Available online at www.sciencedirect.com

SCIENCE DIRECT®

Nuclear Engineering and Design 224 (2003) 65–77

Nuclear Engineering and Design

www.elsevier.com/locate/nucengdes

A conceptual approach to the estimation of societal willingness-to-pay for nuclear safety programs

M.D. Pandey [a,*], J.S. Nathwani [b]

[a] *Institute for Risk Research, University of Waterloo, Waterloo, Ont., Canada*
[b] *Department of Management Sciences, Strategic Planning, Hydro One Inc., 483 Bay Street, Toronto, Ont., Canada*

Received 18 July 2002; received in revised form 18 February 2003; accepted 18 February 2003

Abstract

The design, refurbishment and future decommissioning of nuclear reactors are crucially concerned with reducing the risk of radiation exposure that can result in adverse health effects and potential loss of life. To address this concern, large financial investments have been made to ensure safety of operating nuclear power plants worldwide. The efficacy of the expenditures incurred to provide safety must be judged against the safety benefit to be gained from such investments. We have developed an approach that provides a defendable basis for making that judgement.

If the costs of risk reduction are disproportionate to the safety benefits derived, then the expenditures are not optimal; in essence the societal resources are being diverted away from other critical areas such as health care, education and social services that also enhance the quality of life. Thus, the allocation of society's resources devoted to nuclear safety must be continually appraised in light of competing needs, because there is a limit on the resources that any society can devote to extend life.

The purpose of the paper is to present a simple and methodical approach to assessing the benefits of nuclear safety programs and regulations. The paper presents the Life-Quality Index (LQI) as a tool for the assessment of risk reduction initiatives that would support the public interest and enhance both safety and the quality of life. The LQI is formulated as a utility function consistent with the principles of rational decision analysis. The LQI is applied to quantify the societal willingness-to-pay (SWTP) for safety measures enacted to reduce of the risk of potential exposures to ionising radiation. The proposed approach provides essential support to help improve the cost–benefit analysis of engineering safety programs and safety regulations.

1. Introduction

Large investments have been made for improving safety in nuclear power plants in Canada and elsewhere. To give an idea about the range of expenditures incurred, Tables 1 and 2 summarise costs of various safety features installed in nuclear power plants in Ontario (Ontario Hydro, 1988a). A number of reactors are expected to reach end of service life in next 10–15 years. The cost–benefit analysis of refurbishment versus that of decommissioning of a nuclear reactor poses several challenges (Hoegberg, 1998; Kroger and Fischer, 2000). Refurbishment costs can be prohibitively high due to stringent safety requirement imposed by regulatory authorities with the purpose of minimising radiation exposure to plant workers and neighbouring population. The decommissioning on the other hand raises questions about long-term safety of disposal of nuclear waste (Nordhaus, 1997).

* Corresponding author. Tel.: +1-519-888-4567x5858; fax: +1-519-888-6197.
E-mail address: mdpandey@uwaterloo.ca (M.D. Pandey).

0029-5493/$ – see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0029-5493(03)00062-1

Table 1
Costs of special safety systems in CANDU reactors (Ontario Hydro, 1988a)

Special safety system	Darlington (million C$)	Bruce B (million C$)	Pickering B (million C$)
Shutdown system 1	100	45	24
Shutdown system 2	90	44	28
Emergency coolant injection	80	74	62
Containment	1500	466	308

Risks can always be reduced but at some cost. However, demands for absolute safety, implying zero risk, can do more harm than good. If the costs of risk reduction are disproportionate to the benefits derived, then it diverts societal resources away from objectives that do not enhance the overall quality of life for individuals. The need to strike a balance between the benefits of improved safety (i.e. life extension), risk (potential for loss of life) and cost of risk reduction (i.e. enhancement of quality of life) is compelling. The balancing of impacts on the quality of life and health against economic costs of risk reduction, although controversial, is an essential professional obligation. Our ability to “save lives” is finite and limited by our capacity to create wealth. Thus, the central problem in managing risk, in effect, translates into our ability to allocate a scarce resource wisely.

Table 2
Costs of retrofits or modification of nuclear safety systems (Ontario Hydro, 1988a)

Safety system	Cost (million C$)
Bruce A	
High pressure ECI[a] system	104
Modification for harsh powerhouse environment	12.4
Instrumented pressure relief valves	3.0
Emergency filtered air discharge	5.0
Hydrogen mitigation system	1.1
Pickering A	
High pressure ECI system	90.0
Powerhouse environment	20.0
Rupture panels	6.5
Filtered air discharge pre-monitoring	2.0
Additional shut-off rods	4.5
Shut-off rod upgrading	30.0
Boiler feedline low pressure trip	6.4
Flux tilt trip	9.4
Bruce B	
High pressure ECI system	74
Harsh powerhouse environment	1.9
PHT[b] pump low speed operation	27.0
Emergency filtered air discharge	4.4
Hydrogen mitigation system	0.6
Moderator seismic qualification	2.1
Boiler feedline low pressure trips	1.1
ECI seismic qualification	0.77
Emergency filtered air discharge	4.4
Whole body contamination monitors	2.5
Fuelling machine seismic snubbers	1.5
PHT pump trip on LOCA[c]	0.57

[a] Emergency cooling injection.
[b] Primary heat transport.
[c] Loss of coolant accident.

The purpose of the paper is to present a simple and methodical approach to assessing the benefits of nuclear safety programs and regulations that are intended to promote public welfare and the quality of life. Our work has been partly motivated by developments in Canada in the early 1990s and, in particular, the recommendation of the Government of Canada’s Regulatory Policy which requires comprehensive social and economic impact analysis for setting regulatory standards (Canada, 1995). The goals of the policy are to ensure that the benefits of regulatory interventions must clearly outweigh the costs to Canadians.

When faced with risk, we are attempting to answer, intuitively, three related questions:

(i) Is it safe?
(ii) Is it a big and important risk? and if so,
(iii) At what cost and level of effort would a life-saving proposition be worthwhile to reduce risk?

In this context, we have proposed the use of the Life-Quality Index (LQI) as a tool for assessing the rationale and effectiveness of decisions affecting the management of risk to life, health and safety (Nathwani et al., 1997).

