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Optimization of Public and Occupational Radiation Protection at Nuclear Power Plants

Considerations in Factoring Occupational Dose into Value-Impact and Cost-Benefit Analyses

Prepared by J. J. Cohen

Science Applications, Inc.

Prepared for
U.S. Nuclear Regulatory
Commission

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Until recently decision makers on the Nuclear Regulatory Commission staff have had to evaluate proposals for new maintenance and inspection requirements at nuclear power plants without the benefit of quantitative comparisons between the risk potential averted by the new requirement and the occupational risk created at the same time. While it was fully recognized that the generation of quantitative information of high precision would not be possible, it was also recognized that improved analytical techniques for quantitative comparisons could contribute substantially to the decision making process. Therefore funding was requested for a research project to develop an appropriate technique, to document it, and to provide comprehensive supporting material which would enable users to understand its strenths and weakness and to evaluate the rationale on which it is based. The project was awarded to SAI, Inc., and it has, I believe, been very ably carried out by the SAI staff.

R E Alexander

Robert E. Alexander, Chief
Occupational Radiation Protection Branch
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ABSTRACT

Many NRC decisions intended for the improvement of public health and safety involve concomitant increases in occupational radiation exposure. Previous study (Volume 1) indicates that occupational dose consequences generally have not been considered in cost-benefit and value-impact analyses supporting decisions related to public safety. Such consideration, however, would be consistent with ALARA guidance.

This study derives a methodology for factoring occupational dose into cost benefit analyses. The related issues include: evaluation of occupational vs. public radiation exposure, stochastic vs. non-stochastic effects, probabilistic risk considerations, uncertainty, and de minimus dose levels.

A suggested formulation for determination of total detriment resulting from a given decision is:

$$CD_n = \left[(p \cdot CD_p{}^{\alpha}) + q(p \cdot CD_o)^{\alpha} \right] 0,i,j....$$

and:

CD_p = Public collective dose (man-rem)
CD_o = Occupational collective dose (man-rem)
p = Probability of occurrence
α = Aversion factor
$0,i,j$ = Alternative states
q = Equivalence factor

where:

$$q = \frac{\text{Value per unit of occupational collective dose averted}}{\text{Value per unit of public collective dose averted}}$$

Values for the various factors in the formulation are reviewed and discussed. To a large extent, certain of these factors must be based on the subjective judgment of decision makers. First approximations for these values are suggested.

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1. INTRODUCTION

1.1 Background

An area of growing concern in recent years has been the apparent increase in levels of collective radiation dose to workers at nuclear power plants in the USA (Brooks, 1980; Kasperson, 1982; GAO, 1982). NRC decisions and rulings related to inservice inspection, retrofits, and plant upgrades have been primarily intended to reduce the risk of public radiation exposure resulting from either routine release of radioactivity or potential accident situations. However, implementation of the required control measures and procedures can often result in increased levels of occupational radiation exposure. Recognizing the need to incorporate occupational dose into probabilistic risk assessments (PRA), value-impact, and cost-benefit analyses, the NRC has sponsored this study with the objective of developing an appropriate methodology to factor potential worker exposures into safety assessments.

ALARA guidance for optimization of radiation exposures to the general public requires the consideration of all relevant social and economic as well as technical factors. Clearly, any resultant increase in occupational dose should be included in such assessments. However, a review of several previous PRA's and cost-benefit analyses indicates this has not been the case until recent years. Even in cases where occupational dose has been considered, it has seldom, if ever, been done in a quantitative and analytical manner (Lobner, 1983). In some cases the implementation of decisions intended for reduction of public dose can actually result in collective occupational dose levels exceeding the averted public collective dose (Lombard, 1981). To properly evaluate such situations, guidance is required on methodology for factoring risk to workers into decision processes associated with public safety.

1.2 Statement of Problem

A basic philosophy of radiation protection has evolved over the last fifty years. This philosophy has three fundamental precepts (ICRP, 1977):

- No practice involving possible radiation exposure shall be adopted unless its introduction produces a positive net benefit.
- All exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account.
- The dose equivalent to individuals shall not exceed the applicable numerical dose limits.

These three precepts are usually referred to as justification, optimization and limitation. This report deals primarily with the second of these: exposure optimization.

Historically, exposure optimization has been referred to as "ALAP", as low as practicable, and "ALARA", as low as reasonably achievable. The Nuclear Regulatory Commission addressed ALAP with respect to nuclear power plant effluents in 1975. The result was the promulgation of Appendix I to 10 CFR 50. This rule defined an optimization technique for process effluent control, including a cost-effectiveness criterion. The cost side of the analysis included dollar costs for effluent treatment systems. These costs were weighed against corresponding reductions in offsite radiation exposure. Occupational exposures resulting from control system construction (backfit) and maintenance were not factored into the analysis (10 CFR 50 Appendix I; NRC Regulatory Guide 1.110).

In 10 CFR 20.1(c) (NRC, 1981), the NRC requires radiation exposures and radioactive effluents to be ALARA. The regulation defines ALARA as: "as low as is reasonably achievable taking into account the state of technology, and the economics of improvements in relation to benefits to the public health and safety, and other societal and socioeconomic considerations, and in relation to the utilization of atomic energy in the public interest." Further guidance is given in NRC Regulatory Guide 8.8 (NRC, 1977). However, the balancing of occupational dose incurred against public dose averted has not been addressed.

A major technique for use in dose optimization is cost-benefit analysis. However, in certain cases, it is possible to apply other qualitative or quantitative techniques. This report will explore considerations of cost-benefit techniques, especially the selection of a cost-effectiveness criterion, and balancing of occupational exposures incurred against averted public exposures.

1.3 ALARA

The ICRP (1977) prescribes that all radiation exposures be reduced to levels which are "as low as reasonably achievable" (ALARA) "economic and social factors being taken into account." To determine whether the reduction of dose beyond some given level is justified, ICRP suggests that any increased benefit obtained by further reduction in exposure should be weighed against the cost of obtaining the reduction. The benefit in this case would be the resultant decrease in the risk of adverse health effects resulting from the reduced radiation exposure. A theoretical "optimum" is reached when the sum of all "costs", including direct monetary costs and the surrogate costs ascribed to health detriment, is minimized. An optimum condition can also be determined at the point where the marginal (incremental) cost per unit of benefit (detriment averted) begins to exceed some predetermined cost effectiveness guideline.

1.4 Cost-Benefit Analysis

Cost-benefit analysis provides a methodology for determining the point at which optimal conditions are reached. A more euphemistic synonym is value-impact analysis. The latter term is often preferred since it is less likely to convey a connotation of trading off money against life and health. Explicit consideration of such a tradeoff may be offensive to some observers. Nonetheless, performance of a quantitative cost-benefit (or value-impact) analysis requires placing an explicit value on the avoidance of health detriment so that a common metric can be applied in the analysis. Values can readily be determined for any commodity openly traded in the marketplace. However, setting values for attributes such as good health, longevity, or avoidance of accidents presents a more difficult problem since there is no "market". In such cases it is necessary to ascribe an imputed or surrogate value in order to perform a quantitative analysis. Surrogate values can be imputed from estimates of the extent to which individuals and/or society in general will go toward obtaining or avoiding a given condition. For example, the value of $1,000 per man-rem of radiation dose (10 CFR 50 Appendix I) provides such a surrogate value for radiation dose avoidance.

Although there is necessarily some degree of subjectivity in determining the various values, data, and assumptions in cost-benefit analyses, a major advantage of the approach is that it requires the analyst to explicitly display these determinations in a systematic manner. Although the observer or reviewer of a cost-benefit analysis may not agree with the analyst's choices, he will at least have an opportunity of understanding what they are. If the analytical framework is sound, it is a relatively simple matter to substitute other, perhaps preferable, values into the analysis to evaluate the impact or sensitivity that the altered values might have on the conclusions. Cost-benefit analysis will be discussed in greater detail in later sections of this report.

1.5 Risk Concepts

Terms such as risk, detriment and harm require definitions at the outset to avoid ambiguity. Quantitatively, risk is the product of the probability of occurrence of an event and the magnitude of the consequences, given occurrence of the event. Internationally, the term "risk" has been used to mean the probability of occurrence, while "detriment" is the product of this risk and the consequences (ICRP, 1977).

On an individual basis, a radiation exposure carries a probability of illness. This probability of illness, also called risk, is the product of the effective dose equivalent and the risk per unit dose. For populations, risk is the sum of individual risks, realizing that risk per unit dose could depend on age, sex, and other factors. Another possible measure of harm is the loss of life expectancy. This takes into account the age at which a fatal illness could occur. In this report risk is considered to be the product of severity of consequences and the probability of their occurrence.

