AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 2

**HEALTH RISKS IN PERSPECTIVE:
JUDGING HEALTH RISKS OF ENERGY TECHNOLOGIES**

Michael D. Rowe

September 18, 1992

Prepared for the
Office of Environmental Analysis
U.S. Department of Energy
Washington, DC

**BIOMEDICAL AND ENVIRONMENTAL ASSESSMENT GROUP
ANALYTICAL SCIENCES DIVISION
DEPARTMENT OF APPLIED SCIENCE
BROOKHAVEN NATIONAL LABORATORY
UPTON, NY**

This research was performed under the auspices
of the United States Department of Energy under Contract No.
DE-AC02-76CH00016

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

fr

ACKNOWLEDGMENTS

This work was supported by the Environmental Analysis Division, Office of Policy and Analysis, U.S. Department of Energy, J.R. Morris, Project Manager. I thank L.D. Hamilton for support and guidance. The report was completed by Janice DePass.

TABLE OF CONTENTS

ACKNOWLEDGMENTS	i
CONTENTS	ii
LIST OF TABLES.....	iii
LIST OF FIGURES	v
1. Introduction.....	1
2. Thinking About Risks	3
2.1 Perception and Misperception	3
2.2 Acceptability of Risks	8
3. How do we Die?	14
3.1 Routine Risks	14
3.2 Small Risks	41
4. Risk Regulation	43
4.1 Standard Practice.....	43
4.2 Costs of Risk Regulation.....	51
4.3 The Role of Cost-Effectiveness in Risk Management	53
5. Health Risks of Energy Technologies.	58
5.1 Comparing Risks of Alternative Technologies.....	58
5.2 Recent Estimates of Health Risks of Energy Technologies.....	62
5.21 Health Risk Assessment.....	63
5.22 History.....	64
5.23 Summary of Health Effects.....	65
5.24 Comparisons of Health Effects	66
5.25 Evaluation.....	83
6. Summary and Conclusions	84
7. References	88
8. Appendices	94

LIST OF TABLES

Table 1.	Science Advisory Board rating of risks to the natural ecosystem and human welfare.	4
Table 2.	Summary data on coverage of environmental health risk stories by national evening news broadcasts, 1984-1986.	6
Table 3.	Scores of six energy technologies on five risk attributes by one expert.	13
Table 4.	Fifteen most common causes of death in the United States, 1987.	14
Table 5.	Selected risks to life.	15
Table 6.	Loss of life expectancy from various causes of death in the United States, 1990.	16
Table 7.	Estimated causes of death from cancer in the United States.	31
Table 8.	Examples of low-level risks in the United States, 1987.	41
Table 9.	Statutory approaches to control of toxic substances.	45
Table 10.	Lifetime individual risks of cancer determined to be "significant" by government agencies.	46
Table 11.	Lifetime individual risks of cancer determined not to be "significant" by government agencies.	47
Table 12.	Risks and Cost-Effectiveness of Selected Regulations.	54
Table 13.	Estimated cost-effectiveness of regulated chemical carcinogens.	56
Table 14.	Significant health effects of technologies for generating electricity -- Fuels Group.	67
Table 15.	Significant health effects of technologies for generating electricity -- Renewable Group.	68
Table 16.	Significant health effects of technologies for generating electricity -- Nuclear Group.	68
Table 17.	"Best estimates" of health effects of fuel cycles, not including accidents, Paskievici, 1980.	71
Table 18.	"Best estimates" of health effects of accidents in fuel cycles, Paskievici, 1980.	71

Table 19.	Severe accidents world-wide in the period 1969 to 1986.....	76
Table 20.	Summary of estimated public health risks from routine emissions and transport of fuel for selected energy technologies	79

