Human Costs of Nuclear Power

L. A. Sagan

As public attention has focused on a deteriorating environment, economists have noted that a major contributing factor has been the failure to charge industry for emitting wastes into water and air. They point out that the consequences of this failure are not only excessive pollution, but artificially low prices and higher levels of consumption. These economists (*1*) have proposed a remedy with which to optimize pollution levels, namely, an emissions tax. If such a tax were levied, it would properly be based on some objective estimate of the effects of emissions on human health, as well as the economic, social, and environmental costs of emissions.

This article is concerned with the human costs of producing and utilizing nuclear fuel to generate electricity and with the question of whether these costs are equitably compensated for and represented in the price of such electricity. The analysis is based on estimates of the value of human life, lost productivity, and potential effects of radiation. My conclusion, based on certain assumptions, is that major inequities do indeed exist.

Traditionally, cost-benefit ratios have been the province of economists whose major interest is in engineering the costs of a particular project, with which they compare the savings (benefits) anticipated from that project. An example might be the cost-benefit estimates for a flood control project, in which the costs of a dam are compared to the commercial benefits to navigation and the savings in property damage from the prevention of floods.

Recently the concept has been altered somewhat to include a consideration of human lives, as well as property. An example of this is the calculation of costs to the nation of specific diseases, for example cardiovascular disease and cancer (*2*). This has sometimes taken the form of comparing the benefits to patients with the costs of treatment or the costs of technological advances in medical care (*3*).

There is nothing to suggest that there are greater distortions of human costs in the nuclear industry than in other industries. On the other hand, a cost-benefit evaluation is especially suitable to the nuclear industry, for the following reasons.

1) The International Commission on Radiological Protection (ICRP), in proposing radiation dose limits, recommends that all exposure to radiation be considered potentially damaging to man (*4*) and that industrially produced exposure of the public to radiation be permitted only if it can be justified in terms of risk-benefit ratios. The maximum permissible exposure for an individual in the general population under any circumstances is 500 millirems per year (a rem, the usual measure of radiation dose, is defined as the deposition in tissue of 100 ergs of energy, multiplied by an appropriate modifying factor, which will be specific to the particular type of ionizing radiation and the biological effect produced.) Unfortunately, the ICRP has provided no guidelines for calculating risk-benefit ratios. The methodology I use here implies that one can assign a dollar value to each human exposure incurred and then compare these costs to the costs of reducing such exposures. Whether the exposures are justified (benefits) requires separate consideration and will not be attempted in this article; nor will I attempt to compare these costs with the costs incurred in generating electricity from other fuel sources, although such comparisons are clearly relevant.

2) The nuclear industry is new, still relatively small, and in its formative stages; therefore, practices and capital investments have not yet reached such proportions that changes would cause substantial political, economic, or social dislocation. Thus, alterations suggested by cost considerations are more likely to be implemented in this industry than in a mature industry, where large capital investments have already been made.

3) Nuclear power has entered a phase of rapid growth at a time when public interest in and concern about the environment have become intense, resulting in a demand for extensive analysis and justification of the use of nuclear power.

4) Our knowledge of the biological effects of radiation very probably exceeds our knowledge of the effects of any other chemical or physical agent. We therefore have at our disposal a fairly sophisticated estimate of the human risks involved in radiation exposure. Although far from complete, this knowledge may well be greater than our knowledge about most of the other environmental hazards that may require similar attention.

5) The National Environmental Protection Act of 1969 requires government agencies to consider alternatives to any proposed action that would affect the environment. Under the provisions of the Atomic Energy Act, the U.S. Atomic Energy Commission (AEC) is charged with the responsibility of regulating the radioactive discharges of nuclear reactors. The AEC first attempted to meet its obligation by requiring that a utility applying for a license to construct a reactor facility prepare and submit an environmental report describing alternatives. After judicial review (*5*), the AEC issued a revised requirement, dated 9 September 1971, which read in part: "The environmental report shall include a cost-benefit analysis which considers and balances the environmental effects of the facility and the alternatives available for reducing or avoiding adverse environmental effects, as well as the environmental, economic, technical and other benefits of the facility" (*6*). Although not specific, these instructions would clearly seem to necessitate consideration of the human costs of building, fueling, and operating an electric generating plant, whether it be nuclear or conventional in design.

6) Examining the effects on health of each segment of an industry would seem to have some merit in rationalizing public health efforts. Surely, the magni-

The author is associate director, department of environmental medicine, Palo Alto Medical Clinic, 300 Homer Avenue, Palo Alto, California 94301.

tude of preventive and research expenditures should bear some resemblance to the risks involved in the activities to which they are directed. Unfortunately, public health efforts are often stimulated more by emotionally derived public attitudes toward a problem than by any objective consideration of the problem's real costs to society.

The nuclear industry shows glaring examples of such imbalance in its safety and preventive expenditures.

