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Limitation of the Release of Radioactive Effluents

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Introduction

During the last years there has been a change of emphasis in the criteria determining the amounts of radioactive materials which can be permitted to be released from nuclear installations. It was previously often considered sufficient to limit the release of radioactive material to the environment by limiting the concentrations of the various radionuclides in air and water effluents, the limit usually being a fraction of the Maximum Permissible Concentration recommended by the ICRP in 1959 for application in radiological work. Obviously this procedure does not prevent substantial amounts of radioactive material reaching the environment if the effluent rates are high, nor does it prevent the possibility that ecological concentration processes might cause high concentrations in certain environmental materials resulting in unexpectedly high doses in members of the public. In many cases these eventualities were taken into account by introducing safety factors in the concentration limits or sometimes in the amounts allowed to be released. The present trend of sophistication in radiation protection philosophies has a corresponding influence on waste disposal policies, in particular relating to the limitation of environmental releases and to the assessment of radiological significances of such releases.

The basic principles of radiation protection, as presented in ICRP Publication 26 (ICRP, 1977), require that the following criteria be met when setting release limits to the environment:

(a) The control of the release must be optimized. This source-oriented requirement involves the choice of a level of control such that further reductions of the exposure resulting from the release are less significant than the additional efforts required to achieve such reductions.
(b) Dose limits for individual members of the public (i.e. the critical group) must not be exceeded. In implementing this individual-oriented requirement, release limits must take into account the presence of other sources of radiation exposure, the continuing operation of all

these sources in the future and the eventual installation of new sources.

Several papers (ICRP, 1973, 1977; JACOBI 1975; BENINSON, 1977; LINDELL, 1977a) review the concepts involved in the implementation of these two requirements and the quantities used, such as dose equivalent, effective dose equivalent, their rates and their commitments.

Fulfilment of Requirement (a): Optimization

ICRP Publications 22 (ICRP, 1973) and 26 (ICRP, 1977) give the basis for using optimization techniques to meet the radiation protection requirements of "keeping doses as low as is reasonably achievable". In the context of radioactive effluent control, optimization involves the choice of a level of control which would minimize the combined cost of the control measures and the cost of the radiation detriment corresponding to these control measures.

The release into the environment from a given source can be regarded as composed of several sub-releases, each requiring appropriate control measures. Optimization, as described above, implies:

$$\sum_j (X_j + \alpha S^C_{E,j}) = \text{minimum}$$

where X_j is the cost of control of sub-system j, $S^C_{E,j}$ is the collective effective dose equivalent commitment resulting from sub-system j when its cost of control is X_j, and α is the assigned monetary value per unit collective effective dose equivalent. For establishing the constraining functions in the optimization procedure, it will be assumed that the sub-systems j are *independent*, in the sense that the control in one of them does not influence the collective effective dose equivalent commitments from the others.

The minimum for the above equation can be obtained by differentiating the expression respect to the different $S^C_{E,j}$, making each result equal to zero. The following of equations are obtained for $j = 1, 2, \ldots n$:

$$\frac{dX_j}{dS^C_{E,j}} + \alpha = 0$$

since all $(dX_i/dS^C_{E,i})$ and $(dS^C_{E,i}/dS^C_{E,j})$ are equal to zero for $i \neq j$ due to the independence of the sub-systems.

It follows that the optimization of control can be obtained by optimizing each independent sub-system taken separately and that this condition is obtained if

$$\frac{dX_j}{dS^C_{E,j}} = -\alpha$$

Similarly, the optimization for the total release from several installations at a given site can be obtained by optimizing separately the controls at each installation, provided the condition of independence applies.

