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Radiological Health and Related Standards for Nuclear Power Plants

A.V. Nero and Y.C. Wong

January, 1977

Lawrence Berkeley Laboratory University of California/Berkeley

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RADIOLOGICAL HEALTH AND RELATED STANDARDS FOR NUCLEAR POWER PLANTS

A. V. Nero and Y. C. Wong

Volume 2

of

HEALTH AND SAFETY IMPACTS OF

NUCLEAR, GEOTHERMAL, AND FOSSIL-FUEL

ELECTRIC GENERATION IN CALIFORNIA

Energy and Environment Division
Lawrence Berkeley Laboratory
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Vol. 1: "Health and Safety Impacts of Nuclear, Geothermal, and Fossil-Fuel Electric Generation in California: Overview Report," by the entire staff, Lawrence Berkeley Laboratory Report LBL-5924. Includes "Executive Summary" for the project.

Vol. 2: "Radiological Health and Related Standards for Nuclear Power Plants," by A.V. Nero and Y.C. Wong, Lawrence Berkeley Laboratory Report LBL-5285.

Vol. 3: "A Review of Light-Water Reactor Safety Studies," by A.V. Nero and M.R.K. Farnaam, Lawrence Berkeley Laboratory Report LBL-5286.

Vol. 4: "Radiological Emergency Response Planning for Nuclear Power Plants in California," by W.W.S. Yen, Lawrence Berkeley Laboratory Report LBL-5920.

Vol. 5: "Control of Population Densities Surrounding Nuclear Power Plants," by A.V. Nero, C.H. Schroeder, and W.W.S. Yen, Lawrence Berkeley Laboratory Report LBL-5921.

Vol. 6: "Health Effects and Related Standards for Fossil-Fuel and Geothermal Power Plants," by G.D. Case, T.A. Bertolli, J.C. Bodington, T.A. Choy, and A.V. Nero, Lawrence Berkeley Report LBL-5287.

Vol. 7: "Power Plant Reliability-Availability and State Regulation," by A.V. Nero and I.N.M.N. Bouromand, Lawrence Berkeley Laboratory Report LBL-5922.

Vol. 8: "A Review of Air Quality Modeling Techniques," by L.C. Rosen, Lawrence Berkeley Laboratory Report LBL-5998.

Vol. 9: "Methodologies for Review of the Health and Safety Aspects of Proposed Nuclear, Geothermal, and Fossil-Fuel Sites and Facilities," by A.V. Nero, M.S. Quinby-Hunt, et al., Lawrence Berkeley Laboratory Report LBL-5923.

RADIOLOGICAL HEALTH AND RELATED STANDARDS FOR NUCLEAR POWER PLANTS

ABSTRACT

This report summarizes the status and basis of radiation protection standards, with a view to identifying how they particularly apply to nuclear power plants. The national and international organizations involved in the setting of standards are discussed, paying explicit attention to their jurisdictions and to the considerations they use in setting standards. The routine and accidental radioactive emissions from nuclear power plants are characterized, and the effect of these emissions on ambient radiation levels is discussed. The state of information on the relationship between radiation exposures and health effects is summarized.

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SELECTED ABBREVIATIONS

BEIR	- the National Academy of Sciences - National Research Council Committee on the Biological Effects of Ionizing Radiation; the 1972 report of the BEIR Committee
BWR	- boiling water reactor
CFR	- Code of Federal Regulations
EPA	- Environmental Protection Agency
FRC	- Federal Radiation Council
GESMO	- Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors
GWY	- gigawatt-year
IAEA	- International Atomic Energy Agency
ICRP	- International Commission on Radiological Protection
ICRU	- International Commission on Radiological Units and Measurements
LET	- linear energy transfer
LWR	- light water reactor
MPBB	- maximum permissible body burden
MPC	- maximum permissible concentration
NCRP	- National Council on Radiation Protection and Measurements
NRC	- Nuclear Regulatory Commission
PAG	- protective action guide
PWR	- pressurized water reactor
RBE	- relative biological effectiveness
RG	- Regulatory Guide (NRC)
SAR	- Safety Analysis Report
UNSCEAR	- United Nations Scientific Committee on the Effects of Atomic Radiation; the 1972 report of the UNSCEAR committee

Many of the units used in this report are defined in the Glossary.

1. INTRODUCTION

1.1 Purpose and scope of this report

The purpose of this report is to summarize the radiological implications of emissions from nuclear power plants, considering the emissions from these power plants, the effects which they may have, and the regulations which serve to control these emissions.

Since the discovery of radioactivity around the turn of the century, a substantial body of evidence has accumulated that, although radioactive substances may be used in a variety of ways perceived to be beneficial to mankind, these substances also pose risks. For this reason, substantial attention has been given to the understanding of the attendant risks and to standards for limiting harm to man. The basic considerations underlying such standards, the organizations responsible for setting standards, and the various types of standards are discussed in section 2 and summarized in section 1.2.

Nuclear power plants produce and/or handle large amounts of radioactive material. Under normal circumstances, only a small portion of the radioactivity contained in the reactor can escape to the environment, so that resulting increased radiation exposures of surrounding populations are much smaller than typical background exposures. Section 3 (summarized in section 1.3) first discusses background radiation levels, then treats the increase in radiation levels arising from nuclear power plant operations. Routine emissions are treated, then dispersion of radioactivity and resulting human exposures to radiation are discussed. In addition, radioactive emissions from other types of power plants are briefly characterized. Considerations important for control of both routine and accidental releases from nuclear power plants are presented.

The standards discussed in section 2, and which serve to control the emissions discussed in section 3, are based on the currently available information on the relationship between radiation exposures and harm to humans. This relationship is discussed briefly in section 4 (and summarized in section 1.4), based largely on the information made accessible by several important reviews of dose versus response. The main topics considered in section 4 are acute radiation effects, including both sickness and death, and delayed effects, including genetic damage and somatic effects, particularly cancer. Certain important questions are addressed, including the validity

of assuming a linear relationship between dose and effect, and the adequacy of radionuclide concentration standards.

As discussed in the body of the report and the summary which follows, a large amount is known about the harm which exposures to radiation may cause humans at high dose and dose rates. Although important uncertainties exist on how to extend the relationship to predict the effects at low doses and dose rates, present assessment methods are more likely to be conservative than to underestimate the effect. And although questions have been raised about the adequacy of numerical standards for certain radionuclides, such as plutonium, the probable changes in such standards are not large; moreover, any such changes would not affect the operation of nuclear facilities directly, since the routine emissions are presently so far below the recommended numerical limits. The current radiological standards appear to provide an adequate basis for the control of possible effects arising from man-made radioactive materials.

1.2 Radiological standards for nuclear power plants

Two distinct types of radiological standards applicable to nuclear plants exist. The first are standards recommended by a number of national and international scientific bodies with substantial responsibilities for assembling and analyzing information on the health effects of radiation. In the United States, the body which, on the basis of available information, recommends numerical guidelines for limiting radiation exposures is the National Council on Radiation Protection and Measurement (NCRP). These recommendations are utilized by the Environmental Protection Agency (EPA) and by the Nuclear Regulatory Commission (NRC) as a basis for formulating standards for general applications.

However, more specific standards exist for the regulation of nuclear power plants. The Nuclear Regulatory Commission is the agency which grants licenses for nuclear power plants, and the limitations which it places on resulting exposures of the public are much more severe than the numerical guidelines of the NCRP. In applying the guideline that exposures be "as low as is reasonably achievable", the NRC has numerical guidelines which are approximately 1% of the NCRP limitations. The result is that the exposure which may be attributed to nuclear power plants is a very small percentage of that arising from natural background sources.

The EPA, moreover, has recently promulgated a standard which places limits on the exposure of any individual from nuclear power operations,

and which places overall limitations on actual emissions from the uranium fuel cycle. However, the EPA limitations on exposures are, if anything, less restrictive than those utilized by the NRC in the licensing process for nuclear power plants.

The basic measure of biologically effective radiation dose (actually known as "dose equivalent", see Glossary) is the "rem". The average whole body exposure of individuals in the United States from background radiation sources is approximately 0.13 rem/year. The NCRP numerical limit for man-made radiation (except medical) is 0.5 rem/year to a member of the general public and 0.17 rem/year to a population. The first limitation is one tenth of the suggested limit for occupational exposures. The second is even less, based on the fact that a population would receive somewhat less exposure than its most highly exposed member; the 0.17 rem/year limit can also be based on a desire to limit man-made radiation-induced increases in the mutation rate to 10% of the natural rate.

On the other hand, the NRC limitations now applied to nuclear power plants limit whole body exposures of any member of the general public to 0.005 rem/year and 0.003 rem/year, respectively, from gaseous and liquid effluents. (The EPA limitation is 0.025 rem/year from all nuclear power operations.) The public exposure from routine emissions from nuclear power plants is therefore substantially less than background exposure levels.

The NRC verifies these emissions limitations in the safety review performed as part of the licensing process. The main thrust of that process is actually to assure that large accidental releases of radioactivity have very low probablility. The details of that review process are not the present concern; nor is the risk from accidents the subject of this report. However, it is important to note that routine emissions from nuclear power plants are now sufficiently well-controlled that the preponderance of the average annual public risk from the nuclear power plant itself appears to arise from its potential for accidental releases. (This comparison may be sensitive to how long-lived isotopes are considered.)

Standards also exist for mitigating public exposures during accidental releases. However, these are not complete at the present time. They take the form of EPA Protective Actions Guides (PAG), which specify the levels of projected exposure from a nuclear accident which would warrant actions to limit exposure. For airborne releases, the PAG is now 1 to 5 rem whole body dose. Possible dose-limiting actions are evacuation, sheltering, and prophylactic measures. The details of these measures are not treated in this report.

1.3 Radioactive emissions from nuclear power plants.

During the operation of a nuclear power plant, a large array of radionuclides are produced, principally as fission products (the fragments remaining after the fission of nuclei) or as activation products (the radionuclides resulting from the interactions of a nucleus with some form of radiation, such as a gamma ray or a neutron). Only a small number of these radionuclides can escape from a normally operating nuclear power plant in significant quantities. These are isotopes of hydrogen, carbon, iodine, and the noble gases krypton and xenon. In terms of Curies (see Glossary), the amounts of the most important isotopes routinely emitted from a 1000 MWe light-water reactor (LWR) nuclear power plant are approximately:

^{3}H (tritium, an isotope of hydrogen)	500 Curies/year
^{14}C (carbon)	8 Curies/year
$^{129, 131, 133}I$ (isotopes of iodine)	0.02 Curies/year
^{85}Kr (krypton) and ^{133}Xe (xenon)	10,000 Curies/year

The amounts emitted in any specific case may vary by about a factor of 5 from those given. The carbon, iodine, and noble gases are emitted primarily into the air, while the tritium may be emitted into either air or water. The amounts of tritium and noble gases emitted from the power plant are substantially less than the amounts which would be released into the atmosphere from the spent fuel when it is reprocessed, unless controls are introduced to prevent their escape at the reprocessing plant.

In any case, a more significant quantity than activity, from the point of view of human health, is the amount of exposure to radiation, often expressed in rem. It is the control of exposure that is the goal of regulatory efforts, and - during the regulatory process - the expected exposure of members of the public must be calculated.

As for any pollutant, the process of calculating exposures resulting from specified emissions is a complicated process, most suitably employing a computer-based model to simulate the dispersion of pollutants through the atmosphere or other medium. A significant simplification for treatment of radioactive pollutants, as compared with others, is that the tendency for chemical transformations in air or water to alter the character or effect of resulting pollutants is not as marked as for chemically active pollutants. Moreover, the fact that current estimates for responses to radiation often

employ a linear dose-response function (see below) identifies and simplifies what exposure is to be calcualted.

The emissions from nuclear power plants, and the resulting exposures of the general public, are sensitive to the control measures employed at the particular nuclear plant under consideration. It is relatively difficult to prevent the escape of a certain portion of the radioactive noble gases and iodines from the reactor (as distinguished from the power plant containing the reactor), and the same is true of tritium, which becomes incorporated into water, the liquid used as the reactor coolant in LWRs. On the other hand, the amount of these radioisotopes which ultimately escapes into the environment may be altered by introducing liquid and gaseous cleanup systems, as well as "holdup" systems, which can contain certain short-lived radioactive substances until the greater part of them has decayed radioactively to stable or otherwise harmless substances.

The extent to which such emission control systems are implemented should be determined considering the cost and effectiveness of the systems as compared with the benefit from preventing emissions. This is the philosophy used in implementing the "as low as is reasonably achievable" guideline, and the associated explicit numerical guidelines noted above. However, it is only possible to employ such cost-benefit analyses on the basis of some appreciation of the relationship of exposures to health effects and ultimately some evaluation of human health or life. As discussed below, a usable basis, often regarded as conservative, does exist for quantitatively estimating health effects of radiation exposures.

The same statement may be made of the short-term, but substantial, radiation doses which could result from accidental releases of large amounts of radioactivity from nuclear power plants. Under such circumstances, a larger array of radionuclides could be released, and in much larger amounts, than under routine conditions. The large doses which are possible can cause not only latent damage, but also acute effects, both sickness and death. Calculation of such effects may be performed using the same dispersion modeling procedures as suggested above, but the dose-response function clearly exhibits a threshold, so that the results may be very sensitive to the modeling assumptions.

1.4 Health effects of exposure to radiation: the adequacy of current standards

The fundamental data on the effects of radiation exposures arises from doses substantially larger than ten rem, sustained over relatively short time periods. The major instances of such exposures were the bombings at Hiroshima and Nagasaki, which induced substantial numbers of both latent (such as cancer) and early effects. Data of comparable significance for latent effects arise from certain medical procedures, especially radiation therapy, and from occupational exposures (such as ingestion of radium). Large amounts of important data have also been obtained from laboratory experiments on animals. A number of scientific bodies, both international and national, have taken responsibility for assembling and interpreting information on the health effects of radiation.

It is clear from these data that a whole-body dose of 1000 rem from "external" radiation delivered over a short period of time (such as one day) causes death within a short time (roughly a month). Depending on the medical procedures available for mitigating the effects of radiation damage, the dose which will cause death in 50% of humans is roughly 500 rem. As the dose is reduced to the vicinity of 100 rem, death no longer occurs, but sickness is induced by less acute cellular damage. Such sickness is no longer observed as the dose received becomes lower than approximately 20 rem.

On the other hand, doses of the size just discussed (20 to 1000 rem) may be sustained without early sickness or death if the dose is spread over longer periods, so that the body can repair the acute damage. However, radiation may also cause latent damage, which—among other possibilities—may show itself as cancer, a decade or more later, or cause defects in succeeding generations. A dose which does not cause early death may have some probability of causing death from cancer many years later.

Although early effects could assume some importance during a large release at a nuclear power plant, even for large releases and certainly for routine releases, the delayed effects from low doses delivered at low dose rates are the important question. However, measurement of the dose-response for cancer induction is much more difficult than for early effects because of the large time period required for malignancies to show themselves, and because the effects must be observed statistically out of a population which would experience cancer incidence even in the absence of increased exposure to radiation.

In spite of these difficulties, the data are sufficent to demonstrate a relationship between radiation exposure and cancer. For external exposures, such as the gamma ray and neutron exposures resulting from bombings of Japan, the data may only be used to demonstrate this relationship down to an integrated dose of approximately 100 rem. Extrapolating these data to low dose (and dose rate) in order to estimate the effects of typical doses from nuclear power plants is a subject of much controversy. It has been recent practice--for purpose of risk assessment-- to adopt some version of a simple hypothesis, i.e., to presume that a certain total dose, summed over a population, will produce the same number of effects, regardless of how the dose is distributed among that population. This is equivalent to a statement that the dose-response function is linear and that no threshold exists. The view of most experts and regulatory agencies is that this a "conservative" assumption. In recent assessments of risk, the ratio of number of effects to population dose as obtained from the Hiroshima-Nagasaki and other high dose data has been reduced by approximately a factor of four before applying it to small doses or dose rates. Thus, whereas the high-dose data suggests an increased cancer incidence of roughly one cancer per 10,000 man-rem of population dose (see Glossary), the modification for low dose and dose rate would raise the required population dose to about 40,000 man-rem for purposes of risk assessment.

By way of comparison, the expected dose to the general public from routine releases from recently licensed nuclear power plants is about 5 man-rem per year during years of operation; the expected dose to workers at the plant is about 500 man-rem.

Other delayed effects than cancer may be induced by radiation. Among these are mutations. It is this potential for damage that is a basis of the recommended average dose limit of 0.17 rem/year for populations. The data on genetic damage indicates that the normal incidence of mutations, about 10,000 per million live births, would be approximately doubled if the average person received an additional 20 to 200 rem during his (genetically active) lifetime.

This summary has emphasized the average risk caused by radiation exposures. However, for specific radionuclides, concentration and body burden limits are derived from exposure limits as guides to meeting the more basic limits. Some controversy exists over these derived standards for certain nuclides, plutonium being the most prominent example. However, the consensus in the biomedical community is that for such nuclides the standards are not

substantially in error. Rather, small changes are likely, but these will probably arise from improved modeling methods, rather than from an altered perception of mechanisms for harm to the human organism.

In view of this consensus that current standards are satisfactory overall, but with some possibility of minor change, and that methods are available for assessing the risk associated with particular uses of radioactivity, it appears that a useful and substantive basis for regulation of nuclear power exists. Moreover, because emissions from present-day nuclear power plants are so much less than the basic numerical exposure guidelines, it is unlikely that the small changes which may occur in these guidelines will affect the operation or design of nuclear power plants.

2. Radiological Standards, Guides, and Regulations

The purpose of this section is to set forth basic information on the agencies involved in the setting of standards for radiation protection, on the fundamental considerations leading to formulated standards or to regulatory actions, and on the manner in which radiological aspects of nuclear power plants are regulated. We should emphasize at the outset that the word "standards" is not without ambiguity, since it means generally "that which is established as a measure". Many of the standards discussed in this report are actually formulated as guidelines for agencies which wield direct regulatory power. Furthermore, many of the guides established by those agencies are exactly that, guides to complying with a more broadly applicable, but less specific, regulation.

Discussion of the basic information which is used in the formulation of standards is deferred until Sections 3 and 4. This order of presentation is chosen for the practical reason that, from the point of view of a regulator, it is the standards themselves that are of immediate importance, but also because the interaction between the establishment of regulations and observed emissions (the subject of Section 3) is very strong, as it should be if a comparison of risks and benefits plays an important role in the regulatory process. As will be seen in this section (particularly in Section 2.4), this comparison is of great importance, particularly because the exposures to which the public is subject from nuclear power operations are substantially below the numerical guidelines established by international and national scientific bodies.

Section 2.1 briefly describes the various organizations and agencies involved in establishing standards for radiological protection. Section 2.2 summarizes the basic considerations in the establishment of such standards. Section 2.3 presents, in brief form, the various types of standards which now exist. Section 2.4 discusses the manner in which applicable guidelines are presently used in the regulation of nuclear power plants.

2.1 International and National Authorities Who Set Radiological Standards

A number of bodies are involved in the setting of radiological standards, whether voluntary or compulsory. To a large extent, the work performed by the individual bodies is complementary and interdependent. Several of these bodies are international, and the information they develop is purely advisory to the

TABLE 2-1. International Bodies Involved in Establishment of Radiological Standards

ICRP - In 1928, the Second International Congress of Radiology established the International X-ray and Radium Protection Commission, which later changed its name to the International Commission on Radiological Protection to reflect the expansion of its concern outside the field of medical radiology. It has issued a series of recommendations in its publication series, Radiation Protection.

IAEA - The International Atomic Energy Agency was organized in 1956 as a specialized agency of the United Nations in order to promote the peaceful uses of nuclear energy. Radiological protection measures are contained in its publications, the Safety Series.

ICRU - The International Commission on Radiological -Units and Measurements was formed in 1925 by the First International Congress of Radiology in order to develop recommendations on: 1) quantities and units of radiation and radioactivy, 2) procedures suitable for the measurement and application of these quantities, and 3) physical data needed in the application of these procedures.

UNSCEAR-In 1955 the General Assembly of the United Nations established the UN Scientific Committee on the Effects of Atomic Radiation, which was "to develop a summary of reports received on radiation levels and radiation effects on man and his environment..." UNSCEAR reports have served as a review of worldwide scientific information and opinion on human exposure to radiation.

national bodies which actually have responsibility for the establishment and administration of standards.

Brief background information on the international bodies is given in Table 2-1. In short, the International Commission on Radiological Protection (ICRP) is the international organization which has a general responsibility for providing guidance in matters of radiation safety, primarily through its series of publications on radiation protection. The International Atomic Energy Agency (IAEA), a specialized agency of the United Nations, concerns itself - among other things - with the practical application of the ICRP recommendations to the peaceful uses of nuclear energy; health and safety measures prescribed by the Agency are set forth in its "Safety Series". The International Commission on Radiological Units and Measurements (ICRU) works closely with the ICRP and makes recommendations on radiological units and measurement procedures. Finally, at the international level, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) regularly reviews the state of understanding of the effects of radiation, thereby supporting efforts to develop radiological standards.

Comparable organizations at the national level have more direct regulatory responsibilities. The National Council on Radiation Protection and Measurements (NCRP) makes recommendations on radiation protection in the form of the NCRP report series. Responsibility for the actual regulation of the use of radiation or radioactivity is divided between the Environmental Protection Agency (EPA), which has specific authority to establish environmental radiation standards and to formulate guidelines* for other agencies in the establishment of standards, and the Nuclear Regulatory Commission, which has the power to establish and enforce radiation standards in laboratories and facilities which it licenses, including facilities both for weapons-related work and for commercial nuclear power. The national agency which concerns itself with units and measurement procedures is the National Bureau of Standards. Finally, the National Academy of Sciences - National Research Council Advisory Committee on the Biological Effects of Ionizing Radiation (the BEIR Committee) has served as a national body responsible for reviewing

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*This responsibility was, until 1970, given to the Federal Radiation Council (FRC), whose reports still serve as the basic regulatory guidelines.

