)	56	97	—	98	98	98	85
Average of all surfaces	66	96	94	98	98	98	67

Scraping

The top 2 in. of the soil are removed for subsequent disposition.

Oiling

The oil treatment consists of spreading RC-O (rapid cure) oil over the area with an oil-distribution truck. This forms a semihardened surface within 24 hours.

Oiling and Scraping

Following the oiling operation as described above, the hardened oil crust can be scraped off for subsequent disposal.

Wetting Down with Water and Scraping

Wetting down with approximately 0.3 in. of water tends to temporarily fix the contaminant and permits removal by scraping without excessive resuspension of the contaminant.

Flooding with Water (1 in.)

Flooding with large amounts of water will accelerate the natural weathering action and will tend to leach the contaminant into the soil, thereby reducing the amount of contaminant resuspended in the air.

Decontamination efficiencies for land area methods are listed in Table 8. It should be emphasized that in all decontamination efforts, careful consideration must be given to proper disposal of contaminated waste.

Table 8. Land area fixation and/or decontamination efficiencies.

Method for ground decontamination	Activity present		Efficiency (percent)
	Mean initial (dpm/m^2)	Mean final (dpm/m^2)	
Plowing	8200	140	98
Oil and scrape	4200	80	98
Scrape	500	25	95
Water (0.3 in.) and scrape	1400	100	93
Oil (RC-O road oil)	1000	100	89
Flooding with water (1.0 in.)	1600	225	85
Water-$FeCl_3$ solution (0.3 in.)	4000	630	84
Disking	3000	730	76

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