Health Physics Vol. 45, No. 3 (September), pp. 687–697, 1983
Printed in the U.S.A.

0017–9078/83 $3.00 + .00

Pergamon Press Ltd.

DISCOUNTING IN ASSESSMENT OF FUTURE RADIATION EFFECTS

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(*Received* 2 *April* 1982; *accepted* 1 *November* 1982)

Abstract—There is a question as to whether cancer fatalities to be experienced in the distant future as a result of radioactivity produced today should be treated on a par with those experienced now, or whether there should be discounting in analogy with accounting principles for money to be spent in the future. It is shown that recent trends in cancer cure rates justify about an 0.7% per yr discounting. Other rationales for discounting are developed. Money can, and always will be usable for saving lives; setting up a trust fund for future generations to use for this purpose is much more cost-effective than spending money now to reduce their exposure to radiation. The history of interest rates over the past 5000 yr indicates that at least 3% real annual interest can be expected. It may not be necessary to actually set up a trust fund as its purpose is largely accomplished by the decrease in the public debt when money is not spent. The trust fund approach is mathematically equivalent to discounting lives lost in the far future at 3% per yr. As an alternative to the trust fund, money can be invested in biomedical research. It is shown that per dollar spent, this is usually far more beneficial to the health of future generations than protecting them from radiation as that art is currently practiced, and for purposes of cost-benefit analysis, it corresponds to discounting lives lost in the future by a factor of the order of the number of years before they are lost; e.g. the number of lives calculated to be lost 1000 yr from now should be divided by 1000. Implementation of the biomedical research alternative requires only that about 0.1% of taxes from nuclear plants and 0.1% of government support for biomedical research be re-defined as contributions from nuclear plants to this research.

INTRODUCTION

Some of the health effects of radiation that are currently receiving a great deal of attention will not be realized until far into the future. For example, the effects of ^{14}C releases from reactors and reprocessing plants are often integrated over its 5700-yr half-life, health impacts of radon emissions from uranium ore-processing mill tailings are usually integrated over the 77,000 yr half-life of its ^{230}Th parent, and consequences of radioactivity releases from high-level waste repositories are customarily integrated over hundreds of thousands, or even millions of years. This raises the question as to whether some form of discounting is in order to take account of the long time delays before the price in human health is to be paid.

Discounting is certainly routine practice in matters involving money. For example, in determining the cost of building a plant, the full cost of decommissioning it 40 yr in the future is not included, but rather this cost is divided by $(1 + r)^{40}$ where r is an assumed after-inflation annual interest rate. This typically reduces the present cost by a factor of four, often making it negligible. This practice is clearly justified by the fact that one dollar invested now in any of a number of readily available financial instruments can be expected to yield something like four dollars in true value after 40 yr.

However, when dealing with human lives to be lost due to radiation effects, the problem is much more complicated. There is no obvious analogy with human lives to the way in which money draws interest. In addition approaches to the problem have generally been very crude. For example, it is often stated that we need only consider effects "in our time". This is variously interpreted as extending anywhere from 50 to 1000 yr into the future, with a clear tendency for this extent to increase over the last two decades. It now seems to be fashionable in government documents to integrate effects over 500 yr, but little or no justification for this proceeding is offered. And the morality of not caring about what happens after 500 yr is never discussed.

The purpose of this paper is to consider the rationales for this type of procedure, and to thereby improve upon it. It should be recognized that these are basic problems in health physics practice that have not been, and cannot be avoided. They are also relatively unique to health physics; in no other area do such far-future effects enter so directly into present day decision-making.

If effects occur at a rate R per yr, discounting at an annual rate r gives $R(1-r)^t$ effects in year t. But $(1-r)^t$ is mathematically equal to $\exp(t \cdot \ln(1-r))$, and for $r \ll 1$, $\ln(1-r) \approx -r$, so the number of effects in year t is Re^{-rt}. The total number of effects eventually expected is then

$$\int_0^\infty \mathrm{Re}^{-rt} \mathrm{d}t = R/r.$$

If we do no discounting, but add up effects only over T yr, the total number of effects is RT, so this is equivalent to an infinite integration with a discount rate

$$r = 1/T.$$

Thus, current practice in government documents amounts to discounting future fatalities at a rate of 0.2% per yr.