In many practical assessments of optimization, the changes in control levels are achieved in finite increments, both X and S_E^C being discrete and not continuous variables. The decision of going from a level of control A to a more expensive level of control B would be taken if

$$\frac{X_B - X_A}{{}_A S_E^C - {}_B S_E^C} < \alpha$$

It is possible to influence the dose from effluent releases by several procedures: (1) changing the release technique (stack height, type and position of discharging pipeline, etc.) the dispersion of the effluents in the near environment is influenced; (2) delaying the release (by several delay tanks, etc.) the nuclide composition of the effluent is changed due to decay of the short lived components; (3) removing part of radioactive material in the effluent stream. In the case of long-lived radionuclides, control depends upon capture of the radionuclides from the effluent stream, retention of the captured material and disposal by a technique that ensures isolation of the material from the environment for some significant period.

Specification of control technology requires detailed knowledge of the design of the installation in which it is to be employed. Each process step must be analysed to identify radionuclide inventories, mechanisms and pathways for radionuclide releases in the environment, volume flow rates, and the physical and chemical characteristics of the process stream. Such assessments are highly dependent upon the specific design characteristics and, in particular, the size of the facility under consideration. Although, modifications of the release techniques influence individual doses near the release point, such modifications are in many cases, unable to change significantly the collective dose commitment due to the release. For this reason this paper deals specially with delay and removal systems.

The relevant parameter of continuous release systems controlled by decay is the transit time of radionuclides to their release into the environment. This transit time is governed by the relation between the available volume for decay and the effluent flow rate. The reduction factor applied to the release can be calculated for each relevant nuclide, i, by

$$f = \exp(-\lambda_i)\frac{V}{Q}$$

where :

λ_i is the radioactive decay constant of the nuclide i
V is the available volume for decay
Q is the flow rate

Removal processes, on the other hand, for any specific mode of effluent release, can be specified for each relevant nuclide i by a decontamination factor, F_i defined by the relation:

$$F_i = \frac{C_i^*}{C_i}$$

where:

C_i is the concentration of i in the process input stream; and

C_i^* is the concentration of i in the process effluent stream. The decontamination factor is related to the reduction factor, f_i, by the relation $F_i = f_i^{-1}$.

For a given initial effluent composition, defined by the annual potential released activities of each nuclide, A_i, the collective dose commitment would be given by:

$$S_E^C = \tau(\sum_i s_i A_i F_i^{-1} + \dot{S}_{E,0})$$

where:

s_i is the collective effective dose equivalent commitment per unit activity of i released;

τ is the life-time of the installation; and

$\dot{S}_{E,0}$ is the annual collective effective dose equivalent due to occupational exposures from the control system.

In most cases, the occupational exposure term contributes little to the collective dose commitment.

The release of short-lived noble gases from BWR is discussed as an example of the application of optimization to release control based on decay. In BWRs continuous removal of non-condensible gases in the steam flow occurs via the main condenser air ejector system. The noble gases enter the gaseous waste stream primarily at this point. Secondary pathways include process fluids to ventilated building spaces.

BENINSON (1979) has applied the model to a BWR reactor (BWR 3000 of ASEA-ATOM) in which the cost of the different possible alternatives refers to the Swedish situation. The assessments of collective effective dose equivalent commitment is based on the assumption of 0.1% of fuel with pinhole damage, information on the effectiveness of each alternative and environmental dosimetric model (SNIHS, 1977; UNSCEAR, 1977).

The alternative levels of control based on decay considered are :

A. Sandtank, as a delay allowing for decay, as in the reactors Oskarshamn 1 and 2.

B. Sandtank plus recombiner (of the type of the reactors Barsebäck 1 and 2).

C. Sandtank plus recombiner plus activated charcoal column (of the type of the reactors Forsmarkt 1 and 2).

D. Type C plus an inactive gland seal system.

The collective effective dose equivalent commitment in each alternative (for an assumed plant life of 40 years), and the cost of each alternative (including installation cost and assuming an operation cost for 40 years equal to the installation cost) are shown in the following table, together with the application of the optimization technique:

	Alternatives			
	A	B	C	D
S_E (man rem)	12000	160	12	8
X (10^6 dollar)	2.32	3.26	4.66	9.32
ΔS (10^6 dollar)	0.94	1.4	4.66	
ΔS (man rem)	11840	148	4	
$\frac{\Delta X}{\Delta S}$ (dollar/man rem)	79	9460	1165000	

Using a value of 100-200 dollar/man rem for α, the table indicates the selection of alternative B as the result of optimization. Individual doses in the critical group, in this case, do not have a limiting effect, as for alternative B they turn out to be about 0.2 mrem in a year.