LIST OF FIGURES

Figure 1.	Relationship between judged frequency and actual frequency of causes of death.	7
Figure 2.	Location of 81 hazards on factors "dread risk" and "unknown risk."	11
Figure 3.	Composition of factors "dread risk" and "unknown risk."	11
Figure 4.	Desire to regulate existing hazards located by factors "dread risk" and "unknown risk."	12
Figure 5.	Age-specific and remaining lifetime risk of dying of cancer, 1987.	17
Figure 6a.	Remaining lifetime risk of dying of all cardiovascular diseases and all cancers, White 1987.....	19
Figure 6b.	Remaining lifetime risk of dying of all cardiovascular diseases and all cancers, Black 1987.....	20
Figure 6c.	Remaining lifetime risk of dying of all cardiovascular diseases and all cancers, Other 1987.....	21
Figure 7a.	Remaining lifetime risk of dying of accidents, chronic obstructive pulmonary disease, pneumonia and influenza, and diabetes, White, 1987.....	22
Figure 7b.	Remaining lifetime risk of dying of accidents, chronic obstructive pulmonary disease, pneumonia and influenza, and diabetes, Black 1987.....	23
Figure 7c.	Remaining lifetime risk of dying of accidents, chronic obstructive pulmonary disease, pneumonia and influenza, and diabetes, Other 1987.....	24
Figure 8a.	Remaining lifetime risk of dying of cardiovascular diseases by type, White 1987.	25
Figure 8b.	Remaining lifetime risk of dying of cardiovascular diseases by type, Black 1987.	26
Figure 8c.	Remaining lifetime risk of dying of cardiovascular diseases by type, Other 1987.....	27
Figure 9a.	Remaining lifetime risk of dying of cancers by type, White 1987.	28
Figure 9b.	Remaining lifetime risk of dying of cancers by type, Black 1987.....	29

Figure 9c.	Remaining lifetime risk of dying of cancers by type, Other 1987.....	30
Figure 10a.	Remaining lifetime risk of dying of accidents by type, White 1987.....	32
Figure 10b.	Remaining lifetime risk of dying of accidents by type, Black 1987.....	33
Figure 10c.	Remaining lifetime risk of dying of accidents by type, Other 1987.....	34
Figure 10d.	Remaining lifetime risk of dying of accidents by type, White 1987.....	35
Figure 10e.	Remaining lifetime risk of dying of accidents by type, Black 1987.....	36
Figure 10f.	Remaining lifetime risk of dying of accidents by type, Other 1987.....	37
Figure 10g.	Remaining lifetime risk of dying of accidents by type, White 1987.....	38
Figure 10h.	Remaining lifetime risk of dying of accidents by type, Black 1987.....	39
Figure 10i.	Remaining lifetime risk of dying of accidents by type, Other 1987.....	40
Figure 11.	Forces in environmental policy making.	44
Figure 12.	Risk regulation a function of size of population at risk.....	49
Figure 13.	Cost-effectiveness of federal regulations for chemical carcinogens.	55
Figure 14.	A typology of health risks.	59
Figure 15.	Genealogy of data bases comparing health and safety of energy technologies.	70
Figure 16.	Occupational mortality risks of energy production from all stages of the fuel cycle, without severe accidents.	73
Figure 17.	Public mortality risks of energy production from all stages of the fuel cycle, without severe accidents.	73
Figure 18.	Frequency of acute fatalities per GWe-y electricity production from severe accidents in the nuclear and fossil-fuel systems.	74
Figure 19.	Frequency of acute fatalities per GWe-y electricity production from severe accidents in hydraulic dams.....	75

Figure 20.	Occupational health risks of different energy cycles for generating electricity.	77
Figure 21.	Occupational health risks of different energy cycles for large-scale generation of heat.	78
Figure 22.	Expected range of occupational fatalities per GWe-y from construction, operation, and maintenance of energy facilities.	80

1. INTRODUCTION

Almost daily, Americans receive reports from the mass news media about some new and frightening risk to health and welfare. Most such reports emphasize the newsworthiness of the risks -- the possibility of a crisis, disagreements among experts, how things happened, who is responsible for fixing them, how much will it cost, conflict among parties involved, etc. As a rule, the magnitudes of the risks, or the difficulty of estimating those magnitudes, have limited newsworthiness, and so they are not mentioned.

A reporter's job is news, not education; events, not issues or principles. And the news is the risky thing that has happened, not the difficult determination of how risky it actually is.

Peter M. Sandman, 1986¹

Because of this emphasis in the news media, most people outside the risk assessment community must judge the relative significance of the various risks to which we all are exposed with only that information deemed newsworthy by reporters. This information is biased and shows risks in isolation. There is no basis for understanding and comparing the relative importance of risks among themselves, or for comparing one risk, perhaps a new or newly-discovered one, in the field of all risks.

Lacking this understanding, it is exceedingly difficult to make decisions about risks and appropriate allocations of resources to reduce them. It should not come as a surprise that we often make poor decisions.

