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MEASURES OF EQUIVALENT HAZARD
OF RADIONUCLIDES: A SURVEY

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May 1978

This report was prepared by John W. Poston under subcontract 7278 with Union Carbide Corporation, Nuclear Division. The subcontract was administered by the Office of Waste Isolation.

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OAK RIDGE, TENNESSEE

*prepared for the U.S. DEPARTMENT OF ENERGY under
U.S. GOVERNMENT Contract W-7405 eng 26*

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Abstract

The need for methods to evaluate, on a common scale, the impact of radionuclides on man and his environment has long been recognized. This report reviews a variety of special and general formulations intended to meet this need. It reveals that no single formulation exists which will be totally acceptable in its current state of development. However, particular attention is given to several formulations which exhibit a potential for wider application, especially to the impact of a geologic waste repository.

Introduction

Radiation exposures to external radiation or to releases of radioactivity are controlled by the application of guidelines promulgated by national and international committees on radiation protection. These guidelines usually specify the maximum permissible dose (MPD) or the maximum permissible concentration (MPC) of a radionuclide to which a radiation worker may be exposed. Maximum concentration values have been calculated for a normal work situation (i.e. 40 hrs/wk) and also for continuous exposure (i.e. 168 hrs/wk) for either inhalation (MPC_a) or ingestion (MPC_w) of radionuclides. In addition, it is usually assumed that some fraction of these guidelines (e.g. 1/10th of the 168 hr MPC) is the acceptable exposure level for members of the general population.

These guidelines, especially those for the general population, are utilized in the evaluation of nuclear energy use impacts on man and his environment. The shortcomings of the MPC concept and its applicability in hazards evaluations have long been recognized. The increased emphasis on keeping exposures as low as readily achievable (ALARA) magnifies the need for a concept or guideline for controlling exposures at less than the maximum allowable. Many authors have presented their ideas for new concepts which would be more useful in evaluating the hazard associated with the various uses of nuclear energy. However, most of these concepts still utilize terms such as maximum permissible intake, maximum permissible concentrations, etc.

This manuscript is intended to present the results of a literature

survey and review of some of the most common hazard measure concepts in use in the field. The review represents the first phase of a project intended to derive a more useful and meaningful measure of the relative hazard of a wide variety of radionuclides. The development of such a measure of hazard is intended to have direct applicability to the evaluation of long-term geologic waste disposal concepts. It is also anticipated that the hazard measure should be applicable to all areas requiring the evaluation of impacts of nuclear energy.

General Discussion

Most of the concepts developed for this purpose involve, in some form, the use of the maximum permissible concentration values published by the national and international committees on radiation protection. The most common technique is to express the hazard measure as the quotient of the total inventory of a particular nuclide and the maximum permissible concentration of that radionuclide in air or in water. This quotient, in effect, gives the quantity of air or water necessary to dilute the radionuclide to concentrations below the MPC. These concepts consider only one of the important variables which must be evaluated. The variables to be considered include, not only of the quantities of individual radionuclides, but also their relative toxicities, decay schemes, daughter products, the time period of toxicity, and environmental transport. Nevertheless, these concepts form the basis on which we must build and, therefore, are discussed in the following section.

Hazard Indices

One of the first large-scale attempts directed toward expressing the relative hazard of various radionuclides was published in 1955 by Morgan and his colleagues (Mo55). These authors published relative hazard values for a large number of radionuclides and several different exposure situations. The values were for accidental, single exposures, rather than continuous exposures, and considered only inhalation or injection of either a soluble or insoluble radioactive material. The authors expressed the relative hazard (H), in case of a spill or accident involving 100 mCi of radioactive material, as:

$$H = \frac{10}{(\text{MPI})(\text{mg}/100 \text{ mCi})}$$

In this equation, 10/(mg/100 mCi) is the probability of inhalation of 10 mg of radioactive material. MPI is the maximum permissible intake which can be calculated by equations specified in the text of the paper. The equation was derived based on a consideration of the maximum dust loading of industrial air and a determination of the average radioactivity per shipment of more than 52,000 shipments of radioactive material from ORNL during 1954. So, for convenience, it was assumed that the average accident involved a total activity of 100 mCi. A more general form of the equation, given by these authors, is

$$H = \frac{0.1}{(\text{MPC}) \times D \times (\text{mg}/\text{mCi})}$$

in which (MPC) is the maximum permissible concentration ($\mu\text{Ci}/\text{cm}^3$) in the

medium, D is the daily intake of the medium, and 0.1 (mg/mCi) is the probability, P, of inhalation of a given quantity of the radionuclide. When the value of mg/mCi is less than 0.1, P is set equal to 1.