One place where discounting seems to be obviously applicable but is not used is in effects of occupational exposure. It is common practice to compare the cancer risk from occupational radiation with those from fatal occupational accidents on a one-to-one basis. Death from radiation exposure is typically delayed by about 25 yr, and it would surely be preferable to die 25 yr in the future rather than instantly.

In fact, for any person of working age, the next 25 yr represents over half of the value left in his life. It would therefore be much more realistic to compare fatal cancers from radiation exposure with fatal accidents on a 2 for 1, or 3 for 1 basis. These would correspond to a 3% or 4.5% annual discounting.

Similar arguments would apply when comparing risks to the public from accidents and from radiation. In practice, however, our society is spending orders of magnitude more money to save a life from radiation than from accidents (Co80), which would seem to be highly irrational.

However this paper is largely intended to deal with time periods much longer than a human lifetime. It develops rationales for adopting a discounting practice in assessing far-future consequences of the radioactivity produced in today's nuclear plants. Three separate rationales are presented and quantitative results are obtained for each in the following three sections. A brief qualitative presentation was offered previously (Co80).

IMPROVEMENTS IN CANCER CURE RATES

Since the probability for a cancer to be "cured" is improving with time, a cancer developing in the future is less likely to be fatal than a cancer developing today. This should certainly be taken into account in calculating health impacts of our radiation on future generations, but this is never done. To compensate for this oversight, it is reasonable to apply discounting to lives calculated to be lost in the future.

Relative 5-yr survival percentages for various types of cancer—the ratios of the number surviving 5 yr after diagnosis to the number normally expected to survive for their age distribution—are listed in Table 1 for various time periods of diagnosis (My80; Ax73). The data for 1940–64 (Ax73) are derived from a larger number of hospitals than those for 1960–73, and absolute survival rates can vary between hospitals because of differing patterns of patient referral, so com-

Table 1(a). Percentages of white male patients surviving 5 yr after diagnosis of various types of cancer as compared with normally expected survival (if no cancer)

site	1940-49	1950-59	1960-64	1960-63	1970-73
Lip	87	88	87	84	87
Tongue	24	30	25	23	32
Salivary gland	73	79	-	55	53
Mouth	40	42	40	42	40
Pharynx	16	20	21	21	27
Esophagus	1	3	3	4	4
Stomach	9	12	10	10	12
Colon	29	42	43	42	47
Rectum	26	38	38	36	43
Liver	1	0	2	1	2
Gallbladder and Ducts	4	7	6	6	7
Pancreas	1	1	1	1	2
Nasal Cavity/Middle Ear	22	38	44	39	48
Larynx	41	56	54	54	63
Lung and Bronchus	3	7	8	7	9
Bone	25	32	33	31	38
Soft Tissue	43	50	43	41	52
Melanoma of the Skin	32	51	53	51	62
Prostate gland	37	47	52	50	63
Testis	51	61	65	63	72
Penis	53	68	70	62	56
Urinary Bladder	41	55	57	53	61
Kidney	26	32	37	36	44
Eye	68	75	83	81	78
Brain/Cent.Nerv.Syst.	20	22	25	16	18
Thyroid	51	70	78	75	82
Hodgkin's Disease	21	31	38	34	66
Non-Hodgkin's Lymphoma	23	26	31	31	39
Multiple Myeloma	8	6	11	13	20
Lymphocytic Leukemia					
Acute	0	0	2	4	27
Chronic	22	33	33	29	46
Granulocytic Leukemia					
Acute	1	1	1	2	3
Crhonic	5	9	12	13	18
Monocytic Leukemia	0	2	1	1	3

parisons are really only appropriate within these two groups.

The data in Table 1 show a clear pattern of survival rates improving with time. For example, between the early 1960s and the early 1970s, male survival for all listed cancer types improved from 31.2% to 36.9%, and female survival increased from 47.3 to 51.9%. Omitting the largest single contributors, lung cancer in males and breast cancer in females, survival improved from 36.8 to 44.9% for males, and from 41.5 to 45.6% in females.