How extraordinary! The richest, longest-lived, best-protected, most resourceful civilization, with the highest degree of insight into its own technology, is on its way to becoming the most frightened. Has there ever been, one wonders, a society that produced more uncertainty more often about everyday life? ... Chicken Little is alive and well in America.

Is it our environment or ourselves that have changed? Would people like us have had this sort of concern in the past? Imagine our reaction if most of modern technology were being introduced today? ... Wouldn't airliners crash into skyscrapers that would fall on others, killing tens of thousands? Who could prove otherwise? ... Is it just that we are used to the old or are some of us looking differently at essentially the same sort of experience?

Aaron Wildavsky, 1979²

The purpose of this report is to help calm the Chicken Littles among us - to provide perspective on the various risks to which we are routinely exposed. It serves as a basis for understanding the meaning of quantitative risk estimates and for comparing new or newly-discovered risks with other, better-understood risks. Specific emphasis is placed on health risks of energy technologies.

This report is not a risk assessment; nor does it contain instructions on how to do a risk assessment. Rather, it provides background information on how most of us think about risks and why it is difficult to do it rationally, it provides a philosophy and data with which to do a better job of judging risks more rationally, and it provides an overview of where risks of energy technologies fit within the spectrum of all risks.

Much of the quantitative information provided here is on relative risk of dying of various causes. This is not because risk of dying is seen as the most important kind of risk, but because the statistics on mortality rates by cause are the highest quality data available on health risks in the general population. Like a drunk who looks for his lost keys under a street lamp because that is where the light is, we analyze the data we can get, which are not necessarily the data we need.

These data that we can get illustrate well the important characteristics of health risks with minimum uncertainty related to quality. Nevertheless, it should be understood that for each person dying of a particular cause, many others suffer different, sublethal effects of that cause. **Many health risks of daily life may be more important to us individually, and as a nation, than dying. But they are not as well quantified.**

2. THINKING ABOUT RISKS

2.1 PERCEPTION AND MISPERCEPTION

It is hard to think rationally about risks from any source, especially scary ones. People often make mistakes. A recent survey of public attitudes illustrates the point.

In 1988-90, The Roper Organization developed a comprehensive list of 29 environmental problems, which were rated by a nationally representative sample of adult Americans interviewed in their homes.³ At the top of the list of most worrisome problems were hazardous waste sites, which were considered "very serious" by two-thirds of the respondents. Also high on the list were water pollution from industrial waste, worker exposures to toxic chemicals, accidental oil spills, depletion of the ozone layer, and radiation from nuclear power plants. The primary rationale supporting these judgments was concern for personal health and safety.

At the bottom of the list -- the problems rated least likely to have high risk -- were radiation from microwave ovens, X-rays, and indoor air pollution.

These same environmental problems were independently rated by the Science Advisory Board to the U.S. Environmental Protection Agency.⁴ There was some agreement (Table 1). The Science Advisory Board judged pollution of drinking water, worker exposures to toxic chemicals, and ambient air pollutants (including depletion of ozone) to be relatively high-risk problems and radiation from microwaves and X-rays to be low-risk problems.

But the disagreements were significant. The Science Advisory Board did not even include hazardous waste sites as separate sources of toxic materials in surface waters (medium risk) or ground waters (low risk). And they judged oil spills and radiation from nuclear power plants to be very low-risk problems. In contrast, the Board judged indoor air pollutants to be an exceedingly important problem, and specifically listed indoor radon separately from other very important indoor pollutants. Indoor radon is by far the largest source of human exposure to radiation.⁴

How do these differences occur? The Roper Organization thinks that language, the media, and ignorance are important sources of bias:³

- o Use of the words "hazardous" and "toxic," as opposed to more neutral words like "solid waste" or "trash" generated anxiety regardless of the specific substances or real levels of risk involved.

Table 1. Science Advisory Board rating of risks to the natural ecosystem and human welfare.^a

HIGH RISKS

- o Alteration and destruction of natural habitats.
- o Extinction of species and overall loss of biological diversity
- o Depletion of stratospheric ozone.
- o Change in global climate.

MEDIUM RISKS

- o Herbicides and pesticides.
- o Toxic substances, nutrients, biochemical oxygen demand, turbidity of surface waters.
- o Acid deposition.
- o Airborne toxic substances.