Human costs of two kinds can be considered: accidental injuries and deaths, usually (but not always) occurring among individuals whose occupations are involved with the nuclear fuel cycle; and potential health hazards incurred by those who are exposed to radiation generated throughout the fuel cycle, both in-plant and elsewhere. In order to make comparisons, both of these costs are assessed in dollars. By doing so, I risk the charge of insensitivity, but no other workable method is now in use.

This article represents a "first cut" at assessing the human costs of generating nuclear power. No consideration will be given here to the other portions of the equation: environmental costs and human benefits. Since a great many assumptions and evaluations were, of necessity, arbitrary, the results are presented more as a suggested working model than as a precise estimate of these costs.

Accidents

The very word "accidents" implies the unexpected and even unacceptable. There is, in this society, a myth that we consider life priceless and that no price is too great to pay if it will avoid an accident. Yet, an examination of our practices reveals that we do indeed accept what has been a relatively constant rate of accidents. The record of the past 50 years demonstrates that the death rate in industrial accidents has gradually fallen as automobile death rates have risen, the total showing a gradual, but only slight, decline (*7*).

Accidental deaths, among both industrial and nonindustrial populations, resulting from nuclear power–generating activity have been small, compared to deaths resulting from other industrial activities (*8*). The Department of Labor reports that both the frequency and severity of accidents in the nuclear industry are lower than the national average for manufacturing (*9*). This springs partly from the fact that the hazardous nature of radiation was recognized early and has led to strict regulatory control.

Occupational Injuries: Morbidity and Mortality

The assumptions underlying the following assessments are, to some extent, arbitrary and will undoubtedly be contested. Individuals with more precise data are invited to refine these numbers. In any case, I make the following assumptions.

1) The loss of one day's productivity as a result of injury is assumed to approximate \$50. In August 1971, gross weekly earnings for nonsupervisory employees were \$173.43 for mining, \$220.23 for contract construction, and \$141.69 for manufacturing (*10*); beyond this, the employer bears expenses such as vacation, pension, sick leave, and other administrative costs.

2) In addition to loss of productivity (direct costs), medical expenses (indirect costs) of the injury must also be assessed and allocated. Accepting the ratio of indirect to direct costs that obtains nationally for accidents (*11*), I consider these costs equal and estimate \$50 per day as the indirect cost of injury.

3) The Department of Labor, in its scale of time charges (*9*), assesses a fatality as 6000 working days (20 years) lost. That assessment is accepted here. At \$50 per day for lost time, a fatality would be charged at \$300,000. Since death is inevitable, no indirect costs are assessed: that is, society ultimately pays the medical costs of all deaths, whether natural or otherwise. Furthermore, accidental deaths are, by their nature, far less costly in medical terms than are deaths resulting from chronic disease.

Estimates of the economic value of human life vary widely, depending on a number of variables. One example may serve to illustrate the methodology: Fromm estimated the value of a life lost through an airplane accident (*12*). In addition to the loss of the victim's future earnings and personal consumption, he considered the loss in contributed community service time, employer's recruiting and training costs, and accident investigation costs. On the basis of these factors and the income and age characteristics of the average individual killed in an aviation accident in 1960, a total value of \$373,000 was assigned. The \$373,000 is the sum of the following economic losses resulting from the individual's death: to himself, \$210,000; to his family, \$123,000; to the community, \$28,000; to his employer, \$4000; to the government, \$4000; and to the airlines, \$4000. The value in 1960 of the individual's future earnings and assets was computed from an average salary of \$13,000, a yearly increase of 2.5 percent, assets of \$25,000, an interest rate of 6 percent, and 40 as the average age at death. The assumption is also made that the individual is paid the full value of his labor and is not exploited.

Another estimate is that of Dublin, Lotka, and Spiegelman, who calculated in 1946 the worth of gross future earnings of a person, age 40, earning \$3500 per year. They deducted income tax, estimated savings at 2.5 percent interest, and calculated a future worth to the victim and his dependents of \$54,005 (*13*).

Carlson (*14*) used an indirect method of estimating value of life based on Air Force expenditures for development and maintenance of an ejection system for the B-58 bomber. Since these yearly costs were estimated to be \$9 million, and since it was anticipated that one to three lives per year might be saved by this system, the implied value of life would lie between \$3 million and \$9 million.

Uranium Mining

The United States is the largest producer and consumer of uranium in the world today (*15*). Before World War II, demand was small and uranium was used principally by the ceramic industry; however, the uranium-containing ores, of which pitchblende is one, were mined extensively in the earlier half of the century for the radium found in association with uranium. Following the demonstration of the fission process in 1942, U.S. demand for uranium rose rapidly, primarily to meet AEC needs for weapons development and production. As the use of nuclear power for the generation of electricity increases, uranium will be in demand more for reactor fuels than for weapons.