From these statistics, we see that the probability of dying from a cancer within 5 yr after diagnosis was reduced by about 10% over this 10 yr time period (roughly from 61 to 55%). Since progress has been uneven among the different cancer types and it is difficult to predict where advances will come next, it might be more relevant to average over the improvements for them without weighting by the number of cases: with this procedure, the reduction in mortality probability over the 10 yr time period averages 10.5% for males and 10.0% for females.

We thus conclude that the risk of dying from a cancer once it has appeared has been decreasing at a rate of 1% per yr. If this rate continues, it will be reduced to 81% of its present value after 20 yr, 66% after 40 yr, 35% after 100 yr, 12% after 200 yr, etc.

Since we are primarily interested in radiation effects, it may be preferable to give special consideration to the types of cancer usually associated with radiation. The relevant data for whole-body low-LET radiation, averaged between males and females, are given in Table 2. Col. 2 lists the BEIR Report estimates of risks of each cancer type (Co81) as a percentage of total cancers from whole-body radiation, and Col. 3 gives the percentage reduction in 5 yr mortality from 1960–63

Table 1(b). Percentages of white female patients surviving 5 yr after diagnosis of various types of cancer as compared with normally expected survival (if no cancer)

	1940–49	1950–59	1960–64	1960–63	1970–73
Lip	85	89	83	88	Too few cases
Tongue	45	48	46	44	46
Salivary gland	86	91	-	82	85
Mouth	46	52	52	50	51
Pharynx	26	29	34	35	31
Esophagus	5	7	6	6	4
Stomach	9	13	14	13	14
Colon	35	46	47	44	50
Rectum	33	42	42	41	48
Liver	4	3	7	3	6
Gallbladder and Ducts	3	5	9	9	9
Pancreas	2	2	2	2	2
Nasal Cavity/Middle Ear	33	46	39	44	50
Larynx	37	57	50	46	56
Lung and Bronchus	8	11	12	11	14
Bone	26	38	36	31	36
Soft Tissue	52	58	51	54	54
Melanoma of the Skin	49	60	72	68	75
Breast	53	60	63	63	68
Uterine Cervix	47	59	59	58	64
Uterine Corpus	61	71	72	73	81
Ovary	25	29	34	32	36
Vagina	26	40	34	37	44
Vulva	55	66	62	64	66
Urinary Bladder	44	53	56	53	60
Kidney	27	36	38	39	50
Eye	73	80	75	74	77
Brain/Cent.Nerv.Syst.	29	28	36	21	22
Thyroid	69	83	87	87	87
Hodgkin's Disease	29	38	48	48	69
Non-Hodgkin's Lymphoma	23	30	28	31	43
Multiple Myeloma	7	8	10	10	17
Lymphocytic Leukemia					
Acute	0	1	3	3	29
Chronic	28	39	43	46	59
Granulocytic Leukemia					
Acute	1	9	1	0	2
Chronic	8	12	12	11	19
Monocytic Leukemia	3	0	2	1	4

Table 2. Decrease in mortality from 1960–63 to 1970–73 for cancers induced by radiation. Col. 2 is the percentage of all fatal cancers induced by low-LET whole-body radiation that are of the type indicated (Co81). Col. 3 is the percentage decrease in mortality within 5 yr after diagnosis over the 10 yr period from Table 1. All data are averaged between male and female. All leukemia types other than chronic lymphocytic were given equal weight

Cancer Type	% of Total	% decrease	Cancer Type	% of Total	% decrease
leukemia	19	9	liver	5	2
thyroid	6	14	pancreas	7	1
breast	9	14	urinary	3	16
lung	23	3	lymphoma	2	15
esophagus	2	-1	bone	1	8
stomach	10	2	other	10	10
intestine	5	10	Weighted average ...		7.1

to 1970–73 from Table 1. The average of Col. 3 weighted by Col. 2 is a 7.1% reduction over the 10-yr period. This implies that mortality from cancers induced by whole-body radiation was being reduced at a rate of 0.7% per yr during the past decade or so.

Progress in fighting cancer shifts rapidly and irregularly from one cancer type to another, and it is difficult to predict whether future progress in the types listed in Table 2 will continue as in the past or will be more like the average of all sites listed in Table 1. It is probably even more likely that progress will slow down and stagnate after a few decades, or that there will be major research break-throughs which lead to much more rapid progress.