Two classes of risk in the nuclear industry are those resulting from routine plant operations and from unanticipated events or accidents. In the case of routine operations risks can be mitigated by such measures as shielding, filtration, effluent holdup, etc. In the case of accidents, the risks can be mitigated and/or prevented. Preventive measures include any procedures that would prevent or reduce the probability for occurrence of any event (failure) which would lead to adverse effects. Mitigating measures would reduce the severity of the consequences in the event of such failure.

1.6 Sources of Exposure

Balancing the risk to workers against potential risks to offsite populations at nuclear power plants requires a consideration of sources of exposure. Work performed in a radiation area at a nuclear power plant may or may not be related to an offsite exposure. If it is not, then optimization involves only consideration of occupational exposures. An example of this case is the storage and handling of solid wastes. For purposes of ALARA, dose reduction techniques could reasonably be applied up to the point where costs of these applications outweigh the benefit gained by reduced occupational doses. Optimization of exposures from such activities need not involve consideration of offsite (public) exposures and the procedure is relatively straightforward.

There may also be cases where an onsite activity has a direct relationship to offsite exposures. Effluent control systems are an example. Retention of off-gas effluents to allow for radioactive decay to lower levels prior to their atmospheric release can result in better control (lower offsite doses), but may also entail an increased level of occupational exposure. The optimization performed would require factoring in both occupational exposures and public exposures.

1.7 Occupational vs. Public Radiation Exposure

Cost-benefit analyses involving the balancing of occupational vs. public dose reduction will necessarily require determination of the relative values of each or weighing of one against the other. For example, there is ample evidence that in public health and safety programs, standards for limiting public exposure to hazardous materials are generally far more restrictive than those for worker protection (Johnson, 1982; Hattis, 1982). This is also true in radiation protection where allowable maximum individual doses to workers are typically tenfold higher than for members of the public. Whether such differences should also apply to collective dose limitation is a question that must be resolved in establishing an equitable basis for cost-benefit analysis. Other questions requiring resolution include:

1.7.1 Should high probability, low consequence risks be evaluated on the same basis as equivalent low probability, high consequence risks?

1.7.2 Should the evaluation of population risks consider doses which approach the allowable limit for individual dose in a different manner from those well below the dose limits?

1.7.3 Should factors related to risk perception be incorporated into the evaluation? (as suggested, for example, in NUREG/CR-1614 [NRC, 1980]).

These questions relate to some of the issues which will be dealt with in later sections of this report. It should be noted, however, that resolution of such issues will, to some extent, involve value judgments and subjective analysis. Considering our present state of knowledge and insight, it is unlikely that any rigorously defensible solutions will evolve. We can only suggest reasonable approaches. Ultimately, the judgment of those decision makers responsible for regulating radiation safety will be required. An objective of the current study is to develop a logical framework in which such decisions can be effectively implemented.

2. RADIATION EFFECTS

The assessment of radiation dose in cost-benefit analyses requires an understanding of certain aspects of the biological effects of ionizing radiation. This section of the report is not intended to present a comprehensive tutorial on radiation effects. However, those phenomena having a bearing on cost-benefit assessment will be identified and discussed.

2.1 Dose-Response Relationships

There is clear evidence that high doses of radiation to individuals result in increased incidence of cancer and other harmful effects. Although it is not statistically possible to observe effects of radiation at low doses, such effects can be estimated by extrapolation from effects observed at high doses by assuming some continuous relationship. It is generally believed that there is some degree of harm resulting from any level of radiation dose, no matter how low. The nature of the dose response relationship at low doses has been the subject of extensive study and debate. Figure 2-1 taken from NRC Regulatory Guide 8.29 (NRC, 1981a) presents some possibilities. The majority of scientists appear to endorse either the linear model (curve 1) or the linear-quadratic model (curve 2). A comprehensive discussion on these models is given in the report of the National Research Council Committee on Biological Effects of Ionizing Radiation (BEIR,1980). A few scientists believe that even very low doses may entail significant risks (curve 4) (Brown, 1976). Others believe that there is, in fact, a threshold of dose below which there is no risk (curve 3) (Hall, 1976), or even that low radiation doses may produce a net beneficial effect (Luckey, 1980).

This report assumes the majority view that the linear (or linear-quadratic) dose-response model is most appropriate and applicable in risk assessments. It must be noted that this assumption is crucial, particularly in collective dose assessments (see Section 2.4). From evaluation of the curves in Fig. 2-1, it is apparent that assuming that the net effect of radiation exposure to any population is proportional to the sum of individual doses to its members necessarily presumes an essentially linear dose-response relationship, at least in the low dose range. If, in fact, the models depicted in curves 3 or 4 were valid, conclusions reached by assuming the linear relationship could be grossly in error.

2.2 Dose Equivalence

Various organs and tissues of the human body exhibit widely ranging sensitivities to radiation. In previous years, radiation safety assessments considered effects to individual tissues. In 1977, the International Commission on Radiological Protection determined a method for evaluating radiation risks on the basis of a whole body equivalent dose (ICRP, 1977). The ICRP recommends that dose limitation be "based on the principle that the risk should be equal whether the whole body is irradiated uniformly or whether there is non-uniform irradiation." Note that total whole-body exposure can be related to exposure of individual organs as indicated by ICRP Publication 26. (ICRP, 1977) when the internal doses to each of 11

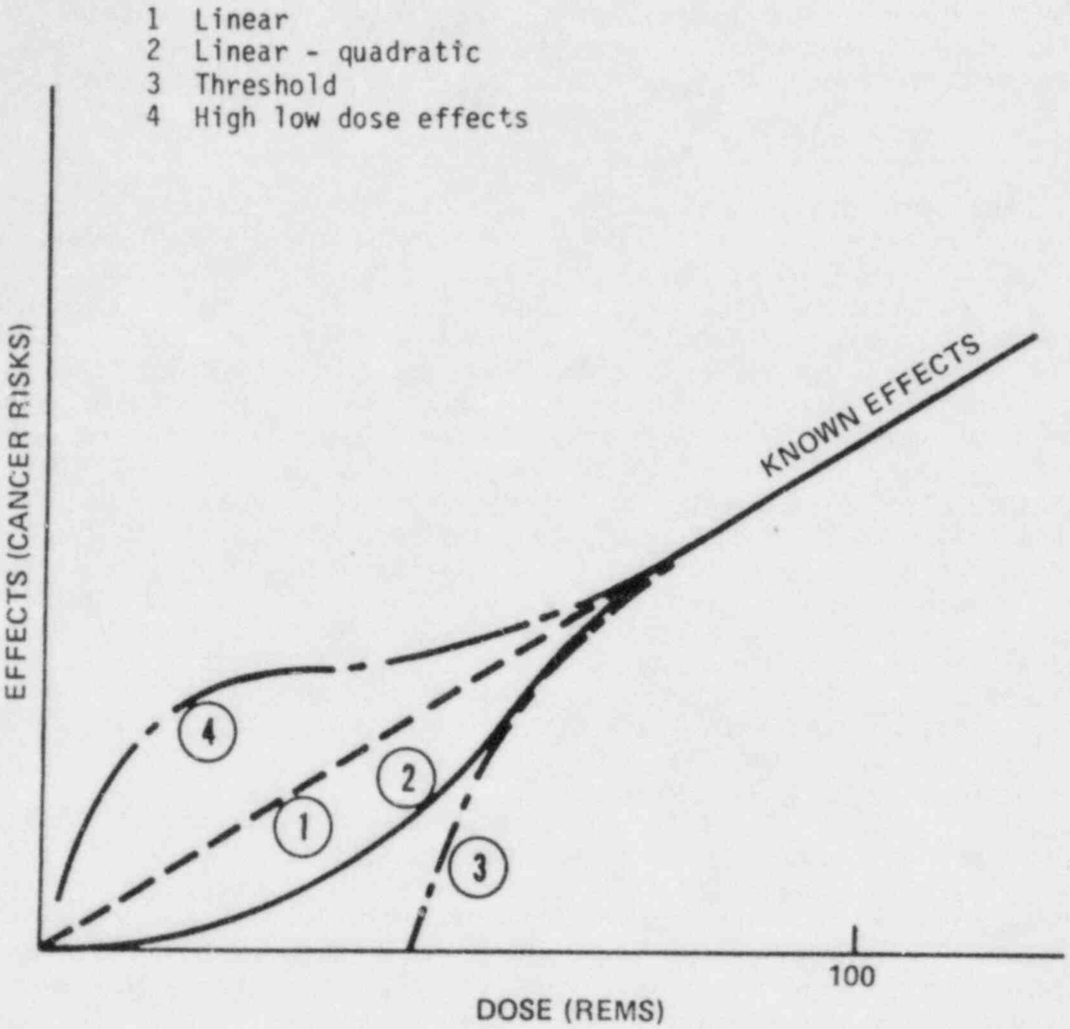

Figure 2-1. Some proposed models for how the effects of radiation vary with doses at low levels.

organs are calculated, summed, and added to the external (whole body) exposure to obtain a corrected value of total wholebody exposure. Again quoting from ICRP Publication 26, page 21 (ICRP, 1977):

> "This condition will be met if
>
> $$\sum_T w_T H_T \leq H_{wb,L}$$
>
> where w_T is 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 is the annual dose equivalent in tissue (T), $H_{wb,L}$ is the recommended annual dose equivalent limit for uniform irradiation of the whole body...."

