JOURNAL OF ENVIRONMENTAL ECONOMICS AND MANAGEMENT 19, 160–174 (1990)

Valuing Future Risks to Life*

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Received May 12, 1988; revised July 17, 1989

Environmental policies that alter future mortality rates may affect both current and future generations. This paper examines willingness to pay for future risk reductions from the perspective of the current generation. The life cycle consumption/saving model implies that an individual discounts future risks to himself at the consumption rate of interest. If capital markets are perfect, the consumption rate equals the market rate of interest; otherwise, the consumption rate exceeds the market rate, and numerical results suggest that the implied discount factor may be substantial. The overlapping generations model implies that a member of the current generation discounts the value of risks to future generations at the rate at which current consumption is substituted for a bequest.

I. INTRODUCTION

The empirical literature on valuing risks to life has focused almost exclusively on valuing mortality risks that occur today—the risk of accidental death a worker faces during the coming year or the risk of dying this month in an auto accident. For many environmental policies the benefits in lives saved are not realized at the time actions are taken, but at some point in the future. For example, the control of carcinogens, such as asbestos, or design restrictions on hazardous waste landfills benefit both the current generation, after a lag, and future generations. Thus, policymakers must value future as well as current risks to life.

To illustrate the problem confronting policymakers, consider a project—the construction of a safer road—for which costs will be incurred today but which confers benefits in the future. To simplify the problem, suppose that members of each generation live at most two periods and that periods are 20 years long. Persons are 20 years old at the beginning of the first period of their lives and 40 at the beginning of the second period. The costs and benefits of the project are pictured schematically below. (See Fig. 1.)

For all users, the safer road reduces the conditional probability of dying at the beginning of period 1 and at the beginning of each subsequent period.[1] At the

*This research was supported by the Computer Science Center, University of Maryland, College Park, and by the U.S. Environmental Protection Agency. We would like to thank Ann Fisher, Paul Portney, two anonymous referees, and an Associate Editor of this *Journal* for their helpful comments.

[1]The conditional probability of dying at age t is the probability that the individual dies between his tth and t + 1st birthdays, assuming he is alive on his tth birthday.

0095-0696/90 $3.00

Period	1	2	3
Generation 1	ΔD_{40}		
Generation 2	ΔD_{20}	ΔD_{40}	
Generation 3		ΔD_{20}	ΔD_{40}

FIG. 1. Changes in the conditional probability of death at age t (D_t) due to construction of a safer road. Each period is 20 years long. Persons live for at most two periods. They are 20 at the beginning of the first period of their lives and 40 at the beginning of the second period.

beginning of period 1 the road reduces the conditional probability of dying at age 40 for members of generation 1 (D_{40}) and the conditional probability of dying at age 20 for members of generation 2 (D_{20}). At the beginning of period 2 it reduces the conditional probability of dying at age 40 for members of generation 2 and the conditional probability of dying at age 20 for members of generation 3.[2]

Assuming that the population is stationary, the age distribution of risk reductions in each period is constant. The question is at what rate to discount the value of future risk reductions to the present. For members of generation 2 who are alive when the road is built, the appropriate rate at which to discount the reduction in D_{40} is implicit in the answer to the question: "What are you willing to pay at age 20 for a reduction in your conditional probability of dying at age 40?" The more difficult questions are how to (1) estimate and (2) discount the value of risk reductions to members of generation 3 who are not alive at the time the road is built.

The purpose of this paper is to examine the implications of two economic models—the life cycle consumption/saving model and the overlapping generations model—for the answers to these questions. A reasonable position is that, for persons currently alive, the rate at which willingness to pay to reduce D_{40} should be discounted to age 20 is the rate the individual himself would choose. The implications of this position can be examined in the context of a life cycle consumption/saving model, under alternative capital market assumptions.

The life cycle model implies that willingness to pay for a future risk should be discounted to the present at the consumption rate of interest—the rate at which a person is willing to substitute consumption next year for consumption this year. In a world of perfect capital markets this will equal the market rate of interest; however, if a person's consumption is constrained by his inability to borrow, he will substitute consumption tomorrow for consumption today at a rate that exceeds the market rate of interest.

We then consider the problem of how to weight benefits accruing to members of future generations relative to benefits accruing to members of the current generation. One approach, reflected in the debate on the social rate of discount [14, 16, 17], is to weight benefits to future generations according to the preferences of the current generation. If the current generation cares about risks to its

[2]For simplicity, we assume that people are at risk of dying only at the beginning of each period.

immediate descendants, who in turn care about risks to their immediate descendants, then one can use an overlapping generations model to value risks to future generations. An alternative approach is to combine the preferences of current and future generations in a social welfare function that satisfies certain widely accepted ethical postulates.

