*Competency 2.8* **Radiation protection personnel shall demonstrate a working level knowledge of national and international radiation protection standards and recommendations.**

## 1. SUPPORTING KNOWLEDGE AND /OR SKILLS

a. Discuss the content and application of the following national and international documents on radiation protection:

- Radiation Protection Guidance to the Federal Agencies for Occupational Exposure (52 FR 2822)
- Recommendations of the International Commission on Radiological Protection (ICRP), Publication 26
- Recommendations of the International Commission on Radiological Protection (ICRP), Publication 30
- 1990 Recommendations of the International Commission of Radiological Protection (ICRP), Publication 60
- BEIR V Executive Summary
- Recommendations on Limits for Exposure to Ionizing Radiation, National Council on Radiological Protection, Report No. 91
- Limitation of Exposure to Ionizing Radiation, National Council on Radiation Protection, Report No. 116
- Practices for Respiratory Protection, American National Standards Institute (ANSI Z88.2-1992)

b. Discuss how the above documents relate to Department of Energy (DOE) radiation protection requirements.

## 2. SUMMARY

***Radiation Protection Guidance to the Federal Agencies for Occupational Exposure,* Jan. 27, 1987 (52 FR 2822)**

This Jan. 27, 1987 document largely involves the dose limitation and assessment philosophies endorsed by ICRP Publication 26 in 1977. In this document, the President approves recommendations that updates previous guidance to Federal agencies for the protection of workers exposed to ionizing radiation. These recommendations were developed cooperatively by the Nuclear Regulatory Commission (NRC), the Occupational Safety and Health Administration (OSHA), the Mine Safety and Health Administration (MSHA), the Department of Defense (DoD), the Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), the Department of Commerce (DOC), the Department of Transportation (DOT), the Department of Health and Human Services (DHHS), and the Environmental Protection Agency (EPA). In addition, the National Council on Radiation Protection and Measurements (NCRP), the National Academy of Sciences (NAS), the Conference of Radiation Control Program Directors (CRCPD) of the states, and the Health Physics Society were consulted during the development of this guidance.

Executive Order 10831, the Atomic Energy Act, as amended, and Reorganization Plan No. 3 of 1970 charge the administrator of the Environmental Protection Agency (EPA) to "...advise the President with respect to radiation matters, directly or indirectly affecting health, including guidance for all Federal agencies in the formulation of radiation standards and in the establishment and execution of programs of cooperation with States." This guidance has historically taken the form of qualitative and quantitative "Federal Radiation Protection Guidance." The recommendations transmitted here replaced those portions of previous Federal guidance (25 FR 4402), approved by President Eisenhower on May 13, 1960, that apply to the protection of workers exposed to ionizing radiation. The portions of the guidance that apply to exposure of the general public did not be change by these recommendations. These approved recommendations then became the basis for new and amended Federal regulations on radiological protection.

These recommendations are based on consideration of current scientific understanding of effects on health from ionizing radiation, recommendations of international and national organizations involved in radiation protection; proposed 46 FR 7836, *Federal Radiation Protection Guidance for Occupational Exposure*, published on Jan. 23, 1981; public comments on that proposed guidance; and the collective experience of the Federal agencies in the control of occupational exposure to ionizing radiation. Public comments on the previously proposed guidance and a response to those comments are contained in EPA 520/1-84-011, *Federal Radiation Protection Guidance for Occupational Exposure -- Response to Comments.*

***Recommendations of the International Commission on Radiological Protection* (ICRP), Publication 26, and *Recommendations of the International Commission on Radiological Protection*, Publication 30**

ICRP 26 was adopted on Jan. 17, 1977. The document superseded ICRP 9 of the same title, which had been adopted in 1966. Although some of the concepts of ICRP 26 were superseded in 1990 by ICRP 60, it is the philosophy of 26 and 30 that are used to establish the dose limits of 10 CFR 835, *Occupational Radiation Protection*.

Prior to the adoption of ICRP 26, occupational exposure limits were expressed in terms of dose equivalent received by organs and tissues of the body in any period of 13 weeks, with an additional restriction on the accumulation of dose, with age, for the gonads, blood-forming organs, and lens of the eye. Individual exposure was limited by the dose equivalent in the critical organ for which the ratio of dose received to the dose limit was greatest.

In Publication 26, The ICRP defines the objective of radiation protection as:

> "The protection of individuals, their progeny, and mankind as a whole, while still allowing necessary activities from which radiation exposure might result."

In support of the realization of this objective, the aim of radiation protection should be to prevent detrimental nonstochastic effects and to limit the probability of stochastic effects to levels deemed to be acceptable. An additional aim is to ensure that practices involving radiation exposure are justified. Thus, for stochastic effects, all exposures should be kept as low as reasonably achievable (ALARA). Stochastic effects are those effects for which the probability of an effect occurring, rather than its severity, is regarded as a function of dose, without threshold. Carcinogenesis (cancer) is the predominant stochastic risk considered when setting dose limits. Nonstochastic effects are effects for which the severity of the effect varies with the dose, and for which a threshold may therefore exist. Typical nonstochastic effects include cataracts to the lens of eye (lens opacification), nonmalignant skin damage, cell depletion in bone marrow causing blood deficiencies, and gonadal cell deformities leading to impairment of fertility, and, for large exposures, acute effects of nausea and vomiting, fatigue, increased temperatures and blood changes. Limits for nonstochastic effects should be set below the threshold dose for the tissue at risk, even for exposure for the whole of a lifetime or for the total working life.

The application of the dose limitation and calculation philosophy of Publication 26 requires an understanding of several basic concepts:

- Detriment
- Dose Equivalent
- Quality Factor
- Committed Dose Equivalent

Detriment (G) is defined as the mathematical "expectation" of the harm incurred from an exposure to radiation, taking into account not only the probability of each type of deleterious effect, but also the severity of the effect. These include effects on health and other effects. It is sometimes convenient to deal separately with effects, or potential effects, on health. These effects then represent a detriment to health, and are characterized by the following relationship:

$$G = P \Sigma_i p_i g_i$$

where:

G = the detriment to health
P = number of persons
$p_i$ = the probability of suffering the effect I
$g_i$ = the weighting factor for the severity of effect I

Dose Equivalent is used by the ICRP to correlate the deleterious effects of radiation exposure, particularly with delayed stochastic effects. Use of this quantity is convenient for radiation protection because the unit absorbed dose (D) is insufficient by itself to predict either the severity or the probability of deleterious effects on health resulting from irradiation. Dose equivalent is defined by the following relationship:

$$H = DQN$$

where:

H = the dose equivalent at a point in tissue
D = the absorbed dose
Q = the quality factor
N = the product of all other modifying factors

Such modifying factors, for example, may take into account the absorbed dose rate and fractionation of dose.

The SI name for the unit of dose equivalent is the sievert (Sv) where:

$$1 \text{ Sv} = 1 \text{ J kg}^{-1}$$
$$= 100 \text{ rem}$$

The quality factor (Q) is intended to allow for the effect on the detriment of the microscopic distribution of energy. It is defined as a function of the collision stopping power ($L_\infty$) in water at the point of interest. Interpolated values of E as a function of L can be obtained from Figure 1, and are based upon the values shown in Table 1.

Figure 1

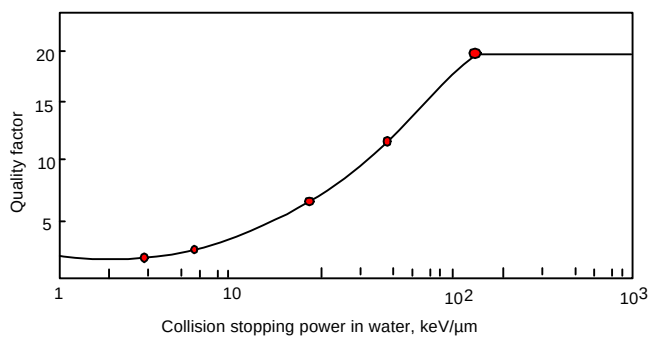



Table 1

$L_\infty$ - $Q$ RELATIONSHIP

| $L_\infty$ in water (keV/$\mu$m) | Q |
|---|---|
| 3.5 (and less) | 1 |
| 7 | 2 |
| 23 | 5 |
| 53 | 10 |
| 175 (and above) | 20 |

According to the International Commission on Radiological Units and Measurements (ICRU), in Supplement to ICRU Report 19, an effective value of Q for a spectrum of radiation can be calculated at the point of interest. When the distribution of radiation in $L_\infty$ is not known at all points in the volume of interest, the ICRP allows the use of approximate values of Q related to the various types of primary radiation. These values are shown in Table 2. In the case of thermal neutrons, the $L_\infty$ is uniquely defined, and an effectiveness value of Q at the point of interest may be taken from the tables and diagrams in ICRP 21, that present the effectiveness value as a function of neutron energy, giving Q = 2.3 for thermal neutrons.

Table 2

Approximate Values of Q for Various Types of Radiation

| **Radiation Type** | **Q Value** |
|---|---|
| X-rays, gamma rays and electrons | 1 |
| Neutrons, protons, and singly-charged particles of rest mass greater than one atomic mass unit of unknown energy | 10 |
| Alpha particles and multiply-charged particles (and particles of unknown charge), of unknown energy | 20 |

Another quantity used in Publication 26 is the committed dose equivalent (CDE), $H_{50}$, to a given organ or tissue from a single intake of radioactive material into the body. CDE is the dose equivalent that will be accumulated over 50 years (representing an occupational working life) following the intake, and is defined by the following integration:

$$H_{50} = \int_{t_o}^{t_o + 50} H(t)\, d(t)$$

where:

$H_{50}$ = committed dose equivalent
$H(t)$ = dose equivalent rate
$t_o$ = time that intake occured
$d(t)$ = elapsed time from $t_o$

Tissues at Risk

Previous to ICRP 26, the ICRP 2 stated that when more than one organ of the body is exposed, the irradiation of one particular organ or tissue is likely to be of greatest importance because of the dose it receives, its sensitivity to radiation, or the importance to health of any damage that results. This tissue or organ was referred to as the critical organ, and dose limitation for the individual and was determined by the dose-equivalent limit for that tissue or organ. This method did not permit the summation of detriment according to the relative radiosensitivities of the irradiated tissues.

The ICRP 26 provided a method for estimating the total risk from an uneven distribution of the dose in the human body. By weighting the dose to individual organs/tissues according to their susceptibility to ionizing radiation, it is possible to sum these weighted doses to obtain a total risk that is equivalent to that risk if the entire body had been irradiated uniformly at that dose equivalent. The sum of the weighted doses is compared to the dose equivalent limit, at present 5 rem/year. The different susceptibilities of different tissues lead to the following weighting factors:

Tissue Weighting Factors

| Tissue | $w_T$ |
|---|---|
| Gonads | 0.25 |
| Breast | 0.15 |
| Red Bone Marrow | 0.12 |
| Lung | 0.12 |
| Thyroid | 0.03 |
| Bone Surfaces | 0.03 |
| Remainder* | 0.30 |

* The value of $w_T$ = 0.06 is applicable to each of the five organs or tissues of the remainder receiving the highest dose equivalents.