The values of w_T recommended by the Commission are shown below:*

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 ICRP approach offers a convenient and straightforward method for converting organ doses to a single whole body equivalent dose. Use of this whole body equivalent dose rather than separate organ doses can be far less cumbersome and confusing in risk assessment applications.

This report adopts the whole body equivalent concept as presented in ICRP-26. Accordingly, the terms dose and dose equivalent are used interchangeably.

2.3 Stochastic vs. Non-Stochastic Effects

Two types of effects can result from radiation exposure. These are acute effects (non-stochastic effects) and chronic effects (stochastic effects). Stochastic effects are the consequences of exposure to low radiation doses. The probability for their occurrence is dependent on the dose level. In accordance with the linear model, it is assumed that there is no threshold for their occurrence. Non-stochastic effects result from exposure to high radiation doses. The severity of the effect is a function of dose level. Non-stochastic effects do not occur below a certain threshold of radiation exposure.

From a review of data on radiation effects, it is reasonable to assume that no non-stochastic effects occur below individual dose levels of 5

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*With the provision that no organ will receive more than 50 rem/y in any case, except for the lens of the eye which has a limit of 30 rem/y.

rem/yr. A primary objective of individual dose limitation is to prevent non-stochastic effects. ICRP-26 (ICRP, 1977) states:

> "In order to prevent any one organ or tissue from receiving a total dose which could contribute significantly to the induction of non-stochastic effects, an overriding annual dose-equivalent limit of 50 mSv [5 rem] should apply. This limit is considerably lower than the corresponding limits recommended for prevention of non-stochastic effects after occupational exposure. The intention is to ensure that the longer exposure period and the practical difficulties in controlling the total exposure from all sources will not result in threshold doses for non-stochastic effects being reached."

Experience indicates that, with rare exceptions, both public and occupational radiation doses are well within the stochastic range. Accordingly, this report will assume (unless otherwise noted) that all doses received lie within the stochastic range and that either the linear or linear-quadratic models apply.

2.4 Individual vs. Collective Dose

Assuming compliance with criteria for limitation of individual dose (exceptions will be discussed in section 5), determination of optimization can be based on a consideration of collective, or population, doses. Collective dose is defined as the product of the average individual dose to all members of a given population and the number of individuals in that population. Units of collective dose will be expressed in terms of man-rem. It can reasonably be assumed that the risk to a given population is proportional to the collective dose if individual doses lie entirely within the stochastic range. If not, then some other approach must be applied to determine equivalent risk.

In this report collective dose to either public or worker population groups will be the measure used for purposes of optimization. Any exceptions to this guideline will be noted.

2.5 Alternative Measures of Harm

Although collective dose (man-rem) will be applied as a measure of harm in this report, it should be noted that several alternative measures can be and have been used. Indeed, these alternative expressions of harm related to radiation exposure have found widespread application in both the technical and popular literature.

2.5.1 Numbers of Effects

The adverse effects most commonly attributed to radiation exposure include malignancies and genetic defects. Although the incidence of these effects resulting from radiation exposure is dependent on age, sex, type of radiation, and several other factors, a review of the BEIR report (BEIR, 1980) indicates that, for average populations, a reasonable approximation is 2×10^{-4} adverse effects per man-rem of collective dose. In many safety assessments, harm has been expressed in terms of numbers of adverse effects. Expressions which have been used for this purpose include (for stochastic effects):

- excess cancers
- cancers
- malignancies
- deaths
- latent deaths
- excess deaths
- genetic effects
- somatic effects
- latent fatalities
- premature deaths

Non-stochastic (acute) effects have been expressed in terms of early or prompt fatalities (NRC, 1975). The U.S. Environmental Protection Agency in their safety assessments prefer to use the more euphemistic term "health effects." In all the above cases, within the range of stochastic effects, the incidence of effects can be estimated from the collective dose using appropriate conversion factors.

2.5.2 Effect on Longevity

Measures of harm such as deaths, early deaths, and cancers may be subject to criticism since they convey an overly grim and perhaps misleading picture. One might ask; death as opposed to what? Certainly not immortality. Another way to look at the problem is to reflect on the reality that a radiation-induced health effect can cause death at an age earlier than it other wise might have occurred. The resultant harm could, therefore, be expressed in terms of its effect on longevity or life expectancy.

For example, it has been estimated that, on the average, a radiation-induced health effect will result in a decreased lifespan of about 12 years to the victim. On the average, each rem of radiation dose is estimated to reduce life expectancy by about one day (NRC, 1981). Accordingly, it can be estimated that a collective dose of 10^6 man-rem administered uniformly to a population group of one million would result in the premature deaths of about 200 people (2×10^{-4} effects/man-rem x 10^6 man-rem). Assuming each of the 200 victims loses 12 years from a normal life expectancy of 70 years (death occurs at age 58), the average loss of life expectancy for the entire population would be 0.0024 years or 0.876 days. Assuming linearity, it can be deduced that each man-rem caused an average decrease in longevity for the total population of about 8.8×10^{-7} years or about 3 seconds loss of life expectancy out of a normal 70-year lifespan. A general formula which may be applied to estimate the average loss of life expectancy in days (Δdays) from a normally expected lifespan of 70 years assuming all individual doses are within the stochastic range is:

$$\Delta \text{days} = \frac{0.876 \times \text{collective dose (man-rem)}}{\text{affected population}}$$

A more precise estimate could be obtained by applying appropriate factors considering the age and sex distribution of the population and type of radiation. However, when such data are unknown, the above formula should provide a reasonable estimate for general populations.

Applying a similar approach, the EPA (Bunger, 1981) performed a study to determine the effect of radiation exposure on life shortening. This study determined that continued exposure to an occupational dose level of 5.0 rem/yr from age 18 to 65 could result in life shortening in excess of the average attributed to industrial accidents.

Determination of the effect of radiation exposure on longevity appears to have merit as an approach since it provides a different perspective on radiation risks. In applying such an approach in cost-benefit analyses, the cost effectiveness of applying preventive measures to reduce radiation exposure might be expressed in terms of dollars per man-day loss of life expectancy prevented.

2.6 Discussion

We have reviewed various measures to express the risk impact of radiation exposures. In the present study, this risk will be described primarily in terms of collective dose (man-rem). This parameter could readily be converted to expression of incidence of adverse effects or effect on longevity, if desired.

3. COST EFFECTIVENESS OF RADIATION RISK REDUCTION

In conformance with ALARA guidance, the minimization of radiation exposures must include a consideration of economic factors. Cost-benefit analysis provides a method for performing the required assessments. This section of the report is not intended to provide a treatise on cost-benefit methodology. Several excellent textbooks are available on the subject, including Ashley (1976) and Wilson (1982). Additionally, cost-benefit methods will be treated in detail in other tasks of the current project. This report section will deal with ancillary issues to be considered in the factoring of occupational dose into cost-benefit analysis. Section 4 will deal more directly with the issue of equivalence between occupational and public collective doses.

3.1 General Observations on Cost-Benefit Analysis

Over the past few decades, cost-benefit analysis has come into prominence as a tool to assist in the decision making process where risk to health and safety is a consideration. Although various organizations have taken differing approaches to its application, there are some fundamental precepts of its exercise that should generally apply. Cost-benefit analysis appears to have been frequently misused, possibly through lack of understanding of the economic principles. These principles, however, are relatively simple. Basically, cost-benefit analysis provides an objective method to estimate whether the value received justifies the expenditure made. Where resources (money, time, effort, etc.) are to be allocated toward health and safety objectives, the question is whether the degree of protection gained is worth the resources expended. From a societal standpoint, such a determination should be independent of the source of risk, or the ability to pay. The questions to be answered include "Are we making the best use of the limited resources intended for protection of health and safety?" or "Could those resources, if spent in other areas of health and safety, achieve a greater reduction in overall risk?" Simply stated, cost-benefit analysis should tell us if we are getting our money's worth. Some of the more salient considerations related to application of cost-benefit analysis are discussed below.

3.1.1 Quantification of Values

Cost-benefit analysis is fundamentally a quantitative exercise dealing with assessment of numerical values. This precept has, however, often not been recognized. For example, in its guidance for the implementation of the National Environmental Policy Act (NEPA), the USAEC in Appendix D to 10 CFR part 50 stated:

> "The cost-benefit analysis shall, to the fullest extent practicable, quantify the various factors considered. To the extent that such factors cannot be quantified, they shall be discussed in qualitative terms."