The release of I-129 from reprocessing plants is discussed as an example of optimization of release control based on effluent decontamination. The example refers to a postulated large reprocessing plant handling 60 GW(e)y of spent fuel per year (OECD-NEA, 1979).

As the half-life of I-129 is 1.7×10^7 years, all that effluent decontamination can do is to remove the iodine and provide for its isolation, which in any case would be short compared to the nuclide's life. In the example (OECD-NEA, 1979) it is assumed that isolation, provided by a repository, is effective for 10^4 years. As differences between collective dose commitments are involved for optimization, the result can be assessed if the collective dose commitment is integrated over 10^4 years.

The alternative options for control are:

Option	*Decontamination factor*
A. None	1
B. Silver zeolite retention, on the dissolver off-gas	100
C. Silver zeolite retention, on the total off-gas	500

Calculating both cost and collective dose commitment for 20 years of operation, and taking a 10^4 truncation of the collective dose commitment, assessed by the UNSCEAR (1977) dosimetric models, the following results are obtained:

		Alternatives		
		A	B	C
$S_E^{10^4 \text{ years}}$	(man rem)	2.52×10^5	2.52×10^3	5.04×10^3
X	(10^6 dollar)	0	2.4	4.8
ΔX	(10^6 dollar)	2.4	2.4	
ΔS	(man rem)	2.49×10^5	2.02×10^3	
$\frac{\Delta X}{\Delta S}$	(dollar/man rem)	9.6	1.2×10^3	

Again, using a value of 100-200 $/man rem for α, the table indicates the selection of alternative B as the result of optimization. As in the previous example, individual doses in the critical group are very small and do not have a limiting effect.

It is conceivable, however, that an optimization study might result in individual effective dose equivalent in the critical group exceeding the limit. It is therefore necessary to ensure that the optimized control is compatible with requirement (b), the respect of dose limits. If this condition is not met, the release limit must be adjusted accordingly. In the rare cases where the effective dose equivalent limit could be approached as a result of the combined sub-system discharges, optimization would require further constraints in the form of limiting equations. The non-linearity of the relationships between cost of control and resulting collective dose equivalent, combined with limiting equations in these infrequent cases, makes necessary the use of non-linear optimization techniques to optimize control (SIDDALL, 1972).

Fulfilment of Requirement (b): Limitation of the Dose in Critical Groups

The ICRP dose limits are primarily intended to ensure adequate protection even for the most highly exposed individuals. Dose limits are important, even with the strong emphasis given at present to cost-benefit analysis for justifying sources or practices. In these analysis, both cost and benefits are taken to include all those accruing to society, and not just those that will be received by particular groups or individuals. Since usually the distribution through the population of these costs and benefits will not be the same, justification of a source or a practice by cost-benefit balancing would be legitimate only if the detriment to each individual is small, not exceeding an acceptable level.

The annual limit for the effective dose equivalent in individual members of the public, recommended by the ICRP, applies to the average effective dose equivalent in the "critical group", namely the group representing the most exposed individuals. If extreme maximizing assumptions are made in the selection of critical groups, the actual effective dose equivalents will be considerably lower than the postulated values and, for these cases, the new ICRP (1977) recommendations maintain the previously recommended value of 500 mrem for the annual limit.

In other cases, however, a more realistic selection of the critical group is required, specially when optimization is the overriding control criterion. In these cases the use of maximizing assumptions would invalidate the optimization because of the bias introduced. When realistic exposure models are used to assess the effective dose equivalent in the critical group, the ICRP (1977) recommends a limit of 100 mrem in a year, unless the exposures are not of a continual nature and not repeated over many years.