The ICRP 26 recommends a procedure which takes into account the risk attributable to the exposure of all tissues irradiated. The procedure is quantified by the inequality:

$$\sum_T w_T H_T \leq H_{wb,\,L}$$

where:

$w_T$ = a weighting factor representing the proportion of the stochastic risk resulting from tissue (T) to the total risk, when the whole body is irradiated uniformly

$H_T$ = the annual dose equivalent in tissue (T)

$H_{wb,\,L}$ = the recommended annual dose-equivalent limit for uniform irradiation of the whole body, namely 50 mSv (5 rem)

A number of organs and tissues must be specified because of their susceptibility to radiation damage, the seriousness of the damage, and the extent to which this damage could be treatable. A single dose equivalent limit is assigned to each organ or tissue based upon average risk levels for each. The respective risk levels are based upon the estimated likelihood of inducing fatal malignant disease, nonstochastic changes, or substantial genetic defects expressed in live-born descendants. The organs and tissues are described in terms of these considerations in

Tables 3 through 11.

| Table 3, Tissue at Risk: Gonads | |
|---|---|
| Deleterious effects of radiation | Tumor induction<br>Impairment of fertility<br>Hereditary effects |
| Sensitivity to induction of cancer by irradiation | Low |
| Impairment of fertility | In females, sensitivity increases with age<br>In males, low sensitivity, due to repopulation of spermatozoa |
| Risk factor for hereditary ill health within the first two generations following irradiation of either parent | $10^{-2}Sv^{-1}$<br>***Note:*** *The average risk factor is 4 x $10^{-3}$ $Sv^{-1}$ when account is taken of the proportion of exposures likely to be genetically significant due to age distributions* . |

| Table 4, Tissue at Risk: Bone | |
|---|---|
| Deleterious effects of radiation | Bone cancer |
| Radiosensitive cells | Endosteal cells, Epithelial cells on bone surfaces |
| Sensitivity to induction of cancer by irradiation | Low, compared to breast, red bone marrow, lung, and thyroid |
| Risk factor for bone cancer | 5 x $10^{-4}$ $Sv^{-1}$ |

| Table 5, Tissue at Risk: Lung | |
|---|---|
| Deleterious effects of radiation | Lung cancer |
| Radiosensitive cells | Lung lining and pulmonary lymphoid tissue |
| Sensitivity to induction of cancer by irradiation | May be less for particulate deposition than for material uniformly distributed throughout lung |
| Risk factor for lung cancer | 2 x $10^{-3}$ $Sv^{-1}$ |

| Table 6, Tissue at Risk: Thyroid Gland | |
|---|---|
| Deleterious effects of radiation | Thyroid cancer induction, rarely resulting in mortality |
| Radiosensitive cells | Epithelial cells of thyroid follicles |
| Sensitivity to induction of cancer | Higher than that of the red bone marrow to the development of leukemia (but mortality from these thyroid cancers is much lower than for leukemia) |
| Risk factor | $5 \times 10^{-4}$ $Sv^{-1}$ |

| Table 7, Tissue at Risk: Breast | |
|---|---|
| Deleterious effects of radiation | Breast cancer |
| Radiosensitivity cells | Very high for female breast during reproductive life |
| Risk factor | $2.5 \times 10^{-3}$ $Sv^{-1}$ |

| Table 8, All Other Tissues | |
|---|---|
| Deleterious effects of irradiation | Cancer and tumor induction |
| Combined risk factor* | $5 \times 10^{-3}$ $Sv^{-1}$ |

*No single tissue is responsible for more than one-fifth of this value

| Table 9, Tissue at Risk: Lens of Eye | |
|---|---|
| Deleterious effects of irradiation | Lens opacification (a nonstochastic effect) |
| Threshold for lens opacification* | 15 Sv (1,500 rem) |
| Depth of highest radiosensitivity | 3 mm behind surface of eye |

* This dose equivalent is protracted over a working lifetime to derive the recommended ICRP annual limit of 0.3 Sv (30 rem)

where:

| | | |
|---|---|---|
| B | = | the net benefit of a product or an operation involving irradiation |
| V | = | gross benefit |
| P | = | basic production cost excluding the cost of radiation protection * |
| X | = | the cost of achieving a selected level of protection * |
| Y | = | the detriment involved in the operation or in the production, use, and disposal of the product |

* Cost includes social as well as purely economic costs.

From calculus, the optimal benefit is obtained when the slope of the above equation for net benefit is zero, that is when the net benefit is optimized. In making this determination, the cost-benefit analysis shifts from a consideration of the benefit of the activity to the change in benefit that might be involved in requiring the activity to be performed at one level of dose rather than another. The optimum net benefit is obtained if:

$$\frac{dV}{dS} - \left( \frac{dP}{dS} + \frac{dX}{dS} + \frac{dY}{dS} \right) = 0$$

where:

S = collective dose equivalent

Optimization for a program is different from optimization for a specific practice. When a specific practice or task is being considered, the gross benefit and the basic production cost are already determined by the program and will not change mush with modest changes in the collective dose. In this case, dP/dS and dV/dS are sufficiently small that optimization for the proctice occurs (the ALARA condition is met) when the incremental benefit of further dose reduction becomes outweighted by the incremental cost in providing that reduction. So, at a value S, the increase in the cost of protection per unit dose equivalent balances the reduction of detriment per unit dose equivalent, and the optimization condition is fulfilled:

$$\left( \frac{dX}{dS} \right)_{S*} = - \left( \frac{dY}{dS} \right)_{S*}$$

Assessments based upon this relationship are made much easier by assigning a monetary value to the unit of collective dose equivalent. Several estimates of the cost equivalent of a man-sievert (person-rem) have been published, and provide possible quantitative inputs to the decision-making process. ICRP Publication 22 (1973) gives estimates of $10 to 250 per person-rad. In 1975, the USNRC selected $1,000 per avoided person-rem in 10 CFR 50, *Domestic Licensing of Production and Utilization Facilities*, rulemaking. Much of the industry uses a value of $5,000, with some figures as high as $100,000 to $1,000,000 per person-rem. PNL-6577, *Department of Energy Health Physics Manual of Good Practices for Reducing Radiation Exposure to Levels that are As Low As Reasonably Achievable (ALARA)*, uses $1,000 per person-rem in all examples and calculations. ICRP 37 (1983), *Cost-Benefit*

*Analysis in the Optimization of Radiation Protection* deals entirely with calculating optimization.

General Basis for Dose Equivalent Limits

Since almost every exposure of the body involves the irradiation of more than one issue, it is appropriate to recommend a dose equivalent limit based upon the total risk of all tissues irradiated. The ICRP 60 dose limitation system sets a single dose equivalent limit for uniform irradiation of the whole body and implements a subsystem designed to ensure that the total risk from irradiations of parts of the body does not exceed the risk from uniform irradiation of the whole body.

For occupational exposures, it is appropriate to assess the levels of risk associated with the dose equivalent limits. A valid method for judging the acceptability of the level of risk in radiation work is to compare this risk with the risk of other occupations recognized as having high standards of safety. These are considered to be occupations having an average annual mortality of less than $10^{-4}$. Therefore, the calculated rate at which fatal malignancies might be induced by occupational exposure to radiation should not exceed this fatality rate. Recommended occupational dose equivalent limits appear in Table 12. Weighting factors used to calculate compliance with the limit to prevent stochastic effects are shown in Table 13. Table 14 relates risk coefficients from the previous section entitled "Tissues at Risk" to the recommended dose equivalent limits. For applicability to regulations, risks are expressed per rem, rather than per Sievert (Sv).

Table 12
Recommended Dose Equivalent Limits

| | |
|---|---|
| Limit to prevent nonstochastic effects to all tissues except the lens of eye | 0.5 Sv (50 rem) |
| Limit to prevent nonstochastic effects to the lens of eye | 0.3 Sv (30 rem) |
| Limit to prevent stochastic effects | $\sum_T w_T H_T \leq 50\ mSv\ (5rem)$<br>Where:<br>$w_T$ = the tissue weighting factor representing the proportion of stochastic risk resulting from irradiation of tissue (*T*) to the total risk when the whole body is irradiated uniformly<br>$H_T$ = annual dose equivalent in tissue (*T*) |

Table 14
Recommended Dose Equivalent Limits to Individual Organs Based Upon Risk Coefficients

| Organs | Risk Coefficients (effects per organ-rem) | $w_T$ | Organ Dose Equivalent Causing Same Risk as 5 Rems to Whole Body (rems) | Permitted Dose Equivalent Based Upon Exposure of One Organ (rem/yr) |
|---|---|---|---|---|
| Gonads | $4 \times 10^{-5}$ | 0.25 | 20 | 20 |
| Breasts | $2.5 \times 10^{-5}$ | 0.15 | 33.33 | 33.33 |
| Lung | $2 \times 10^{-5}$ | 0.12 | 41.67 | 41.67 |
| Red Bone Marrow | $2 \times 10^{-5}$ | 0.12 | 41.67 | 41.67 |
| Bone | $5 \times 10^{-6}$ | 0.03 | 166.67 | 50 |
| Thyroid Gland | $5 \times 10^{-6}$ | 0.03 | 166.67 | 50 |
| 1st Remainder Organ* | $1 \times 10^{-5}$ | 0.06 | 83.33 | 50 |
| 2nd Remainder Organ | $1 \times 10^{-5}$ | 0.06 | 83.33 | 50 |
| 3rd Remainder Organ | $1 \times 10^{-5}$ | 0.06 | 83.33 | 50 |
| 4th Remainder Organ | $1 \times 10^{-5}$ | 0.06 | 83.33 | 50 |
| 5th Remainder Organ | $1 \times 10^{-5}$ | 0.06 | 83.33 | 50 |
| All | $1.65 \times 10^{-4}$ | 1.0 | | |

* The remainder organs are the five organs that receive, from a given radionuclide, the highest EDE, integrated over 50 years.

## Summation of Internal and External Dose

External exposures are assigned based on the dose equivalent index (i.e., the maximum value of dose equivalent that would occur in a 30 cm sphere [ICRU 25, 1976]). The recommended limit is 50 mSv (5 rem) to prevent stochastic effects.

Internal exposures resulting from the intake of radionuclides are based on annual limits on intake (ALI). These ALIs were calculated by ICRP Committee 2 based upon knowledge of the various organ committed dose equivalents per unit intake. These exposures are subject to limits based on stochastic effects:

$$(\sum_T w_T H_T \leq 50 \ mSv \ [5 \ rem])$$

as well as non-stochastic effects:

$$(H_T \leq 0.5 \text{ Sv } [50 \text{ rem}])$$

When external and internal exposures are received together, the recommended dose limitation will not be exceeded if:

$$\frac{H_I}{H_{wb,\ L}} + \sum_j \frac{I_j}{I_{j,\ L}} \leq 1$$

where:

| | | |
|---|---|---|
| $H_I$ | = | annual dose equivalent index |
| $H_{wb,\ L}$ | = | annual dose equivalent limit |
| $I_j$ | = | annual intake of radionuclide j |
| $I_{j,\ L}$ | = | annual limit of intake for radionuclide j |

Planned Special Exposures

In circumstances during normal operations where it may be necessary to permit a few workers to exceed the recommended dose limits, external exposures or intakes of radioactive material may be permitted provided the dose equivalent commitment does not exceed twice the relevant annual limit in any single event, and five times this limit in a lifetime. These exposures are only justified when alternative techniques are either unavailable or impractical.