TABLE 2-2. National Bodies Involved in Establishment of Radiological Standards

NCRP - The National Council on Radiation Protection and Measurements was formed in 1929 (as the Advisory Committee on X-ray and Radium Protection). Based on a consideration of the scientific and technical aspects of radiatoin protection, it makes recommendations that are published as NCRP Reports.

NRC - The Nuclear Regulatory Commission has assumed the power of the former Atomic Energy Commission to establish and enforce radiation standards for its licensees, including federal laboratories and commercial facilities. NRC responsibilities and associated standards are set forth in title 10 of the Code of Federal Regulations (10 CFR). Further, guidelines are provided in the NRC series of Regulatory Guides.

EPA - The Environmental Protection Agency has assumed responsibilities formerly relegated to two bodies. First, the Federal Radiation Council (FRC) was formed in 1959 and, until 1970, issued guidelines in accordance with its mandate to "advise the President with respect to radiation matters directly or indirectly affecting health, including guidance for all Federal agencies in the formulation of radiation standards..." (Public law 86-373). In 1970 the FRC was disbanded and the EPA was given this responsibility. In addition, the EPA received the power to establish "generally applicable environmental standards for the protection of the general environment from radioactive material", a power formerly held by the Atomic Energy Commission.

NBS - The National Bureau of Standards has general responsibility in the United States for the establishment of uniform units and measurement techniques, including radiation units and measurements.

BEIR - In 1964, the National Academy of Sciences - National Research Council established the Advisory Committee to the Federal Radiation Council. This committee, enlarged to become the Advisory Committee on the Biological Effects of Ionizing Radiation in 1970 (the year during which the FRC was disbanded as the EPA assumed its responsibilities), has issued a number of reports reviewing scientific evidence relevant to radiation exposure and protection.

the scientific basis for the establishment of radiation protection standards. Some background information on these organizations and committees is given in Table 2-2. State and local agencies which have responsibilities in the area of radiation protection follow the lead of the national organizations very closely.

The standards, guides, and regulations developed by the above bodies and promulgated by those with regulatory or advisory authority differ widely in their coverage. Specifically, they may limit exposures, concentrations, or emissions. Exposure standards are aimed directly at limiting the actual exposure of humans (or, in principle, other members of the biosphere) to radiation and are the primary type of radiation protection guide. Many of these standards actually state exposure limits in rem per year, but others specify measures which may be taken to limit these exposures. (Examples of the latter are requirements for protection clothing in certain circumstances or for population control or evacuation in others.) Concentration standards set limits on the amount of radioactivity which may be present in environmental media or in the human body. Finally, emission standards attempt to limit the introduction of radioactive material into the general environment by imposing restrictions at the source of such radioactivity. Both concentration and emission standards are derived from the more fundamental exposure standards.

Standards which fit into each of these categories are discussed in Section 2.3. Each of the national organizations responsible for the formulation of radiation protection standards has exercised its responsibilities in each of these areas. Depending on the organization, the resulting standards may have force of law, may be guidelines to satisfying legal requirements, or may only be generally advisory.

For nuclear facilities themselves, the Nuclear Regulatory Commission is the primary agency responsible for setting standards or reviewing their implementation. After noting the rationale for establishing standards or guidelines and the various types of standards, we will return - in Section 2.4 - to the regulation of nuclear power plants.

2.2 Considerations in setting standards and guides

The basic rationale for radiation protection criteria is to provide standards by which the protection of humans, both the general public and individuals who are occupationally exposed, may be assured. The need for

such standards arises from the fact that exposure to radiation may cause harmful effects, the details of which are discussed in Section 4 of this report. For purposes of this section, it is sufficient to point out that: large doses above 25 rem dose equivalent (see glossary), delivered over a short period of time may cause illness and, for very large doses, death soon after exposure; similar doses have some probability of causing latent somatic effects, leading to illness or death decades after exposure; smaller exposures than 25 rem dose equivalent, or larger exposures spread over a large period of time, are understood to have some probability of causing genetic damage (and hence harm to succeeding generations) and possibly latent somatic damage (similar to that at large doses and dose rates, but with lower probability, perhaps proportional to the dose equivalent, but more probably decreased with low dose and dose rate). A very useful summary of the background for radiation protection criteria and of the criteria themselves, is given in NCRP Report No. 39 on Basic Radiation Protection Criteria.[1]

It is the potential for early or latent somatic effects at relatively large doses that has led to the establishment of the current standards for occupational exposures; the numerical whole body dose limit given in such standards is 5 rem per year, with modifications possible, depending on the period considered (see Section 2.3). In accordance with ordinary practice for protection of workers from occupational exposures, a somewhat larger limit had originally been chosen to be approximately a factor of 10 lower than the dose equivalent at which deleterious effects had been observed to occur; the rationale for the limit originally presumed the existence of a "threshold" for such effects. It is useful to consider the manner in which radiation protection philosophy has diverged from this view; a useful, although somewhat outdated, summary is given in the following paragraphs abstracted from the first report (issued in 1960) from the Federal Radiation Council:[2]

*The comment in paragraph 4.1 (quoted from Handbook 59) on non-existence of a threshold for mutagenic effects is particularly questionable in view of more recent evidence.

Federal Radiation Council:[2]

SECTION IV.—THE DERIVATION OF RADIATION PROTECTION STANDARDS

4.1 Shortly after the discovery of x-rays and natural radioactivity in the late 19th century, it became apparent that exposure to sufficiently large doses could produce both acute manifestations and serious later sequelae in man. Based on relatively limited observations on a rather small number of individuals, attempts were made to define a level at which these obvious deleterious effects would not be seen. With increasing scientific knowledge, based on observations of larger numbers of individuals and laboratory animals and a better understanding of radiation damage, these suggested levels have undergone continuous downward revision. For some time, however, the underlying basic philosophy remained unchanged, and radiation protection standards were based on the premise that there was a dose ("tolerance dose") below which damage would not occur. The validity of this basic assumption was subject to increasing question, first in the field of genetic damage, and later in connection with somatic effects. Thus, by 1954, the National Committee on Radiation Protection and Measurements included the following statement in Handbook 59 (NCRP, H59, 1954):

> "The concept of a tolerance dose involves the assumption that if the dose is lower than a certain value—the threshold value—no injury results. Since it seems well established that there is no threshold dose for the production of gene mutations by radiation, it follows that strictly speaking there is no such thing as a tolerance dose when all possible effects of radiation on the individual and future generations are included . . . " and " . . . the concept of a permissible dose envisages the possibility of radiation injury manifestable during the lifetime of the exposed individual or in subsequent generations. However, the probability of the occurrence of such injuries must be so low that the risk would be readily acceptable to the average individual. Permissible dose may then be defined as the dose of ionizing radiation that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his lifetime. As used here, 'appreciable bodily injury' means any bodily injury or effect that the average person would regard as being objectionable and/or competent medical authorities would regard as being deleterious to the health and well-being of the individual . . ."

4.2 With the accumulation of even more quantitative information concerning radiation effects in both animals and humans, and some increased understanding of the mechanisms of radiation injury, the possibility that somatic effects as well as genetic effects might have no threshold appeared acceptable, as a conservative assumption, to increasing numbers of scientists. In discussing its recommendations for additional downward revision of the maximum permissible occupational radiation exposure, the NCRP in 1958 stated (2):

> "The changes in the accumulated MPD (maximum permissible dose) are not the result of positive evidence of damage due to the use of earlier permissible dose levels, but rather are based on the desire to bring the MPD into accord with the trends of scientific opinion; it is recognized that there are still many uncertainties in the available data and information . . . ," and, "The risk to the individual is not precisely determinable but, however small, it is believed not to be zero. Even if the injury should prove to be proportional to the amount of radiation the individual receives, to the best of our present knowledge, the new permissible levels are thought not to constitute an unacceptable risk . . . "

4.3 Thus, over the past decade or two, there has been an increasing reluctance on the part of knowledgeable scientists to establish radiation protection standards on the basis of the existence of a threshold for radiation damage and on the premise that this threshold lies not too distant from the point at which impairment is detectable in an exposed individual. Although many scientists are prepared to express individual opinions as to the likelihood that a threshold does or does not exist, we believe that there is insufficient scientific evidence on which to base a definitive conclusion in this regard. Therefore, the establishment of radiation protection guides, particularly for the whole population, should take into account the possibility of damage, even though it may be small, down to the lowest levels of exposure. This involves considerations other than the presence of readily detectable damage in an exposed individual. It also serves as a basis for such fundamental principles of radiation protection as: there should not be any man-made radiation exposure without the expectation of benefit resulting from such exposure; activities resulting in man-made radiation exposure should be authorized for useful applications provided the recommendations set forth in this staff report are followed.

4.4 If the presence of a threshold could be established by adequate scientific evidence, and if the threshold was above the background level and sufficiently high to represent a reasonable working level, a relatively simple approach to the establishment of radiation standards would be available.

4.5 On the assumption that there is no threshold, every use of radiation involves the possibility of some biological risk either to the individual or his descendents. On the other hand, the use of radiation results in numerous benefits to man in medicine, industry, commerce, and research. If those beneficial uses were fully exploited without regard to radiation protection, the resulting biological risk might well be considered too great. Reducing the risk to zero would virtually eliminate any radiation use, and result in the loss of all possible benefits.

4.6 It is therefore necessary to strike some balance between maximum use and zero risk. In establishing radiation protection standards, the balancing of risk and benefit is a decision involving medical, social, economic, political, and other factors. Such a balance cannot be made on the basis of a precise mathematical formula but must be a matter of informed judgment.

4.7 Risk can be evaluated in several different ways before it is balanced against benefit. A logical first step is the identification of known or postulated biological effects. The uncertainty of our present knowledge is such that the biological effects of any given radiation exposure cannot be determined with precision, so it is usually necessary to make estimates with upper and lower limits.

4.8 It is helpful to compare radiation risk to other known hazards in order to maintain perspective or a sense of proportion with respect to the risk. For example, attempts have been made to compare the relative biological risks of various radiation exposure levels to such other industrial hazards as traumatic injuries and to toxic agents employed in industrial processes. Likewise, the possible hazards from various radiation levels have been reviewed in relation to such everyday risks to the general population as the operation of motor vehicles, the possibility of home accidents, and the contamination of our environment with industrial wastes.

4.9 Effects can also be evaluated in terms of the normal incidence of disease conditions usually present in the population which may also be caused by radiation. In a given instance, the portion of the total number of cases of a given disease which might be attributed to radiation may be quite small. Therefore, the significance of a given radiation exposure can appear superficially to be quite different depending upon whether the data are expressed in terms of the absolute numbers of cases of a given condition which will possibly result, or be expressed as percentages of the normal incidence. However, it is extremely difficult to assign any numerical value to the increase which should be permitted in a given abnormal condition. It is also important to remember that at the present time, any numerical predictions of the number or percentage increase in any given condition anticipated as a result of radiation exposure are based on inadequate data and have extremely limited reliability, even though upper and lower limits can be stipulated.

4.10 The biological risk attributable to man-made radiation may also be compared with that from natural sources. This approach is also important in maintaining perspective. Man and lower forms of life have developed in the presence of such natural sources in spite of any radiation damage that may have been present. Perhaps one of the more important advantages to this approach is that it makes due allowance for qualitative as well as quantitative ignorance of yet unrecognized radiation effects, if such exist. Weighing for various somatic as well as genetic effects is also inherently included. It automatically includes a consideration of the largest body of human and subhuman data on radiation effects. One disadvantage is the degree of conservatism introduced by this approach, since it is likely that only a small fraction of the total incidence of disease results from background radiation.

Summary

4.11 Two factors need to be considered in the formulation of radiation protection standards: biological risk, and the benefits to be derived from radiation use. Maximum benefits cannot be obtained without some risk, and risk cannot be eliminated without foregoing benefits. Therefore some balance must be struck between risk and benefit.

4.12 Since an accurate delineation of risk is impossible, a number of approaches can usefully be employed to aid in the evaluation of risk, and to put risk in reasonable perspective. Each has merit, but such approaches are not mutually exclusive and should be used in combination. An evaluation of benefits in addition to an evaluation of risk is also necessary.

Consideration of the risks and benefits has led to the establishment of numerical dose limiting recommendations, all of which are relatively uniform among the many international and national bodies making such recommendations. The 5 rem/year limit for routine occupational exposures remains the standard for the workplace, considering the risks and benefits. The situation for exposures of the general population is more complex. The limit for dose to any member of the general may be taken to be one tenth of the occupational limit, an approach that is consistent with a conservative approach to setting exposure limits for the general public; however the resulting 0.5 rem/year also turns out to be consistent with the limit which would have been arrived at on the basis of other (primarily genetic) considerations.

This coincidence may be summarized as follows: It had long been understood that radiation, even at low dose and dose rate, had a probability for causing genetic alteration that was proportional to the dose received by the genetic material.* On the basis of such considerations, it had generally been recommended that the total population dose from all sources not exceed 10 rem per 30 years for the average individual. Considering the dose arising from natural background radiation and from medical exposures, only 5 rem of the total 10 could be assigned to other sources (including nuclear power), leading to maximum dose to populations of 5 rem per 30 years or 0.17 rem/year. This is consistent with the 0.5 rem/year noted above for the maximally exposed individual, since it was presumed that limiting the maximal dose to 0.5 rem/year would effectively limit the average dose to an amount not more than one third the maximum, or 0.17 rem/year. We should also note that this somatically significant dose limit of 0.17 rem/year for populations can also generally be based on direct consideration of observed effects such as leukemia and other cancers, rather than on a number derived from the occupational limit of 5 rem/year.

In any case, these numerical limits are not the overriding standards. Although they are derived with due consideration to the risks and benefits associated with the use of radioactivity and other radiation sources, they are not designed for direct application to any particular situation. Every body, whether national or international, which recommends numerical limits

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*However, whether this proportionality strictly applies is not altogether clear; see, for example, Ref. 1.

explicitly states that, in any specific case, the doses should be kept as low as practical, considering the risks and the benefits. For nuclear facilities in the United States, the Nuclear Regulatory Commission implements an "as low as is reasonably achievable" approach, as is discussed in Section 2.4. Regulating on such a basis requires some method for assessing the risk from exposures to radiation at low dose and dose rate. This usually requires the extrapolation from effects observed at high dose and dose rate to effects predicted at low dose and dose rate, since doses due to nuclear facilities are very low compared with doses at which any effects have been observed. The basic approach to such assessment has been a linear extrapolation, presuming no threshold, to low doses and dose rates, although possibly with some modification of the proportionality between dose and effect to take account of the decreased effectiveness of low dose and dose rates. A basic study intended to assess the effects of low doses and dose rates, and often used as a basis for such extrapolation, is the 1972 "BEIR report,"[3] from the BEIR Committee of the National Academy of Sciences - National Research Council. (See Section 4.) The application of such an approach to the licensing of nuclear power facilities has led to the limitation of emissions sufficiently that doses to members of the general public are less than one percent of the recommended limits. (See Section 2.4 and Section 3.) However, as discussed in Section 2.4, the decrease in population exposures has not been based directly on a dose response relationship, but also on a stipulated valuation ($1000) of each man-rem of human exposure. Because of uncertainties in the dose-response relationship, dependence on a linear relationship may not be appropriate in all cases. This question is discussed at length in NCRP 43[4].

It is evident in the above discussion that the criteria at issue there are those applicable to routine exposures. They do not apply to accidental exposures. Awareness of this distinction is clear in the following paragraphs, excerpted from ICRP Publication 9 (1965)[5]:

CONTROLLABLE AND UNCONTROLLED SOURCES OF EXPOSURE

(46) It must be made clear that the Commission deals quite differently with two distinct conditions of exposure :

(i) in which the occurrence of the exposure is foreseen and can be limited in amount by control of the source, and by the development of proper operating procedures ;

(ii) in which the particular exposure is accidental (i.e. has not been planned), and which can be limited in amount only, if at all, by remedial actions.

Limitation of Exposures from Controllable Sources

(47) In conditions where the source of exposure is subject to control, it is desirable and reasonable to set specific dose limitations, so that the associated risk is judged to be appropriately small in relation to the benefits resulting from the practice. Furthermore, the limitation must be set at a sufficiently low level so that any further reduction in risk would not be considered to justify the effort required to accomplish it. In the case of occupational exposure the hazards should not exceed those that are accepted in most other industrial or scientific occupations with a high standard of safety. The risks to members of the public from man-made sources of radiation should be less than or equal to other risks regularly accepted in every-day life, and should be justifiable in terms of benefits that would not otherwise be received.

(48) Once dose limits have been established, the objective should be to plan the use of sources of exposure in such a way that, in normal practice, these doses will not be exceeded. The dose limits assume the additional critical function of acting as a check on proper and adequate working practices at the source of exposure. When dose limits have been exceeded by a small amount, it is generally more significant that there has been a failure of control than that one or more individuals have slightly exceeded a certain agreed dose.

(49) It should be emphasized that dose limits for exposures from controllable sources are not intended for general use in the assessment of the risk of exposures resulting from uncontrolled sources.

(50) The recommended limits for exposures of individuals and populations from controllable sources are discussed in paragraphs 52–95.

Action Levels for Exposures from Uncontrolled Sources

(51) Under conditions in which unforeseen exposures occur, it is no longer a matter of balancing an appropriate risk against any benefit. Instead, questions now arise as to what remedial actions may be available to limit the amount of exposure and increase chances of recovery. In such cases, the hazard or social cost involved in any remedial measure must be justified by the reduction of risk that will result. Because of the great variability of the circumstances in which remedial action might be considered, it is not possible for the Commission to recommend " action levels " that would be appropriate for all occasions. However, for the guidance of national bodies having the responsibility of taking remedial action, the Commission now includes a section dealing with the problems involved in setting action levels (see Section C).

(Please note that "controlled" and "uncontrolled" is best interpreted to mean "routine" and "accidental" to avoid confusion in certain of the guides for routine emissions, which make the distinction between "controlled" and "uncontrolled" areas.)

The distinction between routine and accidental (or uncontrolled) releases had led to the establishment of a special class of radiation protection guides called protective action guides (PAGs), designed to delineate actions which might be taken, again considering the associated costs and benefits, should events lead to exposures which exceed the numerical limits for routine operation. Strictly speaking, this term might be applied to the dose limits applicable to individuals who are engaged in emergency operations (25 rem whole body); however, PAGs are usually considered to include those actions (and the associated action levels) designed to protect members of the population in the event that an accident initiates an unusual release and thereby causes a potential for unusual exposures of the population. The dose limits for routine operation are not aimed at this situation, so that a different set of guidelines are required. As discussed below, the Environmental Protection Agency, having assumed the responsibilities of the Federal Radiation Council, formulates PAGs.

Most of the discussion above is directly applicable to exposures to radiation from external emitters, radionuclides which are outside the body when they expose individuals to radiation from their decay. A large and important class of radionucldies may be taken up by the body, resulting in exposures from internal emission of radiation. For such radionuclides, dose limits may not be as useful as limits to the actual amount of activity (given in Curies - see glossary) which may be carried by the body. For such materials, two different criteria are used. For bone-seeking radionuclides, a maximum permissible body burden (MPBB) is specified, based on a comparison with ^{226}Ra and its daughters. For other radionuclides, the MPBB is based on the amount which would deliver specified doses to a critical organ, the one which is most susceptible to radiation damage under the conditions of interest.

Radium is used as the basis for the bone-seeking limits since, historically, it is the only radionuclide of this type whose effects have been observed in detail. Another important radionuclide which fits into this class is plutonium. On the other hand, uranium is not as strong a bone-seeker, so that limits for its various isotopes (with the exception of ^{238}U, which has such a low specific activity that its primary effect occurs due to chemical poisoning) are determined on the basis of the actual dose to the organ most severely damaged. In each case, once a maximum permissible body burden is determined for occupational workers, similar considerations as

are mentioned in the previous section may be used to determine the corresponding limits for populations or individual members of the general public, i.e., one may divide the occupational limits by 30 and 10, respectively.

Based on either of the types of standards discussed above, exposure limits or maximum permissible body burdens, it is possible to derive maximum permissible concentrations of radionuclide types or of specific radionuclides in air and water which would contribute these exposures or burdens. For external emitters, such derivation requires calculation of the actual exposure resulting from a specified concentration of the radionuclide of interest. For internal emitters, the derivation may be very complex, requiring a detailed understanding of the manner of inhalation or ingestion and of internal pathways and concentration or elimination mechanisms. The result, in either case, can be a table of permissible concentrations in air and water (or other media) for occupational situations or for the general environment (to which the general public would be subjected). For practical radiation protection, these "maximum permissible concentrations" may be a convenient tool, in lieu of the more basic limits on exposure or body burden.

Finally, in the actual identification of sources of radionuclides and in the regulation of these sources, emission rates (in Curies per unit time or per unit output energy, in the case of nuclear power plants) may be a quantity of interest. This would, for example, be an appropriate indicator of the effectiveness of emission control systems (see Sections 2.3 and especially 2.4).

2.3 Existing Standards

The most directly important quantity from the point of view of radiation protection is the actual exposure of individuals and populations to radiation. Such exposures may be expressed in a variety of ways, depending on whether the whole body or specific portions thereof is exposed, on whether the amount of energy absorbed per mass of tissue is specified (along with information on the type of radiation), as opposed to specification of some equivalent biological damage, and on whether the exposure rate is specified. In various instances, it may also be important to specify certain characteristics of the person(s) exposed, such as age. For most exposure standards, a convenient measure is dose

equivalent, given in "rem" (either whole-body or organ-specific), a unit which is directly related to the amount of energy deposited per unit mass of tissue, weighted by a factor which is proportional to the biological damage caused. (The unweighted energy per unit mass is given in "rads". See glossary.) As such, the rem may be regarded as an indicator of the biological damage per unit mass for average tissue.

