

AN OPTIMIZED INVESTIGATION STRATEGY FOR THE DECISION ON REMEDiation OF MINING RELICS IN GERMANY

Klaus Gehrcke

Federal Office for Radiation Protection, D-10318 Berlin, Köpenicker Allee 120-130
Tel.: (+49) 30 50922341

ABSTRACT

In Germany, decisions have to be made on the necessity of remediation measures for mining relics contaminated with radionuclides from the uranium-radium decay series. They will be based on an effective dose criterion. Random sampling errors of the quantities from which doses are calculated are a major source of uncertainty in deciding whether doses exceed the dose level or not. This leads to the necessity of defining a more complex decision rule which satisfies the requirements of a statistically sound decision, legal defensibility and radiation protection under the conditions of intervention. Also, economic cost is an important factor. It sets limits to the investigation effort. Some balancing between these different requirements is, therefore, necessary.

The paper describes an approach that takes into account all these aspects and a procedure that allows to derive optimized site-specific investigation strategies. The procedure is based on a Monte-Carlo simulation of random sample taking. It makes use of the results of preliminary measurements carried out within the framework of a comprehensive federal project finished in 1998 and experiences from remediations already carried out.

INTRODUCTION

The German Government has been confronted with a number of environmental problems after reunification including the consequences of uranium ore mining and milling by the Soviet, later Soviet-German, WISMUT company from the end of W.W.II until 1990. The relics of one of the world's largest uranium producers are currently subject to a remediation programme of the Federal Government.

Besides the sites within the responsibility of WISMUT, there are thousands of relics with enhanced levels of radionuclides of the uranium-radium series in the Federal States of Saxony, Thuringia and Saxony-Anhalt. These originate from traditional mining of ore and coal ranging back to the middle ages. Also, a large number of relatively small uranium mining and milling sites from the early years of the WISMUT operation are no longer under their responsibility. These are not covered within the framework of the WISMUT remediation programme. However, decisions on the necessity of measures to reduce radiation exposure are required there, too. A systematic radiological investigation programme was launched to provide a basis for the decisions. The comprehensive federal project named „Radiological investigation, registration and assessment of mining relics“ was started in the beginning of the 90's and ended up in 1998 (1).

So far, however, there is no legal basis for the final radiological assessment of these relics. Currently existing radiation protection regulations do not cover this specific problem. The German Commission on Radiological Protection (SSK) stated that the situation has to be considered as a so-called intervention situation (2). Dose limits established for planned practices generally do not apply under these circumstances and are, therefore, not suitable for deciding on the necessity of remedial measures. However, based on the fundamental radiation protection principles of justification and optimization recommended by the International Commission on Radiological Protection (3) specific intervention levels may be established to support decision

making. SSK has recommended the application of an effective dose reference level. It is oriented about the variation of natural background. No remedial action is deemed justified if additional radiation doses caused by mining relics are less than this level on the grounds that it was not reasonable to take remedial actions under exposure conditions that may also occur naturally.

Primarily, the recommended dose level is only a 'non-action level'. In practice, however, it is already being dealt with as an action level as well and it is likely that also in new radiation protection regulations to come an effective dose level will be used for the decision on remedial actions.

Problems arise from the fact that the effective dose as a quantity not accessible to direct measurement needs to be calculated on the basis of exposure models and parameters using measurable quantities. To accomplish uniform decision-making fulfilling the requirement of legal defensibility, the action level has to be supplemented by instructions for its use. Standardized procedures and parameters for dose assessments have, therefore, been developed (4) as well as instructions for the measurement of relevant physical quantities. However, these do not cover the treatment of random sampling errors which may lead to considerable uncertainties in deciding whether the action level is exceeded or not. The present paper provides a suggestion how to deal with this problem under the specific conditions of old mining relics in Germany.

Dose Assessment

According to (4) the following pathways have to be considered in evaluating the radiological consequences of mining relics:

- external exposure to γ -radiation from the contaminated areas
- radiation exposure by inhalation of dust contaminated with long-lived α -emitters
- radiation exposure by ingestion of locally produced food (including drinking water)
- direct ingestion of dust and soil contaminated with long-lived α -emitters by children playing outdoors
- radiation exposure by inhalation of radon progeny.