The USAEC in its Regulatory Guide 4.2 (AEC, 1973) states:

> "While the benefit-cost analysis approach discussed in this Guide is conceptually similar to the benefit-cost approach classically employed in a purely economic context, the method recommended differs from it procedurally. This is because the benefits and costs to be evaluated will not all be monetized by the applicant. The incommensurable nature of the benefits and costs makes it virtually impossible to provide a concise assessment of benefits vs. costs in classical quantitative terms."

From a standpoint of classical economics, such guidance is unfortunate since, without quantification of all values to be considered, the assessment is simply not a cost-benefit analysis. Although qualitative assessment of factors may be a worthwhile procedure, it amounts to little more than a simple listing of the positive and negative attributes anticipated from the implementation of an action. This form of accounting may be helpful in decision making. However, as the above statement suggests, from an economic view, such assessment does not constitute cost-benefit analysis.

While it is true that many costs and benefits may not be directly commensurable, application of surrogate values is always possible. Although comparative assessment of various attributes such as excess cancers, pre mature deaths, environmental degradation, and monetary costs may seem like mixing apples and oranges, such comparisons are possible in an economic sense by applying a common metric (Keeny, 1976). In this sense, the mixing of apples and oranges has been described as possibly a "fruitful exercise" (Baecher, 1974). For example, the avoidance of any degree of harm, detriment, or environmental degradation can be evaluated by a common measure based upon the extent (expenditure) to which individuals, governments, or society in general are willing to go to avoid them. Such an exercise is commonly practiced, for example, in budgeting and allocation of funds directed toward health and safety programs. From past decisions in these areas, values can be inferred for various levels of protection.

Another approach to quantifying the value which may be ascribed to health protective measures is the "revealed preference" approach (Starr, 1972) (Otway, 1975). In this approach, values are inferred from societal preferences exhibited in either acceptance or rejection of safety features (seat belts, fire extinguishers, etc.) or health protection measures (immunization, physical examinations, etc.). Inferences may also be made from past decisions involving hazardous activities including occupations (hazard duty pay), or jury awards in injury or loss of life cases (Linnerooth, 1975).

The examples cited above are a few of many possible approaches toward definitive evaluation of risk avoidance. Such evaluation, or quantification, is necessary to the performance of a bona fide cost benefit analysis. As previously discussed, the reviewer may not always agree with the analyst's judgment or methods in determining surrogate costs (or benefits), but he will at least have an opportunity for scrutinizing these factors.

It would then become a relatively simple matter for him to substitute his own preferred values into the analytical framework to assess their relative effect on the conclusions.

3.1.2 Distributional Considerations

A perplexing question often asked in regard to cost-benefit analysis is, "Who gets the costs and who gets the benefits?" In the case of activities that might cause radiation exposures, ICRP-26 (ICRP 1977) suggests that the principle of dose justification be applied such that the activity results in a net societal benefit.

Where potential dose reduction activities are concerned, the decision is more related to other societal areas involving assurance of health and safety. In such areas, the protection of the health of all individuals and groups is considered a public good. Accordingly, questions of who pays and who benefits are generally not major considerations. However, certain factors related to spatial and temporal distribution of costs and/or benefits bear some discussion.

3.1.2.1 Spatial distribution

Risk assessments related to NRC licensees are generally limited to effects occurring within 50 miles of the facility. This practice appears reasonable since it makes the analysis more tenable and, in almost all cases, any effects would predominantly occur within the prescribed area. Notable exceptions include environmental releases of tritium (Cohen, 1971) and krypton-85 (Knox, 1972). Knox, for example, determined that the largest collective dose to any identified group due to noble gas effluent from a single fuel reprocessing plant located at West Valley, N.Y., was to the population of China. This observation simply reflected the facts that the atmospheric distribution of noble gases is essentially ubiquitous, and the Chinese comprise the largest population group. In the context of cost-benefit analysis, such phenomena might raise questions of whether a differential evaluation of cost effectiveness according to national groupings might be in order (e.g., would reduction of one Chinese man-rem justify expenditure equivalent to reduction of an American man-rem?). Such questions are beyond the scope of the present study. In absence of guidance on this question, it would appear prudent to assume spatial equivalence for collective doses.

3.1.2.2 Temporal distribution

A consideration in optimization determinations is the assessment of costs and benefits occurring over wide ranges of time. For monetary costs incurred over long time periods, discounting methods can determine equivalent cost at some fixed point in time. For example, the present value (C_p) of any future anticipated cost can be estimated by:

$$C_p = C_t e^{-it}$$

where C_t = anticipated future cost at time t, and i is the fractional interest rate per unit time.

While the discounting of monetary costs is a commonly accepted practice, the possible discounting of future health benefits or detriment is open to some question. Possible future health detriment has, for example, been a source of serious concern in high-level waste management (DOE, 1980). The concept of discounting future detriment was discussed in NUREG/CR-0579 (Cohen, 1979). In this assessment, it was concluded that, without official guidance, the prudent policy was not to discount future risks. Some argument could be made that in cost-benefit analyses where future costs are discounted, it would be equitable to also discount future benefit or detriment. It is suggested that a discounting term be incorporated in any calculational model for cost-benefit analysis. Where an equivalence of present and future detriment is assumed, an interest (or discount) rate of 0% could be applied. Incorporation of a discounting term would also allow for evaluating the sensitivity of the conclusion to various discounting assumptions.

3.1.2.3 Occupational vs. public collective dose

Application of certain methods and procedures for reduction of public collective dose can result in an increase in collective occupational dose. Development of methods and rationale for factoring occupational dose in cost-benefit analyses is the primary objective of the current study.

From ICRP guidance (ICRP, 1977), the concept of detriment in optimization determinations should consider both public and occupational collective dose. However, the question of their relative equivalency remains to be resolved. Whether occupational man-rem should be given equal weight to public man-rem (assuming both to be below allowable limits for individual dose), or whether limits for individual dose or some other factor should be applied then becomes a major consideration.

In any case, a reasonable approach toward incorporation of occupational dose into public safety assessments would be in terms of net detriment averted:

$$CD_n = CD_p + qCD_o$$

where:
CD_n = net detriment (equivalent collective dose)
CD_p = public collective dose
CD_o = occupational dose
q = equivalency factor

where:

$$q = \frac{\text{Value per unit of occupational collective dose averted}}{\text{Value per unit of public collective dose averted}}$$

Possible equivalency factors between public and occupational collective dose is considered in Section 4.

3.1.3 Marginal vs. Absolute Effects

ICRP-26 suggests that determining whether a reduction in exposure is "reasonably achievable" requires application of a differential cost-benefit analysis (ICRP, 1977). Optimization is obtained at a point where the increase in cost of protection is balanced by the resultant decrease in collective dose. Where only one possible method can be considered for purposes of reducing dose, the judgment of whether to apply that method can be based on a simple comparison of the cost of implementation against the resultant reduction. The results of such an assessment can be expressed in terms of the absolute cost and absolute dose reduction ($/man-rem).

In the predominant number of cases where dose reduction is considered, several possible methods, operations, procedures, or combinations of these can be considered as reasonable approaches to solving the problem. In such cases, the proper application of cost-benefit analysis requires a consideration of the marginal (incremental, differential) costs and benefits of dose reduction.

To determine compliance with ALARA (optimization) the following sequential steps may be applied:

3.1.3.1 Define the dose reduction problem to be solved.

3.1.3.2 Identify all reasonable alternative methods, operations, procedures, or combinations of methods for accomplishing the dose reduction.

3.1.3.3 Eliminate any alternative that could result in an individual dose in excess of allowable levels.

3.1.3.4 Determine the monetary cost (both capital and operational) for each viable alternative.

3.1.3.5 Determine (or estimate) the total collective dose that would result assuming application of each alternative. The no-action alternative should also be considered in such assessments as a baseline.

3.1.3.6 Eliminate any alternative that is inefficient, in that it has both a higher cost and results in a higher collective dose than any other identified alternative.

3.1.3.7 Order the remaining alternatives by increasing cost and decreasing collective dose.

3.1.3.8 Determine the differential cost, differential dose, and resulting cost-effectiveness.

3.1.3.9 Select the optimum alternative using a predetermined cost effectiveness guideline.

To optimize the selection of alternatives according to ALARA, it is first necessary to determine a suitable cost effectiveness guideline. The procedure can be demonstrated by using a hypothetical example. Assume that four alternative systems are being considered for solution of a dose reduction problem. All alternatives meet the maximum individual dose criteria. The steps described in the discussion are carried out as shown in Table 3-1. Also, assume a cost effectiveness guideline of $1000/man-rem is applied. Of the five alternatives shown (A, B, C, D, and "No Action"), B would be selected since the marginal cost of going to C would exceed the cost-effectiveness guideline of $1000/man-rem.

