General Safety Considerations

Edited by J. R. Buchanan

A Cost–Benefit Comparison of Nuclear and Nonnuclear Health and Safety Protective Measures and Regulations

By E. P. O'Donnell* and J. J. Mauro†

[Editor's Note: This article was prepared for *Nuclear Safety* at the invitation of the editor. The article proposes a rationale for the implementation of safety measures and regulations based on a cost–benefit comparison derived from just principles of logic. However, the real world of nuclear power plant licensing makes little use of the principle of balancing monetary costs of safety features against the incremental improvements in safety. On the other hand, NEPA requires that there be a balancing of environmental costs vs. societal benefits. Although the Atomic Energy Act of 1954 requires a showing that the plant can be built without "undue risk" to the health and safety of the public, the term "undue risk" was not defined in such a way as to require balancing against cost. Even though the author faults the Nuclear Regulatory Commission for failing to apply cost–benefit balancing, in reality his complaints are more appropriately directed toward the Congress that passed the legislation.]

Abstract: *This article compares the costs and benefits of health and safety measures and regulations in the nuclear and nonnuclear fields. A cost–benefit methodology for nuclear safety concerns is presented and applied to existing nuclear plant engineered safety features. Comparisons in terms of investment costs to achieve reductions in mortality rates are then made between nuclear plant safety features and the protective measures and regulations associated with nonnuclear risks, particularly with coal-fired power plants. These comparisons reveal a marked inconsistency in the cost effectiveness of health and safety policy, in which nuclear regulatory policy requires much greater investments to reduce the risk of public mortality than is required in nonnuclear areas where reductions in mortality rates could be achieved at much lower cost. A specific example of regulatory disparity regarding gaseous effluent limits for nuclear and fossil-fuel power plants is presented. It is concluded that a consistent health and safety regulatory policy based on uniform risk and cost–benefit criteria should be adopted and that future proposed Nuclear Regulatory Commission regulatory requirements should be critically evaluated from a cost–benefit viewpoint.*

*Edward P. O'Donnell is Chief Nuclear Licensing Engineer with Ebasco Services, Inc. He is responsible for the direction of all nuclear safety and licensing activities in support of Ebasco nuclear projects. He is a graduate of the U. S. Merchant Marine Academy and received the M.S. degree in nuclear engineering from Columbia University in 1968. His involvement in nuclear safety at Ebasco spans 10 years and some 15 domestic and 8 foreign nuclear plants, as well as the Tokamak Fusion Test Reactor project. Mr. O'Donnell also serves as manager of licensing activities for the Ebasco Standard Safety Analysis Report. He is a member of several industry committees on reactor safety and licensing and has served as U. S. consultant to the International Atomic Energy Agency Nuclear Safety Standards Program.

†John J. Mauro is Supervising Engineer in charge of the Radiological Assessment Group at Ebasco Services, Inc. His primary responsibilities include the evaluation of in-plant and off-site radiological exposures at nuclear facilities for both normal and accident conditions. He is also responsible for the development of environmental radiological surveillance programs and emergency plans. Dr. Mauro joined Ebasco in 1973 after receiving his doctoral degree in health physics from the Institute of Environmental Medicine at New York University (NYU). He received the M.S. degree in biology from NYU and a B.S. in biology from Long Island University. In 1976 Dr. Mauro was certified by the American Board of Health Physics.

Protective measures and regulatory policy in the United States regarding health and safety are developed and implemented on a number of governmental levels (federal, state, and local) and at each level by a variety of agencies. In some instances the regulatory policy is focused on a particular type of hazard (e.g., radiation exposure), in others on an individual industry (e.g., automotive safety) or on a particular segment of the population or human activity (e.g., occupational or consumer product safety). The policy is carried out with varying degrees of government involvement and specification as to the precise measures required to provide protection. In some cases very detailed protective regulations are developed and enforced by governmental agencies, whereas in others the policy relies mainly on the self-interest of industry or the public to voluntarily reduce risk.

From its inception the nuclear power industry has been subject to a comprehensive regulatory policy at the highest governmental level, initially administered by the Atomic Energy Commission (AEC) and now by the Nuclear Regulatory Commission (NRC). Yet there are still concerns in some quarters that the existing nuclear regulatory policy is inadequate and that more stringent requirements must be imposed. Indeed, there are those who contend that no amount of regulation can achieve the desired result. Alternatively, there is strong sentiment, particularly within the regulated industry, that existing nuclear regulatory policy has already far surpassed the objective of adequate protection and that additional requirements merely add to the cost of the plants without yielding justifiable benefit.

It is obvious that those holding these diverse opinions are basing their judgments on widely varying perceptions of (1) the residual risk associated with nuclear power, (2) the level at which such risk would become acceptable, or (3) the acceptable cost of achieving further reductions in risk. These perceptions are rarely expressed explicitly or in quantifiable values, but nonetheless they play an important role in shaping regulatory policy.

To provide some basis for judging the validity of these perceptions, it is instructive to review specific NRC licensing requirements against quantitative risk and cost–benefit criteria and to compare these results with similar values for protective measures associated with nonnuclear risks. Of particular interest are comparable regulations applicable to coal-fired power plants since coal is presently the primary alternative source of electric energy. This report summarizes several recent studies by the authors which address this subject.[1-3]

EFFECT OF REGULATORY POLICY ON POWER PLANT COSTS

New regulatory requirements have produced a dramatic impact in recent years on the cost of new power plants, both nuclear and fossil fueled. Since 1969 the capital cost of a new nuclear plant has increased from \$160/kW to \$913/kW, while the comparable cost of a coal-fired plant has gone from \$122/kW to \$639/kW (Ref. 4). Figure 1 shows the elements of this increase. Although inflation contributes to a significant portion, the predominant impact has been attributed to new regulatory requirements, an important element of which has been the cost of licensing delays. These capital cost increases have contributed significantly to changes in the relative cost of producing power at the bus bar for nuclear and coal-fired power plants.

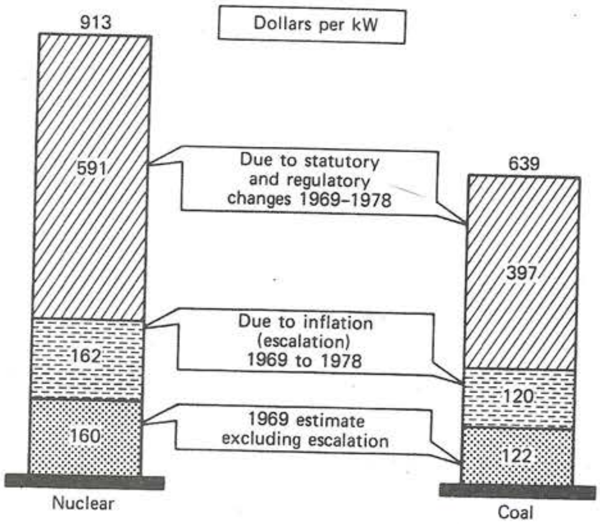
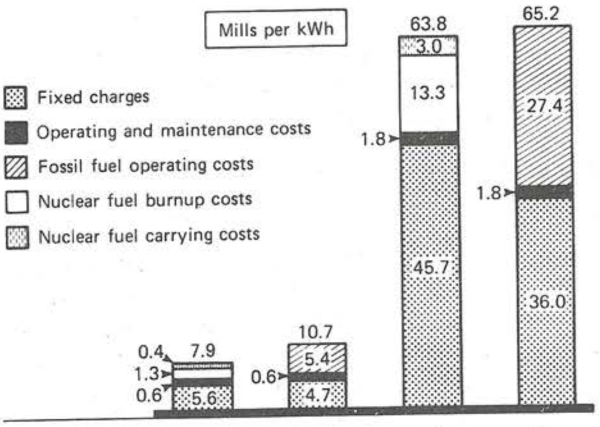


Fig. 1 Allocation of plant cost increases 1969 to 1978 (from Ref. 4).