LOW RISKS

- o Oil spills.
- o Groundwater pollution.
- o Radionuclides.
- o Acid runoff to surface waters.
- o Thermal pollution.

a. Source: Reference 4

- o The news media were clearly important in biasing perception of oil spills at this time through coverage of the Exxon Valdez spill. The proportion of the public rating oil spills "very serious" increased from 38 percent before the spill to 60 percent after.
- o There is much misunderstanding of the nature of health and environmental problems. The public is as much concerned about the ecological impact of outdoor radon as it is about the health risk of radon in homes. Destruction of wetlands is thought to be as much a health problem as it is an ecological problem. These concerns arise from ignorance.

Psychological research on perception of risks has shown that, because of the difficulty of thinking about uncertain events, people use a set of mental rules, or heuristics, in an attempt to make sense of things and reduce the anxieties generated by life's gambles.⁵ While these rules are valid in some circumstances, in others, they are not and can lead to large, persistent biases. As a result, everyone, risk assessment professionals included, has biases in judging uncertain events.⁶ They are systematic, often large, and serious in their implications for decision making.

Important sources of perceptual bias about risk include:⁶

o Misperceptions of randomness.

It is easy to misunderstand or forget the range and distribution of values that should be expected from any random process. Things fluctuate in time and space for totally ordinary reasons related to the natural variability of the world. While it might be unlikely, for example, to toss five heads in a row with coin, nevertheless, it is clearly possible and it should not be surprising that it happens once in a while, usually more often than most people think it should. Thus we must expect that in some places or times, events occur at a higher rate than the average or in some apparent pattern without any special implications related to causality.

There is some question about the significance of first-time extreme events (the Chernobyl reactor accident, for example) and their proper influence on estimated probabilities of such events in the future. This is a complex philosophical and statistical question that is outside the scope of a brief review.

o Overvaluation of small samples or unreliable data.

Also related to randomness, it is difficult to remember that extreme outcomes of random processes are much more likely in small samples than in large ones, which will necessarily be closer to the population mean. In addition, we all overvalue poor-quality information or even noninformation, and we do it often:

- "My uncle smoked all his life and lived to be 98, so smoking can't be too bad for you."
- "I heard everyone on the block got sick."
- "They call that place 'cancer alley'."

Because we hear more such statements than rigorous and qualitative ones, we tend to place more credibility on them than their quality warrants. Often this may confuse us with irrelevancies, but because of an "anchoring bias" (see below), we tend to accept with less question any that support our existing beliefs.

o Neglect of base rates.

The background rate of a particular risk is an essential component for evaluating the significance of a change in that risk or the likelihood of a particular causal relationship. A difference of 10 cancers out of 100, for example, is large; a difference of 10 out of 200,000 is meaningless. Similarly, if most lung cancers are caused by smoking, then we should assume that a lung cancer in a particular smoker is most likely to have been caused by smoking, and not by whatever other cause of lung cancer is currently in the news (perhaps radon gas).

Table 2. Summary data on coverage of environmental health risk stories by national evening news broadcasts, 1984-1986.

Story	Number stories	Percent ≥ 2 minutes	Average No. field reporters	Average No. on-air sources	Average No. films
Smoking/tobacco	57	48	0.61	1.95	0.19
All environmental risk	564	35	0.55	1.53	0.46
Bhopal	61	61	0.88	2.25	0.57
Asbestos	15	27	0.60	1.60	0.27
Ethylene dibromide	16	44	0.81	2.25	0.12
Mexico City earthquake	52	69	1.06	1.71	1.33
Airplane accidents	482	32	0.53	1.27	0.55
Source: Reference 7.					

o Availability bias.

Things that come to mind easily seem more likely than things that do not. Direct experience, memorability of reports, and imaginability of events strongly influence quantitative judgments.

As demonstrated by The Roper Organization for the Exxon Valdez oil spill, The news media have a large role in distorting perceptions of risks by increasing the memorability and imaginability of newsworthy hazards and by higher frequency in reporting of newsworthy hazards over routine hazards. Table 2 shows a summary of the distorted coverage of health risk stories by network evening news, contrasting coverage of the exceedingly high risks of smoking (about 350,000 deaths/yr in the U.S.)⁸ with that of other more newsworthy risks, especially airplane accidents (about 1200 deaths/yr in the U.S.).⁹ Opportunities for spectacular visual images have a large influence on TV news coverage. The effect of availability bias on perceptions of risk is shown in Figure 1.

o Hindsight bias.

Hindsight bias is related to availability bias in that the occurrence of an event provides experience and increases its memorability.

o The "certainty illusion".