The LQI is a social indicator derived to reflect the expected length of life in good health and the quality of life enhanced by wealth. It rests on the premise that helping individuals achieve a long life in good health is a fundamental value and therefore, it is ethical and reasonable to pursue this as a primary objective for risk management. The LQI gives an account of how well that objective is being met. Risk control and mitigation initiatives that do not increase the chance of longer life in good health detract from that objective and their justification remains tenuous. The LQI can help us choose appropriate strategies for managing risk. Applications of LQI to safety of structures and other technical facilities have been illustrated in Rackwitz (2002, submitted for publication) and Skjong and Ronold (2002).

The next section describes four key principles for risk management. Section 3 describes the development of the LQI and addresses issues related to its application to risk management. Section 4 illustrates application of LQI model to the estimation of societal willingness-to-pay (SWTP) for safety programs in general and the supporting empirical validation. In Sections 5 and 6, we describe the application of the LQI measure for judging the efficacy of nuclear safety design features.

2. Principles for managing risks to the public

The broadest goal in managing risk is to serve the public interest that can be summarised as four essential principles of accountability, maximum net benefit, compensation and life measure (Nathwani et al., 1997; Nathwani and Narveson, 1995). These principles also provide the supporting rationale for the use of social indicators in the management of health and safety risks.

2.1. The accountability principle

Decisions for the public in regard to health and safety must be open, quantified, defensible, consistent and apply across the complete range of hazards to life.

A unified rationale for application to all risks is essential if we are to have a working basis for practical professional action in society's interest when risks to life, health or property are important. The requirement may be viewed as a clear statement of what the public has a right to expect and support for those who have to make difficult decisions.

2.2. The principle of maximum net benefit

Risks shall be managed to maximize the total expected net benefit to society.

The principle has been accepted as fundamental to cost–benefit analysis. It satisfies the utilitarian concept of welfare, i.e. the greatest good for the greatest number. A simple and meaningful test of the effectiveness of a risk management allocation is: how much life saving does it buy, and could the same resource, if directed elsewhere, result in better gain for society as a whole? All activities directed at managing risk in the public interest ought to be subjected to this test.

The principle of maximum net benefit treats all persons in a group equally and is ill suited for situations where inequality of the burden of risk or benefits is extreme or individual impacts are known beforehand. In general, the public management of risk balances risks to people at a low level, statistically in the order of one in a thousand to one in a million. Identifiable individuals are not known, a priori. When this assumption of a general imposition of risk breaks down, impacts on known affected individuals must be dealt with separately. On no account may we knowingly "sacrifice" identifiable individuals to the "greater good of the group".

2.3. The Kaldor–Hicks compensation principle

A policy is to be judged socially beneficial if the gainers receive enough benefits that they can compensate the losers fully and still have some net gain left over.

If the losers are in fact compensated fully, they are by definition transformed into non-losers and the policy is Pareto optimal, i.e. optimal for all or at least neutral. The compensating measures may include protective barriers, compensation in kind or in money or relocation—the choice made by the affected individual being given primary weight.

2.4. The life measure principle

The measure of health and safety benefit is the expectancy of life in good health.

The goal of risk reduction efforts should be to maximize the net benefit in terms of the length of life in good health for all members at all ages. The impact of a risky activity on life expectancy (LE) is proposed as the measure of that activity's net safety impact. The concept can also be refined to include qualitative measures such as disability-free health expectancy and other factors that affect the quality of life.

3. Life-Quality Index

3.1. General

We present a model to determine an acceptable level of expenditure that can be justifiably incurred on behalf of the public interest in exchange for a small reduction in the risk of death that results in improved life quality for all. This value can be considered as the SWTP. The proposed approach relies on two major indicators, namely, LE as a measure of longevity and safety, and the real gross domestic product (RGDP) per person as a measure of the quality of life (United Nations Development Program, 1990). It should be commented that LE has been validated over time and again as a universal indicator of social development, environmental quality and public health (Gulis, 2000). Both indicators have been in use for half a century to express the wealth and health of a nation in numbers, and they are reliably measured. We derive the LQI in the following form

$$\mathrm{LQI} = G^q E \tag{1}$$

where G is the RGDP per person per year, E is the LE in the country, and q is the ratio of average work to leisure time available to members of society. Note that $q = w/(1-w)$ where w is the average work time per year for producing G. The derivation and interpretation of LQI is discussed in the following sections.

3.2. Summary of derivation

The general idea is that a person's enjoyment of life, or utility in an economic sense arises from a continuous stream of resources available for consumption over the entire life. Therefore, income required to support consumption and the time to enjoy are two determinants of the life quality. For a person at age a, the lifetime utility can, therefore, be interpreted as total consumption incurred over the remaining lifetime, which is a random variable.

Denote the consumption rate at some age τ as $c(\tau)$ (\$/year), and assume that a valid function, $u[c(\tau)]$, exists that can quantify the utility derived from consumption. The probability of survival in the period a to t is denoted by $S(a, t)$. The present value of life-time utility for a person is equivalent to integration of $u[c(\tau)]$ from the present age a till a terminal age T with a suitable discount rate to reflect the fact that individuals tend to undervalue a prospect of future consumption in comparison to that of present (Yaari, 1965). Thus,

$$L(a) = \frac{1}{S(0, a)} \int_a^T S(a, t) u[c(t)]\, \mathrm{e}^{-r(t-a)}\, \mathrm{d}t \tag{2}$$

where r denotes the discount rate, referred to as rate of time preference for consumption (Skinner, 1985). The implications of discounting are discussed further in Section 3.3.4. Assuming a power utility function and constant consumption rate, i.e. $c(t) = c$, and $u(c) = c^q$, Eq. (2) can be written in a compact form as

$$L(a) = u(c)e(a) = c^q e(a) \tag{3}$$

The complete derivation of this equation is provided in the Appendix A which is included at the end of the paper.

We propose the life-time utility, $L(a)$, as a surrogate measure of quality of life of a person of age a. This type of reasoning primarily originates from the fundamental work of Usher (1973) on the impact of historical improvement of LE on economic growth. This approach was later followed up by Conley (1976) and Arthur (1980) in the discussion of value of life. Shepard and Zechhauser (1984) applied this reasoning to discuss consumer behavior under varying survival probabilities and provided estimates of individual willingness-to-pay (WTP) for different market and insurance scenarios.