Planned special exposures should not be permitted if the worker has previously received abnormal exposure resulting in dose equivalents in excess of five times the relevant annual limit. Any excess over the annual limits should be recorded as a planned special exposure, and should not by itself constitute a reason for excluding a worker from his usual occupation.

Emergency Exposures

Following an abnormal event, decisions will be made about the need for any restriction on the future

employment of those involved in the event. If the dose or the intake exceeds twice the annual limit, the case should be subject to appropriate medical review. The worker may still be allowed to continue routine work if there is no objection from a medical standpoint taking into account previous exposure, health, age, special skills, and social and economic responsibilities. However, the event may have demonstrated individual characteristics indicating unsuitability for further employment in similar work.

Occupational Exposure of Women of Reproductive Capacity

In complying with the annual limit for stochastic effects (50 mSv/5 rem), it is unlikely that any embryo could receive more than 5 mSv (500 mrem) during the first two months of pregnancy. Therefore, the recommended annual limit will provide appropriate protection.

Occupational Exposure of Pregnant Women

It is likely that any pregnancy of more than a two-months duration would be recognized by the woman or her physician. Once pregnancy has been ascertained, it should be ensured that the woman will not exceed three-tenths of the limits for occupational exposure.

Dose Equivalent Limits for Individual Members of the Public

A review of information on risks regularly accepted in everyday life establishes a level of acceptability for fatal risks to the public of an order of magnitude lower than for occupational risks. On this basis, a risk in the range of $10^{-6}$ to $10^{-5}$ per year is likely to be acceptable to any individual member of the public.

Since the total risk of fatality is assumed to be $10^{-2}$ $Sv^{-1}$, the lifetime dose to an individual member of the public that corresponds to a risk of $10^{-5}$ is 1 mSv (.1 rem) per year of lifelong whole-body exposure. However, the ICRP believes that the application of a 5 mSv (.5 rem) limit is likely to result in average dose equivalents less than 0.5 mSv if applied to "critical groups." Critical groups vary depending on factors such as age, size, metabolism, customs, and variations in their environment. When applying the dose-equivalent limit to members of the public, it must be considered that some individuals may belong to more than one critical group.

General Principles of Operational Radiation Protection

The ICRP defines three types of exposure to which its recommendations apply:

- The exposure of individuals in the course of their work
- The exposure of individuals due to medical examination or treatment
- Other exposures

The responsibility for achieving appropriate radiation protection falls upon employers, competent authorities, manufacturers and users of certain products, and, in some cases, the exposed persons. To achieve an appropriate level of radiation protection, the ICRP has defined Protection Standards and the principle of operational optimization.

Protection Standards

The ICRP defines four distinct types of protection standards:

- Basic limits
- Derived limits
- Authorized limits
- Reference levels

Basic limits include dose-equivalent limits and secondary limits. Dose-equivalent limits apply to the dose equivalent, the committed dose equivalent in the organs or tissues of an individual, or the average of one of these quantities over a group of individuals.

Secondary limits apply to external and internal irradiations. In the case of external irradiation of the whole body, the secondary limit applies to the maximum dose equivalent in the body at depths below one cm. Secondary limits for internal exposures are the annual limits on intake (ALI) by inhalation or ingestion.

Derived limits are related to the basic limits by a defined model of the situation and are intended to reflect the basic limits. Examples of derived limits are limits set for quantities such as dose-equivalent rate in a workplace, contamination of air, contamination of surfaces, and contamination of environmental materials. The accuracy of the link between derivation limits and basic limits depends on the realism of the model used in the derivation.

Authorized limits are those limits imposed by the management of an institution and/or competent authorities. These should generally be below derived limits. An authorized limit, when established, should always take precedence over a derived limit.

Reference levels are not limits, but are used to determine a course of action when the value of a quantity

exceeds, or may exceed, its reference level. Actions to be taken may range from recording the information, through investigating causes and consequences, to intervention measures.

Operational Optimization

The process of optimization requires a case-by-case review of situations. In practice, a series of radiation protection strategies is defined. The change in radiation exposure and the differential cost of going from one strategy to the next are then evaluated. Since both variations need to be expressed in comparable terms, calculating optimization poses some difficulty.

Although the ICRP assumes that the relationship between detriment and dose-equivalent is linear, with no threshold, it stresses that this is a cautious assumption; as proportionality factors or risk factors may vary with previously accumulated dose equivalent. However, for practices resulting in small increments of dose equivalent above that corresponding to natural background, the ICRP believes that the additional detriment to health is closely proportional to the CDE.

In practice, the case-by-case optimization of widely used equipment is not appropriate because it would nullify the advantages of standardization and would cause a net social loss. Optimization should, however, play a part in the setting of such standards and specifications.

***1990 Recommendations of the International Commission of Radiological Protection 60***

ICRP 60 was developed based upon the availability of updated information on risk from low dose rate, low linear energy transfer (LET) radiation. The 1990 recommendations supersede those adopted by the ICRP in 1977 with ICRP 26. Although the DOE will evaluate the appropriateness of ICRP 60 for implementation into U.S. Federal radiation protection regulations, it is unlikely that these recommendations will become law during this decade (1990s).

One of the most significant changes between the 1977 and 1990 recommendations are the result of a change in the interpretation of radiation detriment by the ICRP. The detriment of radiation dose under ICRP 26 was based upon cancer mortality in the exposed population and genetic effects in the offspring of the exposed population for two generations. The detriment of radiation dose under ICRP 60 is based upon cancer morbidity (the incidence of carcinogenesis, regardless of mortality) as well as cancer mortality, years of life lost by the exposed population, and genetic effects for all subsequent generations of the exposed population.

The redefinition of detriment in ICRP 60 coupled with updated information on the probability of fatal cancer induction from low dose rate, low LET radiation, has resulted in new values assigned for tissue weighting factors. Table 15 shows a comparison between probabilities of fatal cancer induction, per organ or tissue, in ICRP 26 and 60. In Table 16, these fatality probabilities are added to genetic effects, length of life lost, and cancer morbidity to redefine the relative contribution of organs to the total detriment. The result of the new values, again all based upon the redefinition of detriment, are the new tissue weighting factors that appear in Table 17.

The probability of fatal cancer induction after low dose rate low LET irradiation to the total population, 5/100/Sv, is distributed among the organs as shown in (the table below), second column. The values are compared with those given by ICRP in ICRP 26 for fatal cancer induction in specific sites in the first column.

Table 15
Fatal Cancer Probability Estimates from ICRP Publication 60, as Compared to Publication 26

| Lifetime Mortality in a Population of All Ages from Specific Fatal Cancer After Exposures to Low Doses | | |
|---|---|---|
| Organs | ICRP 26 (1977) (per 10,000 per Sv) | ICRP 60 (1990) (per 10,000 per Sv) |
| Bladder | --- | 30 |
| Bone Marrow | 20 | 50 |
| Bone Surface | 5 | 5 |
| Breast | 25 | 20 |
| Colon | --- | 85 |
| Liver | --- | 15 |
| Lung | 20 | 85 |
| Esophagus | --- | 30 |
| Ovary | --- | 10 |
| Skin | --- | 2 |
| Stomach | --- | 110 |
| Thyroid | 5 | 8 |
| Remainder (1) | 50 | 50 |
| Total | 125(2) | 500(3) |

(l) The composition of the "remainder" is quite different in the two cases.
(2) This total was used for both workers and general public.
(3) General public only. The total fatal cancer risk for a working population is taken to be 400/10,000/Sv.

Table 16
Relative Contribution of Organs to the Total Detriment from ICRP 60

| Organs | Probability of Fatal Cancer (F) (per 10,000 people/Sv) | Severe Genetic Effects (per 10,000 people/Sv) | Relative Length of Life Lost (1/1') | Relative Nonfatal Contribution (2-k) | Product F(1/1')(2-k) (per 10,000 people/Sv) | Relative Contribution |
|---|---|---|---|---|---|---|
| Bladder | 30 | | 0.65 | 1.50 | 29.4 | 0.040 |
| Bone Marrow | 50 | | 2.06 | 1.01 | 104.0 | 0.143 |
| Bone Surface | 5 | | 1.00 | 1.30 | 6.5 | 0.009 |
| Breast | 20 | | 1.21 | 1.50 | 36.4 | 0.050 |
| Colon | 85 | | 0.83 | 1.45 | 102.7 | 0.141 |
| Liver | 15 | | 1.00 | 1.05 | 15.8 | 0.022 |
| Lung | 85 | | 0.90 | 1.05 | 80.3 | 0.111 |
| Esophagus | 30 | | 0.77 | 1.05 | 24.2 | 0.034 |
| Ovary | 10 | | 1.12 | 1.30 | 14.6 | 0.020 |
| Skin | 2 | | 1.00 | 2.00 | 4.0 | 0.006 |
| Stomach | 110 | | 0.83 | 1.10 | 100.0 | 0.139 |
| Thyroid | 8 | | 1.00 | 1.90 | 15.2 | 0.021 |
| Remainder | 50 | | 0.91 | 1.29 | 8.9 | 0.081 |
| Gonads | --- | 100 | 1.33 | --- | 133.3 | 0.183 |
| Total | 500 | | | | 725.3 | 1.000 |

Table 17
ICRP Publication 60 Tissue Weighting Factors

Tissue Weighting Factors[1]

| **Tissue or Organ** | **Tissue Weighting Factor, $w_T$** |
|---|---|
| Gonads | 0.20 |
| Bone Marrow (red) | 0.12 |
| Colon | 0.12 |
| Lung | 0.12 |
| Stomach | 0.12 |
| Bladder | 0.05 |
| Breast | 0.05 |
| Liver | 0.05 |
| Esophagus | 0.05 |
| Thyroid | 0.05 |
| Skin | 0.01 |
| Bone Surface | 0.01 |
| Remainder | 0.05[2,3] |

1 The values have been developed from a reference population of equal numbers of both sexes and a wide range of ages. In the definition of effective dose, they apply to workers, to the whole population, and to either sex.

2 For purposes of calculation, the remainder is composed of the following additional tissues and organs: adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus, and uterus. The list includes organs that are likely to be selectively irradiated. Some organs in the list are known to be susceptible to cancer induction. If other tissues and organs subsequently become identified as having a significant risk of induced cancer, they will then be included either with a specific WT or in this additional list constituting the remainder. The latter may also include other tissues or organs selectively irradiated.

