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CRITICAL VIEWS ON THE APPLICATION OF SOME METHODS FOR EVALUATING ACCIDENT PROBABILITIES AND CONSEQUENCES

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Abstract

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The mathematical expectation of consequence (also referred to as the detriment) is often used as a measure of the potential impact of a source of risk. Boundary curves such as those used in Farmer diagrams may be used to indicate the non-acceptability of certain foreseen risks, for which the detriment exceeds a preset limit. These curves must not be confused, as sometimes happens, with probability density functions expressing the accident probability within differential intervals of consequence. Another useful way of presenting probabilities and consequences, used in many safety assessments, is to present the complement of the cumulative distribution, i.e. the probability that the consequence will exceed given values. The integration of this function gives the detriment. At very low probabilities, the detriment (the product of the low probability and the consequence) will lose its usefulness as a basis for decision-making. It is then no longer a central measure of the distribution and, in addition, the uncertainty of the detriment becomes too large to make it meaningful, even if the probability as such could be estimated by safety assessments with an accurate degree of certainty.

1. INTRODUCTION

This paper is not intended to present new concepts or methods. On the contrary, those who are experts in statistics and probability theory will find it elementary and perhaps somewhat naive.

It is the experience of the authors, however, that physicists and engineers engaged in assessments of accident probabilities and consequences sometimes misuse or misunderstand quantities, concepts and procedures which are quite legitimate if

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properly used. Reports on such assessments are therefore too often confusing to readers who wish to familiarize themselves with the subject without having to study the basic foundations.

The purpose of this paper is to point to the most common sources of misunderstanding. The fact that concepts and methods are sometimes misused, however, does not imply that accident "risks" are over- or underestimated. The only implication is that they are not always well understood.

2. THE CONCEPT OF RISK

The English word "risk" has the double meaning of the *nature* of a harmful event and the *probability* of the event. If the probability of the event to occur within a specified period of time (τ) is $P(\tau)$ and the consequence of the event, if it occurs, is Q, the mathematical expectation of consequence is $E(Q) = P(\tau)\cdot Q$. Unfortunately, some studies have also used the word "risk" for this quantity, unnecessarily giving the word three different meanings.

To avoid confusion, the word "risk" should not be used when a specific interpretation is essential, but may be used when referring to random harmful events in a general sense. The appropriate words for the relevant quantities would be:

Period of risk (*e.g.* the life-time of a nuclear reactor):	τ
Probability of a harmful event (i) to occur within that period:	$P_i(\tau)$
Consequence of the event (i), *if* it occurs:	Q_i
Mathematical *expectation* of consequence from event (i) over the time period (τ):	$E_i(Q) = P_i(\tau)\cdot Q_i$

If p(t) is the probability density over time (dP/dt), the probability $P(\tau)$ over a specified period of time (τ) will be

$$P(\tau) = \int_0^\tau p(t)\,dt$$

The concept "event" may need some explanation. In this paper, an event (i) is synonymous with the occurrence of a particular consequence (Q_i), which by fault-tree analysis may be shown possible to be caused by any of a number of initiating incidents. It would also be meaningful, although we have not done so, to let "event" mean some such initiating incident. In that case, no distinct consequence Q_i would be unequivocally linked to the event (i). However, event-tree analysis would show that there is a conditional expectation ($\bar{Q}_i$) of consequence, given the initiating incident. Although this latter meaning of "event" is probably more useful in practice, we have preferred the first definition of event for our purposes in this paper, bacause it will simplify the presentation of the points we wish to make.