Out of these pathways the actually relevant ones have to be selected taking into account the special conditions at the site in question. If we denote by index i the exposure pathways, the resulting dose may be written

$$D = \sum_i D_i . \quad (1)$$

It is assumed here that the contributions of different pathways may generally be described by the following integral

$$D_i = \frac{1}{V} \int_V C(\vec{r}) \cdot f_i(\vec{r}) dV , \quad (2)$$

where the variables denote

$\vec{r}$ a vector representing a point in the volume of a given relic

$C(\vec{r})$ mass-specific activity at point $\vec{r}$

$f_i(\vec{r})$ a factor converting $C(\vec{r})$ for a given volume element of the relic at point $\vec{r}$ into the corresponding dose contribution. It summarizes all factors influencing the dose except C (e.g. dose factors, transport processes, attenuation, exposure parameters ...)

V the volume of the relic.

For practical use it is necessary to simplify Eq. (2). In this paper, the f_i are considered to take an averaged, constant value within certain, path-specific sub-volumes V_i and they are neglected for the rest of the relic's volume. Under these conditions, D_i is given by

$$D_i = f_i \cdot \frac{1}{V_i} \int_{V_i} C(\vec{r}) dV = f_i \cdot \bar{C}_i. \quad (2a)$$

$\bar{C}_i$ is the arithmetic mean of the mass-specific activity over the sub-volume V_i . Eq. (1) now reads

$$D = \sum_i f_i \cdot \bar{C}_i. \quad (1a)$$

For example, the representative volume for 'external exposure to γ – radiation' is only the upper layer of, at maximum, some ten centimeters. Deeper layers do not contribute to this pathway because of self-absorption processes. On the other hand it is quite clear that the adequate quantity to determine external exposure is not mass-specific activity but γ -dose rate. Its measurement is simple and economical and it may also be used to estimate contributions of other pathways. In this case, averaging has to be done over the surface of the relic instead of the volume. In the following, it is assumed that the radiation exposure may be subdivided in two terms, of which the first one summarizes contributions of pathways which are best described by the mean activity concentration of the whole volume and the second one represents dose contributions from near-surface layers which may well be described by the mean γ -dose rate on the relic, Eq. (1b).

$$D = F_C \cdot \bar{C} + F_R \cdot \bar{R} \quad (1b)$$

Here, $\bar{R}$ is the mean dose rate and the factors F_R and F_C are the sums of the factors f_i for the pathways represented by γ -dose rate or mass-specific activity measurements, respectively.

Influence of Sample Statistics on the Decision

Mass-specific activity C and dose rate R are subject to random measurement errors and random sampling errors. The first may originate, among others, from counting errors of radiation detection systems, the second is caused by the true variation of R and C . As a consequence, the mean values $\bar{R}$ and $\bar{C}$ which have to be estimated on the basis of a finite sample, are random values as well. The first type of random error is not considered explicitly here because it is much lower than the second one and, moreover, experimental estimates used here comprise both.

Since $\bar{R}$ and $\bar{C}$ are random variables the overall dose D is a random variable as well. Under these circumstances, the question whether a given action level AL is exceeded or not cannot be answered definitely. Instead, well-known statistical procedures of hypothesis testing have to be applied, leading to decisions with defined error probabilities. The so-called null hypothesis H_0 is formulated and statistical test procedures are used to check whether it has to be accepted or rejected. It is customary to formulate an H_0 that corresponds to the decision one would prefer in

case of doubt. It has already been discussed in the introduction that, following the recommendation of SSK, no measures are deemed justified below the action level. Taking furthermore into account that it is likely that, according to new radiation protection regulations to come, the decision on remediation will be made by the radiation protection authority of the Federal State but the owner of the relic has to bear the cost, the aspect of legal defensibility of decisions becomes especially important. It seems, therefore, reasonable for the authority to adopt the view of the owner (who will tend to avoid the remediation effort) and to base the decision on the null hypothesis

$$H_0: D \leq AL$$

and a possibly small probability α of rejecting this hypothesis in error, that is, requiring remedial actions although the true dose does not exceed the action level.

The necessity to limit α leads to a modification of the decision rule used so far. Given that the 'true dose' equals AL and D is distributed symmetrically around this value (which may always be assumed for sufficiently high sample sizes) the probability of rejecting H_0 amounts to 50%. This is not acceptable, considering the requirement of legal defensibility. An increase of sample sizes will not help. The distribution will get smaller but nonetheless, D will be distributed symmetrically around AL, so that α will not be influenced. The usual solution is the introduction of a so-called critical value AL^* which is somewhat higher than AL and to base the decision on this level instead of AL. Eq. (3) introduces a tolerance factor t that links both quantities.

$$AL^* = t \cdot AL \quad (3)$$

The introduction of the critical level AL^* gives the opportunity to lower α by increasing the sample size. Fig. 1 illustrates this under the simplifying assumption that doses are normally distributed.