In this paper we use an overlapping generations model with uncertain lifetimes [1, 12] to examine the rate at which benefits of life-saving activities to future generations are discounted to the present by altruistic members of the current generation. The main insight of this model is that the willingness to pay of a member of the current generation for a change in the probability that his descendant in generation t survives to old age is the expected value of what the descendant himself would pay, discounted to the present. When discounting WTP from one generation to another, the rate of discount implied by the model is the rate at which each generation is willing to substitute current consumption for a bequest.

After considering the implications of these models for the discounting issue, we apply these insights to a category of intertemporal problems that arise frequently in an environmental context: reducing exposure to carcinogens. A key feature of carcinogens is that there is often a lag, i.e., a latency period, between exposure and the formation of cancerous cells. Since the individual is safe during the latency period, the benefits of reducing current exposure take the form of a reduction in the conditional probability of dying at the end of the latency period. Compared with the safer road, fewer life years are saved in the steady state. This distinction, however, is often ignored in policy discussions or the latency effect is wrongly treated as a pure discounting issue.

The paper is organized as follows. Section II presents a life cycle consumption/saving model with uncertain lifetime and derives, under the assumption of actuarially fair annuities, willingness to pay at age j for a change in the conditional probability of dying at age k. Section III spells out the implications of the model for discounting future risks to life. The effect of capital market imperfections on these results is examined in section IV. The fifth section of the paper considers risks to future generations, and the sixth section discusses the treatment of latency periods.

II. A LIFE CYCLE MODEL OF WILLINGNESS TO PAY TO REDUCE RISK OF DEATH

A. The Life Cycle Utility Model

The framework that we use to examine discount rates implicit in WTP to reduce risk of death is the life cycle consumption/saving model with uncertain lifetime. This model, originally developed by Yaari [24], has been used to value changes in current risk of death over the life cycle by Arthur [2] and by Shepard and Zeckhauser [18, 19]. We present a discrete-time version of their models.

The model. In the life cycle model the individual has a probability distribution over the date of his death. Let j denote the individual's current age, T the oldest age to which he can survive, and $p_{j,t}$ the probability that he dies at age t, just before his $t + 1$st birthday. Since the $\{p_{j,t}\}$ constitute a probability distribution, it follows that $p_{j,t} \geq 0$, $t = j, j+1, \ldots, T$, and that

$$\sum_{t=j}^{T} p_{j,t} = 1.$$

The probability that the individual survives to his tth birthday, given he is alive at age j, $q_{j,t}$, is the probability that he dies at t (just before his $t+1$st birthday) or later. Formally,

$$q_{j,t} = \sum_{s=t}^{T} p_{j,s}.$$

The probability that the individual survives to his $t+1$st birthday, given that he is alive on his tth, is $q_{j,t+1}/q_{j,t}$. For future reference we denote this conditional probability $1 - D_t$, where D_t is the conditional probability of dying at age t.[3]

Expected lifetime utility at age j is the sum of the utility of living exactly $t - j$ more years times the probability of doing so. Assuming that the individual has no bequest motive, this may be written

$$V_j = \sum_{t=j}^{T} p_{j,t} u_t(c_j, c_{j+1}, \ldots, c_t), \tag{1}$$

where $u_t(\ )$ is the utility of consumption in years j through t. In most applications in the area of risk valuation [2, 18, 19], $u_t(\ )$ is assumed additively separable, implying that (1) may be written as

$$V_j = \sum_{t=j}^{T} (1+\rho)^{j-t} q_{j,t} U(c_t). \tag{2}$$

ρ is the rate of individual time preference and $U(c_t)$, the period utility function, is assumed to be increasing in c_t, strictly concave, and bounded from below.[4]

Two points about (2) should be emphasized. First, the equation assumes that the utility of living depends only on consumption and not on length of life per se. As Bergstrom [3] has pointed out, if derived from preferences on lotteries, the intertemporal objective function should include a term that values survival per se. Second, we treat survival probabilities as exogenous to the individual.

In the life cycle model the individual maximizes expected lifetime utility from age j until T by choosing consumption at each age, given his initial wealth, W_j, annual earnings, y_t, $t = j, \ldots, T$, and capital market opportunities. In this section we follow Arthur [2] and Shepard and Zeckhauser [18, 19] and assume that the individual can save by purchasing actuarially fair annuities and borrow via life-insured loans. This assumption is relaxed in section IV.

If actuarially fair annuities are available, an individual who invests \$1 at the beginning of his jth year will receive $\$(1 + R_j)$ at the end of the year with

[3]Since T is the oldest age to which the individual can live, $D_T = 1$.

