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Performance Objectives for Disposal of Low-Level Radioactive Wastes on the Oak Ridge Reservation

D. C. Kocher

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
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PERFORMANCE OBJECTIVES FOR DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTES ON THE OAK RIDGE RESERVATION

D. C. Kocher

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PERFORMANCE OBJECTIVES FOR DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTES ON THE OAK RIDGE RESERVATION

D. C. Kocher

ABSTRACT

This report presents a set of performance objectives for disposal of low-level radioactive wastes in a new facility on the Oak Ridge Reservation. The principal performance objectives include (1) a limit on annual committed effective dose equivalent averaged over a lifetime of 0.25 mSv (25 mrem) for any member of the public beyond the boundary of the disposal facility, and (2) a limit on annual committed effective dose equivalent averaged over a lifetime of 1 mSv (0.1 rem) and a limit on committed effective dose equivalent in any year of 5 mSv (0.5 rem) for any individual who inadvertently intrudes onto the disposal site after loss of active institutional controls. In addition, releases of radioactivity beyond the site boundary (1) shall not result in annual dose equivalents to any member of the public from all sources of exposure that exceed limits established by Federal regulatory authorities and (2) shall be kept as low as reasonably achievable. The limit on annual dose equivalent averaged over a lifetime for off-site individuals is based primarily on the judgment of the U.S. Nuclear Regulatory Commission that this level of protection is reasonably achievable for near-surface disposal of low-level wastes. The limits on dose equivalents for inadvertent intruders are based on radiation protection standards for the public that have been adopted by the U.S. Department of Energy and that have been recommended by the International Commission on Radiological Protection and are being considered by the National Council on Radiation Protection and Measurements. The use of annual committed effective dose equivalents averaged over a lifetime departs from customary practice in environmental radiation standards in the U.S. of specifying limits on dose equivalents received in any year to whole body or the critical organ, but provides a set of performance objectives that are more closely related to the fundamental goal of limiting risk from chronic lifetime exposures. As background for the performance objectives for low-level waste disposal, this report (1) reviews generally applicable radiation protection standards for the public and environmental radiation standards for specific practices that have been developed by national and international authorities and (2) discusses the use of limits on risk rather than dose as performance objectives and consideration of chemical toxicity rather than radiation dose in establishing limits on intakes of uranium.

EXECUTIVE SUMMARY

This report presents a set of performance objectives for disposal of low-level radioactive wastes in a new facility on the Oak Ridge Reservation.[1-3] The purpose of the performance objectives is to ensure the long-term protection of health and safety for members of the public outside the boundary of the facility and for individuals who might inadvertently intrude onto the site after loss of institutional controls. As is customary in recommendations by radiation protection authorities (e.g., see refs. 4 and 5), the performance objectives are expressed in terms of limits on radiation dose to maximally exposed individuals, rather than limits on radiation risk itself.

The principal performance objectives for low-level waste disposal include separate dose limits for off-site individuals and inadvertent intruders as follows:

[1] a limit on annual committed effective dose equivalent averaged over a lifetime of 0.25 mSv (25 mrem) for any member of the public beyond the boundary of the disposal facility; and

[2] a limit on annual committed effective dose equivalent averaged over a lifetime of 1 mSv (0.1 rem) and a limit on committed effective dose equivalent in any year of 5 mSv (0.5 rem) for any individual who inadvertently intrudes onto the disposal site after loss of active institutional controls.

In addition, releases of radioactivity to the general environment beyond the site boundary -

- shall not result in annual dose equivalents to any member of the public from all sources of exposure, exclusive of natural background and deliberate medical practices, that exceed limits established by Federal regulatory authorities; and

- shall be kept as low as reasonably achievable, economic and social factors being taken into account.

The performance objectives shall apply at any time following closure of the facility.

The latter two requirements ensure that the performance objectives conform to radiation protection standards for the public established by the U.S. Nuclear Regulatory Commission (NRC)[6] and the U.S. Department of Energy (DOE).[7] Current DOE standards, which would apply to operations on

the Oak Ridge Reservation, specify a limit on annual committed effective dose equivalent from all DOE activities of 5 mSv (0.5 rem) for occasional exposures and 1 mSv (0.1 rem) for prolonged exposures (i.e., exposures of duration greater than 5 years).[7] Proposed revisions of the NRC's radiation protection standards also specify a limit on annual committed effective dose equivalent of 5 mSv (0.5 rem).[8] The requirement that off-site releases of radioactivity shall be kept as low as reasonably achievable (ALARA) involves an optimization of population exposures by means of a cost-benefit analysis.[4] Thus, the ALARA requirement ensures protection of population groups as well as maximally exposed individuals.

The choice of a dose limit of 0.25 mSv (25 mrem) as the principal performance objective for exposures of off-site individuals is based primarily on the judgment by the NRC that this level of protection is reasonably achievable for near-surface disposal of low-level wastes.[9] The use of higher dose limits for inadvertent intruders than for off-site individuals also is consistent with the NRC's standards for low-level waste disposal,[9] and can be justified on the grounds that (1) the probability that postulated intrusion scenarios will occur at any time after loss of institutional controls most likely is less than unity and (2) the potentially higher doses to intruders will have little effect on the population dose and risk. The choice of a dose limit for an intruder of 5 mSv (0.5 rem) for any year of exposure is based on the NRC's low-level waste standards[9] and on the current and proposed radiation protection standards of the NRC and DOE for all sources of exposure.[6-8] However, for prolonged exposures of inadvertent intruders, we adopt the recommendations of the International Commission on Radiological Protection (ICRP)[4,10] and a draft committee report of the National Council on Radiation Protection and Measurements (NCRP)[11] that the limit on annual dose equivalent should be lowered to 1 mSv (0.1 rem) to provide an acceptable limit on lifetime risk. As noted above, the lower dose limit for prolonged exposures is contained in current radiation protection standards of the DOE.[7]

The performance objectives for protection of individuals are expressed in terms of limits on annual committed effective dose equivalents averaged over a lifetime. This manner of expressing the performance objectives differs from many current environmental radiation standards in the U.S., including those for low-level waste disposal, which use limits on dose received to whole body or the critical organ for each year of exposure.[6,9,12-14] The rationale for use in the performance objectives of (1) the effective dose equivalent, (2) the committed dose equivalent, and (3) annual dose equivalents averaged over a lifetime is summarized as follows.

[1] Limits on dose equivalent to whole body or the critical organ have the disadvantage that they are not directly related to risk for any type of exposure, even though risk limitation is the basic goal of radiation protection. The ICRP has recognized this difficulty by developing the concept of the effective dose equivalent, which is a weighted sum of dose equivalents received by several organs and tissues, excluding whole body, with the weighting factor for each organ representing the fraction of the total stochastic risk attributable to that organ when the body is irradiated uniformly.[4] Thus, the effective dose equivalent is intended to be proportional to risk for either uniform or nonuniform irradiation of the body, and a limit on effective dose equivalent is directly related to a limit on risk. Use of the effective dose equivalent is recommended in the draft committee report of the NCRP,[11] and limits on effective dose equivalent are an essential feature of current radiation protection standards of the DOE[7] and proposed revisions of the NRC's standards.[8] The effective dose equivalent also appears in recent standards of the U.S. Environmental Protection Agency for airborne releases of radionuclides.[14]

[2] The committed dose equivalent is a concept used in estimating dose from inhaled or ingested activity that takes into account that an acute intake of radionuclides with relatively long residence times in the body results in significant doses received in future years, even with no further intakes, until the activity is removed from the body by radioactive decay and biological elimination.[4] Thus, the dose received in any year from a given intake is expected to be less than or equal to the committed dose from that intake. Although many radiation standards in the U.S. are not expressed in terms of limits on committed dose equivalents,[6,9,12-14] committed doses often are used in calculations for demonstrating compliance with the standards. The advantage of expressing radiation standards for the public in terms of limits on committed dose equivalent is that the resulting allowable intake of a radionuclide by an adult is constant with time. Low-level waste disposal is expected to result in chronic exposures of individuals, and it is highly impractical to use a dose-limitation system that requires knowledge of prior intakes in determining allowable intakes at future times. Current radiation protection standards of the DOE[7] and proposed revisions of the NRC's standards[8] explicitly specify limits on committed dose equivalent.

[3] Radiation standards in the U.S. generally specify dose limits for each year of exposure,[6-9,12-14] which are intended to provide a surrogate for a limit on lifetime risk. For exposures of the public, however, this practice may have the undesirable effect that acceptable system performance will be controlled by potential exposures of infants and children, even though the risk from a continuous lifetime's exposure probably will be determined primarily by intakes and doses received during adult years.[15] Thus, for low-level waste disposal where continuous lifetime exposures are anticipated for both off-site individuals and inadvertent intruders, the use of limits on annual committed dose equivalents averaged over a lifetime corresponds more closely to a limit on lifetime risk. However, this approach also encourages consideration of the age dependence of dose and risk in determining compliance with the performance objectives.

Two additional issues were considered in developing the performance objectives for low-level waste disposal: (1) the explicit use of limits on risk, rather than limits on dose as a surrogate for risk, to take into account the probabilistic distribution of doses that would be received by off-site individuals and inadvertent intruders, and (2) the need to limit exposures to long-lived isotopes of uranium on the basis of chemical toxicity in the kidney, rather than radiation dose.

The use of limits on risk as performance objectives for waste disposal has been recommended by the ICRP[16] and the Nuclear Energy Agency.[17] This approach takes into account that some events and processes which may result in human exposures (e.g., inadvertent intrusion and natural geologic phenomena) have probabilities of occurrence that are less than unity and may vary with time, and the radiation risks from all such processes and events then would be treated on a consistent basis. However, we have chosen not to express the performance objectives directly in terms of limits on risk primarily because estimates of probabilities of events and processes that could lead to human exposures may be quite uncertain and thus contentious and difficult to defend, particularly for events of relatively low probability for which the limit on acceptable risk would correspond to acceptable doses that are considerably above established dose limits for expected processes and events or that would exceed the threshold for nonstochastic radiation effects in some organs and tissues.[4] The concept of risk as the product of a probability and a consequence is poorly understood by the public, and there will be a tendency to focus on the high doses that are acceptable and to ignore their probabilities of occurrence. We believe that control of risks from accidental processes and events is best taken into account by means of

criteria on facility siting and design and on waste acceptance.

Data in humans and animals have clearly established the chemical toxicity of uranium in the kidney for concentrations that exceed a threshold value (e.g., see ref. 18 and references therein). Thus, it is important to consider whether the dose limits for low-level waste disposal would provide adequate protection against chemical toxicity if the dose were due primarily to intakes of long-lived isotopes of uranium. An analysis based on current dosimetric and metabolic models for uranium[18,19] and current information on the threshold concentration for uranium toxicity in the kidney[18] suggests that the limit on annual committed effective dose equivalent averaged over a lifetime of 0.25 mSv (25 mrem) for off-site individuals is sufficiently low to provide adequate protection against uranium toxicity. The higher limit on annual committed effective dose equivalent averaged over a lifetime of 1 mSv (0.1 rem) for inadvertent intruders might not provide adequate protection if the dose were due primarily to ingestion of uranium. However, at dose levels approaching the limit for an inadvertent intruder, the primary pathways of exposure to uranium are expected to be external irradiation and inhalation,[20,21] so the resulting kidney burden will be much less than that associated with an annual committed effective dose equivalent from ingestion of 1 mSv (0.1 rem). Thus, we conclude that separate performance objectives for uranium to protect against chemical toxicity in the kidney probably are not needed.

1. INTRODUCTION

The U.S. Department of Energy (DOE) is proposing to operate a new facility on the Oak Ridge Reservation in Tennessee that will provide for permanent disposal of low-level radioactive wastes generated by normal activities of the three DOE plants in Oak Ridge.[1-3] An important step in developing the new facility is the establishment of objectives for overall performance of the disposal system that ensure long-term protection of public health and safety. Such performance objectives provide constraints on acceptable siting and design of the facility and on the quantities and physicochemical properties of radioactive wastes that may be accepted for disposal.

This report presents a set of performance objectives for new low-level waste disposal facilities in Oak Ridge. The performance objectives are based on the principle that the potential risks from radiation exposure for members of the public shall be limited to levels that are widely regarded as safe. The DOE has established limits on annual committed effective dose equivalent for members of the public from all DOE activities of 5 mSv (0.5 rem) for occasional exposures and 1 mSv (0.1 rem) for prolonged exposures.[7] However, these limits apply to all DOE operations that may impact the public, and considerably lower limits may be more appropriate for a single waste-disposal facility.

The principal performance objectives for low-level waste disposal are expressed as limits on radiation dose that may be received by any member of the public from off-site releases of radioactivity or by individuals who inadvertently intrude onto the disposal site following loss of institutional controls. Specifically, we propose (1) a limit on annual committed effective dose equivalent averaged over a lifetime of 0.25 mSv (25 mrem) for off-site exposures of any member of the public and (2) a principal limit on annual committed effective dose equivalent averaged over a lifetime of 1 mSv (0.1 rem), with a subsidiary limit on committed effective dose equivalent in any year of 5 mSv (0.5 rem), for an inadvertent intruder. In addition, the committed effective dose equivalent that may be received by off-site individuals in any year from all sources is limited to 5 mSv (0.5 mrem), and off-site releases of radioactivity are to be kept as low as reasonably achievable (ALARA). The performance objectives do not apply to individuals who might deliberately intrude into the disposal facility.

The performance objectives presented in this report resemble those developed for near-surface disposal of low-level radioactive wastes by the U.S. Nuclear Regulatory Commission (NRC).[9] The NRC's criteria include (1) limits on annual dose equivalent for off-site exposures of any member of the public of 25 mrem (0.25 mSv) to whole body, 75 mrem (0.75 mSv) to

the thyroid, and 25 mrem (0.25 mSv) to any other organ and (2) limits on acceptable concentrations of radionuclides for disposal that correspond to a limit on annual dose equivalent to whole body for an inadvertent intruder of 0.5 rem (5 mSv). Although a disposal facility on the Oak Ridge Reservation will not be licensed by the NRC, the existence of these criteria and the view of the U.S. Environmental Protection Agency (EPA) that they are reasonable[9] establish the precedent that a DOE facility should conform to standards similar to those for NRC-licensed facilities. However, there are important differences between the performance objectives presented in this report and those developed by the NRC, and these differences are described in detail in this report.

The remainder of this report is organized as follows. Sections 2-4 provide important background information and justifications for the proposed dose limits for low-level waste disposal and the manner in which they are expressed. Section 2 discusses the explicit use in the performance objectives of the effective dose equivalent, the committed dose equivalent, and the annual dose equivalent averaged over a lifetime of an exposed individual. Section 3 reviews the radiation protection standards for the public that have been recommended by national and international authorities and promulgated by the NRC and DOE. Section 4 reviews environmental radiation standards and guidelines for specific practices that have been developed by the NRC, EPA, and DOE, and includes a discussion of performance objectives for low-level waste disposal that have been recommended by international authorities. The reviews in Sections 3 and 4 place the performance objectives presented in this report in the context of historical developments and current approaches in radiation protection. Section 5 then presents the performance objectives for disposal of low-level radioactive wastes on the Oak Ridge Reservation and a summary of the rationale for these objectives. This section also discusses two additional issues related to the development of the performance objectives: (1) the alternative of using limits on risk rather than limits on dose as performance objectives, particularly with regard to protecting inadvertent intruders, and (2) the possible need to limit exposures to long-lived isotopes of uranium based on consideration of the chemical toxicity of uranium in the kidney and the relationship between an acceptable kidney burden of uranium and limits on radiation dose.

2. CONCEPTS IN RADIATION DOSIMETRY

The performance objectives for low-level waste disposal presented in this report are expressed in terms of limits on annual committed effective dose equivalents averaged over a lifetime of an exposed individual. This manner of expressing dose limits is not common practice in the U.S. This section discusses the concepts of effective dose equivalent, committed dose equivalent, and annual dose commitment averaged over a lifetime and the reasons for their use in the performance objectives.*

2.1 Effective Dose Equivalent

Most radiation standards in the U.S. limit exposures of members of the public on the basis of the dose equivalent to whole body or the so-called critical organ,[6,9,12-14] which generally is the organ that receives the highest dose. Dose to the critical organ is used primarily in limiting internal exposures from inhalation or ingestion of radionuclides, since such exposures often result in highly nonuniform irradiations of the body.