3 In those exceptional cases in which a single one of the remainder tissues or organs receives an equivalent dose in excess of the highest dose in any of the twelve organs for which a weighting factor is specified, a weighting factor of 0.025 should be applied to that tissue or organ and a weighting factor of 0.025 to the average dose in the rest of the remainder as defined above.

There are several other significant differences between ICRP 26 and 60. These differences involve the introduction of the following terms in ICRP 60:

- Radiation weighting factor ($w_R$)
- Equivalent dose ($H_T$)
- Effective dose (E)

Radiation weighting factor ($w_R$), which has replaced quality factor (Q) from ICRP 26, is the weighting factor used to average absorbed dose over a tissue or organ for the radiation quality of interest. It is selected for the type and energy of the radiation incident on the body or, in the case of sources within the body, emitted by the source. Radiation weighting factors from ICRP 60 are given in Table 18. This weighted absorbed dose is strictly a dose, and the ICRP has chosen to assign the term equivalent dose in a tissue or organ, using the symbol $H_T$. The change of the name (from dose equivalent in ICRP 26) also serves to indicate the change from quality factor to radiation weighting factor. The equivalent dose in tissue T, is given, then, by the expression:

$$H_T = \sum_R w_R \cdot D_{T,R}$$

where:

$H_T$ = equivalent dose in tissue T
$w_R$ = radiation weighting factor
$D_{T,R}$ = the absorbed dose averaged over the tissue or organ T due to radiation R

The effective dose is the sum of the weighted equivalent doses in all of the tissues and organs of the body, and is given by the expression:

$$E = \sum_T w_T \cdot H_T$$

where:

E = effective dose
$w_T$ = tissue weighting factor for tissue T
$H_T$ = equivalent dose in tissue T

Table 18
Radiation Weighting Factors from ICRP 60

| Type and Energy Range[2] | Radiation Weighting Factor, $w_R$[1] |
|---|---|
| Photons, all energies | 1 |
| Electrons and muons, all energies[3] | 1 |
| Neutrons, energy < 10 keV | 5 |
| 10 keV to 100 keV | 10 |
| > 100 keV to 2 MeV | 20 |
| > 2 MeV to 20 MeV | 10 |
| > 20 MeV | 5 |
| Protons, other than recoil protons, energy > 2 MeV | 5 |
| Alpha particles, fission fragments, heavy nuclei | 20 |

[1] All values relate to the radiation incident on the body or, for internal sources, emitted from the source
[2] The choice of values for other radiations is discussed in Annex A of Publication 60
[3] Excluding Auger electrons emitted from nuclei bound to DNA

New dose limits have been imposed in the recommendations of ICRP 60. The revised values, again, are a direct result of the redefinition of detriment. The ICRP now recommends a limit on effective dose of 20 mSv (2 rem) per year, averaged over five years (10 rem in 5 years), with further provision that the effective dose should not exceed 50 mSv (5 rem) in any single year. The five-year period is intended to be defined by the regulatory agency, such as discrete five-year calendar periods. The ICRP recommends that the dose constraint for optimization should not exceed 20 mSv (2 rem) in a year.

The restrictions on effective dose are recommended to ensure the avoidance of deterministic effects in all body tissues and organs except the lens of the eye, which makes a negligible contribution to the effective dose, and the skin, which is subject to localized exposures. Separate dose limits are needed for these tissues. The annual limits are 150 mSv (15 rem) for the lens and 500 mSv (50 rem) for the skin, averaged over any 1 $cm^2$, regardless of the area exposed. For internal exposure, annual limits on intake (addressed in ICRP 61) will be based on a committed effective dose of 20 mSv. The estimated intakes may be averaged over a period of five years to provide some "flexibility." Recommended dose limits from ICRP 60 are shown in Table 19.

Table 19
Recommended Dose Limits[1] from ICRP 60

| Application | Dose Limit | |
|---|---|---|
| | **Occupational** | **Public** |
| Effective dose | 20 mSv per year, averaged over defined periods of five years[2] | 1 mSv in a year[3] |
| Annual equivalent dose in: | | |
| - the lens of the eye | 150 mSv | 15 mSv |
| - the skin[4] | 500 mSv | 50 mSv |
| - the hands and feet | 500 mSv | --- |

[1] The limits apply to the sum of the relevant doses from external exposure in the specified period and the 50-year committed dose (to age 70 years for children) from intakes in the same period.

[2] With the further provision that the effective dose should not exceed 50 mSv in any single year. Additional restrictions apply to the occupational exposure of pregnant women, which is discussed in Section 5.3.3 of the main text of ICRP 60.

[3] In special circumstances, a higher value of effective dose could be allowed in a single year, provided that the average over five years does not exceed 1 mSv per year.

[4] The limitation on the effective dose provides sufficient protection for the skin against stochastic effects. An additional limit is needed for localized exposures in order to prevent deterministic effects.

## ICRP 61

ICRP 61, *Annual Limits on Intake of Radionuclides by Workers Based on the 1990 Recommendations*, supports the guidance set forth in ICRP 60, and supersedes ICRP 30. ICRP 61, like ICRP 60, was developed to take into account new biological information related to the detriment associated with radiation exposures.

New values of the ALI that incorporate the new dose limits, radiation weighting factors, tissue weighting factors, and metabolic and biokinetic information from ICRP 30 have been calculated. These values are presented in ICRP 61. Future recommendations of the ICRP will include a new respiratory tract model, a new Reference Man report, and new biokinetics models.

Effective dose (as described in ICRP 60) must be committed over an occupational lifetime (50 years) when received from internal sources. Thus, a new term, committed effective dose E(50), must be defined for internal dose calculations in accordance with Publication 61. The committed effective dose is calculated as follows:

$$E(50) = \sum_{T=i}^{T=j} w_T H_T(50) + w_{remainder} \frac{\sum_{T=k}^{T=l} m_T H_T(50)}{\sum_{T=k}^{T=l} m_T}$$

where:

| | | |
|---|---|---|
| E(50) | = | committed effective dose |
| $w_T$ | = | tissue weighting factor for the tissues and organs $T_i$ to $T_j$ (from the 12 tissues named in Table 17) |
| $m_T$ | = | the mass of the remainder tissues $T_k$ to $T_l$ (given in note 2 of Figure 3) |
| $w_{remainder}$ | = | 0.05 (the $w_T$ assigned to the remainder tissue) |

For internal exposure, the ALI is based on a committed effective dose of 0.02 Sv (2 rem). Thus, the annual limit on intake (ALI) for any radionuclide is obtained by dividing the annual average effective dose limit (2 rem) by the committed effective dose, E(50), resulting from the intake of 1 Bq of that radionuclide. In Publication 30, it was pointed out that if the behavior of any specific material was expected to vary significantly from that of the dosimetric model employed, then alterations should be made in the application of the model when specific data are available to justify such alterations. This advice still applies.

**Dose Equivalent Calculations in Compliance with 10 CFR Part 835**

10 CFR 835, *Occupational Radiation Protection*, is based largely upon the dose limitation and calculation philosophy of ICRP 26 and 30. This is due to the parallelism between 10 CFR 835 and the Federal guidance on radiation protection approved by the President in 1987. There are several exceptions, which are addressed in the introduction to 10 CFR 835, to the commonality between these documents, as published in the *Federal Register*. These differences are a result of subsequent changes in the Federal guidance after 1987.

Thus, the following annual occupational dose equivalent limits have been adopted in 10 CFR 835.

| Dose Equivalent Type | Measurement Depth for External Sources (cm) | Annual Limit (rem) |
|---|---|---|
| Total effective dose equivalent (TEDE)[1] | 1 | 5 |
| Sum of the deep dose equivalent and the committed dose equivalent (CDE) to any organ or tissue other that the lens of the eye | 1 | 50 |
| Lens of eye dose equivalent | 0.3 | 15 |
| Shallow dose equivalent, Skin or any extremity | 0.007 | 50 |

[1] The TEDE is the sum of the deep dose equivalent, and the CEDE.

As can be seen, to calculate the total effective dose equivalent (TEDE) data on exposure to radioactive sources, both external and internal exposures to the body must be obtained. External exposures will most often be measured by film or thermoluminescent dosimetry, and less often by portable radiation survey instruments.

Internal dose equivalents can easily be calculated by comparing the intake of a radionuclide of interest to the derived air concentration (DAC) for that radionuclide in Appendix A to 10 CFR 835. Internal dose equivalents can be more accurately determined by comparing the intake to the maximum committed dose equivalent from a unit intake of the nuclide from the exposure-to-dose conversion factors from EPA Federal Guidance Report No. 11 (EPA 520/1-88-020), *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*. These values are the same as those used to calculate the DACs in Part 835.

A logical order in which to calculate dose equivalents to demonstrate compliance with the annual limits is to begin with internal dose equivalents to organs or tissues. Once the committed dose equivalents (CDE) are known for all organs or tissues, the committed effective dose equivalent (CEDE) may be calculated. The CEDE and CDE are then added to the deep dose equivalent obtained from external dosimetry to demonstrate compliance with the annual limit of 5 rem TEDE.

<u>Calculating CDE</u>

The simplest way to calculate a CDE to an organ or tissue is to use the tables of exposure to dose conversion factors for inhalation or ingestion found in EPA Federal Guidance Report No. 11. The CDE to an individual organ or tissue is calculated:

$$CDE = (Intake)(Dose\ Conversion\ Factor)$$

Another way to calculate the CDE to an organ or tissue receiving the largest dose, it to use a ratio of the intake to the nonstochastic ALI (nALI). The nALI for a radionuclide is that amount of the nuclide, which, if taken into the body by the specified route (inhalation or ingestion), would result in a CDE of 50 rem to an individual organ or tissue. The stochastic ALI (sALI) for a radionuclide is that amount of the nuclide, which, if taken into the body by the specified route (inhalation or ingestion), would result in a CEDE of 5 rem. Thus, the CDE when the nALI is given may be calculated as follows:

$$CDE = \frac{I}{nALI} \; x \; 50 \; rem$$

where:

I = intake (µCi)

Even if the sALI is more limiting than the nALI, it is still necessary to demonstrate that the limit of 50 rem is not exceeded for an individual organ or tissue. In this case, the nALI must be calculated using the maximum dose equivalent from a unit intake of the nuclide from the EPA 520 exposure-to-dose conversion factors tables, as follows:

$$nALI = \frac{50}{h_{max}}$$

where:

$h_{max}$ = the greatest dose equivalent value for the class of nuclide found in the table

**NOTE**: h values in the EPA 520 table are given in units of Sv/Bq. These values must be converted to rems/µCi by the multiplication factor, $3.7 \times 10^6$.

The obtained nALI value is then applied to calculate the CDE.

