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Calculating the benefit to workers of averting a radiation exposure lasting longer than the working lifetime

*P.J. Thomas**, *R.D. Jones*

Risk Management, Reliability and Maintenance (RM^2) Centre, School of Engineering and Mathematical Sciences, City University, London EC1V 0HB, United Kingdom

ABSTRACT

The J-value method enables health and safety schemes aimed at preserving or extending life to be assessed on a common, objective basis for the first time, irrespective of industrial sector. For this it requires an estimate of the improvement in life expectancy that the health and safety scheme will bring about. This paper extends the range of nuclear-safety-system lifetimes for which it is possible to calculate the increased life expectancy amongst nuclear-plant workers whose radiation exposure the safety system has reduced. Whereas the previous mathematical technique was able to cater for a nuclear-safety-system lifetime up to the working lifetime of the nuclear-plant workers (typically between 45 and 50 years), the new method extends without limit the range of tractable, safety-system lifetimes. This is important now that the design lifetime of nuclear power stations can be up to 60 years. The development will also facilitate the assessment of safety systems and procedures to protect workers on long-term nuclear decommissioning and waste sites; in the latter case, the service life-time could be hundreds of years. The case when the safety-system lifetime is greater than the working lifetime is addressed by splitting the workforce into a set of three cohorts, one for existing workers and two for new recruits. The discounted life expectancy is found for each cohort, and then a weighted average is used to give the overall value. An additional mathematical device is then used to reduce the number of cohorts required from three to two, namely existing workers and new recruits. A similar mathematical device is applied (in Appendix A) to reduce from three to two the number of workforce cohorts needed when the length of the safety system's service lifetime is less than the working lifetime. Finally, a further mathematical instrument is incorporated in the model equations, which allows a unified treatment to be applied to each of the cohorts, existing workers and new recruits, across all possible service lifetimes of a nuclear safety system. Since new results on gain in life expectancy may be fed into a J-value analysis, this development extends significantly the range of nuclear-safety systems for which the J-value technique may be used to measure cost-effectiveness.

Keywords: Health; Safety; Nuclear; Radiation; Prolonged release; Life expectancy; Risk; J-value

1. Introduction

The J-value method (Thomas et al., 2006a) enables health and safety schemes aimed at preserving or extending life to be assessed on a common, objective basis for the first time, irrespective of industrial sector. The method requires the improvement in life expectancy to be calculated that the new health and safety scheme will bring about. This gain is numerically equal to the loss of life expectancy that would occur in the absence of the new measure.

Lord Marshall provided a technique for calculating the loss of life expectancy caused by a one-off dose exposure following a nuclear accident (Marshall et al., 1983), and it has been reported previously how that technique may be extended to cover a prolonged release of radiation (Thomas et al., 2006b, 2007; Jones et al., 2007a, 2007b). Based on actuarial life-tables (Government Actuary's Department, 2008), the method makes use of the cautious, but generally accepted, risk coefficients for death from radiation-induced cancer, as calculated by the International Commission on Radiological Protection (ICRP)

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* *Corresponding author*. Tel.: +44 20 7040 8110; fax: +44 20 7040 8110.
E-mail address: p.j.thomas@city.ac.uk (P.J. Thomas).