3. USE AND MISUSE OF THE CONSEQUENCE EXPECTATION

In the simple Bernouillian case of one "trial", where the consequence outcome is either zero or a finite value (Q_1) and the probability of the non-zero consequence is P_1, the mathematical expectation of consequence is defined as

$$E(Q) = \bar{Q} = 0\cdot(1-P_1) + Q_1P_1 = Q_1P_1$$

The standard deviation of Q will be

$$\sigma_Q = Q_1 \sqrt{P_1(1-P_1)}$$

The coefficient of variation (v_Q) defined as $\sigma_Q/E(Q)$, will then be

$$v_Q = Q_1 \sqrt{P_1(1-P_1)} \,/Q_1P_1 = \sqrt{\frac{1-P_1}{P_1}}$$

i.e. for $P_1 << 1$, $v_Q \approx 1/\sqrt{P_1}$

In a series of Bernouillian trials, *e.g.* N identical trials each of which with a consequence of either zero or Q_1, the probability of zero consequence is $(1-P_1)^N$ and the probability of *at least* Q_1 in consequence is $1 - (1-P_1)^N$.

In this case the probability of a consequence of magnitude MQ_1 (*i.e.* M "events" out of N trials) can be calculated from the *Binomial distribution* as

$$P(MQ_1) = \binom{N}{M} P_1^M (1-P_1)^{N-M}$$

For example, the probability of a total consequence of magnitude NQ_1 would be P_1^N. Since the standard deviation in the Binomial distribution of *events* is $\sigma = \sqrt{NP_1(1-P_1)}$, the standard deviation of the consequence in the full series of trials is $\sigma_Q = Q_1\sqrt{NP_1(1-P_1)}$.

The "trials" may not only be seen as a repetition in time (assuming constant probability density over time) but also as a repetition in space, *e.g.* with N identical reactors operating over a given period of time. Therefore, if for similar reactors P_1 is the probability of accident for one reactor within one year, the expectation of consequence for N reactor·years will be

$$E(Q) = NP_1Q_1$$

if Q_1 is the consequence of one accident. It also follows that

$$\sigma_Q = Q_1\sqrt{NP_1(1-P_1)} \approx Q_1\sqrt{NP_1}$$

$$v_Q \approx 1/\sqrt{NP_1}$$

In practice, this is an oversimplification because the probability of event for one reactor over one year is likely to vary from year to year and from reactor to reactor. For our purposes of demonstrating basic principles, however, these variations will be neglected.

The numbers in Table I may serve as an illustration. According to the German reactor safety study (the Birkhofer study), there is a probability of $5\cdot10^{-10}$ per year and 25 reactors for an accident that will cause a collective dose of at least 420 000 000 man.rem [1]. This is the basis for the numbers in the table.

With such small probabilities, the standard deviation is many thousand times larger than the calculated expectation of consequence. Even if the probability (P) could be assessed to any desired degree of accuracy, the actual outcome of consequence has a very large inevitable uncertainty, which makes the precise statement of the mathematical expectation misleading (in fact, the expectation value will never occur: in the example the outcome is either zero or 420 000 000 man·rem). It should be added that we have only used the German study as the source of numbers for our example; the study itself has not fallen into the trap of misusing the expectation value.

This shows that, at low probabilities, the mathematical expectation of consequence is not a quantity that can meaningfully be used for comparisons, because of its large inherent

Table I: Example of assessed consequence expectations based on numbers given in the German reactor safety study.

No. of reactors	1	25	25
No. of years	1	1	30
No. of reactor·years (N):	1	25	750
Consequence (Q) of the assumed event, man·rem:	$4.2 \cdot 10^8$		
Probability of this consequence for one reactor-year (P_1):	$2 \cdot 10^{-11}$		
Probability over above-indicated number of reactor·years (P):	$2 \cdot 10^{-11}$	$5 \cdot 10^{-10}$	$1.5 \cdot 10^{-8}$
Expectation of consequence, $E(Q) = P \cdot Q$, man·rem:	0.008	0.2	6
Standard deviation, man·rem $\sigma_Q = Q \cdot \sqrt{P}$	1900	10 000	50 000
Coefficient of variability $v_Q = \sigma_Q / E(Q) = 1/\sqrt{P}$	220 000	45 000	8 000

uncertainty. Nevertheless, it is not unusual to see reports which present mathematical expectations of so and so many deaths to be compared with actually occurring death rates.

Utility functions for decision-making should therefore not necessarily be based on a constant value of the product of probability and consequence. This is the well-known "zero-infinity"-problem, discussed by *i.a.* Page [2] and Rowe [3].