As a compromise among these speculations, I would propose assuming a continuing 0.7%-per-yr reduction in mortality rates from radiation-induced cancer. This means that in estimating the effects of our radioactivity releases on future generations, we should discount the calculated fatality rates at a rate of 0.7% per yr back to the present time. The number of fatalities calculated to occur 50 yr in the future should then be multiplied by $(0.993)^{50} = 0.7$, and reduction factors for 100 and 200 yr in the future would be 0.5 and 0.25. Of course, the speculative aspects of this procedure increase as the time gets longer.

DISCOUNTING VIA THE "TRUST FUND" CONCEPT

In the remainder of this paper, it is assumed that the radioactivity we produce actually will cause premature mortality in future populations in accordance with our risk analysis calculations, so the effects to be discussed are in addition to those of the last section. There is certainly no moral or ethical justification for assuming that the life of a future individual is less valuable than that of a person now living, so discounting cannot be condoned on that basis. The rationales we develop depend, rather, on complex chains or reasoning.

One approach to improving the health of future generations, which we will refer to as the "present method", involves spending money *now* to reduce their exposure to radiation, as by developing super-safe high-level waste repositories, installing equipment to reduce ^{14}C emissions, or putting very elaborate covers on uranium mill-tailing piles to reduce their radon emissions. As a device for aiding our chain of reasoning, we introduce an alternative "trust fund" approach which, for the present, we characterize as setting up a trust fund that future generations can use for life-saving purposes.

The trust fund concept is meaningful only if money can be used to save lives, so let us review the evidence on that point.

In the U.S., well-to-do people have 4 yr longer life expectancy than poor people, and those at the top of the economic ladder have an additional 3 yr more than the former (Co79). On an international basis life expectancy in prosperous countries is 10–30 yr longer than in poor countries. Compared to the rest of the U.S. population, poor people have 70% higher mortality rates from influenza and suicide, 50% higher mortality rates from cerebrovascular disease and accidents, and 20% higher mortality rates from cancer and diabetes. Whites living in poverty areas have a 50% higher infant-mortality rate than those living in non-poverty areas of cities (HEW76).

To address the point more directly, a recent study (Co80) found that many thousands of American lives can be saved each year at a cost below $100,000 each by specific medical screening, medical care, and highway safety programs. Far larger numbers overseas could be saved for less than $5000 each with programs such as food for India and immunization against diphtheria, pertussia, tetanus and tuberculosis in Indonesia. Clearly wealth is exchangeable for health in many ways, and in view of the present situation, it seems conservative to assume that it will always be possible to save lives for a cost in present dollars of $1 M each.

One advantage of the trust fund approach is that it will be much easier for a future population to decide how best to spend money in the interest of their health than for us to do so. For example, we are spending money to protect them from cancer, acting on the assumption that the linear-no threshold dose-response relationship is applicable. But perhaps it will be proven that there is a threshold for radiation-induced cancer, or perhaps cancer will become a curable disease. In either of these cases, the money we are spending to protect them will be wasted. Clearly, future generations will be in a much better position than we are to decide how best to spend money to protect their health.

Of course there can be advantages in the present method over the trust fund. If it will be so important for future generations to reduce their exposure to ^{14}C that they will set up equipment to remove it from the air, it would obviously be far more efficient for us now to provide equipment that prevents its release from our plants. Or if we build a waste repository that will leak so badly as to require frequent expensive remedial action by future generations it would surely be more efficient for us to spend now to avoid those problems.

In comparing the advantages of the present and the trust fund methods there is one other important element to be taken into account. In the latter, the money we bequest to future generations to benefit their health includes interest accrued up to its time of use. Since we are dealing with money, there can be no question but that interest should be credited, and when dealing with multi-century time periods it can be very substantial: factors by which the original deposit is multiplied for various interest rates and time periods are listed in Table 3.

It is relevant here to consider what interest rates can be anticipated during the next several centuries or millenia. Some insight can be gained from a study of the history of interest rates over similar time periods in the past (Ho77). Data on this are shown in Fig. 1 where we see that there is an essentially continuous history of interest going back 5000 yr. Government bonds paying regular interest have been available in all advanced countries for 200 yr or more. The principal pattern in interest rates is the obvious one that they are lower in times of stability and higher when there is societal disruption.