[4]Note that we do not assume $U(0) = 0$; hence the utility function allows a positive subsistence level of consumption below which utility is zero.

probability $1 - D_j$ and nothing with probability D_j. For the annuity to be fair, i.e., to have an expected payout of $1 + r$, where r is the riskless rate of interest, R_j must satisfy

$$(1 + R_j)(1 - D_j) = 1 + r.$$

Since $R_j > r$, an individual who can save via fair annuities will clearly do so. To cover the possibility that he might die before repaying a loan, it is assumed that the individual must also borrow at the actuarial rate of interest.

To prevent unlimited borrowing, the individual's budget constraint requires that the present value of borrowing, discounted at the actuarial rate of interest, equal the value of initial wealth,

$$\sum_{t=j}^{T}\left[\prod_{i=j}^{t-1}(1 + R_i)^{-1}\right](c_t - y_t) = W_j.$$

This is equivalent to requiring that the present value of expected consumption equal the present value of lifetime earnings plus initial wealth,

$$\sum_{t=j}^{T} q_{j,t}(1 + r)^{j-t}c_t = \sum_{t=j}^{T} q_{j,t}(1 + r)^{j-t}y_t + W_j. \tag{3}$$

The pattern of consumption over the life cycle is determined by maximizing (2) subject to (3).

Willingness to pay. We now consider how government health and safety regulations affect lifetime utility. A government regulation alters the probability that a person dies in any year only if he is alive at the beginning of the year. Government programs thus alter D_k, the conditional probability of dying at age k, i.e., the probability that the individual dies between his kth and $k + 1$st birthdays, assuming he is alive on his kth birthday. A program to increase the police force in a city in a single year reduces D_k for that year alone. A program that reduces an individual's exposure at age 30 to a carcinogen with a 20-year latency period reduces the conditional probability of dying at all ages after 50 $(D_{50}, D_{51}, D_{52}, \ldots,)$.[5]

It should be emphasized that when the conditional probability of death is altered at age k, it affects the probability of surviving to ages $k + 1$ and beyond, $q_{j,k+1}, q_{j,k+2}, \ldots, q_{j,T}$, since, by repeated use of the definition of D_t,

$$q_{j,k} = (1 - D_j)(1 - D_{j+1}) \cdots (1 - D_{k-1}).^6$$

In practice, the changes in $\{D_k\}$ corresponding to some public project are likely to be small. For example, it has been estimated that the risk of dying of cancer due to all environmental causes is only 3.6×10^{-5} [5]. For this reason we focus on

[5]Since any arbitrary set of D_j's implies a well-defined probability distribution over length of life (provided $D_T = 1$), one can alter the D_j's in any arbitrary manner.

[6]A change in D_k also affects life expectancy, which is the sum of survival probabilities from the current age onward, $\Sigma_{t=j}^{T} q_{j,t}$. Note, however, that there are many changes in $\{D_k\}$ that result in equivalent changes in life expectancy.

marginal changes in $\{D_k\}$. If more than one D_k changes, WTP for the sum of the changes equals the sum of the WTPs.

Formally, the individual's willingness to pay at age j for a change in D_k, $\mathrm{WTP}_{j,k}$, is the wealth that must be taken away from him at age j to compensate him for a reduction in D_k and keep his expected utility constant,

$$\mathrm{WTP}_{j,k} = -\frac{dV_j/dD_k}{dV_j/dW_j} dD_k .$$

The first term on the right-hand side of the equation, the rate at which the individual is willing to substitute wealth for risk, is typically termed the value of life. Applying the Envelope Theorem to the Lagrangian function that corresponds to (2) and (3), $\mathrm{WTP}_{j,k}$ can be written

$$\mathrm{WTP}_{j,k} = \left[(1 - D_k)^{-1} \sum_{t=k+1}^{T} q_{j,t} \left[(1+\rho)^{j-t} U(c_t) \lambda_j^{-1} + (1+r)^{j-t} (y_t - c_t) \right] \right] dD_k . \tag{4}$$

Willingness to pay at age j for a change in the conditional probability of death at age k equals the loss in expected utility from age $k + 1$ onward, converted to dollars by dividing by the marginal utility of income in year j, λ_j. Added to this is the effect of a change in D_k on the budget constraint. A reduction in D_k makes the individual wealthier by increasing the present value of his expected lifetime earnings from age $k + 1$ onward. An increase in survival probabilities, however, decreases the consumption that the person can afford in years $k + 1$ through T, and his WTP is reduced by the present value of this amount.

It should be emphasized that (4) is likely to constitute a lower bound to WTP. Because (2) does not include a term that values longevity per se, (4) does not reflect the pure value of living, including the utility received from time spent with friends and loved ones.