<u>Calculating CEDE</u>

The simplest way to calculate the CEDE to an individual is to use the tables of exposure to dose conversion factors for inhallation or ingestion found in EPA Federal Guidance Report No. 11. The CEDE to an individual is calculated:

CEDE = (Intake)(Dose Conversion Factor)

Another way to calculate the CEDE to an individual is to use a ratio of the intake to the sALI. Thus, the CEDE may be calculated as follows:

$$CEDE = \frac{I}{sALI} \; x \; 5 \; rem$$

where:

I = intake (µCi)

When an individual is internally exposed to multiple radionuclides, the sum of the CEDEs from each nuclide must be used to express the CEDE:

$$CEDE = \sum_{j=1}^{n} CEDE \; j$$

where:

j = the number of radionuclides up to *n* radionuclides

The CEDE from multiple intakes of a radionuclide can be calculated using the following equation:

$$CEDE = \sum_{j=1}^{n} W_{Ti} \; CDE_i$$

where:

i = a single intake up to n intakes

**NOTE**: In accordance with the footnote to §20.1202, only those organs or tissues that are "significantly irradiated" must be included in the summation. An organ is significantly irradiated if its CDE is greater than 10 percent of the maximum CDE to any other organ irradiated as a result of the intake.

Calculating TEDE

The TEDE is calculated by simply adding the CEDE to the DDE obtained from external dosimetry data at a measurement depth of 1 cm in tissue (a density thickness of 1,000 mg/cm$^2$). This calculation may be represented as follows:

TEDE = deep dose equivalent + CEDE

Calculating Lens of the Eye Dose Equivalent

Dose equivalent to the lens of eye is obtained exclusively from external dosimetry data at a measurement depth of 0.3 cm in tissue (a density thickness of 300 mg/cm$^2$).

Calculating Shallow Dose Equivalent

Shallow dose equivalent is obtained from external dosimetry data at a measurement depth of 0.007 cm in tissue (a density thickness of 7 mg/cm$^2$). To comply with regulatory limits, the shallow dose equivalent will be expressed as shallow dose equivalent to the skin of the whole body or shallow dose equivalent to any extremity.

**Biological Effects of Ionizing Radiation (BEIR) V Executive Summary**

In the early 1950s, the testing of nuclear weapons provoked public concern about the potential health effects of exposure to atomic radiation. Based on this concern, a group was established to study the biological effects from exposure to ionizing radiation. This group was commissioned to generate studies under the National Academy of Sciences. The group produced a study that was called Biological Effects of Atomic Radiation (BEAR), and over a period of years the committee published six reports that are known as the BEAR Reports. Also in this time frame, the United Nations established a committee, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).

With all of the reorganizations and name changes associated with government organizations, a committee that was formed in the 1960s to advise the National Research Council and the Federal Radiation Council (FRC) was renamed the Committee on the Biological Effects of Ionizing Radiation (BEIR). The BEIR committees have provided several in-depth studies over the past years. They are listed below:

- BEIR I: The Effects on Populations of Exposure to Low Levels of Ionizing Radiation, 1972.
- BEIR II: Considerations of Health Benefit-Cost Analysis for Activities Involving Ionizing Radiation Exposure and Alternatives, 1977.
- BEIR III: The Effects on Populations of Exposure to Low Levels of Ionizing Radiation, 1980.
- BEIR IV: Health Risks of Radon and Other Internally Deposited Alpha-Emitters, 1988.
- BEIR V: Health Effects of Exposure to Low Levels of Ionizing Radiation, 1990.

BEIR III was based largely on studies of the survivors from the Hiroshima and Nagasaki atomic bombs. The studies of the survivors were determined to be flawed due to inaccuracies in the bomb yield calculations and the dosimetry models. New studies were performed that included mortality information through 1985. These studies were performed by Japanese and American researchers of the Radiation Effects Research Foundation (RERF) in Hiroshima and Nagasaki. The study was completed in 1988 and included the latest study results and dosimetric models. Based on the new analysis, it was determined that a new study to review the effects of low-level exposure to ionizing radiation was required.

In 1986, a new BEIR Committee was organized to conduct a review of the information that had been published since the BEIR III report in 1980. This would constitute the fifth BEIR Committee (BEIR V). The committee was to look at the available information and provide new estimates of the risks of genetic and somatic effects in humans due to low-level exposures to ionizing radiation. The risk assessments were to take into account both external and internal sources of radiation.

The review was organized into the following categories:

- Heritable genetic effects
- Cellular radiobiology and carcinogenic mechanisms
- Radiation carcinogenesis
- Radiation effects on the fetus
- Radiation epidemiology and risk modeling

The estimates of cancer risks from exposure to low-level radiation in the BEIR V report rely heavily on the Life Span Study (LSS) of the Japanese atomic bomb survivors at Hiroshima and Nagasaki. Other studies were used also, but were primarily for incidence and mortality risks for specific cancer induction sites. Table 20 lists some of the major studies that were used in the preparation of the BEIR V report, and how they were used.

Table 20
Major Characteristics of the Data Sets Used for Model Fitting

| Study Population | Incidence or Mortality | Cancer Sites | Total Cases | Total Person Years |
|---|---|---|---|---|
| Atomic bomb survivors | Mortality | All | 5,936 | 2,185,335 |
| | Incidence | Breast | 376 | 940,000 |
| Ankylosing spondylitis patients | Mortality | Leukemia | 36 | 104,000 |
| | | All except leukemia and colon | 563 | 104,000 |
| Canadian fluoroscopy | Mortality | Breast | 482 | 867,541 |
| Mass. fluoroscopy | Mortality | Breast | 74 | 30,932 |
| N.Y. postpartum mastitis | Incidence | Breast | 115 | 45,000 |
| Israel tinea capitis | Incidence | Thyroid | 55 | 712,000 |
| Rochester thymus | Incidence | Thyroid | 28 | 138,000 |

These studies are all essentially high-exposure situations . The levels of exposure associated with the various groups range from a few rads to several thousand rads. These studies have been used based on the previously discussed criteria. The groups have been exposed to radiation and the documentation has allowed follow-up studies. The low-level exposure effects are then extrapolated from these higher exposure studies.

Studies of the effects of low-level radiation have been conducted throughout the world at various types of facilities. These studies have failed to provide the necessary information to calculate the numerical estimates of risk from exposure to low-level ionizing radiation. The low-level exposure studies do provide valuable information that is applied to verifying the estimates based on higher-exposure levels. Table 21 lists some of the major studies that have been conducted.

As can be seen from Table 21, the studies have included results from variety of radiation workers. There have also been studies of non occupationally-exposed individuals. The studies have covered such areas as diagnostic radiography, fallout from nuclear weapons testing, nuclear installations (living nearby), and high natural background exposure.

These studies have provided no significant evidence that risk estimates for leukemia and other types of cancer combined differ, from the values extrapolated from high-dose studies. Experts state that the results do not contradict or imply possible inaccuracy from the current high-dose based estimates.

Risk Assessment Models

The calculation of the genetic risk associated with the exposure to ionizing radiation is more complex than those involved with other effects. There is very little direct human radiation genetic information available. Again the major resource is the Japanese atomic bomb survivor studies, which are high-level exposure. Many studies have been done with animals, primarily mice, to form a core of information. The results of the mice studies have been extrapolated to "fit" potential human effects. The results from these tests provide indication of mutation rates. These mutation rates are then converted into probabilities of radiation-induced hereditary disorders. There are large areas for error due to the types and magnitude of the necessary assumptions.

There are two kinds of radiation induced genetic damage that are considered significant-- gene mutations and chromosomal aberrations. Gene mutations are alterations in the basic hereditary units, the genes. Chromosomal aberrations are alterations in the structure or number of the chromosomes. The mutations may be either dominant or recessive. Dominant mutations will be apparent in the first generation (passed on from only one parent), and recessive mutations need to be inherited from both parents to take effect.

Table 21
Epidemiologic Studies of Workers Monitored for External Gamma Radiation

| Study | Type of Operation | Years of Employment | Last Year of Follow-up | No. of Individuals in Study | No. of Radiation Workers[a] | Dose[b] (mrem) | Total No. of Cancer Deaths |
|---|---|---|---|---|---|---|---|
| United Kingdom Atomic Energy Authority | Reactor research and development | 1946-1979 | 1979 | 39,546 (29,173 males , 10,373 females) | 20,382 (18,759 males, 1,623 females) | 3,240 | 3,373 |
| British Nuclear Fuels Limited | Plutonium production, fuel reprocessing, etc. | 1946-1975 | 1983 | 14,000 (11,402 males, 2,598 females) | 10,157 | 12,400 | 2,277 |
| Hanford Site | Reactor research and development | 1944-1978 | 1981[c] | 44,100 (31,500 males, 12,600 females) | 36,235 | 4,360 | 7,249[d] |
| Oak Ridge National Laboratory | Reactor research and development; plutonium production, processing, and isotope separation | 1943-1972 | 1977 | 8,375 males | 7,778 | 1,730 | 966 |
| Oak Ridge Y-12 | Uranium enrichment, weapon fabrication | 1947-1974 | 1979 | 6,781 males | 5,278 | 960 | 862 |
| Rocky Flats Nuclear Weapons Plant | Plutonium weapons fabrication | 1952-1979 | 1979 | 5,413 males | | 4,130 | 409 |
| Atomic Energy of Canada | Reactor research and development | 1950-1981 | 1981 | 13,570 (10,278 males, 3,292 females) | 7,865 (6,626 males, 1,239 females) | 4,680 males, 386 females | 946 |
| Ontario Hydro | Power reactor operation | 1970-1985 | 1985 | 23,997 males | 5,039 | | 2,860 |

a. No. of individuals reported or estimated to be monitored.
b. Mean whole-body gamma dose per radiation worker.
c. Deaths occurring in the state of Washington in the years 1982-1985 were also evaluated.
d. Observed deaths from 1945-1981.

When analyzing genetic problems for risk assessment, the term "heredity disorder" is used. Hereditary disorder refers to a pathological condition arising as a consequence of a mutation or chromosomal aberration transmitted from one human generation to the next. There are three major categories of hereditary disorders:

1. Mendelian hereditary disorders: those due to mutations in single genes and that follow Mendel's laws of inheritance.
2. Chromosomal hereditary disorders: due to either numerical or structural abnormalities.
3. Multifactorial hereditary disorders: resulting from the joint action of multiple genetic and environmental factors.

One of the major considerations when calculating the effects of radiation, or any other hazardous source, is trying to distinguish the results of the insult understudy, from the naturally occurring effects. Looking at the three general categories of hereditary disorders: the prevalence per 100 individuals is approximately 1.25% for Mendelian disorders, 0.38% for chromosomal disorders, and 65% for multifactorial disorders. These numbers reflect the large numbers of disorders that are present from natural sources, and that some individuals may have more than one disorder present.

To calculate the genetic risk associated with exposure to ionizing radiation, the epidemiologist must have some mechanism to differentiate from those events that are naturally occurring. Three methods of risk calculation have been used when dealing with radiation exposure and genetic risk: 1) gene number method, 2) direct method, and 3) doubling dose method.

The gene number method is based on the theory that each harmful mutation ultimately causes one genetic death. The genetic death may be expressed all at once, in the death of the exposed individual, or it may be expressed over several generations of individuals. The following equation is used to calculate the number of induced mutations:

*number of induced mutations = number of genes x (induced rate/gene/unit dose) x dose*

This method was used in the earlier reports (BEAR, 1956). Currently, this method is not used because it is difficult to translate into societal costs and human suffering; also, there is no satisfactory definition or estimate of the total number of mutable genes.