As shown in Fig. 2, in 1969 nuclear enjoyed a 26% advantage over coal (7.9 vs. 10.7 mills/kWh), whereas in 1978 this gap narrowed considerably. This is due primarily to increases in the fixed charges, which are in turn mainly influenced by the changes in capital cost which, as noted, have been largely attributed to increased regulatory requirements.



Type of unit	Nuclear	Coal	Nuclear	Coal
Authorized	1969	1969	1978	1978
Commercial operation	1976, '78	1976, '77, '78	1988, '90	1988, '89, '90
Fuel cost levelization period	1977–1987		1989–1999	

Fig. 2 Levelized bus bar power costs for first 10 years of plant operation (70% capacity factor) (from Ref. 4).

It must be noted that these cost estimates are based on composite or average indices of equipment, labor, and fuel costs covering various areas of the United States and are therefore representative of a plant located in a hypothetical "Middletown, USA." Specific estimates of these factors for different areas of the country can and have produced[5,6] different conclusions regarding the relative cost of nuclear and coal-fired plants for specific utility service areas. Nonetheless the results indicate that the future direction of regulatory policy can have a critical influence on future decisions to choose nuclear or coal and could result in reversal of decisions that would otherwise indicate the choice of one over the other based on regional economic factors. The relative cost–benefit effectiveness of regulatory policy regarding these energy sources is therefore of more than academic interest.

COST–BENEFIT METHODOLOGY FOR NUCLEAR PLANT SAFETY FEATURES

A quantitative cost–benefit methodology has been used with respect to assessment of the radiological impact of normal plant operation on the environment and is, in fact, required by NRC regulations.[7] The methodology involves calculating the benefit of a particular design feature in terms of its ability to reduce annual population radiation exposures due to normal plant operation. This benefit (Δ man-rem/year) is then balanced against the annualized incremental cost of the design feature ($/year) to obtain the cost–benefit ratio ($/man-rem) of the feature. Should this ratio compare favorably with (i.e., be less than) the current acceptance criterion of $1000/man-rem, the feature should be incorporated in the plant design. A similar approach can be used to evaluate the cost effectiveness of safety features.

Since such environmental impact assessments are concerned with normal operation, there is no need to consider probabilistic uncertainties. However, when dealing with nuclear safety concerns involving accidents of low probability, the expected annual frequency of the events must be included. A generalized expression for the cost–benefit ratio, which takes into consideration both probability and consequences of events, is as follows:

$$\text{Cost/benefit ratio} = \frac{C}{\sum_{i=1}^{n} [P_i R_i] - \sum_{i=1}^{n} [P_i' R_i']}$$

where C = annualized cost of safety feature, $/year

P_i = probability of ith accident sequence of interest without safety feature installed, year^{-1}

R_i = radiological consequences of ith accident sequence of interest without safety feature installed, man-rem

P_i' = probability of ith accident sequence of interest with safety feature installed, year^{-1}

R_i' = radiological consequences of ith accident sequence of interest with safety feature installed, man-rem

n = number of accident sequences of interest (i.e., those upon which the proposed safety feature would have an effect in reducing probability and/or consequences).

In the following discussions this approach is used to evaluate the cost effectiveness of various engineered safety features (ESFs).

Cost–Benefit Analysis of Existing Engineered Safety Features

The design of current nuclear plant ESFs has been arrived at in a deterministic manner; that is, a set of rules and criteria has been established that specifies certain worst-case assumptions that must be used in determining ESF requirements. These rules are contained in the NRC's General Design Criteria,[8] siting regulations,[9] and in various regulatory guides. They are based, in large part, on a qualitative assessment of what is important to safety and on the concept of "defense in depth." As a result, all plants are now required to have an emergency core-cooling system (ECCS), a containment (including containment heat removal systems and fission product removal system), an on-site source of emergency electric power, and various other engineered safety features.

In applying cost–benefit methodology to such ESFs, the logical process to be followed would be to start with a hypothetical nuclear plant that does not contain these safety features, consisting primarily of design features and equipment necessary for normal operation and equipment protection. A risk assessment would then be performed, taking into account the various accident sequences and their consequences in the absence of ESFs. Then, in step sequence, each ESF would be added, the risk assessment re-performed with the feature added, and its cost–benefit ratio calculated until the established acceptance criterion is satisfied.

Since the *Reactor Safety Study*[10] (WASH-1400) represents a risk assessment of a typical nuclear plant, it can be applied to such an evaluation by modifying the calculated probabilities and consequences of relevant sequences to reflect the absence of various ESFs. In this way, equivalent event sequences that reflect the expected event probabilities and consequences without the ESF can be determined for each event. For example, in a plant without an ECCS or containment, it may be assumed that any loss-of-coolant accident (LOCA) could result in core melting and rapid atmospheric dispersion of the resulting fission products. Although the event of interest is simply any LOCA, the consequences of the event would be the same as for those WASH-1400 event sequences in which the ECCS and containment also fail. However, since the ECCS and containment are nonexistent, their failure probability is unity, and the probability of such severe consequences occurring is the same as the probability of the initiating LOCA, reflecting an increased risk. An example of the application of this approach is given in Table 1.

ESFs Evaluated

A cost–benefit evaluation using the foregoing methodology was made for the following key ESFs for a typical pressurized-water-reactor (PWR) plant as described in WASH-1400:

1. Emergency core-cooling system (ECCS)
2. Containment (including associated heat and fission product removal systems)
3. Emergency on-site alternating-current (a-c) power system [diesel-generator (DG) sets]

These key ESFs were applied individually and in all possible combinations and sequences to a base case involving a PWR devoid of these safety features.

Report WASH-1400 was based on a PWR plant that went into operation in 1972 and, of course, included these basic ESFs. Since that time NRC regulations have required the incorporation of additional ESFs, which are not reflected in the WASH-1400 risk analysis. One such addition is the hydrogen recombiner system, the need for which is based on deterministic assumptions. For the contribution of a hydrogen recombiner system to the reduction of accident risk to be assessed, a cost–benefit evaluation was performed for such a system applied to the complement of ESFs analyzed in WASH-1400 for a typical PWR. In this analysis it was assumed that the hydrogen recombiner system would be capable of eliminating entirely the risk of those accident sequences in which the containment failed due to hydrogen-related overpressure (i.e., all $P_i' = 0$). Since no ESF is capable of reducing the probability of any accident sequence to zero, the actual benefit will be less. This procedure, therefore, provides a lower limit on the cost–benefit ratio for the hydrogen recombiner system.

Probability and Consequence Values

The probabilities (P_i) of the various accident sequences of interest were obtained from WASH-1400, using median estimates for accident sequence probabilities. The fractions of core fission products released for each accident were classified, in the manner of WASH-1400, into nine release categories ranging from Category 1, corresponding to a core melt condition with rapid, direct atmospheric dispersion (i.e., without effective ECCS or containment) to Category 9, corresponding to no core melt with effective containment (i.e., ECCS and containment function as designed).