In recent years, inflation has been an important factor, but this was not the case prior to 1930 since currencies were generally tied to the gold standard. Judging from Fig. 1, it seems reasonable to assume that future interest rates will average at least 3% per yr over the next several centuries.

From the moral-ethical standpoint, there can be no question but that the proper procedure is to spend money so as to deliver the maximum life-saving benefit to future generations. With this in mind, the next item on our agenda is to choose between the present method and the trust fund method on that basis. This should be done independently on each item considered; but in essentially all practical situations, there is no contest between the two. The trust fund approach has a large advantage as long as anything approaching present standards of care is exercised. This is demonstrated in Appendix A for several examples. If we are to be guided by morality, then, the trust fund method should be used.

One might worry about the complications

Table 3. Factors by which the original deposit is multiplied after a given number of years by a given annual interest rate

years Int. rate	100	300	600	1000	2000
1%	2.7	20	400	21,000	4×10^{8}
2%	7.4	400	160,000	4×10^{8}	
3%	19	7000	5×10^{6}	6×10^{12}	
5%	130	2.3×10^{6}	5×10^{12}		

of setting up a trust fund and collecting and reinvesting interest over many centuries, but we now demonstrate that this may not be necessary. It would be natural for such a trust fund to be managed by the government and invested in government bonds. But this is just taking money out of one pocket and putting it into another. It would be completely equivalent financially for the government to use this money for its operations and reduce its debt by that amount. As a result of this action, future generations will have that money (plus the interest it would have cost) available for life-saving activities instead of having to spend it to maintain and/or pay off the public debt. We therefore conclude that if the money is given to the government, the trust fund process is effectively accomplished. It might be worth passing a resolution down to future generations indicating that this money is to be used for life-saving activities, but this is a trivial detail.

If a utility saves money by not spending it to reduce radioactivity releases, where does this money go? The largest utilities are publicly owned, and for them it goes directly to the government. If the utility is private, it increases profits and about 30% of these increased profits go to the government in taxes. The rest is distributed to the public, increasing its ability to pay taxes. Presumably, government taxes the public to the limit of its ability to pay—otherwise how can it justify taxing future generations through the national debt? Eventually, by one process or another, an appreciable fraction of the money saved goes to the government. Whether it is 25, 50