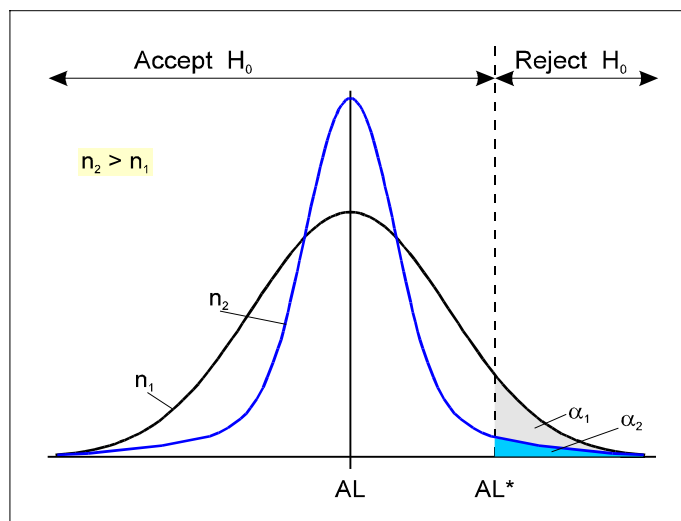


Fig. 1 Illustration of the principle of decision making by introducing the critical level AL^* .

Marked parts under the curves represent error probability α for different sample sizes.

Unfortunately, the introduction of the tolerance factor gives cause to a correspondent increase of the probability β to commit another error, namely to accept H_0 although the true dose is higher

than the action level. In fact, β is higher than 0.5 if the true dose lies between AL and AL^* . It is important to emphasize that this does not conflict with radiation protection requirements under given conditions of intervention. Action levels do not form a boarder line between 'safe' and 'dangerous' but represent a certain level of protection which is considered to be 'reasonably achievable' under given circumstances. This basic idea of radiation protection optimization is only extended from the simple definition of an action level to that of a more complex decision rule, including tolerance factors and error probabilities. The necessity for doing so results from unavoidable uncertainties in dose estimates and the precondition that no remedial measures are justified if doses are below the AL .

So far, the interdependencies between various quantities influencing the decision-making have been discussed qualitatively. In the following, we turn to a quantitative view. Of special interest is the question of the necessary sample size to reach a pre-defined error probability α with a given tolerance factor t . This might be relatively easy in case the doses follow a specific distribution like, for instance, the normal distribution which is shown in Fig. 1. Provided that a reasonable assumption can be made for the standard deviation of the distribution, the required sample sizes may be calculated analytically. Unfortunately, we do not have sufficient knowledge about dose distributions.

From the investigations within the federal project, however, we already have information about the quantities which the doses are calculated from, that is data of mass-specific activities C , dose rates R and a variety of radioactivity concentrations in environmental media like groundwater, plants etc. Here, we concentrate on the statistics of C and R and its implications on dose estimates and decision-making. These quantities are considered to be suitable to describe the contributions of the most important pathways to the dose D according to Eq. (1b).

Very often, environmental data follow lognormal distributions. Since waste rock dumps form the most important group of relics for which decisions have to be made, they are considered here. Fig. 2 shows a frequency diagram of logarithmic concentrations of the radionuclide Ra-226 in waste rock dumps of a selected investigation region of the federal project.