The radiological consequences (R_i) of each accident sequence of interest were calculated in terms of total integrated whole-body dose to an exposed population (man-rem), assuming a uniform population density of 400 persons per square mile surrounding the site. This value is consistent with NRC guidelines[11] on site suitability with respect to population density and is typical, on a cumulative population basis, of many existing nuclear plant sites. The population dose for a

Table 1 Example of ESF Cost–Benefit Analysis

ESF case	Accident event sequence*	Probability, $year^{-1}$	Equivalent WASH-1400 consequence sequence*	Release category	Radiological consequences, man-rem	Risk, man-rem/year
		P_i			R_i	P_iR_i
No ESFs	A	1×10^{-4}	AB – α	1	8.0×10^7	8.0×10^3
	S_1	3×10^{-4}	S_1 B – α	1	8.0×10^7	2.4×10^4
	S_2	1×10^{-3}	S_2 B – α	1	8.0×10^7	8.0×10^4
	TMLB	3×10^{-4}	TMLB – α	1	8.0×10^7	2.4×10^4
						$\Sigma P_iR_i = 1.4 \times 10^5$
		P'_i			R'_i	$P'_iR'_i$
ECCS only	A	1×10^{-4}	A – β	8	4.0×10^4	4.0×10^0
	S_1	3×10^{-4}	S_1 – β	8	4.0×10^4	1.2×10^1
	S_2	1×10^{-3}	S_2 – β	8	4.0×10^4	4.0×10^1
	AB	1×10^{-7}	AB – α	1	8.0×10^7	8.0×10^0
	AD	2×10^{-6}	ADC – α	1	8.0×10^7	1.6×10^2
	AH	1×10^{-6}	AH – α	3	4.4×10^7	4.4×10^1
	S_1 B	2×10^{-7}	S_1 B – α	1	8.0×10^7	1.6×10^1
	S_1 D	3×10^{-6}	S_1 DC – α	1	8.0×10^7	2.4×10^2
	S_1 H	3×10^{-6}	S_2 H – α	3	4.4×10^7	1.3×10^2
	S_2 B	8×10^{-7}	S_2 B – α	1	8.0×10^7	6.4×10^1
	S_2 D	9×10^{-6}	S_2 DC – α	1	8.0×10^7	7.2×10^2
	S_2 H	6×10^{-6}	S_2 H – α	3	4.4×10^7	2.6×10^2
	TMLB	3×10^{-4}	TMLB – α	1	8.0×10^7	2.4×10^4
						$\Sigma P'_iR'_i = 2.5 \times 10^4$

$$\text{ECCS cost–benefit ratio} = \frac{C}{\Sigma P_iR_i - \Sigma P'_iR'_i} = \frac{\$1.5 \times 10^6\text{/year}}{1.4 \times 10^5 - 2.5 \times 10^4} = \$14\text{/man-rem}$$

*Key to PWR accident sequence symbols (from Report WASH-1400, Table 5-2):

A, Intermediate to large LOCA.
B, Failure of electric power to ESFs.
B′, Failure to recover either on-site or off-site electric power within about 1 to 3 h following an initiating transient which is a loss of off-site a-c power.
C, Failure of the containment spray injection system.
D, Failure of the emergency core-cooling injection system.
F, Failure of the containment spray recirculation system.
G, Failure of the containment heat removal system.
H, Failure of the emergency core-cooling recirculation system.
K, Failure of the reactor protection system.
L, Failure of the secondary system steam relief valves and the auxiliary feedwater system.
M, Failure of the secondary system steam relief valves and the power conversion system.
Q, Failure of the primary system safety relief valves to reclose after opening.
R, Massive rupture of the reactor vessel.
S_1, A small LOCA with an equivalent diameter of about 2 to 6 in.
S_2, A small LOCA with an equivalent diameter of about ½ to 2 in.
T, Transient event.
V, Low-pressure injection system (LPIS) check valve failure.
α, Containment rupture due to a reactor vessel steam explosion.
β, Containment failure resulting from inadequate isolation of containment openings and penetrations.
γ, Containment failure due to hydrogen burning.
δ, Containment failure due to overpressure.
ε, Containment vessel melt-through.

Category 1 release was obtained from Fig. VI 13-18 in WASH-1400 (Ref. 10). Total doses for other release categories were obtained on the basis of the fractional quantities of the various nuclides included in each release category and their relative contributions to whole-body dose. Table 2 gives the radiological consequences (R_i) for each release category.

Table 2 Population Doses Resulting from Various Accident Release Categories

Release category	Whole-body dose, man-rem
1	8.0×10^7
2	7.2×10^7
3	4.4×10^7
4	7.6×10^6
5	1.9×10^6
6	4.4×10^5
7	1.0×10^4
8	4.0×10^4
9	40

Cost Values

Annual costs for each ESF were based on estimates for typical PWR plants in 1978 dollars with 8% interest over 40 years. In each case the costs include only the *incremental* cost of providing the ESF function with respect to equipment or structures that would be expected to be provided for normal plant operation. The additional cost of a full-pressure-retaining containment structure and associated systems over the cost of a conventional-type power-plant structure housing the reactor coolant system was estimated for containment. For the ECCS, it was assumed that a residual heat removal system would be provided for normal plant shutdown. Thus the ECCS costs are those associated with the additional equipment (high-pressure safety injection system and accumulators) required to perform the ECCS function. Emergency diesel-generator system costs were based on replacing a small diesel generator used for plant equipment protection with two redundant full-capacity diesel generators capable of supplying ESF loads and housed in a separate seismic Category I building. Hydrogen recombiner system costs are based on actual costs for a typical PWR plant. (ESF cost values are summarized in Table 5.)

ESF Cost–Benefit Ratios

Table 3 gives the summation of (P_i R_i) values for all accidents of interest for the base case (no ESF) and for the ECCS, containment, and DG sets applied individually and in combination. This summation represents the residual risk in man-rem/year for each case. The risk reduction for an ESF in any particular case is the difference between the residual risk for that case and the residual risk for the corresponding case without that ESF. It is this benefit value which must be compared to the annualized cost (C) of the ESF to determine its cost–benefit ratio. Table 4 presents the benefits and cost–benefit ratios for the ECCS, containment, and DG sets applied in various sequences.

An examination of the data given in Table 4 shows that the cost–benefit ratio for any particular ESF is highly dependent on the sequence in which it is applied in the risk assessment. When considered first, the cost–benefit ratio for each of the three ESFs is well below \$1000/man-rem, indicating that, individually, the cost of these features would be well justified in the absence of any other ESFs. However, using the traditional cost–benefit methodology of adding improvements in order of increasing cost–benefit ratio, ESF Sequence 3 would be chosen, which could lead to the faulty conclusion that the containment is not justified since its cost–benefit ratio is \$2083. While this methodology is suitable for determining optimum allocation of a fixed sum of money which is available for investment in safety, it does not necessarily guarantee satisfaction of a criterion which specifies that any and all safety improvements should be made which cost less than \$1000/man-rem. In this case, ESF Sequence 4 results in the optimum cost–benefit utilization of the three ESFs considered, with cost–

Table 3 Nuclear Plant Accident Risks for Various ESFs and Combination of ESFs

Installed ESFs	Residual risk, man-rem/year	Risk reduction factor
Base (no ESFs)	1.4×10^5	
DGs only	1.1×10^5	1.2
ECCS only	2.5×10^4	5.4
Containment only	1.9×10^4	7.2
ECCS + containment	1.8×10^4	7.6
ECCS + DGs	1.8×10^3	76
Containment + DGs	840	160
ECCS + containment + DGs	360	378