The life quality at the societal level is an aggregate of the values for all individuals in the society. To achieve this, $L(a)$, should now be integrated over the distributions of population age and consumption rate. This captures the utilitarian concept of social welfare ("the greatest good for the greatest number").

As a matter of simplification, we assume that the consumption rate is equivalent to the RGDP per person per year (G), a valid measure of average consumption in society. Integrating $L(a)$ over the population age-distribution, $f(a)$, leads to

$$\mathrm{LQI} = \int_0^T L(a)\, f(a)\, \mathrm{d}a = c^q \int_0^T e(a)\, f(a)\, \mathrm{d}a = G^q E \tag{4}$$

where E denotes the discounted LE averaged over the age-distribution of the population.

The societal life-quality function, LQI, is a utility function as well as a composite social indicator, since it consists of two important indicators of development, namely RGDP and LE. In essence, the aggregated function is indicative of quality of life enjoyed by the population, and is referred to as the LQI in our analysis. By setting E equal to LE at birth ($=E_o$) and ignoring the discounting, L ($=G^q E_o$) was used to rank the level of national development (Nathwani et al., 1997) similar to Human Development Index proposed by the United Nations Development Program (1990).

3.3. Interpretation of LQI

The purpose of this section is to determine the specific parameters of the generic form of life-quality function in Eq. (4) by addressing issues related to properties of utility function, discounting, and its aggregation at the societal level.

3.3.1. Utility function for consumption

We have selected a simple and generic power utility function, $u(c) = c^q$, that is commonly used in the literature (Yaari, 1965; Skinner, 1985; Usher, 1973; Conley, 1976; Arthur, 1980; Shepard and Zechhauser, 1984). The exponent q is referred to as the elasticity of utility with respect to consumption, which is taken as a constant regardless of the level of consumption. In simple terms, the utility (enjoyment) of consumption is same for rich and poor persons. Note that the "elasticity" of a function $u(c)$ is technically defined as $[(\partial u(c)/\partial c)/(u(c)/c)]$. The value of q should be bounded between 0 and 1 to satisfy the following desirable principles and values of rational decision making;

(1) $\frac{\partial u(c)}{\partial c} = qc^{q-1} > 0 \quad \text{since } q > 0$

It means that the person prefers more consumption rather than less at any period in life.

(2) $\frac{\partial^2 u(c)}{\partial c^2} = q(q-1)c^{q-2} < 0 \quad \text{since } q < 1$

This constraint implies that the marginal utility of consumption declines at higher levels of consumption. It also signifies that the person is risk averse, meaning that the person is unwilling to accept a gamble in which he is not expected (on average) to gain anything. To be more specific, this function has the property of constant proportion risk aversion ($=1-q$) as defined by Pratt (1964). It means that the degree of risk aversion depends on the proportion of asset likely to be lost in a gamble, regardless of the actual amount of asset under possession. To explain it further, the degree of aversion to a gamble of loosing 5% of \$100 (=\$5) is the same as that of loosing 5% of \$1000 (=\$50). Note that $q > 1$ means risk-prone attitude which is not consistent with the behaviour of reasonable consumers.

Given that the function $L(a)$ is essentially a product of two utility functions, the exponent q serves as a measure of tradeoff between the utility of longevity and utility of consumption (Arthur, 1980). When the value of q is small (close to zero), proportional increases in consumption have minor effect, implying that the life quality is largely derived from the state of being alive. In other words, the person is averse to death and would be willing to pay large amounts for greater LE because each year of life becomes essential to the person. A value of q close to 1 implies that utility is nothing more than cumulative consumption over life time (i.e. human capital). The person would not be willing to pay to extend life when $q = 1$, because the advantage of increased life span is completely offset by decrease in the consumption rate. In the economic literature, this effect is referred to as inter-temporal substitution for consumption (Skinner, 1985). The main implication of $q < 1$ is that quantity (longevity) and quality (money) of life are imperfect substitutes for each other (i.e. the consumer has limited preference for substitution of consumption across years of life). In countries with well-developed economies and high standards of living, an increase in longevity is expected to outweigh consumption consideration, implying a low value of q. In contrast, utility of additional living in poor countries, might be offset by large reductions in consumption due to lack of adequate income, pension and social support.

3.3.2. Utility function for longevity

The utility function for longevity is a linear function of discounted life years, which implies a "risk neutral" preference (Pliskin et al., 1980). The neutrality towards discounted life years is very interesting as it implies a person's risk aversion with respect to undiscounted life years, which is certainly a desirable property of utility function (Bleichrodt et al., 1997). To understand this better, recall that if LE of a person (age a) is t years then discounted LE is given as

$$e(a) = \frac{1}{r}(1 - \mathrm{e}^{-rt}) \tag{5}$$

As shown by Pratt (1964), this function exhibits constant risk aversion with the discount rate, r, being the coefficient of aversion. It means that persons, irrespective of their age being young or old, place identical preference to gaining or aversion to loosing a fixed number of life years.

Now return to a central question: what is a reasonable value of the elasticity term q? We propose to use work versus leisure tradeoff for the estimation of q, as discussed in the next section.

3.3.3. Work versus leisure tradeoff

Presumably, people on the average work just enough so that the marginal value of the wealth produced, or income earned, is equal to the marginal value of the time they lose when at work. This reasoning is also consistent with a notion that disposition of time is the ultimate source of utility, since the quality of life after all depends on the way we spend our time (Zeckhauser, 1973).

A person can increase his or her leisure time by a small amount in two different ways. One way is to reduce the time spent in economic production and so sacrifice consumption. The other way is to reduce life risk in order to increase the LE. We can assume that individuals (or society) on average choose w in a way that maximises their life-time utility over the long term. As shown in Appendix A, we have used this thinking to derive an estimate of exponent q as

$$q = \frac{w}{1 - w} \tag{6}$$

The average value of w can be approximately taken as 1/8 per year over the life span of an individual. The reasoning behind this estimate is as follows (Nathwani et al., 1997). In North America, the "average person" works about 50 years out of 80 years of life, 48 weeks per year out of 52, and about 42 h per week (including time spent travelling to and from work). Work thus consumes roughly the proportion $w = (50/80)(48/52)(42/168)(100\%) = 14.4\%$ per year on average over the life of a typical working person. If we recognize that a considerable proportion of the time spent in economic production goes towards health care, it should be accounted for in this proportion w. The total health care expenditure in Canada in 1995 is about 10.1% of GDP. Thus, we estimate $w = (0.141)(1 - 0.101) = 0.127 \approx 1/8$.