III. DISCOUNTING FUTURE WILLINGNESS TO PAY TO THE PRESENT

Since Eq. (4) holds for any $k \geq j$, it can be used to investigate the relationship between willingness to pay at age 20 for a change in probability of death at age 40 and willingness to pay at age 40 for the same risk reduction. $\mathrm{WTP}_{20,40}$ is simply $\mathrm{WTP}_{40,40}$ discounted to age 20, where the rate of discount in each year t is the rate at which the individual is willing to trade consumption in year t for consumption in year $t + 1$.

To see that this is so, rewrite (4) using the first-order conditions for utility maximization as

$$\mathrm{WTP}_{j,k} = \left[(1 - D_k)^{-1} \sum_{t=k+1}^{T} q_{j,t} (1+r)^{j-t} \left[U(c_t)/U'(c_t) + y_t - c_t \right] \right] dD_k . \tag{5}$$

Using the fact that $q_{j+1,t} = q_{j,t}/(1 - D_j)$, $\mathrm{WTP}_{j+1,k}$ can be written as

$$\mathrm{WTP}_{j+1,k} = (1 + R_j)\mathrm{WTP}_{j,k}. \tag{6}$$

Equation (6) implies that the rate at which WTP at age $j + 1$ for a given change in risk ($\mathrm{WTP}_{j+1,k}$) must be discounted to yield WTP at age j for the same change in risk ($\mathrm{WTP}_{j,k}$) is the actuarial rate of interest. The first-order conditions for utility maximization also imply that this equals the marginal rate of substitution between consumption at age $j + 1$ and consumption at age j,

$$1 + R_j = \frac{\mathrm{WTP}_{j+1,k}}{\mathrm{WTP}_{j,k}} = \frac{U'(c_j)}{U'(c_{j+1})}(1 - D_j)^{-1}(1 + \rho). \tag{7}$$

WTP is thus discounted at the consumption rate of interest, which we define to be the marginal rate of substitution between c_{t+1} and c_t, minus 1.[7] Repeated use of (7) implies that the discount factor $\Gamma_{j,k}$ applied to $\mathrm{WTP}_{k,k}$ to yield $\mathrm{WTP}_{j,k}$ is the product of the annual discount factors $1/(1 + R_t)$, $t = j, \ldots, k - 1$,

$$\mathrm{WTP}_{j,k} = \Gamma_{j,k}\mathrm{WTP}_{k,k}, \qquad \Gamma_{j,k} = \prod_{t=j}^{k-1} (1 + R_t)^{-1}. \tag{8}$$

The empirical significance of Eq. (8) is that, if one can extrapolate estimates of WTP for a change in conditional probability of death in the future ($\mathrm{WTP}_{k,k}$), from labor market or contingent valuation studies, then they can be discounted using (8) to estimate WTP today for the future risk change ($\mathrm{WTP}_{j,k}$). For this to be successful, however, estimates of WTP for a change in current conditional probability of death must be age-dependent and these estimates must be adjusted for cohort effects. Returning to Fig. 1, a CV study conducted in the year the road is built would estimate the value of a change in D_{40} to members of generation 1 ($\mathrm{WTP}_{40,40}$). Before this can be discounted to estimate the value at the beginning of period 1 of a change in D_{40} to persons in generation 2, one must adjust $\mathrm{WTP}_{40,40}$ for differences in lifetime earnings between generations 1 and 2.[8]

In Table I we show, under several different assumptions about individuals' borrowing opportunities, and for several illustrative ages, the rates at which future WTP would be discounted back to age 18. Under the assumption of perfect capital markets, factors that would be used to discount current WTP at various ages back to age 18 are given in the last column of Table I. These discount factors assume that the market rate of interest is 5% and use mortality rates (D_j) for white males.

[7]Adding a term of the form $\Sigma(1 + \rho)^{j-t}q_{j,t}$ to the utility function to reflect the pure utility of living does not alter Eq. (7).

[8]Given that this adjustment is necessary, the reader might suggest that persons in generation 1 be queried directly about their willingness to pay at the beginning of period 1 for a change in D_{40}. While in theory this is possible, one faces the problem of the individual being able to value "commodities" with which he is unfamiliar and being able to distinguish between risks occurring 10 versus 30 years into the future.

TABLE I
Discount Rates by Age, and Factors Used to Discount $\mathrm{WTP}_{k,k}$ to Age 18

Age	No net borrowing			Annuities case
	Wealth constraint binding		Wealth constraint not binding	
k	δ_k	$\Gamma_{18,k}$	$(1+r)^{18-k}$	$\Gamma_{18,k}$
18	0.124	1.000	1.000	1.000
20	0.119	0.793	0.907	0.904
25	0.106	0.462	0.711	0.701
30	0.093	0.286	0.557	0.545
35	0.082	0.187	0.436	0.424
40	0.050	0.136	0.342	0.328
45	0.050	0.107	0.268	0.253
50	0.050	0.084	0.210	0.193
55	0.050	0.066	0.164	0.144
60	0.050	0.051	0.129	0.105
65	0.050	0.040	0.101	0.074

Source. Solution to the lifetime consumption/saving problem described in the text, assuming $\rho = r = 0.05$.