Table 4 Cost–Benefit Ratios for ESFs Applied in Various Sequences

ESF sequence	Sequence of ESF application 1	2	3
1	DG	ECCS	Containment
Risk reduction, Δ man-rem/year	2.4×10^4	1.1×10^5	1.4×10^3
Cost–benefit ratio, \$/man-rem	83	14	2083
2	DG	Containment	ECCS
Risk reduction, Δ man-rem/year	2.4×10^4	1.1×10^5	4.8×10^2
Cost–benefit ratio, \$/man-rem	83	27	3125
3	ECCS	DG	Containment
Risk reduction, Δ man-rem/year	1.1×10^5	2.4×10^4	1.4×10^3
Cost–benefit ratio, \$/man-rem	14	85	2083
4	ECCS	Containment	DG
Risk reduction, Δ man-rem/year	1.1×10^5	6.8×10^3	1.8×10^4
Cost–benefit ratio, \$/man-rem	14	441	111
5	Containment	DG	ECCS
Risk reduction, Δ man-rem/year	1.2×10^5	1.8×10^4	4.8×10^2
Cost–benefit ratio, \$/man-rem	25	111	3125
6	Containment	ECCS	DG
Risk reduction, Δ man-rem/year	1.2×10^5	4.0×10^2	1.8×10^4
Cost–benefit ratio, \$/man-rem	25	3750	111

benefit ratios of \$14, \$441, and \$111 per man-rem for the ECCS, containment, and DG sets, respectively.

The addition of the hydrogen recombiner system to the ECCS, containment, and the DG sets resulted in a minimal additional reduction in risk (less than 0.13 man-rem/year) because, according to WASH-1400, the probability of post-LOCA containment failure due to hydrogen explosions or combustion even without recombiners is extremely low. This estimated benefit value is so small that, even though the cost of the recombiner system is relatively small compared with the other ESFs, the cost–benefit ratio is quite high. The benefits, costs and cost–benefit ratios of hydrogen recombiners compared with the other ESFs are shown in Table 5 for the most cost–beneficial sequence of addition.

Consideration of the Risk to Individuals

The cost–benefit analysis thus far has been based on the risk to populations. Since the effects of radiation doses resulting from accidents generally decline with distance from a plant, the risk to individuals is clearly nonuniform over the entire population. An individual located immediately adjacent to the site boundary may therefore understandably question the validity of cost–benefit criteria that rely on benefit measurements based solely on the risk to populations.

An assessment of the maximum risk to an individual near a nuclear plant site was made to see whether or not such concerns are warranted. The nuclear accident risk to an individual located near the

Table 5 Summary of Cost–Benefit Analysis for Engineered Safety Features

Engineered safety feature	Risk reduction, man-rem/year	Cost, \$/year	Cost–benefit ratio, \$/man-rem
ECCS	1.1×10^5	1.5×10^6	14
Containment	6.8×10^3	3.0×10^6	441
Emergency power system	1.8×10^4	2.0×10^6	111
Hydrogen recombiner system	<0.13	4.0×10^4	$>3 \times 10^5$

site is dominated by the probability of those accidents which could result in core melting and rapid release of resulting fission products to the atmosphere (i.e., WASH-1400 release categories 1 to 5). Such accidents could result in early fatality (death within a year) of any individual directly exposed to the accident plume within a few miles of the site. Other accidents involving release categories 6–9 involve delayed release of much smaller inventories of fission products to the atmosphere. Evacuation procedures and lower exposure dose rates would result in much lower risks, even though the probability of such accidents may be much higher.

The maximum fatality risk to an individual was calculated assuming that the individual is always located near the site and that, in the event of a serious accident, there is a 50% probability that the plume will traverse this location (i.e., the individual is downwind of the plant). It is further assumed that in such an event exposures will result in early fatality. These assumptions are clearly conservative since they do not account for time spent away from the site, narrowness of the plume, and the mitigating effect of intensive medical treatment, all of which would serve to reduce individual risk.

Figure 3 shows the maximum risk to an individual from nuclear plant accidents with respect to the cumulative cost of adding ESFs to reduce that risk. Also shown are the average background risks for an individual from nonnuclear accidents (falls, fires, etc.) and from disease. As indicated, even with no ESFs installed, the maximum risk to an individual is only slightly more than the nonnuclear accident risk and less than 10% of all nonnuclear risk. Adding an ECCS, a containment, and DG sets reduces the nuclear risk to less than 0.1% of the total nonnuclear risk. Conservatively assuming that all persons within 3 miles of the plant would be exposed to this maximum risk and again assuming a density of 400 persons per square mile, the installation of these ESFs would reflect an annual expenditure of over $500 per person to achieve a reduction in nuclear risk from 10% to less than 0.1% of the total background nonnuclear risk.

This figure would seem to compare favorably with the amount individuals themselves are willing to voluntarily pay for nonnuclear risk reduction. For example, it is unlikely that many individuals would be willing to support such a cost–benefit ratio themselves if it were demonstrated to them (as it probably could be) that annual physical examinations costing $500 could reduce by 10% the risk of death due to disease. Indeed, an opinion survey[12] showed that individuals are willing to spend, on the average, only $56 to achieve a reduction in personal risk of five times greater than this. The question of individual risk and individual cost–benefit criteria, therefore, should not be an overriding issue with respect to risk and cost–benefit criteria applied on a population basis.

Discussion

The foregoing analysis demonstrates the usefulness of quantitative cost–benefit analysis as applied to ESFs and nuclear safety concerns. However, the results should not be taken as a definitive cost–benefit analysis on an absolute scale. There are large uncertainties in the probabilities and consequences presented in WASH-1400. Further, the idealized nature of the assumed population distribution could result in significant variations from actual site conditions. In addition there may be other monetary costs or

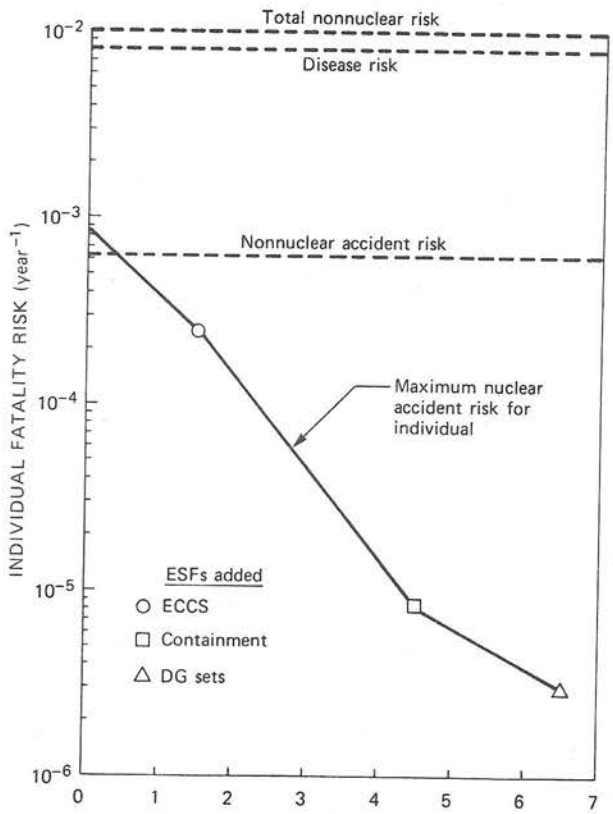


Fig. 3 Maximum risk to an individual from nuclear plant accidents with respect to the cumulative cost of adding engineered safety features (ESFs) to reduce that risk. Also shown are the average background risks for an individual from nonnuclear accidents (falls, fires, etc.) and from disease.

benefits, such as risk of property damage or plant outage, which have not been included here.