A 1000-megawatt (electrical) nuclear reactor of current design requires an average reload equivalent to 0.140 metric ton of uranium oxide (U_3O_8) in concentrate per megawatt per year (*16*); this is aside from the initial core, which remains as a constant plant inventory.

Averaging employment and production data for the 3 years 1967 to 1969 (*17*), one finds that the mining and milling of 140 metric tons of U_3O_8 would require, at the rate of 2.3 metric tons per man, 62 man-years. Assuming that there are 1760 hours of employment per man per year, the total number of hours at risk per reactor per year would be 109,120. Since the rate of fatal accidents was 0.892 per million man-hours (1969 and 1970 averaged) (*18*), 0.1 fatality per year can be allocated to each 1000-megawatt reactor, or one fatality per year for the 10,030-megawatt capacity in the United States as of 1 December 1971 (*19*).

In addition, nonfatal injuries accounted for the loss of 1065 days per million man-hours worked. Charged at $100 per day, total injury costs, both direct and indirect, would be $11,700 per 1000-megawatt reactor. Together fatal and nonfatal injuries resulting from mining and milling activities would cost the nuclear industry $417,000 per year.

Table 1. Accidents in fuel and reactor manufacturing—1969.

Activity	Employees (No.)	Deaths (No.)	Injury* (No. of days lost)
Production of feed materials	1,482	0	193
Production of special materials used in reactors	1,439	0	2,281
Fuel element fabrication	2,905	0	1,876
Reactor design and manufacturing	15,572	1	3,122
Design and engineering nuclear facilities	4,793	1	89
Nuclear instrument manufacturing	2,771	0	1,463
Private research labs, including reactor test facilities	1,257	0	114
Miscellaneous (nuclear activities not classified elsewhere)	2,705	0	56
Total	32,924	2	9,194

* Excludes deaths.

Fuel Manufacture and Reactor Construction

After the mining and milling of the raw uranium ore, it is necessary that the proportion of the ore which is fissionable and therefore useful as reactor fuel, the isotope uranium-235, be increased relative to the nonfissionable isotope uranium-235. This is accomplished by converting the uranium to a gas (UF_6), in which state the increase in uranium-235 can be most easily accomplished. The fuel is then converted to a metal, uranium dioxide, and is formed into small pellets, which are, in turn, encased in long metal tubes, or cladding. Large numbers of these tubes are assembled as bundles and constitute the basic fuel element within the reactor core, which consists of many of these bundles. Before fuel rods are irradiated in the reactor core, they do not produce penetrating radiation; therefore, no significant exposures are encountered in this stage of the fuel cycle.

The Department of Labor maintains injury statistics for each of these stages of manufacture, as well as for design, engineering, and construction of the reactor itself (*9*). These are shown in detail in Table 1 and as assumed total costs in Table 2. The data are for 1969, the most recent year available. Since those rates had been stable, as compared with previous years, it can be assumed that they are still valid today.

Rates of the frequency and severity of injuries are not reported separately for fuel reprocessing, but for fuel fabrication and reprocessing together. Because there are no specific data, the 800 employees involved in reprocessing were removed from the larger group shown in Table 1 and the rates for the larger category were applied to them, thereby producing an estimate of 517 days of injury for the 800 employees.

Radiological Effects

Although effects on human beings of single, high doses of radiation have been identified and quantified, no effects from the levels of radiation encountered in the nuclear power industry are known or detectable. (An exception, uranium-mining activities, will be discussed.) Nevertheless, it cannot logically be, and has not been, assumed that effects do not occur. The assumption of ICRP, as well as of other groups, is that a maximum estimate of risk at low levels of exposure can be made by presuming linearity—that is, by presuming that risk is in a consistent proportion to dose, whether the dose is high or low (*20*). That assumption will be accepted here in order to assess radiation damage to the individual.

Still another assumption that will, of necessity, be accepted here is that dose rate has no influence on effect. Because dose rate affects human beings in almost all exposures to chemical or physical factors (including radiation), this assumption introduces into estimates of risk a safety factor that lies somewhere between zero and infinity. Studies of risk of human carcinogenesis from radiation exposure are based on effects of radiotherapy and atomic bombs, cases in which the dose rate is on the order of 100 rems or more per minute; therefore, estimates extrapolated to dose rates associated with reactor operation, rates that are on the order of millirems to a few rems per year, are clearly likely to be inflated.

Another concept, in which both linearity and absence of a dose rate effect are implied, is that of the man-rem, a measure of both radiation exposure and numbers of people exposed. Specifically,

Table 2. Total yearly costs to society from 10,030-megawatt (electric) nuclear industry.

Industry	Occupational costs		Public radiation ($)	Total ($)
	Injuries ($)	Radiation ($)		
Uranium mining	417,000	46,200		463,200
Manufacturing	1,519,300			1,519,300
Reactor operation	9,890	72,000	14,790	96,680
Reprocessing	51,700	40,020	1,500	93,220
Long-lived nuclides			3,120	3,120
Total	1,997,890	158,220	19,410	2,175,520

Table 3. Risk to individuals involved.