IV. THE EFFECT OF CAPITAL MARKET IMPERFECTIONS ON DISCOUNT RATES

We now consider the possibility that actuarially fair annuities are not available, and see how this affects the rate at which WTP for a future risk is discounted to the present. When annuities are unavailable and the individual can never be a net borrower, the result that WTP for a future risk is discounted at the consumption rate of interest continues to hold. The consumption rate of interest, however, exceeds the market rate of interest if the individual's consumption is constrained by income, as is likely to be the case at the beginning of the life cycle.

Suppose that the individual can borrow and lend at the riskless rate r; however, to guarantee that he does not die insolvent, he is constrained to have nonnegative wealth at the beginning of each period, i.e., to never be a net borrower. This implies that the present discounted value of W_t be non-negative for each t,

$$W_j + \sum_{k=j}^{t} (y_k - c_k)(1+r)^{j-k} \geq 0, \qquad j < t \leq T. \tag{9}$$

While this assumption may seem restrictive, it can be justified by the fact that opportunities for unsecured borrowing are usually limited.

When (9) replaces (3), WTP at age j for a change in the conditional probability of dying at age k becomes

$$\mathrm{WTP}_{j,k} = \left[(1-D_k)^{-1}\left[U'(c_j)\right]^{-1} \sum_{t=k+1}^{T} (1+\rho)^{j-t} q_{j,t} U(c_t)\right] dD_k. \tag{10}$$

Equation (10) states that the value to a person at age j of reducing his conditional probability of death at age k is the expected utility he would lose if he died at age k, divided by the marginal utility of money at age j. The income and consumption terms in (4) no longer appear, since a change in D_k has no effect on the budget constraint.

Combining expression (10) evaluated at ages j and $j+1$ with the first-order conditions for utility maximization in the no-net-borrowing case yields the result that WTP for a future risk is discounted at the consumption rate of interest,

$$\frac{\mathrm{WTP}_{j+1,k}}{\mathrm{WTP}_{j,k}} = \frac{U'(c_j)}{U'(c_{j+1})}(1 - D_j)^{-1}(1 + \rho) = 1 + \delta_j. \tag{11}$$

If it is the case that the wealth constraint is not binding, then the consumption rate of interest equals the market rate of interest ($\delta_t = r$) and the discount factor, which is again denoted $\Gamma_{j,k}$, can be computed from market interest rates. Alternately, if the wealth constraint is binding, then obtaining discount rates δ_t by age is likely to prove more difficult. Although several studies [7, 22] have estimated individuals' discount rates, none of these presents discount rates by age. For this reason we shall examine the rate of which a rational individual discounts $\mathrm{WTP}_{k,k}$ back to age j by solving the individual's lifetime consumption/saving plan.

To illustrate possible values that δ_t and $\Gamma_{j,k}$ might assume, we have computed the solution to the life cycle consumption problem for the isoelastic utility function

$$U(c) = c^{\beta}, \qquad \beta = 0.2,^{9} \tag{12}$$

and a rate of time preference equal to the market rate of interest, which is assumed to be 0.05.[10] Lifetime earnings are assumed equal to the average 1979 earnings (measured in 1981 dollars) of white males with 1–3 years of college education [20]. These earnings, when combined with mortality rates for white males (U.S. Department of Health and Human Services, National Center for Health Statistics, 1980), imply that the individual's expected lifetime earnings, discounted to age 18, are approximately \$400,000. W_{18} is assumed equal to zero.

The set of discount rates $\{\delta_t\}$ implied by this solution and the corresponding factors $\Gamma_{18,k}$ that would be used to discount $\mathrm{WTP}_{k,k}$ back to age 18 appear in Table I. In Table I the wealth constraint is binding through the consumer's 37th year, and δ_{18} equals 0.124, which is almost 2.5 times the market rate of interest. The fact that discount rates are above the market rate of interest until age 38 causes the age-40 discount factor, $\Gamma_{18,40} = 0.136$, to be less than half the discount factor when the market rate of interest is used (0.342). Even at age 65 the factor used to discount willingness to pay back to age 18 is less than half what would obtain if the wealth constraint were never binding, $(1 + r)^{j-k}$.