It is interesting to note in this example that if alternative B did not exist, the marginal cost of selecting C over A would have been $833/man-rem and would have met the cost-effectiveness guideline. However, the existence of B should preclude the selection of C. If, for example, one could ignore the existence of B and select C as being a cost-effective choice over A, then one could just as readily ignore the existence of C also. In doing so, the remaining choice would be between A and D. In that case, A would be selected since D could not be justified on a cost-effectiveness basis.

3.2 Cost Effectiveness Guideline

Judging the acceptable cost effectiveness for implementation of a dose reduction action requires a guideline expressed in terms of marginal cost per unit of dose averted ($/man-rem). In deliberating the ALAP for light water reactor effluents leading to promulgation of Appendix I of 10 CFR 50, the NRC reviewed several previously suggested guidelines ranging from $10 to $980/man- rem and determined the value of $1000/man-rem (Rodger, 1974). This selection was made with the intent to be "conservative." Although the $1000/man-rem was developed for application to LWR effluent, this figure has subsequently been used as a point of reference in several risk assesments. Although this study will not attempt to establish an appropriate cost effectiveness guideline for public and/or occupational dose avoidance, some general observations are offered.

3.2.1 Guideline Applicability

A somewhat questionable practice has been to consider different cost effectiveness guidelines for applications to different operations and procedures. From a standpoint of economics, the guideline implies the justifiable cost per unit of collective dose reduction. The benefit of reduced radiation dose logically should be independent of [illegible] source of exposure since the harm inflicted per unit dose is also independent of the source. For reasons discussed in Section 3.1, it will be assumed that whatever cost effectiveness guideline for reduction of collective radiation dose is selected, it should apply across the board and not be related to any specific operation or activity. From a social and economic standpoint, the source of risk should not be a consideration in determining the cost effectiveness guideline for dose reduction.

3.2.2 Conservatism

Application of conservative (or pessimistic) estimates for parameters in a risk assessment is generally considered to be a prudent approach in estimating individual radiation doses to determine compliance with criteria for maximum allowable dose. This approach produces so called "worst case" estimates for the consequences. If the worst case results still fall below acceptable limits, it is reasonable to assume that any more likely outcome will also be within the acceptable limits.

Table 3-1

EXAMPLE OF OPTIMIZATION PROBLEM

1. Assume four alternative solutions plus "no-action"
2. Assume cost effectiveness guideline is $1000/man-rem

Alternative	Cost		Resultant Net Collective Dose (CDn)		Cost Effectiveness
	$	Δ $	Man-Rem	Δ Man-Rem	Δ ($/Man-Rem)
No Action	0		2500		
		1.5×10^5		1500	$100\ (<\$10^3)$
A	1.5×10^5		1000		
		5×10^4		200	$250\ (<\$10^3)$
B	2.0×10^5		800		
		2.0×10^5		100	$2000\ (>\$10^3)$
C	4.0×10^5		700		
		6.0×10^5		50	$12000\ (>\$10^3)$
D	1.0×10^6		650		

Therefore select alternative B on basis of ALARA.

In selecting a cost effectiveness guideline for optimization of collective doses, however, it should be noted that high values are not necessarily conservative in assuring safety. The nature of cost-benefit analysis is such that the guideline value should reflect an optimal cost per unit of risk reduction in any given area. As guidelines deviate from optimal in either direction, the objective of general public health and safety becomes less served.

For example, the cost effectiveness guideline of \$1000/man-rem averted selected by the NRC could be equated with a value of ∿ \$5 million per effect averted (1000 \$/man-rem/2×10^{-4} effects/man-rem). This value is extremely high relative to expenditures in other areas of health and safety (Cohen, 1980). A strong case could be made that such expenditures, if spent in other areas of health and safety, would be far more cost effective. It therefore follows that selection of a cost effectiveness guideline should reflect general societal preferences in areas of health and safety. It has been suggested by Niehaus (1979) that any safety expenditure in excess of \$30 million per death averted is inefficient even without considering the cost. They estimate that there is an average of one industrial fatality resulting from the manufacture and installation of \$30 million in safety equipment. Therefore, from a societal view, there would be no net benefit despite the cost. A recent PNL study (NUREG-0933) indicates that a more reasonable cost effectiveness guideline should be in the low hundreds of dollars per man-rem averted. A value of \$100/man-rem would likely be more consistent with expenditures in other areas of health and safety.

3.3 De Minimus

Certain operations in the nuclear fuel cycle can result in causing very low radiation exposure to extremely large population groups. (See discussion in 3.1.2.1.) Although individual exposures may be extremely low, a significantly high collective dose may result due to the large population exposed. Since a no threshold dose-response relationship is assumed in calculating collective doses, all levels of dose must be considered regardless of how low they may be. Some have questioned the wisdom of this practice. It has been described by Rodger (1974) as "multiplying zero times infinity and assuming the result is meaningful."

To deal with this situation, a "de minimus" radiation level has been proposed (Davis, 1981) whereby an individual dose below a certain value (∿ 1.0 mrem/yr) is to be considered essentially zero and not included in the assessment of collective dose. Although the concept appears to have merit, it has not as yet gained official sanction.

3.4 Uncertainty

Prediction of collective dose consequences will generally require dealing with some degree of uncertainty. In predicting individual dose, problems of uncertainty are handled by making "worst case" estimates and applying these estimates to judge compliance with criteria for maximum allowable exposure. The reasonable assumption underlying this practice is that any errors, if made, would be on the safe side.

In predicting collective doses for purposes of inclusion in a cost-benefit analysis, however, the conservative approach is invalid (see Section 3.2.2). The method for dealing with uncertainty in this case requires "best estimates" or most probable parameter values be incorporated in the calculations. Since cost-benefit analysis is a comparative determination, the objective must be consistent in assessment of all factors. The conservative approach would only be valid if an equal degree of conservatism were applied in estimating all factors (i.e., those involved in determining cost as well as those in assessing risk). Accordingly, the most sound approach, given the objective of consistency, would be to apply "best estimates" in selecting parameter values since it would be difficult, if not impossible, to apply an equal degree of conservatism in all cases. Use of best estimates would clearly provide the most objective and consistent form of analysis.

3.5 Probabilistic Risk

In normal routine effluent releases or occupational tasks, the resulting collective dose exposure levels are fairly certain and predictable. However, in many cases, exposure can result as a consequence of failure, accident or other unanticipated disruptive events. Evaluation of collective doses in the latter case requires a consideration of the event probability as well as the probability of various consequences given occurence of the event. A fundamental question in such cases is whether, for purposes of cost-benefit analysis, equal weight should be given to the "expected" consequences regardless of their probability for occurence. For example, assume an event with a 0.01 yr^{-1} probability for occurrence. Further assuming that the resultant collective dose is 100 man-rem, then the annual expected collective dose is 1.0 man- rem. A question in this regard is whether the same level of resources should be committed to prevention of such an occurence as would be devoted to avoiding a certain exposure of 1.0 man-rem.

3.5.1 High Probability-Low Consequence versus Low Probability-High Consequence Events

NUREG-0739 (NRC, 1980a) discusses the fact that society is risk adverse in comparing infrequent high consequence accidents relative to a number of small accidents of equal net consequences. The authors suggest an approach for determining net equivalent social cost such that:

$$\text{Equivalent Social Cost} = \sum_{\text{Accidents}} (\text{Frequency})(\text{Consequence})^{\alpha}$$

The α factor in the above relationship is intended to account for societal aversion to high consequence events. Values for α factors as high as 2 or 3 have been proposed in the literature for prevention of accident fatalities. However, it is suggested that such high values, if implemented, would prohibit currently existing technological applications such as dams and hazardous chemical storage. In NUREG-0739 an α factor of 1.2 is suggested as a guide to the assessment of social cost of potential accidents involving early deaths.

The α factor provides the capability of considering societal aversion to high consequences into risk assessments. Where such scaling is not desired, a value of 1.0 could be applied thereby negating any assumption of a nonlinear relationship between social cost and magnitude of consequences.

Although the concept of the α factor in risk assessments is intended for application where fatalities might be involved, the approach might also be applicable to the avoidance of large scale collective dose consequences. Where risk perception might be a consideration, it might be well advised to expend relatively more resources toward the avoidance of high consequence risks than to equivalent low consequence risks.

3.5.2 Risk Perception

Decisions related to safety are often motivated by considerations of risk perception. Since high consequence risk events have a greater public visibility, greater efforts toward their avoidance may be justified.

Effective management of perceived risks requires a consideration of psychological and social factors (NRC, 1980a) which are beyond the scope of the present study. Although in many cases risk perception could be a significant factor in the decision process, this study will concentrate on actual or quantifiable risk. Possible application of α factors may however, provide a means of incorporating risk perception into the risk assessment.