Use of the dose equivalent to whole body or the critical organ in radiation standards has three important drawbacks: (1) a given dose limit for two different tissues generally does not correspond to the same risk of radiation-induced health effects (i.e., fatal cancers plus genetic defects); (2) potentially important doses and risks to tissues other than the critical organ are ignored; and (3) "whole body" is not a tissue at risk from radiation exposure, but it is particular organs or tissues in which health effects are expressed. Thus, a limit on dose to whole body or the critical organ is not directly related to a limit on risk for arbitrary exposures, even though risk limitation is the fundamental goal of radiation standards.

The International Commission on Radiological Protection (ICRP) has recognized the difficulties with radiation standards expressed as limits on dose equivalent to whole body or the critical organ by developing the concept of the effective dose equivalent.[4] The effective dose equivalent is intended to be proportional to risk for either uniform or nonuniform irradiations of the body. Thus, exposures with equal effective dose equivalents should result in equal risks regardless of the particular

* In this report, the term dose equivalent, which is the quantity obtained by multiplying absorbed dose (i.e., energy deposited per unit mass of tissue) by a quality factor that accounts for the differences between various types of ionizing radiations in causing deleterious effects in tissue, frequently is abbreviated to dose.

distribution of doses among different organs, and limits on effective dose equivalent are directly related to limits on risk.

The effective dose equivalent is defined by the ICRP as a weighted sum of dose equivalents to different organs:[4]

$$H_E = \sum_i w_i H_i \ , \qquad (1)$$

where H_E is the effective dose equivalent, H_i is the dose equivalent to organ i, and w_i is a weighting factor representing the fraction of the total stochastic risk attributable to organ i when the whole body is irradiated uniformly. Thus, the ICRP has replaced consideration of the dose equivalent to whole body or the critical organ by consideration of doses to several organs.

The weighting factors for different organs recommended by the ICRP for calculating effective dose equivalents[4,22] are given in Table 1. The first six organs always are considered in calculating the effective dose equivalent, but skin is considered only for external exposures. The organ labeled "remainder" consists of the five other organs that receive the highest dose equivalents for the particular exposure, and each of these is assigned a weighting factor of 0.06. Thus, calculation of the effective dose equivalent involves a weighted sum of dose equivalents received by 11 or 12 different organs. It is important to note that "whole body" is not included in the "remainder" category and dose to whole body is not used in calculating the effective dose equivalent. The particular organs included in the "remainder" category depend on the radionuclide and mode of exposure.

The interpretation of the weighting factors in Table 1 in terms of risk is as follows. The ICRP recommends a total stochastic risk from uniform whole-body irradiation of 2×10^{-2} per Sv (2×10^{-4} per rem).[4] Thus, for example, 3% of the stochastic risk from uniform whole-body irradiation would be due to induction of bone cancer, and the risk factor for irradiation of bone surfaces is 6×10^{-4} per Sv (6×10^{-6} per rem). The recommended risk factors for the different organs from uniform whole-body irradiation then are assumed to apply to nonuniform irradiations as well; i.e., the risk per unit dose equivalent for each organ is assumed to be independent of the mode of exposure.

2.2 Committed Dose Equivalent

The performance objectives in this report are expressed in terms of committed dose equivalents (also called dose commitments), as opposed to the usual practice of specifying limits on dose equivalent received during

Table 1. Organ-specific weighting factors for calculation of effective dose equivalents[a]

Organ	w_i
Gonads	0.25
Breast	0.15
Red marrow	0.12
Lungs	0.12
Thyroid	0.03
Bone surfaces	0.03
Skin[b]	0.01
Remainder	0.30

[a]Values from ref. 4, except value for skin from ref. 22.

[b]Weighting factor for skin may be used for calculation of effective dose equivalents from external exposure but generally is not used for internal exposures.

each year of exposure.[6,9,12-14] The committed dose equivalent is a concept used in estimating dose from inhaled or ingested activity that takes into account that an acute intake of some radionuclides (e.g., long-lived radionuclides that deposit in bone) results in significant doses received in future years, even with no further intakes, until the activity is removed from the body by radioactive decay and biological elimination.[4] The committed dose equivalent over time T following an acute intake at time t_0 is given by

$$H(T) = \int_{t_0}^{t_0+T} (dH/dt)\, dt \,, \qquad (2)$$

where dH/dt is the dose-equivalent rate as a function of time following the acute intake and takes into account not only radioactive decay and biological elimination of the inhaled or ingested radionuclide but also the buildup, decay, and biological retention in the body of any radioactive daughter products. Dose commitments normally are evaluated for a time period T = 50 y, which is the average lifespan of an adult,[4] but 70-year dose commitments may be considered for exposures of the general public. Dose commitments per unit intake of radionuclides via

inhalation or ingestion often are referred to as internal dose conversion factors.

Hypothetical dose rates and doses over time following an acute intake of a radionuclide with a long retention time in the body are shown in Fig. 1. Biological retention often is described as a sum of exponential terms,[19] and the example in Fig. 1 assumes a single such term; i.e., the dose rate as a function of time after intake is assumed to obey the relation

$$dH/dt \propto \exp(-\lambda t) \ , \tag{3}$$

and H(0) is assumed to be zero. Here, λ is the rate constant for removal of the radionuclide from the body given by

$$\lambda = \lambda_r + \lambda_b \ ,$$

where λ_r and λ_b are the rate constants for radioactive decay and biological elimination, respectively. The dose received during any time after intake is the time-integral of the dose rate; thus,

$$H \propto [1 - \exp(-\lambda t)]/\lambda \ . \tag{4}$$

The dose essentially reaches its asymptotic value within about 7 half-times for physical plus biological removal, where the half-time is $(\ln 2)/\lambda$. Again, the committed dose equivalent usually is calculated as the dose equivalent received during the first 50 or 70 years after intake. The curves in Fig. 1 are based on an assumed half-time for radioactive decay plus biological retention of 10 years, and the removal rate constant then is

$$\lambda = (\ln 2)/(10 \text{ y}) = 0.0693 \text{ y}^{-1} \ .$$

Half-times of this magnitude or longer are common for long-lived radionuclides that preferentially deposit in bone.[19]

Exposures of the public following routine releases of radionuclides to the environment generally will involve chronic rather than acute intakes. For any retention function of radionuclides in the body that decreases monotonically with time, is independent of the age of the individual, and for which the integral over infinite time is finite (e.g., a sum of exponential terms), the following important relationship holds:

> The dose received over any time t following an acute intake of a radionuclide is numerically equal to the dose rate at time t from a chronic intake of the same quantity of the radionuclide per unit time.

That is, the curve for dose vs time from an acute intake in Fig. 1 also gives the dose rate vs time from a chronic intake at a constant rate. For

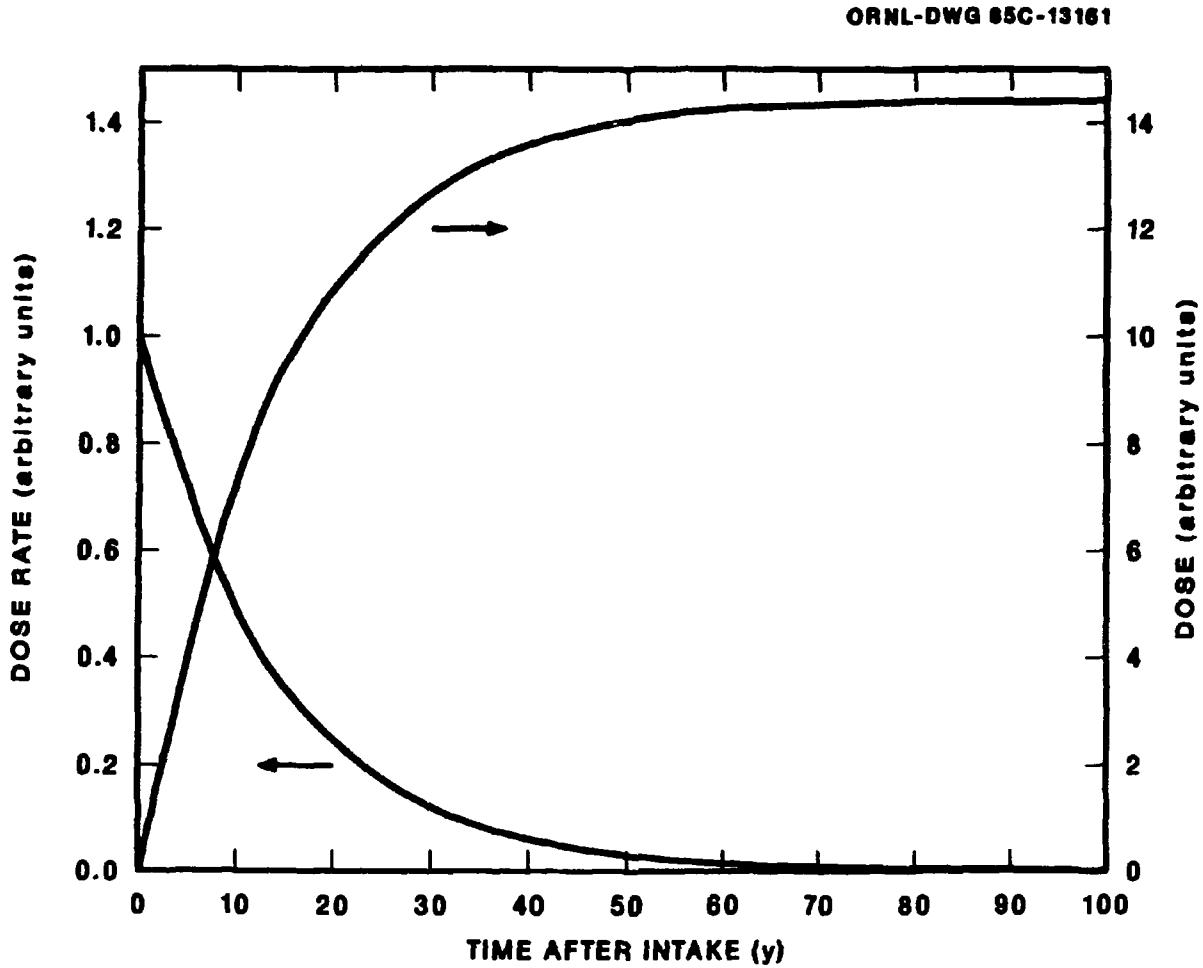

Fig. 1. Hypothetical dose rate (monotonically decreasing curve) and dose (monotonically increasing curve) vs time following an acute intake of a radionuclide; the assumed half-time for radioactive decay plus biological retention in the body is 10 years.

example, the 50-year committed dose equivalent in Sv (rem) from an acute intake of 1 Bq (Ci) of a radionuclide is numerically equal to the dose-equivalent rate at the end of the 50th year in Sv/y (rem/y) from a chronic intake at the rate of 1 Bq/y (Ci/y). For retention half-times of radionuclides in the body less than about 7 years, the dose rate from a chronic intake essentially reaches its steady-state value within 50 years; i.e., after 50 years of constant intakes, the intake rate is nearly equal to the rate of removal by radioactive decay and biological elimination, and the dose rate is essentially constant with time at the value given by the dose commitment from one year's intake. For retention half-times that are considerably longer than 7 years, the dose rate from a constant intake over 50 years will not reach steady state during that time, but the dose rate at the end of the 50th year still will equal the 50-year dose commitment from one year's intake.

The relationship stated above between the dose from an acute intake and the dose rate from a chronic intake provides the basis for use of the committed dose equivalent, rather than dose equivalent received in each year, in the performance objectives presented in this report. Although there are many radionuclides with retention half-times in the body that are considerably less than one year,[19] in which case the annual committed dose equivalent and the dose equivalent received in the first year after intake are essentially the same, there are important instances where the two are not the same and use of the committed dose equivalent is the only reasonable choice. We illustrate this point by means of two examples.

The first example involves an assumed chronic intake of a radionuclide with no radioactive daughter products for which the half-time for radioactive decay plus biological retention is 10 years and the retention function is the monotonically decreasing curve in Fig. 1. Again, this example is illustrative of actual retention of long-lived radionuclides that deposit in bone. If an individual were to experience an intake during the first year that gave a dose during that year equal to an assumed limit on dose received in any year, then the dose received during the next year from the first year's intake would be approximately 90% of the first year's dose, and the allowable intake during the second year would only be 10% of the first year's intake in order to meet the dose limit during the second year. The same fractional decrease in allowable intakes would recur in all subsequent years of exposure if the dose received in each year is not to exceed the dose limit.

This example clearly shows that specifying a limit on annual dose equivalent in terms of dose received in each year of exposure is quite impractical for routine releases of radioactivity to the environment, because maximum acceptable intakes by exposed individuals (or the corresponding limits on acceptable concentrations in environmental media)

would decrease with time. In essence, such a dose-limitation system would require knowledge of prior intakes in order to determine acceptable intakes at present and future times, but it is unreasonable to assume that members of the public will have knowledge of their prior exposures and will take action to reduce them in the future. A dose-limitation system based on committed dose equivalents alleviates this difficulty, because a limit on annual committed dose equivalent leads to constant allowable intake rates over time by an adult, and the dose equivalent received in any year always will be less than or equal to the limit on committed dose equivalent.

A second example illustrating the need for a dose-limitation system based on the committed dose equivalent involves an assumed acute intake of a radionuclide that decays to a radioactive daughter product. We specifically consider an acute intake of ^{241}Pu with a half-life for radioactive decay of 14.4 years, which decays to ^{241}Am with a half-life of 432 years.[23] Both radionuclides have long half-times for biological retention (100 years in bone, 40 years in the liver, and permanent retention in the gonads).[19]

Figure 2 shows the dose rate to bone surfaces vs time following an acute intake of ^{241}Pu via ingestion; the effective dose-equivalent rate shows a similar behavior. Since ^{241}Pu primarily emits low-energy electrons but ^{241}Am emits high-energy alpha particles,[23] the dose rate increases dramatically with time after an acute intake of the parent due to ingrowth and decay of the radiologically more significant daughter. Thus, if an individual were to experience an intake of ^{241}Pu that results in a dose received during the first year that is equal to an assumed dose limit for each year of exposure, then the dose received in all subsequent years would greatly exceed the limit even with no further intakes. A dose-limitation system based on the committed dose equivalent again alleviates this difficulty, because the dose commitment takes into account ingrowth and decay of any daughter radionuclides following an intake of the parent and the allowable intake rate of ^{241}Pu by an adult would be constant with time.

In practice, the problems illustrated above with standards that are expressed in terms of limits on dose equivalents received for each year of exposure normally are circumvented by using committed dose equivalents in calculations for assessing compliance with the standards. However, even if this is the case, we believe it is preferable to incorporate the concept of committed dose explicitly into performance objectives that involve limits on dose, in order to ensure consistency between the performance objectives and the calculations used to assess compliance. Again, the advantage of expressing radiation standards for the public in terms of limits on committed dose equivalent is that the resulting

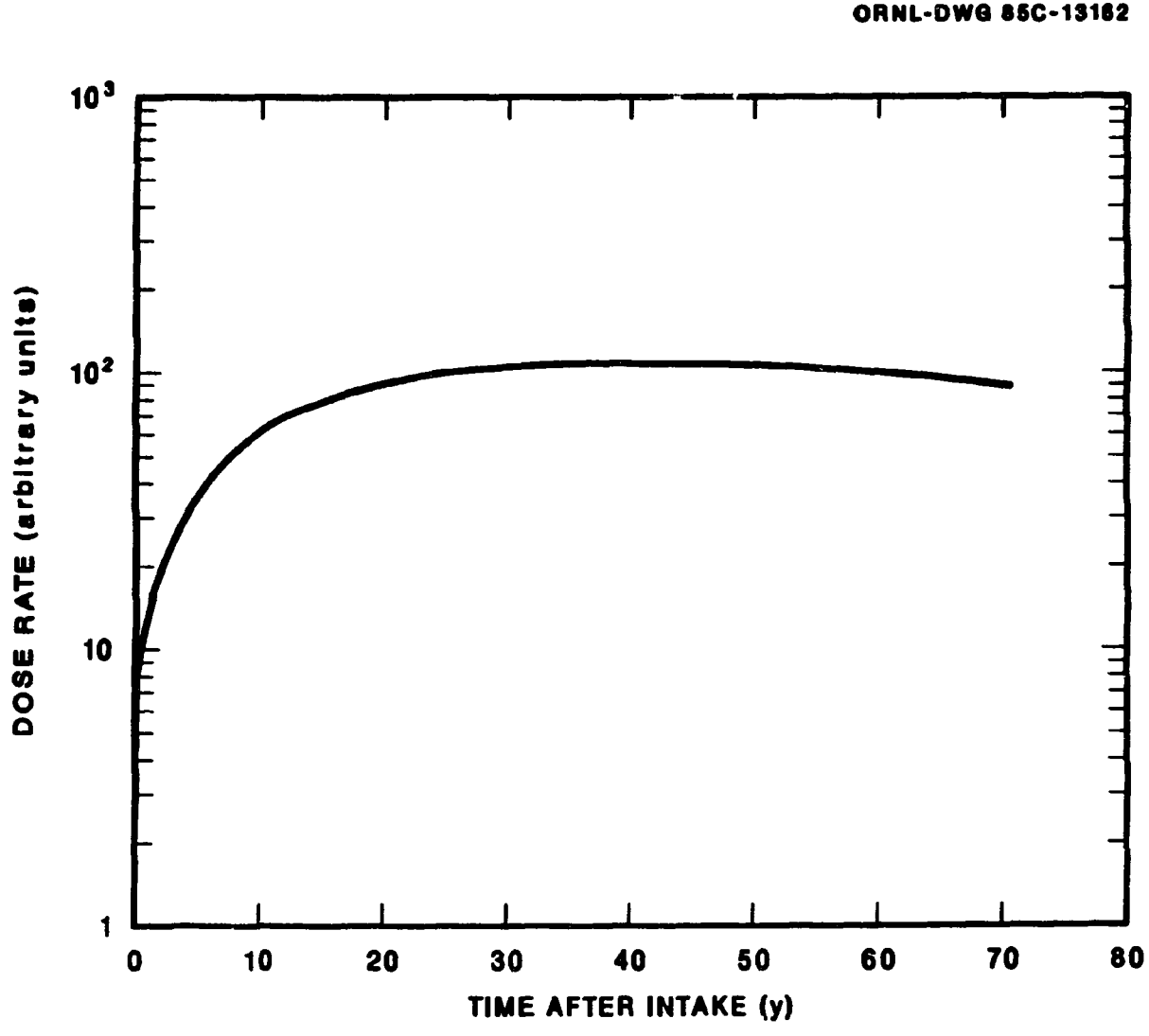

Fig. 2. Dose rate to bone surfaces vs time following an acute ingestion intake of ^{241}Pu.

allowable intake of a radionuclide by an adult is constant with time.