From Eq. (6), $q = 1/7 \approx 0.15$ can be easily calculated, which compares well with other empirical estimates reported in the literature. For example, Shepard and Zechhauser (1984) used a value of 0.2, and suggested an upper bound in the range of 0.2–0.4. Lutter et al. (1999) estimated income elasticity range of 0.12–0.22 by analysing expenditures on both healthy and risky products and services.

3.3.4. Remarks on discounting

In resource allocation decisions that involve intertemporal elements, it is necessary to establish some relative weights on deferred outcomes as opposed to immediate impacts. Inter-temporal tradeoffs are inherent to almost all risk mitigation programs and regulations. In Eq. (3), discounting the utility of future consumption with a suitable rate is intended to reflect the fact that owing to uncertainty about future people have higher preferences for present consumption. The discount rate is referred to as the rate of time preference for consumption and it should be conceptually distinguished from the interest rate. The discounting of future consumption is equivalent to discounting of LE when the rate of consumption is constant, as seen from Eq. (3). Although discounting of life years has been debated extensively, there is growing consensus that it is necessary to achieve consistency in cost–benefit analysis.

The discounting is consistent with the fact that risks and actions that have long latency periods and that are long deferred can have small value to many people, especially young people. The young may appear reckless on this account, but such behavior is not irrational. As a consequence of discounting, the WTP for risk mitigation would depend on how far away the hazard is from the present, the farther away it is, the smaller is the WTP to reduce it. An effect of ignoring discounting, according to Viscusi (1996), is that societal decisions will place more emphasis on well being of future generations rather than improving welfare of those now alive. To incorporate the effect of future economic growth, Viscusi (1996) proposed the concept of "net discount rate". If the annual rate of GDP growth is r_g, then a net discount rate of $(r-r_g)$ should be used in decision analysis. The discount rate in health-related matters is typically in the range of 1–4%.

4. Societal willingness-to-pay

4.1. General

Any project, program or regulation that materially affects the public by modifying risk through expenditure will have an impact on the LQI. Using Eq. (4), a small change in the LQI due to a project or a change in policy or regulation can be assessed as

$$\frac{\mathrm{d}L}{L} = q\frac{\mathrm{d}G}{G} + \frac{\mathrm{d}E}{E} \tag{7}$$

In Eq. (7) $\mathrm{d}G$ may represent the monetary cost of implementing a regulation ($\mathrm{d}G$ negative) or the monetary benefits that arise from a project ($\mathrm{d}G$ positive). The term $\mathrm{d}E$ is the change in LE due to a change in the level of risk to the population associated with a project or, regulation. The net benefit criterion requires that $\mathrm{d}L$ be positive or,

$$\frac{\mathrm{d}G}{G} + K\frac{\mathrm{d}E}{E} \geq 0 \tag{8}$$

where $K = 1/q = (1-w)/w = 7$ for $w = 1/8$. The best option among several options is the one that maximises the gain in LQI as shown before.

The concept of SWTP originates from the definition of compensating variation by Hicks (1939). It is the sum received by or from the individual which, following a welfare change, leaves him at his original level of welfare. It can be obtained from Eq. (7) by setting $\mathrm{d}L/L = 0$ and rearranging the terms leads to

$$(-\mathrm{d}G) = \frac{G}{q}\left(\frac{\mathrm{d}E}{E}\right) \quad (\$/\text{person/year}) \tag{9}$$

Suppose benefits of a safety regulation are received by a population of size N, the aggregated value of SWTP, i.e. the amount that will not alter the population life quality is equivalent to

$$\text{SWTP} = (-\mathrm{d}G) \times N = \frac{NG}{q}\left(\frac{\mathrm{d}E}{E}\right) \quad (\$/\text{year}) \tag{10}$$

The proposed measure of SWTP is consistent with general principle of welfare economics that the benefits of a public program are most appropriately measured by the aggregate WTP on the part of those benefiting from the program. The rationale for using WTP in public policy rests on the acceptance of the "potential Pareto improvement criterion" which asks if the gainers gain enough to compensate fully the losers. SWTP evaluates quantitatively how much better off people are as a result of the program as opposed to the effect on them of the program's absence (Pauly, 1996). The idea is that if the person received the benefit by paying less than his WTP, he is better off with the program than without it. Furthermore, excess of their payment over cost could be used to compensate other. Another fine point of consistency, as argued by Viscusi (1996), is that the discount rate should be applied to a monetary value of WTP figure rather than to a number of lives saved amount. The proposed LQI measure consistently incorporates this effect in the analysis.

Concepts of life-time utility, discounting, WTP, and age-related variation of preferences for consumption and survival have been discussed in scattered forms in the literature. Our main contribution is to integrate consistently and comprehensively all these concepts into the LQI model that also satisfies principles of utility theory and rational decision making.

4.2. Illustrative calculation

Consider a safety standard that can permanently decrease the probability of death by one in a million in the population of million people. The risk reduction is uniform across all ages (0–100 years). The most recent Canadian life table (1990–1992) is used to model the population survival pattern and calculate changes in LE (Statistics Canada, 1995). The variation of LE with ages and discounting rate is shown in Fig. 1, which is calculated using expression (5). The age-distribution, $f(a)$, of stationary population of life table can be

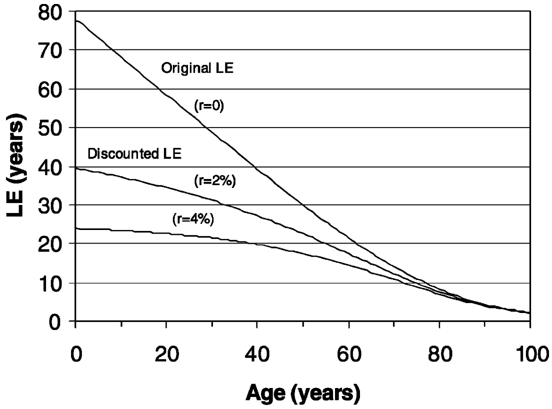

Fig. 1. Variation of LE in Canada with age and discount rate.

calculated as (Keyfitz, 1985)

$$f(t) = \frac{S(0, t)}{e(0)} \quad (11)$$

where $S(0, t)$ is the probability of survival in the interval from 0 to t, and $e(0)$ is the LE at birth without discounting.