The ICRP recommends also an additional limit for members of the public of 5 rem for the annual dose equivalent in any organ or tissue to ensure that non-stochastic effects are not induced.

All the limits in the new ICRP recommendations (1977), specially the limit for effective dose equivalent, are not design or planning values but the lower boundary of a forbidden range of values. Values above the limits are specifically to be avoided, but values below the limits are not automatically permitted. In this sense, the limits are constraints for the optimization procedures.

The use of environmental models allows the establishment of relationships between discharges, environmental levels and resulting doses, making it possible to relate releases of radioactive materials into the environment to the resulting effective dose equivalents in the critical group. The chain of events leading from the primary release of radioactive substances to irradiation of human tissues can be schematically represented by compartment models, in which the rates of transfer of radioactivity between compartments are specified by constants or by time functions. The use of compartment models, even if they are very complex, implies considerable simplification of the real transfer processes.

In most practical cases, and for the purpose of radiation protection, it is sufficient to assess the effective dose equivalent commitment resulting from a given release. In these cases, the time-functions describing the dose rates and the concentrations in different compartments of the environment need not be evaluated, because the time-integral values of those functions provide the information required.

A continued practice at a constant rate of effluent discharge may be regarded as a series of events, each generating a per caput effective dose equivalent rate which is a function of the time elapsed since the event. The combined per caput effective dose equivalent rate will increase reaching eventually a steady state value. This value, $\bar{\dot{H}}^*_E$, can be calculated by integrating the contributions to an arbitrary time T after steady state has been reached (BENINSON, 1977):

$$\bar{\dot{H}}^*_E = \int_{-\infty}^{T} RH_{E,1}\,(T-t)dt = R \int_0^{\infty} H_{E,1}(t)\,dt = RH^C_{E,1}$$

where R is the practice rate (units of practice per unit time), and the other quantities have been defined earlier. If the group size remains constant (N) then $\bar{\dot{H}}^*_E = \frac{R}{N}\, S^C_{E,1}$.

If the movement of radionuclides in the environment is described by a non-feedback transfer model, a knowledge of the transfer factors will be sufficient to predict the time-integral values of the quantities in the compartments. These *transfer factors* F_{ij} in the pathway from input of radionuclides into the environment to the subsequent radiation dose in man can be defined as:

$$F_{ij} = \frac{\int_{-\infty}^{\infty} M_j(t)dt}{\int_{-\infty}^{\infty} M_i(t)dt}$$

where F_{ij} is the factor relating compartments i and j, and $M_i(t)$ and $M_j(t)$ are the appropriate quantities (i.e. activity concentration) in the compartments at time t. The factors F_{ij} must be expressed in terms of the dimensions of the two quantities they link.

The network of pathways linking the release of radioactive materials (input) to human exposures consists of pathways in series and in parallel. The total transfer factor of a branch (pathway in series) is the product of the transfer factors involved; the total transfer factor of several branches in parallel is the sum of the transfer factors of the branches. The effective dose equivalent commitment, $H^C_{E,Q}$, from a given discharge Q of a nuclide can, therefore, be calculated as (UNSCEAR, 1977)

$$\bar{H}^C_{E,Q} = Q \sum_p \prod_s F$$

the products $\prod_s$ being carried out over all pathways in series and the summation $\sum_p$ over the branches in parallel. The discharge Q is a characterized by the nuclide and the activity released. Similarly, the per caput steady state effective dose equivalent rate can be expressed as

$$\bar{\dot{H}}^*_E = RQ_1 \sum_p \prod_s F$$

where R is the practice rate (e.g. the number of MWy per year) and Q_1 is is the discharge per unit practice (e.g. per MWy).