Each of the organizations with responsibilities for radiological standards has made recommendations on the yearly maximum permissible dose for occupational workers, individual members of the general public, and populations. Dose limits for emergencies are also specified. The recommendations of the NCRP[1] are given as an example in Table 2-3. In some cases the limits are the same as those recommended by the ICRP,[5] but in other cases they are lower. For initial planning of occupational exposures, the "prospective" annual limit should be used; if it is found to be exceeded, no remedial procedure is necessary unless the "retrospective" annual limit is exceeded. Note that individual members of the general public are to be exposed to no more than one tenth of the limit for radiation workers and that, further, the limit for genetically or somatically significant population exposures is lower by approximately a factor of three. The dose limits stated in the Code of Federal Regulations (10 CFR 20) and in the California Administrative Code (17 CAC 3) are similar to those given in Table 2-3. Note that the table lists not only dose limits for routine exposure, but also limits for emergency situations, in particular for workers who purposely subject themselves to unusually large doses during emergency actions, such as to save a life.

Exposure standards of the type discussed above are generally recommendations. The EPA and the NRC have promulgated other standards of more limited application with - in some cases - lower limits. The EPA recently promulgated[6] an environmental standard for nuclear power operations based on the uranium fuel cycle under normal operating conditions. This standard places limits on the dose contributed to any member of the

TABLE 2-3. Summary of NCRP Dose-Limiting Recommendations.*

Dose limits for occupational exposures	
whole body (or red bone marrow, gonads, and lenses of the eyes)	
prospective annual limit	5 rem/year
retrospective annual limit	10-15 rem/year
long term accumulation	5(N-18) rem, where N is age in years
skin	15 rem/year
hands	75 rem/year (25 rems/quarter)
forearms	30 rem/year (19 rems/quarter)
other organs, tissues and organ systems	15 rem/year (5 rems/quarter)
fertile women (with respect to fetus)	0.5 rem in gestation period
Dose limits for the public or occasionally exposed individual	
individual (occasional)	0.5 rem/year
students in educational work	0.1 rem/year
Population dose limits	
genetic	0.17 rem average/year
somatic	0.17 rem average/year
Emergency dose limits - life saving	
individual (older than 45 if possible)	100 rem
hands and forearms	200 rem, additional (300 rem, total)
Emergency dose limits - less urgent	
individual	25 rem
hands and forearms	100 rem, total
Family of radioactive patients	
individual (under age 45)	0.5 rem in any one year
individual (over age 45)	5 rem in any one year

*From Ref. 1.

general public* and on the amount of certain radionuclides which may be discharged to the environment* as a result of fuel cycle operations. It should be noted that the limits on dose contributed from the uranium fuel cycle is considerably lower than the 500 millirems (0.5 rems) permitted yearly to individual members of the public from all man made sources (excepting medical procedures). However, the 25 millirem/year whole body dose in the proposed standard is greater than the numerical design objectives used by the NRC in the licensing of nuclear power plants themselves (see below).

In addition to the generally applicable radiation protection guidelines (a responsibility assumed from the Federal Radiation Council) and the standards being developed for nuclear power operations under normal conditions, the EPA promulgates "protective action guides" (PAGs) for use in case of "nuclear incidents" involving abnormal releases of radioactivity. These guides are intended to specify doses to the public from airborne radioactivity, from deposited radioactivity, and from radioactively contaminated foodstuffs, which would warrant protective actions (such as evacuation) to mitigate exposures. Only guides for airborne radioactivity have, as yet, been developed and even these are incomplete (see Table 2-4 from Ref. 7).

The EPA develops standards and guidelines in accordance with its general responsibilities for the protection of the environment and the public. On the other hand, the Nuclear Regulatory Commission performs similar functions in its capacity as the regulator of specifically nuclear-based activities. In this capacity, the NRC utilizes a range of guidelines as specified in Title 10 of the Code of Federal Regulations. The parts of direct interest in radiation protection associated with nuclear facilities are:

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*The specifications are as follows:
"(a) The annual dose equivalent shall not exceed 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other organ of any member of the public as the result of exposure to planned discharges of radioactive materials, radon and its daughters excepted, to the general environment from uranium fuel cycle operations and radiation from these operations."
"(b) The total quantity of radioactive materials entering the general environment from the entire uranium fuel cycle, per gigawatt-year of electrical energy produced by the fuel cycle, shall contain less than 50,000 curies of krypton-85, 5 millicuries of iodine-129, and 0.5 millicuries combined of plutonium-239 and other alpha-emitting transuranic radionuclides with half-lives greater than one year." [6]

TABLE 2-4. Emergency Response Protective Action Guides*
Airborne Releases from Fixed Nuclear Facilities

Population at Risk	Projected Dose (rem)		
	Whole Body gamma	Thyroid	Inhalation of Particulates
Nonessential personnel (a)	1 to 5	5-25	(c)
Emergency workers	25	125	(c)
Lifesaving activities	75	(b)	(c)

(a) When ranges are shown, the lowest should be used if there are no major local constraints in providing protection at that level, especially to sensitive populations. Local constraints may make lower values impractical to use, but in no case should the higher value be exceeded in determining the need for protective action.

(b) No specific upper limit is given for thyroid exposure, since in the extreme case complete surgical or radiological thyroid loss might be an acceptable penalty for a life saved. However, loss should not be necessary if respirators and/or thyroid protection for rescue personnel are available as the result of adequate planning.

(c) Under development

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*From Ref. 7

Part 20 - Standards for Protection against radiation

Part 50 - Licensing of production and utilization facilities

Part 100- Reactor site criteria.

In support of its regulatory function as specified in 10 CFR, the NRC has been developing a series of Regulatory Guides, organized into divisions that are applicable to each regulatory function.*

10 CFR 20 contains standards and guidelines comparable to those described above from the NCRP (Table 2-3) and others. It also contains more detailed stipulations on conditions and warnings necessary in occupational and other environments. (Division 8, Occupational Health, of the Regulatory Guides have been developed in support of this section.) Finally, Part 20 contains specification of maximum permissible concentrations for radionuclides, as discussed in the next section.

10 CFR 50 generally applies to licensing of nuclear cycle facilities. Appendix I specifies numerical design objectives for limiting exposure to that which is "as low as is reasonably achievable". Details are given in Section 2.4. An indication of the limits desired is given by the objectives for whole body dose from liquid and gaseous effluents for each nuclear power plant, 3 mrem/year and 5 mrem/year, respectively. These design objectives are smaller than those proposed by the EPA for all nuclear power operations, so that the EPA and NRC limits are not incompatible. Regulatory Guides, division 1, Power Reactors, contain many guides specifically directed at implementation of these guidelines and are discussed more fully in Section 2.4.

10 CFR 100 guides the NRC in its evaluation of the suitability of proposed reactor sites. One of the prime considerations is limitation of the potential for population exposures. Such limitation cannot be considered independently of the dose limits discussed above. However, Part 100 defines specific methods for achieving such limitation. In particular, it defines the exclusion zone, the low population zone, and the population center distance, parameters which are useful in site evaluation. (See Section 2.4).

*The Regulatory Guide divisions are: 1) power reactors, 2) research and test reactors, 3) fuels and materials facilities, 4) environmental and siting, 5) materials and plant protection, 6) products, 7) transportation, 8) occupational health, 9) antitrust review, 10) general.

Division 4 of the Regulatory Guides, Environmental and Siting, is directly related to these considerations, as well as to the general question of radiological monitoring.

In general, it is important to realize that although specific numerical dose limits are given in the various standards the basic tenet underlying radiation protection philosophy is that doses be kept as low as possible, practicable, or reasonably achievable. No doses should be permitted without adequate reason and without due consideration of the risks and benefits.

Maximum permissible concentration and body burdens

As discussed in the last portion of Section 2.2, radiological standards may also take the form of maximum permissible body burdens and maximum permissible concentrations in environmental media from which doses or body burdens could be accumulated. An example of maximum permissible concentration specification is given in 10 CFR 20, where limitations on concentrations of various radionuclides in air and water are specified in tabular form for occupational and general public exposures. As an indication of some of the radionuclides that are expected to be important due to their use or production in nuclear power operations, we have extracted portions of that table to form Table 2-5.

Until recently, standards for other media had not been formulated. However a standard of 10 nCi/gm for alpha-emitters in soil has been proposed.[8]

Emission limitations and dose commitment

Two types of limitations on emission, either directly applicable or by implication, have been mentioned in Section 2.3. One is the overall EPA limitation[6] on routine emission of specified radionuclides per gigawatt-year of nuclear power production. This limitation applies, not only to the nuclear reactor, but also to other facilities, such as any reprocessing facilities.

The second type of limitation is part of the design and licensing review in accordance with the numerical design objectives of 10 CFR 50, Appendix I. The NRC Regulatory Guides, Division 1, include many which give direction pertinent to achievement of these objectives. Because the NRC licensing process has the more direct role in the regulation of nuclear power plants and because the Appendix I-based numerical objectives are lower than those given in the EPA limits, it is the implementation of the NRC regulatory process

TABLE 2-5. Maximum Permissible Concentrations of Selected Nuclear Power Related Radionuclides[a]

(Units are μCi/mℓ)

Element (atomic number)	Isotope	Form[b]	Occupationally exposed		General Public	
			Air	Water	Air	Water
Carbon(6)	C 14	S[c]	4×10^{-6}	2×10^{-2}	1×10^{-7}	8×10^{-4}
		CO_2	5×10^{-5}	—	1×10^{-6}	—
Cesium(55)	Cs 137	S	6×10^{-8}	4×10^{-4}	2×10^{-10}	2×10^{-5}
		I	1×10^{-8}	1×10^{-3}	5×10^{-10}	4×10^{-5}
Iodine(53)	I 131	S	9×10^{-9}	6×10^{-5}	1×10^{-10}	3×10^{-7}
		I	3×10^{-7}	2×10^{-3}	1×10^{-8}	6×10^{-5}
Krypton(36)	Kr 85		1×10^{-5}	—	3×10^{-7}	—
Plutonium(94)	Pu 239	S	2×10^{-12}	1×10^{-4}	6×10^{-14}	5×10^{-6}
		I	4×10^{-11}	8×10^{-4}	1×10^{-12}	3×10^{-5}
Radon(86)	Rn 222	S	3×10^{-8}	—	1×10^{-9}	—
Strontium(38)	Sr 90	S	1×10^{-9}	1×10^{-5}	3×10^{-11}	3×10^{-7}
		I	5×10^{-9}	1×10^{-3}	2×10^{-10}	4×10^{-5}
Uranium(92)	U 235	S	5×10^{-10}	8×10^{-4}	2×10^{-11}	3×10^{-5}
		I	1×10^{-10}	8×10^{-4}	4×10^{-12}	3×10^{-5}

[a] Abstracted from 10 CFR 20

[b] The form of the radionuclide is usually specified by a letter, S for soluble, I for insoluble.

that establishes the practical limits on human exposures and facility emissions.

Finally, a concept which has become increasingly important is that of "dose commitment", which, although it is based on exposures to humans, is directly related to emissions. The emissions during a given year may expose populations to radiation, not only in the year of emission, but also in subsequent years. Dose commitment is related to the total dose associated with the emission. It is defined, as circumstances may warrant, to include subsequent doses associated with the emitted radionuclides, both because these materials may remain in the environment for an extended period and because, once ingested by an individual, they may continue to irradiate that person over an extended period. Annual doses from operation of nuclear plants or from other sources may be ambiguous unless it is clearly specified whether dose commitment is included and how it is calculated. This ambiguity, for example, may obscure comparison of exposure from routine or accidental emissions. Moreover, it is difficult to decide how to treat radionuclides with very long half-lives, such as ^{14}C,

2.4 Regulations for Nuclear Power Plants

From the point of view of radiological protection, the Nuclear Regulatory Commissions's review of proposed nuclear power plants serves to limit both types of radiation exposures which might be imagined: routine and accidental. This concern of the NRC pertains to possible exposures of both workers and the public. Its actions in the area of radiological protection from routine exposures are in accordance with the recommendations of various standards-setting bodies, and where the public is concerned it has given very detailed attention to the implementation of the guideline that exposures be as low as is reasonably achievable. Moreover, its attention to the detailed design of nuclear reactor power stations is very extensive and intended to limit the probability of serious accidents, as well as their consequences, should large radioactive releases occur.

A central element in the NRC review of proposed facilities is the submission by the applicant of a Safety Analysis Report (SAR), which describes the proposed plant (and site) in sufficient detail that the NRC can determine its compliance with applicable regulations. A preliminary SAR is submitted before construction may begin, and a final version is submitted in support of the final application for an operating license. The SAR is a very sub-

TABLE 2-6. Contents of Safety Analysis Report

1. INTRODUCTION AND GENERAL DESCRIPTION OF PLANT - presents an introduction to the report and a general description of the plant. This chapter should enable the reader to obtain a basic understanding of the overall facility without having to refer to the subsequent chapters. Review of the detailed chapters that follow can then be accomplished with better perspective and with recognition of the relative safety importance of each individual item to the overall plant design.

2. SITE CHARACTERISTICS - provides information on the geological, seismological, hydrological, and meteorological characteristics of the site and vicinity, in conjunction with present and projected population distribution and land use and site activities and controls. The purpose is to indicate how these site characteristics have influenced plant design and operating criteria and to show the adequacy of the site characteristics from a safety viewpoint.

3. DESIGN OF STRUCTURES, COMPONENTS, EQUIPMENT, AND SYSTEMS - should identify, describe, and discuss the principal architectural and engineering design of those structures, components, equipment, and systems important to safety; discusses the seismic and quality group classifications, then the criteria for qualifying various components and systems.

4. REACTOR - provides evaluation and supporting information to establish the capability of the reactor to perform its safety functions throughout its design lifetime under all normal operational modes, including both transient and steady-state, and accident conditions. Should include information to support the analyses presented in Chapter 15. The major topics to be considered in Chapter 4 are fuel system design, nuclear design, thermal and hydraulic design, reactor materials, and the design of the reactivity control systems.

5. REACTOR COOLANT SYSTEM AND CONNECTED SYSTEMS - provides information of the reactor coolant system and systems connected to it, making a point to include information on the entire "reactor coolant pressure boundary" as defined in 10 CFR 50.2(v). Topics included are a summary description, the integrity of the reactor coolant pressure boundary, the reactor vessel, and component and subsystem design.

6. ENGINEERED SAFETY FEATURES - provides enough information on features designed to mitigate the consequences of postulated accidents that an adequate evaluation of their performance ispermitted. The information includes experience and testing, consideration of component reliability and system design, provisions for inservice test and inspection, and evidence that materials will stand the accident environment. Systems to be considered may include containment systems, emergency core cooling systems, habitability systems, fission product removal and control systems, and others.

7. INSTRUMENTATION AND CONTROLS - provides information on the reactor instrumentation which senses the various reactor parameters and transmits appropriate signals to the regulating systems during normal operation, and to the reactor trip and engineered safety feature systems during abnormal and accident conditions; emphasizes those instruments and associated equipment which constitute the reactor protection system.

8. ELECTRIC POWER - provides information directed toward establishing the functional adequacy of safety-related electric power systems and ensuring that these systems have adequate redundancy, independence, and testability in conformance with current criteria.

TABLE 2-6 (continued)

9. AUXILIARY SYSTEMS - provides information on auxiliary systems including fuel storage and handling, water systems, process auxiliaries (such as air handling, water drainage, etc.), ventilation systems, and others (such as fire protection, lighting, etc.). Systems that are essential for safe plant shutdown or for the protection of the public health and safety should be identified and discussed in detail (design bases, safety evaluation, etc.).

10. STEAM AND POWER CONVERSION SYSTEM - provides information on the steam system and turbine generator units, as defined by the secondary coolant system in a PWR or by the system beyond the reactor steam isolation valves in a BWR. Information should be broadly descriptive, with emphasis on those aspects of design or operation which might affect the reactor and its safety features or contribute toward the control of radioactivity.

11. RADIOACTIVE WASTE MANAGEMENT - describes 1) the capabilities of the plant to control, collect, handle, process, store, and dispose of liquid, gaseous, and solid wastes that may contain radioactive materials, and 2) the instrumentation used to monitor the release of radioactive wastes; information covers normal operation, including anticipated operational occurrences. Radwaste systems should be capable of complying with 10 CFR 20 and 50, Appendix I.

12. RADIATION PROTECTION - provides information on methods for radiation protection and on estimated occupational exposures of operating and construction personnel during normal operation and anticipated operational occurrences; should describe facility and equipment design, the planning and procedures programs, and the techniques and practices employed to meet 10 CFR 20.

13. CONDUCT OF OPERATIONS - provides information relating to the preparations and plans for operation of the plant; the purpose is to provide assurance that the applicant will establish and maintain a staff of adequate size and technical competence and that operating plans to be followed by the licensee are adequate to protect the public health and safety.

14. INITIAL TEST PROGRAM - provides information on the initial test program for structures, systems, components, and design features for both the nuclear portion of the plant and the balance of the plant. The information provided should address major phases of the test program, including preoperational tests, initial fuel loading and initial criticality, low-power tests, and power-ascension tests.

15. ACCIDENT ANALYSES - includes analyses of the response of the plant to postulated disturbances in process variables and to postulated malfunctions or failures of equipment. Previous SAR chapters evaluated structures, systems, and components important to safety for their susceptibility to malfunction or failure. In this chapter, the effects of anticipated process disturbances and postulated component failures should be examined to determine their consequences and to evaluate the capability built into the plant to control or accommodate such failures and situations; analysis should include anticipated operational occurrences, off-design transients that induce fuel failures above those expected from normal operational occurrences, and postulated accidents of low probability.

16. TECHNICAL SPECIFICATIONS - the applicant proposes Technical Specifications that set forth the limits, operating conditions, and other requirements imposed on the facility operation for, among other purposes, the protection of the health and safety of the public.

17. QUALITY ASSURANCE - provides a description of the applicant's quality assurance program to be established during design, construction, preoperational testing and operation.

stantial document, submitted in a standardized form, the contents of which are specified by one of the Regulatory Guides (1.70),* and the review of which is described in detail in Standard Review Plans which the NRC has prepared and which are available publicly. The SAR, RG 1.70, and the Standard Review Plans are all similarly divided; the basic contents of the SAR are described briefly in Table 2-6, which is abstracted largely from RG 1.70.

The basic regulations with which the NRC determines compliance are those given in Title 10 of the Code of Federal Regulations, in particular Parts 20, 50, and 100. Part 20 gives generally applicable radiation protection criteria; Part 50 specifies criteria for power reactors themselves; and Part 100 specifies siting criteria. However, as a guide to compliance with these criteria, the NRC develops Regulatory Guides, as mentioned above. Although having no regulatory force themselves, they are effectively regulations, except that the applicant may propose alternative means to complying with the required criteria. Division 1 of the Regulatory Guides deals explicitly with power reactors; Division 4 contains siting and environmental guides; Division 8 specifies guides for occupational protection. In turn, many of these guides often refer to other generally available publications, especially voluntary engineering standards, as bases for complying with regulations.

The purpose of the present discussion is to point out those portions of the NRC regulations, and related regulatory guides, which pertain directly to the questions of emissions of radioactivity and resulting exposures. Although this technically includes 10 CFR 20, from a practical point of view it is 10 CFR 50 that is important, because as presently applied 10 CFR 50 limits routine exposures of the public to levels which are far below the guidelines given in 10 CFR 20. (This is not, however, true of occupational exposures.)

For routine exposures of the general public, the most significant portion of 10 CFR 50 is Appendix I, which gives numerical objectives for limiting exposures from nuclear power plants to a level that is "as low as is reasonably achievable." A number of regulatory guides are directly relevant to the review of a proposed plant's compliance with this appendix. These are described briefly in Table 2-7.

The numerical design objectives are the following maximum off-site doses:

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*Regulatory Guide 1.70: "Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants. LWR Edition" (Revision 2, 10/75).

TYPE OF DOSE	DESIGN OBJECTIVE (per unit)
Liquid effluents	
dose to total body from all pathways	3 mrem/yr
dose to any organ from all pathways	10 mrem/yr
Gaseous effluents(only for noble gases)	
gamma dose in air	10 mrad/yr
beta dose in air	20 mrad/yr
dose to total body	5 mrem/yr
dose to skin	15 mrem/yr
Radioiodines and particulates released to the atmosphere	
dose to any organ from all pathways	15 mrem/yr

Note that these doses are small compared with the guidelines of Table 2-3 or with the doses from other sources (see Section 3.1). Moreover, a general risk-benefit analysis is to be performed for balancing additional rad-waste equipment against doses to populations within 50 miles of the site. The interim cost-benefit criterion to be employed is that each man-rem or man-thyroid-rem of reduction in the projected dose is to be valued at $1000. The regulatory guides set forth in Table 2-7 provide an acceptable set of approaches to determining compliance of a proposed power plant with the specifications of Appendix I. A brief discussion of the question of effluent dispersion is contained in Section 3.2.2; a description of types of atmospheric dispersion models in contained in a separate report.[9] (We should note, too, that the NRC is presently developing regulatory guides on "Design, testing, and maintenance criteria for exhaust filtration and adsorption units" and "Design basis guidance for radioactive waste management systems installed in light-water-cooled power plants". Finally, a guide not listed in Table 2-7 is RG 1.21, "Measuring, evaluating, and reporting radioactivity in solid wastes and releases of radioactive materials in liquid and solid effluents from light-water-cooled nuclear power plants" (Revision 1, 6/74).)