Activity	Persons involved (No.)	Cost ($)	Annual cost per person ($)
Uranium mining and milling	620	463,200	747.09
Manufacturing	33,724	1,519,300	45.00
Reactor operation	1,290	81,890	63.00
Reprocessing	800	91,720	115.00
Public near reactor	33,841,000	19,410	0.0004
Total U.S.	200,000,000	2,175,520	0.10

a man-rem represents the effect of 1 rem of exposure, whether delivered to one individual or fractionally to a larger number of people.

A number of estimates of the dollar value of the risk of 1 man-rem have been made. Cohen's estimate is the highest, $250 (*21*). Other estimates are $100 (*22*), and "a few pounds sterling" (*23*).

On the basis of all available scientific evidence, and relying on the conservatism of both the theory of linearity and the disregard of any dose rate effect, ICRP has established an upper level of radiation risk. In 1965, they estimated (*20*) that 1000 millirems of radiation received by each of 1 million people at any time will result in approximately 15 cases of leukemia and a total of 15 cases of all other types of cancer during the lifetimes of the exposed population, in addition to the approximately 250,000 cases that would normally occur in a nonirradiated population of 1 million persons. In other words, 1000 millirems would increase the risk of cancer by about 0.01 percent. Accepting that estimate of radiation risk, and accepting the assumptions both of linearity and of the absence of a dose rate effect, one can calculate the risk of cancer to persons exposed to the maximum levels near a nuclear plant and to those persons living within the vicinity of the plant who receive typical exposures.

The risk estimates used in these calculations were reviewed by ICRP in 1969 (*24*). Reference was made to the growing incidence of cancer among patients receiving radiation therapy for rheumatoid spondylitis. Making the assumption that, among these persons, all cancers found in numbers greater than are found in the general population resulted from radiation, the ICRP estimated that cases of other types of cancer may occur six times more frequently than leukemia as a result of radiation. However, in the paper that originally reported this study of spondylitis (*25*), as well as in the 1969 ICRP report, it was carefully pointed out that many of the cancers occurring among spondylitic patients could be the result of factors other than radiation—for example, drug treatment, excess smoking, or a spontaneous effect (not caused by treatment) associated directly with the disease.

Based on the assumption that 1 rem produces 100 cases of cancer per million persons exposed (that is, per million man-rems) and that the cost per life is $300,000 (derived purely from economic considerations), then risk-cost per rem per person would be $30, the estimate to be used here. Implicit in that estimate is the assumption that death caused by radiation-induced cancer would shorten life as much as death caused by accidental injury would—that is, by 6000 working days. Precise data on the latent period between radiation exposure and malignancy do not exist. The data that do exist are conflicting and, furthermore, are based on single exposures and high doses. Latent periods for leukemia, which are the best documented, are relatively short. Among the Japanese who survived the atomic bombs, leukemia began to appear early, reached a peak in about 1953, and declined after 1958 to the rates found among nonexposed groups in the mid-1960's (*26*). In the British study of spondylitics treated with radiation (*25*), leukemia rates rose to a peak 2 years after exposure and then slowly declined.

The latent period for types of cancer other than leukemia may well be much longer. Cancer among persons exposed as children to the atomic bomb is only now beginning to appear (*27*), and types of cancer other than leukemia have a distinctly longer latent period among the spondylitic population. Evans has noted that the latent period is inversely related to body burden of radium among radium dial painters (*28*).

An estimate of $30 can also be reached by extrapolating from the known lethal dose for a single exposure, 1000 rems. Assuming a risk reduced by a factor of 10 for long-term exposures (based on a single lethal dose of 1000 rems and an estimate of 100 cases of cancer per million man-rems), then

$$\frac{\$300{,}000}{(1000) \times (10)} = \$30$$

Still another approach would be to consider radiation-induced life shortening. Storer has recently reviewed studies relating to life shortening and concludes that the best estimate for man is 1 day life shortening per rem of exposure (*29*). This life-shortening approach to an estimate of radiation risk therefore produces a value of $50 per man-rem, which is, considering all of the variables and unknowns involved, fairly close to the $30 estimate arrived at through a consideration of cancer induction.

Missing from consideration in the above estimate of radiation risk are the genetic effects that have been amply demonstrated in studies of animals. To date, however, and in contrast with the somatic effects described above, no genetic effects have been demonstrated in irradiated human populations. Because it is not known whether such effects might occur at low doses, or what form they might take, no attempt is made here to quantify them in economic terms.

Uranium Mining

It has been demonstrated beyond any reasonable doubt that exposure to radiation at high dose rates in uranium mining leads to lung cancer (*30*). The source of the radiation is not uranium, but the radium and products of radium decay that are found in uranium ores. Radium decays to radon, a gas that is radioactive and that, in turn, decays to a number of other radioactive materials, generally called radon daughter products. Daughter products quickly become absorbed on dust particles that can be inhaled and deposited on lung surfaces, where they can further decay, generating highly energetic alpha particles.