In 1964, Morgan and his colleagues (Mo64) published the results of additional calculations utilizing the term, relative hazard. In this case, H was given for various radionuclides under uniform working conditions. For convenience, in this comparison, ^{226}Ra was taken as the reference standard. In other words, the relative hazard, H, is equal to 1 for ^{226}Ra . The general equation for the relative hazard in this case is

$$H = \frac{2.92 \times 10^{-11} \phi(\text{c/g})}{\text{MPC}}$$

where the MPC is the maximum permissible concentration in the particular medium and $\phi(\text{c/g})$ is a function of the specific activity (Ci/g) of the radionuclide. For simplicity it was assumed that $\phi(\text{c/g}) = \text{Ci/g} \leq 10$ and $\phi(\text{c/g}) = 10$ if $\text{Ci/g} > 10$. Note that, for $H = 1$ and $\phi(\text{c/g}) = 1$, the MPC for ^{226}Ra is about $3 \times 10^{-11} \mu\text{Ci/cm}^3$ which corresponds to the $(\text{MPC})_a$ for the soluble material as given by the International Commission on Radiological Protection (ICRP59).

Morgan et al (Mo64) pointed out that there were significant uncertainties in the biological data used in the calculations of MPC values for the handbooks. Because of this, the hazards of ^{226}Ra and ^{239}Pu were approximately equivalent and it was possible also to use the same equation to express the hazard of a particular radionuclide relative to

^{239}Pu rather than ^{226}Ra . It was this latter formulation, i.e. relative hazard normalized to ^{239}Pu , that was adopted for use at the Oak Ridge National Laboratory (see, for example, Applied Health Physics and Safety Procedure 1.5). The formulation was called the Hazard Equivalent Plutonium (HEP), but was based on the consideration of radionuclide hazards relative to ^{226}Ra .

Gera and Jacobs (Ge71) proposed a potential hazard index (PHI) which was an extension of a widely used hazard index (HI) attributed to Hilliar (Hi68). This latter author proposed to estimate the relative hazard of radionuclides by the relation

$$\text{HI} = \frac{Q}{\text{MPC}}$$

where Q is the total activity of a particular radionuclide. MPC is the maximum permissible concentration in either air or water depending upon whether the intake pathway of concern is ingestion or inhalation. It has been pointed out (Sm76) that HI is a good measure of the short-term hazard of a radionuclide or a mixture of radionuclides. However, it does not explicitly account for the long-term radionuclide availability.

The potential hazard index, proposed by Gera and Jacobs, is represented by the equation:

$$\text{PHI} = e^{\left(\frac{T}{\ln 2}\right)} \left(\frac{Q}{\text{MPI}}\right)$$

where e is the biological availability of the radionuclide once it is

dispersed to the environment, r represents the reliability of containment of the radioactive materials, T is the radioactive half-life, Q is the activity of the radionuclide, and MPI is the maximum permissible annual intake of the radionuclide. This particular formulation was intended to apply specifically to the long-term global risks to mankind from the presence of radionuclides in the environment. Since e and r were not known it was assumed, in all cases, that they both were equal to unity.

Jacobs and Gera compared their results, obtained by evaluating the PHI for ingestion and inhalation exposures, to the data reported by several authors. These included Morgan et al (Mo64) and Hilliar (Hi68). They calculated the PHI for 23 radionuclides ranging from 3H to ^{244}Cm and normalized all the data to a hazard of one for tritium. It is interesting to note, see Table I for representative values, that in some cases the comparisons agree well whereas in other cases there are order of magnitude discrepancies.