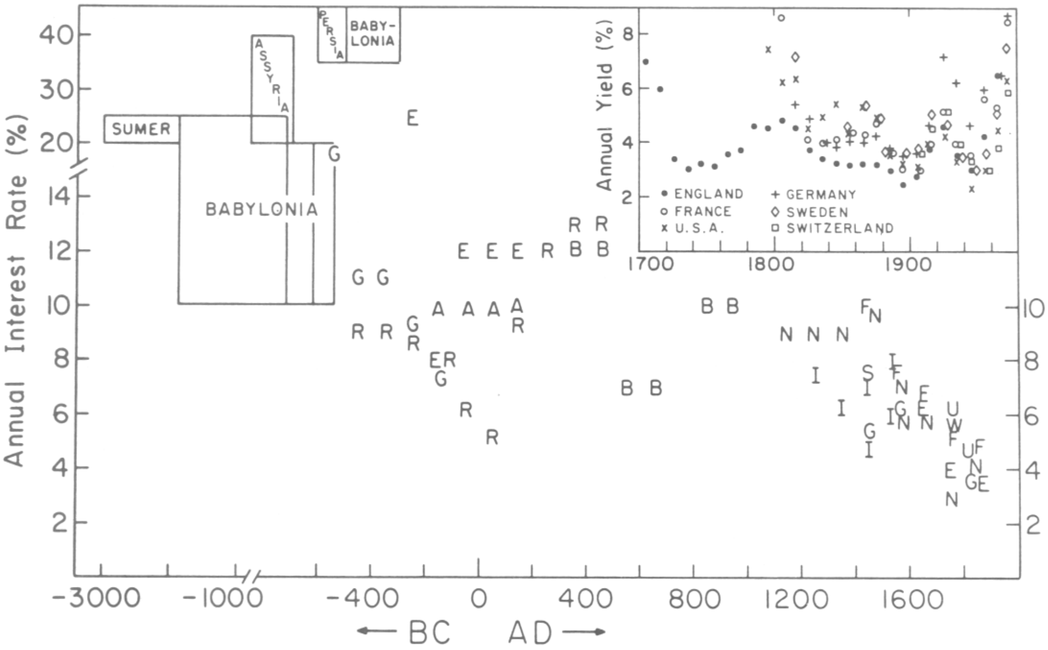

FIG. 1. Interest rates in various countries during various time periods. In all cases data are for the longest term and most secure loans available. Letters correspond to countries as follows up to 1000 AD: G–Greece, R–Rome, E–Egypt, A–Roman Asia, B–Byzantine; after 1000 AD, N–Netherlands, I–Italy (or parts of what is modern Italy), F–France, S–Spain, E–England, G–Germany, U–U.S., W–Sweden. Inset is the average annual *yield* on long-term government bonds, averaged over 10 yr periods (except last point which is averaged over 1970–75).

or 100% is not really important because our considerations are of an order-of-magnitude nature.

Our overall conclusion is, then, that when money in *not* spent to avert radiation exposure to future generations, some of it is effectively being put into a trust fund for them to use.

For example, if \$1M is given to the government instead of being spent, the national debt is immediately reduced by \$1M. If the government pays 3.5% real interest on its debt, which corresponds to a 20-yr doubling time, the national debt 100 yr from now will be $2 \times 2 \times 2 \times 2 \times 2 \times \$1M$ less. Alternatively, if a trust fund were set up with \$1M now, at 100 yr from now it would be worth \$32M. In either case, an extra \$32M is available. Thus, not spending government money, and putting money in a trust fund to be used by the government, are completely equivalent. In either case, there is an extra \$32M available to spend, leaving the debt the same as it would have been if no action had been taken.

One bothersome aspect of the trust fund approach as it has been presented is that it requires faith in the government to act responsibly over a long time period. However, to a large extent, its failure to do so is automatically compensated. For example, if the government uses inflation to reduce it debt, or arbitrarily cancels part of its debt, interest rates rise to compensate. If future governments decide to use this money for other purposes than for life saving, those who suffer from our radioactivity releases should blame them rather than us. However, some might consider this to be a fatal flaw in the trust fund approach, in which case they must fall back on the other approaches suggested in this paper.

One last point remains to complete our chain of reasoning, namely to show that the trust fund approach is equivalent to discounting lives lost. Suppose we can pay X dollars for device A which will save N lives in our generation, or Y dollars for device B which will save N lives in future generations, and we do a cost-benefit analysis for each. We have shown that the ethical procedure is to use the trust fund approach, and in doing so we include accrued interest in evaluating B, which introduces a multiplier m. The cost-per-life saved is then mY/N for B, and X/N for A. But the former is mathematically equivalent to not including interest (the usual procedure) but discounting the number of lives saved to N/m; the cost-per-life saved still comes out mY/N.

Our final conclusion from this section, then, is that in decision making by cost-benefit analysis, it is proper, moral and ethical to discount lives lost in the far future back to the present time at an interest rate something like 3% per yr. Not to discount, or to discount at a much lower rate such as the 0.2% used in government reports, is immoral, since it will result in unnecessary loss of life.

THE BIOMEDICAL RESEARCH ALTERNATIVE

One might object to the trust fund approach because it is not specifically directed toward saving lives. One could insist that if we are damaging the health of future generations, we can only compensate by acting directly to improve their health. One obvious method for doing this is by increasing our efforts in biomedical research.

From a rather elaborate regression-analysis study, Muskin (Mu79) concluded that for each 1% added input into biomedical research between 1900–75, age adjusted mortality rates dropped by 0.1%; for biomedical research between 1930 and 1975, the decrease in the age-adjusted mortality rate was 0.05%. The total U.S. expenditure on biomedical research in the latter period was \$68 billion (all costs here are in 1975 dollars), so the 1% corresponds to an added \$680 million spent. Present U.S. mortality is about 2×10^6/yr, so an 0.05% decrease represents averting 1000 fatalities/yr. This research is, therefore, now saving 1 life/yr for each \$600,000 spent. (Expenditures between 1900 and 1930 were only \$310 million and they were averting about an equal number of fatalities, so they were more than 200 times more cost effective, saving 1 life/yr for every \$3000 spent!)

