WHAT IF?

ICRP GUIDANCE ON POTENTIAL RADIATION EXPOSURE

BY JACK VALENTIN

Underpinning the world's regulations for radiation safety are the recommendations of the International Commission on Radiation Protection (ICRP), based in Sweden. In the 1990s, experts have focused special attention on the unexpected -- namely, the analysis of "what if?" situations that theoretically could expose people to potentially dangerous sources of radiation.

Potential exposures are not normally expected to occur, but they can be anticipated, and the probability of their occurrence can be forecast. Early ICRP thoughts about this concept were developed in considerations about final disposal of long-lived radioactive waste, and about major accidents such as nuclear disasters.

The ICRP has now examined a third situation: accidents affecting one or a few persons only (but sometimes with severe consequences for those affected). While such accidents do not have the disruptive societal effect of the dreaded large nuclear accident, they do occur with a frightening regularity and may have devastating effects for those affected.

This article reviews the ICRP's conceptual framework, criteria, and methodology of radiation protection from potential exposures in selected cases. Protection against such "restricted" potential exposures starts with a structured analysis of scenarios, using methods that hitherto may have been more familiar to safety engineers than to radiation protection specialists. Given probabilities derived from such analyses, the expected detriment from potential exposures can be computed. This risk can be compared to a risk constraint, which need not be particularly complicated for the small-scale accidents being considered here. After this initial analysis, an iterative optimization process can be applied in order to ensure that the risk or potential exposure, as well as the doses incurred, are as low as reasonably achievable.

THE CONCEPTUAL FRAMEWORK

According to ICRP Publication 60 -- entitled *1990 Recommendations of the ICRP* -- normal exposure from a practice is expected to occur with near certainty, from operations conducted as planned or from unintended, high-probability but low-consequence events. In contrast, potential exposure is not certain to occur. It results from unplanned events such as equipment failure or departure from planned operating procedures. Such events cannot be predicted in detail, but they can be theoretically predicted and a probability of their occurrence can be assigned.

Dose limits do not apply to potential exposures. They must be supplemented by risk constraints. The theoretical basis for such a tool was developed in ICRP Publication 64, *Protection from Potential Exposure: A Conceptual Framework*. A more recent report, ICRP Publication 76, *Protection from Potential Exposures: Application to Selected Radiation Sources*, is aimed at demonstrating how that tool could be applied in practice in "limited accidents" such as unsafe entry into an irradiation room.

The number of individuals affected is small in such cases. Detriment is largely limited to health effects to the persons actually exposed. The processes leading to potential exposure are relatively simple, and may be the predominant threat associated with the practice.

In contrast, large disasters such as major nuclear accidents invoke detriment beyond health effects to exposed

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persons (agricultural restrictions, food consumption controls, etc., and vast costs). The International Nuclear Safety Advisory Group (INSAG) has discussed such problems. Final disposal of long-lived waste adds a further dimension of potential exposures in the far future. This was discussed in ICRP Publication 46, *Radiation Protection Principles for the Disposal of Solid Radioactive Waste*, and the ICRP now is finalizing an amendment to that report.

THE ICRP MISSION

With roots dating back to 1928, the International Commission on Radiological Protection (ICRP) is a non-profit organization that provides general guidance on the widespread use of radiation sources from developments in the various fields of nuclear energy. Its recommendations cover all aspects of protection against ionizing radiation and today form the basis for radiation safety throughout the world, including standards and guidance issued by the IAEA. More information may be obtained from the ICRP Scientific Secretariat, headquartered in Stockholm, Sweden, at SE-171, 16 Stockholm. The facsimile number is +46-8-729-729-8 and the email is scient.secretary@icrp.org. On the Internet, the Web site is at www.icrp.org.

CRITERIA OF ACCEPTABILITY

In *Publications 60 and 64*, the ICRP recommended that health risks due to potential exposures be limited and constrained to the same order of magnitude as that implied by dose limits and constraints for normal exposures. These health risks involve two different probability distributions. First the exposure occurs with a specific probability, say, *P*. Given the exposure, the conditional probability of stochastic and/or deterministic health detriment is a function of the dose, say *f(E)*. The unconditional probability of health detriment is therefore the product of these two probabilities, i.e. *P* ∗ *AE)*. This quantity should be kept at or lower than a reference risk, say *R*. For the limited accidents discussed here, *R* can be regarded as a source-related individual risk constraint.