A more complete expression for the potential hazard index was also presented by Gera and Jacobs in this same manuscript. This relation can be written:

$$PHI = rQ \frac{T}{\ln 2} \left[\frac{a}{(MPI)_{inh.}} + \frac{b}{(MPI)_{ing.}} \right]$$

where

r = the reliability of the containment of radioactive materials

Q = the total activity of the radionuclide

T = the radioactive half-life of the material

Table I. Comparison of Relative Hazard Indices*

Radionuclide	Morgan et al.	Hilliard	Jacobs and Gera	
			Inhalation	Ingestion
^3H	1	1	1	1
^{14}C	7.0×10^{-1}	1.5	6.3×10^2	1.8×10^3
^{32}P	7.4×10^1	7.5×10^1	2.1×10^{-1}	5.4×10^{-1}
^{58}Co	9.7×10^1	9.7×10^1	1.3	5.6×10^{-1}
^{60}Co	6.0×10^2	6.0×10^2	2.3×10^2	3.9×10^1
^{90}Sr	1.8×10^4	1.8×10^4	9.2×10^3	1.8×10^4
^{106}Ru	9.5×10^2	9.5×10^2	6.9×10^1	2.2×10^1
^{131}I	6.1×10^2	6.2×10^2	1.0	2.8
^{137}Cs	3.6×10^2	3.6×10^2	7.9×10^2	5.2×10^2
^{144}Ce	8.2×10^2	8.2×10^2	4.6×10^1	1.7×10^1
^{210}Pb	4.2×10^4	4.2×10^4	6.7×10^4	4.7×10^4
^{210}Po	2.6×10^4	2.6×10^4	7.2×10^2	1.3×10^2
^{226}Ra	1.8×10^4	1.8×10^5	2.2×10^7	3.4×10^7
^{239}Pu	1.9×10^4	3.1×10^6	5.4×10^9	1.4×10^6
^{240}Pu	6.9×10^4	3.1×10^6	1.5×10^9	3.8×10^5
^{241}Pu	5.8×10^4	5.8×10^4	5.5×10^4	1.5×10^1
^{241}Am	2.9×10^5	9.0×10^5	2.9×10^7	3.1×10^4
^{242}Cm	4.4×10^4	4.4×10^4	1.4×10^3	4.9
^{244}Cm	5.8×10^5	5.8×10^5	7.3×10^5	6.4×10^2

* Adapted from Gera and Jacobs (Ge71).

a,b = factors representing the biological availability (or probability of intake) of the material for inhalation and ingestion, respectively

$(MPI)_{inh}$, $(MPI)_{ing}$ = the maximum permissible intake by inhalation and ingestion, respectively.

These authors point out that, in the above equation, r is the only factor on which human action can have an effect. This factor represents the probability of pollution of the environment by the radioactive materials. For radioactive materials the factor r must be evaluated for the particular situation. That is, although the potential hazard index was designed specifically to be applied to the storage of radioactive wastes, the index is applicable to any situation through a careful evaluation of the factor, r.

The term radiotoxic hazard measure (RHM) has been introduced by Hamstra (Ha75). This author followed closely the work of Bell and Dillon (Be71) and Claiborne (Cl72). He defined the radiotoxic hazard measure as

$$(RHM)_i = \frac{Q_i}{(MPC_w)_i}$$

where Q_i is the radioactivity of nuclide i in curies and $(MPC_w)_i$ is the maximum permissible concentration in drinking water for nuclide i in curies per cubic meter. Hamstra utilized the RHM to evaluate the impact of reprocessing waste from light water reactors for various decay periods. He also presented data which compared LWRs and LMFBRs in terms of the radiotoxic hazard measures for the reprocessing wastes.

The most recent hazard concept was introduced by Smith and his colleagues (Sm76). This index was designed to provide an evaluation of

nuclide hazards appropriate for long-term management of radioactive material. The relative hazard index was defined in its general form by:

$$H(t,d) = \sum_j \int_t^{t+d} \frac{Q_j(t')}{MPI_j} dt'$$

where the activity of nuclide j as a function of time is given by Q_j ; MPI_j is the maximum permissible annual intake of nuclide j ; and j is an index that permits summation over the given nuclide and its radioactive daughters. H is functionally dependent on the integral limit parameter t and d . The physical meanings of these parameters are that t is the time at which the radionuclides are released to the environment, and the period of time t to $t+d$ is the time interval of concern for the hazard calculation.