Discount rates δ_t are quite sensitive to the individual's rate of time preference, ρ. Table II contrasts the $\{\delta_t\}$ implied by the solution to the life cycle consumption problem when the rate of time preference is 0.03, 0.05, and 0.07. When the rate of time preference is 0.03, consumption is limited by income through age 26 and

[9] This is the value of β used by Shepard and Zeckhauser [18, 19]. It is also consistent with empirical estimates of WTP based on labor market data and safety decisions [15, 23].

[10] A real rate of interest equal to 0.05 is consistent with the experience of the 1980s, although it may be high historically. Numerical results are presented for three alternative rates of time preference.

TABLE II
Discount Rates by Age for Alternative Rates of Time Preference, No-Net-Borrowing Case

k	δ_k		
	$\rho = 0.03$	$\rho = 0.05$	$\rho = 0.07$
18	0.103	0.124	0.146
20	0.098	0.119	0.141
25	0.085	0.106	0.127
30	0.050	0.093	0.114
35	0.050	0.081	0.101
40	0.050	0.050	0.089
45	0.050	0.050	0.078
50	0.050	0.050	0.050
55	0.050	0.050	0.050

Source. Solution to life cycle consumption saving problem described in text.

$\delta_{18} = 0.103$. When the rate of time preference is 0.07 the wealth constraint is binding until age 47 and $\delta_{18} = 0.146$.

These illustrations suggest that a 40-year-old's willingness to pay to reduce current risk of death would have to be discounted substantially to reflect an 18-year-old's willingness to pay to reduce his risk of death at age 40. In general, the magnitude of $\text{WTP}_{j,k}$ can be inferred from estimates of WTP to reduce current risk of death by persons of different ages ($\text{WTP}_{k,k}$). Jones-Lee *et al.* [9] and Jones-Lee [10] provide estimates of WTP for a current risk, by age, which in Table III have been discounted to age 18, using the discount factors in Table I. These computations suggest that $\text{WTP}_{18,40}$ is under \$300,000 (1985\$).

V. WTP IN AN OVERLAPPING GENERATIONS MODEL WITH ALTRUISTIC INDIVIDUALS

As Fuchs and Zeckhauser [7] have pointed out, the relationship between WTP today for a future risk and WTP in the future for a current risk is fundamentally different when the future risk is borne by members of another generation. The rate

TABLE III
Willingness to Pay at Age 18 for a Reduction in Risk of Death at Age k (Mil. 1985\$)

k	$\text{WTP}_{k,k}/dD_k$	$\text{WTP}_{18,k}/dD_k$
18	1.52	1.52
20	1.76	1.21
30	2.04	0.502
40	2.28	0.278
50	1.81	0.190
60	1.60	0.0928

Source. $\text{WTP}_{k,k}$ is the answer to question 18(b) of Jones-Lee *et al.* [9], converted to dollars using the 1985 exchange rate of £1 = \$1.30. $\text{WTP}_{18,k}$ was obtained by multiplying $\text{WTP}_{k,k}$ by the appropriate discount factor from Table I.

at which $\mathrm{WTP}_{k,k}$ should be discounted to yield $\mathrm{WTP}_{j,k}$, for a single individual can be answered by the individual himself. When j and k refer to different generations, the rate at which a future generation's WTP to increase its life expectancy should be discounted to the present necessarily involves questions of intergenerational equity. This discount rate is implicit in the social welfare function and the set of production possibilities confronting a social planner.

At least two approaches for incorporating the preferences of future generations in a social welfare function (SWF) have been taken. One view is that decisions regarding future generations should be based on the altruisitic preferences of the current generation. A second is that decisions regarding future generations should be based on a SWF that aggregates the preferences of each generation in an ethically acceptable way.

The first view was implicitly adopted by Sen [16, 17], Marglin [14], and other participants in the debate on the relationship between social and private discount rates. Regarding the second approach, there is a large literature on the implications of various ethical precepts for the form of the social welfare function. Paramount among these is that if one wishes to aggregate the preferences of members of an infinite number of generations into a social ordering that is complete and transitive, some discounting of future utilities must occur [4, 11]. Whether the utilities of future generations are discounted in the social welfare function or not, some discounting of future benefits will occur if opportunities for investing current resources are open to the social planner.

If the first approach is adopted—decisions regarding future generations are based on the altruistic preferences of the current generation—the rate at which benefits to future generations are discounted depends on the opportunities for borrowing and lending facing the current generation. To examine these further we adopt the framework of the overlapping generations model.[11] In this model each generation receives utility from its own consumption and that of its immediate descendants. Because this is true of all generations, the current generation necessarily takes into account the utilities of all future generations in making its consumption and bequest plans. We can, therefore, ask what a member of the current generation is willing to pay to increase the survival probabilities of his descendants t generations hence.