The situation is quite different at higher total probabilities, as encountered in other areas. There will then be a significant probability of more than one event, as described by the Binomial distribution. Under certain conditions (large number of identical trials and low probability of event per trial) this may be approximated by the *Poisson distribution*. In this case, the probability P(x) of exactly x events over the total period is

$$P(x) = \frac{\lambda^x}{x!} e^{-\lambda}$$

Here, the parameter λ is also the mathematical expectation of x, *i.e.* E(x) or $\bar{x}$. In this case, however, λ is also very close to the mode (*i.e.* the most frequent value) of the distribution. For such high probabilities that the expectation of consequence is also a frequent outcome, the expectation has a great practical value. For example, by knowing the expected number of traffic accidents or cases of various diseases, authorities may plan remedial actions or hospital resources.

4. CRITERION CURVES FOR A DISCRETE NUMBER OF ACCIDENTS

It is obvious that, in the choice of two accidents with the same probability, the one with the smallest *consequence* should be preferred. Also, of two accidents with the same consequence, the one with the lowest *probability* would be preferred. It is therefore easy to understand that it has been natural to use the product of probability and consequence, *i.e.* the expectation of consequence, in the utility function for decision-making. At high probabilities, the actual consequence or number of events will in the long run approach the expectation. It is only at low probabilities that the product of probability and consequence is not necessarily the best utility function and some other monotonous function of the two quantities may be preferred.

For the purpose of decision-making, a *criterion curve* was proposed by F.R. Farmer in 1967 [4]. This is a curve combining all hypothetical points, which in a probability *vs.* consequence diagram represent events with one and the same mathematical expectation of consequence.

In the special case (*cf.* Fig. 1) where only one single event is conceivable and known as regards probability and consequence, this curve can be used as the reference to indicate whether the event has a higher consequence expectation than the events represented by the criterion curve. In that case, the point describing the event will fall in the (forbidden) area above the curve. If the point falls in the area below the curve,

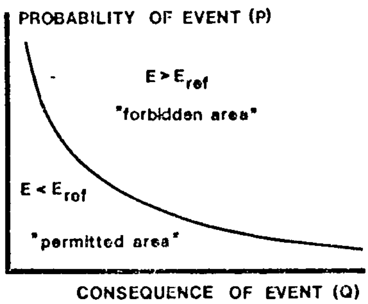


FIG.1. Criterion curve combining points representing events with a given reference expectation of consequence, E_{ref}. *The curve reflects the condition that* $P \cdot Q$ *is constant and equal to* E_{ref}.

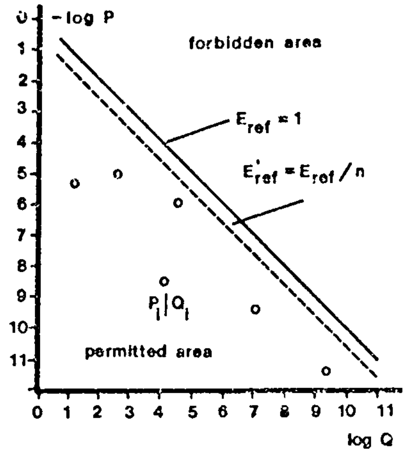


FIG.2. Criterion curve in a logarithmic diagram. Consequence in arbitrary units. $P \cdot Q = E_{ref} = 1$ *(arbitrary units).*

the event has a lower consequence expectation than that represented by the criterion curve and the event may therefore be acceptable.

In a logarithmic diagram, the criterion curve is a straight line (*cf.* Fig. 2), since

$$\ln P = \ln E_{ref} - \ln Q$$

It follows that the slope of this line is -1.

We have already shown that the mathematical expectation of consequence at low probabilities is rather meaningless because of the very large inherent uncertainty of the actual outcome. This reduces the practical usefulness of the criterion curve if the main objective is to limit the expectation of consequence. This does not necessarily say that the product $P \cdot Q$ cannot be used to give some guidance for decisions. However, most authors agree that at very low probabilities the consequence should be given relatively larger weight, *e.g.* by using $P \cdot Q^{\mu}$ ($\mu > 1$).