The important features of this hazard index are that it takes into account multiple decay schemes, conditions of buildup and equilibrium as well as simple decay, and it allows the time period of concern to be explicitly stated. However, this index of nuclide hazard applies only to the intrinsic hazard due to the nuclide radioactivity over the specified time period. It does not attempt to treat exposure pathways which can be effected by chemical and physical forms, geographic location, systems for management and containment, and similar factors.

Other Proposed Indices of Hazard

The Environmental Protection Agency has proposed a concept called the "environmental radiation dose commitment" (EPA74). However, this concept has caused some controversy in the open literature (Li74, Ri75). This

concept is defined simply as the sum of all doses to individuals over the entire time period the material persists in the environment in a state available for interaction with humans.

In equation form, the environmental dose commitment is given by:

$$D_i(t) = \sum_{n=0}^{\infty} Q_i(t) e^{-\lambda_i n} T_i(n) F_i P(t+n)$$

where $D_i(t)$ is the cumulative population dose resulting from the release of radionuclide i in calendar year t and $Q_i(t)$ is the quantity of radionuclide i released in the year t . The other parameters are the radioactive decay factor for radionuclide i , λ_i ; the pathway model conversion factor, $T_i(n)$, relating the quantity of radionuclide i released to its concentration in the medium at the location of interest or years following release; F_i is the dosimetry conversion factor relating concentration of the radionuclide in the medium to resultant dose to individuals exposed. The factor $P(t+n)$ is the number of persons exposed in calendar year of release and n is the number of years from year t .

The concept was tested, through calculations, for four selected groups of radionuclides. These were tritium, ^{85}Kr , ^{129}I , and the actinides including ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Pu , ^{242}Cm , and ^{244}Cm . The evaluation included not only calculation of the dose commitment, but also an estimation of the number of health effects (both fatal and nonfatal) which would arise from such exposures.

A concept which was introduced recently is based on suggestions of Jacobi on the "effective dose" (Ja75). Laws and Rosenstein (La77) have formulated what is termed a somatic dose index for diagnostic radiology.

This concept is not directly applicable to the evaluation of the geologic disposal of radioactive wastes. However, some of the parameters factored into this index could ultimately be included in a similar index for the dosimetry associated with radioactive wastes. Therefore, the somatic dose index, I_D , is defined as:

$$I_D = \frac{\sum_{i=1}^n S_i \alpha_i \bar{D}_i}{\sum_{i=1}^n S_i \alpha_i}$$

where i indicates the organ of interest, $\bar{D}_i$ is the average absorbed dose in the organ, and n is the total number of organs under consideration.

The factor $S_i \alpha_i$ represents the sensitivity of the organ for the effect. The application of this concept requires the definitive knowledge of the absolute risks (α_i) for cancer induction and the relative severities (S_i).

The term "CUE" was introduced in 1970 by Rohwer et al. (Ro70). The concept, embodied in this acronym, was originally intended as a radiation safety guide for transient exposures. CUE was developed and applied to the evaluation of a sea-level "Panama" canal constructed with nuclear explosives. There were two methods used to calculate CUE. The first method was based on the organ-burden limitation. The initial step in this method is determination of the organ burden consistent with the selected annual dose limit. The organ burden estimate is used in conjunction with an uptake fraction and an inhalation rate to determine CUE for a single-mode (inhalation) exposure as follows:

$$CUE_{ij}^{inh.} = \frac{b_{ij}}{(f_a)_{ij} 8.33 \times 10^5}$$

where

$CUE_{ij}^{inh.}$ = transient-exposure guide ($\mu\text{Ci} - \text{hr}/\text{cm}^3$) for the i^{th} radionuclide based on exposure of the j^{th} organ via inhalation only,

b_{ij} = burden (μCi) for the i^{th} radionuclide in the j^{th} organ, consistent with the selected annual dose limit,

$(f_a)_{ij}$ = fraction of inhaled i^{th} radionuclide reaching the j^{th} organ

8.33×10^5 = inhalation rate (cm^3/hr).