The methodology does provide insight into the relative cost effectiveness of existing ESFs and the manner in which they contribute to reducing accident risk. The results show that the major contributors to risk are the small LOCAs and transient events involving loss of electric power. As might be expected, the DGs by themselves provide a small fractional risk reduction factor (see Table 3). The ECCS or containment each reduces risk by a factor of 5 to 7. With diesel generators installed, the effectiveness of the ECCS or the containment is increased by at least an order of magnitude and, with all three, the overall risk is reduced by almost a factor of 400. This interdependence supports the defense-in-depth concept wherein the effectiveness of each ESF is amplified greatly in combination with other ESFs.

It would also appear that the regulatory policy regarding the need for ECCS, containment, and emergency power systems is supported on a quantitative cost–benefit basis at least with respect to the \$1000/man-rem criterion. However, the cost–benefit evaluation for hydrogen recombiners shows that they are orders of magnitude less cost effective relative to the three other basic safety features evaluated. Moreover, even considering large uncertainties in the WASH-1400 risk values, they probably could not be justified with respect to a \$1000/man-rem acceptance criterion, which is generally recognized to be a conservatively high value.

This conclusion may seem unwarranted in view of the apparently prominent role played by hydrogen recombiners in the recent Three Mile Island accident. However, a number of factors would seem to indicate that the actual risk of serious population exposures due to hydrogen-related containment failure in that event would not have been great even if recombiners had not been installed prior to the accident.

From preliminary data on the event, it appears that the hydrogen level in the containment quickly rose to about 2.5% within about 4 days after the onset of the event and remained at about that level even though the recombiners were not brought into operation until an additional 2 days had elapsed. This indicates that there probably would have been considerable additional time available before hydrogen levels would have reached even the lower flammability limit of 4%. It then would have permitted consideration of such alternative actions as bringing a portable recombiner unit from offsite for emergency operation or reliance on controlled purging to limit hydrogen levels in the absence of permanently installed recombiners. Ultimately, evacuation of the surrounding population, already partially achieved, could have been (and presumably would have been) extended out to several miles or more if recombiners had not been available and containment hydrogen levels approached dangerous levels. While certainly not a public relations coup, this would have drastically reduced population exposures in the event of additional releases of contained fission products due to controlled purging or even hydrogen-related containment failure. Furthermore, it is not at all clear whether the containment would have failed catastrophically in the event of hydrogen burning or explosion.

Of course, given a set of preexisting events involving release of fission products and hydrogen to the containment, such as occurred at Three Mile Island, hydrogen recombiners could most probably be shown to be cost effective on a *conditional* basis. This may support the concept of sharing a portable recombiner among a number of plants with provisions for its installation and operation in any unit. However, it does not necessarily follow that the inclusion of redundant recombiners as permanently installed engineered safety features in all plants is cost-effective as a predetermined design decision, particularly when considered relative to alternative engineered safety features. The very same post-Three Mile Island knowledge which appears to support the wisdom of having recombiners installed also clearly demonstrates the greater relative importance of the emergency feedwater system, ECCS, and the containment and indicates that other design measures (such as positive indication of pressurizer relief valve position, which could have averted the accident) may have been, in retrospect, far more cost-effective.

COMPARISON WITH COAL-FIRED POWER PLANTS AND OTHER NONNUCLEAR RISKS

For an even broader perspective to be achieved on the effectiveness of the guidelines under which the nuclear power industry is regulated, it is meaningful to compare the risk and cost–benefit values for nuclear regulatory policies with those for the protective measures associated with nonnuclear risks, particularly with regulations for coal-fired power plants.

For such comparisons to be made, a common standard of measuring cost–benefit effectiveness must be used. A commonly used index relates investment costs to expected reduction in health effects in terms of the reduced excess mortality rates achieved. This should not be taken as a precise or complete measure of effectiveness since there may be additional health and safety benefits (i.e., reduction in illnesses or injuries) or additional cost impacts or benefits (e.g., reduced risk of property damage) associated with regulations or protective measures. However, it does provide a useful measure for making order-of-magnitude comparisons of cost effectiveness since it relates costs and benefits in consistent units for both nuclear and nonnuclear risks.

Proposed EPA Regulations for SO_2 Removal

There is considerable uncertainty in estimating the health effects associated with coal-fired power plants. However, it is generally agreed that increased sulfur dioxide (SO_2) emissions are highly correlated with observed increases in morbidity and mortality. If a linear relationship is assumed for SO_2-related mortality,[13] these effects could be reduced linearly by reducing the amount of SO_2 discharged to the atmosphere. This could be accomplished either by burning low-sulfur coal or by removing the SO_2 deposited in the plant's vent stack (scrubbing) after combustion.

The Environmental Protection Agency (EPA) has proposed regulations[14] that would limit the permissible concentrations of various pollutants in the emissions from fossil-fuel plants and would, in particular, require full scrubbing (at least 85% removal) of sulfur dioxide regardless of the sulfur content of the fuel. Within the power industry there are serious questions as to the technical feasibility of meeting these proposed regulations, and a "sliding scale" for SO_2 removal, ranging from 40 to 85% depending on the sulfur content of the coal, has been suggested as an alternative.

Because of the large uncertainty in regard to the health effects of SO_2 and uncertainties in the installation and operating cost of SO_2 removal equipment, it is difficult to assign a single cost–benefit value for scrubbers. Hamilton and Manne[15] have estimated a range of values for SO_2-related mortality for situations involving the use of high- and low-sulfur coal with and without scrubbers. The Hamilton and Manne (Ref. 15) SO_2–mortality estimates provide a basis for comparison with the nuclear plant cost–benefit ratios since they are based on an equivalent unit size [1000 MW(e)] and population distribution (400 persons per square mile).

These values, adjusted for 85% removal, were used in conjunction with high and low estimates of the costs of scrubbers to provide maximum and minimum cost–benefit ratios.

Nuclear and Nonnuclear Cost–Benefit Ratios

Table 6 presents a comparison of cost–benefit values in terms of investment costs necessary to achieve a reduction in mortality risk for NRC-mandated

Table 6 Cost–Benefit Ratios for Various Health and Safety Protective Measures

	Cost–benefit ratio, \$1 million/life saved
Nuclear power-plant design features	
Radwaste effluent treatment systems	10
ECCS	0.1
Containment	4
DG sets	1
Hydrogen recombiners	>3000
Coal-fired power plant design features	
High-sulfur coal with SO_2 scrubbers, 85% removal	0.1–1.4
Low-sulfur coal with SO_2 scrubbers, 85% removal	0.7–10
Occupational health and safety	
OSHA* coke fume regulations	4.5
OSHA benzene regulations	300
Environmental protection	
EPA† vinyl chloride regulations	4
Proposed EPA drinking water regulations	2.5
Fire protection	
Proposed CPSC‡ upholstered furniture flammability standards	0.5
Smoke detectors	0.05–0.08
Automotive and highway safety	
Highway safety programs	0.14
Auto safety improvements, 1966–1970	0.13
Air bags	0.32
Seat belts	0.08
Medical and health programs	
Kidney dialysis treatment units	0.2
Mobile cardiac emergency treatment units	0.03
Cancer screening programs	0.01–0.08

*OSHA, Occupational Safety and Health Administration.
†EPA, Environmental Protection Agency.
‡CPSC, Consumer Product Safety Commission.

nuclear plant design features, EPA-proposed coal-plant design features, and other nonnuclear health and safety protective measures. For the nuclear plant radwaste systems and engineered safety features, these values are based on a linear dose–mortality relationship of 1.0×10^{-4} excess deaths per man-rem exposure,[16] using the \$1000/man-rem criterion for radwaste systems and the \$/man-rem cost–benefit ratios developed previously for the ESFs. The range of values for SO_2 scrubbers was established as described above. Cost–benefit ratios for other protective measures were obtained from Refs. 12, 17, and 18 through 22.