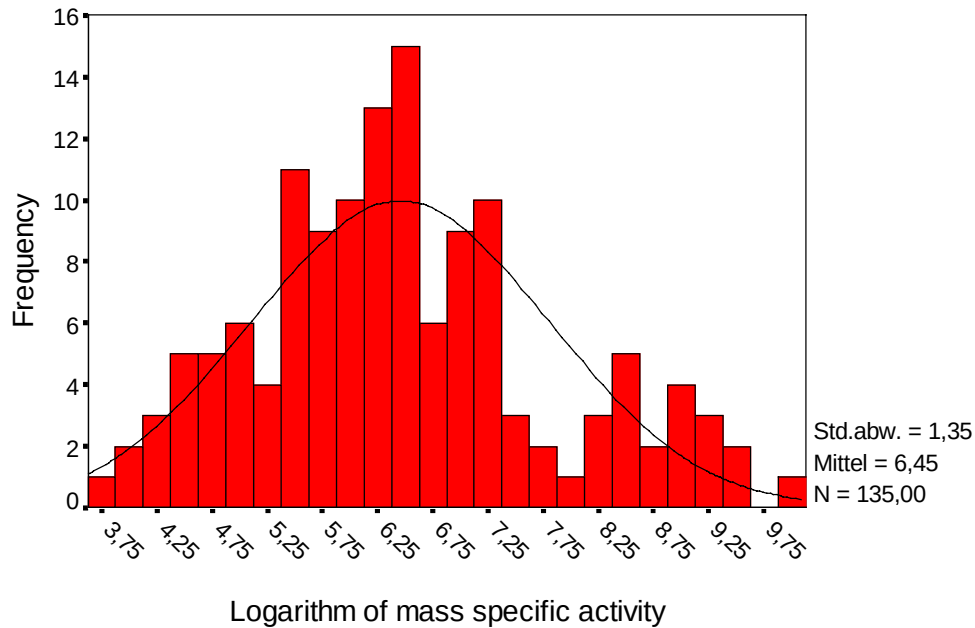


Fig. 2 Frequency diagram of logarithmic Ra-226 concentrations in mining dumps of the region 'Mechelgrün/Zobes'

The diagram indicates that the data do not belong to a unique parent population, because there are two maxima. A deeper analysis proved that the second maximum is caused by a few dumps with a significant share of low-grade ore. That means, these are not pure waste rock dumps. If they are considered separately, the resulting distributions show only one maximum and they may be considered to be essentially lognormal.

Since a variety of different types of dumps have been investigated in the project, e.g. of slag, coal ash and others, fig. 2 makes clear that it is necessary to consider them separately.

The analysis of the distributions of the two groups of dumps mentioned as well as that of single dumps with sufficient available data has shown that a value of $\sigma_c = 1.2$ for the standard deviation of the logarithmic data is likely to be not exceeded. Therefore, this value is used for further considerations.

Equivalent analyses have been made for the results of γ -dose rate measurements at the dumps. The underlying distribution may be considered lognormal, too, with a considerably lower value of $\sigma_D = 0.5$.

It must be emphasized that it is assumed here that the standard deviations are the same for all relics of the same type, independently on the dump volume. However, most data originate from large volume dumps. Possibly, the standard deviations for the mass specific activity are smaller for smaller dumps but the available investigations do not give reliable hints for that. Also, high densities of measurements of γ -dose rate may lead to correlated data of neighboring points. The possible consequences have not been investigated thoroughly enough so far and they are neglected here.

Knowledge of the type of the distribution of variables C and R and the parameters σ_C and σ_R gives the opportunity to investigate the distributions of $\bar{C}$, $\bar{R}$ and the resulting distribution of D , as a function of the sample sizes n_C and n_R , according to Eq. (1b). A Monte-Carlo procedure has been used to simulate random sample taking from dumps as well as dose rate measurements. The error probability α takes on its maximum value if the true dose equals the action level AL. This is the case on which, therefore, the simulation is based. The error probability α corresponds to the quantile $(1 - \alpha)$ of the dose distribution. The program allows to estimate the dependency of quantiles of D on n_C and n_R , both separately and in combination. At first, the simple cases have been investigated in which D depends on one of both quantities only. One of the summands in Eq. (1b) then equals zero and the sampling error of the remaining quantity passes fully on to D . The results of the simulation are given in Fig. 3. It shows the factor by which the quantiles $(1 - \alpha)$ of the resulting dose distributions exceeds the true value AL for selected α 's as a function of the sample size. According to Eq. (3) this is the tolerance factor t .