Control of an exposure situation to meet this time-integrated radionuclide concentration in air will restrict the inhalation dose to the j^{th} organ in accordance with an organ burden consistent with the annual dose limit selected for that organ. This method provides a transient radiation guide which is useful for radionuclides with short half-lives, but is not so useful for radionuclides with long half-lives. The second method of calculating CUE provides more conservative guidance for radionuclides with long effective half-lives.

The second method of calculating CUE is based on a dose commitment limitation. "Dose Commitment" is defined as the total dose an individual will accrue within a lifetime as a result of a radionuclide intake. A $CUE_{ij}^{inh.}$ calculated by the following method is intended to restrict intake via inhalation such that the resulting dose commitment will not exceed the annual dose limit.

$$CUE_{ij}^{inh.} = \frac{R_j}{d_{ij}^{inh.} \cdot 8.33 \times 10^5} \mu\text{Ci} - \text{hr}/\text{cm}^3$$

where

R_j = selected dose limit (rems/year) for the j^{th} organ, as apportioned to the type of exposure under consideration.

$d_{ij}^{inh.}$ = dose commitment to the j^{th} organ per microcurie of the i^{th} radionuclide inhaled [rems/lifetime (years)/ μCi],

8.33×10^5 = inhalation rate (cm^3/hr).

$CUE_{ij}^{inh.}$ values obtained with this method are less restrictive (i.e., larger values) for radionuclides with short (less than a few months) effective half-lives and are more restrictive for radionuclides with long (years) effective half-lives.

An exposure equivalent to $CUE_{ij}^{inh.}$ would result, according to these relations, in a dose or dose commitment via inhalation which is equal to the selected annual dose limit. Any dose or dose commitment from other exposure modes would result in a total dose or dose commitment exceeding that limit. For this reason, $CUE_{ij}^{inh.}$ must be reduced proportionately, depending upon dose contributions from other exposure modes. Thus,

$$CUE_{ij} = CUE_{ij}^{inh.} \frac{R_j}{R_j + (D_{ij} - D_{ij}^{inh.})}$$

where

CUE = transient exposure guide ($\mu\text{Ci-hr}/\text{cm}^3$) for the i^{th} radionuclide based on exposure of the j^{th} organ via all exposure modes.

D_{ij} = dose or dose commitment (rems/year) to the j^{th} organ
 from the i^{th} radionuclide via all exposure modes for
 an exposure equivalent to $CUE_{ij}^{\text{inh.}}$,
 $D_{ij}^{\text{inh.}}$ = dose or dose commitment (rems/year) to the j^{th} organ
 from the i^{th} radionuclide via inhalation only for an
 exposure equivalent to $CUE_{ij}^{\text{inh.}}$.

Modification of CUE to incorporate external dose contributions resulting from submersion in a radioactive cloud is an easy adjustment to make. Adjustment of CUE to include possible dose contributions resulting from ingestion of radioactive materials is more difficult.

CUE is calculated for each radionuclide assuming that no other radionuclides are present. To assess the impact of one radionuclide requires only a direct comparison of the time-integrated exposure (microcurie-hours per cubic centimeter) with the appropriate value of CUE. Assessment of an event involving a mixture of radionuclides requires an additional calculation. For exposure to a mixture of radionuclides, the following conditions for each organ must be satisfied if the total dose expected from all radionuclides is not to exceed the selected annual dose limits:

$$\sum_{i=0}^n \frac{E_i}{CUE_{ij}} \leq 1$$

where E_i is the time integrated exposure for the i^{th} radionuclide and CUE_{ij} is as previously defined.

By 1971, the CUE concept had been extended and modified to consider continuous release situations (Ro71). The concept was renamed CUEX,

an acronym for Cumulative Exposure Index. CUEX was developed to facilitate realistic dose assessment from environmental contamination. The aim of the concept was to assess the release on the basis of time-integrated radionuclide concentrations measured in suitable environmental sampling media. Nevertheless, the basic concept and equations were essentially the same as those discussed above for CUE.