2.3 Annual Dose Commitment Averaged Over a Lifetime

The performance objectives in this report are expressed in terms of limits on annual committed dose equivalents averaged over a lifetime, as opposed to the usual practice of specifying a limit on dose equivalent for each year of exposure.[6,9,12-14] This choice allows higher doses in some years, provided they are compensated by lower doses in other years, and is based on consideration of the risk resulting from chronic intakes over a lifetime, including the age dependence of dose and risk. Chronic lifetime exposures, rather than acute exposures, are expected to occur with low-level waste disposal for both off-site individuals and inadvertent intruders.

The primary purpose of radiation standards, including the performance objectives for low-level waste disposal presented in this report, is limitation of lifetime risk from any exposures. A limit on dose thus is used as a surrogate for a limit on risk, and the dose limits should be expressed in a manner that is closely related to a limit on lifetime risk.

The usual practice in radiation standards for the public of specifying a dose limit for each year of exposure is based on accepted practice for radiation workers where, in essence, a limit on lifetime dose corresponding to a limit on lifetime risk is expressed in terms of equal annualized increments. This is a reasonable approach for limiting exposures of workers, because such exposures are controllable at all times; and, furthermore, there is a need to protect the economic livelihood of workers over the normal working lifetime, to measure and record exposures at frequent intervals, and to prevent nonstochastic effects from large acute doses that would be below lifetime dose limits.[4] However, none of these conditions apply to exposures of the public from low-level waste disposal.

An important difference between exposures of radiation workers and exposures of the public is that the latter involve age groups other than adults. Infants, children, and adolescents may experience significantly higher doses and risks than adults for some types of acute exposures, due to such factors as greater absorption of ingested activity from the gastrointestinal (GI) tract into blood, particularly for radionuclides with low GI-tract absorption in adults, increased deposition of absorbed activity in the skeleton for many elements, smaller organ masses, and greater risks per unit dose for some types of cancers.[15] Thus, exposures of infants and children should be considered in establishing performance objectives for low-level waste disposal.

The most obvious way of accounting for different age groups in the public would be to specify a limit on committed dose equivalent for each year of exposure that applies to all ages. However, for practices such as low-level waste disposal that are expected to result in chronic exposures over a lifetime, this approach may not achieve the closest correspondence with the goal of limiting lifetime risk when the age dependence of dose and risk is taken into account. For low-level waste disposal, exposures of off-site individuals and inadvertent intruders are expected to vary slowly with time,[3,24,25] so that total intakes of radionuclides over an average lifetime should be greater for adults than for younger age groups. Furthermore, for radionuclides with long retention half-times in the body, a significant fraction of the committed dose from intakes by infants or children may be received during adult years. Thus, the risk from chronic lifetime exposures probably will be determined primarily by intakes and doses received during adult years, even though the largest annual committed doses may be experienced by infants and children. We illustrate this point with the following examples.

We first consider the dose commitments that would result from ingestion of unit concentrations of ^{90}Sr and natural uranium in drinking water as a function of age at intake. Estimates of annual committed effective dose equivalents per unit concentration of ^{90}Sr and natural uranium in drinking water for different age groups relative to values for adults are shown in Figs. 3 and 4, respectively. The ages for the different groups are those recommended by the NRC:[26] infant, 0-1 y; child, 1-11 y; teenager, 11-17 y; and adult, >17 y. These results were obtained from estimates of committed effective dose equivalents per unit activity ingested for each age group[27,28] multiplied by the annual intakes of drinking water for maximally exposed individuals in each age group recommended by the NRC.[26] The calculations of committed dose equivalents as a function of age at intake take into account the age dependence of GI-tract absorption, deposition and retention of absorbed activity in body organs, and the mass and location of body organs and tissues.

For ^{90}Sr, the results in Fig. 3 show that the annual committed effective dose equivalent per unit concentration in water is 2.6 times higher for infants than adults, and the values for the child and teenager are about the same as for adults. As a result, most of the committed dose from a lifetime's intakes (i.e., 74%) results from intakes by adults, and the annual committed effective dose equivalent averaged over a lifetime is equal to the annual dose commitment for an adult. For natural uranium, the results in Fig. 4 show that the annual committed effective dose equivalent per unit concentration in water is 28 times higher for infants than adults, and the values decrease progressively with increasing age at intake. However, the largest portion of the committed dose from a

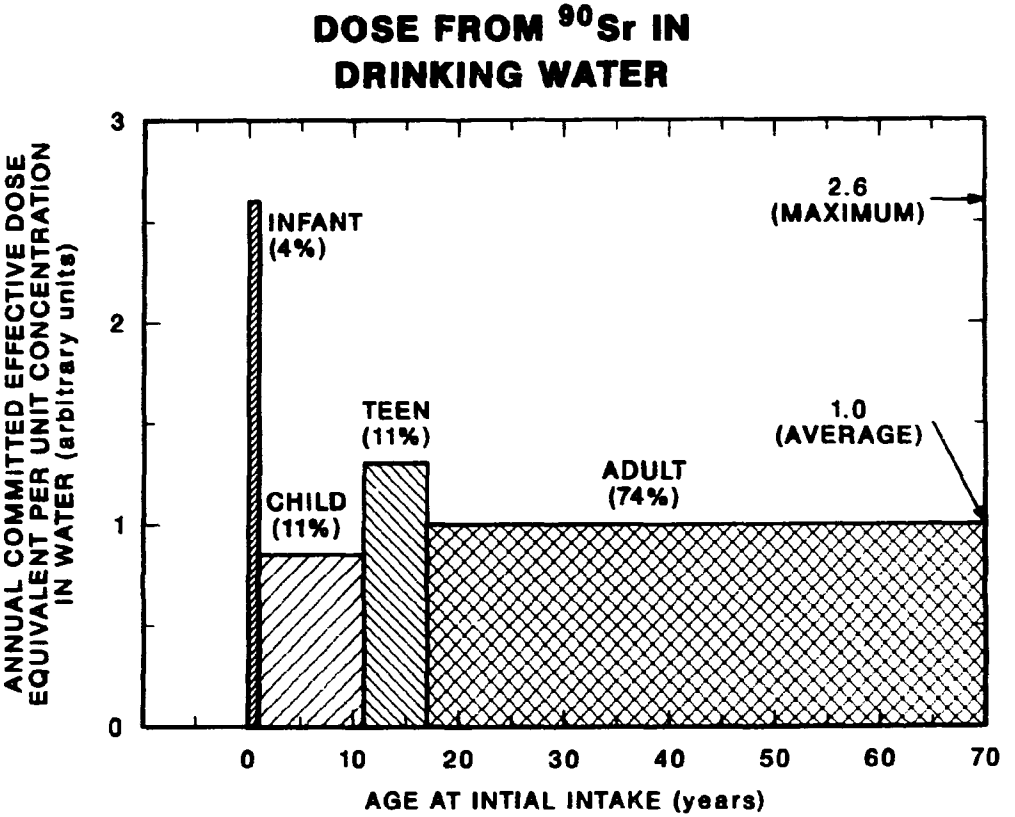

Fig. 3. Annual committed effective dose equivalent from ingestion of ^{90}Sr per unit concentration in drinking water vs age at initial intake, normalized to the value for adults. The calculations take into account the age dependence of water intakes and radiation dose to body organs. The percentages give the portion of the committed dose from a lifetime's intakes attributable to each age group, and the numbers on the right-hand side give the maximum annual dose for any age group and the annual dose averaged over a lifetime's exposure.

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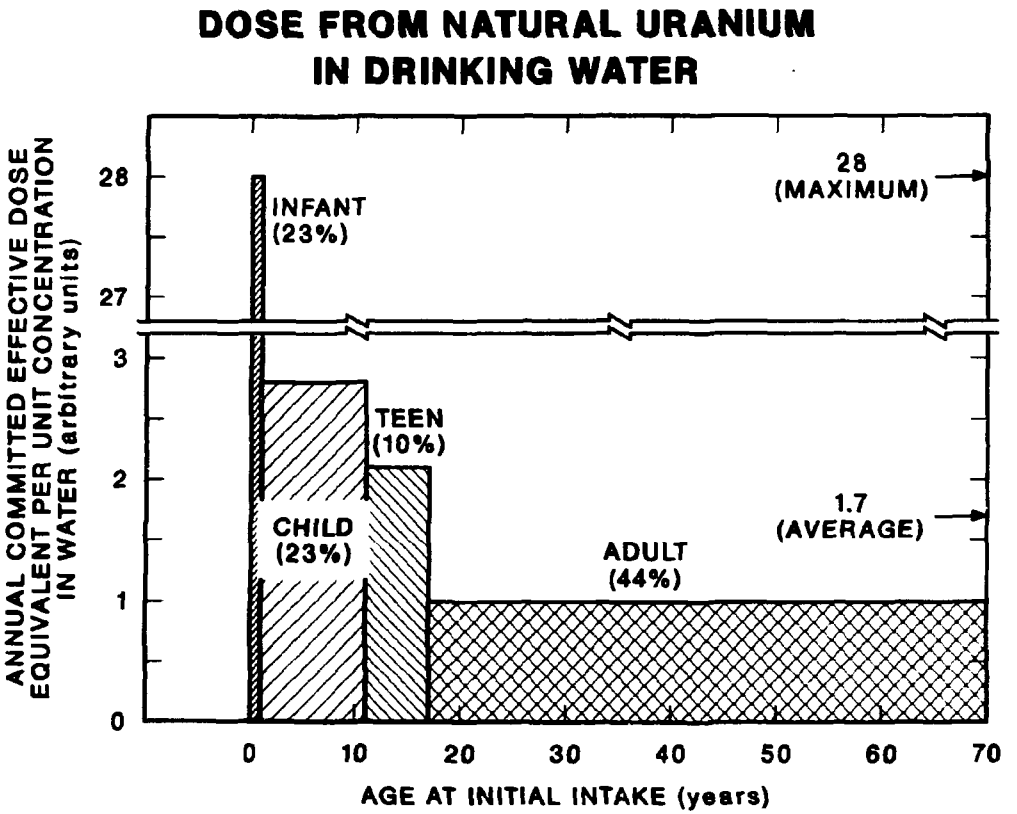

Fig. 4. Annual committed effective dose equivalent from ingestion of natural uranium per unit concentration in drinking water vs age at initial intake, normalized to the value for adults. The calculations take into account the age dependence of water intakes and radiation dose to body organs. The percentages give the portion of the committed dose from a lifetime's intakes attributable to each age group, and the numbers on the right-hand side give the maximum annual dose for any age group and the annual dose averaged over a lifetime's exposure.

lifetime's intakes (44%) still results from intakes by adults, and the annual committed effective dose equivalent averaged over a lifetime is within a factor of 2 of the value for an adult.

If radiation standards are expressed in terms of limits on committed dose for each year of exposure, then the results in Figs. 3 and 4 show clearly that limits on releases of these radionuclides to sources of drinking water will be determined by predicted intakes by infants, and the annual committed doses resulting from intakes by adults will be far less than the dose limit even though the annual committed dose averaged over a lifetime's intakes will be determined primarily by intakes by adults. Thus, a limit on committed dose for each year of exposure does not correspond well with the level of acceptable lifetime risk embodied in the standard.

A possible deficiency with the results in Figs. 3 and 4 is that the organ-specific weighting factors used to calculate the effective dose equivalents for all age groups are the values for adults recommended by the ICRP,[4] but risk factors for some organs and tissues are known to vary with age at exposure.[29] For example, the annual committed effective dose equivalent to infants in Fig. 4 may provide an overestimate of risk for that age group relative to the risk for adults, because the risk per unit dose to the kidney, which is an important contributor to the committed effective dose equivalent from ingestion of uranium,[28] is believed to be much less in infants and children than in adults.[29]

A proper calculation of risk per unit concentration of radioactivity in environmental media as a function of age at intake would involve combining the dose rate as a function of time after intake at any age, taking into account the relevant age-dependent effects, with the risk per unit dose as a function of age. An example of this type of calculation[15] is shown in Fig. 5. The curves are proportional to the risk of leukemia from ingestion of ^{90}Sr as a function of age at intake. The model for the age dependence of dose rate to bone marrow per unit ingestion intake of ^{90}Sr at any age[27] is the same as the model used to generate the results in Fig. 3, and the intake of ^{90}Sr and risk of leukemia as a function of age are given in Figs. 3 and 19 of ref. 15, respectively. Results are given assuming both an absolute and a relative risk model for induction of leukemia.[29] These calculations clearly show that for chronic lifetime intakes at constant concentrations of ^{90}Sr in the environment, the lifetime risk is dominated by intakes by adults even though the risk from any year of intake may be the highest for infants. With the absolute risk model, about 60% of the risk from chronic lifetime intakes would result from intakes by adults, and the percentage is considerably higher with the relative risk model.