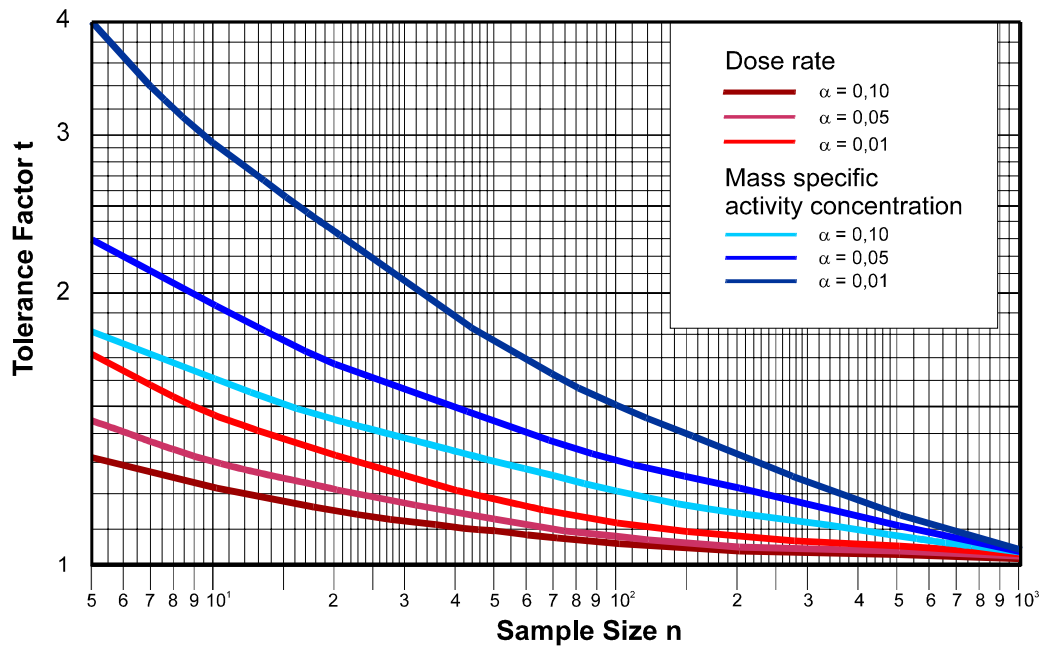


Fig. 3 Tolerance factor t as a function of sample size n for various error probabilities α for measurements of mass-specific activity and γ -dose rate, respectively (result of Monte-Carlo simulation of random sampling).

The curves of Fig. 3 allow to determine suitable combinations of α , t and n for both measurement methods. If, for example, a maximum α of 0.1 and a tolerance factor of $t = 1.1$ is given, the sample sizes required amount to $n_R = 50$ and $n_C = 400$, respectively.

In this example, the choice of α and t is, of course, arbitrary. Moreover, it suggests that one has the free choice of parameter combinations and that even the smallest predefined values of α and t could be reached by sufficiently high sample sizes. For practical applications, however, the

sample sizes will usually have to be confined for economical reasons. The cost of a single γ -spectrometric analysis of a sample from mining dumps amounts to up to 200 DM. Multiplication with the number of 400 required samples from the above example gives a value of nearly 10^5 DM for the analysis only and the cost of sample taking has to be added. This might even exceed the cost of a possible remediation, at least for smaller dumps. The consequences will be discussed in the next section.

Inclusion of Economic Aspects

It has been shown that the economic cost of the investigation of dumps may be considerable, especially if invasive sample taking methods are used. Some limitation of sample sizes will be necessary, therefore, and it seems reasonable to orient such limitation about the cost of a potential remediation, for instance by requiring that the cost of investigation must not exceed a certain fraction of that of the remediation in question. In the following, it is assumed that the authority decides to spend one tenth of the potential remediation cost for the radiological investigation of dumps and that an error probability of $\alpha = 0.1$ meets the requirement of legal defensibility. Under these circumstances, the tolerance factor t becomes a function of the dump volume and the specific cost of the investigation method. These dependencies are discussed in more detail now.

At first, the remediation cost is considered. It differs, of course, for different remediation options and sites. According to the experiences of the WISMUT remediation programme, however, it may be considered proportional to the dump volume and the cost per cubic meter may be assumed to be about 5 DM (5). Correspondingly, the specific financial resources available for the radiological investigation are assumed to be 0.5 DM/m^3 .

To estimate the cost of investigations, an assumption was made about the shape of the dumps considered. A simple cuboid model (square base surface, the height amounting to one third of the edge length) has been used here and simple grid sampling was assumed. As to the specific cost of the investigation methods the experiences from the federal project (1) have been used (cost of drilling, γ -spectrometric analysis, dose rate measurements).

One remark is necessary concerning the sample sizes of dose rate measurements. In the introduction, averaging over the whole surface of a dump has been assumed. This is only possible if the corresponding radiation exposures may be averaged, as well. Considering the fact that the surface is directly accessible to people and that high dose rate sub-areas might be unreasonably 'diluted', confinement of averaging areas is normally required for radiation protection reasons. It is assumed here that averaging is confined to an area of 100 m^2 and that the decision about remediation is based on that sub-area causing the highest dose. This implicates that the requirements of statistics discussed have to be fulfilled for each of the sub-areas, while the financial resources available have to be split correspondingly.