The term radionuclide importance index (RII) was introduced by Leonard and his colleagues (Le69). This index was developed as an ancillary portion of a larger program directed toward an evaluation of available information on radionuclide production in advanced reactor types. This evaluation would provide some insight into the public health concerns arising from the potential release of small amounts of these radionuclides during routine operation.

The radionuclide importance index is defined as:

$$RII = \frac{P}{B} \times \frac{\tau}{t}$$

where

P = production rate of the radionuclide (atoms/cm³-sec),

B = biological importance factor (disintegrations/atom-cm³-sec),

τ = physical half-life (seconds),

t = characteristic time for transport and release to the environment (seconds).

The production rate factor, P, represents the average rate at which a given radionuclide is formed (by fission and subsequent decay or by neutron absorption) in a nuclear reactor.

The RII is directly proportional to P since a nuclide can be of concern only if it is produced in a significant quantity.

The biological importance factor, B, represents the allowable exposure to a particular radionuclide for the general public based on direct ingestion. This factor is defined as:

$$B = \frac{CMR}{T f_a \epsilon [1 - \exp (-0.693\tau/T)]}$$

where

B = biological factor (dis/sec.cm³),

C = numerical conversion constant,

M = mass of critical body organ for a specific radionuclide (grams),

R = effective radius of the critical body organ (cm),

T = effective half-life (years).

ϵ = effective energy per decay (MeV),

f_a = fraction of the radionuclide ingested reaching the critical organ,

τ = physical half-life (years).

This factor accounts for exposure of the critical organ by direct ingestion, including consideration of the effective biological half-life. A higher value of this maximum permissible concentration indicates a lower level of health concern, all other factors being constant. Consequently, B appears in the denominator of the RII expression.

Leonard and his colleagues list a large number of radionuclides which could conceivably be present in fuel in appreciable quantities based on

fundamental fission yield, decay, and absorption relationships. They also compare the list they compiled to several other lists compiled for various hazards evaluations. In all, their data table provides some information on about 230 radionuclides.

Two very specialized papers have appeared which treat the relative inhalation hazard of radionuclides. The first of these was the work of Raabe (Ra70) who presented an approach which involved the relative probabilities of accidental release and the relative probabilities of the production of airborne material of soluble or insoluble forms with respect to lung clearance. He combined estimated release probabilities and solubility probabilities with organ dose calculations at 7 days and 6000 days to rank the various nuclides with respect to their potential importance if inhalation is the route of entry into the body. The ranking was based on the multiplication of (a) the reactor inventory values, (b) relative release probability, (c) the relative solubility probability (or its complement for insoluble forms), and (d) the dose to organ of highest dose (for the two time periods of concern) after inhalation deposition of $1\mu\text{Ci}$ in the lower lung. The results emphasize the importance of I-131, Cm-242, Ce/Pr-144, Pu-238, Sr/Y-90, Y-91, Te/I-132, Sr-89, Ba/La-140, Mo-99, Np-239, Pu-239, Zr/Nb-95, Cs/Ba-137, and Ru/Rh-103.

The work of Ramu (Ram74) was even more specialized. He described a new approach to minimize inhalation risk from particulate pollutants in industries, taking into account lung volumes, breathing frequencies, and their influence on aerosol deposition in the human lung. The index of inhalation risk was defined as the ratio of the functional residual volume to the tidal volume for a given breathing frequency. However, the

index has a limited use in that it does not include the clearance rates of the deposited particles. To make the index more meaningful, several factors should be added into the formulation. These factors include the dependence of the clearance rates on phagocytic activity and the efficiency of ciliary movement of the mucus.

Summary and Conclusions

There have been many attempts to formulate a concept which can be used to relate the hazards of radionuclides one-to-another on a common scale. These efforts date back to the very early beginnings of the radiation protection profession (Mo55). Several efforts are now underway to formulate a more useful hazard measure based on previous work (Le77, Go77, Ma78). This review has discussed a number of these concepts and formulations, some in more detail than others. The detailed discussion indicates the potential applicability of the concept to the evaluation of the impact of a radioactive waste repository on man and his environment.