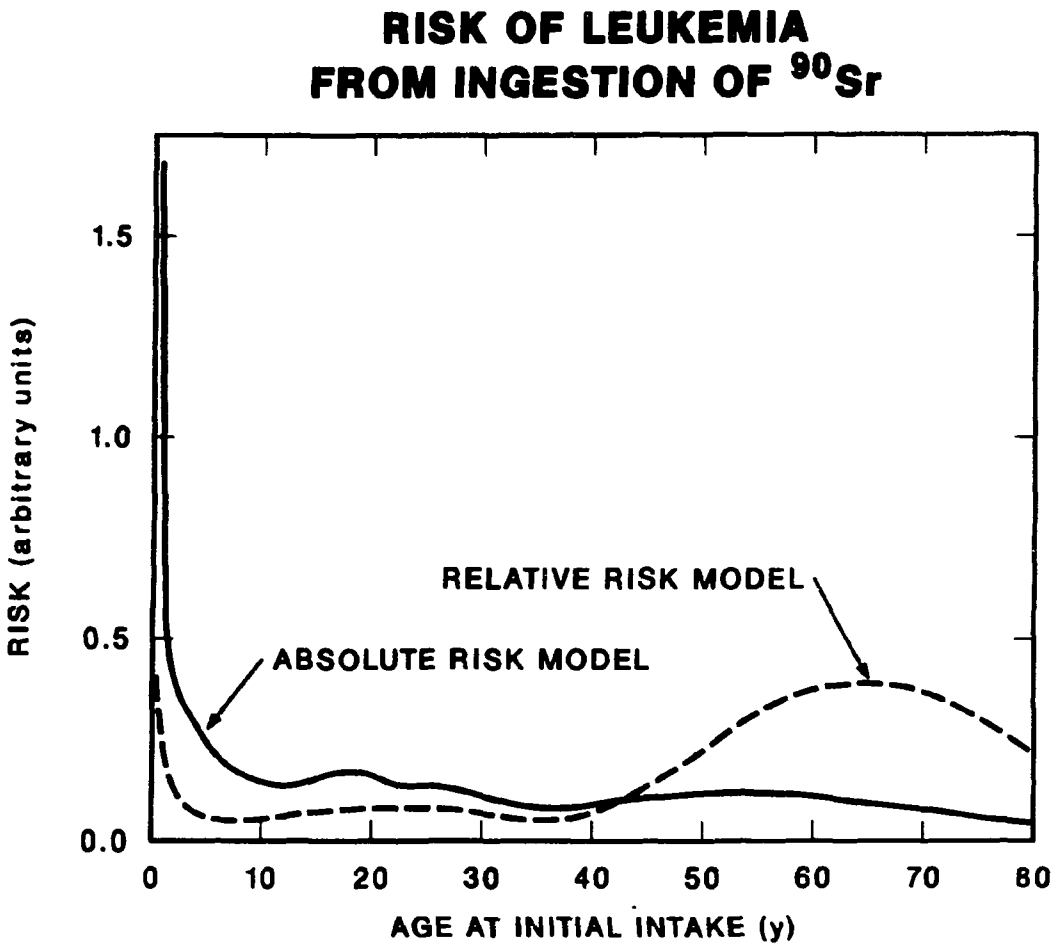

Fig. 5. Risk of leukemia from ingestion of ^{90}Sr vs age at initial intake; results are given using absolute and relative risk models.

The arguments and examples presented above show that specifying a limit on committed dose equivalent for each year of exposure in performance objectives for low-level waste disposal is largely a matter of custom, and this practice may have the undesirable effect that acceptable system performance is controlled by potential exposures of infants and children even though the risk from continuous lifetime exposures probably will be determined primarily by intakes and doses received during adult years. The preferred alternative of specifying a limit on annual committed dose equivalent averaged over a lifetime corresponds more closely to a desired limit on lifetime risk that is embodied in the dose limit. Furthermore, we have shown that this approach leads to a primary focus on committed doses resulting from intakes by adults in evaluating system performance, because annual committed dose equivalents to adults are expected to be nearly the same as annual dose commitments averaged over a lifetime. However, consideration of committed doses from intakes by infants and children still is encouraged in evaluating annual committed effective dose equivalents averaged over a lifetime. We emphasize that if the limit on annual committed dose averaged over a lifetime is set sufficiently low, then any higher doses that might be received by infants and children still would result in an acceptable lifetime risk. Higher limits on committed dose for each year of exposure also can be specified to preclude unacceptable risks for any age group, and we have adopted this approach in the performance objectives presented in this report.

We would also note as a matter of practical concern that models for estimating internal dose in infants and children generally are not as well developed as the models for adults, so it is more difficult to evaluate compliance with limits on annual committed dose equivalents for younger age groups. Proper age-dependent internal dose calculations would be based on current ICRP recommendations,[4,19] but would take into account the age dependence of (1) organ masses and their shapes and locations within the body, (2) radionuclide absorption in the GI tract, (3) deposition and retention of inhaled radionuclides in the lungs, and (4) the distribution and retention of absorbed activity in different body organs and tissues. Internal dose conversion factors for different age groups that properly account for all age-dependent factors have been calculated only for a few radionuclides of importance to low-level waste disposal, e.g., for ^{131}I, ^{137}Cs, and a number of bone-seeking radionuclides.[27,28,30,31] Other extensive compilations of age-dependent dose conversion factors[32,33] based on the current ICRP methodology generally do not take into account the age dependence of shapes and locations of organs within the body and probably do not account properly for the age dependence of retention of most radionuclides in different organs and tissues, so that proper age-dependent factors probably are obtained only for a few radionuclides,

e.g., for ^{3}H and ^{14}C. Still other compilations[34,35] are based on an outdated methodology of the ICRP[36] and, thus, do not take into account cross-irradiations of different source and target organs. Except for ^{3}H and isotopes of iodine and cesium, these calculations also do not consider the age dependence of radionuclide retention in the body.

3. GENERALLY APPLICABLE RADIATION PROTECTION STANDARDS FOR THE PUBLIC

3.1 Introduction

This section presents a review of generally applicable radiation protection standards for the public that have been recommended by national and international authorities and promulgated by the NRC and DOE for use in the U.S. This review focuses on standards that have been developed since about 1958. The national and international authorities that have developed recommendations for radiation protection standards include the Federal Radiation Council (FRC), the ICRP, and the NCRP.

Generally applicable radiation protection standards specify limits on dose equivalents that may be received by members of the public from all sources of exposure, exclusive of natural background radiation and deliberate medical practices. These limits are not to be exceeded, except in unusual circumstances, regardless of the costs associated with meeting the standards. The dose limits are based on an assumed limit on acceptable risk from radiation exposure of the public (i.e., a risk in the range 10^{-4}-10^{-5} per year) and an assumed risk per unit dose equivalent of 1-2 x 10^{-2} per Sv (1-2 x 10^{-4} per rem).[4]

3.2 Recommendations of the Federal Radiation Council

The FRC was formed in 1959 to provide policy guidance on limiting radiation exposures in the U.S. The radiation protection guidances for the public developed by the FRC are summarized as follows:[37]

- a limit on annual dose equivalent to whole body for maximally exposed individuals of 0.5 rem (5 mSv);
- a limit on annual dose equivalent to whole body for average individuals in the exposed population of 0.17 rem (1.7 mSv); and
- a limit on dose equivalent to gonads for individuals in large population groups of 5 rem (50 mSv) in 30 years.

The dose limits for whole body limit the risk of latent cancer fatalities for individuals and population groups, whereas the dose limit for gonads limits the risk of genetic defects in the population. The FRC also recommended that reasonable efforts be made to keep public exposures as far below the dose limits as practicable.

The responsibilities of the FRC were transferred to the EPA in 1970. However, the EPA has not yet issued generally applicable radiation protection standards for the public.

3.3 Recommendations of the ICRP

The ICRP is an international advisory group that develops recommendations for radiation protection of workers and the public. The development of radiation protection regulations is left to responsible national authorities in individual countries, but ICRP recommendations have greatly influenced the development of radiation protection standards in the U.S. and elsewhere.

3.3.1 *ICRP Publications 1 and 2*

In 1958 and 1959, the ICRP developed recommended dose limits for radiation workers, and further recommended that dose limits for members of the public be set at one-tenth of the limits for workers.[36,38] The recommendations for limits on annual dose equivalents* for members of the public were as follows:

- 0.5 rem (5 mSv) to total body or gonads;

- 3 rem (30 mSv) to bone, thyroid, or skin; and

- 1.5 rem (15 mSv) to any other organ.

Thus, the recommendations involved limits on dose equivalent to total body or the critical organ. The variation in the dose limit among the different organs reflects assumed differences in organ-specific risks per unit dose equivalent.

For purposes of implementing the dose limits for total body or the critical organ in the case of internal exposures of workers, ICRP Publication 2 presented secondary limits on permissible concentrations of radionuclides in air and water.[36] The maximum permissible concentrations in the workplace were derived using standard breathing and water consumption rates for a reference adult and models developed by the ICRP for estimating dose commitments per unit intake of radionuclides via

* The limits generally apply to the sum of committed dose equivalents from internal exposures and dose equivalents from external exposures.

inhalation and ingestion.[36] The maximum permissible concentrations for public exposures then could be obtained as one-tenth of the values for workers assuming exposures for 168 hours per week.

3.3.2 *ICRP Publication 26*

The dose limits recommended in ICRP Publications 1 and 2 were superceded in 1977 by those in ICRP Publication 26.[4] As discussed in Section 2.1 of this report, the most important change in the recommendations involved replacement of the dose equivalent to total body or the critical organ by the risk-based effective dose equivalent.

An essential aspect of the recommendations in ICRP Publication 26 is the following set of principles which comprise the system of dose limitation:[4]

[1] no practice shall be adopted unless it produces a positive net benefit;

[2] all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account; and

[3] the dose equivalent to individuals shall not exceed the recommended limits.

Thus, the system of dose limitation recommended by the ICRP involves (1) justification, (2) optimization, and (3) dose limitation. Optimization of exposures, which is known as the ALARA principle (ALARA = As Low As Reasonably Achievable), involves a balancing of reductions in population dose with the increased costs of achieving such reductions and is to be performed before determining whether doses to individuals are below the recommended limits. If the optimization procedure results in individual doses that are below the limits, then no further reductions in exposures are necessary. If, however, the optimization procedure results in individual doses that exceed the limits, then the individual exposures must be reduced below the limits regardless of cost.

ICRP Publication 26 follows the previous ICRP recommendations of setting a dose limit for members of the public that is one-tenth of the limit for workers.[4] The principal recommendation for limiting exposures of members of the public was as follows:

- a limit on annual committed effective dose equivalent of 5 mSv (0.5 rem).

In addition, the ICRP recognized that prolonged exposures at the dose limit could result in a lifetime risk for members of the public that is unacceptably high. Thus, for life-long exposures, the ICRP further recommended that exposures be limited on the basis of an annual committed effective dose equivalent averaged over a lifetime of 1 mSv (0.1 rem).

3.3.3 *Current ICRP recommendations*

In 1985, the ICRP clarified the dose limits for members of the public in Publication 26 by issuing the following recommendations:[10]

- a principal limit on annual committed effective dose equivalent of 1 mSv (0.1 rem); and

- a subsidiary limit on annual committed effective dose equivalent of 5 mSv (0.5 rem) for some years, provided the annual committed effective dose equivalent averaged over a lifetime does not exceed 1 mSv (0.1 rem).

Thus, the ICRP's current recommendations emphasize the primacy of 1 mSv (0.1 rem) as the limit on annual dose equivalent for public exposures, with 5 mSv (0.5 rem) permitted only for occasional exposures.

3.4 Recommendations of the NCRP

The NCRP is an organization chartered in the U.S. which develops recommendations on radiation protection. Current recommendations on radiation protection of the public are contained in NCRP Report No. 39,[5] but a revised set of recommendations is being developed.[11]

3.4.1 *NCRP Report No. 39*

In 1970, the NCRP recommended a set of dose limits for the public[5] that were similar to those of the FRC[37] but included a limit for the critical organ as well as whole body. The limits on annual dose equivalent were as follows:

- 0.5 rem (5 mSv) to whole body or the critical organ for maximally exposed individuals;

- 0.17 rem (1.7 mSv) to whole body or the critical organ for average individuals in the exposed population; and

- 0.17 rem (1.7 mSv) to gonads for average individuals in the exposed population.

3.4.2 *Proposed revisions of NCRP recommendations*

Scientific Committee 1 of the NCRP recently has issued a draft report containing proposed revisions of recommendations for radiation protection of the public.[11] The proposed dose limits are as follows:

- a limit on annual committed effective dose equivalent of 1 mSv (0.1 rem) for continuous or repeated exposures; and

- a limit on annual committed effective dose equivalent of 5 mSv (0.5 rem) for occasional exposures.

Thus, the draft committee report recommends use of the effective dose equivalent developed in ICRP Publication 26,[4] and the separate dose limits for continuous and occasional exposures are similar to the current recommendations of the ICRP[10] described in Section 3.3.3.

3.5 Radiation Protection Standards in the U.S.

3.5.1 *Nuclear Regulatory Commission*

Current standards. In 10 CFR Part 20,[6] the NRC has developed radiation protection standards for members of the public which apply to all facilities licensed by the NRC and essentially represent a codification of dose limits recommended by the FRC,[37] the ICRP,[36,38] and the NCRP.[5] The standards for public exposures contain limits on permissible levels of radiation and limits on concentrations of radionuclides in air and water. Furthermore, reasonable efforts should be made to maintain radiation exposures and releases of radioactive materials to unrestricted areas as low as reasonably achievable (ALARA).

The permissible levels of radiation for members of the public are expressed as limits on dose equivalent from uniform whole-body irradiation. These limits are as follows:

- 0.5 rem (5 mSv) per year;

- 2 mrem (0.02 mSv) in any hour; and

- 0.1 rem (1 mSv) in any 7 consecutive days.

The limits on concentrations of radionuclides in air and water are one-tenth of the corresponding limits in ICRP Publication 2 for 168 hours per week of occupational exposure.[36] Thus, the maximum permissible concentrations are based on the dose limits for total body or the critical organ given in Section 3.3.1.

Proposed revisions. The NRC has proposed an extensive revision of the radiation protection standards in 10 CFR Part 20.[8] These standards essentially would represent a codification of recommendations in ICRP Publications 26 and 30.[4,19] As in the present 10 CFR Part 20,[6] the proposed rulemaking contains a dose limit for any member of the public, concentration limits for radionuclides in air and water, and the requirement that releases to unrestricted areas shall be kept as low as reasonably achievable (ALARA).

In the proposed rulemaking, the total annual dose equivalent to any member of the public shall not exceed 0.5 rem (5 mSv), where the total dose is the sum of the dose equivalent to whole body from external exposures and the committed effective dose equivalent from internal exposures. This limit would apply to all known sources and operations, licensed and unlicensed, except for natural background radiation, deliberate medical practices, and radioactive material disposed into sanitary sewage according to proposed standards.[8] In addition, the proposed rulemaking establishes a reference-level annual dose equivalent of 0.1 rem (1 mSv) to take into account the possibility of exposures to multiple sources, uncertainties involving dosimetry, intakes of food and water, and other living habits, and other confounding factors in estimating dose to the public. A licensee will be in compliance with the dose limit from all sources of exposure if sources under the licensee's control will not result in an annual dose equivalent to any individual in excess of the reference level.

The limits on concentrations of radionuclides in air and water in the proposed rulemaking are derived from the reference-level dose described above using models in ICRP Publication 30 for estimating annual committed effective dose equivalents per unit intake of radionuclides via inhalation

and ingestion.[19] However, the concentrations calculated for adults have been reduced by a factor of 2 to provide adequate protection of other age groups in the public; i.e., the proposed reference-level concentrations are based on an annual committed effective dose equivalent to an adult of 0.05 rem (0.5 mSv).

3.5.2 *Department of Energy*

The DOE develops its own radiation protection standards for members of the public that are applicable to all DOE and DOE-contractor operations. Such operations are not licensed by the NRC and, thus, are not currently regulated under 10 CFR Part 20.[6] The DOE standards are similar to those of the NRC, however, in that they include dose limits for public exposures, limits on concentrations of radionuclides in air and water, and the requirement that releases to the environment shall be kept ALARA.

The current DOE radiation protection standards for members of the public[7] were developed in 1985 and are consistent with recent draft proposals and recommendations of the NCRP.[11,39] The DOE standards are particularly noteworthy in that they involve the first use in the U.S. of the effective dose equivalent developed in ICRP Publication 26.[4]

The DOE standards include dose limits for all release pathways and separate dose limits for airborne releases only. The standards for all release pathways are as follows:

- a limit on annual committed effective dose equivalent of 0.5 rem (5 mSv) for occasional exposures;

- a limit on annual committed effective dose equivalent of 0.1 rem (1 mSv) for prolonged exposures; and

- a limit on annual dose equivalent to any organ of 5 rem (50 mSv).

A prolonged exposure is one that lasts longer than 5 years. Thus, the DOE has established dose limits for continuous and occasional exposures that essentially are the same as those currently recommended by the ICRP[10] and under consideration by the NCRP.[11] The dose limit for any organ is intended to prevent nonstochastic radiation effects from exposures of the public, and is one-tenth of the dose limit for any organ of radiation workers recommended in ICRP Publication 26.[4]

The standards for airborne releases only are as follows:

- a limit on annual dose equivalent to whole body of 25 mrem (0.25 mSv); and

- a limit on annual dose equivalent to any organ of 75 mrem (0.75 mSv).

These dose limits were based on recommendations of the NCRP[39] and are consistent with the EPA's emission standards for hazardous air pollutants that are applicable to DOE facilities[14] (see Section 4.8).

For many years prior to the revision of the DOE standards in 1985, the dose limits for DOE operations were similar to those recommended by the FRC[37] in 1959 and the NCRP[5] in 1971 (e.g., see ref. 40). The limits on annual dose equivalents included (1) 0.5 rem (5 mSv) to whole body, gonads, or red bone marrow and 1.5 rem (15 mSv) to other organs for maximally exposed individuals and (2) 0.17 rem (1.7 mSv) to whole body, gonads, or red bone marrow and 0.5 rem (5 mSv) to other organs for average individuals in the exposed population.