3.6 Non-Stochastic Effects

Certain large scale accidents could possibly lead to massive individual exposures in the non-stochastic range. These effects could result in illness. or death at relatively early times following exposure. Clearly a 1000 rem dose to an individual would have a far different and more serious consequence than a 1.0 rem dose to 1000 individuals despite the fact that 1000 man-rem are received in both cases.

Where the possibility of non-stochastic effects must be considered in a cost-benefit analysis, an equivalency assumption must be incorporated. For example, where early fatalities might result, an equivalency factor (f) might be applied for purposes of comparative evaluation against stochastic collective doses, where early fatality = (f) stochastic man-rem.

A significant consideration in non-stochastic effects is that collective dose is relatively meaningless. Beyond some level of individual dose (~500 rem) where a consequence of death is likely, it makes little difference what the dose level is (i.e., an individual dose of 1000, or 10,000 rem would have essentially the same consequence). Clearly the social cost of averting nonstochastic effects is not related to collective dose as is the case with stochastic effects. Nonetheless, as previously suggested, an equivalency can certainly be estimated.

A possible methodology for incorporating non-stochastic effects in cost benefit analyses will be discussed in Section 5.

4. EQUIVALENCE OF PUBLIC AND OCCUPATIONAL COLLECTIVE DOSES

The primary objective of the present task is to determine a methodology to factor occupational dose into public safety assessments. Often such an assessment involves decreasing public collective dose at the expense of increasing occupational doses. Ideally, both public and occupational doses should be minimized. However, when possible tradeoffs between one and the other must be determined, a guideline toward evaluation of their relative importance is required (see discussion in Section 3.1.2.3).

4.1 General Considerations

It has traditionally been accepted that pursuing one's trade will involve risks, and that those risks may allowably be greater than for nonoccupational activities. It is only recently that a systematic effort has been made to reduce work hazards (and only in just a few prosperous nations). Therefore, the discounting of occupational risks has strong historical precedent.

This is probably due to the fact that 1) workers are paid for what they do, and 2) they do it voluntarily. The concept of "hazard duty pay" reinforces this bias. If we assume that workers are paid to take risks, then it becomes difficult to compare occupational exposure with public exposures. When worker exposures are discounted to this degree, they cease to be a factor in public dose optimization. On the other hand, if we assume that workers are paid for their skills and that public health is served by reducing all potentially harmful exposures, then occupational exposures are comparable, if not equivalent, to public exposures. Recent literature (Kasperson, 1982; Johnson, 1982; Hattis, 1982; Derr et al., 1981 and Melville, 1981) supports the latter assumption. A typical view is, "protecting workers at the same level as members of the public is highly desirable if it can be accomplished without undue economic hardship for the industry, the consumers of electricity, or the workers" (Kasperson, 1982). It appears that greater concern over occupational health and safety is moving us away from earlier attitudes.

If we assume that collective occupational and public exposures, are comparable, then the question of equivalence must be assessed. In cost-benefit analyses, for example, should we assume that one public man-rem is worth one occupational man-rem? Perhaps the ratio of worth of occupational to public exposures should be more like ten to one. Some viewpoints indicate that occupational collective dose reduction should be valued even higher than prevention of public dose. In this section we explore those factors that might influence such a judgement, including: individual exposures and risks, consent to exposures, and discounting of exposures.

One factor in the comparison of collective exposures is the level of individual exposures resulting from nuclear power production. Members of the public receive a much lower individual annual exposure (usually less than 1 mrem), than power plant workers (about 700 mrem, average). As long as risk factors assume a linear hypothesis with no threshold, individual dose is not important. Risk to the population is based only on collective doses as long as individual doses are anywhere in the stochastic range (note: a possible exception would be if a de minimus dose level were determined and applied). The implications of this basic assumption were discussed in Section 2.

Another consideration is the voluntariness of the two exposure groups. Occupational exposure is more voluntary than public exposure. This tends to discount occupational exposure. A principle of justice presented by Derr, et al. (1981) states, "An allocation of risks is just if, and only if, it has the consent of those upon whom the risks are imposed." Derr et al. go on to argue that it cannot automatically be assumed that a worker consents to occupational risks. They cite the case where financial needs could limit a worker's ability to turn down risky employment. Also, lack of job mobility could undercut the possibility of truly free consent to occupational hazards. Finally, they point out that not all workers have a thorough understanding of the risks involved. An apparent conclusion that may be drawn is that involuntary risks that citizens have to bear are the ones the government has the greatest responsibility to regulate (Lowrance, 1976).

Another factor to be considered is potential large public exposures from accidents having small probabilities of occurrence. In such cases, a consideration of a certain increase in occupational dose (due to required increased inspection, maintenance, etc.) must be evaluated against reducing the probability of a possibly large public dose.

4.2 Review of Standards

Some insight on the equivalence of public and occupational collective doses might be gained from a review of individual dose limitation standards related to both.

4.2.1 Radiological Standards

In 1960, USAEC promulgated regulations that allowed up to 500 mrem/yr to a member of the public, and allowed up to 5000 mrem/yr to an average worker. More recently, the public limit for the nuclear fuel cycle was set by EPA at 25 mrem/yr. The occupational limit now includes ALARA considerations, and the anticipated dose rate is about one-tenth of the regulatory limit, or 500 mrem/yr (ICRP, 1977; EPA, 1981).

In these two cases, the ratio of individual occupational exposure limits to public limits is a factor of 10 and 20, respectively. Does this imply that their social cost differs by an order of magnitude or more? It has been argued that this difference does represent an inequity (Kasperson, 1982; Derr et al., 1981). Derr et al. found an order of magnitude difference in health protection by looking at the individual probability of death, which, of course is higher for larger individual radiation dose limits. However, they also make a comparison of public and occupational annual mortality for forty hazards. This comparison shows that 27 of the hazards result in similar mortality estimates for the two groups. The remainder of the hazards are about equally divided between those resulting in much higher occupational mortality and those where the public mortality is greater. Thus, looking at population mortality estimates rather than individual dose limits tends to counter the argument of inequity between the two groups. Mortality estimates from nuclear power radiation exposures were not identified.

The limit for public exposure was set lower than occupational exposure for several reasons. The primary one is that the public population is much larger than the worker population, and would contain more injurious health effects per rem of dose (Morgan, 1973). Second, the number of years of occupational exposure may be less than the number of years of environmental exposure. Both of these factors suggest that the risks to the two populations, under these standards, would tend toward equivalence. The setting of radiological standards points toward equivalent value given to public and occupational collective doses, although this equivalence may not have been an explicit goal.

Another factor in the difference in individual dose standards between the two groups has to do with a possible difference in risk factors (Morgan, 1973). Population groups other than occupational are more likely to contain children, embryos, and other individuals more sensitive to radiation damage. This difference in risk factors is offset, however, by the fact that a justification for the public exposure has been made (as defined in ICRP 26). That is, most of the benefits arising from the activity accrue to the public (e.g., electricity produced). This difference can actually be further offset by using these different risk factors when performing the exposure optimization analysis.

4.2.2 Non-Radiological Standards

A similar comparison was made for non-radiological standards. Table 4-1 shows this comparison for selected air pollutants. The ratio of the occupational standard to the public standard varies from a factor of 5 to a factor of 167 (average 62). These are comparisons of ambient exposure standards and not of collective dose standards. Consideration of both time of exposure and numbers of people exposed tend toward giving both groups more similar levels of protection.

Environmental standards in Table 4-1 (annual arithmetic mean concentration allow exposure at this level 24 hours for an average day (e.g. SO_2, NO_2). However, the occupational standards for these pollutants assume no more than an eight hour exposure and only on workdays. As in the case of radiation standards, the public exposure group is larger than the occupational group. These are both reasons for the more restrictive public standard. In his discussion of worker protection versus public protection, Lowrance (1976) concludes that equality of risks is an admirable goal.

As discussed in the previous section, Derr et al.(1981) make the case against a double standard for worker vs. public protection. When looking only at individual exposure limits, a clear difference appears to exist. However, a difference in protection is not as obvious when other measures, such as group mortality, are used. Whether such a difference in protection level is actual or not, it is important to note that Derr, and others, argue for an equivalence of risk for the two populations.

Table 4-1

ENVIRONMENTAL VERSUS OCCUPATIONAL STANDARDS FOR SELECTED AIR POLLUTANTS*

Pollutant	Environmental Standard(EPA)	Occupational Standard(OSHA)
Sulfur dioxide[a] (annual arithmetic mean)	0.03 ppm[b]	5 ppm
Carbon monoxide (max. 8 hr. once/year[a])	9 ppm	50 ppm
Nitrogen dioxide (annual arithmetic mean)	0.5 ppm	5 ppm
Particulates (respirable fraction, annual arithmetic mean)	0.075 mg/m^3[c]	5 mg/m^3

[a] Ambient air standards are given several values for short-term concentrations: that is, "maximum n-hour concentration not to be exceeded more than once per year." All in-plant exposures are presumably for an eight hour day.