In the following discussion, *local environment* means all locations where similar radioactive discharges will affect the same critical group. If it could be assumed that no other sources of exposure, except the releases, involve the critical group, requirement (b) implies that

$$Q \sum_z \phi_z \sum_p \prod_s F_z < \dot{H}_{E,L}$$

where $\dot{H}_L$ is the annual effective dose equivalent limit and the Q is the annual released activity from all sources having effluents discharged in the local environment, F_z are the transfer parameters of nuclide z and ϕ_z is the proportion of nuclide z in the total discharged activity. The value

$$\frac{\dot{H}_{E,L}}{\sum_z \phi_z \sum_p \prod_s F_z} = L_d$$

is usually called the "derived limit" for release in the local environment. It is the input of radioactivity of specified composition which will result in an effective dose equivalent commitment in the critical group equal to the

recommended annual limit, or which if repeated year after year will cause eventually an annual effective dose equivalent equal to the annual limit.

The derived limit for release used to be called the "capacity of the local environment", and was used in the past as the sole release limitation criterion. As such, "the capacity of environment" is an obsolete concept. It is not suitable to be used as an actual operational release limit, because it could cause exposures at the limit from one single practice, leaving no space for other exposures of the same critical group. Furthermore, it was based on the previous interpretation of the limit as a design value instead of the present meaning as the lower boundary of the unacceptable region.

Regional global contributions from far away similar sources (e.g. reactor discharges) may also expose the critical group involved in the discharge under control. As a rough approximation it can be assumed that the exposure in the critical group is equal to the per caput exposure in the region or world-wide respectively (LINDELL, 1977b). The corresponding per caput effective dose equivalents would be given by

$$\bar{\dot{H}}^*_{E,r} = \left(\frac{R}{N}\right)_r S^C_{E,r,1}$$

$$\bar{\dot{H}}^*_{E,g} = \left(\frac{R}{N}\right)_g S^C_{E,g,1}$$

where $\bar{\dot{H}}^*_{E,r}$ and $\bar{\dot{H}}^*_{E,g}$ are the steady state per caput effective dose equivalent rate in the region and in the world, respectively; $(R/N)_r$ is the per caput practice rate in the region; $(R/N)_g$ is the global per caput practice rate; $S^C_{E,r,1}$ is the regional collective effective dose equivalent commitment per unit practice, and $S^C_{E,g,1}$ is the global collective dose equivalent commitment per unit practice.

Requirement (b), individual dose limitation, can then be reformulated as

$$Q_1 \sum_z \phi_{1,z} \sum_p \prod_s F_z + \left(\frac{R}{N}\right)_r S^C_{E,r,1} + \left(\frac{R}{N}\right)_g S^C_{E,g,1} < f\dot{H}_{E,L}$$

where Q_1 is the local release rate, f is a factor smaller than 1 to allow for exposures of other types to the same critical group, and the other symbols have the same meaning as in previous equations.

The application of the requirement of individual dose limitation, as given in the previous paragraph, covers present and future conditions, provided that some projections can be made of the values of R/N. If it is assumed that in the future R/N will be approximately the same for all regions, then the previous equation reduces to

$$Q_1 < \frac{f\dot{H}_{E,L} - \frac{R}{N} S^C_{E,1}}{\sum_z \phi_z \sum_p \prod_s F_z}$$

where Q_1 is the total release in the local environment and $S^C_{E,1}$ is the total collective effective dose equivalent commitment per unit practice. The

second member of the inequality could be called the "adjusted derived limit" for discharge. The adjusted derived limit for discharge corresponds to a given effective dose equivalent rate value for the exposures of the critical group caused by the local releases. This value, which might be called the "site dose limit", $\dot{H}_s$, is given by the expression

$$\dot{H}_s = f\dot{H}_{E,L} - \frac{R}{N} S^C_{E,1}$$

The interplay for these parameters can be seen in an arbitrary example. Choosing a value of 0.5 for f, assuming a future per caput nuclear installed capacity of 5 kW and using a value of 3 man rem per MW(e)y for $S^C_{E,1}$ (UNSCEAR, 1977), the site dose limit becomes $\dot{H}_s = 35$ mrem/y. In general, planning is necessary to decide on the value of the factor f to be selected and in some cases on the necessity of applying limits to the collective dose equivalent commitments per unit practice.

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