3.6 Summary

Generally applicable radiation protection standards for the public are based on an assumed level of risk from radiation exposures that would be acceptable to most individuals. The limit on acceptable risk is expressed as a limit on radiation dose using an assumed value for the risk per unit dose equivalent. Generally applicable radiation protection standards have two essential components:

- a limit on dose equivalent to maximally exposed individuals in the public from all sources of exposure, exclusive of natural background and deliberate medical practices; and

- a requirement that population exposures be reduced as low as reasonably achievable (ALARA).

The dose limit for individuals must be met, except under unusual circumstances, regardless of the cost of achieving the necessary controls on exposures.

Radiation protection standards in the U.S. have been established by the NRC for its licensees[6] and by the DOE for all its operations[7] on the basis of recommendations of the FRC,[37] the ICRP,[4,10,36,38] and the NCRP.[5,11] Standards based on current recommendations have two essential

features:

- the dose limits are expressed in terms of the effective dose equivalent,[4] instead of the dose equivalent to whole body or the critical organ,[5,36,38] and the limits apply to the sum of effective dose equivalents from external exposures and committed effective dose equivalents from internal exposures; and

- the principal limit on annual effective dose equivalent has been set at 1 mSv (0.1 rem) with a subsidiary limit of 5 mSv (0.5 rem) for some years, provided the annual dose equivalent averaged over a lifetime does not exceed the principal limit, instead of the single limit on annual dose equivalent of 5 mSv (0.5 rem) used previously.

The lowering of the dose limit resulted from the realization that prolonged exposures at a limit of 5 mSv (0.5 rem) per year could lead to lifetime risks that are unacceptably high for members of the public.

4. ENVIRONMENTAL RADIATION STANDARDS FOR SPECIFIC PRACTICES

4.1 Introduction

This section presents a review of environmental radiation standards and guidelines for specific practices that have been developed by regulatory authorities in the U.S. The specific practices for which standards or guidelines have been developed include low-level waste disposal, operations of nuclear power reactors and other parts of the nuclear fuel cycle, radioactivity in drinking water, disposal of uranium and thorium mill tailings at facilities licensed by the NRC, high-level waste disposal, airborne emissions of radioactivity, and residual radioactivity from uranium and thorium processing operations at DOE facilities. Recommendations on performance objectives for solid waste disposal that have been developed by the ICRP and by the Nuclear Energy Agency in Europe also are discussed.

It is important to understand the relationship between the environmental radiation standards for specific practices discussed in this section and the generally applicable radiation protection standards discussed in Section 3. The latter apply to all sources of exposure, excluding natural background radiation and deliberate medical practices, and are based only on consideration of a limit on acceptable risk to members of the public. Thus, radiation protection standards define limits on radiation exposures that are believed to be necessary for the protection of public health and safety, and are developed without regard to the technology and its associated costs that would be required to meet the standards. Environmental radiation standards for specific practices then necessarily involve limits on exposures that do not exceed the limits from all sources.

While environmental radiation standards for specific practices must meet the goal of protecting public health and safety, they also involve consideration of available technologies for controlling exposures and their associated costs; i.e., in deciding how far below a radiation protection standard permissible exposures for a specific practice should be, regulatory authorities perform an analysis of the costs of achieving different levels of protection vs the benefits of reduced population exposures. In essence, the establishment of limits on exposures for specific practices that are below the limits from all sources represents a judgment by the regulatory authorities that the limits are "reasonably achievable" for those practices. This judgment often is based on the concept of "best available technology" or, in the case of standards for naturally occurring radionuclides, on a comparison with background levels of dose or radionuclide concentrations. Because a cost-benefit analysis

is used in developing standards for specific practices, the exposure limits that are judged to be "reasonably achievable" need not be the same for all practices.

It is because considerations beyond protection of public health and safety are involved in establishing standards for specific practices that we do not refer to them as radiation protection standards. Rather, we refer to standards for specific practices as environmental radiation standards.

4.2 Standards for Low-Level Waste Disposal in the U.S.

4.2.1 *Nuclear Regulatory Commission (10 CFR Part 61)*

In 10 CFR Part 61, the NRC has established performance objectives for near-surface land disposal of low-level radioactive wastes.[9] The performance objectives are as follows:

- a limit on annual dose equivalent to any member of the public from releases of radioactive material to the general environment of 25 mrem to whole body, 75 mrem to the thyroid, and 25 mrem to any other organ;

- reasonable effort should be made to maintain releases to the general environment as low as reasonably achievable (ALARA); and

- the design, operation, and closure of the disposal facility must ensure protection of any inadvertent intruder onto the disposal site following loss of active institutional controls over the facility.

The dose limits for off-site exposures are the same as those in the EPA's uranium fuel-cycle standard (40 CFR Part 190),[12] which is discussed in Section 4.4. The requirement for protection of inadvertent intruders is implemented in the standard by means of limits on concentrations of radionuclides that are generally acceptable for near-surface disposal. These concentration limits are based on a limit on annual dose equivalent to whole body of 0.5 rem, and are derived principally from a pathways analysis of postulated exposure scenarios for an intruder.

4.2.2 *Environmental Protection Agency (40 CFR Part 193)*

The EPA is developing standards for low-level waste disposal, and has performed an extensive analysis of doses and risks associated with different disposal technologies.[25] This analysis has not indicated any standards that might be considered appropriate for low-level waste disposal. However, in commenting on the NRC's low-level waste standard in 10 CFR Part 61, the EPA stated that a limit on annual dose equivalent to individuals beyond the site boundary in the range 1-25 mrem should encompass any standard which the EPA might derive.[9]

4.2.3 *Department of Energy*

In Order 5820.2, the DOE has established policies and guidelines for management of radioactive wastes, including low-level wastes, at DOE facilities.[41] In implementing the policies in Order 5820.2, the DOE has issued guidance that all planning for new low-level waste disposal facilities should assume as an interim performance objective for off-site exposures a limit on annual dose equivalent of 25 mrem (0.25 mSv).[42] The dose limit in the guidance presumably refers to the dose equivalent from uniform whole-body irradiation.

4.3 NRC Design Objectives for Nuclear Power Reactors

In 10 CFR Part 50, the NRC has established design objectives for equipment to control releases of radioactive materials from nuclear power reactors.[43] The design objectives are not standards for operating reactors, but are used by the NRC in evaluating an application for a construction permit. Environmental radiation standards for operating reactors have been established by the EPA,[12] as described in Section 4.4.

The principal design objective for nuclear reactors is that releases of radioactive materials to unrestricted areas shall be kept as low as reasonably achievable (ALARA). Appendix I of 10 CFR Part 50 then gives numerical guides for acceptable controls of releases of radioactive materials and for implementing the ALARA criterion.[43] These numerical guides are as follows:

- a limit on annual dose equivalent or committed dose equivalent to any individual from liquid effluents of 3 mrem to total body or 10 mrem to any organ for all pathways of exposure;

- a limit on annual external dose equivalent to any individual from gaseous effluents of 5 mrem to total body or 15 mrem to skin;

- a limit on annual dose equivalent or committed dose equivalent to any individual from radioactive iodine and particulates in airborne effluents of 15 mrem to any organ for all pathways of exposure; and

- additional measures to control releases of radioactivity shall be taken if the cost is less than $1,000 per person-rem averted to total body or the thyroid for the population within 50 miles.

4.4 EPA Standards for Nuclear Power Operations

In 40 CFR Part 190, the EPA has established environmental radiation standards for normal operations of parts of the uranium fuel cycle including milling of uranium ore, chemical conversion of uranium, fabrication of uranium fuel, generation of electricity in a nuclear power plant, and reprocessing of spent uranium fuel.[12] These standards do not apply to mining operations, operations at waste disposal sites, transportation of radioactive material in support of these operations, and reuse of recovered non-uranium special nuclear and by-product materials from the uranium fuel cycle.

The EPA's uranium fuel-cycle standards are as follows:

- a limit on annual dose equivalent to any individual from all radionuclides except radon and its daughters of 25 mrem to whole body, 75 mrem to thyroid, and 25 mrem to any other organ; and

- limits on releases to the general environment per gigawatt-year of electricity produced by the fuel cycle of (1) 50,000 Ci of ^{85}Kr, (2) 5 mCi of ^{129}I, and (3) 0.5 mCi combined of ^{239}Pu and other alpha-emitting transuranic radionuclides with half-lives greater than one year.

The limits on releases of specific radionuclides are not directly related to limits on dose equivalent but result from considerations of best available technology for control of releases.

The EPA's uranium fuel-cycle standards do not explicitly require use of the ALARA principle to reduce releases to the general environment below the specified limits. However, the ALARA requirement in the NRC's radiation protection standards[6] in 10 CFR Part 20 applies to operations covered by the EPA standard.

4.5 EPA Standards for Radioactivity in Drinking Water

In 40 CFR Part 141, the EPA has established interim standards for acceptable levels of radioactivity in community drinking water systems.[44] The standards are as follows:

- a concentration limit of 5 pCi/L for ^{226}Ra and ^{228}Ra combined;
- a concentration limit of 15 pCi/L for gross alpha-particle activity, including ^{226}Ra but excluding radon and uranium; and
- a limit on annual dose equivalent to any individual of 4 mrem to total body or any organ from man-made radionuclides that emit beta and gamma radiation.

These standards apply to radioactivity in drinking water at the point of consumption, not at the source. Thus, the effects of water treatment systems on reducing concentrations of radioactivity can be taken into account in meeting the requirements.

The standards for radium and gross alpha-particle activity were based (1) on an analysis of costs vs reductions in health risks in the U.S. population as a function of concentration limit for ^{226}Ra and (2) on consideration of the radiotoxicities of ^{228}Ra and other naturally occurring, alpha-emitting radionuclides relative to the radiotoxicity of ^{226}Ra. The limit on annual dose equivalent from man-made beta- and gamma-emitting radionuclides was based on levels of ^{90}Sr and ^{137}Cs in drinking water from fallout and correspond to a level that the EPA anticipated would not often be exceeded and, thus, would not impose an unjustified cost on water treatment systems.

The EPA is developing revisions to the interim primary drinking water regulations.[45,46] While the concentration limit for ^{226}Ra and the limit on annual dose equivalent from man-made beta- and gamma-emitting radionuclides may not change, three revisions apparently are being considered: (1) a separate concentration limit for ^{228}Ra, which may be 2-3 times less than the limit for ^{226}Ra; (2) a concentration limit for uranium, which may be about twice the limit for ^{226}Ra; (3) a concentration limit for radon, which may be about an order of magnitude greater than the limit for radium or uranium; and (4) use of the concentration limit for gross alpha-particle activity only as a screening tool in monitoring requirements. In addition, the EPA is considering an alternative of replacing the separate concentration or dose limits for different radionuclides by a single limit on annual committed effective dose equivalent for all radionuclides.[46]

4.6 Standards for Uranium and Thorium Mill Tailings

4.6.1 *Environmental Protection Agency (40 CFR Part 192)*

In 40 CFR Part 192, the EPA has established environmental radiation standards for uranium and thorium mill tailings,[47] which are concerned with the control and cleanup of residual radioactive materials from inactive uranium processing sites that are licensed by the NRC and with the management of uranium and thorium byproduct materials. The standards are summarized as follows:

- (1) a limit on release rate of ^{222}Rn to the atmosphere averaged over the surface of the disposal site and over a time period of at least one year of 20 $pCi/m^2/s$, or (2) a limit on annual average concentration of ^{222}Rn in air above background at any location outside the disposal site of 0.5 pCi/L;

- a limit on ^{226}Ra concentration in soil of (1) 5 pCi/g averaged over the first 15 cm below the surface and (2) 15 pCi/g averaged over 15-cm thick layers more than 15 cm below the surface;

- a limit on radon decay product concentration (including background) in any occupied or habitable building of 0.03 Working Levels (WL),* with an objective for remedial action of 0.02 WL;

- a limit on gamma radiation level above background in any occupied or habitable building of 20 $\mu R/h$;

- a limit on concentrations in ground water of (1) 5 pCi/L for ^{226}Ra and ^{228}Ra combined and (2) 15 pCi/L for gross alpha-particle activity excluding radon and uranium;

- a limit on annual dose equivalent to any individual from thorium processing operations of 25 mrem to whole body, 75 mrem to the thyroid, and 25 mrem to any other organ; and

- the provisions applicable to uranium, ^{222}Rn, and ^{226}Ra also apply to thorium, ^{220}Rn, and ^{228}Ra, respectively.

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* A Working Level is defined as any combination of short-lived daughter products of radon in one liter of air that will result in the emission of 1.3×10^5 MeV of alpha-particle energy.[48] For short-lived daughter products of ^{222}Rn in secular equilibrium in air, 1 WL = 100 pCi/L.

The standards for control of radon emissions shall be effective for up to 1,000 years, to the extent reasonably achievable, and in any case for at least 200 years.

The dose limits from thorium processing operations are the same as those for the uranium fuel cycle in 40 CFR Part 190.[12] The standards for radon emissions, radium concentrations in soil, and indoor levels of radon decay products and gamma radiation are based primarily on consideration of background levels in the western U.S., where the uranium deposits exist from which residual and byproduct materials are obtained. Thus, the standards represent a judgment by the EPA that it is unreasonable to require control and cleanup of residual radioactivity to levels that are near those that would exist if the uranium and thorium had been left in their undisturbed state.

Annual doses to individuals associated with the control and cleanup standards for uranium and thorium mill tailings are considerably higher than the dose limits in other environmental radiation standards, e.g., the EPA's uranium fuel-cycle standard.[12] For example, the EPA has estimated that radium concentrations in soil of 5 pCi/g to a depth of several feet can produce annual external dose equivalents to an individual standing on the ground of about 80 mrem.[49] Furthermore, continuous inhalation for a period of 20 hours per day of indoor radon decay products at a concentration of 0.03 WL corresponds to an annual dose equivalent to the bronchial epithelium of an average adult of about 17 rem and an annual committed effective dose equivalent of about 2 rem.[48] Finally, the limit on indoor gamma radiation level of 20 μR/h corresponds to an annual effective dose equivalent of about 80 mrem for an indoor residence time of 20 hours per day.

4.6.2 *Nuclear Regulatory Commission (10 CFR Part 40)*

The NRC developed its initial criteria for the operation of uranium mills and the disposal of mill tailings in Appendix A of 10 CFR Part 40.[50] The performance objectives for disposal of uranium mill tailings included (1) a limit on radon emanation rate of 2 pCi/m^2/s, which is a typical background level in the western U.S., and (2) reduction of external photon exposures to background levels.

Following establishment of the EPA's environmental standards for uranium and thorium mill tailings[47] described above, the NRC issued revised standards[51] that conform in many respects to the EPA's requirements. The revised NRC standards contain detailed technical criteria for the siting and design of disposal facilities and the protection of ground water, and they also require that airborne effluents

from milling operations shall be ALARA. The radiological criteria that conform to the EPA's regulations include those on (1) control of ^{222}Rn releases to the atmosphere and the time period over which the controls shall be effective, (2) limits on ^{226}Ra concentrations in soil, and (3) limits on annual dose equivalents from releases during thorium processing operations. However, the NRC has maintained its previous requirement[50] that external photon exposures from the tailings or wastes should be reduced to background levels, and the standards do not address indoor concentrations of radon decay products. The revised NRC regulations also do not establish separate standards for ground-water protection from those in the EPA's regulations.[47]

4.7 Standards for Management and Disposal of High-Level Wastes

4.7.1 *Environmental Protection Agency (40 CFR Part 191)*

In 40 CFR Part 191, the EPA has established environmental standards for the management and disposal of spent nuclear fuel, high-level wastes, and transuranic wastes.[14]

The standards for management and storage of wastes at facilities that are regulated by the NRC or by so-called Agreement States (i.e., states that enter into agreements with the NRC) are as follows:

- a limit on annual dose equivalent to any individual (1) from management and storage of such wastes and (2) from all operations covered by 40 CFR Part 190 of 25 mrem to whole body, 75 mrem to the thyroid, and 25 mrem to any other organ.

These standards thus are consistent with those previously established by the EPA for other parts of the uranium fuel cycle.[12]

The EPA also specifies standards for management and storage of wastes at facilities that are operated by the DOE but not regulated by the NRC or Agreement States. These standards are as follows:

- a limit on annual dose equivalent to any individual of 25 mrem to whole body and 75 mrem to any organ; or

- upon application for an alternative standard, a limit on annual dose equivalent to any individual from all sources, excluding natural background and medical practices, of 0.1 rem for continuous exposure and 0.5 rem for infrequent exposure.