Unwarranted confidence in level of knowledge arises from lack of awareness of the extent of ignorance. Most of us think we know and understand more than we do, and this provides a false sense of confidence.

Figure 1. Relationship between judged frequency and actual frequency of causes of death. (Source: Reference 12.)

o Anchoring bias.

Beliefs change slowly, and then only with much pushing and shoving. Information that supports current beliefs is seen as reliable and informative; contrary information is dismissed as unreliable, erroneous, or unrepresentative. So changes based on new information are usually small adjustments from the origin, and we can not expect disagreements about risk simply to disappear in the face of evidence. Sometimes even completely irrelevant information can form an anchoring point for beliefs.

o Desire for too much or redundant information.

This bias arises from insecurity about making judgments in the face of uncertainty. Many would rather not make a judgment at all than "guess" based on what they perceive to be inadequate information. But of course, making no judgment amounts in effect to judgment by default. This is reinforced by the anchoring bias and leads to passive acceptance of the status quo.

These classifications for biases are obviously not mutually exclusive, but have many interactions and overlaps.

2.2 ACCEPTABILITY OF RISKS

Risk analysts can estimate the magnitude of a risk -- the expected value and perhaps the distribution of accidents, diseases, worker-days lost, fatalities, years of life lost, etc -- but we now know that magnitude, alone, only partly determines its acceptability to the persons at risk. Acceptability is an exceedingly complex function of a broad range of poorly-understood characteristics of the risk, itself and of the persons judging it.

Fischhoff, Slovic, and Lichtenstein did much of the pioneering work yielding understanding of the variables affecting perception of risk.¹⁰ Sandman divides them into a "hazards" component, which includes the quantitative evaluations of magnitude normally evaluated by risk assessors, and an "outrage" component, which includes highly interconnected and non-technical considerations that affect how people respond to and evaluate the magnitudes.¹¹ The elements of the outrage components include:

- o Voluntariness.
People become angry when risks are forced on them by others. The anger is translated into a magnification of the perceived seriousness of the risk and reduces its acceptability. Consider the difference between public response to a mountain climber who falls because of equipment failure and a tourist who falls when a guard rail fails.
- o Control.
Most people overestimate their own ability to avoid hazards and so feel more comfortable when they are in control than when others are in control; they would rather be a driver than a passenger. Risks over which there is some individual control are evaluated as less risky and more acceptable than those that can not be controlled. Uncontrolled risks create feelings of helplessness.
- o Fairness.
Risks that fall equally on all are more acceptable than those that fall more heavily on a few. If they are unevenly distributed, then they should be balanced with some compensating benefit. Unfair risks make people angry.
- o Trustworthiness of source.
Information from a source with an obvious self-interest is distrusted, regardless of its apparent quality. People automatically inflate untrustworthy estimates of risk, but they do not correspondingly deflate trustworthy ones, which are taken at face value. In contrast, sources with an interest in overstating risks to promote regulation are most often seen as protecting the public rather than being self-

interested, thus they are not perceived as untrustworthy and their estimates are not properly discounted.

- o Ethicality.
Risks that appear to have no socially redeeming benefits are seen as unreasonable regardless of magnitude. Former EPA Administrator Milton Russell has said that speaking to some people about an acceptable level of pollution is like talking about an acceptable number of child molesters.
- o Naturalness.
Natural risks have no cause at which anger can be directed, and so are less likely to promote outrage. Even relatively high natural hazards are routinely ignored by people who become exceedingly upset by the same hazard from man-made sources. Natural versus man-made radon contamination in houses is an example.
- o Familiarity.
Familiar risks seem less threatening than unfamiliar, new ones. The seriousness of the new risks is inflated to account for the uncertainty created by lack of experience. This is linked to availability bias.
- o Memorability.
Risks for which examples come readily to mind are easy to understand and therefore are scarier and seem more likely and more serious. Catastrophic accidents fall in this category. This is also linked to availability bias.

Other important characteristics more closely related to the specific nature of the hazard are:

- o Immediacy.
A delay between exposure and effect increases the uncertainty and thus the perceived riskiness of that effect. Cancer and other genetic effects are examples. Effects on future generations are seen as inequitable.
- o Observability.
Effects that can be seen are easier to understand and to quantify mentally. Invisible effects are more uncertain so are seen as more risky.
- o Understandability.
Lack of understanding increases individual uncertainty, which increases perceived riskiness. It breaks the logical chain of causality, which allows the mind greater freedom to imagine bad outcomes.