This distribution is used to determine the population average of change in LE (i.e. dE/E). The RGDP in Canada in 1996, $G = 28{,}575$ \$/person/year, was used in calculation to facilitate a comparison with other empirical estimates of the value of statistical life (VSL) utilised in Canada that are given in 1996 C\$ (Canadian dollar; The Royal Society of Canada (RSC), 2001). For the given uniform risk reduction (1×10^{-6}) and zero discounting rate, an increase in LE was calculated as $dE/E = 3.21 \times 10^{-5}$. Using Eq. (9), the individual WTP was calculated as 4.4 \$/person/year. To avoid this risk over a population of one million people, SWTP was subsequently calculated as 4.4 million \$/year from Eq. (10). SWTP values for discount rates ranging from 1 to 8% are given in Table 3. From the LQI model, the VSL can be inferred as money per unit reduction of risk of death, which is equal to $\$4.4/10^{-6} = \$4.4$ million.

4.3. Empirical validation

It is interesting to compare results of the LQI model with other "VSL" estimates reported in the literature and utilised in cost–benefit analyses. Surveys of various life-saving programs and regulations indicate that the implied value of "cost per life" can vary from a few thousand dollars to billions of dollars (Tengs et al., 1995). Such estimates largely reflect subjective decisions (preferences) of program administrators rather than being indicative of tradeoffs or peoples' WTP for risk reduction.

In the context of cost–benefit analysis of air pollution control options, an expert panel appointed by The RSC compiled several VSL estimates (RSC, 2001), which were derived from different wage-risk models and contingent-valuation surveys reported in the literature. These estimates vary from \$2 to \$10 million (1996 C\$) as summarised in Table 4. The Canadian Standards Development Committee adopted \$4.1 million as an age-adjusted central estimate of VSL. The LQI model results in an estimate of \$4.4 million (Table 3) which is close to \$4.1 million value used in Canada. Using results of a WTP survey in Hamilton (Canada), Krupnick et al. (2000) estimated VSL as \$1.2–\$3.8 million (Krupnick et al., 2000). This range of VSL is seen in Table 3 for discount rates between 5 and 1%, respectively.

The point to make here is that the implied VSL estimates from the proposed model are in line with those

Table 3
LQI estimates of SWTP for averting 1×10^{-6} annual risk of death

Rate of time preference (%)	SWTP (1996 million C\$)
0	4.4
1	3.4
2	2.6
3	2.0
4	1.5
5	1.1
6	0.9
7	0.7
8	0.6

Table 4
Estimates of VSL used in the Canadian cost–benefit analysis of air pollution control program (RSC, 2001)

Population age group	VSL estimates (1996 million C\$)		
	Low (\$)	Central (\$)	High (\$)
Age ≥65 years old	2.3	3.9	7.8
Age <65 years old	3.1	5.2	10.4
Age-weighted average VSL = 0.85 (age ≥ 65) + 0.15 (age < 65)	2.4	4.1	8.2

obtained by wage differential and contingent-valuation surveys, thus providing an empirical validation of the LQI approach. Although the basis for selecting a VSL value is generally a controversial problem, the LQI model can still provide an alternative approach to this issue.

5. Applications to risk of ionising radiation exposure

Low-level ionising radiation (alpha-, beta-, gamma- or X-rays) is held to be harmful, increasing the risk of cancer and genetic damage. The age-adjusted mortality risk has been estimated as 0.026 lives/Sv or 26×10^{-6}/mSv (National Academy of Sciences, 1990; Cohen, 1991), though death is delayed by several years after an exposure, typically by 10–20 years (Cohen, 1991). This section illustrates the procedure for using LQI to provide a "figure-of-merit" estimate of the acceptable expenditures for preventing radiation exposure. All cost data are reported in Canadian dollars throughout the paper.

Consider the evaluation of SWTP for the installation of new equipment that has the potential of reducing radiation exposure by 1 mSv/year/person over its 30 years of service life. We evaluate the safety impact of this equipment on a person with an average age of 35 years. To estimate the improvement in LE (de/e term) due to reduced radiation exposure over a 30-year period, the mortality risk is uniformly reduced by 26×10^{-6} in the age interval of 35–64 years. Ignoring the discounting, the change in LE is estimated as $de/e = 5.1982 \times 10^{-4}$. Since the remaining LE at age 35 is about 44 years, the change in LE is equal to 8.4 days. Since the GDP per person in Canada in 2000 was $G = 31{,}024$ \$/year, the SWTP is estimated from Eq. (9) as 112.9 \$/year/person/mSv. This amount should be paid by a person over his remaining life in exchange for the proposed reduction in risk. Since the remaining LE is 44 years for a 35-year-old person, the total compensation is $112.9 \times 44 = \$4967$. If we consider that it should be paid by an annuity over a 30-year period (i.e. equipment lifetime), its present value can be calculated as 2545 \$/person/mSv assuming the interest rate as 5%. This amount can be interpreted as an acceptable dose equivalent that can be spent for improving safety while being in harmony with the general public interest as reflected in the LQI. It should be emphasised that this amount corresponds to eliminating the exposure of 1 mSv/year for a period of 30 years, and it should be recalculated for other scenarios of radiation exposure.