Table 6 shows that, in general, nuclear plant regulatory policy results in a considerably higher investment to achieve reductions in public mortality risk than for other activities. With the exception of the ECCS, all other nuclear plant design features have cost–benefit ratios of \$1 million or more per life saved, with the hydrogen recombiners having a ratio in excess of \$3 billion per life saved.

With respect to coal-fired plants, it would appear that requirements for full scrubbing where low-sulfur coal is used could yield cost–benefit values comparable to those associated with nuclear plant design features. However, even with the use of scrubbers and low-sulfur coal, the residual mortality risk for a coal plant remains significantly higher than for a nuclear plant (0.4 to 7 vs. 0.04 excess deaths per year), though well below that associated with other commonly accepted risks.

Of greater significance, Table 6 demonstrates a complete lack of consistency in health and safety policy on any uniform cost–benefit basis among agencies or even within agencies. With respect to occupational hazards, it has been estimated that the Occupational Safety and Health Administration's (OSHA) near-zero limit on benzene in the work place will prevent two cancer deaths every 6 years at a cost of \$300 million each. These regulations have been challenged and struck down in court because OSHA has not shown that the benefits of its requirements justify the cost. However, OSHA has maintained that it is not required to make cost–benefit judgments, and has taken the case before the Supreme Court which should rule on this important matter soon. By contrast, OSHA's regulations for limiting coke fumes in the steel industry have been estimated at \$4.5 million per worker life saved.[12]

The EPA regulations for controlling vinyl chloride emissions have been estimated to cost at least \$4 million per life saved,[19] and drinking water regulations proposed by EPA imply a cost of \$2.5 million[17] per reduced fatality in the exposed population.

In the area of consumer product safety, the National Bureau of Standards has proposed a comprehensive analytical approach to determining cost effectiveness of regulations.[20] A preliminary application of this methodology[21] to standards being considered by the Consumer Product Safety Commission (CPSC) to reduce the fire hazards of upholstered furniture shows that several hundred lives could be saved each year at a cost of about \$500,000 per reduced fatality. However, it appears that the standards may not be adopted owing to the perceived inflationary and economic impact on the furniture industry.

A value of \$140,000 per life has been used explicitly in decision making regarding highway safety programs,[17] and many highway improvements (such as guardrail installation, better surfaces for skid resistance, and improved warning signals) that could save many lives could be made at costs between \$20,000 and \$100,000 per life saved.

In automotive safety, improvements made between 1966 and 1970 have been estimated to have reduced traffic fatalities by 28,200 during this period at a cost of \$130,000 per life saved. Among these, seat belts save 5,000 lives per year at a cost of \$80,000 per life. Installation of airbags in new cars, a safety measure that has been delayed because of concern for the cost (about \$200 per car), could save additional lives at a cost of about \$320,000 per life.[22]

One of the best life-saving bargains available appears to be the smoke detector. It has been estimated that placing smoke detectors in all residences in the United States could result in several thousand fewer deaths annually at a cost of between \$50,000 and \$80,000 per life saved.[18] However, no comprehensive regulatory policy yet exists to require their use.

In the area of medical treatment, it has been estimated that kidney dialysis treatment units and mobile emergency cardiac units save lives at an investment cost of \$200,000 and \$30,000 per life, respectively.[22] The federal government has established a program for subsidizing the cost of dialysis treatment, which undoubtedly has saved numerous lives, but has left the determination of need and funding for emergency cardiac units largely up to local political jurisdictions, with predictably uneven results in degree of protection provided. Various cancer screening programs, which are largely voluntary, have been demonstrated to prevent cancer deaths at costs between \$10,000 and \$80,000 per life saved.[27]

All these cost–benefit ratios imply a monetary value for a statistical life.* Although this is a highly subjective and controversial matter, there have been estimates made on the basis of implied and explicit values which society has associated with the actual or potential loss of human life. Table 7 lists some of these values.

Table 7 Costs Placed on a Statistical Life

	Cost, dollars per life
Average loss of income due to death (6000 lost working days at $50/day)*	300,000
Jury awards in loss-of-life lawsuit†	50,000–500,000
Hazardous duty pay for pilots, taking into account the probability of death†	135,000–980,000
Dollar value of property loss in cases where people near an accident primarily remembered the property loss rather than the loss of life†	200,000

*Ref. 23.
†Ref. 24.

The cost–benefit ratios for nuclear plant-design features compare favorably with the statistical life values given in Table 7; i.e., the amount being spent to reduce mortality risk is well in excess of the amount that has been associated with the statistical value of human life. Many of the cost–benefit values for nonnuclear risks are well below these values, indicating that the public should be willing to support greater investments in protective measures to reduce these risks further. This suggests that the regulatory emphasis on further reducing nuclear plant risks may not be justified in view of the availability of more cost-effective means of reducing risks that are not being fully pursued. Indeed, it would appear that the $4 million annual cost involved in equipping 100 nuclear plants with hydrogen recombiners could more effectively be invested in emergency cardiac treatment units or cancer screening programs, which at the cost–benefit values cited for them, could result in several hundred additional lives saved per year.

*It is important to distinguish between a statistical (or unidentified, theoretically calculated) loss of life and an actual (or identified) loss of life.

COMPARISON OF GASEOUS EFFLUENT STANDARDS FOR NUCLEAR AND FOSSIL-FUEL POWER PLANTS

The analysis presented above indicates a marked inconsistency between the cost–benefit effectiveness of public health and safety policy regarding nuclear and nonnuclear risks. A specific example of this disparity can be seen in a direct comparison of regulatory standards for gaseous effluents from nuclear and fossil-fuel power plants. Lave and Freeburg[13] addressed this subject in 1973; however, the regulatory limits have since been drastically changed as a result of Appendix I to Title 10, *Code of Federal Regulations,* Part 50 (10 CFR 50) and the 1977 amendment to the Clean Air Act. The regulations considered appropriate for performing a comparison of limitations imposed on gaseous effluents from nuclear fossil-fuel power plants are Appendix I to 10 CFR 50, Section II for nuclear plants and Section 163(b)(2) of the Clean Air Act (as amended) for fossil-fuel plants.

Gaseous Effluents Limitations for Nuclear Power Plants

Appendix I to 10 CFR 50, Section II requires that the design of a nuclear power facility must provide assurance that (1) the calculated annual total quantity of all radioactive material above background to be released to the atmosphere from each light-water-cooled nuclear power reactor will not result in an estimated annual dose of 5 mrems to the whole body of any individual in an unrestricted area, and (2) the calculated annual total quantity of all radioactive iodine and radioactive material in particulate form to be released to the atmosphere in effluents from each light-water-cooled nuclear power reactor will not result in an estimated annual dose or dose commitment to any individual in an unrestricted area from all pathways of exposure in excess of 15 mrems to any organ. These regulations establish the design basis of the building ventilation and gaseous radwaste systems of nuclear power facilities.

