IChemE

www.icheme.org/psep
doi: 10.1205/psep05007

0957–5820/06/$30.00+0.00

Trans IChemE, Part B, September 2006
Process Safety and Environmental Protection, 84(B5): 344–354

THE LIFE EXTENSION ACHIEVED BY ELIMINATING A PROLONGED RADIATION EXPOSURE

P. J. THOMAS*, D. W. STUPPLES and M. A. ALGHAFFAR

Risk Management, Reliability and Maintenance (RM^2) Centre, School of Engineering and Mathematical Sciences, City University, London, UK

A key parameter for evaluating the worth of safety equipment is the extension to life expectancy that it brings about in the population it is intended to protect. Since this is numerically equal to the decrease in life expectancy that would occur were the equipment not there, its value may be calculated by estimating the effect of the prolonged radiation exposure that would occur in the equipment's absence. This paper describes a procedure for carrying out this computation efficiently for cost-benefit studies using the J-value method.

Keywords: health; safety; nuclear; radiation; prolonged release; life expectancy; risk.

INTRODUCTION

In a pioneering study, Lord Marshall (Marshall *et al.*, 1982) emphasized the need to calculate the loss of life expectancy as a key parameter against which to assess the severity of a nuclear release. But while the Marshall study was concerned primarily with a short-term release resulting from a nuclear accident, there is also a requirement to calculate the loss of life expectancy resulting from a release of radiation where the start date and the finish date may be separated by a finite but long time interval—quite possibly decades apart. Specifically such a figure allows quantification of the safety benefit of equipment installed to eliminate the prolonged exposure and thus prevent the harm.

Pandey and Nathwani (2003) attempted to characterize the change in life expectancy following prolonged exposure using delay as a deterministic parameter (set at 0, 10 and 20 years successively). However, as Marshall pointed out, while no effects are seen until a substantial period has passed, the health effects are then stochastic over a long interval. We have adopted Marshall's model of stochastic effects following a delay, and extended it to encompass radiation releases of finite but prolonged duration (many years) as well as short exposures as a necessary preliminary to calculating the benefit of safety equipment. Following Marshall *et al.* (1982), we have assumed a linear relationship between dose and the probability of harm, but we have taken the opportunity to increase the total risk coefficients by a factor of about four, in line with the 1990 recommendations of the International Commission on Radiation Protection (ICRP).

The method is fully suitable for providing the gain in life expectancy from the elimination of a prolonged radiation exposure as an input to the J-value procedure (Thomas *et al.*, 2006a, b) for judging whether any given safety expenditure is justifiable. The conservative basis of the ICRP recommendations means that the calculated change in life expectancy is likely to be somewhat high, which adds to the conservatism of nuclear J-values.

CHANGE IN THE HAZARD RATE

Let the radiation exposure begin at time $x = 0$ and continue until time, $x = T_R$. Let the rate of radiation exposure be $d_r(x)$ (Sv y^{-1}), shown schematically in Figure 1, so that the integrated dose, D_r (Sv), experienced by individuals in the exposed population will be given by

$$D_r = \int_{x=0}^{\infty} d_r(x)\,dx \qquad (1)$$

The fraction of all radiation-induced deaths caused by exposure in the interval x to $x + dx$ will be the dose fraction, $(d_r(x)\,dx)/D_r$, implying a probability density, $g(x)$, for dose fraction and hence the fraction of radiation-induced deaths given by

$$g(x) = \frac{d_r(x)}{D_r} \qquad (2)$$

Over all time, the expected number of deaths in a population of size, N, resulting from a radiation exposure causing this integrated individual dose, D_r, will be $c_T N D_r$, where c_T is the total risk coefficient, taken as 0.05 per Sievert for the general population and 0.04 per Sv for the working population

**Correspondence to*: Professor P. J. Thomas, Risk Management, Reliability and Maintenance (RM^2) Centre, School of Engineering and Mathematical Sciences, City University, Northampton Square, London EC1V OHB.
E-mail: p.j.thomas@city.ac.uk

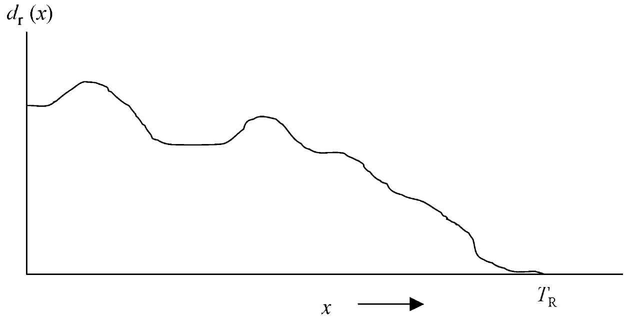

Figure 1. Radiation dose, $d_r(x)$ versus time, x.