Mushkin also interprets a study by Auster *et al.* (Au69) as concluding that research between 1955 and 1965 decreased age-adjusted mortality rates by 5%. Expenditures in this period were \$20 billion, and a 5% reduction in mortality rates represents a saving of 100,000 lives/yr. According to that study, then, 1 life/yr is being saved for every \$200,000 spent in the 1960 era.

If one does not trust complex analyses, a rough estimate can be derived from noting that age-adjusted U.S. mortality rates have been declining by about 1% per yr, and crudely estimating that 25% of this is due to biomedical research. Each year's advances then save $(2 \times 10^6 \times 0.01 \times 0.25 =)$ 5000 lives/yr. Recent annual expenditures have been about \$5 billion, which corresponds to saving 1 life/yr for each \$1M spent.

While these other analyses contribute confidence that no large errors are being made, the best analysis is probably the Mushkin estimate, which reduces to 1 life/yr saved for each \$680,000 spent between 1930 and 1975. It may now be an order-of-magnitude more difficult to save lives through biomedical research than in that time period, and there has been inflation since 1975, so perhaps the present cost is as high as \$10M for each life-per-year saved. On the other hand, American research saves lives in other countries to a much larger extent than their research saves lives here, and a large fraction of biomedical research can be credited to relieving various forms of human suffering that are not connected with mortality. Each of these considerations reduce the cost for each life/yr saved by a substantial factor.

For purposes of discussion, it is necessary to pick a single value, so we will hereafter assume that one extra life/yr can be saved for each \$4 million invested in biomedical research. From the above discussion, this would seem to be a very conservative estimate. It is extremely important here to recognize that this in *not* the cost to save one life, but rather it is the one time cost to save one life *per year* indefinitely into the future.

To continue the discussion we need a value for cost-per-life saved to be spent on equipment to reduce radiation exposure in the immediate future, although the results are not very sensitive to that value. The natural choice would be to base it on the NRC requirement (NRC76) that equipment to reduce radioactivity exposure be installed if it costs less than \$1000/man-rem averted. With the BEIR Report (NAS80) estimate of 120×10^{-6} fatal cancers per man-rem, this corresponds to $(\$1000/120 \times 10^{-6} =)$ \$8M to save one life.

If this life is saved T years in the future, putting the \$8 million into medical research would save 2 lives/yr, a total of $2T$ lives up to year T. Thus, the number of lives saved by choosing the research alternative is increased by a factor $2T$, so it is obviously more cost effective. It is equivalent to drawing 200% annual simple interest.

Consider a practical example where we are trying to decide whether to add a \$4-million piece of equipment to reduce radioactivity releases which would otherwise cause fatalities 200 yr in the future. By contributing this \$4 million to biomedical research, it will save 1 life/yr or 200 lives over the next 200 yr, costing $(4 \times 10^6/200 =)$ \$20,000/life saved. It would therefore be better to do this than to install the equipment unless the latter saves lives for \$20,000 or less. However, if that equipment would save lives now, it would be installed if it costs \$8 million per life saved. In doing cost-benefit analysis, it is therefore worth 400 times more to save a life now than 200 yr in the future. Effectively, lives lost T years in the future are discounted by a factor $2T$.

It could be argued that the NRC requirement of \$8 million per life saved is unreasonably high and that our argument is invalid because it compares a reasonable approach to averting future fatalities with an unreasonable one to averting fatalities now. However, the results are not very sensitive to the \$8-million-per-life-saved assumption. If we had used \$1-million-per-life-saved instead, the advantage of the medical research would be reduced from a factor of 400 to a factor of 50. In general, the discount factor would be reduced from $2T$ to $1/4T$.

Regardless of how we choose our estimates, the discount factor is of the order of T, the number of years before the fatalities materialize. That is because the cost of research to save 1 life/yr and society's willingness to spend money to save a single life are both of the same order of magnitude, probably well under \$1M and conservatively a few million dollars.