The magnitude of the risk constraint will not necessarily be set once and for all. It could be case specific and may be adjusted for various reasons. However, ICRP *Publication 76* provides a generic risk constraint which could be used as a starting point when case-specific constraints are chosen. For occupational exposures, this generic constraint is based on an annual effective dose of 5 mSv. In many optimized operations, maximum normal annual doses are in that order. Using the cancer death risk coefficient for occupational exposure of $4 \cdot 10^{-2}$ Sv^{-1}, the generic reference risk of death *R* becomes $2 \cdot 10^{-4}$ a^{-1}.

It is then possible to assess whether the probability *P* of unsafe events is acceptably low, and whether the engineered safety and operational procedures of the installation are acceptable. For instance, if the event under study is unsafe entry into a radiation room, where dose rates are high enough that death will always follow an entry (i.e. $f(E) = 1$), the probability *P* should be kept less than *R*. If upon analysis *P* is found to exceed *R* further steps need to be taken to improve safety.

Because of the restricted nature of the accidents discussed here, public exposure is not always an issue. However, in some scenarios, for instance involving lost or stolen sealed sources of radiation, exposure of one or a few members of the public may be the major event under study. Maximum normal doses to the public would usually be constrained to be less than in the order of 10^{-4} Sv a^{-1}, and the cancer death risk coefficient for public exposure is $5 \cdot 10^{-2}$, so the generic reference risk of death *R* as applied to public exposure would be $5 \cdot 10^{-6}$.

In the analysis, it must be recalled that in some cases, depending on the physical characteristics of the source, loss of control of a source also conveys a risk of widespread contamination and exposures of many members of the public. If such a scenario seems possible, the psychological and economical situation may be more akin to that in nuclear disasters (albeit less dramatic), and the methods described here may be too simplistic.

SETTING UP THE SCENARIOS

An analysis aimed at estimating the probability *P* of unsafe events occurring needs to identify all types of scenarios that could contribute significantly to potential exposure, In principle, this is fairly straightforward: one sits down and lists the various ways in which accidents are thought to be possible. However, it is of course easy to overlook some possibility, and a structured approach is advisable. There are several techniques to formalize the analysis, such as hazard and operability studies, failure modes and effects analysis, etc. These various techniques address issues such as how to ensure completeness, guide words to be used when compiling lists of events, etc., that is, matters which may seem to be "just common sense" -- which is exactly where failures have so often in the past caused accidents.

In each scenario, demands will be placed on a protection system. Analysis aims at determining whether the system fails when demanded. Demands will be both "normal" actions that routinely challenge the system and "random" events (human or equipment failures).

Once all relevant scenarios are believed to be listed, their logical structure must be determined. This type of analysis is well known in engineering. Usually, such structuring is presented in event trees or fault trees.

Event trees start with an initiating demand on a system, and move through successive responses of the system, describing the outcome in terms of success or failure of individual steps and devices. Fault trees begin at the other end, with a specified unwanted outcome, and work backward to analyze possible ways in which this outcome could have occurred. As an example, consider a very simple interlock system with two independent sensors and an actuator controlling access to a radiation room. The default position of the actuator is to keep the door locked. It can be unlocked only if neither of the two sensors reports that radiation is present. The purpose of having two sensors is to provide redundancy, i.e. a backup function in case the first sensor fails. This simple system can readily be described by either an event tree or a fault tree.

Conceptually, the mathematical analysis of event or fault trees is simple, being based on elementary probability theory. However, the practical application of this theory is often quite difficult because of the many alternative outcomes under study, and in all but the simplest cases computer processing is recommended for correct computation.

OPTIMIZATION OF PROTECTION

Formal, analytical methods of optimization of protection against potential esposure are still largely unresolved, particularly when probabilities are low and consequences are big. In *Publication 76*, the ICRP therefore recommended that the analyst resort to an indirect method of setting the target for optimization.