The NRC review extends more broadly to the entire area of nuclear safety. A portion of the safety area that is directly pertinent to the question of radiological safety is the possibility of accidental releases of radioactivity per se. Detailed review of the plant design is intended to forestall the possibility of accidents, but a selection of regulatory guides deal explicitly with analysis and protective measures for such events. These are listed in Table 2-8. Section 3.5 briefly discusses evaluation of the probability and consequences of accidental releases.

TABLE 2-7. Regulatory Guides Pertaining to Evaluation of Routine Emissions from Nuclear Power Plants

1.23: ONSITE METEOROLOGICAL PROGRAMS FROM NUCLEAR POWER PLANTS (2/72) - describes the meteorological program which provides information required both for the evaluation of radioactivity dispersal during emergencies and for the calculation of expected doses form routine effluents. The basic meteorological parameters to be measured are wind direction, wind speed, temperature at two elevations, and (where appropriate) humidity. The data are to be compiled in a manner giving information on wind velocity versus atmospheric stability class, as specified by the change in temperature with altitude (see Section 3.2.2).

1.109 CALCULATION OF ANNUAL DOSES TO MAN FROM ROUTINE RELEASES OF REACTOR EFFLUENTS FOR THE PURPOSE OF EVALUATING COMPLIANCE WITH 10 CFR 50, APPENDIX I (3/76) - provides methods for calculating dose to man from liquid effluent, gaseous effluent, and radioiodine pathways to evaluate compliance with the design objectives of Appendix I. The appendices of RG 1.109 provide detailed information on dose conversion coefficients. In addition, the last appendix described methods for calculating the population dose (in man-rem or man-thyroid-rem) to populations within 50 miles of the site in order to test agreement with the general risk-benefit criterion of $1000 per man-rem. Methods for calculating dispersion of effluents are described in succeeding regulatory guides.

1.110 COST-BENEFIT ANALYSIS FOR RADWASTE SYSTEMS FOR LIGHT-WATER-COOLED NUCLEAR POWER STATIONS (3/76) - provides a methodology for performing the cost-benefit analysis required by 10 CFR 50 Appendix I. The methods described in RG 1.109 are acceptable for calculating the population doses required for this comparison. RF 1.110 describes the methods to be used in evaluating the cost of both liquid and gaseous radwaste systems, including direct equipment cost and the cost of building space, supportive services, maintenance, interest, and operating costs.

1.111 METHODS FOR ESTIMATING ATMOSPHERIC TRANSPORT AND DISPERSION OF GASEOUS EFFLUENTS IN ROUTINE RELEASES FROM LIGHT-WATER-COOLED REACTORS (3/76) - delineates acceptable methods for calculating the transport and dispersion of routine radioactive releases. The models which are listed are the "particle-in-cell", "puff advection" and "straight-line airflow" models. The guide discusses source configuration considerations: elevated releases, releases other than elevated, and building wake corrections. The removal mechanisms discussed are radioactive decay, dry and wet deposition.

1.112 CALCULATION OF RELEASES OF RADIOACTIVE MATERIALS IN GASEOUS AND LIQUID EFFLUENTS FROM LIGHT-WATER-COOLED POWER REACTORS (4/76) - specifies how to establish the source terms for routine releases in effluents from power reactors. The actual calculations are to be performed by the "GALE" computer codes, with particular versions for PWRs and BWRs, as described in NRC publications. The appendices to this regulatory guide specify the data needed to perform the calculations. The data required characterize the basic reactor systems, the liquid and gaseous waste processing systems, and the ventilation and exhaust systems.

1.113 ESTIMATING AQUATIC DISPERSION OF EFFLUENTS FROM ACCIDENTAL AND ROUTINE RELEASES FOR THE PURPOSE OF IMPLEMENTING APPENDIX I (5/76) - describes in general terms the types of models which may be used to calculate aquatic dispersion of effluents (with the exception of ground water dispersion). The discussion include the initial dilution at the source, the dispersion in rivers coastal areas, estuaries, and reservoirs or cooling ponds, and the description of water usage and sediment uptake. These models may be used for treatment of dispersion of both routine and accidental releases.

TABLE 2-8. Regulatory Guides Pertaining to Evaluation of Accidental Releases from Nuclear Power Plants

1.3 ASSUMPTIONS USED FOR EVALUATING THE POTENTIAL RADIOLOGICAL CONSEQUENCES OF A LOSS OF COOLANT ACCIDENT FOR BOILING WATER REACTORS (Revision 2, 6/74)

1.4 ASSUMPTIONS USED FOR EVALUATING THE POTENTIAL RADIOLOGICAL CONSEQUENCES OF A LOSS OF COOLANT ACCIDENT FOR PRESSURIZED WATER REACTORS (Revision 2, 6/74)

1.5 ASSUMPTIONS USED FOR EVALUATING THE POTENTIAL RADIOLOGICAL CONSEQUENCES OF A STEAM LINE BREAK ACCIDENT FOR BOILING WATER REACTORS (3/71)

1.24 ASSUMPTIONS USED FOR EVALUATING THE POTENTIAL RADIOLOGICAL CONSEQUENCES OF A PRESSURIZED WATER REACTOR RADIOACTIVE GAS STORAGE TANK FAILURE (3/72)

1.25 ASSUMPTIONS USED FOR EVALUATING THE POTENTIAL RADIOLOGICAL CONSEQUENCES OF A FUEL HANDLING ACCIDENT IN THE FUEL HANDLING AND STORAGE FACILITY FOR BOILING WATER AND PRESSURIZED WATER REACTORS (3/72)

1.52 DESIGN, TESTING, AND MAINTENANCE CRITERIA FOR ENGINEERED-SAFETY-FEATURE ATMOSPHERE CLEANUP SYSTEM AIR FILTRATION AND ADSORPTION UNITS OF LIGHT-WATER-COOLED NUCLEAR POWER PLANTS (7/76)

1.98 ASSUMPTIONS USED FOR EVALUATING THE POTENTIAL RADIOLOGICAL CONSEQUENCES OF A RADIOACTIVE OFFGAS SYSTEM FAILURE IN A BOILING WATER REACTOR (3/76)

1.101 EMERGENCY PLANNING FOR NUCLEAR POWER PLANTS

(In addition, see 1.23 and 1.113 of Table 2-7)

The models for evaluating the dispersion of accidental atmospheric releases above are extremely simple, due to the fact that it is only required that the maximum exposure of an individual outside the site be calculated. In each of the guides above pertaining to gaseous releases, the concentration to be calculated is that at the centerline of a Gaussian plume. The concentration is given in graphical form and depends on the atmospheric stability class associated with the particular site. A regulatory guide from division 4 that is closely associated with the evaluation of accidental release is.

4.7 GENERAL SITE SUITABILITY CRITERIA FOR NUCLEAR POWER STATIONS

This guide summarizes the site features that are related to safety, as well as more general environmental considerations. In addition to the obviously safety aspects of seismicity, flood potential, etc. (see the guides listed below), attention is given to the definition of population zones and their relationship to the potential releases associated with postulated accidents (such as those given in the guides above).

1.59 DESIGN BASIS FLOODS FOR NUCLEAR POWER PLANTS

1.60 DESIGN RESPONSE SPECTRA FOR SEISMIC DESIGN OF NUCLEAR POWER PLANTS

1.76 DESIGN BASIS TORNADO FOR NUCLEAR POWER PLANTS

References for Section 2

1. National Council on Radiation Protection and Measurements, "Basic Radiation Protection Criteria", NCRP Report no. 39, January 1971.

2. Federal Radiation Council, "Background Material for the Development of Radiation Protection Standards", FRC Report No. 1, May 1960.

3. The BEIR Committee of the National Academy of Sciences - National Research Council, "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation", Report of the Advisory Committee on the Biological Effects of Ionizing Radiation, November 1972.

4. National Council on Radiation Protection and Measurements, "Review of the Current State of Radiation Protection Philosophy", NCRP Report No. 43, January 1975.

5. International Commission on Radiological Protection, Publication 9, September 1965.

6. Environmental Protection Agency, 40 CFR 190: "Environmental Radiation Protection Standards for Nuclear Power Operations," published in the Federal Register, Vol. 42, No. 9, pp. 2858-2861, January 13, 1977.

7. Environmental Protection Agency, "Manual of Protective Action Guides and Protective Actions for Nuclear Incidents", September 1975 (under development).

8. See, for example, J. W. Healy, "A Proposed Interim Standard for Plutonium in Soils", Los Alamos Laboratory informal report LA-5483-MS, January 1974.

9. L. C. Rosen, "A Review of Air Quality Modeling Techniques", Lawrence Berkeley Laboratory Report LBL-5998.

3. Power Plant Emission, Dispersion, and Control

3.1 Background radiation levels

3.1.1 Background doses

From the point of view of radiation protection, the most fundamental consideration is the dose received by human beings. Because of this emphasis, most of this report treats dose-limiting standards and the effects of exposures (typically stated in terms of dose equivalent in rem) on humans. Because any increase in human exposures due to human activities will occur against the background of other exposures which would occur in any case, it is important to consider the size and source of these background exposures. Not only do these background exposures complicate the problem of ascertaining exposure increases due to human activities, but they provide a possible perspective on the importance of small increases.

Due to the emphasis on nuclear power contributions to human exposures, background radiation levels are often stated to include all contributions except those from nuclear power. We follow this custom, specifying dose contributions in enough detail that the effects of other human activities on the total average dose will be apparent. Table 3-1, adapted from references 1 and 2, summarizes doses that individuals may be subject to in the absence of contributions from nuclear power operations; the table includes exposures from natural sources and from human activities. Because of the variability of exposures themselves, as well as the variability of exposures quoted in various sources, the numbers in Table 3-1 are to be taken as representative rather than definitive.

The most important natural radiation sources are cosmic rays (energetic particles penetrating the earth's atmosphere from sources in outer space) and terrestrial radionuclides present in the earth, including rocks, soil, and - perforce - building materials. Substantial contributions also come from radionuclides which are present in the human body. In summary, cosmic, external terrestrial, and internal sources are said to contribute, respectively, averages of approximately 44, 50, and 20 mrem/year to residents of the United States, for a total of about 115 mrem/year. More detailed information on natural background in the United States is contained in a recent NCRP publication, NCRP 45.[3] Table 3-2, from that report, summarizes naturally induced doses to specific organs. Note that the doses attributed to cosmic and internal radiation are

Table 3-1. Population Exposures from Natural and Human Sources.

	Individual Annual Dose	Average Annual Dose
Natural sources[a]		
cosmic radiation	30-40 mrem (sea level); add about 1 mrem per 120 feet of elevation	44 mrem
external terrestrial	30-130 mrem	40,55 mrem
internal terrestrial	variable	18,25 mrem
total natural	70-400 mrem	102-125 mrem
Human sources		
weapons test fallout[b]	variable	4 mrem
medical exposures[c]	highly variable	60 mrem
miscellaneous (consumer products, jet travel)[b]	highly variable	2 mrem
occupational (mostly medical) exposures	highly variable	0.8 mrem
	TOTAL AVERAGE	170-190 mrem

[a] taken from NCRP 39 (ref. 1) and from BEIR (ref. 2). These are, roughly, whole body exposures. See, however, NCRP 45 (ref. 3).

[b] from BEIR (ref. 2), whole body exposures.

[c] from NCRP 39 (ref. 1) and BEIR (ref. 2); number given is for "abdominal dose", roughly corresponding to genetically significant dose.

Table 3-2. (Reproduced from NCRP 45[a]). Summary of average dose equivalent rates (mrem/y) from various sources of natural background radiation in the United States.

Source	Gonads	Lung	Bone		G.I. Tract
			Surfaces	Marrow	
Cosmic Radiation[a]	28	28	28	28	28
Cosmogenic Radionuclides	0.7	0.7	0.8	0.7	0.7
External Terrestrial[b]	26	26	26	26	26
Inhaled Radionuclides[c]	—	100[d]	—	—	—
Radionuclides in the Body[e]	27	24	60	24	24[f]
Rounded Totals	80	180	120	80	80

[a] "Cosmic Radiation" includes 10% reduction to account for structural shielding.

[b] "External Terrestrial" includes 20% reduction for shielding by housing and 20% reduction for shielding by the body.

[c] Doses to organs other than lung included in "Radionuclides in the Body."

[d] Local dose equivalent rate to segmental bronchioles is 450 mrem/y.

[e] Excluding the cosmogenic contribution shown separately.

[f] This does not include any contribution from radionuclides in the gut contents.

[a] ref. 3

somewhat smaller than those given in Table 3-1.

It is convenient to group human-caused exposures as those due to fallout from weapons testing, to medical procedures, and to miscellaneous (consumer-oriented) activities. This order follows approximately the degree of voluntary exposure, fallout contributions being essentially unavoidable and consumer-related exposures being almost completely voluntary. Fallout from atmospheric weapons tests has decreased from the peak values of the 1960s, due to the limitation of such testing; recent typical exposures have been 4 mrem/year. Exposure due to medical procedures varies greatly, depending on the individual, yielding averages which are almost as great as the average dose due to natural sources. Contributions from the miscellaneous category are much smaller, averaging 2 mrem/year. Voluntary exposures due to choice of occupation average even less, although in individual cases these may range up to 5000 mrem/year, in accordance with occupational guidelines.

The total average exposure, due to non-nuclear power sources, is in the vicinity of 180 mrem dose equivalent per year, two thirds of which is due to natural sources. These averages are subject to large uncertainties. They depend, not only on such highly variable contributions as medical exposures, but even on geographic location because of altitude, latitude, and the amounts of radioactive materials present in the earth. (Cosmic radiation contributions increase by a factor of 3 in going from sea level to an altitude of 10,000 feet.) Average natural background exposures in California, for example, are slightly less than the average U. S. value.

The general philosphy of radiation protection is to limit doses as much as is practical. For this reason, although the generally applicable limits for exposure of members of the general public are comparable to the doses already received from the above "background" sources, efforts are made to keep doses well below this, as indicated by the EPA and NRC limits for nuclear power operations, which are presently about 25 and 10 mrem/year, respectively. (See Sections 2.3 and 2.4). Moreover, these are the limits applicable to any individual member of the public. The resulting increased average dosage to members of the public would be much smaller. As discussed in Section 3.2, even a large-scale nuclear power system, including, for example, 1000 gigawatt nuclear power stations and related fuel-cycle facilities, would increase the average whole-body dose by less than 1 mrem/year, including only the dose from routine emissions from nuclear facilities. (This does not include occupational exposures, which are comparable if averaged over the entire population.)

In addition to refs. 1-3, a substantial amount of information on background sources of radiation is contained in the 1972 UNSCEAR Report.[4]

3.1.2 Important radionuclides for background exposures and nuclear-related Exposures

It is useful to point out which radionuclides contribute to the background doses and which might become important as a result of nuclear power operations. For the background doses, we neglect contributors which result in average doses that are much below 1 mrem/year. We also note that most of the discussion below is in terms of mrad/year, a unit that is roughly equivalent to mrem/year for doses from beta and gamma radiation (see Glossary), which are the most important contributors to the average background dose. (However, for the bone-lining cells, in particular, this difference can be important because a significant portion of their dose equivalent exposure arises from alpha radiation.)

As in the previous section, we can distinguish usefully between internal and external doses, a distinction that is made in the first part of Table 3-3, taken from ref. 4. The prime source of natural internal dose is the potassium 40 (^{40}K) which constitutes 0.01% of natural potassium and which contributes an average internal dose rate of 19 mrad/year.* In addition, carbon 14 and rubidium 87 contribute slightly less than 1 mrad/year apiece. Finally, polonium 210, one of the radon daughters, contributes approximately 1 mrad/year of alpha radiation (corresponding, therefore, to about 10 mrem/year, because of the higher biological effectiveness of alphas). This last contribution constitutes most of the whole body alpha dose from background sources. The total background dose from internal emitters is approximately 25 mrem/year.

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*These rates, abstracted primarily from ref. 4 (especially Table 3-3) are to be taken as only approximate, particularly since the rates for internal exposures will depend on the portion of the body considered, as is evident - for example - for bone-seeking radionuclides. In general, the numbers quoted in this section are to be considered indicative for general body tissue or for the gonads, rather than for tissues with special uptake properties, such as the bone-lining cells. We should also note that these results differ slightly from the data on which Table 3-2 is based, and are chosen because of the convenient division into external and internal.

Table 3-3. (Reproduced from UNSCEAR[a])

Dose Rates due to Internal and External Irradiation from Natural Sources in "Normal" Areas. Estimates of the 1966 Report are given in Parentheses.

Source of irradiation	Dose rates (mrad y⁻¹)				
	Gonads		Bone-lining cells	Bone marrow	
External irradiation					
Cosmic rays: ionizing component	28	(28)	28	28	(28)
neutron component	0.35	(0.7)	0.35	0.35	(0.7)
Terrestrial radiation (including) air	44	(50)	44	44	(50)
Internal irradiation					
^{3}H	0.001	(—)	0.001	0.001	(—)
^{14}C	0.7	(0.7)	0.8	0.7	(1.6)
^{40}K	19	(20)	15	15	(15)
^{87}Rb	0.3	(0.3)	0.6	0.6	(<0.3)
^{210}Po	0.6	(0.3)	1.6	0.3	(0.3)
^{220}Rn	0.003	(—)	0.05	0.05	(—)
^{222}Rn	0.07	(0.3)	0.08	0.08	(0.3)
^{226}Ra	0.02	(—)	0.6	0.1	(0.03)
^{228}Ra	0.03	(—)	0.8	0.1	(0.03)
^{238}U	0.03	(—)	0.3	0.06	(—)
ROUNDED TOTAL	93	(100)	92	89	(96)
Percentage from alpha particles plus neutrons	1.2	(1.3)	4.1	1.2	(1.4)

Dose Commitments from Nuclear Tests carried out before 1971. (The Dose Commitments from Nuclear Tests carried out before 1968, taken from the 1969 Report, are indicated between Parentheses).

Source of radiation	Dose commitments (mrad) for the north temperate zone			Dose commitments (mrad) for the south temperate zone			Dose commitments (mrad) to the world population		
	Gonads	Bone-lining cells	Bone marrow	Gonads	Bone-lining cells	Bone marrow	Gonads	Bone-lining cells	Bone marrow
External									
Short-lived	65 (36)	65 (36)	65 (36)	19 (8)	19 (8)	19 (8)	44	44	44
^{137}Cs	59 (36)	59 (36)	59 (36)	16 (8)	16 (8)	16 (8)	40	40	40
^{85}Kr	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$
Internal									
^{3}H	4	4	4	1	1	1	4	4	4
^{14}C[a]	12 (13)	15 (16)	12 (13)	12 (13)	15 (16)	12 (13)	12	15	12
^{55}Fe	1	1	0.6	0.3	0.3	0.2	0.7	0.7	0.4
^{90}Sr		85 (130)	62 (64)		23 (28)	17 (14)		57	42
^{137}Cs	26 (21)	26 (21)	26 (21)	7 (4)	7 (4)	7 (4)	18	18	18
^{239}Pu[b]		0.2			0.05			0.1	
TOTAL[c]	170 (110)	260 (240)	230 (170)	55 (33)	81 (64)	72 (47)	120	180	160

[a] Dose accumulated up to year 2000. The total dose commitment to the gonads and bone marrow is about 140 mrad; it is about 170 mrad to cells lining bone surfaces.

[b] The dose commitment to bone-lining cells for the north temperate zone has been taken to be equal to the integrated dose over 50 years to bone. A reduction by a factor of four has been assumed for the south temperate zone. Because of insufficient data, the dose commitments to gonads and to bone marrow have not been estimated.

[c] Totals have been rounded off to two significant figures.

[a] ref. 4

The external dose from naturally occurring radionuclides is almost entirely due to gamma radiation from ^{40}K and from the radioactive decay daughters of uranium 238 and thorium 232. (^{210}Po, mentioned in the above paragraph, is one of the ^{238}U series.) These radionuclides contribute approximately the following external doses: ^{40}K 17 mrad/year, the ^{238}U series 13 mrad/year, and the ^{232}Th series 25 mrad/year, for a total of 55 mrad/year.

It is evident that the radionuclides of primary importance for background exposures are ^{40}K and the ^{238}U and ^{232}Th series. Furthermore, about 98% of the exposure in mrad/year is due to gamma and beta radiation, with relative biological effectiveness close to 1, so that the numerical values quoted here are not greatly different than the dose equivalent values given in the table of the previous section. In summary, radionuclides in the environment and the human body constitute about 60% of the background dose at sea level.

The above radionuclides are not, for the most part, the most significant emissions from nuclear power. The latter are more similar to nuclides contributing most of the dose from nuclear weapons test fallout. As indicated in the previous section, a typical dose from fallout from this testing is 4 mrem/year. Most atmospheric testing occurred before 1970, and - in the absence of a renewal of large-scale testing - the annual dose from fallout would be expected to decrease as radionuclides decay or decrease in availability. For this reason, it can be useful to express the effects of fallout in terms of dose commitment rather than annual dose. The total dose commitment to world population from testing prior to 1971 approximates 200 mrad (see Table 3-3). Almost half of this commitment is due to ^{137}Cs, which exposes populations to both external and internal radiation. Approximately half of the external radiation portion (which totals about 120 mrad) arises from relatively short-lived fission products, most of which contributed most of their dose during the actual years of testing. The remainder of the external dose comes almost exclusively from the ^{137}Cs. ^{137}Cs contributes about 26 mrad to the internal radiation whole body dose commitment. The commitment from ^{14}C is more important if one integrates over its long half-life (14,000 years), but is smaller if one - for example - only includes the commitment to the year 2000. The other major contributor to dose commitment to the whole body is tritium, with approximately 4 mrad. On the other hand, other radionuclides, such as ^{131}I and ^{90}Sr, contributed important doses to specific organs (thyoid and bone, respectively). The remaining radionuclides contributed much less to the dose commitment; for example,

the commitment from ^{239}Pu is about 0.2 mrad to the bone-lining cells. It is important to emphasize again that these numbers are for dose commitment, not annual dose, which has recently been in the vicinity of 4 mrad/year. We mention these fallout radionuclides in such detail largely because these are the major contributors to dose from nuclear power operations, particularly if one includes potential accidental releases.