The direct method is based on measuring of effects from high dose-rate radiation and then extrapolating to lower dose rate radiations. The initial studies for this method were done with animals that were selected based on the class of defect to be studied. For example, mice were used for study of cataracts and skeletal anomalies.

This method was not accepted based on the large number of assumptions and estimates required to derive the estimates. This method was used as a check for the doubling dose method to ensure consistency.

The doubling dose is simply the dose that is required to double the naturally occurring number of effects. The doubling dose is based on equilibrium conditions. But, it can be accurately used for short term (first several generations) calculations by utilizing proportional values. The doubling dose method is based on the following mathematical relationship:

*induced burden = spontaneous burden x (1/doubling dose) x mutation component x dose*

The doubling dose method is based on the following assumptions: 1) there is a known proportional relationship between mutation and hereditary disorders, 2) that there is an equilibrium between mutations that arise (naturally) and those that are eliminated by selection every generation, and 3) with continuous irradiation (and subsequent mutations), the population will reach a new equilibrium value. From this information, estimates are made that concern single exposures because, with single exposures, there will be no new equilibrium. The mutations caused by the exposure will be selectively eliminated and eventually the level will drop to the original equilibrium value. These assumptions allow the manipulation of the available data to derive the doubling dose for single exposures.

BEIR V (1990) uses the doubling dose method for its calculations. The BEIR V report limits its use of this method to only the linear portions of the dose-response curve because of the focus of the report to low-level exposures. Based on the results from the Japanese atomic bomb survivors and studies involving mice, the report estimates the doubling dose to be about 100 rem (1 Sv). Table 22 lists selected genetic effects and how they will be affected by 1 rem of exposure.

Table 22
Estimated Genetic Effects of 1 rem per Generation

| **Genetic Disorder Category** | **Cases per Million Liveborn Offspring** | |
|---|---|---|
| | **Natural Prevalence** | **Added Cases per rem (First Generation)** |
| Autosomal dominant | 10,000 | 6-35 |
| X-linked | 400 | 0-1 |
| Recessive | 2,500 | 0-1 |
| Chromosomal | 4,400 | 0-6 |
| Congenital anomalies | 30,000 | 10 |

When estimating the effects of exposures that are different from those that were used for the determination of the risk models, the dose rate effectiveness factor (DREF) must be used. DREF is

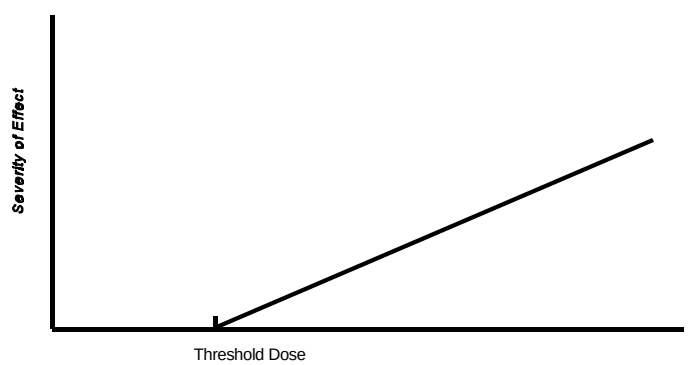
defined as a factor by which the effect caused by a specific dose of radiation changes at low as compared to high dose rates. In cases of leukemia, based on a linear-quadratic relationship, there is an implicit dose rate effect based on the linear portion of the curve. The magnitude of this reduction is expressed by the DREF values. For other situations and exposures, the use of a DREF value is offset by other factors. An example is for exposure to x-rays. For x-ray exposure, a DREF value of 2 has been suggested, however, based on an relative biological effectiveness (RBE) of x-ray exposure being over estimated by as much as a factor of 2, the DREF and the RBE are self-canceling.

Another concept that is encountered in the area of genetic risk is genetically significant dose (GSD.) GSD is defined as the fraction of radiation that deposits energy in the gonads (ovaries and testes) of persons of childbearing potential. This concept was derived for studies involving background radiation effects. GSD studies were then applied to medical procedures to determine what potential genetic effects might exist based on a specific procedure. The process involves calculating what portion of the dose would actually impact the gonads.

Dose-Response Models

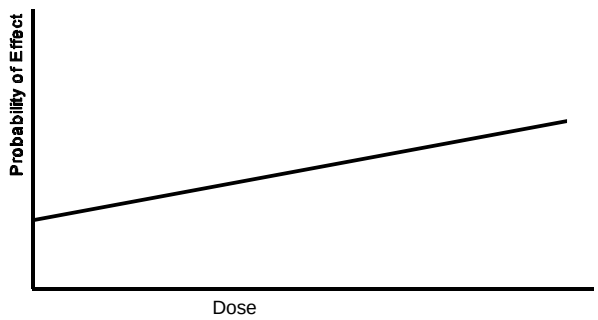
The type of model used to depict the effects of radiation exposure versus actual exposure has gone through several modifications over time. Early in the history of radiation biology, it was thought that a certain amount of radiation had to be received before any effects whatsoever would occur in the body. This was called the threshold theory and is shown in Figure 7. It applies to acute radiation exposures only. The theory is currently accepted for nonstochastic effects such as cataracts, hair loss, etc.

Threshold Theory



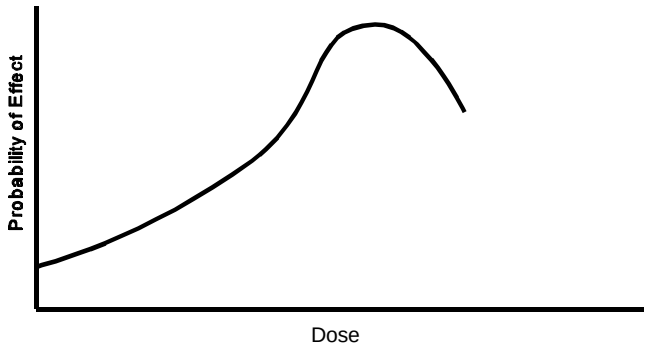
As the research on dose versus effect was refined, it became harder and harder to establish a well-defined relationship between those two factors. Because of this, the threshold theory was replaced by the nonthreshold theory, which holds that any exposure, no matter how little, has some effect on the body. Figure 8 shows this theory as it was originally proposed, in terms of a linear relationship. BEIR V endorses this model for "hard" cancers.

Linear Non-threshold Theory
(LNT Model)




BEIR III report, 1980, has further refined the nonthreshold theory. It is no longer represented as a linear function. The new functional form of the theory is basically linear with modifications that allow the fitted curve to express increasing effects (a conservative approach) at low doses and decreasing effects at high doses to account for cell-killing effects. The following figure shows this new dose-response function, the linear quadratic theory. The intercept on the incidence axis is indicative of the naturally occurring or spontaneous frequency of the effect in the population. This model is endorsed by BEIR V for leukemia.

Linear Quadratic Theory




Current dose-response theory has been further redefined in the BEIR V Report (1990). This report deals

primarily with the induction of cancers from radiation in humans. Due primarily to increased data on atomic bomb survivors, the largest irradiated population, and changes in atomic bomb dosimetry, the committee based dose effect projections on the linear nonthreshold dose-response model as shown in Figure 8. The data presented in BEIR V follows the linear model for all solid cancers, the exception being radiation-induced leukemia. This effect is more compatible with the linear quadratic dose-response model shown in the figure.

On Dec. 19, 1989, the National Academy of Sciences/National Research Council released the fifth report from its Committee on the Biological Effects of Ionizing Radiation (BEIR V report). The BEIR V report identified an increased risk of cancer resulting from exposure to x-ray and gamma radiation. In response to a request by the Secretary of Energy, the Office of Health (EH-40), formerly the Office of Safety Policy and Standards, performed a review of the implications of the BEIR V report to DOE.

The DOE report *A Technical Review and Assessment of the BEIR V Report* (DOE/EH-0149T) formed the technical basis for the Department's response to the issuance of the BEIR V Report in 1990. The response was entitled *Implications of the BEIR V Report to the Department of Energy* (DOE/EH-0158T) and is described below.

EH-40 initiated both external and internal review efforts to assess the implications to the DOE of the BEIR V report. An external Technical Review Committee (TRC), consisting of recognized authorities in the radiation sciences, was organized and directed to perform a scientific assessment of BEIR V. A DOE Internal Review Committee (IRC), consisting of Headquarters Program Office and Operations Office representatives, was organized to perform an internal review of BEIR V and identify potential BEIR V impacts. The IRC also developed a survey questionnaire for DOE contractors to complete, designed to quantify the potential impacts of BEIR V on the DOE complex.

The TRC's report provided an extensive analysis of the scientific content of the BEIR V report. The TRC report identified that the cancer risk estimates as reported in the BEIR V report contain large uncertainties when extrapolated to low dose and dose rate conditions and are not directly applicable to the DOE occupational exposure setting. The TRC stated that appropriate modification of the BEIR V risk estimates may significantly reduce the reported increase in cancer risk. The TRC concluded that the BEIR V risk estimates, when applied to the DOE exposure situation, did not justify an immediate reduction of radiation protection limits.

A review of DOE worker exposure statistics by the IRC identified that the average DOE worker consistently receives an annual dose equivalent less than 4% of the current annual limit. The majority (93%) of DOE workers and visitors typically receive an annual dose equivalent less than 10% of the current annual limit. Consequently, the majority of DOE workers are being exposed significantly below current limits and would not necessarily benefit if a modification, to the DOE occupational radiation exposure limits in response to BEIR V was made.
In consideration of the TRC report and the above exposure statistics, the IRC concluded that the increased risk cited in the BEIR V report did not justify immediate revisions to the DOE occupational

radiation exposure limits. A recommendation that no such revisions be made was included in the Interim Report on the Implications of the BEIR V Report, which was forwarded to the Secretary of Energy on March 20, 1990.

The IRC recognizes, however, that various national and international scientific advisory groups have reviewed or are currently reviewing the BEIR V report and related scientific reports. Unlike the BEIR V committee, these advisory groups make specific recommendations concerning radiation exposure limits. Two such advisory groups are the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP). Recommendations on radiation exposure limits from these groups may significantly influence the Environmental Protection Agency (EPA), which has Federal guidance authority to develop and recommend radiation exposure limits to the President, for implementation by competent Federal authority.

The ICRP recently released a draft revision to its basic recommendations on radiation dose limits that were last revised in 1977. The ICRP draft revision proposes reduced radiation dose limits, based on a perceived approximate factor of three increase in overall risk associated with radiation exposure. The draft revision recommends limiting occupational worker effective dose equivalent (EDE) to 10 rem over a five-year period; however workers may receive an EDE up to 5 rem in any one year. Current DOE Orders limit occupational workers to an EDE of 5 rem in one year. The ICRP draft revision also recommends that the quality factors used to translate neutron exposure to dose equivalent be doubled from values currently utilized by DOE.