Estimates of radiation dose from this form of exposure cannot easily be expressed in rems because of the great number of physiological and physical variables involved, variables that are only poorly understood. For this reason, estimates of dose, and epidemiological studies based thereupon, are based on concentrations of radon daughter products in the air. The unit is known as a working level (WL), which is any combination of short-lived radon daughters in 1 liter of air that will result in the ultimate emission of 1.3×10^5 mega electron volts of potential alpha energy. Occupational exposure to 1 WL for a period of 1 month is known as a working level month, or WLM. Since 1968, standards for underground uranium mines have limited exposures to 12 WLM per year; as of 1 July 1971 exposures were limited to 4 WLM per year (*31*).

Of the men involved in mining and milling from 1967 to 1969, 31 percent were in milling; of those who were engaged in mining, only 67.9 percent were underground rather than on the surface or in open-pit mining. Therefore, of the 62 men required to do the mining and milling for nuclear fuel to supply one reactor per year, only 29 would be underground and exposed to radiation. In their recently published monograph, Lundin, Wagoner, and Archer have made refined estimates of the anticipated number of lung cancers to be found among 10,000 miners working at 1, 4, and 12 WLM per year, beginning at age 20 and continuing to age 50 (*30*). They predict 353 lung cancers to age 80 for men exposed to 0 WLM per year, 512 for 4 WLM per year (average exposure of 0.3 WL) and 684 for 12 WLM per year (average exposure of 1 WL). From these numbers, it can be easily calculated that one man working for 1 year at 4 WL incurs an additional risk of lung cancer of 0.00053 case. For the 29 men required to work underground at 4 WLM per year to supply one reactor, total projected cases would be 0.0154, at a cost of \$4620 for one reactor, or \$46,200 for the currently operating 10,030-megawatt U.S. industry.

Reactor Operation

Radioactive materials are released to the environment both as gases that leave the stack and form a plume and as soluble and insoluble materials that are diluted and released into the water of the cooling stream. These materials could find their way into the human food chain through many pathways (*32*), but in practice this has been found to be a negligible source of exposure, compared to the clouds of radioactive gases. These gases are, for the most part, noble gases; they produce external exposures only, and do not enter into any biological processes. Gamertsfelder (*33*) has estimated that the total exposure of the general population to radioactive gases from U.S. reactor operations is 483 man-rems per year.

Since exposures to radiation among employees of reactor plants occur primarily among contract employees, particularly during shutdown for refueling, reported exposures are undoubtedly underestimated.

Goldman (*34*) estimated the total U.S. in-plant exposures in 1971 to be 2400 man-rems. Actual film badge readings of exposures for 1970 totaled 2039 man-rems (*35*). These estimates include only utility employees, not contract personnel. The former estimate would produce a cost of \$72,000.

Fuel Reprocessing

Following their removal from the reactor, the "spent" fuel rods, which are intensely radioactive, are first stored at the reactor site to allow for preliminary decay; the rods are then transported to a reprocessing center, where they are both physically and chemically treated to reclaim uranium and other materials; the fission products are separated and prepared for final storage elsewhere.

The sole reprocessing plant for fuel rods from operating nuclear power plants is located in West Valley, New York. Although the radionuclide mixture released from this facility differs considerably from that of a power reactor, the dose limits are the same as those established for a reactor facility. A U.S. Public Health Service survey shows this facility to be operating well within these limits (*36*); therefore, it will be assumed that total exposure to radiation of the nonemployee population living adjacent to the plant is 50 man-rems from this source, at a cost of \$1500.

Occupational exposures for fuel reprocessing were 1334 man-rads in 1970 (*35*). This calculation, from film badge readings, excludes film badge readings between 0 and 125 millirems, the great majority of which are 0.

Long-Lived Nuclides

In addition to exposing populations near nuclear facilities to radiation, long-lived fission products generated from both reactor operation and from reprocessing (particularly the latter) accumulate in the environment and are distributed, through natural processes, over very large areas. The importance of these products derives not from the magnitude of dose to individuals, which is small, but from the large number of people exposed. The two nuclides of greatest significance, in terms of curies released and half-life, are krypton-85, a noble gas, and tritium in the form of tritiated water. Neither of these can be easily contained by presently available technology, and they are liberated to the environment. Estimates of individual exposures from current nuclear operations are 0.005 millirem from krypton-85 (*37*) and 10^{-6} millirem from tritium (*38*). This would produce total U.S. man-rem exposures of 100 and 4, respectively, or a cost of \$3000 and \$120, respectively.