According to this procedure. protection against normal exposures is first carried out using the conventional methods (ranging from simple common sense to complex quantitative techniques). This will generate an expected average normal dose. The cancer death risk associated with this optimized normal dose is then used as a Reference Risk value which should be used in the optimization against potential exposure. The actual optimization will involve an iterative process of investigating cost efficiency and practicability of various alterations to operational design, safety devices, and procedures.

In this context, it is useful to follow a "Safety Precedence Sequence". It ranks, in order, the: 1) design for minimum hazard, 2) reduction of hazards through safety devices (e.g. interlocks), 3) safety warning devices (e.g., radiation alarms), 4) procedures and training for workers, and 5) identification of residual hazards for management review.

HUMAN ERROR & DEFENSE-IN-DEPTH

The Safety Precedence Sequence indicates that technical layers of defense -- starting, of course, with a minimized possibility of accidents happening -- are usually preferred to reliance on human actions. This is because human errors are often the most significant contributors to potential exposure.

Unfortunately, they are also among the most difficult to quantify. They are strongly dependent on the situation and so-called "performance shaping factors" (layout of the workplace, amount of noise and distraction, level of stress, etc). The probability of repeated human error may also increase with time, if on a first occasion a given error did not lead to untoward consequences.

Defense-in-depth is an important principle of radiation safety, according to which overlapping safety provisions commensurate with the risk posed by the source are imposed on a system. The practical application of this principle involves both "redundancy", where multiple copies or versions of the same protective layer are available in parallel, and "diversification", where alternative modes of protection are available for a particular problem.

This well-established principle is just as valid in the smallest operation as for large installations. Consider, for instance, mobile industrial gamma radiography, which may well be an operation run by a single self-employed person using a single set of equipment. After operation of this equipment, the source is designed to be withdrawn into its shielding house as a first layer of defense against accidental exposure.

As a second layer of defense, there is usually a position indicator intended to show the success or failure of the withdrawal of the source. In some cases, there may be two independent indicators, providing redundancy at this step. A third level of defense is that even if no indication of failure is given, the operator should, by procedure, check the work area with a monitoring instrument.

As a diversification, the operator should also be wearing a dose meter with an audible alarm. Finally, if either indicators or area monitoring indicate that the source has not been properly retracted, the operator shall leave the area temporarily fenced off until the source has been recovered.

SOME COMPLICATIONS

If modifications of proven designs are contemplated "in the field", there is considerable risk of potential exposure because of a high probability of human error. Except for pressing circumstances where immediate action is necessary, no modification should be performed until a thorough safety assessment has been carried out and the proposed modification and the assessment are clearly documented.

Sometimes, reduction of a particular type of exposure may be associated with a trade-off in the shape of an increase of other exposure. For instance, inspections are performed regularly in order to detect defects before they cause component failure. An increased inspection frequency of, for example, an accelerator may improve the rate of early detection of defects and therefore decrease the probability of potential exposure.

However, due to the radiation fields present in such an installation, it would also entail increased occupational exposure. Both types of exposure must therefore be taken into account in an optimization of protection.

In medical radiation usage, an added complication is that not only excessive doses but also too small doses to the patient may be unsafe. This may preclude comparisons of expected detriment with the risk criterion R. However, structured analysis is still useful in order to identify major contributors of risk. Measures that might be taken to reduce risk to the patient can then be contemplated.

The above considerations concern the probability P of exposure. The probability $f(E)$ of detriment, given a dose, may also involve complications. For instance, potential exposure situations may entail doses high enough to cause certain death due to deterministic effects. This introduces the possibility of a greater loss of lifetime than that associated with stochastically caused death, which occurs later in life. However, no additional weighting for early death seems warranted, in view of the general uncertainty in the probability calculations.

Furthermore, in some practices and operational environments, localized deterministic effects from potential exposures will be the dominating threat. For exposures within present dose limits, deterministic effects are well nigh impossible. Therefore, the ICRP has expressly chosen not to take such detriment into account for nomal exposures.

However, for potential exposure it will be inevitable to assess detriment from deterministic effects. At the same time, while certainly worth assessing, loss of a finger, for instance, can obviously not be equated to death. Thus, weighting for severity is required. A generic weighting factor of 0.25 is suggested in ICRP *Publication 76*. This is based on various insurance and compensation schemes and considers the need for reasonably simple generic weighting factors. ❐