The answers to a number of questions have been sought during this review. These questions were not answered specifically in the discussion of each concept. However, they formed the basis for the initial review. These questions include: How are the concepts used? Are the concepts used correctly? Are the concepts potentially useful in many areas of radiation protection? Can any of the concepts be modified or extended to be applicable to the general needs in radiation protection? And, more specifically, can they be used in the evaluation of the impact of a radioactive waste repository on man and his environment?

Some formulations have been included in the discussion to illustrate both the simplicities and complexities involved in the process. In some cases the formulation encompasses a very simple idea and has only limited applicability. In other cases, important parameters are included which are extremely hard to quantify. However, a check list of important points to be considered in any concept has been compiled.

These points include the following.

a) The concept should consider a number of parameters:

- (1) Mode of intake; ingestion, inhalation, incorporation in foodstuffs, etc.
- (2) Chemical form of the radionuclides; solubility, volatility, most likely form, etc.
- (3) Some measure of the quantity must be selected; e.g., mass, activity, concentration, etc.
- (4) The important organ or organ system must be identified; e.g., whole body, organ specific, relative radiosensitivity of the organs, etc. In addition, the distribution of the radionuclide in the organ must be considered.
- (5) The appropriate period over which the effect must be evaluated should be considered. That is, acute exposure (accident conditions) as well as chronic exposures must be included. Should the period over which chronic exposure is to be considered be 50, 70, or 100 years?
- (6) Environment transport and discrimination factors.

c) The concept should also consider the radiotoxicity of the radionuclide in relation to the chemical toxicity of the substance.

The important point here is that the concepts which have been used employed only a few of the above parameters. This is the reason the concepts generally have found only limited use. The above listing, although perhaps still incomplete, may represent an unattainable goal. However, the goal should always be kept in mind during the further evaluation of existing concepts and/or the development of a more generalized concept.

In summary, no "universal" hazard measure has been found which will have applicability in every area of radiation protection. However, several of the concepts discussed have a potential for modification and extension, especially in the evaluation of the impacts of a radioactive waste repository. These concepts include those of Gera and Jacobs (Ge71), Rohwer et al. (Ro70,Ro71), and Smith et al. (Sm76). There are other evaluation systems which have been formulated (e.g., So74,So76), but these do not encompass the relative hazards of a wide variety of radionuclides. One major problem remains to be solved; all formulations include either a maximum permissible intake or a maximum permissible exposure term. With the continued emphasis on ALARA and the controversy over low-level radiation effects, the use of such "maximum" terms will probably not be completely acceptable to the regulatory agencies nor the public. Thus, in order to obtain wide acceptance, any formulation should include the introduction of an alternate method of hazard comparison. No such alternate exists at this time. However, the proposed evaluation scheme introduced recently by the ICRP (ICRP77) and its use in the forthcoming ICRP Committee 2 report (ICRP78) may provide the necessary

guidance. At this time the report is in draft and detailed discussions may prove inaccurate. It is recommended that both a detailed consideration of ICRP26 and the report of Committee 2 be factored into the early stages of Phase II of this project.

Acknowledgments

The author would like to express his appreciation to those who have contributed to this manuscript. Special thanks is due Elliott D. Lesses (Savannah River Plant) for the valuable discussions and interchanges during the early stages of this review. Thanks also to J. B. Martin (BNWL), R. L. Shoup (OWI), W. A. Goldsmith (OWI), and their colleagues for their very helpful comments and criticisms of the drafts of this manuscript. Finally, a special thanks to Mrs. R. Salley for her patience and care in typing this report.