- o Fatality.
For obvious reasons, any risk of fatality is perceived as more important than risk of injury, however widespread or severe. And a slow death is worse than a fast death.
- o Dreadness.
Some diseases are more feared than others, probably because they tend to be relatively slow and painful, unavoidable, incurable, and poorly understood. Many have a shame factor implying fault. AIDS is the prime example now; cancer and genetic defects were until fairly recently, but are now gaining more acceptance as they become more common; epilepsy, leprosy, and tuberculosis used to be. Death from such dread diseases is perceived as worse than death from more familiar causes. Similarly, some sources of risk are more feared; exposure to radiation is the most notable because it has an especially large complement of frightening characteristics.

Many of these characteristics are interconnected in people's minds -- voluntary risks are also seen as controllable; delayed risks are seen as unknown and poorly understood. Statistical analysis of responses to these characteristics shows that they tend to be grouped in people's minds into two general factors (Figure 2).¹² The first and most important factor is called "dread risk," defined by level of control, dreadness of effect, potential for catastrophe, fatal consequences, and inequitable distributions of costs and benefits (Figure 3). Man-made radioactivity (nuclear power and nuclear weapons) scores highest in this factor. The second factor is called "unknown risk," defined by level of observability, knowledge, newness, and delay in effects. Chemical technologies (medicines, DNA research, etc.) score highest in this factor. A third factor found in several studies is numbers of persons exposed (not shown in Figure 3).

Among persons who are not experts in risk assessment, the higher on these factor scales hazards are considered to be, the greater are their perceived risks and the more people would like to have them reduced below current levels (Figure 4). In contrast, expert's perceptions of risks are closely related to expected mortality and are not much affected by these other characteristics. This difference is an obvious barrier to communication and understanding between the experts and the people who seek their expertise.

Figure 2. Location of 81 hazards on factors "dread risk" and "unknown risk." (Source: Reference 12.)

Figure 3. Composition of factors "dread risk" and "unknown risk." (Source: Reference 12.)

Figure 4. Desire to regulate existing hazards located by factors "dread risk" and "unknown risk." The larger the point, the greater the desire for regulation. (Source: Reference 12.)

In this difference, it is common that the experts accuse the nonexperts of "irrational judgments," because they do not treat all deaths as equal. But in fact, a large portion of the fault lies with the experts, who are unable to quantify all of the important effects, and so leave them out.

It is known, for example, that the impacts of accidents extend far beyond the direct harm to victims -- death, injury, illness, property damage, etc -- as analyzed in traditional economic and risk analysis. Accidents are like a stone dropped in water.¹² Ripples spread out encompassing first the directly affected victims, then the responsible company or agency, and then other related companies, agencies and industries. The total indirect effects can be enormous and correlated only slightly or not at all with the direct harm to victims.

The accident at the Three Mile Island nuclear reactor is a dramatic example. No one died, and very few if any latent cancer fatalities are predicted. Yet no other accident in history has produced such costly societal impacts.¹² It devastated the operating utility, and imposed an estimated cost of \$500 billion on the nuclear industry and on society through increased costs from stricter regulation, reduced operation of reactors worldwide,

Table 3. Scores of six energy technologies on five risk attributes by one expert. ^a						
Attribute	Coal	Hydro	Energy Technology Large wind	Small wind	Nuclear	Conser- vation
Public deaths	80	10	20	5	10	5
Occupational deaths	30	20	10	30	5	10
Morbidity	20	20	40	50	10	40
Unknown risk	70	60	90	50	80	40
Dread risk	50	50	40	20	90	10
a. Source: Reference 14						

public opposition to nuclear power, and reliance on more expensive sources of energy. It may even have increased hostility toward other complex technologies, such as chemical manufacturing and genetic engineering.

The important characteristic of the accident at Three Mile Island was its "signal potential" as a harbinger of possible catastrophic accidents in the future. Slovic, *et al.* believe that the maximum possible risk is exceedingly high.¹³ More than 25 percent of respondents in one study believed that the maximum could exceed 100,000 fatalities, and in another study, some people believed that the immediate fatalities could be in the hundreds of thousands to the millions. (There is no mechanism that could cause such high rates.) Thus it is what people **fear might happen** that is important, not what **has happened or can happen**. Signal potential is closely related to position in the factor space for risk perception.