In the overlapping generations model each individual in generation t, $t = 0, 1, 2, \dots$, lives at most two periods. When he is young, which occurs with certainty, he earns income Y_t (the t subscript indexes generations) and consumes C_t^Y. If he reaches old age, which occurs with probability $1 - p_t$, he earns nothing more but consumes C_t^0. The individual chooses C_t^Y, C_t^0 and his bequest to the next generation, I_{t+1}, to maximize the present value of his utility and that of his child,[12]

$$V_t(W_t) = U(C_t^Y) + \alpha(1 - p_t)U(C_t^0) + \alpha\theta\left[(1 - p_t)V_{t+1}^A(W_{t+1}^A) + p_t V_{t+1}^D(W_{t+1}^D)\right] \tag{13}$$

[11] Support for this framework is provided by Kotlikoff and Summers [13] who claim that "intergenerational transfers account for the vast majority of aggregate U.S. capital formation" (p. 706).

[12] For simplicity, there is exactly one person per family per generation. Members of generation $t + 1$ are born at the end of their parents' youth. I_{t+1} is transferred to them at that time whether or not their parents live to old age.

subject to (14) and (15)

$$W_{t+1}^{A} = Y_{t+1} + (1+r)W_t - (1+r)C_t^{Y} - C_t^{0} \tag{14}$$

$$W_{t+1}^{D} = Y_{t+1} + (1+r)W_t - (1+r)C_t^{Y}, \tag{15}$$

where $W_t = Y_t + I_t$, and the superscripts A and D indicate whether the person in generation t lives to old age or dies at the end of his youth. θ is a weight attached to descendant's utility and $\alpha = 1/(1+\rho)$. When annuities markets do not exist, the amount that generation i is willing to pay at birth for a small change in p_t is given by

$$\mathrm{WTP}_{t,t} = \frac{\alpha U(C_t^0)}{V'_t(W_t)} + \frac{\alpha\theta(V_{t+1}^{A} - V_{t+1}^{D})}{V'_t(W_t)}. \tag{16}$$

The first term in (16), the utility enjoyed during old age, divided by the marginal utility of wealth, is analogous to (10). The second term indicates that altruism for one's descendants increases WTP if one's heirs would be better off if one were alive than dead, and reduces WTP if the converse holds.

The amount that generation 0 is willing to pay for a change in p_t is the expected value of (16) discounted to the present at the market rate of interest,

$$\mathrm{WTP}_{0,t} = (1+r)^{-t}\,\frac{\alpha EU(C_t^0) + \alpha\theta E(V_{t+1}^{A} - V_{t+1}^{D})}{EV'_t(W_t)}. \tag{17}$$

Expected values appear in (17) since C_t^0, W_t, W_{t+1}^{A}, and W_{t+1}^{D} are random from the viewpoint of the present generation. The main difference between (17) and its counterpart in the single-generation case [Eq. (10)] concerns the rate at which future WTP is discounted. When discounting to age 18 the amount an individual would pay at age 40 for a change in his conditional probability of death at age 40, the rate of discount is the rate at which the individual substitutes consumption at age 40 for consumption at age 18. This may or may not equal the market rate of interest. When discounting WTP from one generation to another, the rate of discount implied by the model is the rate at which each generation is willing to substitute current consumption for a bequest.

An interesting implication of (17) is that the present generation's WTP on behalf of generation t should be higher the better off generation t is. It may seem surprising that the present generation should worry so much about risks to its descendants if those descendants may be better off than the current generation; however, one must remember that in the model (and, possibly, in reality) the current generation will leave less to future generations in the form of a bequest the higher the incomes of future generations are thought to be.[13] Thus, although

[13]Formally, I_{t+1} is a decreasing function of Y_{t+1}.

Period	1	2	3
Generation 1	-		
Generation 2	-	ΔD_{40}	
Generation 3		-	ΔD_{40}

FIG. 2. Changes in the conditional probability of death at age t (D_t) due to asbestos removal, assuming a 20-year latency period. Each period is 20 years long. Persons live for at most two periods. They are 20 at the beginning of the first period of their lives and 40 at the beginning of the second period.

generation 0's WTP to reduce risks to generation t depends on generation t's consumption, generation 0 influences that consumption through the size of its bequest.

VI. THE EFFECT OF A LATENCY PERIOD ON RISK VALUATION

We now use the preceding results to evaluate the benefits of reducing exposure to a carcinogen, such as asbestos, which involves a lag (latency period) between exposure and effect. To illustrate the implications of a latency period, Fig. 2 presents schematically the benefits of eliminating asbestos in buildings at the beginning of period 1. This reduces the exposure to asbestos of persons in the current and in all future generations. The difference between Figs. 1 and 2, however, is that asbestos is assumed to have a 20-year latency period. Since members of each generation are assumed to live for at most two 20-year periods, this implies that a reduction in exposure at the beginning of the second period of life has no life-saving effects, and that a reduction in exposure at the beginning of the first period of life reduces the probability of dying only at the beginning of the second period.