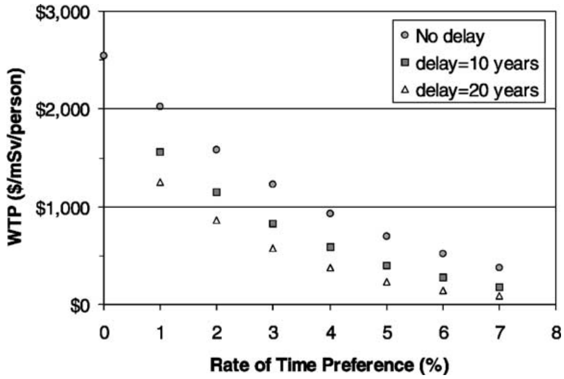

Fig. 2. Variation of SWTP (2000 C$) with rate of time preference and delay in cancer-related death (example of Section 5).

The factors to be considered in the analysis are, namely: (1) delay in cancer-related death by several years, (2) rate of time preference that discounts gain/loss of life year, and (3) interest rate of return used to calculate the annuity. The results of sensitivity analysis are presented in Fig. 2. As expected, SWTP declines with increase in rate of time preference (rtp) and delay in death after exposure. For rtp = 3%, SWTP is estimated as 1223 \$/mSv/person, which declines to 576 \$/mSv if we assume delay of 20 years in cancer-related death. Such a transparent sensitivity analysis can provide a useful input to cost–benefit analysis of nuclear safety programs, as shown in the next section.

6. Application to nuclear safety design features

6.1. Background

Some special safety systems have no role in the normal operation of plant, but they are installed to control accident sequences and to mitigate consequences of failure. The safety features are designed on the basis of "defence in depth" approach in which a second and third level of defences are provided to prevent releases of fission products and to limit the exposure to the

Table 5
Radiation dose limits under accident conditions as specified in the Siting Guide (Ontario Hydro, 1988b)

Situation	Assumed maximum frequency	Maximum dose limit (whole body)	
		Individual (mSv)	Population (Sv)
Serious process equipment failure	1 per 3 year	5	100
Process equipment failure plus failure of any safety system	1 per 3000 year	250	10000

public in the event of such a release. The main features of this approach are diversity, redundancy and independence of safety systems from process equipment. The main elements of safety systems in the CANDU reactors are: (i) two shutdown systems (SDS1 and SDS2) that provide two independent and diverse means for rapidly stopping the nuclear reaction; (ii) an emergency coolant injection (ECI) system for cooling the nuclear fuel in the event that the normal coolant system pressure boundary is breached; and (iii) a containment system which provides a method for containing any radioactive substances that may be released from the process systems (Fraser, 1988; Ontario Hydro, 1988b).

The total costs associated with the design and installation of the safety systems for three of the new CANDU stations built by Ontario Hydro are shown in Table 1 (Ontario Hydro, 1988a). The costs quoted are the original costs incurred (in C$) during the construction of each of the three generating stations (four reactors per station). The in-service dates for the three stations are as follows: Pickering B (March 1983–February 1986); Bruce B (March 1985–May 1987); and Darlington A (1989–1993). Large financial investments have been made in implementing several design modifications and retrofits at operating nuclear stations as shown in Table 2 (Ontario Hydro, 1988a).

The Canadian regulatory framework is intended to achieve risk levels associated with nuclear power production that are lower than equivalent existing industries. Most of Ontario's nuclear plants have been licensed according to the Siting Guide developed by the Atomic Energy Control Board (Ontario Hydro, 1988b). The Guide specifies the reference dose limits for accident conditions, as described in Table 5.

The importance of special safety systems in significantly reducing the risk of radiation exposure is further exemplified in a comprehensive probabilistic safety evaluation of Darlington station (Ontario Hydro, 1987). In this study, all accidents causing fuel damage that give rise to a release of radioactivity off-site were modelled as six Ex-Plant Release Categories (0–5). The mean frequency and associated consequences in terms of individual and population dose for each category are reproduced in Table 6. It shows that safety systems are highly efficient in reducing the annual risk of radiation exposure, though the reduction in risk comes at a high price as shown in Table 1.

6.2. Results and discussion

We use the LQI to evaluate the efficacy of the investment in the special safety systems. Ideally, it would be best to start with a hypothetical nuclear power plant without any of the special safety systems. Such a plant would consist primarily of design features and equipment necessary for normal operation and equipment protection. Then a risk assessment could be performed, taking into account the various accident initiating events and the consequences to members of the public

Table 6
Estimates of public health risk imposed by Darlington Nuclear Generating Station (Ontario Hydro, 1987)

Ex-Plant Release Category	Annual release frequency	Mean radiation dose per release		Annual radiation exposure risk	
		Individual (mSv)	Population (Sv)	Individual (mSv/year)	Population (Sv/year)
1	9.2×10^{-6}	240	1300	2.2×10^{-3}	1.2×10^{-2}
2	5.7×10^{-6}	5.9	320	3.4×10^{-5}	1.8×10^{-3}
3	1.7×10^{-5}	1.2	29	2.0×10^{-5}	4.9×10^{-4}
4	1.5×10^{-4}	0.07	1.9	1.0×10^{-5}	2.8×10^{-4}

Table 7
The estimates of potential dose averted that are imputed from the LQI criterion for retrofits of safety systems at Bruce B nuclear station

Safety system	Cost (million C$)	Dose averted (Sv)
Bruce B		
High pressure ECI[a]	74	79.74
Harsh powerhouse environment	1.9	2.05
PHT[b] pump low speed operation	27.0	29.09
Emergency filtered air discharge	4.4	4.74
Hydrogen mitigation system	0.6	0.65
Moderator seismic qualification	2.1	2.26
Boiler feedline low pressure trips	1.1	1.19
ECI seismic qualification	0.77	0.83
Emergency filtered air discharge	4.4	4.74
Whole body contamination monitors	2.5	2.69
Fuelling machine seismic snubbers	1.5	1.62
PHT pump trip on LOCA[c]	0.57	0.61

[a] Emergency cooling injection.
[b] Primary heat transport.
[c] Loss of coolant accident.

in the absence of the safety features. In a logical step by step approach, new safety features would be added and the risk reduction from additional safety features evaluated. The risk reduction that can be attributed directly to the design safety feature would then be documented against the costs. This process would continue until an established acceptance criterion is satisfied.