If there is more than one conceivable event, but the number of events is limited and known, criterion curves may still be used. In this case, however, the judgement will be obvious only for those events which are represented by points in the forbidden area of Figure 1. A set of points ($P_i|Q_i$) in the permitted area (*cf.* Fig. 2) may or may not constitute an acceptable situation. With a discrete number of events, it is not the consequence expectation of any one event but that of all that is of interest to compare with the criterion that $E < E_{ref}$. The criterion therefore becomes

$$\sum_i P_i Q_i < E_{ref}$$

It cannot be seen directly from the original criterion diagram if this condition is fulfilled. Only if each of a limited number (n) of discrete events is represented by a point below a new curve satisfying the condition $P \cdot Q = E'_{ref} = E_{ref}/n$, there is a clearcut conclusion that the situation is acceptable (*cf.* the broken line in Fig. 2). If some points fall above and some below the new curve with no points above the original curve, the situation may or may not be acceptable and the sum of the products $P_i Q_i$ has to be calculated.

5. PROBABILITY FUNCTIONS: (1) THE DENSITY FUNCTION

In reality, the number of possible events is not known and, in fact, it may not be possible to define discrete events, since the consequence may be a continuous variable (*e.g.* the amount of radioactive substances released, or the area of land with a radioactive deposition above a specified value). However, in principle, the events may be grouped in a number of classes according to their consequence. Then a histogram (Fig. 3) would indicate the assumed probability density $\Delta P/\Delta Q$ for the class intervals.

This histogram has no relation to the criterion curve and does not describe events with equal consequence expectation. Instead, for each source for which a safety analysis is made, for example a nuclear reactor, the histogram is an approximation of the *density function* f(Q) of the probability distribution. Each column in the histogram is a measure of the probability of accident per unit consequence interval within the interval indicated by the column. If also the interval including zero consequence is included, the total area under the histogram is the probability that there will be either some or no consequence, *i.e.* a probability of one.

At least conceptually, the histogram may be replaced by a curve representing the continuous density function $f(Q) = dP/dQ$, Fig. 4.

It is merely fortuitous that the curves in Fig. 1 and Fig. 4 have similar shapes. The shape of the criterion curve in Fig. 1 is determined by the *decision* not to accept the same probability for an event with large consequence as for an event with small consequence and to let the acceptability criterion for

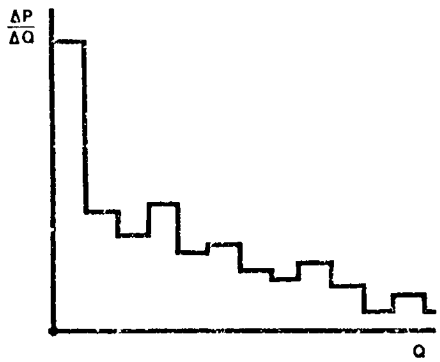


FIG.3. Event probability by classes of event (consequence).

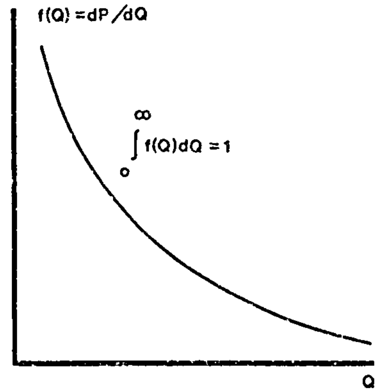


FIG.4. Illustration of the probability density function.

single events be $P \cdot Q$ = const = E_{ref}. The shape of the curve describing the probability density function (Fig. 4) is determined by the *fact* that events with large consequences tend to have lower probabilities than events with small consequences.

These two entirely different reasons for the shape of each curve are not intercorrelated and the similarity of shape is just fortuitous. The curves describe entirely different things. One gives the highest acceptable probability P(Q) for a single discrete event of consequence Q, the other gives the assumed density function $f(Q) = dP/dQ$, *i.e.* plots a quantity with a different dimension. Still, one can sometimes see one misused for the other.