Fischhoff, *et al.*¹⁴ suggest that any attempt to define and quantify health "risk" should include at least three dimensions: fatalities, morbidity, and "concern." Concern should be expressed in some way that accounts for position in the factor space for risk perception.

Table 13 shows a five-dimensional description of six energy technologies developed by Fischhoff, *et al.* for one expert. These estimates are admittedly unreliable, but they illustrate the differences among technologies. The relative riskiness of these technologies must be some combination of these (and other) risk attributes weighted by their relative importance to perception of risk. Different weights produce different results.

3. HOW DO WE DIE?

3.1 ROUTINE RISKS

We don't like to think about it much, but in the end we all die. And few of us die in the spectacular and frightening ways we hear and read about in the news media. Mostly we die of ordinary, familiar and unspectacular things that don't provoke discussion or visual clips on the evening news.

So how do we die?

Table 4 shows the fifteen most common single causes of death in the United States in 1987, from which it is clear that we mostly die from heart disease and cancer. Table 5 shows another list that compares various risks per person exposed to the source rather than the total population, and Table 6 shows yet another list that quantifies risks in terms of days of lost life expectancy, which provides more information on the relative severity of the risks.

Table 4. Fifteen most common causes of death in the United States, 1987.	
Cause of Death	Percent of Total Deaths
Heart disease	35.8
Cancer	22.5
Stroke	7.1
Accidents and adverse effects	4.5
Motor vehicle accidents	2.3
All other accidents and adverse effects	2.2
Chronic obstructive lung disease and allied conditions	3.7
Pneumonia and influenza	3.3
Diabetes	1.8
Suicide	1.5
Chronic liver disease and cirrhosis	1.2
Hardening of the arteries	1.1
Kidney diseases	1.0
Homicide and legal intervention	1.0
Blood poisoning	0.9
Complications of child-bearing	0.9
AIDS	0.6

Table 5. Selected risks to life.^a

Cause of death	Mortality risk ^b per million persons exposed	Average risk per exposed person
Smoking (1 pack/day) (includes cancer and heart disease) ^d	252,000	1 in 4.0
Heart disease (all causes) ^g	230,000	1 in 4.3
Cancer (all causes) ^{c,g}	196,000	1 in 5.1
Motor vehicle accidents ⁱ	13,400	1 in 75
Passenger cars, restraints used	4,816	1 in 210
Passenger cars, no restraints used	8,757	1 in 110
Home accidents ^d	7,700	1 in 130
Homicides ^g	7,000	1 in 140
White females, 15-24 years ^c	400	1 in 2,500
White males, 15-24 years ^c	1,100	1 in 910
Black females, 15-24 years ^c	1,700	1 in 590
Black males, 15-24 ^c	10,100	1 in 100
Drowning ^f	2,520	1 in 400
Medical X-rays (cancer) ^f	1,400	1 in 710
Fires ^f	960	1 in 1,050
Increase in cosmic radiation from living at 5280 feet instead of at sea level (cancer) ^f	560	1 in 1,800
Aflatoxin in 4 tablespoons of peanut butter per day ^{d,f}	560	1 in 1,800
Electrocution ^e	371	1 in 2,700
1.5 pCi/l radon in drinking water (cancer) ^d	259	1 in 3,900
Commercial aircraft accidents (1 round trip per year) ^h	51	1 in 19,600
0.1 mg chloroform in drinking water (cancer) ^d	42	1 in 24,000
Lighting ^e	35	1 in 28,500
Bites and stings of venomous animals and insects ^e	17	1 in 58,800

a. Source: Reference 15

b. Based on a 70 year average lifetime.

c. Based on 10 years within age category.

d. Reference 16

e. Reference 17

f. Reference 18

g. Estimated from Vital Statistics of the United States.

h. Derived from U.S. Department of Transportation, National Transportation Statistics, 1989.

j. Derived by the U.S. Department of Transportation from the Fatal Accident Reporting System.