As will be seen in Section 3.2, the important contributors to dose from routine nuclear power operations are tritium, ^{85}Kr, and ^{14}C. On the other hand, a broader spectrum of radionuclides - iodine, cesium and strontium, among others- could assume great importance in nuclear reactor accidents.

3.2 Increase in radiation levels due to nuclear power operations

3.2.1 Observed and projected emissions

A sufficient amount of experience has been had in operating large commercial nuclear power plants that their routine emissions may be characterized. However, a potentially more important source of radionuclides is the fuel reprocessing plant, since that operation systematically frees the products of the nuclear chain reaction from the spent fuel that contains them. The mining and milling operations are another important site of routine releases; these releases are, however, of naturally-occurring radioactive materials, rather than of reactor-produced radionuclides.

An indication of the radionuclide releases from light-water power plants, as they are presently operating, is given in Table 3-4, which states gaseous releases from a number of reports. The first column is taken from the fuel cycle diagrams of Pigford et al.[5] The second column gives the predicted emissions, as stated in their Final Environmental Statements, of large PWRs at two sites of California.[6-7] The third column is taken from a more recent draft environmental statement.[8] The last column gives data used in the recently published GESMO report.[9] The results vary somewhat, but are generally consistent. Also shown are predicted releases from reprocessing operations, which are seen to contribute more substantially than reactors to the environmental radionuclide burden. In each case, the emissions given in the tables are the more important emissions: tritium, iodine, noble gases (including krypton), and carbon 14. For the reprocessing plant, transuranic releases are also given.

The emissions in Table 3-4 are based largely on currently operating facilities. It is possible to reduce these emissions with improved radwaste systems. In fact, a comparison of these emissions with the new EPA

Table 3-4. Yearly Routine Gaseous Emissions from LWR Power Plant (Ci/reactor-year, uranium fuel cycle).

Radionuclide	California Plants (PWR)			Kosh.[e] (PWR)	GESMO[f] (PWR)	Processing[g]
	PWR(BWR)	RS[c]	(DC)[d]			
^{3}H[a]	10 to 50(same)	900	(not given)	580	1100	2.1×10^{4}
^{131}I	0.016(0.016)	0.011	(0.28)	0.009	0.025	0.06(^{129}, ^{131}I)
Krypton, Xenon	7000(50,000)	12,000	(3700)	330	13,000	1.8×10^{5}(^{85}Kr)
^{14}C	Not given	Not given		9	8	15
(transuranics)						(0.004)

[a] It should be noted that a trade-off can occur between tritium discharges into air versus water, so that these numbers can be highly variable, even aside from normal considerations of control technology.

[b] from Pigford et al, reference 5.

[c] from the 1973 Final Environmental Statement for the 900 MWe PWR unit at Rancho Seco, reference 6.

[d] from the 1973 Final Environmental Statement for each 1060 MWe PWR unit at Diablo Canyon, reference 7.

[e] from the 1976 draft environmental statement for each 994 MWe PWR unit at Koshkonong, reference 8.

[f] PWR releases assumed by GESMO[9] for radwaste systems of the current type; releases calculated in accordance with Regulatory Guide 1.112.

[g] Approximate numbers for releases in Curie per gigawatt-year from reprocessing plants; taken from reference 5, except for ^{14}C, which is taken from reference 9. For radionuclides other than ^{14}C, the two references broadly agree, except that the numbers are more difficult to extract from reference 9.

standard shows that, although the power plant emissions are within limits, the fuel reprocessing plants could exceed the standard. The EPA limits appear to presume improvements in process or control equipment. This is true both in the case of the ^{85}Kr limit (the 1.8×10^5 Ci/gigawatt-year for fuel reprocessing exceeds the 50,000 Ci/gigawatt-year limit) and for transuranics, where the limit of 0.5 mCi/gigawatt-year is considerably smaller than the 4 mCi/GW-yr given in Table 3-3, a value that is consistent with the experience at the Nuclear Fuel Services Plant (see Reference 10, Table 4-3). On the other hand, the new plant at Barnwell would appear to be designed to release a much smaller fraction of alpha-active radionuclides, including plutonium.[11]

It is a straightforward matter, based on emission rates such as those given in Table 3-4, to calculate the total radionuclide emission rate for a nuclear power system of specified size. Certain of the world-wide radionuclide release rates or resulting inventories will exceed, sometimes by large factors, the natural worldwide production rates or inventories of these species. For the gaseous releases, it is appropriate that they be considered on a worldwide basis. The radionuclides which are necessarily considered in this way are tritium and krypton, which - by virtue of their chemical properties - would disperse throughout the world biosphere. The natural inventory of tritium is approximately 30 million curies (30 megacuries), within a factor of two,[4] most of which is high in the atmosphere, where it is produced by cosmic rays. A substantial nuclear power system, of the order of 1000 gigawatts capacity, would increase this inventory by approximately 100 megacuries,[12] all of which would be introduced into the biosphere at ground level. Such a nuclear power system would yield a worldwide ^{85}Kr inventory of approximately 3 billion curies,[12] much more than the natural inventory. (However, this assumes essentially complete release of the ^{85}Kr at the reprocessing plant.) Both of these isotopes have half-lives on the order of 10 years, so that, if the nuclear industry reaches a steady-state condition, the worldwide inventory will soon follow. The GESMO report[9] has calculated year 2000 inventories resulting from a nuclear power industry which grows to a 500 gigawatt capacity by that year. The results of reprocessing effluents (including both gaseous and liquid, primarily the former) are shown in Table 3-5 for reprocessing with and without plutonium recycle. Note that the tritium and ^{85}Kr inventories are smaller than those given above, due to the still growing and smaller nuclear industry presumed in GESMO. However, for these nuclides, the accumulated inventory is less

Table 3-5 (Reproduced from GESMO)[a]
REPROCESSING INDUSTRY RADIOACTIVE EFFLUENTS

Basis: The projected U. S. fuel reprocessing industry, years 1975 through 2000.

- Total fuel mix is 11% MOX + 89% UO_2 fuel with Pu recycle.*
- Average fuel exposure is 33,000 MWd/MT.
- Radionuclides present in the environment at the end of year 2000,
- 100% of ^{3}H, ^{14}C, and ^{85}Kr is released to the atmosphere.**

Curies Remaining in the Environment at the End of Year 2000 by Source

Radionuclide	UO_2 Fuel	UO_2 + MOX Fuel
^{3}H	42,000,000	42,600,000
^{14}C	78,300	75,000
^{85}Kr	876,000,000	841,000,000
^{129}I	110	114
Other Fission Products	156	163
Pu, Am, & Cm	62	83

*Without U or Pu recycle, there is no requirement for reprocessing spent fuel. MOX = mixed oxides of Pu and U.

**No credit taken for prospective retention of these radionuclides.

[a]Reference 9

than total emissions, due to decay of these relatively short-lived isotopes. On the other hand, the ^{14}C has a much longer half-life (14,000 years) and the remaining inventory is essentially equal to the total emissions.

The important quantity, from the human point of view - presuming that the emissions have no physical impact on the environment - is projected dose or dose commitment. These are discussed in Section 3.2.3. Moreover, the possibilty of ^{85}Kr perturbation of atmospheric electrical processes has been raised.[13]

3.2.2 Dispersion of radioactivity and resulting human exposures

Given the radionuclide emission rates from nuclear power plants and other facilities of the fuel cycle, realistic calculation of human exposure involves several steps. The conditions of release determine the manner in which each of the radioactive species will disperse in the environment. Aside from the obvious consideration of whether the release is gaseous, liquid, or solid, the specific routes into the environment must be considered. For releases of effluents into the atmosphere, the release may be characterized by physical point of release (for example, the stack height), chemical and physical form, and meteorological-geographic conditions. This information can then be used to determine the manner in which the radionuclides are distributed into the environment.

This distribution, which in principle is time dependent (particularly in the case of accidental releases), may be used as the basis for determining the extent of human (or general biological) exposure. This last determination requires detailed consideration of the manner in which particular types of radiation interact with organisms and, indeed, of the manner in which certain radioactive species may be taken up, concentrated, and/or retained by the body. The NRC Regulatory Guides (discussed in Section 2.4) prescribe calculational methods which are acceptable in the licensing process for nuclear power plants. A summary of exposure pathways to man is given in Fig. 3-1 from Ref. 8.

3.2.2.1 Atmospheric dispersion

The detail and/or precision of dispersion calculations varies widely, depending on the information sought and the resources available for the calculation. For radioactive emissions, the primary considerations in the meteorological modeling itself are the atmospheric transport of the materials, and depletion of the amount in the atmosphere by either radioactive decay or ground deposition through various chemical or physical processes. With the

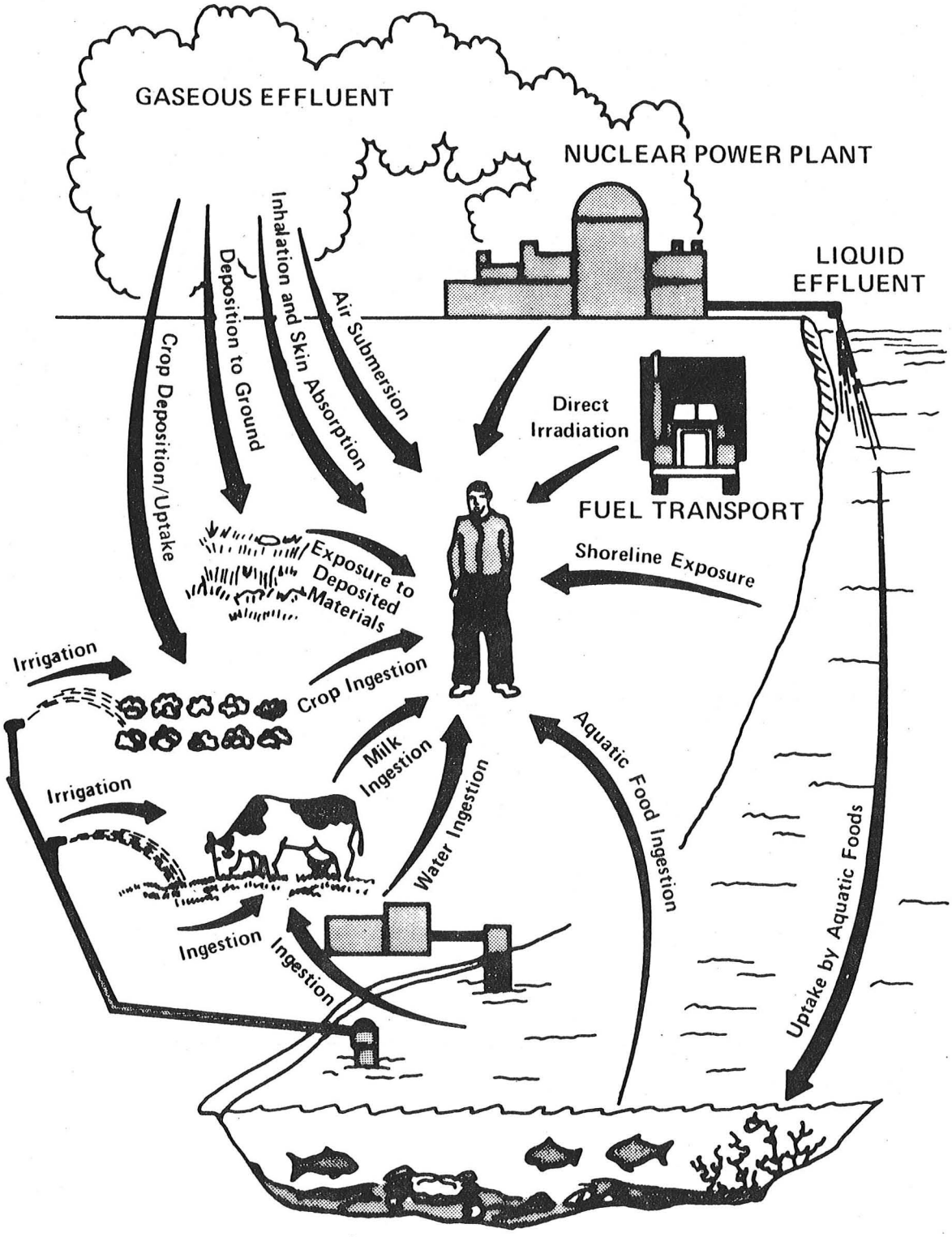

Fig. 3-1. Exposure pathways to man (reproduced from reference 8).

exception of the fact that radionuclides can decay, treatment of dispersion of radioactivity is the same as treatment of "conventional" emissions. Even considering radioactive decay, the problems are not dissimilar, since conventional pollutants can be chemically transformed, which may alter their biological significance and therefore remove them from consideration.

Simulation of radionuclide transport can be attempted in ways which only grossly approximate the physical processes or in ways which model these processes in detail. The basic processes are movement of the radionuclides through gross transport by prevailing winds and through turbulent diffusion caused by atmospheric eddies. In rough terms, gross transport due to winds provides a mechanism for linear transport of emissions from the source in the form of a "plume"; turbulent diffusion causes a widening of the plume as distance from the source increases. The vertical mixing of the plume may be limited by the existence of a "mixing layer", throughout which atmospheric convection occurs but out of which diffusion is limited. The extent of turbulent diffusion and the depth of a mixing layer depend on meteorological stability, which is related to the "lapse rate", the change in air temperature with height. Atmospheric stability is often specified as one of seven "Pasquill" classes, varying from extremely stable to extremely unstable.

One of the most basic types of atmospheric transport models simulates gross transport by assigning a wind direction (which may, in principle, be allowed to vary) and introduces diffusion by assigning a diffusion parameter which, in the context of a simple diffusion equation, simulates the diffusion process in an average way. (Dependence on stability conditions and the existence of a mixing layer may be then incorporated in such a model.) When this simple approach is taken, the resulting form of the mathematical expression for the cross-section of the plume is what is called a "Gaussian" function, so that the model is typically referred to as a Gaussian plume model. This is, for example, the form of model used in the atmospheric transport calculations of the NRC's Reactor Safety Study[14] (see Section 3.5). It is, moreover, the approach required in the accident analysis required in the Safety Analysis Report for a nuclear power plant (see Section 2.4).

Gaussian models of varying complexity can be formulated in an attempt to simulate the details of varying meteorological conditions. However, a precise simulation of those conditions requires departure from the macroscopic treatment implicit in the diffusion equation approach. For example, the

modeler may attempt to actually construct a wind "field" in an air basin, representing numerical values of wind velocity (i.e., speed and direction) as a function of position within the basin and as a function of time. Construction of such a field requires detailed treatment of the factors affecting air movement, including the topographic variations and boundaries of the basin and the physical conservation of air volume. A detailed consideration of such modeling approaches is beyond the scope of the present discussion. Examples of models using various approaches are given in a separate report.[15] Regulatory Guide 1.111 (see Table 2-7) gives several approaches which are acceptable to the NRC staff.

In addition to simulation of air movement and the resulting transport of radioactivity, the dispersion model must simulate the manner in which the radionuclides are deposited onto surfaces in the plume (or basin). Deposition may occur from various processes, including chemical reactions and physical impaction. Moreover, decrease in the amounts of radionuclides and changes in the radionuclide composition occur due to radioactive decay; these changes must be included in a model to give correctly the resulting radionuclide concentrations in the environment.

3.2.2.2 Exposures to radiation or radionuclides

Any organism in the emission plume or in areas where radionuclides have been deposited or transported will, to some extent, be subject to exposure to radiotion. These exposures may be due to external radiation from radionuclides in the air and deposited on surfaces, to internal irradiation from inhalation of radionuclides in the air (including that resuspended from surface deposition), and to internal irradiation from ingestion with food or water.

Comparatively speaking, dosimetric modeling of external radiation is relatively straightforward, since simple relationships may be used for the interaction of radiation (i.e., alpha, beta, gamma, and X radiation) with body tissues. For the most important doses, dose is relatively insensitive to characteristics of individual organs or can easily be calculated. Moreover, even though shielding effects (of, for example, buildings) must be considered, simple relationships can still be used for the interaction of radiation with matter.

On the other hand, movement of radionuclides within the body requires additional consideration of detailed biological, chemical, and transport

processes. As a result of extensive research on these processes, considerable information on transport within the human body is available, so that it is possible to model this movement. Therefore, on the basis of ingestion of radionuclides determined from atmospheric dispersion models, the resulting internal distribution of the various radionuclides may be determined. Once this is known, doses to various organs may be calculated.

The International Commission on Radiological Protection (ICRP) Committee II has been responsible for assembling information on internal radionuclide transport, deposition, and elimination; on the basis of this information, the Committee has constructed models which may be used to simulate these processes and to calculate resulting doses from internal radiation.[16] A primary purpose of this effort has been to establish a basis for understanding the effects of radiation and to formulate appropriate radiation protection guidelines, such as maximum permissible concentrations or body burdens. However, this same information may also be used for the task of calculating, independently of such standards, internal radiation doses, to test compliance with applicable standards or to assess risks. These internal models provide a connection be-between radionuclide concentrations in air, food, or water and doses to human organs. Once the detailed calculations are performed for a given set of assumptions, the results may be tabulated for future use, eliminating the need to use the detailed models for every application. The Nuclear Regulatory Commission has used this tabular approach in its Regulatory Guide 1.111 "Calculation of Annual Doses to man from routine releases of reactor effluents for the purpose of evaluating compliance with 10 CFR 50, Appendix I". (See Section 2.4.) A similar approach may be used in any calculation of doses from radionuclides in the environment.

3.2.3 Alteration of average exposures due to nuclear power operations

Presuming that the dose limitations of the Nuclear Regulatory Commission and the Environmental Protection Agency (see Section 2) are met, it is clear that the routine dose to members of the general public from nuclear power operations will be substantially less than that from natural and medical exposures. Average doses to the general population from routine operations should, moreover, be substantially less than the regulatory limits. The effects of accidental releases are not considered in detail in this report, but are considered briefly in Section 3.5 and more thoroughly in a separate report on reactor safety studies.[17] This section considers only routine releases.

We begin by summarizing the doses arising from the typical plant effluents cited in Table 3-4, i.e., for nuclear power plants at Rancho Seco, Diablo Canyon, and Koshkonong. The maximum annual doses to surrounding populations range from a fraction of a millirem to several millirem, thereby complying with Appendix I. The population dose to members of the general public is several man-rem, a very small number compared with the typical background population dose for the same group, which is on the order of 100,000 man-rem. Note that the population group that absorbs most of the dose from routine operations is the on-site workers. Furthermore, a major portion of the relatively low population dose arises from transportation of spent fuel and radioactive wastes.

Having considered the local doses arising from operation of the nuclear power plant itself, we can now consider the overall effect of operating a nuclear power system. Section 3.2.1 presented information on overall effluents, which arise primarily from fuel reprocessing. Data from two sources will be cited. The first is the BEIR report,[2] which estimated average population exposures for a nuclear power system growing to 800 gigawatts capacity by the year 2000. Assuming that the dose rate at the site boundaries were 5 mrem/year, it was estimated that the average annual dose from power plants would be 0.17 mrem/year. A similar dose was attributed to fuel reprocessing operations. In each case, these doses did not include the effects of the worldwide distribution of tritium and ^{85}Kr. However, the whole body doses from these effluents would be less than the above contributions (although the skin dose would be substantially greater), so that the total dose would be approximately 0.5 mrem/year. However, this presumes a dose rate of 5 mrem/year at the site boundary. New plants typically have somewhat lower dose rates than this.

The GESMO report[9] makes estimates of population doses between 1975 and 2000, based on a nuclear power industry that grows to 500 gigawatts in 2000 and presuming effluents equal to those actually observed in plants currently operating. GESMO calculates the total man-rem commitment to populations living during the 25 year period considered.* Most of the commitment to off-site populations arises from the radon 222 released during mining and milling operation, about 3 million man-rem; operation of the nuclear plants themselves only

*Other methods of calculating dose commitment are possible.

Table 3-6. Doses from Typical (PWR) Nuclear Power Plants.

	Rancho Seco[a]	Diablo Canyon[b]	Koshkonong[c]
	Maximum Annual Dose (mrem)		
	whole body (thyroid)	whole body (thyroid)	whole body (thyroid)
Gaseous effluents:			0.64(1.1)
direct radiation from air and ground	0.77(0.77)	0.13(0.13)	
inhalation	0.05(0.05)	<0.01(0.07)	
terrestrial food chain	0.01(0.17)	<0.01(0.06)	
Liquid Effluents			0.94(0.74)
aquatic food chain	6.4 (3.3)	<0.01(0.02)	
direct radiation from water and shores	5.4 (5.4)	<0.01(0.01)	
	Population Dose (man-rem) within 50 miles		
Gaseous effluents	1.2	0.5	4.6 (from terrestrial foods)
Liquid effluent	2.1	<0.1	
Transportation (entire routes)	2.4	2.7	3
Total	5.7	3.2	

Occupational on-site personnel: 450 (average value for nuclear plants)

[a] Final Envir. Statement (Ref. 6); gaseous dose calculated at site boundary (0.4 miles). Liquid effluent maximal doses assume individual making substantial use of creek into which effluents are released.

[b] Final Envir. Statement (Ref. 7); gaseous dose calculated for nearest residence (1.5 miles). Dose would be larger at site boundary (e.g., 0.98 mrem due to direct radiation from air and ground). Liquid effluents are released to Pacific ocean.