We have already indicated that, in the case of so many possible events that Q may be considered as a continuous variable, it is not the expectation of consequence from one event but from all events that has to be compared with the criterion.

Instead of $E = P \cdot Q$ we therefore have to assess

$$E(Q) = \bar{Q} = \int_0^\infty Q\, f(Q)\, dQ \;<\; E_{ref}$$

The estimated density curves of the type shown in Fig. 4 would therefore have to be compared with a new type of criterion curve, with $f_{ref}(Q)$ as a function of Q and so designed that

$$\int_0^\infty f_{ref}(Q)\, Q\, dQ = E_{ref}$$

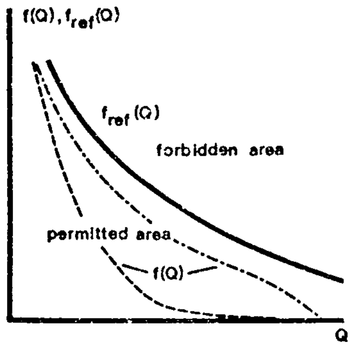


FIG.5. Example of comparing the assessed probability density function f(Q) *with a stipulated criterion function* $f_{ref}(Q)$.

This condition, however, is met by many different functions $f_{ref}(Q)$ and does not define one single criterion curve. Only if we introduce additional conditions may we define $f_{ref}(Q)$ unambiguously. We might then obtain a criterion curve which could be used directly in the probability density diagram because it would describe a quantity which also has the dimension of probability density over consequence. In comparing f(Q) (the assessed probability density) with $f_{ref}(Q)$ (the stipulated criterion) we would therefore compare quantities with the same dimension, *cf.* Fig. 5. Only if the curves cross would we need further criteria for decisions.

We have seen that the criterion curve for single events (or a limited number of discrete events) would be a straight line in a logarithmic diagram if the criterion is that P·Q should be less than E_{ref} (or, in general, with slope $-\mu$ if $P{\cdot}Q^{\mu}$ is used as the criterion basis). If we also expect $f_{ref}(Q)$ to be presented by a straight line in a logarithmic diagram, we have to assume that

$$f_{ref}(Q) = a/Q^{b}$$

a and b being constant. A further obvious requirement is that

$$\int_0^{\infty} f_{ref}(Q)\, dQ = 1$$

The two requirements are only compatible if the region of the straight line is limited to values of Q between Q and Q

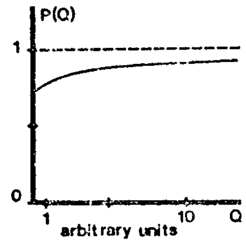


FIG.6. Probability distribution, P(Q).

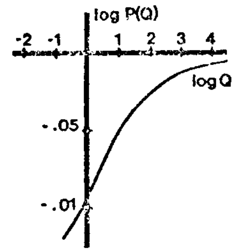


FIG.7. Logarithmic display of the probability distribution.

with $f_{ref}(Q<Q_o) \leq f_{ref}(Q_o)$. In practice Q_{max} is set by physical limits of consequence. For example, the release of iodine from a nuclear reactor can never exceed the amount of iodine present in the core and in storaged spent fuel, waste and filter systems. Without these boundaries, the straight line would imply infinite consequence expectation. With the boundaries, the straight line is possible but arbitrary.

6. PROBABILITY FUNCTIONS: (2) THE DISTRIBUTION FUNCTION

The *probability distribution*, P(Q) is the integral of the density function. It is the total probability of events less than or equal to a specified consequence Q:

$$P(Q) = \int_0^Q f(Q)\, dQ$$

The probability distribution may be presented in logarithmic as well as in linear diagrams, *cf.* Figures 6 and 7.

When the interest is focussed on events with low probabilities, the probability distribution is not very illustrative, since $P(Q) \approx 1$ for the consequences of interest. Instead, the complement to P(Q), *i.e.* $T(Q) = 1 - P(Q)$, is often used. It may be called the "tail distribution", *cf.* Fig. 8.