(International Commission on Radiation Protection, 1990). The probability of a given individual contracting a radiation-induced cancer will be equal to the fraction of people contracting the disease:

$$p(radcancer) = \frac{c_T N D_r}{N} = c_T D_r \tag{3}$$

Let $f_M(y)$ be the probability distribution for the mortality period, the interval between cancer being induced and death, given in terms of the time, y, that has elapsed between the time of induction, x, and the current time, τ, so that $y = \tau - x$, as shown schematically in Figure 2. The probability for death in the near vicinity of time, τ, following induction in the vicinity of time, x, is simply the product of the probability of induction between ages, x and $x + dx$, namely $g_r(x)\,dx$, and the probability that the mortality period lies between y and $y + dy$, namely $f_M(y)\,dy$. This product is $f_M(y)g(x)\,dx\,dy$ or $f_M(\tau - x)\,g(x)\,dx\,dy$. Thus the probability density for death occurring at time, τ, given induction at time, x, is given by $f_M(\tau - x)g(x)\,dx$.

But death at time, τ, could have been caused by a cancer induced over a large range of possible, earlier times, x. To find the total probability density for death from radiation-induced cancer at time, τ, we need to integrate from the start of the radiation release to the current time, τ:

$$f_T(\tau) = \int_{x=0}^{\tau} f_M(\tau - x)g(x)\,dx \tag{4}$$

However, this probability density is evaluated under the assumption that the person is sure to contract a radiation cancer and die. To find the probability density for an individual contracting a radiation-induced cancer and dying at time, τ, we need to multiply this figure by the absolute probability of contracting a radiation cancer, $p(radcancer)$, given in equation (3) above, and so arrive at $c_T D_r f_T(\tau)$.

The hazard rate is a fundamental, actuarial parameter, representing the probability density for death given that the individual has survived so far (see Appendix 1). The hazard rate will increase after the radiation release by the probability density, $c_T D_r f_T(\tau)$, just calculated. Hence the increase in hazard rate at time, τ, into the radiation exposure will be

$$\delta h(\tau) = c_T D_r \int_{x=0}^{\tau} f_M(\tau - x)g(x)\,dx \tag{5}$$

We may use equation (2) to recast equation (5) as

$$\delta h(\tau) = c_T \int_{x=0}^{\tau} f_M(\tau - x)d_r(x)\,dx \tag{6}$$

Equation (6) will not be integrable for all conceivable probability distributions, f_M, nor for all conceivable dose rate functions, $d_r(x)$, although numerical integration will normally be possible. However, we may proceed further analytically through choosing simplified functions that can still give a good representation of reality.

Let us consider the case of a plant imposing a radiation dose rate that is constant over the period 0 to T_R at an annual dose, d_a, as shown graphically in Figure 3. Since the integrated dose is simply $d_a T_R$, the corresponding probability distribution for dose fraction is simply

$$\begin{aligned} g(x) &= \frac{1}{T_R} \quad \text{for } 0 \le x \le T_R \\ &= 0 \quad \text{for } x > T_R \end{aligned} \tag{7}$$

The dose rate over all time may be represented using step or 'jump' functions, $J_P(x)$:

$$d_r(x) = d_a(1 - J_P(x - T_R)) \tag{8}$$

where

$$\begin{aligned} J_P(x) &= 1 \quad \text{for } x \ge 0 \\ &= 0 \quad \text{for } x < 0 \end{aligned} \tag{9}$$

As described above, radiation-induced cancers of various types may lead to death at a random point between times

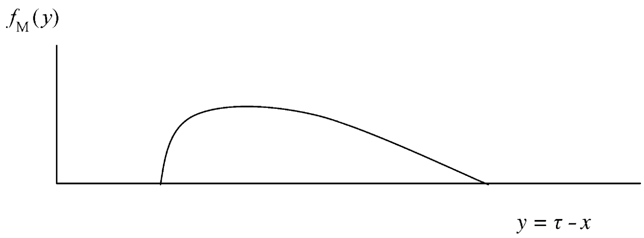

Figure 2. Probability density for the mortality period, y.

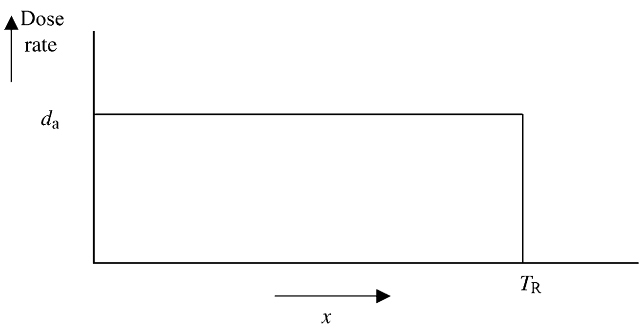

Figure 3. Dose rate constant over prolonged interval.