[c] Draft Envir. Statement (Ref. 8); calculated for nearest location.

contributes about 0.3 million* man-rem; fuel reprocessing operations would contribute approximately 1 million man-rem. Assuming a United States population of 200 million over this 25 year period, these commitments correspond roughly to average yearly individual dose commitments of 0.6, 0.06, and 0.2 mrem, respectively. Thus the total average dose remains, as suggested by earlier work, less than 1 mrem/year. Furthermore, although the operation of the nuclear power plants themselves contributes a much more substantial dose to on-site workers than to off-site populations, when the contributions of fuel cycle facilities are considered, the total dose commitments to the two groups become similar; however, in view of the fact that occupational exposures occur to a small portion of the population, the average dose to members of this group, as expected, is much larger than to individuals in the off-site population.

The conclusion to be obtained from these considerations is that the average radiation dose caused by routine nuclear power operations is less than 1% of the average doses from natural background and medical exposures. However, this does not include consideration of the doses resulting from accidents at nuclear facilities. Average accidental exposures due to accidents at nuclear power plants, predicted on the basis of the results of the Reactor Safety Study,[14] would be comparable to the routine average exposure from the entire fuel cycle and considerably larger than the average exposure from routine release from the power plants themselves. However, it is not clear how dose commitments compare. (See further discussion in Section 3.5.)

3.3 Radioactive emissions from fossil-fuel and geothermal power plants

Radionuclide releases are associated not only with nuclear power, but also with other technologies. Nuclear power plants are distinguished from these only in that the reactor actually produces a large array of radionuclides, some in very large quantities. However, this does not imply that the radioactive emissions from these plants are more significant than those from other types of power plants.

*Since the 25 year period considered includes approximately 5000 gigawatt-years of operation, the nuclear power plants cause dose commitments of 60 man-rem/GWY. This is larger than the population doses given in Table 3-6 presumably because the dose commitment includes doses in years subsequent to the actual emissions of radionuclides. Moreover, average population densities, rather than site-specific data were used.

The actual radionuclide emissions associated with fossil-fuel and geothermal power plants are discussed briefly in a separate report on emissions from those plants.[18] The most important emissions from fossil-fuel plants are trace amounts of radium and thorium: amounts released from coal-fired plants without particulate control are on the order of 1 Curie per gigawatt-year (Ci/GWY); amounts released from oil-fired plants are somewhat less. The major emission from geothermal plants is radon 222, a gas which results from the alpha decay of radium 226 in the earth's crust. (This is also the origin of the radon gas which causes the bulk of the dose commitment from the nuclear fuel cycle; see Section 3.2.3.) The amounts of radon carried to the earth's surface by geothermal fluids vary greatly with the resource: the Geyser's plants yield approximately 1500 Ci/GWY; resources in the Imperial Valley carry an amount per equivalent output energy that is up to 1000 times this amount, but this activity might be better controlled.

It is difficult to assess the significance of these releases or to compare them with releases from nuclear power. The radium and thorium releases associated with the burning of fossil-fuels are much larger than similar releases from nuclear power plants or the nuclear fuel cycle. However, the important emissions from nuclear power plants are of other radionuclides. It is clear, however, that the releases from fossil-fuel plants do not exceed applicable standards; in any case, the release of "conventional" pollutants are the primary concern associated with fossil-fuel plants. Indeed, control of conventional particulates at these plants significantly decreases radionuclide releases in the fly ash.

Since radon is the principal radioactive release from geothermal facilities, a more apt comparison may be made with nuclear power, in view of the fact that that the major dose commitment from the nuclear fuel cycle arises from radon releases. In both cases, nuclear and geothermal, the radon arises from the decay of ^{226}Ra which was already in the earth's crust. As noted in the last section, the GESMO report[9] gives radon emissions from the mining and milling operations; the stated emissions correspond to approximately 4000 Ci/GWY. This release rate is comparable to the rate from the Geysers, but would be dwarfed by the rate from Imperial resources, unless reinjection is relatively efficient. Moreover, as noted previously, the contribution to the population dose from emissions from the nuclear power plants themselves is considerably smaller than the commitment from the mining and milling operations.

This leads to the conclusion that the routine radioactive emissions from a geothermal plant could be more significant than those from a nuclear power plant. However, it is important to note that the rate of emissions depends strongly on control measures and the significance of emissions depends greatly on the distribution of populations around the plant site. In general geothermal plants are more remotely sited than the average nuclear power plant. However, the nuclear fuel cycle radon emissions come largely from mining and milling operations which are also relatively remote.* In either case, the total population dose caused by power plant radionuclide emissions is extremely small compared with the dose due to natural background.

In general, these comparisons show the difficulty with using dose commitment as a measure of human impacts. Although there are some advantages to summing the total impact of a given amount of activity over its effective lifetime, there are disadvantages because of the difficulty of maintaining a consistent approach. Furthermore, the effects of other human activities are not normally considered in a comparable manner, even when this might appropriately be done.

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*Even considering the differences arising from local population density considerations, the geothermal emissions and the nuclear GESMO numbers cannot be directly compared, because the nuclear radon emissions are only those which occur during the years 1975-2000. Most of the nuclear radon, however, will emanate after 2000, since it arises from the decay of relatively long-lived isotopes of radiation (or its parent, thorium) left in mill tailings. On the other hand, only a small portions of the radon can diffuse out of the tailings pile, particularly if appropriate measured are taken to contain it. As is apparent, it is difficult to establish a simple basis for comparison of alternative technologies.

In the same vein, the radium and thorium emissions from coal-fired plants may be compared to nuclear and geothermal with respect to their principal avenue to impact on humans, the production of radon. The approximately one Curie/GWY from uncontrolled coal plants would be dispersed effectively in the atmosphere, possibly in relatively densely inhabited regions. The resulting radon would appear in these areas at low concentrations, but, due to the long half lives of radium and thorium (millenia), exposures would extend over a very long period, much as in the case of the radon from uranium mill tailings. But in the coal case, there is no way to control the radon, once the particulates are released from the generating plant. However, effective particulate control would severely decrease the radioactive emissions from coal-fired plants. This comparison, though, employs numbers which do not consider the relative availability of the radon-daughter products to humans. It also does not consider the other risks and benefits from alternative technologies.

3.4 Control of Routine Emissions from Nuclear Power Plants

The basic philosophy of effluent control at nuclear power plants is to limit resulting exposures to the public to a level that is "as low as is reasonably achievable" (10 CFR 50, Appendix I). Choice of radwaste systems is directly based on this goal; the numerical design objectives stated in Appendix I were based on the detailed consideration of costs and benefits as described in the Final Environmental Statement on Appendix I (WASH-1258).[19] WASH-1258 explicitly considered the various components and systems which could be incorporated into plant design to limit public exposures to routine radioactive releases. During NRC review of proposed nuclear power plants, the effectiveness of radwaste control systems is considered in the manner specified in the Regulatory Guides given in Table 2-7.

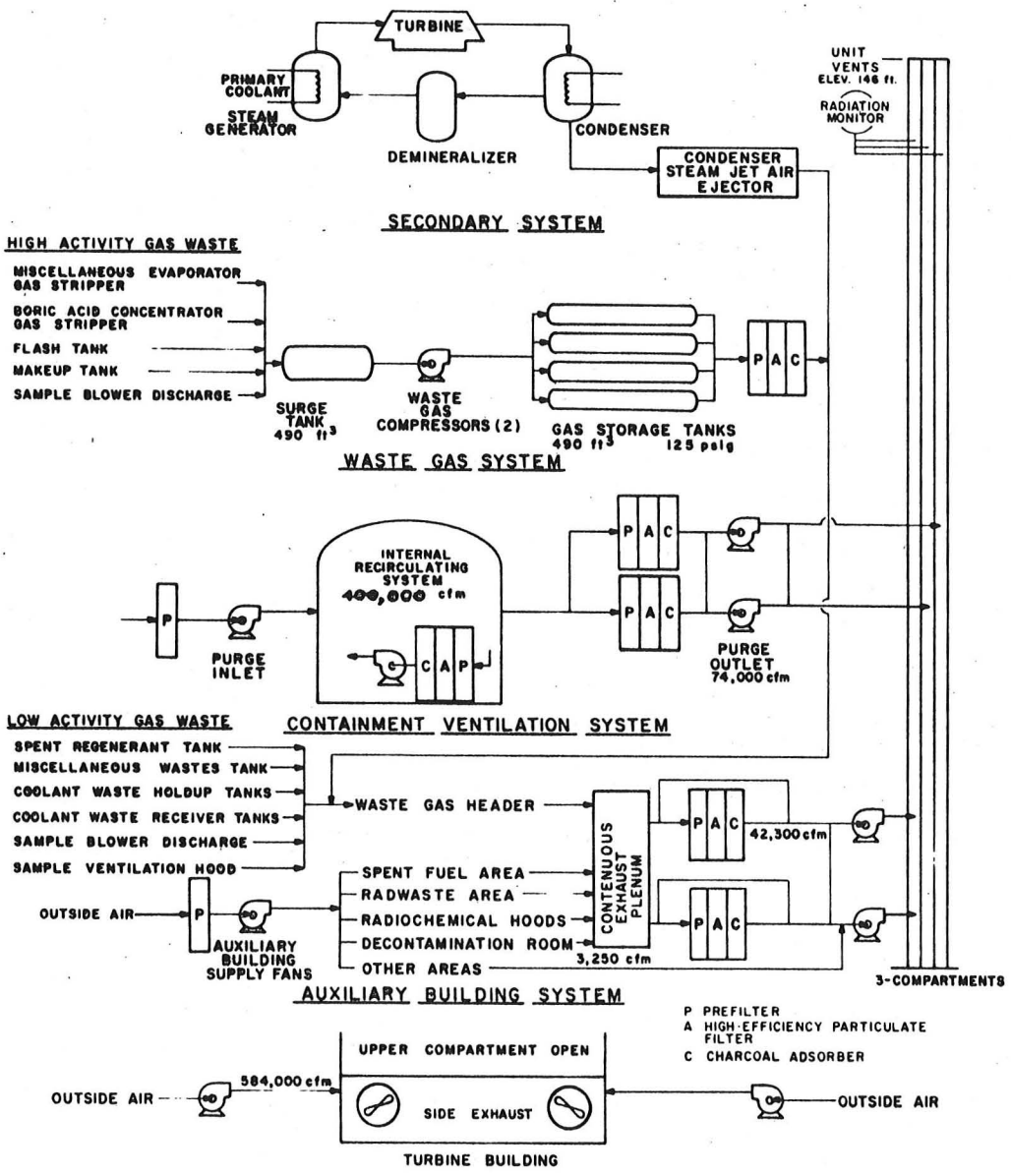
To quote from Regulatory Guide 1.111, "Calculation of Releases of Radioactive Materials in Gaseous and Liquid Effluents from Light-Water-Cooled Power Reactors" on PWRs:

> 1. Each application for a permit to construct a nuclear power reactor should include in-plant control measures to maintain releases of radioactive materials in liquid and gaseous effluents to the environment as low as is reasonably achievable in accordance with the requirements of paragraph 20.1(c) of 10 CFR Part 20 and of § 50.34a, § 50.36a, and Appendix I of 10 CFR Part 50. For gaseous effluents, such measures could include storage for decay of noble gases removed from the primary coolant and charcoal adsorbers or HEPA filters to remove radioiodine and radioactive particulates released from building ventilation exhaust systems. For liquid effluents, such measures could include storage for decay, demineralization, reverse osmosis, and evaporation.

As an example of systems for control of gaseous and liquid wastes at nuclear power plants, Figures 3-2 and 3-3, respectively, show such systems for the Rancho Seco pressurized-water reactor power plant. As previously noted, the average annual total population exposure for this systems was projected (in reference 6) to be on the order of 5 man-rem.

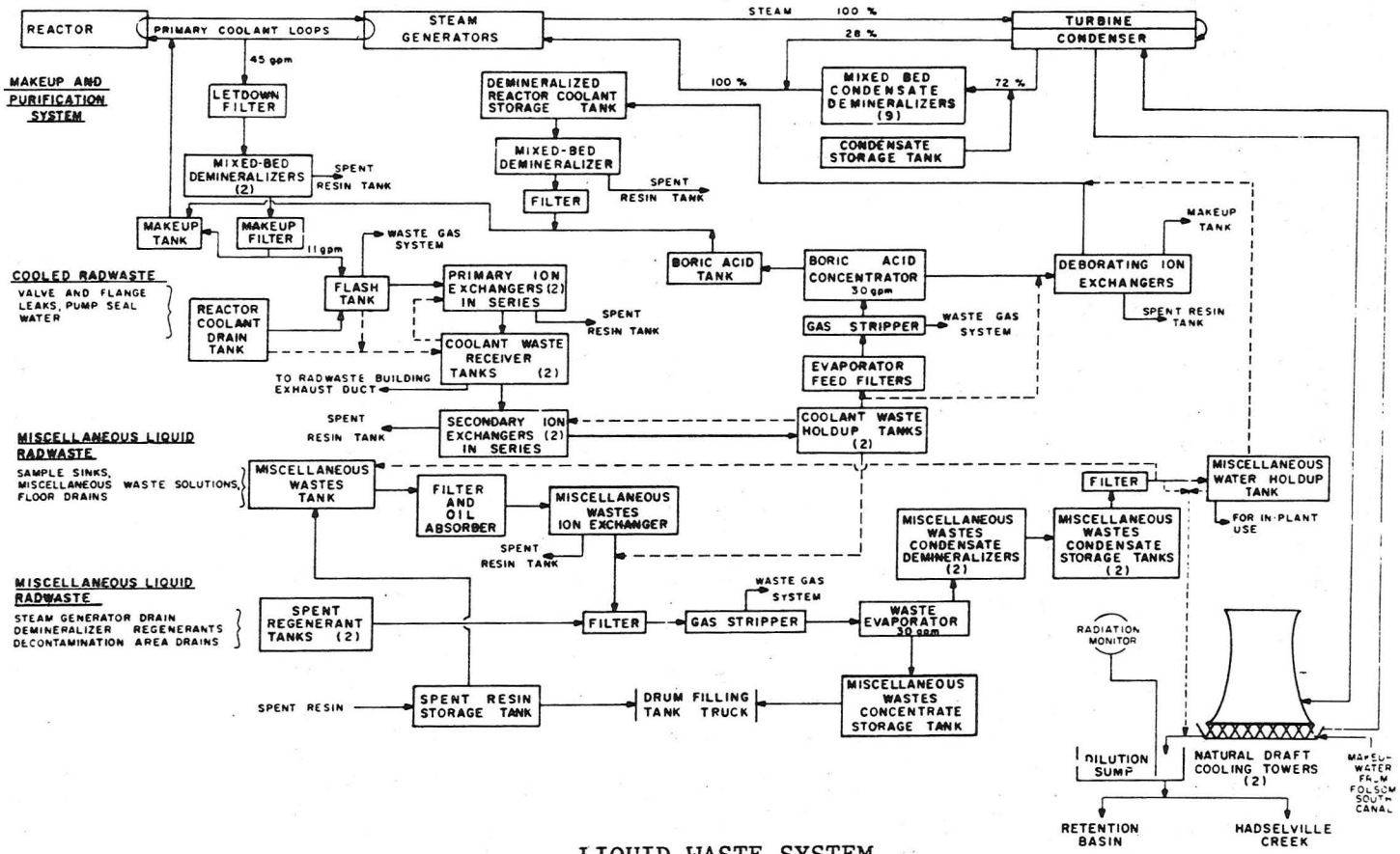
3.5 Control of Accidental Releases from Nuclear Power Plants

Although consideration of the potential for accidental radioactive releases from nuclear power plants is the subject of another report,[17] we briefly mention the manner in which this potential is controlled through "engineered safety features." That this potential be controlled is at least as important as control of routine emissions, in view of the fact that - as suggested in Table 3-6 - the annualized average exposure from accidents at nuclear plants is



GASEOUS WASTE DISPOSAL AND VENTILATION SYSTEM

Figure 3-2. (Reproduced from Ref. 6)



LIQUID WASTE SYSTEM

Figure 3-3. (Reproduced from Ref. 6)

estimated to be larger than that from routine emissions. Of particular importance are the systems which, after a severe nuclear accident, would clean the containment atmosphere of radioactivity to prevent its escape into the environment.

In this context, it is important, perhaps, to identify the class of accidents which is primarily responsbile for the overall risk from accidental releases. The discussion in WASH-1400[14] and typical environmental statements for nuclear power plants[6-8] gives the distinct impression that small accidents (that is, those with small consequences or those with small releases to the atmosphere) contribute most of the risk, i.e., probability times consequences. However, the data from WASH-1400 shows that it is the accidents with large releases that contributes most of the risk.* This fact should have implications, not only for risk assessment, but for the consideration of the various accident mitigating systems to be incorporated in plant designs.

Two types of systems control releases to the atmosphere after large releases from the reactor vessel. One is the containment which surrounds the reactor. The other is the related system for cleaning the containment atmosphere. The details of these systems vary among reactors. From one point of view they are not different conceptually from the systems for controlling routine gaseous emissions. However, in detail they are quite different, because the conditions under which they must operate are very different. The environmental conditions (pressure and temperature) inside the containment during a major accident would be extremely severe, and specific systems are designed to prevent the containment from failing from overpressure. Moreover, the quantity and type of radioactivity in the containment would be very different after a major release than the relatively small amount of gaseous species which escape to the containment under normal operating conditions.

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*However, we should be careful to note that this conclusion is derived from the data presented in WASH-1400, which did not take care to identify risks from different accident types; it is possible that various approximations employed in the WASH-1400 calculations may have had the effect of altering the probability distribution among the various release categories (see Ref. 17).

Finally, we note the importance of instrumentation for monitoring the course of an accident and for predicting the timing, mode, and amount of any release to the atmosphere. Rather sophisticated versions of such monitoring and warning systems are now under consideration.[20] However, the systems in currently operating plants are relatively primitive and may not be adequate to provide sufficient warning (with sufficient detail on release size) for implementation of the most effective measures for protecting the surrounding population.

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20. For example, Regulatory Guide 1.97: Instrumentation for Light-Water Cooled Nuclear Power Plants to Assess Plant Conditions During and Following an Accident (12/1975).

4. A summary of the effects of radiation on health

Since the realization early this century that radiation could be hazardous to human health, a great deal of effort has been devoted to elucidating its possible impacts. This effort has taken the form of epidemiological investigations of human populations exposed to radiation, laboratory investigation of the effects of radiation on organisms, and basic biochemical studies of radiation effects and transport of radioactivity. During recent years, several important and comprehensive reviews[1-4] of the state of information on the effects of radiation, particularly on human health, have been published. Because these provide an adequate overall picture of these effects, we have not undertaken to duplicate their work here. Rather we summarize radiation effects briefly and go on to discuss some issues which have recently been raised and which, in some degree, remain to be resolved. We also note that some of the basic considerations in the formulation of standards are discussed in section 2.

The basic mechanism whereby radiation produces damage occurs at the biochemical and cellular level, where the ionization caused by the passage of radiation disrupts fundamental processes and structures. Depending on the size of the dose received and the rate at which it is received, this disruption may lead to either acute or delayed effects. The acute effects are manifested as disturbances of normal bodily functions, and may lead to illness or death; the delayed effects include both illness, death, and genetic damage. As discussed below, the dose-response relationship for acute effects is relatively well understood quantitatively; however, the functional relationship between radiation doses and the probability of delayed effects is not nearly as well known, particularly for small doses.

Great care must be taken in combining information from various types of sources to achieve an understanding of the relationship between radiation dose and health effects. Not only must the relationship between a specific type of radiation and its effects be determined, but the relative effect of differing types of radiation must be measured by independent experiments. This fact severely complicates the analysis of data where more than one type of radiation is involved.

As just suggested, the category "radiation" is not monolithic. Ionizing radiation occurs both as electromagnetic (gamma and X) radiation and as particulate (alpha, beta, and neutron) radiation. For any particular source, the radiation will also have a characteristic energy or energy range. A related quantity that is important from the radiological point of view is the "linear energy

transfer" (LET), the energy deposited by the radiation per unit length through which it passes. The LET depends both on the type of radiation and its energy. The biological damage of a given "dose" (specified in "rads", a measure of energy deposited per unit mass of tissue) depends on the type and energy of the radiation, and is related to the LET of the radiation. Because of this dependence, exposures are often given in terms of "dose equivalent" (specified in "rem"), a measure of exposure that takes some account of the relative biological effectiveness of the radiation being considered. (See Glossary.)

Even the dose equivalent is not fully informative. The rate at which it is delivered is extremely important, as discussed in succeeding sections. Moreover, the effect of given dose (equivalent) depends strongly on where it is delivered, i.e., to what organ(s). The organ dose, in turn, depends on the type of radioactivity and, often, on uptake properties. These matters were suggested in section 2.2, where the distinction between internal and external exposures was made. Analysis of the effects of external emitters is simplified because of the relative uniformity of exposure as compared with internal emitters, which irradiate the surrounding tissues from the sites at which they are deposited. This analysis complicates our understanding of the effects of radiation on the human organism. Rather complex models must be developed for treatment of the ingestion, transport, deposition, and elimination processes. As noted in section 3.3.3, these same models may be used to understand the routes by which specific radionuclides deliver doses to the body.

Both the International Commission on Radiological Protection (ICRP) and the National Committee on Radiation Protection and Measurements (NCRP) devote considerable efforts to analysis of information on health effects of radiation, in support of their function of recommending guidelines for radiological protection. Committees of the United Nations and the National Academy of Sciences also perform review functions, but without the task of setting standards.

Perhaps the most notable report summarizing current information on radiological health effects is the 1972 report of the United National Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) on "Ionizing Radiation: Levels and Effects."[1] The UNSCEAR Committee is charged with the responsibility of acting as a repository of information on health effects of radiation and on issuing reports on important aspects of this question. Six substantive reports have been issued. The 1972 report is divided into two sections, the first on

sources and doses of radiation ("levels"), the second on specific possible responses to radiation doses ("effects"). The effects considered in this report were genetic effects, effects on the immune response, and carcinogenesis. Other effects were considered in earlier reports. The 1962 report treated the acute consequences of massive amounts of radiation.