The tail distribution is often used in logarithmic diagrams to present the probability of accidents with *at least* a specified consequence, *e.g.* in the U.S. Reactor Safety Study (the Rasmussen report [5]), *cf.* Fig. 9. It has an interesting

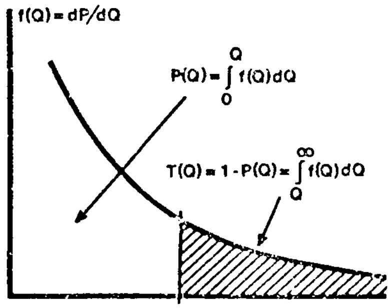


FIG.8. Deriving the tail distribution.

property in that its total integral is equal to the mathematical expectation of consequence:

$$\int_0^\infty T(Q)\,dQ = \int_0^\infty [1 - P(Q)]\,dQ =$$

$$= \Big|_0^\infty [1 - P(Q)]\cdot Q + \int_0^\infty Q\cdot P'(Q)\,dQ =$$

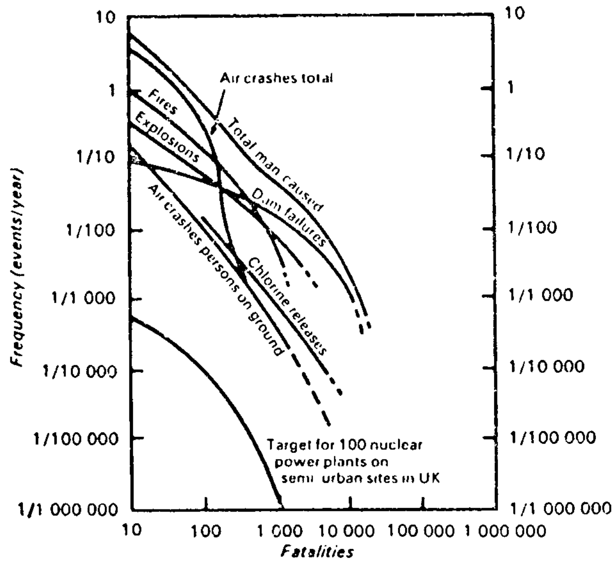
$$= \int_0^\infty Q\,f(Q)\,dQ = E(Q)$$

The requirement that $E(Q) < E_{ref}(Q)$ – the choice of $E_{ref}(Q)$ being essentially a social value judgement – is obviously satisfied for any tail distribution with a smaller integral than that of any criterion tail distribution with an integral equal to $E_{ref}(Q)$.

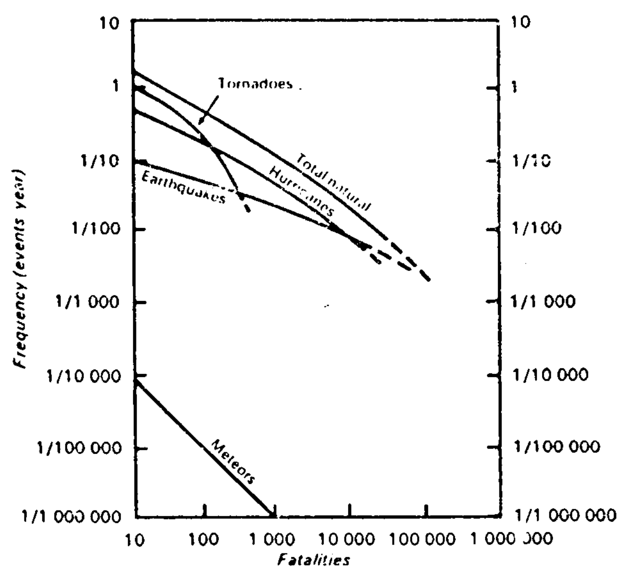
7. THE TAIL DISTRIBUTION AS CRITERION FUNCTION

Criterion curves are sometimes presented in logarithmic diagrams in a way that makes it difficult to tell whether they are intended for comparison with single events (as the curve in Fig. 2) or with tail distributions (as in Fig. 9). This was not even clear in the early use of the Farmer criterion for releases of iodine-131 (*cf.* Fig. 10).