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Nomenclature

a	age, y
a_1	starting age for employment, y
a_2	retirement age, y
a_M	the greatest age an employee can have and still experience the maximum benefit from the safety system ($=a_2-T_R$ when $T_R \le a_w$; $=a_1$ when $a_w > T_R$), y
a_w	working lifetime ($=a_2-a_1$), y
c	risk coefficient for radiation dose rate, $\mathrm{Sv}^{-1}\,\mathrm{y}^{-1}$
d_a	radiation dose per year, $\mathrm{Sv\,y}^{-1}$
d_j	radiation dose in year j, Sv
h	index, $= a_w - T_R + i$
i	number of years after safety-system installation at which recruitment takes place, y
I_ϕ	integral of the product of the survival probability and the integrated hazard function for a point radiation exposure
$I_{\phi d}$	discounted integral function
$I_\psi^{(i)}(a_1)$	integral term defined by $I_\psi^{(i)}(a_1) = \int_0^\infty S(t)\psi^{(T_R-i)}(t-a_1)\,dt$
j	index used to denote e.g. the number of years since installation of safety system, y
k	index used to denote recruitment date after T_{D0}, y
m	age of a worker above the starting age, a, at the time the safety system was installed, y
N_a	number of individuals per unit age interval
N_T	total number of workers receiving some benefit from the safety system
p	$=k+T_{D0}$, number of years since safety system installation for the cohort of recruits receiving a tapering benefit
q_j	binary coefficient defined by Eq. (57)
r	discount rate, y^{-1}
r_j	binary coefficient defined by Eq. (48)
$S(a)$	survival probability to age, a
$S_d(a)$	discounted survival probability to age, a
T	duration of averted radiation dose, as experienced by an individual of a given age, y
T_D	time after installation that recruitment occurs, y
T_{D0}	excess of the safety-system lifetime over the working lifetime, $T_R - a_w$, y
T_M	$= a_M - a_1 = a_w - T_R$ for $T_R \le a_w$, y
T_P	time protected by the safety system, y
T_R	duration of averted prolonged exposure, y
T_S	minimum of T_R and a_w, y
T_U	time unprotected by the safety system, y
x	age, y
$X(t)$	life expectancy at age t, y
$W(t)$	integrated hazard rate from age, 0, to age, t, as defined by equation (19) of Thomas et al. (2006b)
δX	change in life expectancy, y
δX_d	change in discounted life expectancy, y
$\delta X_d^{(i)}(a_1)$	change in discounted life expectancy for an individual starting work at age, a_1, i years after the installation of the safety system, y
$\delta\tilde{X}_d^{(i)}(a_1)$	expression related to $\delta X_d^{(i)}(a_1)$, defined by Eq. (43), y
$\delta\tilde{\tilde{X}}_d^{(i)}(a_1)$	expression defined by Eq. (49) but fully equivalent to $\delta X_d^{(i)}(a_1)$, y
$\delta X_d(a_1+m)$	change in discounted life expectancy for a worker of age, a_1+m years at the installation of the safety system, y
$\delta\tilde{X}_d(a_1+m)$	expression related to $\delta X_d(a_1+m)$, defined by Eq. (53), y
$\delta\tilde{\tilde{X}}_d(a_1+m)$	expression defined by Eq. (58) but fully equivalent to $\delta X_d(a_1+m)$, y
$\delta X_{d3,1}$	change in discounted life expectancy for the cohort of recruits beginning work within T_{D0} years of the installation of the safety system, y
$\delta X_{d3,2}$	change in discounted life expectancy for the cohort of recruits beginning work between T_{D0} and T_R years after the installation of the safety system, y
δX_{d3}	change in discounted life expectancy for the cohort of new recruits since the start of the notional exposure, y
δX_{d4}	change in discounted life expectancy for the cohort of workers receiving a tapered benefit from the safety system, y
δX_{d6}	change in discounted life expectancy for those in work at the time when the safety system was installed, y

Greek symbols

ϕ_1	integrated hazard function for a point radiation exposure, y
ψ_1	integrated hazard function for a prolonged radiation exposure, y^2
$\psi_1^{(T_R-i)}$	ψ_1 function where the duration of the notional release is T_R-i rather than T_R, y^2

and updated from time to time in the light of new data and studies (ICRP, 1990, 2007). These risk coefficients, which provide an expert view of the probability of premature death from radiation-induced cancer based on the best, available evidence, may be used to give an equivalent change in life expectancy in the manner explained in detail in Thomas and Jones (submitted).

However, the existing methods for calculating the improvement in life expectancy of workers (Thomas et al., 2006b, 2007; Jones et al., 2007a,b) brought about by a safety system that averts a nuclear radiation dose make the assumption that the system's service lifetime is no greater than the working lifetime, which in the UK may be 49 years. While this is likely to cover the service lifetimes of most nuclear safety systems, the extension of the design life of a Pressurised Water Reactor power station to 60 years, for example, means that it is necessary to extend the coverage of the method to treat safety systems expected to outlast even the most recent recruit to the workforce. The new development may also be applied to long-term nuclear decommissioning and waste sites, once it is reasonable to assume that the workforce will remain at a roughly constant level, for monitoring and surveillance, for instance. Here it is easy to imagine that the service lifetime of a safety procedure could extend past a hundred years.

Algebraic symbols are explained where they arise, but the definitions are included in the Nomenclature for ease of further reference.