Injuries to the Public

No accidental injuries or radiation exposures beyond permissible limits to members of the public are known as a result of the U.S. nuclear power industry. Clearly, some risk of accidental release of radioactivity exists. Otway estimates that, if the total U.S. power demand were met by 200 reactors located near urban areas, total deaths caused by reactor accidents would be expected to be 0.02 per year (*39*). Since this risk is small, I have ignored it, and I assume that this neglect will not affect my conclusions.

Summary and Interpretation

Approximately 10,030 megawatts of nuclear power are produced by plants now operating in the United States (*19*). According to the estimates developed here, the human costs of generating that electric power are approximately 0.026 mill per killowatt hour. In terms of risk per person exposed (Table 3), the mining of uranium is the costliest portion of the entire fuel cycle. This is particularly significant because these effects are real, in contrast to the hypothetical effects of low-level

Table 4. Cost of dose reduction from Brown's Ferry nuclear plant.

Equipment	Reduction in external dose (man-rem)	Cost ($)	Cost per man-rem of radiation reduction ($)	Incremental cost per man-rem of radiation reduction ($)
Recombiners only	3,600	6,000,000	1,700	1,700
Recombiners and 6 charcoal beds	4,305	9,000,000	2,070	4,250
Recombiners and 12 charcoal beds	4,350	10,500,000	2,400	30,000

radiation exposure, and would clearly deserve far more attention than the off-site exposures from reactors, which have been receiving the greatest amount of public attention. Nor is it clear that the miners themselves or their political representatives have perceived accurately the magnitude of the risk. Compensation for this risk might be reflected either in adequate death benefits (that is, $300,000) or in wages. Death benefits in the state of Colorado average $17,000. Starr (*40*) has argued that wages for various soft- and hard-rock mining activities reflect the degree of risk involved. This view has been challenged by Connelly and Mazur (*41*). Whether wages in industrial activities generally in our society do contain some element of compensation for risk has not yet been carefully studied.

In a study carried out for the Federal Radiation Council, the economic effects of reducing radiation levels within uranium mines from the former requirement of 1.0 WL to 0.3 WL (as now required) were considered (*17*). The investigators concluded that additional production costs, primarily for ventilation equipment required to achieve this level, would be 24 cents per pound of U_3O_8. The total production costs for the industry would rise to about $7 million per year, or an increase in cost to the consumer of 0.18 percent.

Again using the model of Lundin, Wagoner, and Archer (*30*, table 44, p. 109), I find that a reduction of radon levels from 1.0 to 0.3 will reduce the future lung cancer risk for the 2700 U.S. underground miners by 1.54 cases per year of exposure and therefore reduce the cost of uranium mining by $462,000 per year in return for the $7 million annual increase in operating cost. To implement such a program of risk reduction would imply an assumed value for human life of $4.5 million.

Based solely on the controversial theory that some excess risk may exist at 1.0 WL, the Environmental Protection Agency required that the 0.3 WL be mandatory as of 1 January 1971 (*31*). Unfortunately, the $7 million that the industry must spend to reach 0.3 WL does not benefit the miners, but the ventilation equipment manufacturers. Deaths that do occur among uranium miners as a result of lung cancer or trauma are compensated at a maximum of $24,492.25 for a widow with three or more children (*42*)—a small fraction of what is assumed here to be the just value of a man's life, and an amount too small to provide an economic incentive to improve safety conditions. Death benefits vary among states, but average a legal maximum of about $20,000 (*43*).

It cannot be assumed that the much larger costs of nonfatal injuries are entirely compensated. Analysis (*43*) of workmen's compensation provisions for injury, whether permanently or temporarily disabling, shows that income during disability is typically at two-thirds of full employment levels.

With respect to radiation exposures from reactor operation alone, a far greater total exposure is incurred by plant employees than by other persons. Off-site exposures are very small in comparison with radiation from natural sources or medical exposures. However total exposures are distributed between the public and industrial employees, these costs (risks) should be compensated; and, from both an economic and a biological point of view, it is the total exposure that is of concern. For this reason, occupational and public exposures should be considered together, particularly since technology, or standards influenced by public pressures, may reduce public exposures while producing for reactor employees inordinately greater exposures to radiation. Indeed, Goldman has recently argued that the use of additional equipment within the plant to reduce off-site exposures may actually produce a greater occupational exposure because of the additional maintenance requirements (*34*).

The AEC, which regulates reactor emissions, requires that the level of those emissions be maintained as low as technologically practicable (*44*). Under intense public pressure, it has pursued this goal beyond economic justification. The following example, based on data developed by the Tennessee Valley Authority (TVA) for the three reactors at the Brown's Ferry plant (*45*), illustrates the point. Radioactive gases generated by the fission process in the reactor core will decay to very low levels of radioactivity if there is substantial delay before they are released. Delay is influenced by the volume of gas generated, and since large quantities of hydrogen and oxygen are produced by radiation effects on cooling water, hydrogen recombiners can reduce radiation dose by a factor of 6. In addition, charcoal beds, by absorbing radioactive xenon and krypton, can further delay release and thus reduce exposure. Cost of equipment, dose reduction, and incremental cost per man-rem of dose reduction are shown in Table 4 for recombiners and for recombiners with one and two sets of charcoal beds.