If the curve in Fig. 10 is applied to a single, predominating event, it is the basic criterion curve as in Fig. 2. If, on the other hand, it is used in the assessment of a source for which a probability density function can be assumed, it has to be interpreted as a reference density function as in Fig. 5. Then, however, the dimension of f(Q) is incorrect. The only reasonable interpretation would be that it is a reference tail distribution. But in that case there is no obvious reason why



Incidence of man-made disasters (in the USA).



Incidence of natural disasters (in the USA).

US Nuclear Regulatory Commission.

FIG. 9. Example of the use of the tail distribution in presenting the results of safety analyses (from the US Reactor Safety Study [5] as illustrated in Ref. [6]).

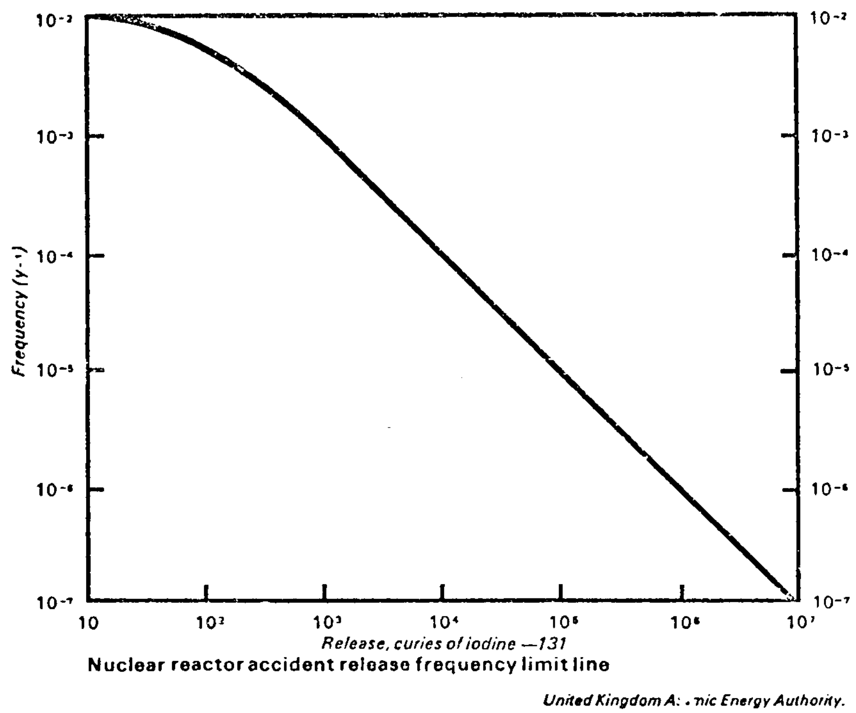


FIG.10. The Farmer criterion as tail distribution (diagram reproduced from Ref. [6]).

the slope should be -1 although the integral should yield $E_{ref}(Q)$.

Farmer's quoted proposal [6] was that an acceptable and realistic design criterion would be that a single reactor should not present a higher probability than 10^{-6} in a year for a release of (we must assume *more than*) 10^6 curies of iodine-131. This assumption, however, merely gives one point of the tail distribution. The rest of the curve seems to have been drawn on the assumption that, at each point, the product of the value of the tail distribution at that point and the release indicated at the same point is constant. This is an arbitrary assumption which may have been caused by confusion with the stipulated property of the design criterion curve for single events (Fig. 2).

8. PROBABILITIES AND DECISION CRITERIA

We have already indicated the need of knowing both the probabilities and the consequences of accidents and have pointed out that the mathematical expectation of consequence has no useful meaning at low probabilities. In practice, therefore, it may be necessary to look at the various part of the tail distribution and to apply reasonable criteria for the acceptance of consequences of various magnitudes. As shown by Rowe [3] and others [*e.g.*7], the consequence expectation may be the relevant quantity at high probabilities, while the absolute probability of the consequence is of less importance when the consequence is large. We may refuse to accept a very large *new* type of consequence irrespective of its probability, while we might accept a large consequence from a new source if we are already exposed to the possibility of that type of consequence from other sources. In that case it is the increase in the overall probability of the particular type of consequence which determines our attitude.