The standards for facilities that are not regulated by the NRC or Agreement States are consistent with those established by the EPA for airborne emissions of radionuclides from DOE facilities[14] (see Section 4.8). The alternative standard would allow annual dose equivalents from management and storage of high-level wastes that exceed 25 mrem to whole body and 75 mrem to any organ, provided the resulting doses from all sources of exposure do not exceed the prescribed limits. These limits presumably refer to uniform whole-body irradiation.

The standards for disposal of wastes involve containment requirements for the disposal system, requirements for protection of members of the public, and ground-water protection requirements. These standards are described below.

The containment requirements for waste disposal are expressed as limits on cumulative releases of radionuclides to the accessible environment (i.e., the atmosphere, land surface, surface waters, oceans, and all of the lithosphere that is more than 5 km from the outer boundary of the original location of wastes in the disposal system) for 10,000 years after disposal. The requirements are as follows:

- cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal shall (1) have a likelihood of less than one chance in 10 of exceeding the specified limits and (2) have a likelihood of less than one chance in 1,000 of exceeding ten times the specified limits.

These requirements thus embody two features not found in other environmental radiation standards in the U.S. First, the specification of limits on cumulative releases of radionuclides provides, in effect, a limit on population dose and health effects, rather than the usual practice of limiting dose to maximally exposed individuals. The release limits correspond to approximately 1,000 fatal cancers plus genetic defects per repository over 10,000 years[52,53] (i.e., a lifetime risk of about 5×10^{-8} to an average individual in the U.S. population). Second, the containment requirements recognize explicitly that expected performance of the disposal system will involve a distribution of cumulative releases with differing probabilities. Thus, demonstrations of compliance with the containment requirements will require a probabilistic risk analysis of long-term performance of the disposal system, taking into account all significant processes and events that may affect system performance.

The requirements for protection of individuals in the exposed population apply for 1,000 years after disposal and are as follows:

- for 1,000 years after disposal and assuming undisturbed performance of the disposal system, a limit on annual dose equivalent to any individual in the accessible environment of 25 mrem to whole body or 75 mrem to any organ.

The term "undisturbed performance" refers to the predicted behavior of the disposal system if there is no disruption by human intrusion or the occurrence of unlikely natural events.

The ground-water protection requirements also apply for 1,000 years after disposal and are similar to the interim standards for radionuclides in drinking water[45] described in Section 4.5. These requirements are as follows:

- for 1,000 years after disposal and assuming undisturbed performance of the disposal system, a limit on radionuclide concentrations averaged over any year in water withdrawn from a special source of ground water of (1) 5 pCi/L for ^{226}Ra and ^{228}Ra combined, (2) 15 pCi/L for alpha-emitting radionuclides (including ^{226}Ra and ^{228}Ra but excluding radon), and (3) values for all beta- and gamma-emitting radionuclides that would produce an annual dose equivalent to whole body or any organ of 4 mrem.

- if any of the annual average radionuclide concentrations in a special source of ground water before construction of the disposal system exceed the limits specified above, then, for 1,000 years after disposal, undisturbed performance of the disposal system shall not increase the existing concentrations by more than the specified limits.

A special source of ground water is one that (1) lies within a boundary 5 km beyond the outer boundary of the original location of the waste in the disposal system, (2) is supplying drinking water for thousands of persons at the time site characterization is undertaken by the DOE, and (3) is irreplaceable as a source of drinking water for that population. The ground-water protection requirements for waste disposal implicitly include a concentration limit for uranium, which is excluded from the current drinking water standards,[45] and they apply to drinking water at the source rather than at the point of consumption.

4.7.2 *Nuclear Regulatory Commission (10 CFR Part 60)*

In 10 CFR Part 60, the NRC has established performance objectives and technical criteria for the management and disposal of high-level wastes[55] that are intended to be compatible with the EPA standard described above. The NRC requires that releases during operations at a disposal facility will be maintained within the limits specified in environmental radiation standards established by the EPA. Thus, limits on annual dose equivalent to any member of the public during operations at a repository are 25 mrem to whole body, 75 mrem to the thyroid, and 25 mrem to any other organ.[13]

The performance objectives for waste disposal established by the NRC do not explicitly involve radiological criteria. Rather, the NRC has established performance objectives for the engineered barrier system and the geologic setting that are compatible with the limits on cumulative releases of radionuclides to the accessible environment established by the EPA.[13]

4.8 EPA Standards for Airborne Emissions of Radionuclides

In 40 CFR Part 61, the EPA has established national emission standards for airborne releases of radionuclides that apply to DOE facilities, NRC-licensed and non-DOE Federal facilities, and elemental phosphorus plants.[14] Proposed standards for underground uranium mines[55] have not been issued in final form.

The emission standards for airborne releases from DOE facilities and from NRC-licensed and non-DOE Federal facilities are as follows:

- a limit on annual dose equivalent to any individual from emissions of radionuclides to the air of 25 mrem to whole body or 75 mrem to any organ, exclusive of doses due to radon and its decay products; or

- upon application for an alternative standard, a limit on annual effective dose equivalent to any individual from all sources, exclusive of natural background and medical practices, of 0.1 rem for continuous exposure and 0.5 rem for noncontinuous exposure.

The alternative standard, which allows higher dose limits for those facilities that may exceed the limits of 25 mrem to whole body or 75 mrem to any organ, represents the first use of the effective dose equivalent in radiation standards in the U.S. However, the EPA has not yet indicated the values of organ-specific weighting factors that are to be used in calculating the effective dose equivalent.

The emission standard for elemental phosphorus plants is a limit on annual emissions of ^{210}Po to air of 21 Ci. The standard does not relate this release limit to expected doses to the public.

4.9 DOE Guidelines for Residual Radioactivity at FUSRAP and Remote SFMP Sites

The DOE has established guidelines for acceptable levels of residual radioactivity at FUSRAP (Formerly Utilized Sites Remedial Action Program) and remote SFMP (Surplus Facilities Management Program) sites that are not licensed by the NRC.[56] The guidelines contain dose limits for members of the public and limits on acceptable levels of radioactivity.

The dose limits in the DOE guidelines are as follows:

- a limit on annual committed effective dose equivalent to any individual of 0.5 rem for a period of exposure not to exceed 5 years and an average of 0.1 rem over a lifetime.

These dose limits thus are consistent with recent recommendations on radiation protection by the ICRP[10] and the NCRP,[11] and with radiation protection standards established by the DOE.[7]

The guidelines for acceptable levels of residual radioactivity are as follows:

- a limit on residual concentrations of ^{232}Th, ^{230}Th, ^{228}Ra, and ^{226}Ra in soil material of (1) 5 pCi/g averaged over the first 15 cm below the surface and (2) 15 pCi/g averaged over 15-cm thick layers more than 15 cm below the surface, with guidelines for residual concentrations of all other radionuclides to be derived from the basic dose limits by means of an environmental pathway analysis using site-specific data;

- a limit on radon decay-product concentration (including background) in any occupied or habitable building of 0.03 WL, with an objective for remedial action of 0.02 WL;

- a limit on average gamma radiation level above background in any occupied or habitable building of 20 μR/h; and

- limits on average, maximum, and removable residual surface contamination of different radionuclides, which are applicable to both interior and exterior surfaces of existing structures and

equipment that will not be demolished and buried, as obtained from current guidelines of the NRC.[57]

With the exception of the limits on surface contamination of different radionuclides, the guidelines for residual activity are based on the EPA standards for uranium and thorium mill tailings[47] (see Section 4.6.1). Regarding the limits on surface contamination, the guidelines also state that the average and maximum absorbed dose rates in air at a distance of 1 cm resulting from beta/gamma-emitting radionuclides should not exceed 0.2 and 1 mrad/h, respectively. The other concentration limits in the guidelines are not related to dose to exposed individuals.

The guidelines for control of residual radioactivity are as follows:

- during interim storage, a limit on concentrations of ^{222}Rn in air above facility surfaces or openings of (1) 100 pCi/L at any given point, (2) 30 pCi/L averaged over a year and over the facility site, and (3) 3 pCi/L averaged over a year at any location outside the facility site; and

- for long-term management, (1) a limit on releases of ^{222}Rn to the atmosphere of 20 pCi/m^2/s averaged over a year, and (2) a limit on the increase in annual average ^{222}Rn concentration at any location outside the boundary of the contaminated area of 0.5 pCi/L.

The guidelines for radon concentrations during interim storage shall be effective for up to 50 years, and in any case for at least 25 years. The guidelines for long-term management shall be effective for up to 1,000 years, and in any case for at least 200 years. The guidelines for long-term control of radon releases also are based on the EPA standards for uranium and thorium mill tailings.[47]

4.10 ICRP Recommendations for Solid Waste Disposal

The ICRP has issued a set of recommendations on radiation protection principles for disposal of solid radioactive wastes.[16] These recommendations represent an extension of previous ICRP recommendations on radiation protection[4,10] (see Sections 3.3.2 and 3.3.3) in that they apply to situations in which doses are not controlled and can be limited only by intervention.

The essential feature of the ICRP recommendations for solid waste disposal is that protection of individuals should be expressed in terms of limits on risk, rather than dose. Here, risk is defined as the product of

the probability of an initiating event that give rise to a dose and the probability of a deleterious health effect arising from that dose. Thus, this approach takes into account that some processes and events which may cause releases of radionuclides into the general environment and result in human exposures have probabilities of occurrence that are less than unity and may vary with time.

For releases which are expected to occur with unit probability, the limit on annual committed effective dose equivalent of 1 mSv (0.1 rem) recommended by the ICRP for prolonged exposures[4,10] corresponds to an annual risk of about 10^{-5}. Thus, the ICRP recommends for probabilistic events that the annual risk be limited to 10^{-5} and that this limit apply at any time after disposal. In effect, the limit on acceptable dose then increases as the probability that the dose will be received decreases.

4.11 NEA Standards for Low-Level Waste Disposal

An expert group of the Nuclear Energy Agency (NEA) of the Organization for Economic Co-Operation and Development in Europe is developing a set of radiological acceptance criteria for radioactive wastes to be disposed of by shallow-land burial.[17] These standards resemble the ICRP recommendations discussed above in that protection of individuals is expressed in terms of limits on risk.

The NEA expert group recommends that limits on individual risk for shallow-land burial correspond to the risks associated with current ICRP recommendations on dose limits[4,10] (see Sections 3.3.2 and 3.3.3). The recommended risk limits are as follows:

- a limit on annual risk to any individual of 10^{-5} for those scenarios where exposures are expected to persist for a decade or more; and

- a limit on annual risk to any individual of 5×10^{-5} for those scenarios where exposures are expected to be of short duration.

For exposures that occur with a probability of unity, the risk limits for continuous and occasional exposures thus correspond to annual dose equivalents of 1 mSv (0.1 rem) and 5 mSv (0.5 rem), respectively.

4.12 Summary

This section has described environmental radiation standards for specific practices that have been developed by regulatory authorities in the U.S. These standards must correspond to a level of protection of the public that is equal to or greater than the level of protection provided by the generally applicable radiation protection standards described in Section 3. The particular level of protection that is provided by the standards for a specific practice is based on a judgment by the regulatory authorities that the standards are reasonably achievable. This judgment is based either on consideration of the level of controls that can be obtained by current or foreseeable technology and the associated costs or, in the case of radionuclides that are naturally occurring, on existing background levels.

Although standards for different practices need not correspond to the same level of protection, examination of current environmental radiation standards in the U.S. shows that a limit on annual dose equivalent to any individual of 25 mrem has been widely used for different practices that do not primarily involve naturally occurring radionuclides. Of particular importance to the development of the performance objectives in this report is the finding by the NRC and the EPA that a limit on annual dose equivalent of 25 mrem for off-site exposures of individuals is reasonably achievable for low-level waste disposal.[9]

A recent development by the ICRP and the NEA is the recommendation that protection of individuals from waste disposal should be expressed in terms of limits on risk rather than dose. This approach takes into account that many events and processes that lead to human exposures may occur with a probability less than unity and can have particularly important consequences with regard to the development of waste acceptance criteria for the protection of inadvertent intruders. The use of limits on risk as performance objectives for low-level waste disposal is discussed further in Section 5.2.

5. PERFORMANCE OBJECTIVES - STATEMENT AND SUMMARY OF RATIONALE

This section presents the performance objectives for disposal of low-level radioactive wastes in a new facility on the Oak Ridge Reservation.[1-3] The purpose of the performance objectives is to ensure the long-term protection of health and safety for members of the public outside the boundary of the facility and for individuals who might inadvertently intrude onto the site after loss of institutional controls. Section 5.1 presents the performance objectives for low-level waste disposal, including a discussion of their intended application and a summary of the rationale for the dose limits and the manner in which they are expressed. Sections 5.2 and 5.3 then discuss two additional issues of concern in developing the performance objectives: (1) alternatives for providing protection of individuals that involve limits on risk rather than limits on dose; and (2) the potential importance of the chemical toxicity of uranium in the kidney in determining acceptable intakes by individuals.

5.1 Presentation of Performance Objectives

The performance objectives for low-level waste disposal presented in this report follow from the discussions in Section 2 on fundamental concepts in radiation dosimetry and the reviews in Sections 3 and 4 on generally applicable radiation protection standards and environmental radiation standards for specific practices, respectively.

5.1.1 *Statement of performance objectives*

The performance objectives for low-level waste disposal include requirements related to (1) limits on releases of radioactivity to the general environment beyond the site boundary and (2) limits on exposures of inadvertent intruders. The principal performance objectives include separate dose limits for off-site individuals and inadvertent intruders as follows:

[1] a limit on annual committed effective dose equivalent averaged over a lifetime of 0.25 mSv (25 mrem) for any member of the public beyond the boundary of the disposal facility; and

[2] a limit on annual committed effective dose equivalent averaged over a lifetime of 1 mSv (0.1 rem) and a limit on committed effective dose equivalent in any year of 5 mSv (0.5 rem) for any individual who inadvertently intrudes onto the disposal site after loss of active institutional controls.

In addition, releases of radioactivity to the general environment beyond the site boundary -

- shall not result in annual dose equivalents to any member of the public from all sources of exposure, exclusive of natural background and deliberate medical practices, that exceed limits established by Federal regulatory authorities; and

- shall be kept as low as reasonably achievable, economic and social factors being taken into account.

The purpose of the latter two requirements is to ensure that the performance objectives for low-level waste disposal conform to radiation protection standards for the public established by the NRC[6] and DOE.[7] Current DOE standards have established limits on annual committed effective dose equivalents to any individual from all DOE activities of 5 mSv (0.5 rem) for occasional exposures and 1 mSv (0.1 rem) for prolonged exposures (i.e., exposures of duration greater than 5 years).[7]

5.1.2 *Intended applications of performance objectives*

Time period for performance objectives. The performance objectives for low-level waste disposal do not define explicitly the time period over which the dose limits apply. The intent is that the dose limits shall apply at any time following closure of the facility. However, the effects of radioactive decay and the dispersibility of radionuclides in the environment over time likely will result in maximum doses to individuals that occur well within 10,000 years,[3,24,25] so assessments of individual doses probably will not be required over unreasonably long time periods in the future. In particular, maximum doses to inadvertent intruders likely will decrease with time following loss of institutional controls, because intruder doses probably will be determined in most cases by exposures to radionuclides in the disposal facility itself.[3,20,21,24,25]

In 10 CFR Part 61, the NRC states that requirements on siting and design of the facility and the stability of waste forms should be evaluated for at least 500 years, and that a period of 500 years also

should be applied to the determination of expected natural events or processes that could impact the disposal facility; however, the performance objectives for off-site exposures and the protection of inadvertent intruders should be considered applicable over the indefinite future.[9] Thus, our intent that the dose limits apply at any time after closure of the facility conforms to the NRC regulations.

In applying the ALARA principle to optimization of population exposures, it would be reasonable to apply a time cutoff to the calculations. Otherwise, the population dose must be calculated until all activity is removed from the environment by radioactive decay, regardless of the half-lives of the radionuclides and the magnitude of doses received by individuals in the population. Particularly for long-lived radionuclides, the absence of a time cutoff for the calculations usually leads to estimates of population dose and health effects that are obtained primarily by accruing very small individual doses over very large populations for time periods of millions of years or more, but the estimated health risks to most individuals over that time are trifling compared with risks from normal activities that are accepted by most people. Thus, for long-lived radionuclides, calculations of population dose without a time cutoff do not provide a reasonable basis for application of the ALARA principle.