One might be bothered by the complicated implementation of a plan whereby nuclear plants contribute to biomedical research, but actually such a plan is not necessary. The total contribution from a plant should be a few hundred thousands dollars, which is something like 0.1% of the amount it pays the government in taxes, and the sum of these contributions from all plants would then represent about 0.1% of the amount government now contributes to biomedical research. The entire matter could, therefore, be handled by a statement that 0.1% of the taxes are redefined as contributions to the government's program of support for biomedical research. The only purpose to be served by a more elaborate arrangement would be in the realm of public relations.

Our overall conclusion from this section is that in cost-benefit analyses, lives lost in the future should be discounted by a factor of the order of the number of years in the future when the fatalities occur. For example if the fatalities are expected to occur in 1000 yr, their estimated number should be divided by 1000. This discussion was centered on deriving a discount factor, but of course a much more important conclusion is the obvious one that it is far more cost effective to save future lives by expanding biomedical research than by protecting future generations from radiation as the latter activity is currently practiced.

RESIDUAL MORAL QUESTIONS

There seems to be a current of opinion that doing harm to future generations is immoral regardless of how much good we do for them in compensation. The problem with such an attitude is that it is highly unrealistic. Many of our current activities are harmful to future generations. Perhaps the most serious is our voracious consumption of the world's mineral resources, including not only oil, gas and coal, but metals such as copper, zinc, tin, lead, silver and mercury, most of which will be gone within a very few generations. Other harmful legacies are over-population, highly destructive military weapons, large public debts, long lasting socio-political problems—all enormously more harmful than the tiny amounts of radiation we expose them to. The only realistic approach is to leave them compensating beneficial legacies, as we are proposing to do with regard to radiation.

It is sometimes theorized that there may be a lack of continuity in our civilization in which all our beneficial legacies are lost, but yet our harmful legacy of extra radiation will survive. If there should be such a collapse of civilization, the residual radiation would be the least of the problems. There would surely be mass starvation as the world population would have to shrink back to its pre-industrial revolution level. Life expectancy would be reduced back to about 35 yr, which in itself represents an enormous amount of human suffering. But as a result, cancer resulting from radiation exposure, which is largely a disease of old age, would be far less of a danger than we calculate with today's life expectancies.

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APPENDIX A

Examples of relative benefits from "present method" and "trust fund method"

We assume that the trust fund method can draw compound interest at 3% per yr, and at any time in the future, it can be used for life saving at a cost of \$1M/life saved.

Example 1: High level waste. DOE recently decided to spend several hundred million dollars extra to convert the West Valley high-level waste to glass and bury it in a future repository, rather than to mix it with cement and leave it in place. The expected number of fatalities from the latter course would be very much less than one (Co79a) so the cost-per-life-saved will be in the billions of dollars.

The decision not to simply dump vitrified civilian high-level waste in the ocean was shown previously (Co80) to correspond to spending \$18M/life saved. It was also shown in that paper that the choice of methods for disposal of Savannah River Plant high-level waste corresponds to spending \$200M/per life saved.

Even without counting interest, the trust fund approach is more efficient in these high-level waste situations by 1–3 orders of magnitude. But all of the life saving in these calculations will occur thousands of years in the future, so the interest accrued increases the advantage of the trust fund by many orders of magnitude.

Example 2: Covers for uranium mill tailings. The cost of covering uranium mill tailings is estimated to be \$110,000/GWe-yr, and the number of lives saved by doing so is 3×10^{-3}/yr/GWe-yr (Co82). The 3% interest on \$110,000 would be \$3300/yr, so the cost-per-life-saved each year is ($3300/3 \times 10^{-3} =$) \$1M, making the trust fund method only equally as efficient as the present method.

However, the covers reduce radon emission exponentially, while their cost is linear with cover thickness. Thus, instead of using 5 m cover thickness to reduce emissions by a factor of 200, the NRC could require a 4 m thickness which reduces radon emissions by a factor of 70. For 1GWe-yr, the difference between the 5 and 4 m covers is then $[(1/70 - 1/200) \times 3 \times 10^{-3} =]$ 3×10^{-5} lives/yr saved at a cost of ($1/5 \times \$110.000 =$) \$22,000, on which the interest is \$660/yr. The cost-per-life-saved then becomes ($660/3 \times 10^{-5} \approx$) \$20M. In adding the top meter of cover, the trust fund method is therefore 20 times more cost effective than the present method.