[b] Parts per million.

[c] Milligrams per cubic meter.

*Adapted from Lowrance (1976).

4.3 Individual Risks vs. Collective Risks

In the foregoing discussion of equity aspects of radiation protection for the public and the worker, equity of individual risks seems to be at odds with equity of collective risks. Is it possible to have equity of both individual and collective risks? According to the arguments given above, equity of individual risk can be achieved by setting the same annual dose limits for the public and for the worker. However, as shown above, differences in population size and exposure time might then increase the collective risk to the public. Thus it appears that lowering individual risk in one group to obtain equality creates an inequity in collective risk.

Another approach toward equitable radiation standards involves limiting collective doses as well as individual doses. The EPA (1981) suggested a lifetime dose limit for radiation workers. This limit, 100 rem lifetime exposure per worker, was proposed to insure that an individual's lifetime risk in the nuclear industry did not exceed that of a worker in a comparable industry. This concept addresses the question of regulatory equivalence between other industries and hazards. However, the approach did not call for a limit to the total number of workers exposed. Furthermore, any attempt to set collective dose limits for the public would have been even more difficult than for workers. This effort would be confounded by the fact that many people receive exposures from multiple sources. Furthermore, the public is not monitored for exposure to the extent that workers are.

The British have looked at individual risk vs. collective risk in the context of dose optimization (NRPB, 1980, Clark, 1981). Their goal was to optimize public exposures using the "critical group" concept. That is, "It is no longer sufficient to assess only the collective dose equivalent but that a knowledge of the individual dose equivalent distribution is also needed to cost the resulting detriment" (NRPB, 1980). In other words, in reducing facility effluents, one should not only reduce collective public exposures, but also strive to reduce the exposure of those individuals with the highest doses.

The NRPB recommends that the way to achieve this goal is through the cost-effectiveness criterion. This criterion is assumed to be a function of individual dose. Possible values begin at £20 (~ $35) per man-rem when individual dose rates are below 5 mrem/yr, and increase steadily to £500 (~$875) per man-rem when these dose rates approach the limit of 500 mrem/yr. This has the effect of requiring higher operator expenditures to reduce public exposures when individual doses are higher. This may be one way to address the question of individual vs. population risk. However, application of such "elastic" cost-effectiveness criteria is questionable when the individual doses rates are well within the stochastic range. For example, it is difficult to understand how a 10 mrem/yr increase in dose could have significantly more serious health consequences if it raised the annual dose level from 490 to 500 mrem as opposed to raising it from 0 to 10 mrem.

4.4 Discussion of Equivalence

Most radiation standards indicate that individual dose limits for the public are an order of magnitude less than for workers. Does this indicate that public risk is given ten times more importance than occupational risk?

Since the health effects incurred are more or less the same for equal man-rem, the problem is not technical but subjective. Using the example of effluent treatment at nuclear power plants, the question can be addressed.

For example, the factors surrounding a decision to augment the effluent control system, might include:

1) lowered public exposure
2) increased occupational exposure
3) increased solid waste produced
4) increased capital and operating costs
5) increased occupational risk due to construction

All of these factors except 1 are generally considered minor when dealing with control of severe pollution. However, in the case of nuclear reactors, the control measures for public dose generally result in low dose reduction at such high marginal costs that all factors need consideration. The list of factors can be reduced by combining factors 3 and 4. Factor 5 can be combined with 2 in terms of occupational risk. This leaves a trade-off between lowered public exposures and increased costs plus occupational risks.

An example optimization analysis was performed on a French PWR considering public and occupational collective doses by Lombard (1981). In this assessment, equivalence factors (q) of 1, 1/3, 1/10, and 0 were applied to determine the sensitivity of the results to this factor. The q factor (see 3.1.2.3) is defined as the ratio between the social value of averting one public man-rem and one occupational man-rem. The results indicate that the assumed equivalence factor can have a profound effect upon the conclusion. In many of the alternatives considered in the Lombard study, the net occupational dose (where $q = 1.0$) actually exceeded the public dose. However, when occupational doses were discounted, most of the alternatives appeared to be cost effective.

As can be seen in this example, the consideration of occupational exposures could greatly affect the optimization of public protection. Other important factors include: protection of a critical group (see discussion of British approach above), selecting treatment systems based on budget constraints (which, in France, is a measure of how much the public feels should be expended to reduce risk), and safety improvements provided by added controls.

Previous discussion has presented arguments for $q < 1.0$ (i.e., where the social benefit of averting a man-rem of public collective dose would exceed that of averting an occupational man-rem). Some rationale has been presented indicating cases justifying a $q > 1.0$. For example, Pelletier

(1978) discussed potential benefits of reducing occupational radiation exposure. In that study, it was found that at nuclear power plants the cost incurred by allowing occupational exposures approaching limits for individual exposure could far exceed $1000/man-rem. Considering this aspect of occupational exposure, the economic incentive toward minimization of occupational doses is great, at least for the utility. It should be pointed out, however, that such expenditures are generally not considered social costs. Although such costs are real, their incorporation in cost-benefit analysis should be in the form of operating costs. Whether such costs could legitimately be described as a public good might be somewhat questionable.

4.5 Discussion

From the material presented in this section it would appear that from a standpoint of overall public benefit, collective occupational and public exposures should be given equal weight. When optimizing public exposures, occupational exposures should be factored in on a man-rem for man-rem basis. Likewise, when optimizing occupational exposures, any public exposures should be included on the same basis. As a first approximation a $q = 1.0$ assumption would appear to be reasonable. Since the decision maker may have compelling reasons to assume some $q \neq 1.0$, the q factor should be included explicitly in the calculation of cost-benefit analysis.

Lowrance's (1976) goal of equalizing occupational risks and risks to the public leads to equivalence of public and occupational man-rem. Public health is served by reducing all exposures, no matter where they occur. This approach is already being applied to medical exposures to patients as well as technicians.

As discussed above, Derr et al. (1981) argue for giving workers equal protection from hazards against which the public is protected. These arguments point to differences in limits for individual exposure levels, and suggest that occupational limits should be set equal to environmental limits. If this argument is modified to include such factors as population size and duration of exposure, then equivalence of collective dose is what should be assumed.

Finally, the ICRP in Report No. 37 (ICRP, 1982) provides a discussion of optimization of public and occupational exposures. The report presents an example of optimization of exposures from environmental releases of radioactive materials. These releases result in exposures to both the public and the workforce as discussed in Section 1.2 of this report. Thus, occupational exposure should be factored into an optimization analysis of public exposures. This is done in the ICRP example, but without discussion. In paragraph 157, the collective occupational dose is simply added to the collective environmental dose. No weighting (equivalence) factors are used in this summation indicating that occupational exposures are to be factored into this optimization analysis on a man-rem for man-rem basis. This implied equivalence from ICRP can be extended to other cases of optimization where the causes of the exposures are plant effluents (public exposure) and plant systems influencing the effluents (occupational exposures). It is clear that optimizing public exposure should include the "cost" of increased occupational exposure as well as public exposure on an equal basis.

5. MEASUREMENT OF NET DETRIMENT

Performance of cost benefit analysis requires an objective measure of the net detriment or harm that might result from implementation of each of the alternatives being considered including "no action." The net detriment for adverse radiological effects can be expressed in terms of the predicted net equivalent collective dose (CD_n). As previously discussed, CD_n should consider resultant occupational as well as the public radiation doses and other harmful effects.

5.1 Formulation

Based upon consideration of those factors discussed in Section 3, a reasonable formulation for evaluating the net collective dose equivalent (CD_n) is:

$$CD_n = \Big[(p \cdot CD_p^{\alpha}) + q(p \cdot CD_o^{\alpha}) \Big] \quad o,i,j\ldots$$

where: CD_p = Public collective dose (man-rem)
CD_o = Occupational collective dose (man-rem)
p = Probability
α = Risk aversion factor
o,i,j = Alternative state
q = Equivalence factor

and:

$$q = \frac{\text{Value per unit of occupational collective dose averted}}{\text{Value per unit of public collective dose averted}}$$

5.2 Occupational Dose Equivalence (q)

As shown in Lombard (1981), the q factor could have a significant effect on determination of net detriment. As discussed in Section 4.4, arguments can be made for setting the q factor at levels less than, equal to, or even greater than unity. Completely ignoring occupational dose in risk assessments and cost-benefit analyses has the effect of setting a q value of zero. Clearly, this practice is not consistent with ALARA principals.

As a first approximation, a q value of 1.0 is suggested. This approach essentially implies that avoidance of occupational collective dose is equally as important as avoidance of public collective dose. However, the formulation provides a basis for incorporating occupational dose in the risk assessment process at any desired level of equivalence.