The ICRP draft revision is currently undergoing significant review and comment by various scientific groups and federal agencies, including DOE. However, in a stated public announcement, the ICRP intends to proceed on its recommendations. The NCRP is currently reviewing its recommendations but has not released draft recommendations for public review. In their 1987 recommendations, the NCRP proposed a cumulative limit on worker lifetime exposure. In light of the ICRP draft, however, it appears likely that occupational radiation dose limits may be lowered within the next several years. The IRC consequently recommended in the interim report that DOE contractors be directed to review their existing administrative exposure control systems in anticipation of such reductions. The Secretary of Energy approved the interim report and its recommendations on March 30, 1990. A memorandum was sent from EH-1 to the Operations Offices in June 1990, directing contractors to review their administrative exposure control systems.

Contractor responses to the IRC survey questionnaire identified that a reduction in the occupational radiation exposure limits would require significant increases in personnel, and facility modification costs as well as result in increased collective exposure. As an example, initial cost estimates

associated with the adoption of a 2 rem/year EDE limit and a doubling of the neutron quality factor (survey questionnaire endpoints that most closely reflect the ICRP draft recommendations) include

the following:

| | | |
|---|---|---|
| Increased Personnel Costs | $15 M | |
| Facility Modifications | $369 M | |
| Radiation Protection Program Upgrades | $17 M | |
| Increased Collective Exposure | 243 | person-rem |

The above cost estimates are based on an approximate 60% facility response. The cost estimates do not include input from the Rocky Flats plant and the Los Alamos National Laboratory, two significant contributors to overall DOE collective exposure. It should also be noted that the cost estimates identified through this survey are not highly reliable and should not be considered definitive planning estimates. Cost estimates associated with the adoption of a 1.0 and 0.5 rem annual EDE limit are also provided in the body of this report.

Based on its analysis of the TRC report and DOE current exposure data, the IRC concludes that the BEIR V report does not justify immediate revisions to the DOE radiation exposure annual limits, and specifically recommends such revisions not be made. The IRC also recognizes, however, that reductions to the Federal occupational radiation exposure limits may occur within the next several years, based in part on more restrictive recommendations by the ICRP and potentially the NCRP. The current survey identifies that costs and manpower needs associated with any such reduction would be significant. The IRC recommends that DOE take an active role in anticipating and responding to potential reductions to occupational exposure limits and associated impacts. The following specific recommendations are made to support this role:

1. No immediate revisions to the existing DOE radiation exposure limits should be made in response to the BEIR V report. Instead, DOE should continue to participate in the technical review and comment process associated with the BEIR V report, the ICRP draft recommendations, and any forthcoming recommendations from the NCRP. DOE should continue to actively participate with other federal agencies to ensure a coordinated Federal approach and response.
2. To ensure that the operational and financial impacts of potential revisions to the radiation dose limits are adequately anticipated, the IRC recommends that a DOE ALARA committee, consisting of upper-level representation from both the Operations Offices and cognizant Headquarters program offices, be formally established. The purpose of this committee would be to: (a) remain cognizant of potential and impending revisions to the radiation dose limits, as identified in 1 above; (b) further evaluate potential cost impacts of such reductions as identified in this study and request additional cost estimates as necessary from the contractors; (c) provide direction for and track progress on the recommendations of this report; (d) periodically review and make relevant recommendations based on DOE exposure statistics; and (e) generally ensure that a high level of attention and appropriate resources are directed toward achieving a progressive series of radiation exposure reductions

throughout the DOE complex.

3. A cost-benefit evaluation should be performed to evaluate the adoption of a facility radiological design limit for normal operations of 0.5 rem/year. This design limit should include a doubling of the current neutron quality factor as an assumption in dose calculations.
4. ALARA engineering reviews should be conducted at those facilities with significant collective exposures or with a significant worker population receiving greater than 2 rem/year EDE. The purpose of these reviews is to better identify the facility modifications and improvements necessary to comply with potentially reduced dose limits.
5. The current study identified that the majority of DOE contractors are utilizing outdated radiogenic cancer risk factors. DOE should issue interim guidance for the DOE contractors specifying appropriate radiogenic cancer risk factors to be used for various radiation exposure situations. The interim guidance would specifically be applied to DOE safety analyses, risk assessments, and National Environmental Policy Act (NEPA) evaluations of newly designed and significantly modified DOE facilities.
6. The BEIR V survey responses indicated that exposures to declared-pregnant female radiation workers are typically minimal and well-controlled. The survey also indicated, however, that a significant number of facilities have programs in place directed only at limiting the gestation period total exposure, and not the monthly or most sensitive period (i.e., gestation period weeks 8 - 15) exposure. The DOE should consequently develop additional guidance related to the appropriate control of occupational radiation exposure to declared-pregnant female workers.

***Recommendations on Limits for Exposure to Ionizing Radiation*, National Council on Radiation Protection and Measurements, Report No. 91, and *Limitation of Exposure to Ionizing Radiation*, National Council on Radiation Protection and Measurements, Report No. 116**

NCRP published its last complete set of basic recommendations specifying dose limits for exposure to ionizing radiation in NCRP 91, which was published in 1987 (NCRP, 1987). During the preparation of that report, three factors were recognized as important consequences of the emerging information from the continuing study of the atomic bomb survivors by the Radiation Effects Research Foundation (RERF). The first was the continued appearance of excess cancers observed during the latest survey period.

Second, these cancers were appearing at a rate consistent with a multiplicative projection model. The third factor was the effect on risk estimates of revised dose estimates. These factors all suggested that there would be increases in projected risk. However, since the anticipated new risk estimates were unavailable, the council employed the risk estimates given in ICRP 26. NCRP 91 recommended an annual occupational dose limit of 50 mSv and an annual limit for members of the public (excluding natural background and medical exposures) of 1 mSv for continuous exposures; 5 mSv for infrequent annual exposures. At that time, however, the council anticipated a potential increase in risk estimates. Consequently, it encouraged a control on lifetime occupational exposure and cautioned the user to

consider the dose limits as upper limits rather than design goals.

Now that UNSCEAR, 1988; NAS/NRC, 1990, on the Biological Effects of Ionizing Radiation (BEIR V); ICRP, 1991a; and NCRP Scientific Committee 1-2 1993a have completed their risk assessment activities, the council has reexamined its 1987 recommendations. NCRP 116 is the result of this reexamination and it replaces NCRP 91, *Recommendations on Limits for Exposure to Ionizing Radiation*, in its entirety. The basic framework of the report, the approach to dose limitation, and the principle of a negligible individual dose (NID), however, are based on the earlier report NCRP 91.

The recommendations and concepts provided in ICRP 60 have been carefully reviewed and in the interest of a uniform international approach to radiation protection have, in general, been incorporated in NCRP 116. Deviation from their recommendations was deemed necessary in a few cases where greater flexibility could be obtained at similar or less risk (e.g., the occupational dose limits) or where increased protection was considered to be warranted (e.g., a monthly exposure limit for the embryo-fetus). Table 23 provides a comparison of the radiation risk data, recommendations, and other factors used in NCRP 91 and ICRP 60 with those used in NCRP 116.

Table 23
Comparison of Radiation Risk Data, Recommendations, and Other Factors

| **Recommendations, Risk Values, and Other factors** | **NCRP Report No. 91 (NCRP, 1987)** | **ICRP Publication 60 (ICRP, 1991a)** | **NCRP Report No. 116 (NCRP, 1993)** |
|---|---|---|---|
| **Assumed Radiation Risks** | | | |
| Workers | $1.25 \times 10^{-2} Sv^{-1}$ for fatal cancer[a]<br><br>$0.4 \times 10^{-2} Sv^{-1}$ for severe genetic effects[a] | $4.0 \times 10^{-2} Sv^{-1}$ for fatal cancer<br><br>$0.8 \times 10^{-2} Sv^{-1}$ nonfatal cancer detriment<br><br>$0.8 \times 10^{-2} Sv^{-1}$ for severe genetic effects | $4.0 \times 10^{-2} Sv^{-1}$ for fatal cancer<br><br>$0.8 \times 10^{-2} Sv^{-1}$ nonfatal cancer detriment<br><br>$0.8 \times 10^{-2} Sv^{-1}$ for severe genetic effects[a] |
| Members of the public | (not specifically addressed) | $5.0 \times 10^{-2} Sv^{-1}$ for fatal cancer<br><br>$1.0 \times 10^{-2} Sv^{-1}$ for nonfatal cancer<br><br>$1.3 \times 10^{-2} Sv^{-1}$ for severe genetic effects | $5.0 \times 10^{-2} Sv^{-1}$ for fatal cancer<br><br>$1.0 \times 10^{-2} Sv^{-1}$ for nonfatal cancer<br><br>$1.3 \times 10^{-2} Sv^{-1}$ for severe genetic effects |
| Embryo-fetus | $20 \times 10^{-2} Sv^{-1}$ total detriment (UNSCEAR, 1986) | (not specifically stated) | $\sim 10 \times 10^{-2} Sv^{-1}$ |
| **Occupational Dose Limits[b]** | | | |
| Based on Stochastic Effects | 50 mSv annual effective dose equivalent limit<br>*and*<br>10 mSv x age (y) cumulative effective dose equivalent guidance for the workplace[c] | 50 mSv annual effective dose limit<br>*and*<br>100 mSv in 5 y cumulative effective dose limit[c] | 50 mSv annual effective dose limit<br>*and*<br>10 mSv x age (y) cumulative effective dose limit[c] |
| Annual Limits on Intake (ALI) | $\frac{50\ mSv}{H_g\ (50)\ Bq^{-1}}$ | $\frac{20\ mSv}{E\ (50)\ Bq^{-1}}$ | ---- |
| Annual Reference Levels of Intake (ARLI) | ---- | ---- | $\frac{20\ mSv}{E\ (50)\ Bq^{-1}}$ |

| **Public Dose Limits**[b] | | | |
|---|---|---|---|
| Based on stochastic effects | 1 mSv annual effective dose equivalent limit for continuous exposure<br>*and*<br>5 mSv annual effective dose equivalent limit for infrequent exposure[c] | 1 mSv annual effective dose limit and, if needed, higher values provided that the annual average over five years does not exceed 1 mSv[c] | 1 mSv annual effective dose limit for continuous exposure<br>*and*<br>5 mSv annual effective dose limit for infrequent exposure[c] |
| Based on deterministic effects | 50 mSv annual dose equivalent limit to lens of eye, skin, and extremities[d] | 15 mSv annual equivalent dose limit to lens of eye<br>*and*<br>50 mSv annual equivalent dose limit to skin, hands, and feet[d] | 50 mSv annual equivalent dose limit to lens of eye, skin, and extremities[d] |
| Embryo-fetus | 5 mSv dose equivalent limit and a dose equivalent limit in a month of 0.5 mSv once pregnancy is known[d] | 2 mSv equivalent dose to the woman's abdomen once pregnancy has been declared and limiting intakes of radionuclides to about 1/20 of an ALI[d] | 0.5 mSv equivalent dose limit in a month once pregnancy is known[d] |
| Negligible Individual Dose (NID) | 0.01 mSv annual effective dose equivalent per source or practice[e] | ---- | 0.01 mSv annual effective dose per source or practice[e] |