In the United States, the National Academy of Sciences - National Research Council Advisory Committee on the Biological Effects of Ionizing Radiation (the BEIR Committee) issued a report in 1972 that was comparable to the 1972 UNSCEAR report, although somewhat less comprehensive. Its primary purpose was to consider "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation."[2] The effects considered were genetic effects, effects on growth and development, and somatic effects (primarily neoplasia).

These reports deserve substantial attention because they treat what is the most uncertain question relating to radiation effects, i.e., to what extent the available information predicts the effect of low levels of radiation. However, the UNSCEAR report refrains from stating quantitatively an effect at these low levels, while the BEIR report does present such estimates, for tentative use in the assessment of health impacts.

The useful information on the effects of high levels of radiation, i.e., large doses delivered over a short time, is much greater than the information on low levels. This information is derived directly from exposed populations, i.e., the inhabitants of Hiroshima and Nagasaki at the time nuclear weapons were used there, patients who have received substantial doses as a result of medical procedures, and—in some cases—occupational exposures. The information from these sources is supplemented by laboratory experiments with animals.

The routine operations of nuclear reactors expose the public and workers to low levels of radiation, the public to much less than they would receive from background sources and the workers to as much as thirty times background. This is the range of exposures whose effects are relatively ill defined. On the other hand, accidents at nuclear facilities could not only increase the population exposed to elevated doses of radiation, but could subject both workers and the public to large doses, giving rise to sickness and even death soon after exposure. For this reason, both categories of exposure are considered below, largely in the form of excerpts from publicly available

reviews. We begin with acute effects (section 4.1), then consider delayed effects (section 4.2). Section 4.3 considers important issues in radiological protection, while section 4.4 summarizes the current state of information on the effects of radiation on human health.

4.1 Acute effects of radiation

The primary source of information on acute effects or radiation on humans is from the Hiroshima and Nagasaki bombings, supplemented by a few accidents resulting from mishandling of radioactive materials. Acute exposures to radiation can damage important physiological systems enough that at low doses illness occurs, and at high doses, death.

The variation of effect on humans with whole body dose is shown in table 4-1 for doses in the range between those that cause no early effects and those that cause death. Below about 25 rad,* no early effects are observed; above that dose, physiological effects may be observed, increasing to serious illness above 100 to 200 rad, significant probability of death above 300 rad, and almost certain death around 1000 rad. The various symptoms observed are caused by several distinct types of damage to the body, but in the range just described (roughly several hundred rem), should death occur, it would be due to damage to the bone marrow. The illness felt by the person exposed soon after exposure is due to other damage, such as to the gasto-intestinal tract. At sufficiently large doses, damage to these other organs would be the cause of death. This discussion, incidentally, assumes the dose is delivered very rapidly. Lengthening the period of exposure (even to only a week) gives the body some time to repair damage, so that the doses for specific responses change.

For purposes of assessment of the probable effects of acute radiation exposure, it is useful to characterize the relationship between dose and effect by a single number. For acute exposures leading to death, the quantity chosen is the dose that is lethal for 50% of those exposed, within some specified time interval. The LD_{50}† (50% lethal dose) is typically around 500 rad. For half

*For whole body dose from external radiation, which arises largely from gamma rays, the rem and rad are roughly equal numerically. In this discussion, we use rad because rem, a radiological protection unit, is not defined for acute exposures.

†Because of the acute nature of the syndrome leading to death, this dose is not highly dependent on the period chosen. Periods in the range of 30-60 days are typical. For 30 days, the 50% lethal dose would be expressed as $LD_{50/30}$.

Table 4-1 (Reproduced from FRC 1[a])

SUMMARY OF EFFECTS RESULTING FROM ACUTE WHOLE BODY EXTERNAL EXPOSURE OF RADIATION TO MAN[1]

0-25 r	25-100 r	100-200 r	200-300 r	300-600 r	600 or more
No detectable clinical effects. Delayed effects may occur.	Slight transient reductions in lymphocytes and neutrophils. Disabling sickness not common, exposed individuals should be able to proceed with usual duties. Delayed effects possible, but serious effects on average individual very improbable.	Nausea and fatigue, with possible vomiting above 125 r. Reduction in lymphocytes and neutrophils with delayed recovery. Delayed effects may shorten life expectancy in the order of one per cent.	Nausea and vomiting on first day. Latent period up to two weeks or perhaps longer. Following latent period symptoms appear but are not severe: loss of appetite, and general malaise, sore throat, pallor, petecheae, diarrhea, moderate emaciation. Recovery likely in about 3 months unless complicated by poor previous health, superimposed injuries or infections.	Nausea, vomiting and diarrhea in first few hours. Latent period with no definite symptoms, perhaps as long as one week. Epilation, loss of appetite, general malaise, and fever during second week, followed by hemorrhage, purpura, petecheae, inflammation of mouth and throat, diarrhea, and emaciation in the third week. Some deaths in 2 to 6 weeks. Possible eventual death to 50% of the exposed individuals for about 450 roentgens.	Nausea, vomiting and diarrhea in first few hours. Short latent period with no definite symptoms in some cases during first week. Diarrhea, hemorrhage, purpura, inflammation of mouth and throat, fever toward end of first week. Rapid emaciation and death as early as the second week with possible eventual death of up to 100% of exposed individuals.

[1]Adapted from "The Effects of Nuclear Weapons," U. S. Government Printing Office, 1957.

[a]reference 5

this dose, death is very unlikely. For twice the dose, it is certain. There is some dependence of this probability on the kind of medical treatment after exposure, but it is ordinarily not large. (Treatment less than heroic may alter the LD_{50} by at most 50%.)

For whole body doses less than about 25 rad, acute effects are not observed, but there may be delayed effects. (See section 4.2.)

Higher doses to specific organs other than the bone marrow and the gastro-intestinal tract may lead to other types of illness; ingestion of radioactivity may lead to selective radiation of organs at these higher doses. One such organ is the thyroid, which concentrates iodine. This mode of exposure assumes great importance, relative to many others, because radioiodine is produced in substantial quantities in nuclear reactors. However, it is unlikely that dose to this organ would lead to death of itself, since circumstances likely to contribute the required dose would probably also deliver a lethal dose to the bone marrow. The more probable damage to the thyroid is delayed induction of a nodule, which can be surgically removed.

4.2 Delayed effects of radiation

The damage caused by radiation can lead to several types of delayed effects, some from damage to the genetic material leading to possible effects in later generations, and some from somatic damage, leading to various effects in the individual exposed. Of the latter class, the most important possibility is cancer, which often leads to death. For information on these effects, we rely heavily on the UNSCEAR[1] and BEIR[2] reports.

4.2.1 Genetic effects

Radiation can cause mutations and chromosome abberations. Such events occur in the absence of radiation from man-made sources, perhaps partially due to background radiation. The probable effects of increases in radiation exposure are often couched in terms of increases in the natural mutation rate. As discussed in section 2, such increases have been the basis of the recommended limits on population exposure.

We do not attempt to discuss the various types of genetic damage. For the purposes of understanding the possible risk from nuclear power, it is sufficient to establish an understanding of the overall damage to be expected from expected levels of exposure. A perspective on this risk is given in tabel 4-2, taken from the BEIR report.[2] This table summarizes the current estimates of incidence of mutation and the increase in incidence due to specified doses per generation.* The 5 rem dose considered in the table corresponds roughly to the 0.17 rem/year recommended limit on population dose. (Five rem is also approximately equal to the normal lifetime genetically-significant dose from background radiation.) The geometric mean of the equilibrium increase (800 per million live births) implies roughly an 8% increase in the mutation rate.

This range of estimates is based on a value for the doubling dose for mutation rate of 20 to 200 rem (65 rem geometric mean). That is, this dose would be expected to double the current incidence of mutations. This value is consistent with the UNSCEAR value[1] of 1% increase in the mutation rate per rad of exposure.

Table 4-2 (Reproduced from BEIR[2])

Estimated effects of radiation for specific genetic damage. The range of estimates is based on doubling doses of 20 and 200 rem. The values given are the expected numbers per million live births.

	Current incidence per million live births	Number that are new mutants	Effect of 5 rem per generation	
			First generation	Equilibrium
Autosomal dominant traits	10,000	2,000	50-500	250-2,500
X-chromosome-linked traits	400	65	0-15	10-100
Recessive traits	1,500	?	very few	very slow increase

*These estimates are made considering the low rate at which the dose is received.

4.2.2 Somatic effects of radiation

A number of somatic effects have been observed at relatively high doses of radiation, usually the equivalent of 100 rem or greater. They have not been observed at low doses; however, they may occur at these doses and are a major consideration in the specification of dose limitations and in the assessment of risk from radiation exposures.

The somatic effects that are considered to be important[2] are cancer, cataracts, impairment of fertility, defective development of the fetus, and life shortening. (Note that effects related to fertility and the fetus may be regarded as "genetic".)

> "Of these, cancer is the chief concern, because it usually involves greater detriment to an affected individual than do any of the others and because the risk of cancer may conceivably be increased by smaller amounts of radiation than are required to cause any of the other effects in question."[2]

However, as we shall see in section 4.3, the dose-response relationships at low dose and dose rate are largely unknown.

Cancers of several types have been studied in detail. In particular, information is available on radiation-induced cancer of the bone marrow (leukemia), thyroid, bone, skin, breast, and lung. Rather than attempt to discuss these here, we quote from the succinct summary of reference 1.

This summary from UNSCEAR gives the risk, for a number of cancer types, in terms of cases per million man-rad (i.e., summed dose over a population; see definition of person-rem in glossary). Summing the various categories (including "other") gives a total of 70 to 140 cases of cancer per million man-rad. This is consistent with the BEIR estimate of 50 to 165 cases per million man-rem.

However, the two reports are by no means consistent in the use to which they put these results. The primary source of information for these cancer estimates is the survivors of the Hiroshima and Nagasaki bombings. The data are significant only for groups with estimated doses of about 50 rem or greater. The UNSCEAR report emphasizes that these data cannot be reliably extrapolated to lower doses or dose rates. On the other hand, the BEIR report actually uses

From the UNSCEAR report[1]:

RADIATION CARCINOGENESIS[12]

51. While experiments with animals suggest that malignant transformations may occur in most mammalian tissues if they are exposed to sufficient radiation doses, the number of people exposed to substantial doses is so small that the relationship between dose and incidence of malignancies in man can only be studied for the most radio-sensitive tissues. By far the largest and most informative groups of irradiated subjects continue to be the survivors of the atomic bombings at Hiroshima and Nagasaki. To these must be added several groups of patients treated by radiotherapy and followed up for several decades, and a few groups of workers exposed to radiation in the course of their occupation—especially underground uranium miners. Children exposed while *in utero*, in the course of radiological examinations of their pregnant mothers, form a special category.

52. Leukæmia is the best known of the radiation-induced malignancies. All evidence indicates that the incidence of certain types of leukæmia increases with dose as a result of post-natal irradiation at high dose rate in the 50-500 rad interval.[13] At higher doses the rise in frequency decreases, possibly because an increasingly large fraction of cells that would otherwise become leukæmic are destroyed by radiation. Radiation-induced leukæmias tend to occur most frequently within a few years after exposure and, after 25 years, the frequency tends to return to the levels expected in the absence of irradiation. By that time some 15-40 cases of leukæmias per rad[14] per million exposed have been observed.

53. Lung cancers appear to have been induced at Hiroshima by doses estimated on the basis of crude assumptions to be equivalent to some 30 rads of external gamma radiation delivered at high dose rate, and to have increased with dose up to a dose of about 100 rads. The higher incidence of this type of cancer among irradiated people has been revealed by other surveys also but it is not yet known whether the increase, which starts some 15 years after irradiation, will be sustained for a long time or will eventually subside. Taken at face value, however, the data indicate that from 10 (at 250 rad) to 40 (at 30 rad) cases of cancer per rad per million exposed develop during the first 25 years after exposure to high-dose-rate gamma radiation.

54. Information is available also on the induction of thyroid and breast cancers. Because those affected by these cancers have long survival times, only in the very long run do mortality data reflect the incidence of these tumours. Thus, while breast cancer mortality at Hiroshima suggests a risk of 6-20 cases per million per rad in the first 25 years after irradiation among women exposed to between 60 and 400 rads, this is probably an underestimate of the total yield. For thyroid cancers, an average figure of about 40 cases per million per rad in the same range of doses over the same period of time is obtained from more reliable morbidity data, but the estimate has large uncertainties due to the small number of cases observed. As for lung tumours, there is no information as to whether the increased annual incidence of tumours in the irradiated populations will subside and when.

55. Many surveys of externally irradiated people confirm an increase in other types of cancer taken together, although it is not possible at this stage to identify the specific types whose frequency is enhanced. Among the survivors of the atomic bombing at Hiroshima there is a clear trend for mortality from malignancies other than leukæmia and lung and breast cancers to increase with increasing dose, but quantitative estimates of the rate of increase are hampered by our ignorance of the doses to the tissues concerned. Only a tentative estimate of 40 cases of cancers (other than leukæmias and breast and lung cancer) per rad per million occurring during the first 25 years after exposure to 250 rads can be advanced on the basis of crude assumptions about tissue doses. Here also it is not known how many additional cases may develop at times later than 25 years.

56. In considering these estimates it must be clearly borne in mind that they are based on observations made after doses of at least tens of rads delivered at high dose rates. These dose rates, and occasionally these doses, are of the order of those that can be received in the course of certain radiological procedures carried out on medical indications, but much higher than those at which we are irradiated by environmental sources, both natural and man-made. It is a matter of speculation whether doses of the order of those received continuously from natural sources may have similar effects. Animal experiments suggest that the yield of tumours per unit dose should be lower at very low doses, except when the target tissue has a susceptibility to radiation induction of malignancies much higher than has been observed in man. Animal experiments also indicate that radiation given continuously or in several fractions is usually less carcinogenic than if administered in a single dose within a short period of time. The figures given in the preceding paragraphs are therefore likely to be overestimates of the risk of doses and dose rates such as are received from environmental sources.

57. Studies of people exposed to internal irradiation at substantial doses are few. They concern workers and patients contaminated with radium isotopes and miners exposed to radon gas. Radium-226 is deposited in bones, irradiates bone-forming cells continuously at a decreasing rate for decades after being absorbed into the body and gives rise to bone tumours. Radium-224 causes similar effects after a shorter period of irradiation.

58. Miners exposed to high levels of radon and its radio-active daughters show a very high incidence of lung cancers. The frequency appears to rise in proportion to the level and duration of exposure. The range of exposures within which the increased incidence has been reported corresponds to doses of at least a few hundred rads of alpha radiation. However, dosimetry is difficult and the role of other carcinogenic factors such as smoking habits has not yet been fully assessed.

59. The effects of pre-natal irradiation have been the subject of much research. A number of large surveys of children that were exposed to radiation for medical reasons before birth, and that must have received thereby doses of at most a few rads at high dose rate, indicate that pre-natal irradiation is associated with a significant increase of the risk of malignancies in the first 10 years of life. The extent to which the increased risk of malignancies in the medically irradiated is due to radiation rather than to an association with the cause that prompted the irradiation must still be considered as open.

[12] For details, see annexes G and H.

[13] 1 rad ~ 10 times the annual dose received from natural sources.

[14] The estimate applies to doses between 60 and 400 rads of gamma rays.

these estimates to calculate increases in incidence of cancer for assumed small increases in the average individual dose in the United States. The risk estimates used in that calculation are given in table 4-3.

Note that the above risk estimates, about 100 cancers per million man-rem, are given in absolute terms, i.e., the numerical increase in incidence is specified. The increased risk may also be stated relative to the incidence in the absence of increased exposures. In the discussion of mutations in the last section, the statement of 20 to 200 rem as the doubling dose is couched in terms of relative risk.

Table 4-3 Cancer Risk (Reproduced from BEIR[2])

Age at Irradiation	Type of Cancer	Duration of Latent Period (years)	Duration of Plateau Region (years)[a]	Risk Estimate	
				Absolute Risk[b] (deaths/10^6/yr/rem)	Relative Risk (% incr. in deaths/rem)
In Utero	Leukemia	0	10	25	50
	All other cancer	0	10	25	50
0-9 Years	Leukemia	2	25	2.0	5.0
	All other cancer	15	(a)30 (b)Life	1.0	2.0
10 + Years	Leukemia	2	25	1.0	2.0
	All other cancer	15	(a)30 (b)Life	5.0	0.2

[a] Plateau region = interval following latent period during which risk remains elevated.

[b] The absolute risk for those aged 10 or more at the time of irradiation for all cancer excluding leukemia can be broken down into the respective sites as follows:

Type of Cancer	Deaths/10^6/year/rem
Breast	1.5*
Lung	1.3
GI incl. Stomach	1.0
Bone	0.2
All other cancer	1.0
Total	5.0

* This is derived from the value of 6.0 quoted in Appendix II, Section A 1 e corrected for a 50% cure rate and the inclusion of males as well as females in the population.

The cancer risk may be stated in either fashion, and is done so in table 4-3. If no alterations occur in the natural incidence, then there is no significant difference in the ways of stating risk. However, if the risk due to increases in radiation is, for some reason, actually proportional to the natural risk, then the statement of relative risk is more appropriate. It may even be important to do so, should the natural incidence change due to other factors than radiation exposures. (See discussion of section 4.3.)

Of other somatic effects, one that can be quite significant, because of the potentially large releases of iodine from nuclear power plants, is incidence of thyroid tumors. However, these tumors are largely benign, and may be removed surgically. The incidence is greatest among children exposed to radiation, approaching 100% at thyroid doses of 1000 rad.[2] On the other hand, the incidence of malignancies is substantially smaller, approximately 1 to 10 per million child-rem.[2] The risk from irradiation of adults is considerably smaller.

Direct epidemiological information on the effects of low doses and dose rates may never be obtained. Out of even a large population, a relatively small increase in incidence is expected, assuming that an extrapolation from higher doses yields an upper bound; in general, small increases in incidence are difficult to observe. The largest available study group has been employees of contractors to the Atomic Energy Commission at Oak Ridge and Hanford. A long-term study of these populations has been conducted by a number of groups, but no consensus has developed on any statistical correlation between the low radiation exposures of these populations and possible increases in cancer incidence. The recent paper by Mancuso, Stewart and Kneale[6] purports to establish such a correlation for several types of cancer, with a doubling dose of from 1 to 10 rads; this would be a surprisingly low dose (or high response), and serious objections have been raised to their methodology and conclusions. If anything, most workers in the field expect that the BEIR estimates overestimate effects, at low doses and dose rates, not the converse. (See section 4.3.1.)

4.3 Recent questions on dose response

As suggested in the last section, the precise relationship between exposures to radiation and increased cancer is not known. The most substantial uncertainty pertains to the effect of low doses and dose rates. Other prominent questions in recent years have concerned interpretation of the absolute versus relative risk estimates and the effects of radioactivity distribution on the dose response (the "hot particle" question).

4.3.1 Low dose and dose rate

Although the data discussed in the last section, on cancer incidence, were obtained at high doses and dose rates, the BEIR report[2] applies the resulting relationship between cancer incidence and population dose to situations involving low dose and dose rate. Using the incidence-to-population-dose ratio in this manner is equivalent to a presumption that the dose response relationship is linear, with no threshold. In recent years, the Environmental Protection Agency has employed such an assumption for assessment purposes.

This practice constituted the major reason, in 1976, for EPA criticism of the dose-response relationship employed in the NRC Reactor Safety Study* (see reference 7 for discussion). The EPA regards use of a strict linear hypothesis, without reduction for low dose or dose rate, to be appropriate for assessment functions.[8] On the other hand, the panel assembled by the Reactor Safety Study regarded a reduction of response necessary for realistic estimation of the effects of radiation under such exposure conditions. A similar position is expected to be taken by a forthcoming NCRP report on the subject.

The reduction in effects resulting from the suggested adjustments is approximately a factor of four, leading to a response-to-dose ratio of approximately 25 cancers per million man-rem. (Thus, whereas the BEIR estimate was equivalent, roughly, to one cancer per 10,000 man-rem, this would be equivalent to one per 40,000, of which cancers about half would be fatal.)

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*Appendix VI of WASH-1400[3] includes an extensive discussion of the study's dosimetric and dose-response models.

On the other hand, the consensus appears to be allowing more specifically for the possibility that the linear approximation is not a substantial overestimate of the dose response relationship at low doses and dose rates. The possibility that such large overestimates might occur was emphasized by the NCRP in a 1975 report.[9] However, the factor of four reduction discussed above points to a less emphatic perception of this overestimate. For the case of external radiation, there are those who attempt to make the case, from a fundamental point of view, that the linear hypothesis should not seriously overestimate cancer incidence.[10]

4.3.2 Absolute and relative risk models

As indicated in section 4.2.2, cancer incidence may be expressed on either an absolute or a relative risk basis. Were the data on all types of cancer complete, and were there no variation in natural incidence from one group to another, the basis used would not affect resulting risks estimates. However, neither of these conditions is true, so—depending on the point of view of the investigator—different predictions may result.

One of the more extreme examples of possible differences may be seen by comparing the BEIR dose response ratio with that of Gofman as expressed in connection with plutonium toxicity[11] (see also next section). Gofman cites a "lung cancer dose" (the increased population dose that would result in one added case of lung cancer) of 1310 rem. For purposes of comparison, the UNSCEAR estimate of 10 to 30 per million man-rad (of gamma rays) corresponds to between 33,000 and 100,000 man-rem as the "lung cancer dose." BEIR would give a similar result. The biomedical community is strongly inclined to subscribe to the lower (non-Gofman) incidence and to use of "absolute" risk models.