Gaseous Effluent Limitations for Fossil-Fuel Power Plants

With the issuance of the August 1977 amendment to the Clean Air Act and the anticipated regulatory modifications associated therewith, it is difficult to select a gaseous effluent limitation for fossil-fuel plants that can be appropriately compared to the nuclear plant limits. However, considering the new source

Table 8 Individual Mortality Risks Associated with Gaseous Effluent Standards for Nuclear and Fossil-Fuel Plants

NUCLEAR PLANT STANDARDS			
Risk contributor	10 CFR 50 App. I regulatory limit, rem/year	Risk* coefficient, deaths/rem	Mortality risk per year
Whole-body dose	0.005	1.0×10^{-4}	5.0×10^{-7}
Thyroid dose	0.015	5.0×10^{-6}	7.5×10^{-8}
		Total individual risk per year = 5.8×10^{-7}	

FOSSIL-FUEL PLANT STANDARDS			
Risk contributor	PSD Class II regulatory limit, $\mu g/m^3$	Risk† coefficient, deaths/(year)($\mu g/m^3$)	Mortality risk per year
Sulfur dioxide	20	3.9×10^{-6}	7.8×10^{-5}
Particulates	19	8.5×10^{-6}	1.6×10^{-4}
		Total individual risk per year = 2.4×10^{-4}	

*From Ref. 16. †From Ref. 13.

performance standards, the existing primary and secondary national ambient air quality standards, and the prevention of significant deterioration (PSD) limits for Classes I, II, and III as described in Section 163 of the Clean Air Act as amended in August 1977, the Class II concentration limits are considered the most appropriate for comparison to the nuclear effluent guidelines. This section of the act sets a limit on the maximum allowable increase in concentrations of sulfur dioxide and particulate matter over the existing baseline concentration.

Comparison of Risks to Individuals

The gaseous effluent regulations cited establish radionuclide and air pollution limits to which an individual may be exposed. Since these peak average annual concentrations would only occur at specific "maximum" locations off-site, the number of people exposed to these limited concentrations would be limited. The general population would be exposed to levels well below these limits.

Table 8 presents the maximum risks associated with exposure to the regulatory limits for gaseous effluents from nuclear and fossil-fuel plants. These results reveal that the potential adverse health implications of the effluent limits for gaseous effluents for nuclear plants are about 400-fold less than those for coal-fired power plants. When we consider that adverse human health effects associated with ambient SO_2 concentrations which are close to the PSD Class II regulatory limits[25] have been observed, but no adverse effects have been observed from radiological exposures which are well above the Appendix I regulatory limits,[26,27] the disparity in actual risks may be much greater than indicated.

To put these risks into perspective, the public thinks an individual risk is high if it is greater than 10^{-4}/year and low if it is less than 10^{-4}/year (Ref. 28). Clearly, by this criterion the nuclear risks (5.8×10^{-8} per year) should be acceptable and the fossil-fuel risks (2.4×10^{-4} per year) should be borderline.

Comparing these risks with the risks to individuals in the general population from various types of accidents[10] reveals that (1) the maximum calculated individual risk from exposure to nuclear plant effluents at their regulatory limits is comparable to the actual risk of being struck by lightning (8×10^{-7} year^{-1}) and (2) the calculated individual risk from exposures to the gaseous effluent from a coal plant operating at the PSD Class II regulatory limits is comparable to the risk of death by a motor vehicle accident (2.8×10^{-4} year^{-1}).

On the basis of the preceding comparisons of individual risk of death, it seems the regulations limiting gaseous effluent emission from fossil-fuel plants are less restrictive than the regulations that set radiological limits for nuclear plants by at least two orders of magnitude.

At each step in the foregoing analysis there are numerous assumptions that could be modified to give different results. However, each assumption was selected so that the measure of risk for each pollutant has the same degree of inherent conservatism. Accordingly, the values of 5.8×10^{-7}/year for radiological risks and 2.4×10^{-4}/year for fossil-fuel risks should be viewed as an index of risk rather than an accurate expression of absolute risk.

Comparison of the Risks to Populations

If a power plant is discharging gaseous effluents at its regulatory limits, the average member of a population in the vicinity of the plant would be exposed to concentrations of airborne pollutants, both radiological and nonradiological, which are well below the regulatory limits. This is a result of atmospheric dispersion, in-transit depletion, and, for radioactive effluents, radiological decay. Assuming that a nuclear power plant is operating at its regulatory limit, the average individual within 50 miles of the plant would receive an exposure of less than 0.1 mrem/year to the whole body and the thyroid gland. At a comparable coal-plant site, the average individual would be exposed to less than 0.1 $\mu g/m^3$ of SO_2 and particulates. This is based on an assumed 100-fold difference between the peak annual and average annual concentration within a 50-mile radius of the plant.

Accordingly, the nuclear regulatory limits are also at least 100-fold more restrictive than fossil-fuel effluent limits when assessed in terms of health impact on the population in general. It could be argued that the difference is even greater since SO_2 is transformed to sulfates during transport and the concentration of sulfates relative to SO_2 increases as a function of distance from the source of release. Since sulfates are believed to be more toxic than SO_2 [EPA-450/2-75-007 (Ref. 25)], the risk as a function of distance from the point of release may not decline as rapidly as it does for radiological effluents. In addition, the population density in the vicinity of a fossil-fuel plant is usually greater than that in the vicinity of a nuclear power plant, causing relatively greater cumulative impacts on the population.

Cost Implications of Regulatory Disparities

The apparent two-orders-of-magnitude disparity between the health effects of effluent limits for nuclear and fossil-fuel power plants has cost implications. For example, the present generation of nuclear power plants is provided with extensive effluent processing capabilities to meet the stringent requirements of Appendix I to 10 CFR 50. For the individual dose limits of Appendix I to be met, many gaseous-waste processing systems are required to provide holdup and filtration of radioactive effluents. When the costs of these additions are amortized over the life of the plant and operating and maintenance costs are included, the total annual cost for the additions required to meet Appendix I is approximately $0.5 million per plant. Since none of these additions to the radwaste system would be required if the effluent guidelines were 100-fold less restrictive (i.e., comparable to the fossil-fuel plant limits), it is clear that the disparity between the gaseous effluent limits for fossil-fuel and nuclear power plants has adverse economic implications for nuclear plants. Alternatively, if fossil-fuel plants were required to effect an additional 100-fold reduction in effluent releases to attain a health impact comparable to that of nuclear plants, it would in all probability render construction of such plants economically and technically unfeasible.

The preceding discussion is not intended to imply that the power industry is not spending large sums of money to meet the existing regulations for fossil-fuel plants. In fact, the costs of meeting the new Clean Air Act guidelines for a coal plant is well in excess of $0.5 million per year. The point is that the industry would be spending about $0.5 million per year less for each nuclear plant if the NRC's effluent guidelines for nuclear plants were comparable to those for fossil-fuel plants in terms of ill health.

CONCLUSION

The foregoing analyses indicate a marked lack of uniformity in the level of public health and safety protection on a comparative risk or cost–benefit basis. This raises the fundamental questions of whether such disparities as these should be allowed to continue and, if not, how they may be resolved.