On this basis, resulting t-factors have been calculated for selected dump volumes. To begin with, it is assumed that dose assessments are based on either measurements of mass-specific activity or γ -dose rate alone. One of the summands on the right hand side of Eq. (1b) equals zero then. Making measurements of specific activity only may be reasonable if pathways dominate the exposure that mainly depend on the total activity. For example, a dump might be inaccessible, so that external exposure does not play a significant role, but radon exposure and groundwater contamination may have to be considered because of the size of the dump. For smaller dumps, on

the other hand, it is thinkable that the exposure may be sufficiently described by dose rate measurements only. The results of the calculations are presented in Table 1.

Table I

Tolerance factors resulting for selected dump volumes, assuming that either dose rate measurements (t_R) or sample taking and gamma spectrometric analysis (t_C) are used for the investigation

V [m ³]	10 ³	10 ⁴	10 ⁵	10 ⁶	10 ⁷
t_R	1.10	1.07	1.05	-	-
t_C	-	1.77	1.26	1.07	1.04

The table clearly shows the expected tendency that, due to the fact that the standard deviations are considered to be independent on the dump volume V but financial means increase proportionally to V, resulting t-factors decrease with the dump volume. The values for dose rate measurements are considerably smaller not only because of the smaller standard deviation but especially because of the low price which is in the order of magnitude of one or two percent of that for the sample taking and analysis.

If one relies on sample measurements only, the tolerance factors are rather high for smaller dumps, reaching considerably lower values for large dumps. For very small dumps the financial means are not sufficient for sample taking from the dump volume. This need not be critical, however, because small dumps do not contribute significantly to the corresponding pathways (e.g. radon exhalation and groundwater contamination). Normally, external exposure to γ -radiation and other pathways that may be described by γ -dose rate measurements play the most important role. Using dose rate measurements only leads to low t factors of 1.1 or less but will normally not suffice to describe the exposure for large dumps. For high dump volumes, no values are given for t_R , because densities of measurement points of about 1 m⁻² are reached. It is expected that auto-correlation effects between neighboring points influence the statistics but this has not been sufficiently investigated so far, see previous section.

Especially for larger dumps it will usually be appropriate to use a combination of both types of measurements. Both summands in Eq. (1b) have to be taken into account then and the tolerance factor t is a function of both, n_R and n_C . Within a given financial framework, different combinations of sample sizes are possible. In general, these will lead to different values for t . So, an optimum combination must be found that minimizes t for a given dump volume or investigation cost, respectively. Additional information is necessary, however, to accomplish this, because the influence of random sampling errors of $\bar{C}$ and $\bar{R}$ on the resulting dose D depends on the relative contributions of D_R and D_C to the overall dose D . Since this is known only when the investigations are completed, a reasonable estimate on the basis of preliminary measurements has to be used. Assuming that the true dose equals the action level AL, the Monte-Carlo simulation of sample taking may also be used to find optimal combinations of sample sizes.

An example of resulting tolerance factors is given in fig. 4 with the ratio between the dose contribution of paths described via dose rate measurements and the total dose as parameter.