Because a reasonable estimate of the cost of biological damage from 1 man-rem is $30, the addition of any of this equipment could not be justified in economic terms. Nevertheless, TVA has decided to add both the recombiners and six charcoal beds to the plant in order to meet AEC requirements. Ideally, in a society with unlimited resources, no expenditures would be spared to reduce risk, regardless of cost; but practically, radiation protection must compete with other pressing societal needs.

Studies of radiation protection alone indicate that there are far greater economies in reducing public exposure from other sources of radiation than in reducing public exposure from nuclear plants. For instance, Terrill (*46*) has presented a comparative cost-benefit analysis for radiation dose reduction from medical and from reactor-produced exposures. He found that, from the use of automatic collimators on diagnostic x-ray equipment, costs per man-rem reduction are about $7, compared to his estimated cost of $10,000 to $100,000 per man-rem for reducing reactor-produced radiation. He points out that current exposures of the U.S. population to radiation are 430 man-rems from nuclear plants versus 18.7 million man-rems from diagnostic x-rays.

What is left to be explained is why occupational injuries, particularly deaths, are not adequately compensated, whereas the risk to the public of radiation exposure is uneconomically overregulated, researched, and financed. To an extent, this reflects the general attitude within our society that certain occupational groups are expected to accept higher risks than the public. This attitude can be demonstrated in a number of ways, both within the nuclear industry and without. Standards for permissible levels of exposure to radiation are tenfold higher for employees than they are for the general public. It is also significant that federal support for research in occupational health in all areas (through the National Institute for Occupational Safety and Health) is less than $5 million per year, while research funds for radiation biology are $90 million annually from the Atomic Energy Commission alone. Undoubtedly an argument can be made that those individuals whose jobs are involved with radiation should take greater risks than others, but it is difficult to conceive of an argument that would allow the risks to remain less than fully compensated, other than the undemonstrated thesis that undercompensation serves as a deterrent to accidents. In these days of egalitarianism, such a discrepancy is an anachronism. Hopefully, the Department of Health, Education, and Welfare's Commission on Workmen's Compensation will recommend reforms in compensatory practices to correct this abuse, which is not peculiar to the nuclear industry.

In contrast, public and political interest in protection from radiation exposure has been intense and has led to technological restrictions far out of proportion to what can be justified on an economic basis. This undoubtedly reflects a number of widespread biases arising from the knowledge that nuclear energy is used in weaponry, and that radiation in high doses is associated with cancer.

Although radiation-induced lung cancer is compensated among uranium miners, there is extreme difficulty in compensating others occupationally exposed to radiation because of the problem of establishing a causal relation between their past exposure and disease. In the absence of techniques for distinguishing radiation-induced disease from other causes, a "no fault" insurance against leukemia and cancer, contributed to by both employer and employee, would seem an equitable solution.

Conclusion

This analysis provides some useful insights into the magnitude and distribution of the human costs of generating electricity from nuclear fuels. Our society is able to maintain low prices by evading environmental costs and, as shown here, by failing to pay the costs of occupational injuries. At the same time, the price of nuclear energy is maintained at an artificially high level by an overprotective governmental policy that restricts the public's exposures to radiation to a far greater extent than can be justified in terms of risk reduction or the costs of reducing other (that is, medical) exposures to radiation.