| Recommendations, Risk Values, and Other Factors | NCRP 91 (NCRP, 1987) | ICRP 60 (ICRP, 1991a) | NCRP 116 (NCRP, 1993) |
|---|---|---|---|
| **Organ or Tissue Weighting Factor ($w_T$)[a]** | | | |
| Gonads | 0.25 | 0.20 | 0.20 |
| Red bone marrow | 0.12 | 0.12 | 0.12 |
| Colon | --- | 0.12 | 0.12 |
| Lung | 0.12 | 0.12 | 0.12 |
| Stomach | --- | 0.12 | 0.12 |
| Bladder | --- | 0.05 | 0.05 |
| Breast | 0.15 | 0.05 | 0.05 |
| Liver | --- | 0.05 | 0.05 |
| Esophagus | --- | 0.05 | 0.05 |
| Thyroid | 0.03 | 0.05 | 0.05 |
| Skin | 0.01 | 0.01 | 0.01 |
| Bone surface | 0.03 | 0.01 | 0.01 |
| Remainder | 0.30 | 0.05 | 0.05 |
| Radiation Weighting Factor ($w_R$) and Quality Factor (Q) | Q | $w_R$ | $w_R$ |
| X- and gamma-rays, electrons, positrons, and muons | 1 | 1 | 1 |
| Neutrons | | | |
| Thermal neutrons | 5 | | |
| Neutrons other than thermal | 20 | | |
| Energy <10 keV | | 5 | 5 |
| 10 keV to 100 keV | | 10 | 10 |
| > 100 keV to 2 MeV | | 20 | 20 |
| > 2 MeV to 20 MeV | | 10 | 10 |
| >20 MeV | | 5 | 5 |
| Protons Energy > 2 MeV | | 5 | 2 |
| Alpha particles, fission fragments, nonrelativistic heavy nuclei | 20 | 20 | 20 |

[a] In NCRP 91, it was recognized that the total risk estimate of 1.65 x $10^{-2}$ $Sv^{-1}$ for a working population and possibly the values for the organ or tissue weighting factor ($w_T$) would change as a result of the reassessment of the data for the Japanese survivors that was then under way.

[b] The dose limits exclude medical and natural background exposures.

[c] The concepts of effective dose equivalent and effective dose are different.

[d] The concepts of equivalent dose and dose equivalent are also different.

[e] In this report, the negligible individual risk level (NIRL) introduced in NCRP 91 is changed to a negligible individual dose (NID) with the same numerical value of 0.01 mSv but without a corresponding risk level.

***Practices for Respiratory Protection* , American National Standards Institute (ANSI Z88.2-1992)**

The purpose of this standard is to help establish, implement, and administer an effective respiratory protection program. Changes were made in 1992 reflecting the current state of knowledge. The clause on the classification, description, and limitations of respirators has been combined with the clause on the selection of respirators to clarify the decision-making process by which a respirator is selected. A decision matrix for respirator selection has also been added to this clause to draw all the elements of respirator selection together. Respirator protection factors have been revised in this standard to reflect the current state of knowledge. A new definition has been developed for "oxygen deficiency–immediately dangerous to life or health." The clauses for fit testing, breathing air supplies, and written procedures/records have been modified. A requirement for fit testing of atmosphere-supplying positive pressure respirators has been added to this standard. Owing to the importance of the values of the assigned protection factors and the proliferation of new respirator designs, a new subcommittee has been formed to consider an extension of this material and to provide the rationale for the choice of each assigned protection factor value.

The first version of ANSI Z88.2 was approved Aug. 11, 1969, and was a revision of the respiratory protection portion of American National Standard safety code for head, eye, and respiratory protection, ANSI Z2. 1-1959. The second revision of this American National Standard was approved May 22, 1980, and was entitled *American National Standard Practices for Respiratory Protection*, ANSI Z88.2-1980.

The minimum acceptable requirements for a respiratory protection program for radionuclides are summarized below. Respiratory protection factors are given in Table 24.

<u>Minimum Acceptable Respiratory Protection Program Requirements</u>

- Written standard operating procedures and a policy statement
- Proper selection of equipment, based on the hazard
- Proper training and instruction of users
- Proper fitting, use, cleaning, storage, inspection, quality assurance, and maintenance of equipment
- Appropriate surveillance of work area conditions, degree of employee exposure to stress
- Regular inspection and evaluation to determine the continued program effectiveness
- Program responsibility must be vested in one qualified individual
- An adequate medical surveillance program for respirator users
- Use of only Bureau of Mines/NIOSH-certified equipment
- Maintenance of a bioassay program

Table 24
Respiratory Protection Factors

| Type of Respirator | Respiratory inlet covering | |
|---|---|---|
| | **Half Mask** [1] | **Full Face Piece** |
| Air Purifying | 10 | 100 |
| Atmosphere supplying | | |
| SCBA (demand) [2] | 10 | 100 |
| Airline (demand) | 10 | 100 |

| Type of Respirator | Respiratory inlet covering | | | |
|---|---|---|---|---|
| | **Half Mask** | **Full Face** | **Helmet/Hood** | **Loose-Fitting Face Piece** |
| Powered air purifying | 50 | 1000 [3] | 1000 [3] | 25 |
| Atmosphere supplying | | | | |
| airline | 50 | 1000 | -- | -- |
| pressure demand | 50 | 1000 | 1000 | 25 |
| continuous flow | | | | |
| Self-contained | | | | |
| breathing apparatus | -- | 4) | -- | -- |
| pressure demand | | | | |
| open/closed circuit | | | | |

1 Includes ¼ mask, disposable half masks, and half masks with elastomeric face piece.
2 Demand SCBA must not be used for emergency situations such as fire fighting.
3 Protection factors listed are for high-efficiency filters and sorbents (cartridges and canisters). With dust filters, an assigned protection factor of 100 is to be used due to the limitations of the filter.
4 Although positive-pressure respirators are currently regarded as providing the highest level of respiratory protection, a limited number of recent simulated workplace studies concluded that all users may not achieve protection factors of 10,000. Based on this limited data, a definitive assigned protection factor could not be listed for positive pressure SCBAs. For emergency planning purposes where hazardous concentrations can be estimated, an assigned protection factor of no higher than 10,000 should be used.

**NOTE:** Assigned protection factors are not applicable for escape respirators. For combination respirators (e.g., airline respirators equipped with an air-purifying filter) the mode of operation in use will dictate the assigned protection factor to be applied.

## 3. SELF-STUDY SCENARIOS/ACTIVITIES AND SOLUTIONS

### *Activity*

In order to increase your familiarity with the aforementioned national and international documents on radiation protection, locate answers to the following questions. List your findings on the chart below

| Questions | Answer Location |
|---|---|
| **Example:** What is the document that was the driver for DOE's development of DOE Order 5480.11, *Radiation Protection for Occupational Workers* ? | *Radiation Protection Guidance to the Federal Agencies for Occupational Exposure* (52 FR 2822). |
| 1. What document has superseded 5480.11, *Radiation Protection for Occupational Workers* ? | |
| 2. What document(s) was used to establish the dose limits of 10 CFR 835? | |
| 3. What document superseded some of the concepts of ICRP 26? | |
| 4. What is the aim of ICRP 60? | |
| 5. What is the most significant change from ICRP 26 to ICRP 60? | |
| 6. What is a TEDE and how do you calculate it? | |
| 7. What does the acronym BEIR stand for? | |
| 8. How many BEIR Committees have there been and what was the study done by the last committee? | |
| 9. Has DOE adopted the findings of the BEIR V Committee? Why or why not? | |
| 10. What is the purpose of NCRP 91, which has been superseded by NCRP 116? | |
| 11. What is the purpose of ANSI Z88.2-1992? | |

### *Activity Solution*

| Questions | Answer Location |
|---|---|
| **Example:** What is the document that was the driver for DOE's development of DOE Order 5480.11, *Radiation Protection for Occupational Workers* ? | *Radiation Protection Guidance to the Federal Agencies for Occupational Exposure* (52 FR 2822). |
| 1. What document has superseded 5480.11, *Radiation Protection for Occupational Workers* ? | 10 CFR 835, *Occupational Radiation Protection; Final Rule*, and 441.2, *Radiological Protection for DOE Activities.* |
| 2. What document(s) was used to establish the dose limits of 10 CFR 835? | *Radiation Protection Guidance to the Federal Agencies for Occupational Exposure* (52 FR 2822). |
| 3. What document superseded some of the concepts of ICRP 26? | ICRP 60. |
| 4. What is the aim of ICRP 60? | To provide guidance on the fundamental principles on which appropriate radiological protection can be based. |
| 5. What is the most significant change from ICRP 26 to ICRP 60? | The interpretation of radiation detriment, resulting in a revision of the recommended dose limits. |
| 6. What is a TEDE and how do you calculate it? | Total effective dose equivalent is the sum of the deep dose equivalent and the committed effective dose equivalent and must be calculated on data on exposure to radioactive sources both external and internal to the body. |
| 7. What does the acronym BEIR stand for? | Biological Effects of Ionizing Radiation |
| 8. How many BEIR Committees have there been and what was the study done by the last committee? | V (5) and "Health Effects of Exposure to Low Levels of Ionizing Radiation," 1990. |
| 9. Has DOE adopted the findings of the BEIR V Committee? Why or why not? | No. An external Technical Review Committee concluded that the BEIR V risk estimates, when applied to DOE exposure situations, did not justify an immediate reduction of radiation protection limits. |
| 10. What is the purpose of NCRP 91, which has been superseded by NCRP 116? | It is a complete set of basic recommendations specifying dose limits for exposure to ionizing radiation. |
| 11. What is the purpose of ANSI Z88.2-1992? | To help establish, implement, and administer an effective respiratory protection program. |

## 4. SUGGESTED READINGS AND/OR COURSES

- *Radiation Protection Guidance to the Federal Agencies for Occupational Exposure* (52 FR 2822)
- *Recommendations of the Internal Commission on Radiological Protection*, International Commission on Radiological Protection (ICRP), Publication 26
- *1990 Recommendations of the International Commission on Radiological Protection*, Publication 60
- *A Technical Review and Assessment of the BEIR V Report* (DOE/EH-0149T), DOE Technical Review Committee
- Final Report to the Secretary of Energy,*Implications of the BEIR V Report to the Department of Energy* (DOE/EH-0158T)
- *Recommendations on Limits for Exposure to Ionizing Radiation*, National Council on Radiation Protection and Measurements (NCRP), Report No. 91
- *Limitation of Exposure to Ionizing Radiation*, National Council on Radiation Protection and Measurements (NCRP), Report No. 116
- *Practices for Respiratory Protection*, American National Standards Institute (ANSI Z88.2-1992)