Instead of specifying an explicit time cutoff for the calculation of population dose, which necessarily would be somewhat arbitrary, a more reasonable approach would be to specify a lower cutoff on dose to individuals that would be included in the calculations. For example, the NCRP is developing a recommendation that calculations of population dose include only those individuals who receive annual committed effective dose equivalents in excess of 0.01 mSv (1 mrem),[11,58] and the same dose cutoff has been proposed by the NRC.[8] Annual doses to individuals below this level are regarded as *de minimis* and, thus, of no concern to regulatory authorities. This approach provides an effective time cutoff for population dose calculations, but one that is directly related to control of health risks in the exposed population.

Active institutional controls over the disposal facility are assumed to prevent inadvertent intrusion for some time after closure of the facility, but the time period for maintenance of institutional controls is not specified in the performance objectives. The institutional control period is important for determining allowable concentrations of some radionuclides for disposal, as derived from the dose limits for inadvertent intruders by means of a pathways analysis of postulated exposure scenarios, particularly when the half-life for radioactive decay is comparable to or less than the control period. On the basis of the conclusion of the NRC that an institutional control period of 100 years is

the most reasonable assumption for low-level waste disposal,[9] and the same conclusion of the EPA for high-level waste disposal,[13] a control period of 100 years is recommended for application to dose assessments for inadvertent intruders at a low-level waste disposal facility on the Oak Ridge Reservation. However, this choice does not preclude the use of disposal technologies or engineered barriers that would prevent intrusion into the wastes for time periods beyond 100 years.

Processes and events to which performance objectives apply. The performance objectives, including use of the ALARA principle, are intended for application only to expected or reasonably foreseeable occurrences that could affect long-term performance of the disposal system and lead to exposures of off-site individuals or inadvertent intruders. The performance objectives are not intended for application to unexpected or accidental disruptive events or processes that would occur with low probability and that might lead to doses above the specified limits for expected occurrences. The exclusion of low-probability accident scenarios from consideration in meeting the performance objectives is embodied in the NRC's low-level waste standards,[9] and is a common feature of performance objectives for other practices that involve limits on dose, e.g., the EPA's uranium fuel-cycle standard (40 CFR Part 190).[12]

Since the performance objectives are intended for application only to expected processes and events, it then would be reasonable to take unexpected processes and events into account by means of siting and design criteria for the facility and criteria for the acceptability of waste forms. Such criteria presumably would not involve limits on dose or risk. Alternatives for performance objectives expressed as limits on risk, rather than dose, that can be applied to unexpected as well as expected processes and events are discussed in Section 5.2.

Definition of an exposed individual. The performance objectives state that the dose limits apply to "any member of the public" or "any individual." However, the dose limits do not apply literally to that single real individual in a diverse population who might receive the highest dose. Rather, the limits apply to a more hypothetical reference individual who is a member of the critical group in the exposed population.[4] The critical group is that group of individuals who are expected to receive the highest dose, and the dose limits apply to the average dose received by members of the critical group. Because of the innate variability of doses received within apparently homogeneous population groups, some members of the critical group will receive higher doses than the mean and, thus, could appear to exceed the dose limits. However, because of the maximizing assumptions that usually are made in estimating dose, actual doses received are expected to be less than estimated doses to average reference individuals in the critical group.

5.1.3 *Summary of rationale for performance objectives*

This section presents a summary of the rationale for the performance objectives presented in Section 5.1.1. More detailed discussions are presented in Sections 2-4.

Basis for protection of individuals and populations. Consistent with the requirements in radiation protection standards of the NRC[6] and DOE,[7] the primary goal of the performance objectives for low-level waste disposal is to ensure protection of both individuals and population groups. This goal is accomplished by establishing dose limits for individuals and the ALARA requirement for optimizing population exposures. From the presentations in Sections 3 and 4, it is evident that the use of dose limits for individuals as a surrogate for limits on risk conforms to conventional radiation protection practice in the U.S.

Dose limits for off-site exposures. The choice of 0.25 mSv (25 mrem) as the limit on annual dose equivalent averaged over a lifetime for off-site individuals is based primarily on the judgment by the NRC that this level of protection is reasonably achievable for low-level waste disposal, given the current state of disposal technology and its associated costs,[9] and on the view of the EPA that this dose limit should be encompassed by any standard that the EPA might develop.[9] Thus, the development of new low-level waste disposal facilities on the Oak Ridge Reservation would conform to generally applicable standards for this practice that have been established by Federal regulatory authorities. A limit on annual dose equivalent of 0.25 mSv (25 mrem) for off-site exposures also has been adopted by the DOE as an interim performance objective in planning for new low-level waste disposal facilities.[42]

On the basis of an assumed risk factor from radiation exposure of 2×10^{-2} per Sv (2×10^{-4} per rem),[4] continuous exposure over a 70-year lifetime at an average rate of 0.25 mSv (25 mrem) per year corresponds to a lifetime risk of 3.5×10^{-4}. This risk is about one-fourth of the estimated lifetime risk due to natural background radiation and is about 600 times less than the current lifetime risk of fatal cancers in the U.S. population.[59] However, continuous exposures over a lifetime at the dose limit are highly unlikely for a disposal facility that meets the performance objectives on dose to an off-site individual and application of the ALARA principle.

Dose limits for inadvertent intruders. The use of higher dose limits for inadvertent intruders than for off-site individuals is consistent with NRC standards for low-level waste disposal.[9] Higher doses to inadvertent intruders can be justified on the grounds that relatively few individuals are likely to intrude onto the site, so that intruder exposures will have little effect on population dose, and the postulated exposure scenarios

for inadvertent intruders will not necessarily occur with unit probability at any time after loss of institutional controls. The choice of 1 mSv (0.1 rem) as a limit on annual dose equivalent averaged over a lifetime for inadvertent intruders is based on recent recommendations and proposals for prolonged exposures to all sources by the ICRP,[4,10] the NCRP,[11] and the DOE.[7] The higher limit of 5 mSv (0.5 rem) for any year of exposure is based on current radiation protection standards[6,7] and recent recommendations and proposals of various agencies.[4,7,8,10,11] The dose limit for any year of exposure also conforms to the limit for inadvertent intruders that is implicit in the NRC's low-level waste standards.[9]

Continuous exposure over a 70-year lifetime at an average rate of 1 mSv (0.1 rem) per year corresponds to a lifetime risk of 1.4×10^{-3}. Again, however, for a disposal facility that meets the performance objectives for dose to an inadvertent intruder, it is highly unlikely that any individuals would experience a lifetime risk as large as this.

Use of committed effective dose equivalents averaged over a lifetime. As described in Sections 2-4, the specification of dose limits to individuals in terms of committed effective dose equivalents averaged over a lifetime does not conform to current radiation protection practice in the U.S. However, we have shown that this approach has two important advantages compared with the customary practice of expressing standards in terms of limits on doses received to whole body or the critical organ for each year of exposure. First, the dose limits are more closely related to the fundamental goal of limiting risk from a lifetime's exposure. Second, acceptable intakes of a radionuclide by adults are constant with time, and knowledge of prior intakes in estimating acceptable intakes at present and future times is not required.

5.2 Consideration of Limits on Risk as Performance Objectives for Protection of Individuals

5.2.1 *Difficulties with dose limits as performance objectives*

The performance objectives for low-level waste disposal presented in this report use limits on radiation dose to provide protection of exposed individuals. As discussed in Section 2.3, limits on dose are used as a surrogate for limits on risk, since it is risk limitation that is the fundamental goal of radiation standards. As shown in Sections 3 and 4, the use of limits on dose to provide limits on risk is a common practice in radiation standards, including the NRC's standards for low-level waste disposal.[9]

A limit on dose is an appropriate representation of a limit on risk only for processes and events that have a probability near unity of leading to human exposures, because risk is the product of the probability of receiving a dose and the probability that a dose received will give rise to deleterious health effects. Thus, dose limits are most appropriate for limiting routine releases from controlled sources, such as nuclear power reactors.

For uncontrolled sources, such as a low-level waste disposal facility after loss of active institutional controls, human exposures may result from processes and events whose probabilities vary with time and are much less than unity. However, when the performance objectives for such practices involve limits on dose, there is no need to evaluate probabilities over time for processes and events that lead to human exposures. Therefore, dose assessments for low-level waste disposal often involve deterministic calculations with conservative assumptions for the performance of the disposal system that maximize estimated doses, e.g., complete failure of the disposal system followed by rapid mobilization of the wastes in environmental media at a particular time after loss of institutional controls and the occurrence of intruder exposures according to postulated scenarios with probability of unity at any time after loss of institutional controls.[1,3] While this type of analysis probably leads to estimates of dose and risk to individuals that far exceed any values that actually would be experienced, the calculations also may be so unrealistic as to result in restrictions on siting and design of the disposal facility and on waste acceptance criteria that are not directly related to protection of health and safety. Unrealistic assumptions in performance assessments also can lead to unreasonable conclusions in applying the ALARA principle to optimization of population exposures. Furthermore, a deterministic analysis provides no information on uncertainties in the calculation or on the extent of overprediction of dose and risk.

Some of the difficulties in interpreting the results of deterministic calculations can be addressed by means of a probabilistic dose analysis, which attempts to take into account uncertainties (i.e., probability distribution functions) in model parameter values to generate probability distributions of dose to off-site individuals or inadvertent intruders. For expected processes and events, such calculations thus give estimates of the probability that any dose will be exceeded. However, probabilities for processes and events that lead to human exposures (e.g., probabilities for inadvertent intrusion or disruptive natural processes) still are not taken into account. Furthermore, it may be difficult to decide whether a disposal system is in compliance with a dose limit when the distribution of estimated doses overlaps the limit to any significant extent; i.e., one

must decide what fraction of the probability distribution of dose could lie above the dose limit and still be in compliance with the standard.

5.2.2 *Alternative performance objectives based directly on risk*

As described in Sections 4.10 and 4.11, the ICRP and the NEA have addressed problems associated with the use of dose limits for low-level waste disposal by recommending that the performance objectives for protection of individuals be expressed directly in terms of limits on risk.[16,17] The advantage of this approach is that all processes and events that lead to human exposures would be treated on the same basis, regardless of their probabilities of occurrence over time, and the performance objectives would be directly related to risk limitation.

A possible disadvantage with performance objectives expressed as limits on risk is that processes or events with low probability will be associated with acceptable doses that are quite high. For example, with the limit on annual risk for exposures of limited duration of 5×10^{-5} recommended by the NEA,[17] exposures with probability less than 0.01 would correspond to acceptable annual dose equivalents greater than 0.5 Sv (50 rem), which would exceed the threshold for nonstochastic radiation effects in some organs or tissues.[4] Thus, the performance objectives also might need to specify that doses above a certain level be reasonably precluded by means of siting, design, or waste acceptance criteria.

An alternative approach to performance objectives that are expressed as limits on dose but also take probabilities of processes and events into account would be to specify several dose limits that increase as the estimated probability of receiving the dose decreases.[60] Thus, for example, one could specify that the annual committed effective dose equivalent averaged over a lifetime for an inadvertent intruder shall (1) be expected to be less than 1 mSv (0.1 rem), (2) be quite unlikely to be more than 5 mSv (0.5 rem), and (3) not exceed 50 mSv (5 rem) in any credible circumstances. In this approach, the dose limits are a step function of the probability that the dose will be received, whereas, in performance objectives that are expressed in terms of risk itself, the implicit dose limits are inversely proportional to probability. One then must decide what probabilities correspond to the expressions "quite unlikely" and "in any credible circumstances." While the interpretation of these expressions as quantitative probabilities may seem quite subjective, this subjectivity may reflect properly the uncertainties in estimating probabilities of disruptive events and processes that could lead to human exposures.

5.2.3 *Choice of dose limits as performance objectives*

In spite of the attractiveness of using limits on risk as performance objectives for low-level waste disposal, there are several considerations that have led to the use of dose limits in this report.

[1] The use of limits on dose is consistent with conventional radiation protection practice in the U.S., including the NRC's standards for low-level waste disposal.[9] There is no prior experience in the U.S. with demonstrating compliance for licensing purposes with performance objectives expressed directly in terms of limits on risk.

[2] The concept of risk as the product of a probability that a dose is received by an individual and the probability of a health effect resulting from that dose is poorly understood by the public. Particularly for exposures of high consequence that are predicted to occur with relatively low probability, the public will tend to focus on the high dose and ignore the probability of occurrence, and such events may be regarded as unacceptable even though they correspond to an acceptable level of risk.

[3] Estimates of probabilities of processes and events that lead to human exposures may be quite contentious and difficult to defend, e.g., estimates of probabilities for inadvertent human intrusion. All estimates of probabilities will involve a high degree of subjective scientific judgment that will be difficult to quantify, and it may be difficult to gain acceptance for these estimates in licensing.

Thus, we conclude that it is reasonable to express performance objectives for low-level waste disposal in terms of limits on dose to off-site individuals and inadvertent intruders and to focus on expected processes and events in evaluating compliance with the dose limits. However, there is a need to use reasonably realistic models and parameter values in demonstrations of compliance, and to develop defensible technical data to support the calculations. Unexpected processes and events then can be taken into account by means of siting, design, and waste acceptance criteria; i.e., such criteria reasonably can be used to preclude doses that would exceed the dose limits but that would occur with low probability. Subjective scientific judgments and qualitative findings of "reasonable assurance" will play an important role in the process of demonstrating compliance with the performance objectives, but no more so

than in the case of performance objectives expressed directly in terms of limits on risk.

5.3 Consideration of Chemical Toxicity of Uranium in Establishing Limits on Intake

5.3.1 *Recommended limits on kidney burden of uranium*

A large body of data in animals and humans clearly has established the chemical toxicity of uranium in the kidney (e.g., see ref. 18 and references therein). It then is important to investigate whether limits on intake of uranium that are derived from limits on radiation dose would be sufficiently low to prevent chemical toxicity in the kidney. If this is not the case, then separate considerations of limits on intake based on chemical toxicity are needed. Of the radionuclides that are expected to occur in substantial quantities in low-level wastes on the Oak Ridge Reservation,[1,3] uranium apparently is the only one for which consideration of chemical toxicity is needed.

The chemical toxicity of uranium long has been of concern in establishing protection criteria for occupational and environmental exposures. In ICRP Publication 6, maximum permissible concentrations for soluble compounds of ^{238}U, ^{235}U, and natural uranium in air and water for limiting occupational exposures were based on preventing chemical toxicity in the kidney, not on limiting radiation dose to bone.[61] The maximum permissible concentrations in air and water were based on an assumed threshold concentration for nonstochastic chemical effects of 3 μg of uranium per gram of kidney. The more recent calculations of limits on intakes of uranium by workers in ICRP Publication 30 were based not on consideration of chemical toxicity in the kidney but on a limit on committed effective dose equivalent.[19] However, the ICRP acknowledged that chemical effects of uranium may present the greater risk.

As described in Sections 3.3.1 and 3.3.2, it has been standard practice in radiation protection to set limits on exposures of the public at one-tenth of the limits for workers.[4,36] This practice also has been recommended for protection of the public from the chemical effects of uranium, so a recommended limit on uranium concentration in the kidney for members of the public was 0.3 μg/g.[62]

A recent review by Wrenn *et al.* of the metabolism and dosimetry of uranium for application to drinking water standards for the public again has led to the recommendation that intakes of natural uranium in water be limited by consideration of chemical toxicity in the kidney, not radiation dose to bone.[18] The primary reason for this recommendation remains the

fact that chemical toxicity has been observed in man and quantified in animals, whereas a hypothetical radiological toxicity for uranium in skeletal tissues has not been observed in either man or animals. Wrenn *et al.* adopted a threshold concentration for uranium toxicity in the kidney of 1 $\mu g/g$,[18] which is a factor of 3 less than the value assumed by the ICRP.[61] An additional safety factor of 50 then was applied to exposures of average individuals in the public to ensure that permanent kidney damage would be unlikely. Thus, the suggested limit on uranium concentration in the kidney for average individuals in the public was 0.02 $\mu g/g$.[18] This value is a factor of 15 less than the previous recommendation for maximally exposed individuals in the public cited above,[62] and is about 45 times higher than the average background level of uranium in the kidney of an adult of 4.4×10^{-4} $\mu g/g$.[18]

5.3.2 *Correspondence between kidney burden and radiation dose*

Given knowledge of the chemical toxicity of uranium in the kidney, the question then is whether the limits on radiation dose for off-site individuals and inadvertent intruders developed in this report also would provide adequate protection against chemical effects if the radiation dose were due entirely to ingestion of uranium. We address this question by means of calculations of the annual effective dose equivalent and uranium concentration in the kidney that would result from chronic ingestion of uranium at a constant rate by an adult; at steady state, the effective dose equivalent from the given intake is equal to the committed effective dose equivalent. The limiting case (i.e., the largest kidney burden per unit effective dose equivalent) occurs for intakes of ^{238}U, which has the lowest specific activity of any uranium isotope. We also perform calculations for natural uranium, which essentially contains ^{238}U and ^{234}U in secular equilibrium. Results for ^{235}U are not presented, but the kidney burden per unit effective dose equivalent for this isotope is intermediate between the values for ^{238}U and natural uranium.