References

- AHPS ORNL Applied Health Physics and Safety Manual, Procedure 1.5, Radiation Safety Review and Authorization of Operations and Experiments (1970).
- Be71 M. J. Bell and R. S. Dillon, "The Long-Term Hazard of Radioactive Wastes Produced by the Enriched Uranium, Pu-²³⁸U, and ²³³U-Th Fuel Cycles," USAEC Report ORNL-TM-3548, Oak Ridge National Laboratory (November 1971).
- C172 H. C. Claiborne, "Neutron-Induced Transmutation of High-Level Radioactive Waste," USAEC Report ORNL-TM-3964, Oak Ridge National Laboratory (December 1972).
- EPA74 "Environmental Radiation Dose Commitment: An Application to the Nuclear Power Industry," USEPA Office of Radiation Programs (June 1974).
- Ge71 F. Gera and D. G. Jacobs, "Hazard Potential of Radioactive Wastes," Proc. Int. Conf. Radioecology Applied to the Protection of Man and his Environment, EUR-4800 (Rome 1971).
- Go77 W. A. Goldsmith, Personal Communication (1977).
- Ha75 J. Hamstra, "Radiotoxic Hazard Measure for Buried Solid Radioactive Waste," Nuclear Safety 16 (2) (March-April 1975).
- Hi68 R. A. Hilliar, "Relative Inhalation Hazards from Nuclides Present in Fresh Irradiated Fuel," RD/B/N/-1143 (1968).
- ICRP59 Recommendations of the International Commission on Radiological Protection, Report of Committee II on Permissible Dose for Internal Radiation, ICRP Publication 2, Pergamon Press (1959).
- ICRP77 Recommendations of the International Commission on Radiological Protection, ICRP Publication 26, Annals of the ICRP, Pergamon Press (1977).
- ICRP78 Report of the International Commission on Radiological Protection, Committee 2, "Limits for Intakes of Radionuclides by Workers," draft February (1978).
- Ja75 W. Jacobi, "The Concept of the Effective Dose - A Proposal for the Combination of Organ Doses," Rad. Environm. Biophys. 12, 101-109 (1975).
- La77 P. W. Laws and M. Rosenstein, "A Somatic Dose Index for Diagnostic Radiology," 22nd Annual Mtg. of the Health Physics Society, Atlanta (July 1977).

- Le69 J. H. Leonard, L. E. Eckart and J. E. Mountain, "Radionuclide Production and Release in Advanced Nuclear Reactor Types," Final Summary Report for Contract CPE-R-69-12, University of Cincinnati (October 1969).
- Le77 E. D. Lesses, Personal Communication (1977).
- Li74 B. Lindell, "The 'New' Concept of the EPA," Health Physics 27, 324-325 (1974).
- Ma78 J. B. Martin, Personal Communication (1978).
- Mo55 K. Z. Morgan, W. S. Snyder and M. R. Ford, "Maximum Permissible Concentration of Radioisotopes in Air and Water for Short Period Exposure," Proc. 1st Int'l Conf. Peaceful Uses of Atomic Energy, 13, 139-158 (1955).
- Mo64 K. Z. Morgan, W. S. Snyder and M. R. Ford, "Relative Hazard of the Various Radioactive Materials," Health Physics 10, 151-169 (1964).
- Ra70 Otto G. Raabe, "Estimation of the Relative Inhalation Hazard of Reactor Inventory Radionuclides," 5th Midyear Topical Symposium of the Health Physics Society, Idaho Falls (Idaho 1970).
- Ram74 M. C. Subba Ramu, "An Index of Risk for Inhalation Hazard Evaluation," Health Physics 27, 353-358 (1974).
- Ri75 A. C. B. Richardson, "Environmental Dose Commitment," Health Physics 29, 353-354 (1975).
- Ro70 P. S. Rohwer, S. V. Kaye, J. R. Lund, E. G. Struxness, R. S. Booth and B. F. Roberts, "Development of Radiation Safety Guides for Transient Exposures," Health Phys. Div. Ann. Prog. Rpt., ORNL-4584 (October 1970).
- Ro71 P. S. Rohwer, R. S. Booth, S. V. Kaye and E. G. Struxness, "Development of Radiation Safety Guides for Environmental Releases of Radioactivity," Health Phys. Div. Ann. Prog. Rpt., ORNL-4720 (October 1971).
- Sm76 C. F. Smith, T. W. T. Burnett and W. E. Kastenberg, "A New Relative Hazard Index," Proc. of a Symp. on Biol. Effects of Low-Level Radiation, 325-333, IAEA (1976).
- So74 J. K. Soldat, N. M. Robinson and D. A. Baker, "Models and Computer Codes for Evaluating Environmental Radiation Doses," BNWL-1754, February (1974).
- So76 J. K. Soldat, "Radiation Doses from Iodine-129 in the Environment," Health Phys. 30, 61-70 (1976).