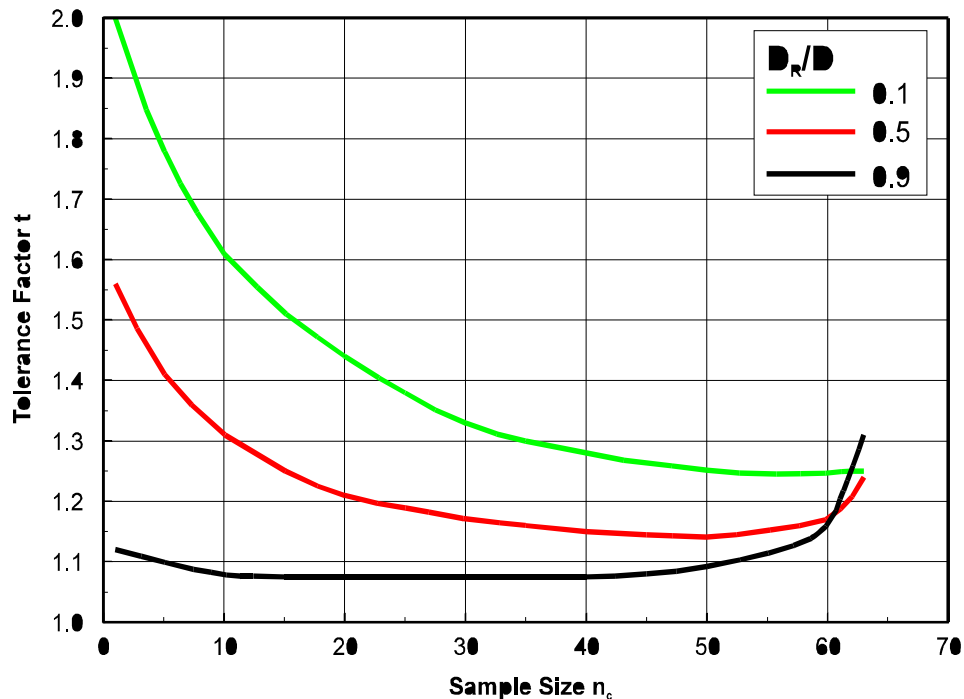


Fig. 4 Tolerance factor t as a function of sample size n_c for a combination of γ -dose rate and mass-specific activity measurements with overall investigation costs limited to 1/10-th of potential remediation costs. Calculations refer to a fictitious dump having a volume of 10^5 m^3 . Arbitrary ratios D_R / D have been chosen.

Fig. 4 demonstrates that, of course, the influence of sample size n_c on t is the higher, the higher the contribution of D_C to the overall dose D is. Only for small contributions of D_C the tolerance factor falls below a level of 1.1 (lower curve). It is possible to choose the optimum combination of n_c and n_R , that means, the one leading to the smallest t -factor under given circumstances. Nonetheless, values of up to about 1.25 have to be accepted, depending on the ratio between D_R and D which has to be estimated specifically for each site.

CONCLUSIONS

The results show that the approach described is a suitable means to get to decisions on remediation of mining relics which take into account all relevant aspects like legal defensibility of decisions, statistical requirements, radiation protection principles under the conditions of intervention and economic costs. The Monte-Carlo simulation provides the possibility to choose optimized, site specific combinations of sample sizes for γ -dose rate and mass-specific activity measurements that minimize necessary tolerance factors t under the conditions of limited financial means.

The impact of investigation costs on the decision has been demonstrated clearly. As far as possible, dose calculations should be based on economical dose rate measurements. The availability of less expensive investigation methods for mass-specific activity, on the other hand,

might minimize tolerance factors. To integrate other methods into the procedure basic knowledge about the distribution and estimates of the standard deviation are necessary.

Of course, the approach described is not free of arbitrariness. For example, it might be decided to use a fixed value of t and to choose the combination of measurements that minimizes the investigation cost. Also, the parameters used may have to be changed for dumps of different origin and, of course, for different types of relics. The procedure itself remains applicable in any case.

In summary, it has to be emphasized that the basic radiation protection principle of optimization has to be extended to the investigation strategy in the case of costly sampling and analyzing techniques and that action levels have to be used within the framework of a more complex decision rule.

REFERENCES

1. E. ETTENHUBER, M. JURK, W. KRAUS and H. BIESOLD, „Radiological assessment of sites contaminated due to former mining activities - the general procedure in Germany“, Proc. of the Fifth International Conference on Radioactive Waste Management and Environmental Remediation, Vol. 2, ICRP '95, Berlin, Germany, September 3 - 7 (1995)
2. „Radiological protection principles concerning the safeguard, use or release of contaminated materials, buildings, areas or dumps from uranium mining“, Recommendations of the Commission on Radiological Protection with Explanations, Gustav Fischer Verlag, Stuttgart Jena New York (1992)
3. International Commission on Radiological Protection: 1990 Recommendations of the International Commission on Radiological Protection, ICRP Publication 60, Vol 21, No. 1-3, Pergamon Press, Oxford (1991)
4. „Berechnungsgrundlagen zur Ermittlung der Strahlenexposition infolge bergbaubedingter Umweltradioaktivität (Berechnungsgrundlagen- Bergbau)“ - Draft 1998
5. M. KÜMMEL, „Abschätzung eines zu erwartenden Kostenaufwandes für Sanierungsmaßnahmen bergbaulicher Altlasten“, Bundesamt für Strahlenschutz, Fachbereich ST, Berlin (1998)