Given the existing situation (namely, operating nuclear power plants with all the elaborate safety systems having already been built), we can still use the LQI to test whether the investment embedded in the safety design features provides a sufficient return in terms of "radiation dose avoided" or "lives saved". Furthermore, it is our objective to provide some information on how the LQI could be used in the future to justify incremental costs of new safety features against the potential benefits from such expenditures.

As shown in Section 5, the LQI criterion can be used to determine acceptable expenditure (SWTP) to prevent 1 mSv/year exposure during the service life (30 years) of a safety system. Considering that Canadian GDP in 1990s was approximately 25,000$ /person/year and assuming: (1) 10 years delay in cancer-related death, and (2) a low value, 2% per year, of the rate of time preference, the SWTP is estimated as 928 $/mSv. Table 1 shows that the total investment in special safety systems for Darlington equals $1770 million. The potential dose averted can be imputed as $\$1770 \times 10^6/928\,\$/\text{mSv} = 1.907 \times 10^6\,\text{mSv}$ or 1907 Sv. In absence of special safety systems, the mean population dose is expected to be in the range of 1300–1400 Sv (Ontario Hydro, 1987; O'Donnell and Mauro, 1979), which is close to the value estimated from LQI criterion. The comparison indicates that investments in special safety systems are reasonable. Note that the Ontario Hydro study (Ontario Hydro, 1987) derived the estimates of population dose through a careful consideration of population distribution near the plant site and environmental conditions affecting the dispersion of radiation. The potential dose averted by the installation of other safety systems can be estimated in a similar manner. A set of results is presented in Table 7 to illustrate the imputed values of potential dose averted due to retrofits or modification of safety systems at the Bruce B nuclear station. The results are calculated using the LQI estimate of 928 C$/mSv as derived before.

7. Conclusions

The concept of life quality to enhance the basis of the cost–benefit analysis of nuclear safety programs involving risk to life is the primary contribution of the paper.

We propose the management of public risks into the broader context of social policy by presenting four principles that reflect the necessary general attributes of the good life in a modern state. These principles are public accountability, maximum net benefit for all, compensation for those who lose when there is change, and long life in good health with maximum personal choice.

The paper presents a LQI that gives the necessary criterion to determine the level of expenditure beyond which it is no longer justifiable to spend resources in the name of safety. It is referred to as "SWTP". The proposed approach is comprehensive as it incorporates several difficult issues/concepts in public policy analysis, namely, discounting of life years, competing mortality risks, and inter-temporal tradeoffs. The significant aspect is that integration of these issues is done in a consistent and transparent manner to support a credible analysis.

Acknowledgements

The first author (M.D.P.) gratefully acknowledges the financial support for this study that is provided by the Natural Science and Engineering Council of Canada.

Appendix A. Derivation of Life-Quality Index

Assume that the consumption rate at some age τ as $c(\tau)$ (\$/year), and associated utility function is $u[c(\tau)]$. The life-time utility for a person is equivalent to integration of $u[c(\tau)]$ from the present age a till age at death t:

$$U(a,t)=\int_a^t u[c(\tau)]\,\mathrm{d}\tau \tag{A.1}$$

The net-present value of life utility of consumption can be determined as

$$U(a,t)=\int_a^t u[c(\tau)]\,\mathrm{e}^{-r(\tau-a)}\,\mathrm{d}\tau \tag{A.2}$$

where r is the discount rate, also referred to as the rate of time preference for consumption. If the probability distribution of survival age is denoted by $p(t)$, then the product $U(a,t)\times p(t)$ is the expected value of utility. Since the age at death can vary randomly between a and some maximum value T (≈100 years) with probabilities described by an actuarial survival function (e.g. life tables), the expected value of life-time utility can be obtained as

$$L(a)=\frac{1}{S(0,a)}\int_a^T p(t)U(a,t)\,\mathrm{d}t \tag{A.3}$$

where $S(0,a)=\int_0^a p(t)\,\mathrm{d}t$ denotes the probability of surviving a person up to age a. Substituting for $U(a,t)$ from Eq. (A.2) into Eq. (A.3)

$$L(a)=\frac{1}{S(0,a)}\int_a^T p(t)\,\mathrm{d}t\int_a^t u[c(\tau)]\,\mathrm{e}^{-r(\tau-a)}\,\mathrm{d}\tau \tag{A.4}$$

and rearranging the terms leads to

$$L(a)=\frac{1}{S(0,a)}\int_a^T u[c(t)]\,\mathrm{e}^{-r(t-a)}\,\mathrm{d}t\left(\int_a^t p(\tau)\,\mathrm{d}\tau\right) \tag{A.5}$$

Defining the probability of survival in the period a to t as $S(a,t)=\int_a^t p(\tau)\,\mathrm{d}\tau$, Eq. (A.5) and using a time invariant utility function $u[c(t)]=c^q$, Eq. (A.5) can be further simplified to

$$L(a)=c^q\int_a^T \frac{S(a,t)}{S(0,a)}\mathrm{e}^{-r(t-a)}\,\mathrm{d}t=c^q e(a) \tag{A.6}$$

Note that the discounting factor applied to utility of consumption is now merged in Eq. (A.6) with the survival probability integral. The integral term in Eq. (A.6) is also referred to as the discounted value of remaining life years at age a (Yaari, 1965), which is denoted here by $e(a)$.

As discussed in Section 3.3.3, we used the "work versus leisure tradeoff" to estimate a value of exponent q. Let w denote the fraction of time spent in producing income that supports the consumption. The leisure time available to a person is then a fraction of LE. In other words, $c\propto we(a)$ and leisure time $e_{\mathrm{L}}\propto(1-w)e(a)$, such that the life-quality function can be expressed in a proportional form

$$L(a)\propto(w\times e)^q[(1-w)e] \tag{A.7}$$

The first order condition for maximising life-quality, $\mathrm{d}L/\mathrm{d}w=0$, along with Eq. (A.9) leads to

$$q=\frac{w}{1-w} \tag{A.8}$$

Since w is practically constant, especially for industrialised and developed countries, we drop the factor

$(1 - w)$ from Eq. (A.7) and obtain the following expression for the life-quality function

$$L(a) = c^{w/(1-w)}e(a) \tag{A.9}$$

References

Arthur, W.B., 1980. The economics of risks to life. Am. Econ. Rev. 71 (1), 54–64.