5.3 Risk Aversion Factor (α)

A risk aversion factor (α) has been suggested in NUREG-0739 to account for the fact that people are generally more averse to high consequence risk than to equivalent risks of low consequence even though their probability may be high. A value for α of 1.2 is suggested in NUREG-0739 for risks resulting in early death. NUREG/CR-0579 suggests a value for α as high as 3. A strong (rational) argument can also be made for dealing with "expected risk" ($\alpha = 1.0$) as the best means of achieving optimal efficiency in health and safety programs. Determination of an appropriate α factor requires a subjective or administrative judgment and cannot be made on a rigorous basis at this time.

As a "first approximation" an α value of 1.2 as proposed in NUREG/CR-0579 is suggested, although further study may provide a more objective basis for its determination. The formulation suggested in Section 5.1 provides a basis for quantitatively scaling consequences according to the determined degree of aversiveness to high consequence risks. Table 5-1 shows the effect of various α factor assumptions ranging from 1.0 to 1.5. It can be seen that a higher α factor can have a profound effect on the net dose calculated for high consequence risks. The risk aversion factor affords the opportunity of incorporating nonlinear perceptions of risks in the calculation. If it is determined that risk aversion is not to be considered, the α factor can simply be assigned a value of unity.

5.4 Discounting

As discussed in Section 3, it may, under certain conditions, be determined that a discounting of predicted future collective doses (similar to discounting of future cash flows) would be desirable. In such cases the calculation of present "value" can be accomplished by applying a simple discount formula:

$$CD_o = CD_t e^{-it}$$

where: CD_o = Present value of future collective dose
CD_t = Predicted collective dose at time t
i = assumed fractional discount rate

As suggested in NUREG/CR-0579, there appears to be no established basis for discounting future harm. Accordingly, it might be prudent initially to assume a discount rate of zero, thereby considering radiation doses to be of equivalent concern regardless of when they are incurred. Given this assumption, $i = 0$ and dose of harm would be discounted.

5.5 Non-Stochastic Effects

Conditions which could lead to large scale accidents that might result in massive short duration radiation exposures present a special case for consideration. While increased levels of collective doses within the stochastic dose range can result in an increased probability of latent cancers at some future time, massive (non-stochastic) doses could result in early death to the victim(s). As previously discussed, measuring the consequences in terms of collective dose (man-rem) would not be appropriate in such cases. Various approaches, have been suggested to determine the relative weighting factor (f) for early deaths as opposed to delayed

TABLE 5-1

EFFECT OF AVERSION FACTOR (α) ON NET EQUIVALENT COLLECTIVE DOSE (CD_n) FOR VARIOUS RISKS HAVING AN "EXPECTED DOSE" OF ONE MAN-REM

$$CD_n = p \cdot CD^{\alpha}$$

		CD_n			
p	CD	$\alpha = 1.0$	$\alpha = 1.1$	$\alpha = 1.2$	$\alpha = 1.5$
1.0	1	1.0	1.0	1.0	1.0
10^{-2}	10^{2}	1.0	1.58	2.51	10.0
10^{-4}	10^{4}	1.0	2.51	6.31	100.0
10^{-6}	10^{6}	1.0	3.98	15.8	1000.0

(e.g., Avoiding a risk with a 10^{-6} probability of incurring 10^{6} man-rem, given $\alpha = 1.2$, would be treated as the equivalent of avoiding a certain 15.8 man-rem) cancer deaths. In terms of loss of life expectancy a factor of two or three might seem reasonable. A factor as high as thirty for the greater importance of early death has been suggested based upon a review of historical data (Litai, 1980). NUREG-0739 suggests a value of five between the limit of risk of delayed cancer death vs. early death. Accepting this suggestion as a reasonable approach, the equivalent collective dose would be 25,000 man-rem. Accordingly, it would appear reasonable to assign a surrogate value of 2.5×10^4 man-rem for each predicted early death for purposes of cost-benefit analysis ($f = 2.5 \times 10^4$ man-rem/early death).

5.6 Cost Effectiveness Guideline (Cg)

In selecting a cost effectiveness guideline for optimization of collective dose, it was noted in Section 3.2 that high values are not necessarily conservative in assuring safety. The nature of cost-benefit analysis is such that the guideline should reflect an optimal cost per unit of risk reduction. As guidelines deviate from optimal in either direction, the objective of general public health and safety becomes less well served.

As previously discussed (Section 3.2), the guideline of $1000/man-rem suggested in Appendix I of 10 CFR 50 appears excessive relative to expenditures in other areas of health and safety (Cohen, 1979). Other values suggested in the literature range from $10 to $1000 per man-rem (Cohen, 1973)(Rodger, 1974). Voilleque' (1981) indicates that it would be reasonable to assign a value of $300/man-rem for occupational dose reduction and $30/man-rem for members of the general public whose exposures are well below relevant dose limits. (Note: this approach would suggest an equivalence factor of $q = 10$.) A review of previous recommendations indicates that a value of $100/man-rem would be reasonable for purposes of the present study.

5.7 Summary of Factors

From the previous discussion, it is apparent that certain factors required in cost-benefit analysis cannot be determined on an entirely rigorous and objective basis. Various suggestions and recommendations for these factors have been reviewed and are summarized in Table 5-2. The final column of this table presents our suggested first approximations. It should be noted that in actual applications, these factors will require either an official determination or appropriate judgment by responsible decision makers. The suggested first approximations can serve for preliminary cost-benefit analyses and as a useful starting point in sensitivity studies.

TABLE 5-2

COST-BENEFIT ANALYSIS FACTORS REQUIRING SUBJECTIVE DETERMINATION

Factor	Definition	Range of Previous Suggestions	Suggested First Approximation
α	Risk Aversion Factor	1 - 3	1.2
q	Occupational Dose Equivalence Factor	0 - 10	1.0
i	Discount Factor	0 - 0.1	0
f	Collective Dose (man-rem) Equivalent for Non-Stochastic Effects (Early Deaths)	5×10^3 - 1.5×10^5	2.5×10^4
C_g	Cost Effectiveness Guideline ($/man-rem)	$10 - $1000	$100

6. SUMMARY AND CONCLUSIONS

ALARA guidance for optimization of radiation exposures requires a consideration of all relevant social and economic factors. Although it has not been general practice in the past, the incorporation of occupational radiation exposures into safety assessments (cost-benefit or value-impact analyses) is clearly indicated in conformance with ALARA guidance.

In this study, a method for incorporating occupational dose consequences into cost benefit analyses related to public safety has been developed and suggested. As a measure of benefit (risk avoided) in any proposed action, the concept of net detriment is applied. Net detriment can be expressed in terms of net collective dose equivalent (CD_n) where:

$$CD_n = \left[(p \cdot CD_p^{\alpha}) + q(p \cdot CD_o^{\alpha}) \right]_{0,i,j....}$$

and: CD_p = Public collective dose (man-rem)
CD_o = Occupational collective dose (man-rem)
p = Probability
α = Aversion factor
$0,i,j..$ =Alternative states
q = Equivalence factor

where:

$$q = \frac{\text{value per unit of collective occupational dose averted}}{\text{value per unit of collective public dose averted}}$$

Values for the various factors in the formulation have been reviewed and discussed. First approximations for these values are suggested. To a large extent, these factors must be based on the subjective judgment of decision makers.

Further work in the current project is being devoted to development of calculational methods for estimating the risks to workers and the general public from various operations and activities in nuclear power production.

For example, it is known that occupational dose levels generally increase with increased frequency of inspection and maintenance, while levels of public risk may decrease as a result. Decreased public risk could result either from a decreased probability of accidents which could involve releases of radioactivity, from improved control measures which minimize quantities of released material, or from some combination of controls. Optimization of radiation exposures requires a consideration of factors related to both public and occupational risk as well as the monetary costs in determining safety improvements.

It is recommended that future effort be devoted to performance of assessments of several actual problems at existing nuclear power plants that involve a consideration of both occupational and public dose consequences. Performance of sensitivity analyses incorporating a range of those factors which must be subjectively determined (α, q, Cg, t, and i) will provide the insights that will be necessary in selecting suitable values for general application. Application of generally accepted values would in turn lead to consistent decisions in areas of public and occupational safety.

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Many NRC decisions intended for the improvement of public health and safety involve concomitant increases in occupational radiation exposure. Previous study (Volume 1) indicates that occupational dose consequences generally have not been considered in cost-benefit and value-impact analyses supporting decisions related to public safety. Such consideration, however, would be consistent with ALARA guidance. This study derives a methodology for factoring occupational dose into cost-benefit analyses. The related issues include: evaluation of occupational vs. public radiation exposure, stochastic vs. non-stochastic effects, probabilistic risk considerations, uncertainty, and de minimus levels.

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