We have discussed *probabilities* as if we had means to know the "true" probabilities. Probabilities are essentially of three types: the classical probability of games of chance, the frequency probability and the subjective probability. The condition for the classical probability is the existence of identical entities, *i.e.* the requirement of "symmetry" which usually does not exist in practice. The condition for the frequency probability is that the empirical experience that gives a frequency estimate must be relevant also to the new situation for which we need a probability estimate. This relevance requirement is usually not met. For example, a frequency estimate - including experience of zero accidents - from one type of reactor during a given period of time may not be relevant to other reactors or other periods of time. In most cases, we have to rely upon subjective probabilities ("educated guesses"). It is important to realize that this is a legitimate assessment for the purpose of decision-making. These probabilities are called "subjective" because they will depend upon the experience and knowledge of those who make the estimate. Since it is difficult to judge if knowledge is complete - which it rarely is - we must not draw too far-reaching conclusions from such estimates. In particular, they can hardly be complemented by any measures of accuracy or reliability other than in a subjective way. It may even be inappropriate to use the term "probability" in these cases: we deal with utility functions for decision-making rather than with truly stochastic quantities. However, Apostolakis [8] has made the point that the use of subjective probabilities is perfectly acceptable as long as the person who makes the assessment complies with the requirement of coherence.

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DISCUSSION

A.K. BURKART: Dr. Beninson, the frequencies you quoted refer to a specific combination of release category, weather sequence, wind direction, and site. The expectation values to be published in Appendix 8 of the German Risk Study (Deutsche Risikostudie Kernkraftwerke) are calculated by summing over all possible combinations. A breakdown according to release categories will be given in order to facilitate analysis.

D. BENINSON: I think it is a good practice to give such a breakdown when a consequence expectation is presented, because certain components may carry most of the uncertainty qualifying the expectation. Comparisons can then validly be carried out for particular components, and no information is lost as it would be if only the total consequence expectation were given.

H. HOERTNER: You say that subjective probabilities are used for risk assessment and that uncertainties for such probabilities have no meaning because subjective probabilities can scarcely be complemented by any measure of accuracy other than a subjective one. I cannot see this difficulty: just as one can use subjectively estimated probability values, one can also use subjective uncertainty bounds.

You also said that we must not draw excessively far-reaching conclusions from the probability assessments because these are based on subjective data. The subjective probabilities used for component failures in the German Risk Study, for instance, are based on both a comprehensive evaluation of data from the literature and on information collected over 6 years in a coal-fired power plant. The probabilities are subjective because the components in nuclear power plants must not show the same failure rates as the components described in the literature or the components in conventional power plants. Data evaluations carried out recently in the reference plant used for the German Risk Study indicate that practically all components show lower expectation values for the failure rates and lower uncertainties than had been taken as the basis for risk assessment. Thus the system failure probabilities calculated in the German Risk Study would seem to be pessimistic values.

D. BENINSON: The use of subjective probabilities is perfectly valid as long as they comply with the requirement of coherence. The main problem is how to combine statistical evidence (frequency probabilities) with subjective probabilities. As we understand it, this is usually not done by the techniques appropriate to subjective probabilities (Bayesian), and therefore the confidence limits obtained are not confidence limits in the strict sense. The failure probabilities you quote, which are derived from observations in other types of installation, might be regarded as frequency probabilities representing upper estimates of the values applying to the reference plant, since your studies have shown that in this case all components showed values more favourable than these.

H. HOERTNER: In this context it must be stressed that a risk assessment does not define the risk of an individual plant but estimates the risk presented by a number of plants of a particular type. Therefore both probabilities and frequencies do not have only one value which may be right or wrong. Uncertainties in the probabilities and in the frequencies have to take variations between components and in their operating conditions into account.