4.3.3 Plutonium questions

Because of the expected increase in the amount of plutonium in the commercial nuclear power system, and the high toxicity of plutonium, much attention has been drawn to claims that the prevalent biomedical understanding of the extent of this toxicity may be seriously in error. Radioactive decay of plutonium

and the other actinides takes place through emission of alpha particles. Because of their short range in matter, alpha emitters are not a significant source of human exposure unless the decaying radionuclide resides in the body.

Plutonium is most toxic if it is ingested in a form that is soluble, in which case it is a bone-seeker, like radium. However, plutonium is more likely to be encountered as insoluble particulates. In such a form, the critical organ is the lung, which may be irradiated by deposited plutonium. Most of the controversy about plutonium toxicity has arisen with respect to the dose-response relationship for such deposits.

The "hot particle" hypothesis is the more prominent of the two questions we will note. This hypothesis raises the possibility that, because plutonium is concentrated into particles, tissue immediately adjacent to these particles will be very heavily irradiated, possibly leading to enhanced risk of cancer. The possibility of increased risk from intense local irradiation had been examined previously, but was raised again in a 1974 petition from the Natural Resources Defense Council, asking the Atomic Energy Commission to establish specific radiological protection standards for "hot particles." The Natural Resources Defense Council suggested an enhancement factor of 115,000. This petition was denied[12] in 1976 on the basis of the prevailing biomedical opinion that no large enhancement occurred due to particulate form. This decision has been supported recently by a National Academy of Sciences report[13] on the subject.

Gofman has also raised questions about the toxicity of inhaled plutonium,[11] but on a different basis. He suggests that plutonium may be more toxic than previously accepted, particularly for cigarette smokers. He postulates a steep dose response relationship (see the previous section) and a reduced lung clearance function for smokers. His suggestions, and related ones by other critics of nuclear power, are presently being subjected to the scrutiny of the biomedical community. However, there is no general expectation that the prevalent opinion about plutonium toxicity will change radically.

4.4 Current perception of the effect of radiation on human health

The previous sections have given some indication of the state of knowledge of the relationship between exposure to radiation and incidence of health effects, primarily cancer. In general, it can be said that much is known about this relationship, although there are notable uncertainties when considering low doses or particular radionuclides.

To recapitulate, the response to acute doses of radiation is relatively well understood, at least as far as the required dose is concerned. A whole body dose of 500 rad is roughly the level at which 50% fatalities would occur. For low doses, delayed genetic and somatic effects may occur: a dose of 20 to 200 rem is expected to double the incidence of mutations; a population dose of somewhat more (but perhaps not much more) than 10,000 man-rem corresponds roughly to an increase of one case of cancer. This latter statement appears to be the current consensus, although individuals may differ with it.

With regard to particular radiation protection standards, no great change in any area appears to be likely. Most changes now expected will be in the nature of a slight alteration in the standards, based on a more complete or accurate modeling of the processes whereby radionuclides reside within the body and irradiate bodily tissues. For this reason, the standards may be considered to be broadly satisfactory.

It must also be emphasized that the recommended numerical standards for exposure limits and for radionuclide concentrations all give exposures which are far higher than those presently (or expected to be) experienced as a result of nuclear power operations. From the point of view of assessments of nuclear power, the more important question is the overall dose response relationship between radiation and health effects. Although the evidence is not sufficient to specify this relationship, a linear dose-response function appears to be a usable, probably conservative, tool for risk assessment.

References for Section 4

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8. See, for example, W. H. M. Ellett and A. C. B. Richardson, "Estimates of the Cancer Risk Due to Nuclear-Electric Power Generation", U.S. Environmental Protection Agency Technical Note ORP/CSD-76-2, October 1976.

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11. J. W. Gofman, "The Cancer Hazard from Inhaled Plutonium", Committee for Nuclear Responsibility Report 1975-1-R, May 1975.

12. Federal Register, Vol. 41, page 15371, April 12, 1976.

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GLOSSARY

ABCC: Atomic Bomb Casualty Commission

Absolute risk: Product of assumed relative risk times the total population at risk. The number of cases that will result from exposure of a given population.

Absorption coefficient: Fractional decrease in the intensity of a beam of x or gamma radiation per unit thickness (linear absorption coefficient), per unit mass (mass absorption coefficient), or per atom (atomic absorption coefficient) of absorber, due to deposition of energy in the absorber. The total absorption coefficient is the sum of individual energy absorption processes (Compton effect, photoelectric effect, and pair production).

Accelerator (particle accelerator): A device for imparting large kinetic energy to electrically charged particles such as electrons, protons, deuterons and helium ions. Common types of particle accelerators are direct voltage accelerators, cyclotrons, etatrons, and linear accelerators.

Alpha particle: A charged particle emitted from the nucleus of an atom having a mass and charge equal in magnitude to a helium nucleus: i.e., two protons and two neutrons.

Angstrom unit: One angstrom unit equals 10^{-8} cm (Symbol: A).

Anion: Negatively charged ion.

Atomic mass: The mass of a neutral atom of a nuclide, usually expressed in terms of "atomic mass units." The "atomic mass unit" is one-twelfth the mass of one neutral atom of carbon-12; equivalent to 1 6604 X 10^{-24} g Symbol: u).

Attenuation: The process by which a beam of radiation is reduced in intensity when passing through some material. It is the combination of absorption and scattering processes and leads to a decrease in flux density of the beam when projected through matter.

Average life (mean life): The average of the individual lives of all the atoms of a particular radioactive substance. It is 1.443 times the radioactive half-life.

BEAR Committee: Advisory Committee on the Biological Effects of Atomic Radiation (Precursor of the BEIR Committee).

BEIR Committee: Advisory Committee on the Biological Effects of Ionizing Radiation.

Beta particle: Charged particle emitted from the nucleus of an atom, with a mass and charge equal in magnitude to that of the electron.

Bone seeker: Any compound or ion which migrates in the body preferentially into bone.

Bremsstrahlung: Secondary photon radiation produced by deceleration of charged particles passing through matter.

Carrier: A quantity of non-radioactive or non-labeled material of the same chemical composition as its corresponding radioactive or labeled counterpart. When mixed with the corresponding radioactive labeled material, so as to form a chemically inseparable mixture, the carrier permits chemical (and some physical) manipulation of the mixture with less label or radioactivity loss than would be true for the undiluted label or radioactivity.

Cation: Positively charged ion.

Chamber, ionization: An instrument designed to measure a quantity of ionizing radiation in terms of the charge of electricity associated with ions produced within a defined volume.

Curie: The special unit of activity. One curie equals 3,700 × 10^{10} nuclear transformations per second. (Abbr. Ci.) Common fractions are:

Megacurie: One million curies (Abbr. MCi)
Microcurie: One millionth of a curie (3.7×10^{4} disintegrations per second. Abbr. μCi)
Millicurie: One-thousandth of a curie (3.7×10^{7} disintegrations per second. Abbr. mCi.)
Nanocurie: One-billionth of a curie (Abbr. nCi)
Picocurie: One-millionth of a microcurie (3.7×10^{-2}) disintegrations per second. (Abbr. pCi)

Daughter: Synonym for decay product.

Decay product: A nuclide resulting from the radioactive disintegration of a radionuclide, formed either directly or as the result of successive transformations in a radioactive series. A decay product may be either radioactive or stable.

Decay, radioactive: Disintegration of the nucleus of an unstable nuclide by spontaneous emission of charged particles and/or photons.

Dose: A general form denoting the quantity of radiation or energy absorbed. For special purposes it must be appropriately qualified. If unqualified, it refers to absorbed dose.

Absorbed dose: The energy imparted to matter by ionizing radiation per unit mass of irradiated material at the place of interest. The unit of absorbed dose is the rad. One rad = 100 ergs per gram, or 0.01 J/pg.
Cumulative dose: Total dose resulting from repeated exposure to radiation.

Dose equivalent (DE): Quantity that expresses all radiations on a common scale for calculating the effective absorbed dose. It is defined as the product of the absorbed dose in rads and certain modifying factors. The unit of DE is the rem.

Genetically significant dose (GSD): The gonad dose from medical exposure which, if received by every member of the population, would be expected to produce the same

reproduced from BEIR: "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation", report of the National Academy of Sciences - National Research Council Advisory Committee on the Biological Effects of Ionizing Radiation, November 1972.

total genetic effect on the population as the sum of the individual doses actually received. The GSD can be expressed algebraically as:

$$GSD = \frac{\sum D_i N_i P_i}{\sum N_i P_i}$$

D_i = Average gonad dose to persons age i who received x-ray examinations

N_i = Number of persons in population of age i who receive x-ray examinations

Pi = Expected future number of children for person of age i

Ni = number of persons in population of age i.

In 1964 the GSD was computed to be 55 millirads per person per year, for the United States. An estimated 55% of the population were receiving x-rays at that time. Thus, the average dose to those receiving medical radiation could be computed to be approximately 80 millirads.

Maximum Permissible Dose Equivalent (MPD): The greatest dose equivalent that a person or specified part thereof shall be allowed to receive in a given period of time.

Median Lethal Dose (MLD): Dose of radiation required to kill, within a specified period, 50% of the individuals in a large group of animals or organisms. Also called LD_{50}.

Permissible Dose: The dose of radiation which may be received by an individual within a specified period with expectation of no significantly harmful result.

Threshold Dose: The minimum absorbed dose that will produce a detectable degree of any given effect.

Doubling Dose: The amount of radiation needed to double the natural incidence of a genetic or somatic anomaly.

Dose, Fractionation: A method of administering radiation, in which relatively small doses are given daily or at longer intervals.

Dose, Protraction: A method of administering radiation by delivering it continuously over a relatively long period at a low dose rate.

Dose rate: Absorbed dose delivered per unit time.

Electron Volt: A unit of energy equivalent to the energy gained by an electron in passing through a potential difference of one volt. Larger multiple units of the electron volt are frequently used: KeV for thousand or *kilo electron volts;* MeV for million or *mega electron volts.* (Abbr. eV, 1 eV = 1.6×10^{-12} erg.)

EPA: Environmental Protection Agency

Exposure: A measure of the ionization produced in air by x or gamma radiation. It is the sum of the electrical charges on all ions of one sign produced in air when all electrons liberated by photons in a volume element of air are completely stopped in air, divided by the mass of the air in the volume element. The special unit of exposure is the roentgen.

Acute exposure: Radiation exposure of short duration.

Chronic exposure: Radiation exposure of long duration by fractionation or protraction.

Fission, nuclear: A nuclear transformation characterized by the splitting of a nucleus into at least two other nuclei and the release of a relatively large amount of energy.

Fission products: Elements or compounds resulting from fission.

Fission yield: The percentage of fissions leading to a particular nuclide.

FRC: Federal Radiation Council

Fuel cycle: The sequence of steps, such as utilization, reprocessing, and refabrication, through which nuclear fuel passes.

Fusion, nuclear: Act of coalescing two or more atomic nuclei

Gamma ray: Short wavelength electromagnetic radiation of nuclear origin (range of energy from 10KeV to 9MeV) emitted from the nucleus.

Gram atomic weight: A mass in grams numerically equal to the atomic weight of an element.

Gram molecular weight (gram-mole): Mass in grams numerically equal to the molecular weight of a substance.

Gram-Rad: Unit of integral dose equal to 100 ergs.

Half-life, biological: The time required for the body to eliminate one-half of an administered dosage of any substance by regular processes of elimination. Approximately the same for both stable and radioactive isotopes of a particular element.

Half-life, effective: Time required for a radioactive element in an animal body to be diminished 50% as a result of the combined action of radioactive decay and biological elimination.

$$\text{Effective half-life} = \frac{\text{Biological half-life} \times \text{radioactive Half-life}}{\text{Biological half-life} + \text{Radioactive half-life}}$$

Half-life, radioactive: Time required for a radioactive substance to lose 50% of its activity by decay. Each radionuclide has a unique half-life.

ICRP: International Commission on Radiological Protection

ICRU: International Commission on Radiation Units and Measurements

Incidence: The rate of occurrence of a disease within a specified period of time; usually expressed in number of cases per million (10^6) per year.

Ion: Atomic particle, atom, or chemical radical bearing an electrical charge, either negative or positive.

Ion exchange: A chemical process involving reversible interchange of ions between a solution and a particular solid material such as an ion exchange resin consisting of a matrix of insoluble material interspersed with fixed ions of opposite charge.

Ionization: The process by which a neutral atom or molecule acquires a positive or negative charge.

Primary ionization: In collision theory; the ionization produced by the primary particles as contrasted to the "total ionization" which includes the "secondary ionization" produced by delta rays.

Secondary ionization: Ionization produced by delta rays.

Ionization density: Number of ion pairs per unit volume.

Ionization path (track): The trail of ion pairs produced by an ionizing radiation in its passage through matter.

Isotopes: Nuclides having the same number of protons in their nuclei, and hence the same atomic number, but differing in the number of neutrons, and therefore in the mass number. Almost identical chemical properties exist between isotopes of a particular element. The term should not be used as a synonym for nuclide.

Labeled compound: A compound consisting, in part, of labeled molecules. By observations of radioactivity or isotopic composition, this compound or its fragments may be followed through physical, chemical, or biological processes.

Latent period: The period or state of seeming inactivity between the time of exposure of tissue to an injurious agent and response.

LD_{50} (radiation dose) (See: Dose, median lethal.

Linear energy transfer (LET): The average amount of energy lost per unit of particle spur-track length.

Low-LET: Radiation characteristic of electrons, x rays, and gamma rays

High-LET: Radiation characteristic of protons or fast neutrons

Average LET is specified to even out the effect of a particle that is slowing down near the end of its path and to allow for the fact that secondary particles from photon or fast-neutron beams are not all of the same energy.

AVERAGE LET VALUES

Particle	Mass	Charge	Energy	Average LET	Tissue Penetration
	amu		(KeV)	(KeV/micron)	(microns)
Electron	0.00055	-1	1	12.3	.01
			10	2.3	1
			100	0.42	180
			1000	0.25	5000
Proton	1	+1	100	90	3
			2000	16	80
			5000	8	350
			10000	4	1400
Deuteron	2	+1	10000	6	700
			200000	1.0	190000
Alpha	4	+2	100	260	1
			5000	95	35
			200000	5	20000

Linear hypothesis: The assumption that a dose-effect curve derived from data in the high dose and high dose-rate ranges may be extrapolated through the low dose and low dose range to zero, implying that, theoretically, any amount of radiation will cause some damage.

Nam-rems: See person-rems.

Maximum credible accident: The worst accident in a reactor or nuclear energy installation that, by agreement, need be taken into account in deriving protective measures.

Medical exposure: Exposure to ionizing radition in the course of diagnostic or therapeutic procedures. As used in this report, the term includes:

1. Diagnostic radiology (e.g., x rays)
2. Exposure to radioisotopes in nuclear medicine (e.g., iodine-131 in thyroid treatment)
3. Therapeutic radiation (e.g., cobalt treatment for cancer)
4. Dental exposure

Micron: Unite of length equal to 10^{-6} meters. (symbol μ)

Morbidity: 1. The condition of being diseased.
2. The ratio of sick to well persons in a community.

NAS-NRC: National Academy of Sciences - National Research Council

NCRP: National Council on Radiation Protection and Measurements

Neoplasm: Any new and abnormal growth, such as a tumor. The term "neoplastic disease" refers to any disease which forms tumors, malignant or benign.

Nuclide: A species of atom characterized by the constitution of its nucleus. The nuclear constitution is specified by the number of protons (Z), number of neutrons (N), and energy content; or, alternatively, by the atomic number (Z), mass number A=(N+Z), and atomic mass. To be regarded as a distinct nuclide, the atom must be capable of existing for a measurable time. Thus, nuclear isomers are separate nuclides, whereas promptly decaying excited nuclear states and unstable intermediates in nuclear reactions are not so considered.

Person-rems: The product of the average individual dose in a population times the number of individuals in the population. Syn: man-rems.

Plateau: A period of above-normal, relative uniform, incidence of morbidity or mortality in response to a given biological insult.

Prevalence: The number of cases of disease in existence at a certain time in a designated area.

Quality Factor (QF): The linear-energy-transfer-dependent factor by which absorbed doses are multiplied to obtain (for radiation protection purposes) a quantity that expresses — on a common scale for all ionizing radiations — the effectiveness of the absorbed dose.

Rad. The unit of absorbed dose equal to 0.01 J/kg in any medium.

Radiation: 1) The emission and propagation of energy through space or through a material medium in the form of waves; e.g., the emission and propagation of electromagnetic waves, or of sound and elastic waves. 2) The energy propagated through space or through a material medium as waves. The term radiation or radiant energy, when unqualified, usually refers to electromagnetic radiation. Such radiation is commonly classified by frequency: Hertzian, infrared, visible, ultraviolet, x ray, and gamma ray. 3) Corpuscular emissions, such as alpha and beta radiation, or rays of mixed or unknown type, as cosmic radiation.

Background radiation: Radiation arising from radioactive material other than the one directly under consideration. Background radiation due to cosmic rays and natural radioactivity is always present. There may also be background radiation due to the presence of radioactive substances in other parts of the building, in the building material itself, etc.

External radiation: Radiation from a source outside the body.

Internal radiation: Radiation from a source within the body (as a result of deposition of radionuclides in body tissue).

Ionizing radiation: Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, in its passage through matter.

Secondary radiation: Radiation resulting from absorption or other radiation in matter. It may be either electromagnetic or particulate.

Radioactivity: The property of certain nuclides of spontaneously emitting particles or gamma radiation or of emitting X radiation following orbital electron capture or of undergoing spontaneous fission.

Artificial radioactivity: Manmade radioactivity produced by particle bombardment or electromagnetic irradiation.

Natural radioactivity: The property of radioactivity exhibited by naturally occurring radionuclides.

Radiosensitivity: Relative susceptibility of cells, tissues, organs, organisms, or any living substance to the injurious action of radiation. Radiosensitivity and its antonym *radioresistance*, are currently used in a comparative sense, rather than in an absolute one.

Rate, recovery: The rate at which recovery takes place after radiation injury. It may proceed at different rates for different tissues. "Differential recovery rate": Among tissues recovering at different rates, those having slower rates will ultimately suffer greater damage from a series of successive irradiations. This differential effect is considered in fractionated radiation therapy if the neoplastic tissues have a slower recovery rate than surrounding normal structures.

Rays:

Alpha: Beams of helium nuclei (2 protons and 2 neutrons)

Beta: Beams of electrons or positrons.

Gamma: Beams of high-energy photons from radioactively decaying elements.

X: Beams of mixed lower energy photons.

Neutron: Beams of neutrons.

Proton: Beams of protons.

Reactor, breeder: A reactor which produces more fissile material than it consumes; i.e., has a conversion ratio greater than unity.

Reactor converter: A reactor which produces fissile atoms from fertile atoms, but has a conversion ratio less than one.

Reactor, nuclear: An apparatus in which nuclear fission may be sustained in a self-supporting chain reaction.

Relative Biological Effectiveness (RBE): The RBE is a factor used to compare the biological effectiveness of absorbed radiation doses (i.e., rads) due to different types of ionizing radiation; more specifically, it is the experimentally determined ratio of an absorbed dose of a radiation in question to the absorbed dose of a reference radiation required to produce an idential biological effect in a particular experimental organism or tissues. The RBE is the ratio of rem to rad. (If 1 rad of fast neutrons equalled in lethality 3.2 rads of 250 KVP x rays, the RBE of the fast neutrons would be 3.2).

Relative risk: The ratio of the risk in those exposed to the risk to those not exposed (incidence in exposed population to incidence in control population).

Rem: A special unit of dose equivalent. The dose equivalent in rems is numerically equal to the absorbed dose in rads multiplied by the quality factor, the distribution factor, and any other necessary modifying factors. The *rem* represents that quantity of radiation that is equivalent—in biological damage of a specified sort—to 1 rad of 250 KVP x rays. See note p. 86.

Roentgen (R): The special unit of exposure. One roentgen equals 2.58×10^{-4} coulomb per kilogram of air.

Sickness, radiation: A self-limited syndrome characterized by nausea, vomiting, diarrhea, and psychic depression, following exposure to appreciable doses of ionizing radiation, particularly to the abdominal region. Its mechanism is unknown and there is no satisfactory remedy. It usually appears a few hours after irradiation and may subside within a day. It may be sufficiently severe to necessitate interrupting the treatment series or to incapacitate the patients.

Sigmoid curve: S-shaped curve, often characteristic, e.g., of a dose-effect curve in radiobiological studies.

Softness: A relative specification of the quality or penetrating power of x rays. In general, the longer the wave length the softer the radiation.

Specific activity: Total activity of a given nuclide per gram of a compound, element, or radioactive nuclide.

Target theory (Hit Theory): A theory explaining some biological effects of radiation on the basis that ionization, occurring in a discrete volume (the target) within the cell, directly causes a lesion which subsequently results in a physiological response to the damage at that location. One, two, or more "hits" (ionizing events within the target) may be necessary to elicit the response.

Threshold hypothesis: the assumption that no radiation injury occurs below a specified dose level.

UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation

Working Level (WL): Any combination of short-lived radon daughters in 1 liter of air that will result in the ultimate emission of 1.3×10^5 MeV of potential alpha energy.

Working Level Month (WLM): Inhalation of air with a concentration of 1 WL of radon daughters for 170 working hours results in an exposure of 1 WLM.

X rays: Penetrating electromagnetic radiations whose wave lengths are shorter than those of visible light. They are usually produced by bombarding a metallic target with fast electrons in a high vacuum. In nuclear reactions, it is customary to refer to photons originating in the nucleus as gamma rays, and those originating in the extranuclear part of the atom as X rays. These rays are sometimes called roentgen rays, after their discoverer, W. C. Roentgen.

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