Bleichrodt, H., Wakker, P., Johannesson, M., 1997. Characterizing QALYs by risk neutrality. J. Risk Uncertainty 15, 107–114.

Canada, 1995. Government of Canada Regulatory Policy. Treasury Board Secretariat, pp. 1–2.

Cohen, B.L., 1991. Catalog of risks extended and updated. Health Phys. 61 (3), 317–335.

Conley, B.C., 1976. The value of human life in demand for safety. Am. Econ. Rev. 66 (1), 45–55.

Fraser, P.M., 1988. A review of the design related aspects of the safety of Ontario Hydro's nuclear generating stations. In: Ontario Nuclear Safety Review, vol. 2: Appendices. Toronto, Ont., pp. 2.1–2.154.

Gulis, G., 2000. Life expectancy as an indicator of environmental health. Eur. J. Epidemiol. 16, 161–165.

Hicks, J.R., 1939. The foundation of welfare economics. Econ. J. 49 (196), 696–712.

Hoegberg, L., 1998. Risk perception, safety goals and regulatory decision making. Reliability Eng. Syst. Safety 59, 135–139.

Keyfitz, N., 1985. Applied Mathematical Demography. Springer, New York.

Kroger, W., Fischer, P.U., 2000. Balancing safety and economics. Nucl. Eng. Des. 195, 101–108.

Krupnick, A.J., Alberini, A., Cropper, M., Simon, N., O'Brien, B., Goeree, R., Heintzelman, M., 2000. Age, health and willingness-to-pay for mortality risk reduction. Discussion Paper, Resources for Future, DP00-37, Washington, DC.

Lutter, R., Morrall, J.F., Viscusi, W.K., 1999. The cost-per-life-saved cutoff for safety-enhancing regulations. Econ. Inq. 37 (4), 599–608.

Nathwani, J.S., Narveson, J., 1995. Three principles for managing risk in the public interest. Risk Anal. 15 (6), 615–626.

Nathwani, J.S., Lind, N.C., Pandey, M.D., 1997. Affordable Safety by Choice: The Life Quality Method. Institute for Risk Research, University of Waterloo, Canada, p. 230.

National Academy of Sciences, 1990. Committee on the Biological Effects of Ionizing Radiation. Health Effects of Exposure to Low Levels of Ionizing Radiation (BEIR V). National Academy Press, Washington, DC.

Nordhaus, W.D., 1997. The Swedish Nuclear Dilemma: Energy and the Environment. Resources for the Future. Washington, DC, p. 167.

O'Donnell, E.P., Mauro, J.J., 1979. A cost benefit analysis of nuclear safety and nonnuclear health and safety protective measures and regulations. Nucl. Safety 20 (5), 525–540.

Ontario Hydro, 1987. Darlington NGS Probabilistic Safety Evaluation: Summary Report. Nuclear Safety and Studies Department, Ontario Hydro, Toronto, Ont.

Ontario Hydro, 1988a. The Safety of Ontario's Nuclear Power Reactors: A Scientific and Technical Review. Chapter 17: Costs of Nuclear Safety, vol. 1. Ontario Nuclear Safety Review. Toronto, Ont.

Ontario Hydro, 1988b. The Safety of Ontario's Nuclear Power Reactors: A Scientific and Technical Review. Section 1: Management of Nuclear Safety in Ontario Hydro, vol. 1. Ontario Nuclear Safety Review. Toronto, Ont.

Pauly, M.V., 1996. Valuing health care benefits in money terms. In: Sloan, F.A. (Ed.), Valuing Health Care: Costs, Benefits, and Effectiveness of Pharmaceuticals and Other Medical Technologies. Cambridge University Press, UK, pp. 99–124.

Pliskin, J.S., Shepard, D.S., Weinstein, M.C., 1980. Utility functions for life years and health status. J. Operations Res. 28 (1), 206–224.

Pratt, J.W., 1964. Risk aversion in the small and in the large. Econometrica 32 (1/2), 122–136.

Rackwitz, R., 2002. Optimization and risk acceptability based on the Life Quality Index. J. Struct. Safety 24 (2–4), 297–331.

Rackwitz, R., 2002. A rational risk acceptability criterion based on the Life Quality Index. Invited keynote lecture, OMAE-Conference, 2002, Oslo.

Shepard, D.S., Zechhauser, R.J., 1984. Survival vs. consumption. Manag. Sci. 30 (4), 423–439.

Skinner, J., 1985. Variable life span and the interntemporal elasticity of consumption. Rev. Econ. Stat. 67 (4), 616–623.

Skjong, R., Ronold, K.O., 2002. So much for safety. In: Proceedings of OMAE 2002, Paper 28451, Oslo, Norway, June 23–28, 2002.

Statistics Canada, 1995. Life Tables, Canada and Provinces, 1990–1992. Catalogue 84–537, Ottawa, Ont.

Tengs, T.O., Adams, M.E., Pliskin, J.S., Safran, D.G., Siegel, J.E., Weinstein, M.C., Graham, J.D., 1995. Five hundred life-saving interventions and their cost-effectiveness. Risk Anal. 15 (3), 369–390.

The Royal Society of Canada, 2001. Report of an Expert Panel to Review the Socio-Economic Models and Related Components Supporting the Development of Canada Wide Standards for Particulate Matter and Ozone.

United Nations Development Program, 1990. The Human Development Report. Oxford University Press, UK.

Usher, D., 1973. An imputation to the measure of economic growth for changes in life expectancy. Published in National Accounting and Economic Theory: The Collected Papers of Dan Usher, vol. 1. Edward Elgar Publishing Ltd., UK, pp. 105–144.

Viscusi, W.K., 1996. Discounting health effects for medical decision. In: Sloan, F.A. (Ed.), Valuing Health Care: Costs, Benefits, and Effectiveness of Pharmaceuticals and Other Medical Technologies. Cambridge University Press, UK, pp. 125–147.

Yaari, M.E., 1965. Uncertain lifetime, life insurance, and the theory of the consumer. Rev. Econ. Studies 32 (2), 137–150.

Zeckhauser, R., 1973. Time as the ultimate source of utility. Q. J. Econ. 87 (4), 668–675.