References and Notes

1. J. H. Dales, *Pollution, Property and Prices* (Univ. of Toronto Press, Toronto, 1968); L. E. Ruff, *Public Interest* **19**, 69 (1970); R. M. Solow, *Science* **173**, 498 (1971).
2. D. Rice, *Economic Costs of Cardiovascular Disease and Cancer, 1962*, Health Economics Series No. 5, PHS Publ. No. 947-5 (Government Printing Office, Washington, D.C., 1965).
3. B. Weisbrod, *Economics of Public Health* (Univ. of Pennsylvania Press, Philadelphia, 1961).
4. *Recommendations of the International Commission on Radiological Protection: Report of Committee II on Permissible Dose for Internal Radiation* (ICRP Publ. No. 2) (Pergamon, London, 1959).
5. Calvert Cliffs Coordinating Committee Inc. *v.* U.S. Atomic Energy Commission and U.S.A., 449 Fed. Rep., 2nd ser. 1109 (D.C. Cir. Ct., 1971).
6. Subsection A.3, appendix D, part 50, AEC 10 CFR.
7. R. A. McFarland, *Arch. Environ. Health* **19**, 244 (1969).
8. F. D. Sowby, in *Environmental Aspects of Nuclear Power Stations* (International Atomic Energy Agency, Vienna, 1971), pp. 919–925.
9. U.S. Department of Labor, *Work Injuries in Atomic Energy*, Bureau of Labor Statistics report No. 385 (Government Printing Office, Washington, D.C., 1969).
10. U.S. Department of Labor, Bureau of Labor Statistics, *Empl. Earn.* **18** (No. 5), 93 (1971).
11. D. Rice, *Estimating the Cost of Illness*, Health Economics Series No. 6, PHS Publ. No. 947-6 (Government Printing Office, Washington, D.C., 1966).
12. G. Fromm, *Measuring Benefits of Government Investments* (Brookings Institution, Washington, D.C., 1965).
13. L. I. Dublin, A. J. Lotka, M. Spiegelman, *The Money Value of a Man* (Ronald, New York, 1946).
14. J. W. Carlson, thesis, Harvard University (1963).
15. J. A. DeCarlo and C. E. Shortt, in *Mineral Facts and Problems, 1970*, Bureau of Mines Bull. No. 650 (Government Printing Office, Washington, D.C., 1970), p. 219.
16. *Forecast of Growth of Nuclear Power*, Wash-1139 (U.S. Atomic Energy Commission, Washington, D.C., 1971).
17. *An Assessment of the Economic Effects of Radiation Exposure Standards for Uranium Miners*, report to the Federal Radiation Council (Arthur D. Little, 1970).
18. *Mineral Industry Surveys* (U.S. Department of the Interior, Bureau of Mines, Washington, D.C., 1970).
19. *Status of Central Station Nuclear Power Reactors: Significant Milestones* (U.S. Atomic Energy Commission, Washington, D.C., 1971).
20. International Commission on Radiological Protection, *Health Phys.* **12**, 239 (1966).
21. J. J. Cohen, *ibid.* **19**, 633 (1970).
22. A. Hedgran and B. Lindell, *ibid.*, p. 121.
23. H. J. Dunster and A. S. MacLean, *ibid.*
24. International Commission on Radiological Protection, *Radiosensitivity and Spatial Distribution of Dose* (ICRP Publ. No. 14) (Pergamon, Edinburgh, 1969).
25. W. M. Court-Brown and R. Doll, *Brit. Med. J.* **2**, 1327 (1965).
26. O. J. Bizozzero, K. G. Johnson, A. Ciocco, *New Engl. J. Med.* **274**, 1095 (1966).
27. S. Jablon, J. L. Belsky, K. Tachikawa, A. Steer, *Lancet* **1971-I**, 927 (1971).
28. R. D. Evans, *Health Phys.* **13**, 267 (1967).
29. J. B. Storer, *ibid.* **17**, 3 (1969).
30. F. E. Lundin, Jr., J. K. Wagoner, V. E. Archer, *Radon Daughter Exposure and Respiratory Cancer, Quantitative and Temporal Aspects*, National Institute for Occupational Safety and Health and National Institute of Environmental Health Sciences joint monograph No. 1 (National Technical Information Service, U.S. Department of Commerce, Springfield, Va. 22151).
31. *Fed. Regist.* **36** (No. 132), p. 12921 (1971).
32. L. A. Sagan, *Arch. Environ. Health* **22**, 487 (1971).
33. C. C. Gamertsfelder, "Regulatory experience and projections for future design criteria," paper given at the Southern Conference on Environmental Radiation Protection at Nuclear Power Plants, St. Petersburg, Fla. (1971).
34. M. I. Goldman, "New developments in nuclear power plant waste treatment," paper presented at the American Nuclear Society winter meeting, Miami Beach, Fla. (1971).
35. C. Eason, personal communication (1971).
36. B. Shleien, *Northeastern Radiological Health Laboratory Technical Report BRH/NERHL 70-1* (Bureau of Radiological Health, Public Health Service, Rockville, Md., 1970).
37. C. E. Larson, statement for the record, Joint Committee on Atomic Energy, *Hearings on Environmental Effects of Producing Electric Power* (91st Congr., 1st sess., 1971), p. 214–284.
38. D. G. Jacobs, *Sources of Tritium and Its Behavior Upon Release to the Environment* (Division of Technical Information, U.S. Atomic Energy Commission, Oak Ridge, Tenn., 1968).
39. H. H. Otway and R. C. Erdman, *Nucl. Eng. Des.* **13**, 365 (1970).
40. C. Starr, *Science* **165**, 1232 (1969).
41. T. Connolly and I. Mazur, *Proc. 6th Annu. Health Phys. Soc. Trop. Symp.* **1**, 401 (1971).
42. H. E. Kneeland, personal communication (1972).
43. *Analysis of Workmen's Compensation Laws* (Chamber of Commerce of the United States, Washington, D.C., 1970).
44. U.S. Atomic Energy Regulations 10 CFR, part 50, appendix D.
45. O. M. Derryberry, personal communication (1971).
46. J. G. Terrill, Jr., paper presented at American Public Health Association annual meeting, Chicago, Ill. (11 October 1971).