A comparison of Figs. 1 and 2 indicates that, assuming equal changes in the D_j's, fewer expected life years are saved in the case of asbestos removal than in the case of road safety. This fact, however, is often ignored in risk–benefit analyses. An example of failure to take a latency period into account is EPA's analysis of the benefits of prohibiting the manufacture of certain asbestos-containing products under Toxic Substances Control Act (TSCA) [22]. In analyzing the benefits of these programs, EPA assumed that the reduction in risk began on the date of exposure rather than at the end of the latency period. Assuming that 40 is the average age of exposure, this is equivalent to valuing lives saved using $\mathrm{WTP}_{40,40}$. If, however, asbestos does not result in cancer until 20 years after exposure, and if the average age of persons currently exposed is 40, then it may be preferable to value the program by discounting $\mathrm{WTP}_{60,60}$ back to the present rather than using $\mathrm{WTP}_{40,40}$.

It should be emphasized that the difference between $\mathrm{WTP}_{60,60}$, discounted to the present, and $\mathrm{WTP}_{40,40}$ is the result of two factors: discounting, and the fact that, because of the latency period, only life years after age 60 are saved by asbestos removal. To gauge the relative importance of these two factors, note from Table III that $WTP_{60,60}$ is 70% of $WTP_{40,40}$. Thus, even with a zero discount rate, a 20-year latency period reduces WTP by 30%. If the discount factor $\Gamma_{40,60}$, computed using $\delta_t = 0.05$, is applied to $WTP_{60,60}$, WTP is reduced by 74%.

VII. CONCLUSIONS

Numerous policies, such as those to control exposure to carcinogens or make the disposal of toxic waste safer, can have a lagged effect, so that at least some of the impacts are borne by current generations at some future date and by future generations. In this paper we have viewed risk changes—both to current and future generations—from the perspective of the current generation.

To evaluate risks that occur in the future to members of the current generation, we have constructed a life cycle model of willingness to pay and compared the amount an individual is willing to pay today at age j for a reduction in future risk at age k ($WTP_{j,k}$), with the amount an individual would be willing to pay for a reduction in current risk at age k, $WTP_{k,k}$. A comparison of $WTP_{j,k}$ with $WTP_{k,k}$ indicates that the amount an individual is willing to pay today to reduce future risk equals the amount the same individual would be willing to pay in the future for a reduction in current risk, discounted back to the present. The discount rate in each intermediate period t is the rate at which the individual is willing to trade consumption in year $t + 1$ for consumption in year t. This will equal the actuarial rate of interest whenever the individual can invest in annuities and borrow via life-insured loans. If the individual can lend at the market rate of interest, but can never be a net borrower, the consumption rate of discount equals the market rate of interest if the wealth constraint is not binding, but exceeds it when current consumption is constrained by income.

Using data on earnings and mortality rates and solving the model for an isoelastic utility function suggests that, in the no-net-borrowing case, if the rate of time preference equals the market rate of interest (assumed to be 0.05), the individual's consumption is constrained by income prior to age 38. For risks occurring more than 10 years into the future, the discount factor at age 18 is less than half the discount factor using a market interest rate of 0.05. For example, $WTP_{18,60}$ is approximately one-twentieth $WTP_{60,60}$; a discount rate of 0.05 would imply a discount factor greater than one-tenth. Using an empirical estimate of $WTP_{60,60}$ equal to 1.60 million (1985$) suggests that willingness to pay at age 18 for risk at age 60 may be as low as 93,600 (1985$).

The impact on willingness to pay of a latency period may also be estimated using the life cycle model. When valuing a reduction in exposure to asbestos at age 40, the appropriate benefit measure, assuming a 20-year latency period, is what the individual would pay at age 60 for a reduction in current risk of death ($WTP_{60,60}$) discounted to age 40 at the consumption rate of interest. This is lower than willingness to pay at age 40 for a reduction in current risk of death ($WTP_{40,40}$) for two reasons: (1) $WTP_{60,60}$ is less than $WTP_{40,40}$ because fewer expected life years are at risk in the former case; (2) $WTP_{60,60}$ is discounted to the present.

A final issue that we address is the problem of valuing risks to future generations. If one asks an altruistic member of the present generation what he would pay for a change in the survival probability of one of his descendants t generations hence, his answer is likely to be "what the descendant himself would pay, discounted to the present." The appropriate discount rate in this case is the rate at which generation i is willing to substitute consumption for a bequest to its immediate descendants.

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