The fact that these inconsistencies exist is the result of (1) having the public health and safety protection administered by a host of agencies, each independently focusing on specific industries or hazards, and (2) a philosophy whereby regulations are set as far below the hazardous level as the market can bear. Regulating a particular industry in this manner can have the effect of subsidizing an otherwise non-competitive alternative at the cost of the health and well-being of the general public. These disparities could

ceedings of the American Nuclear Society Topical Meeting, Los Angeles, Calif., May 8–10, 1978, American Nuclear Society, LaGrange Park, Ill., 1978.
18. M. Singer, How to Reduce Risks Rationally, *Public Interest,* 51: 93-112 (1978).
19. E. A. Kazmarek, Evaluation of Reasonable Risk, paper presented at the 51st Annual Conference of The Water Pollution Control Federation, October 1–6, 1978, Anaheim, Calif.
20. C. O. Muelhause, A Cost/Benefit Framework for Consumer Product Safety Standards, *J. Res. Natl. Bur. Stand.,* 83(5): 459-483 (September–October 1978).
21. B. Buchbinder, S. G. Helzer, and F. L. Offersend, *Preliminary Report on Evaluating Alternatives for Reducing Upholstered Furniture Fire Losses,* Report NBSIR-77-1381 (PB-273 943), National Bureau of Standards, NTIS, 1977.
22. B. L. Cohen, Society's Valuation of Life Saving in Radiation Protection and Other Contexts.
23. National Research Council, Advisory Committee on the Biological Effects of Ionizing Radiation, *Considerations of Health Benefit–Cost Analysis for Activities Involving Ionizing Radiation Exposures and Their Alternatives,* Report EPA 520/4-77/003 (PB-286 555), NTIS, 1977.
24. H. J. Otway, The Quantification of Social Values, in *Risk Vs. Benefit: Solution or Dream,* H. J. Otway (Ed.), USAEC Report LA-4860-MS, pp. 1–13, Los Alamos Scientific Laboratory, February 1972, NTIS.
25. U.S. Environmental Protection Agency, *Position Paper on Regulation of Atmospheric Sulfates,* Report EPA-450/2-75-007 (PB-245 760), September 1975, NTIS.
26. National Research Council, Advisory Committee on the Biological Effects of Ionizing Radiation, *The Effects on Populations of Exposure to Low Levels of Ionizing Radiation,* Report PB-239 735, November 1972, NTIS.
27. United Nations Scientific Committee on the Effects of Atomic Radiation, *Sources and Effects of Ionizing Radiation,* Report to the General Assembly, 1977.
28. C. L. Comar and L. A. Sagan, Health Effects of Energy Production and Conversion, in *Annual Review of Energy,* Vol. 1, pp. 581-600, 1976.

be resolved by a unified regulatory philosophy founded on uniform cost–benefit and risk standards. This approach would ensure that the cost savings of a safe technology could be passed on to the public or applied in a more cost-effective manner to reduce other hazards rather than spent on design augmentation that is not cost effective.

For example, it is conceivable that a broad set of regulatory limits could be established which (1) define an upper level of risk to which no individual should be exposed and, after meeting this individual risk criterion, (2) define cost–benefit criteria for additional reductions in the cumulative allowable risk to the exposed population. The former would protect the individual, and the latter would ensure that incremental investments in health and safety protection are made in a manner which provides optimum benefit to society.

It is recognized that this type of regulatory structure would require much more definitive data on the nature and levels of many hazards than presently exist and would involve complex analyses and collective agreement on many basic societal value judgments. Furthermore, additional work is required to develop much more comprehensive methodology for balancing costs and benefits, including consideration of nonquantifiable parameters. Therefore, although it is desirable, such a development is unlikely within the near future. However, the policies of individual regulatory agencies can be effectively viewed even now in this broad perspective.

The analysis indicates that NRC policy regarding changes to plant designs to achieve improvements in safety should be critically evaluated on a relative cost–benefit basis to ensure that additional investments in safety provide maximum benefit in terms of reduced risk. With regard to comparisons between the use of nuclear fuel or coal for the production of electricity, nuclear appears to cause lower adverse health impacts than does coal, although both compare favorably with other accepted risks. It would be highly ironic, therefore, if the pursuit of greater protection of the public health and safety through increased regulation of nuclear plants were to result in the choice of coal over nuclear as a result of higher nuclear plant costs.

This effect of such a regulatory policy would be a net decrease in public health and safety protection. Thus the NRC has an obligation to ensure that additional costs imposed in the name of public health and safety are justified on a cost–benefit basis and result in maximum net benefit to society.

REFERENCES

1. E. P. O'Donnell, The Need for a Cost–Benefit Perspective in the Nuclear Regulatory Process, *Trans. Am. Nucl. Soc.*, 30: 482-484 (November 1978).
2. E. P. O'Donnell, What Price Safety? A Probabilistic Cost–Benefit Evaluation of Existing Engineered Safety Features, paper presented at the European Nuclear Society/American Nuclear Society International Topical Meeting on Nuclear Power Reactor Safety, Oct. 16–19, 1978, Brussels, Belgium.
3. J. Mauro, Comparison of Gaseous Effluent Standards for Nuclear and Fossil Fuel Power Production Facilities, *Trans. Am. Nucl. Soc.*, 30: 123-124 (November 1978).
4. R. R. Bennett and D. Kettler, Ebasco Services, Inc., Dramatic Changes in the Costs of Nuclear and Fossil-Fueled Plants, paper presented at Symposium on Energy: Effects on the Future of Louisiana, sponsored by the University of New Orleans, Jan. 12, 1979.
5. A. D. Rossin and T. A. Rieck, Economics of Nuclear Power, *Science*, 201(4356): 582-589 (Aug. 18, 1978).
6. V. S. Boyer, *Electric Power Generation Economics*, Philadelphia Electric Company, 1978.
7. *Code of Federal Regulations*, Title 10, Energy, Part 50, Licensing of Production and Utilization Facilities, Appendix I, Numerical Guidelines for Design Objectives and Limiting Conditions for Operation to Meet the Criterion "As Low As Practicable" for Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents, Revised Jan. 1, 1978.
8. *Code of Federal Regulations*, Title 10, Energy, Part 50, Licensing of Production and Utilization Facilities, Appendix A, General Design Criteria for Nuclear Power Plants, Revised Jan. 1, 1978.
9. *Code of Federal Regulations*, Title 10, Energy, Part 100, Reactor Site Criteria, Revised Jan. 1, 1978.
10. Nuclear Regulatory Commission, *Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants*, NRC Report WASH-1400 (NUREG-75/104), October 1975, NTIS.
11. *The Site Population Factor: A Technique for Consideration of Population in Site Comparison*, USAEC Report WASH-1235, October 1974, GPO.
12. S. E. Rhoads, How Much Should We Spend to Save a Life, *Public Interest*, 51: 74-92 (1978).
13. L. B. Lave and L. C. Freeburg, Health Effects of Electricity Generation from Coal, Oil, and Nuclear Fuel, *Nucl. Safety*, 14(5): 409-428 (September–October 1973).
14. Environmental Protection Agency, Standards of Performance for New Stationary Sources, Proposed Amendments to 40 CFR 60, *Fed. Regist.*, 43(182): 42154-42198 (Sept. 19, 1978).
15. L. D. Hamilton and A. S. Manne, Health and Economic Costs of Alternative Energy Sources, *IAEA Bull.*, 20(4): 44-58 (August 1978).
16. F. D. Sowby (Ed.), *Annals of the ICRP*, Vol. 1, No. 3: *Radiation Protection—Recommendations of the International Commission on Radiation Protection* 2nd ed., Pergamon Press, Elmsford, N.Y., 1977; ICRP Publication No. 26.
17. R. A. Howard et al., The Value of Life and Nuclear Design, in *Probabilistic Analysis of Nuclear Reactor Safety*, Pro-