For a chronic ingestion intake of uranium, the amount of uranium that resides in any organ or tissue at steady state is proportional to the fraction of ingested uranium that is absorbed into blood from the GI tract, the fraction of absorbed uranium that is deposited in the particular organ, and the biological half-time for retention of uranium in that organ.[18,19] Thus, for a given kidney burden, the corresponding intake rate depends on the assumed GI-tract absorption and metabolic parameters for uranium in the kidney. Similarly, the annual effective dose equivalent for a given intake rate depends on the GI-tract absorption and metabolic parameters for several organs and tissues.[4] For uranium,

the most important contributors to the effective dose equivalent from ingestion are the dose equivalents to bone and the kidney.[63]

For chronic ingestion intakes, we have calculated the annual effective dose equivalent vs uranium concentration in the kidney at steady state for ^{238}U or natural uranium using two different sets of parameter values for GI-tract absorption and organ metabolism. The first set of results shown in Fig. 6 is based on the parameters recommended by the ICRP,[19] which were developed for application to occupational exposures. The second set of results shown in Fig. 7 is based on a model that was developed by Wrenn *et al.* explicitly for application to low levels of uranium in the environment.[18]

At steady state, the kidney burden per unit intake rate of uranium is about a factor of 3 higher with the ICRP model, due primarily to the difference of nearly a factor of 4 in GI-tract absorption used in the two models.[18,19] However, the annual effective dose equivalents per unit intake of ^{238}U or natural uranium at steady state are only about 20% higher with the ICRP model, because the higher GI-tract absorption in this model is largely compensated by the smaller (by a factor of about 5) biological half-time for retention in bone, and the dose equivalent to bone is the largest contributor to the effective dose equivalent. Thus, the annual effective dose equivalent from ingestion for a given kidney burden of ^{238}U or natural uranium is about a factor of 3 less with the ICRP model[19] in Fig. 6 than with the model of Wrenn *et al.*[18] in Fig. 7.

Estimated effective dose equivalents for selected concentrations of uranium in the kidney at steady state obtained from the two models are given in Table 2. As described in Section 5.3.1, the two largest concentrations in the table are the assumed thresholds for chemical toxicity that were adopted by the ICRP[61] and Wrenn *et al.*,[18] respectively. The two intermediate values then reflect the recommendation that limits on kidney burden for maximally exposed individuals in the public should be a factor of 10 below the assumed threshold.[62] The smallest value corresponds to the recent suggestion of Wrenn *et al.* for limiting ingestion of uranium in drinking water by average individuals in the public that includes an extra safety factor.[18]

5.3.3 *Implications of chemical toxicity for performance objectives*

The results in Figs. 6 and 7 and in Table 2 suggest that if exposure to uranium occurs via ingestion only and if the limit on uranium concentration in the kidney is set at the low end of the range of values that have been discussed in the literature,[18,61,62] then the performance objectives for radiation dose developed in this report would not ensure

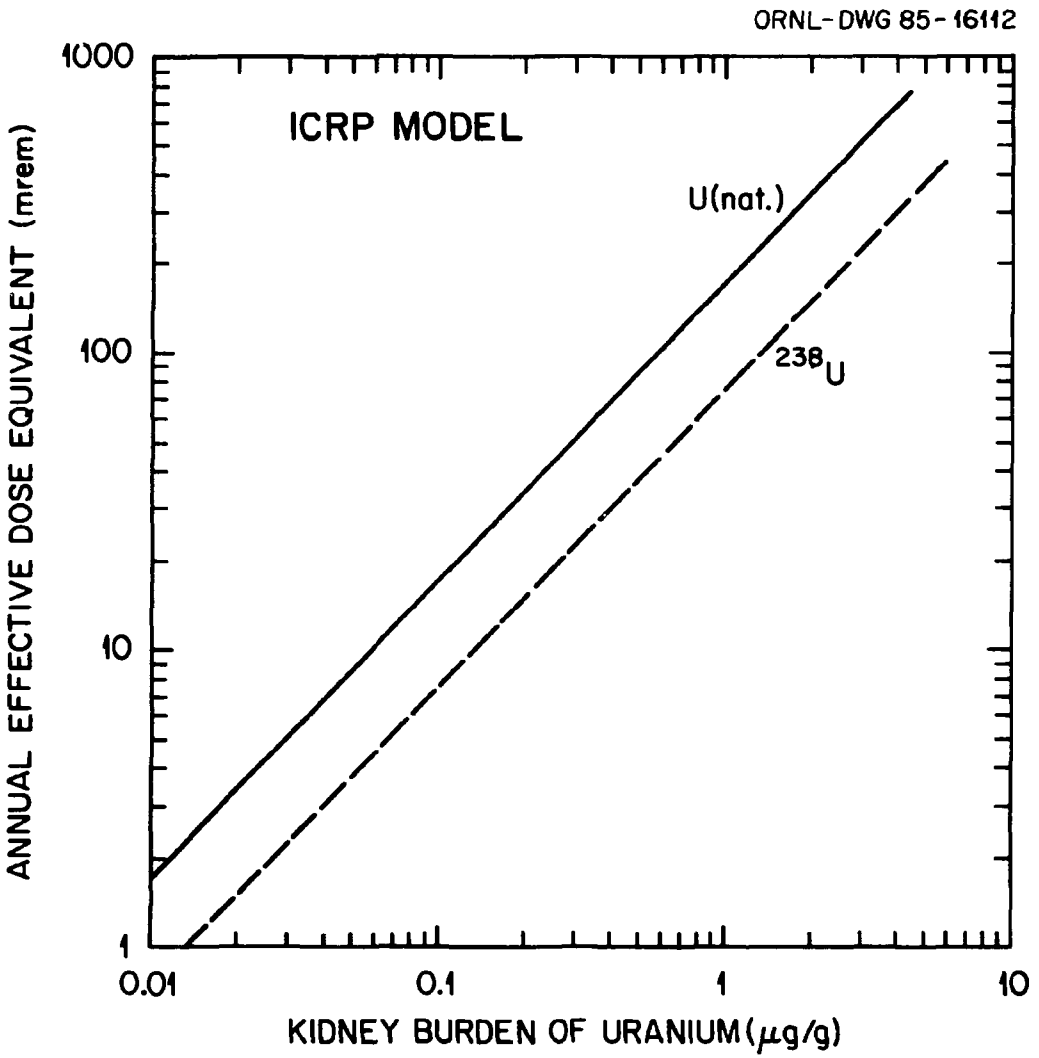

Fig. 6. Annual effective dose equivalent from ingestion vs concentration in the kidney at steady state for ^{238}U and natural uranium based on the models and parameter values in Publication 30 of the ICRP.[19]

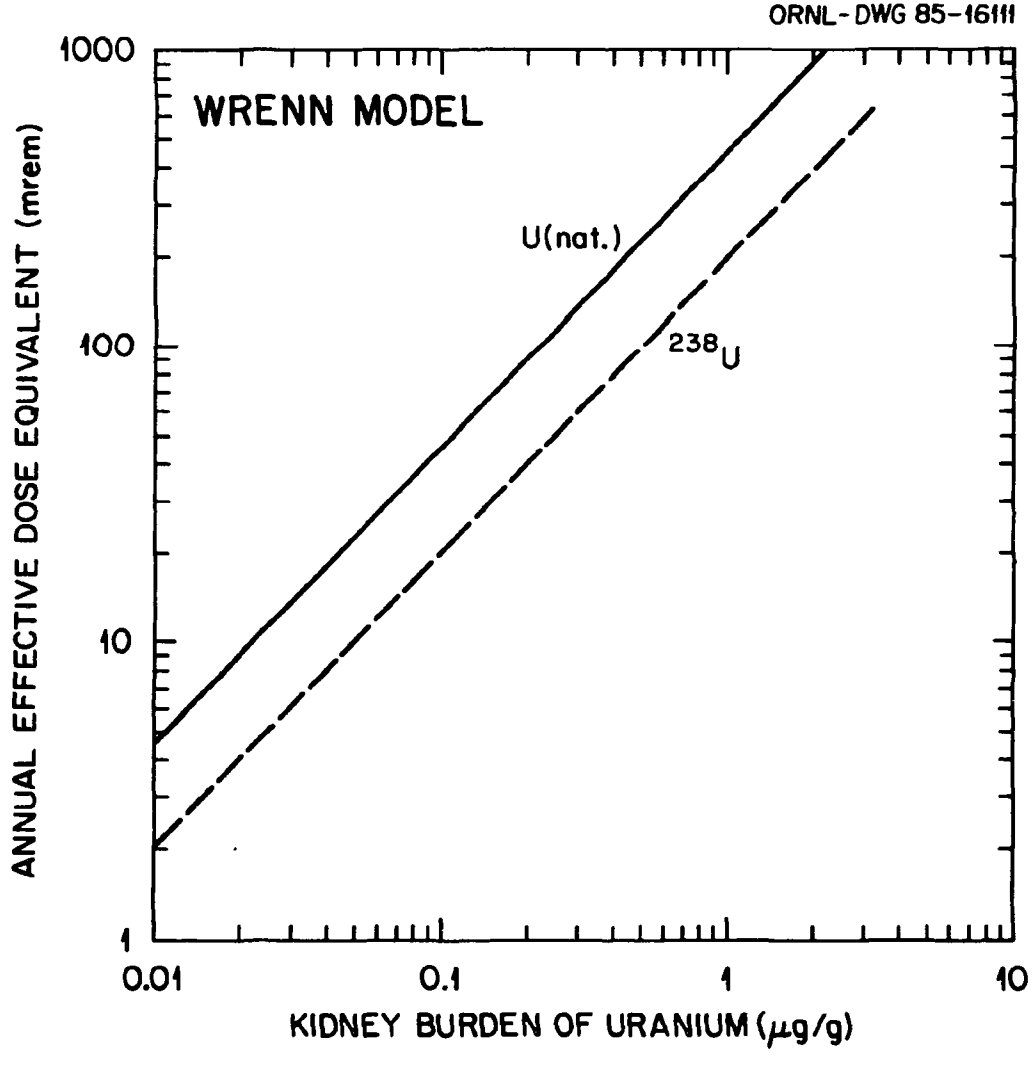

Fig. 7. Annual effective dose equivalent from ingestion vs concentration in the kidney at steady state for ^{238}U and natural uranium based on the models and parameter values of Wrenn *et al.*[18]

Table 2. Annual effective dose equivalents from ingestion of ^{238}U and natural uranium corresponding to different limits on uranium concentration in the kidney at steady state

Uranium concentration in the kidney ($\mu g/g$)	Annual effective dose equivalent (mrem)			
	ICRP model[a]		Wrenn model[b]	
	^{238}U	U(nat.)	^{238}U	U(nat.)
3	235	510	600	1400
1	75	170	200	460
0.3	23	50	60	140
0.1	7.5	17	20	46
0.02	1.5	3	4	9

[a]Model from ref. 19.

[b]Model from ref. 18.

that the limit on uranium concentration in the kidney would be met. For example, the limit on annual committed effective dose equivalent averaged over a lifetime of 25 mrem (0.25 mSv) for off-site individuals would correspond to concentrations of ^{238}U or natural uranium in the kidney at steady state that exceed the suggested limit for average individuals[18] of 0.02 $\mu g/g$ by a factor of 3-17, depending upon the mixture of uranium isotopes and the metabolic model selected, and the dose limit for inadvertent intruders could further increase the kidney burden by a factor of 4.

In evaluating these results, however, it is important to note first that the concentration limit for uranium in the kidney of 0.02 $\mu g/g$ recommended by Wrenn *et al.* is intended for application to average individuals in large population groups,[18] rather than to maximally exposed individuals to whom the dose limits apply. As indicated in Sections 3.2 and 3.4.1, it has been standard practice in radiation protection to set acceptable levels of dose for average individuals at one-third of the values for maximally exposed individuals. If this practice were adopted for chemical effects, then the limit on uranium concentration in the kidney for maximally exposed individuals corresponding to the recommendation of Wrenn *et al.*[18] would be 0.06 $\mu g/g$, and an annual effective dose equivalent of 25 mrem (0.25 mSv) would correspond to uranium concentrations in the kidney that exceed the limit by a factor of

6 or less. Second, if the drinking water pathway is the most important for uranium, then the limit on solubility of uranium in water[3] may limit annual effective dose equivalents to values less than 25 mrem (0.25 mSv) and, thus, may reduce kidney burdens correspondingly. Finally, exposures of inadvertent intruders to uranium are expected to be determined primarily by external photon irradiation and inhalation, so the kidney burden per unit effective dose equivalent for an inadvertent intruder would be much less than values based on ingestion intakes only.[20,21]

For illustrative purposes only, we consider the implications of one set of assumptions for establishing performance objectives for exposures to environmental uranium. We assume that the threshold concentration for chemical toxicity in the kidney is 1 μg/g,[18] and we assume that the model of Wrenn *et al.*[18] describes GI-tract absorption and organ metabolism for ingested uranium. We further assume that a safety factor of 10 below the threshold concentration is appropriate for maximally exposed individuals in the public, so the concentration limit for off-site individuals becomes 0.1 μg/g. From Table 2, a limit on annual effective dose equivalent of 25 mrem (0.25 mSv) for off-site individuals corresponds to a kidney concentration for natural uranium of about a factor of 2 less than the limit of 0.1 μg/g, so the dose limit would provide adequate protection from chemical toxicity in this case. For ^{238}U, the dose limit for off-site individuals corresponds to a kidney concentration that exceeds the limit of 0.1 μg/g, but only by about 25%. However, uranium wastes containing ^{238}U always will contain admixtures of the higher specific-activity isotopes ^{234}U and ^{235}U, so the kidney concentration per unit effective dose equivalent always will be less than the value for ^{238}U alone. Finally, we assume that a smaller safety factor of 2 below the threshold concentration is appropriate for exposures of the few inadvertent intruders, which gives a concentration limit in this case of 0.5 μg/g. From Fig. 7, the limit on annual effective dose equivalent of 0.1 rem (1 mSv) for inadvertent intruders corresponds to kidney concentrations for ^{238}U and natural uranium that are below the concentration limit, even if ingestion is the only exposure pathway. We have previously noted that ingestion of uranium is expected to be relatively unimportant for inadvertent intruders,[20,21] so the dose limit for inadvertent intruders should provide kidney concentrations of uranium that are much less than those indicated in Fig. 7.

There are several difficulties with establishing performance objectives for exposures to environmental uranium that are directed explicitly at prevention of chemical toxicity in the kidney. In addition to uncertainty over the value of the threshold concentration for chemical effects in adults, the following factors are not well established: (1) the threshold concentration for chemical toxicity in infants and

children; (2) the GI-tract absorption, organ metabolism, and radiation dosimetry of ingested uranium in infants and children (but see ref. 28 for recent calculations); (3) the appropriate margin of safety below the threshold concentration for maximally exposed and average individuals in the public; and (4) the extent to which a relatively few inadvertent intruders could be allowed higher kidney burdens than off-site individuals. On this basis alone, it may be inappropriate to establish performance objectives for intakes of uranium that would be more stringent than those for radiation dose presented in this report.

In summary, an analysis presented in this section suggests that it probably is not necessary to establish separate performance objectives for exposures of the public to uranium for the purpose of preventing chemical toxicity in the kidney. The radiation dose limits presented in this report appear to correspond to uranium concentrations in the kidney that are sufficiently far below established thresholds for chemical effects as to provide an adequate margin of safety, even if the dose is due only to ingestion of uranium. Additional reductions in expected kidney burdens of uranium in exposed individuals would result from the fact that the dose limits apply to all radionuclides in the disposal facility, and that exposures of inadvertent intruders to uranium are expected to occur primarily by pathways other than ingestion.

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