Table 6. Loss of life expectancy from various causes of death in the United States, 1990. ^a	
Disease	Days lost
Tuberculosis	4.7
Viral hepatitis	3.3
Cancer -- all types	1247
Lip, oral, pharynx	22
Digestive organs	269
Respiratory	343
Breast	109
Genital organs	113
Urinary organs	114
Leukemia	46
Diabetes	82
Nutrition deficiency	3.5
Cardiovascular disease	2043
Heart disease	1607
Cerebrovascular	250
Atherosclerosis	24
Pneumonia	103
Influenza	2.3
Chronic pulmonary disease	164
Bronchitis	7.3
Emphysema	32
Asthma	11.3
Ulcer	11.8
Appendicitis	1.2
Liver diseases	81
Gallbladder	4.7
Nephritis	41
Accidents	365
Motor vehicle	205
All other	158
Suicide	115
Homicide	93
a. Source: Reference 16	

As can be seen in part from Table 5, risk of dying by specific causes is a function of who and what we are -- mostly our age, sex, race, and economic status. This section presents more detailed graphic representations of risks of dying from specific causes by age, sex, and race. Economic status is not included because the mortality statistics are not accumulated that way, but many of the differences attributable to economic status are fairly obvious. Rich people fly more than poor people, for example, so they have greater risk of dying in a plane accident. Similarly, poor people tend to seek less medical care than rich people, so they have greater risk of dying of causes related to neglect.

Figure 5. Age-specific and remaining lifetime risk of dying of cancer, 1987.^a

- a. The lower line is the risk of dying of cancer within that age category; the upper line is the remaining lifetime risk of ever dying of cancer from the beginning of that age category into the future.

The risks of dying shown in this section are calculated in a way not normally seen. Risk of dying is usually shown as age-specific mortality rates -- the expected number of deaths per 100,000 persons (or sometimes percent) within age categories. Thus, we see figures in which risk of dying increasing as a function of age for most causes.

But few of us are especially concerned about the risk of dying at a specific age. Except for the elderly, risks by specific causes of death are exceedingly low. Instead, we are concerned about the risk of ever dying of specific causes, from now into the future -- the remaining lifetime risk.

Figure 5 shows the difference in these two risk functions for cancer. Note that the age-specific risk of dying of cancer increases with age, but the remaining lifetime risk of ever dying of cancer decreases. This is because the risk of dying of other causes increases faster with age than does that of cancer.

The figures in this section show the remaining lifetime risk of ever dying of specific causes as a function of age. The age category 85+ is not included, because these data are known to be of low quality. Statisticians will recognize that the poor quality of the data in the last category also produces a small bias in the estimates of remaining lifetime risk. The causes of death recorded in multiple-cause deaths are not consistent.

Figures 6a through 6c show the remaining lifetime risk of dying of cardiovascular disease and cancer, the two most important causes of death in the United States, comprising about 65 percent of all deaths²⁰ and three-quarters or more of the remaining lifetime risk of dying for most individuals. (The difference between these two numbers is related to the age structure of the population.) Figures 7a through 7c show the four next-most-important causes of death, accidents, chronic obstructive lung disease, pneumonia and influenza, and diabetes. Between them, these two figures represent about 90 percent of the remaining lifetime risk by cause in the United States. Other causes of death cannot be shown on the same risk scale.

Figures 8a through 9c show breakdowns of remaining lifetime risk of dying of cardiovascular disease and cancer into more specific types. Cardiovascular disease is dominated by chronic ischemic heart disease -- heart attack from insufficient blood (oxygen) supply to the heart. The risk of stroke is about one quarter that of heart attack, and all other cardiovascular diseases are very much lower -- one to two percent or less. Note that, contrary to common belief, the differences in the remaining lifetime risk of cardiovascular diseases in men and women is only a few percent.

Remaining lifetime risk of cancer in males is dominated by lung, digestive, and genital cancers. Note the rapid decline in risk of lung cancer after age 60. This is most likely because the individuals at highest risk of lung cancer (especially smokers) die relatively young, so those remaining are less susceptible. Among males, only remaining lifetime risk of dying of genital cancer increases beyond age 60.

Table 7 shows the best current estimates of the factors contributing to fatal cancers in the United States. Contrary to popular belief in the extreme risks from "pollution," most cancers are thought to be caused by characteristics of lifestyle. Except for cancer of the respiratory tract (from smoking) and melanoma, the types of cancers that are currently common are not particularly modern diseases and are likely to depend chiefly on long-established factor(s).²¹ Roughly 75 percent of these cancers are controllable through changes in diet, smoking, sexual behavior, and consumption of alcohol. Only two percent are thought to be caused directly by general pollution in the environment, and another four percent by direct occupational exposures. An additional one to two percent is thought to be caused by food additives and industrial products.

WHITE MALES

WHITE FEMALES

Figure 6a. Remaining lifetime risk of dying of all cardiovascular diseases and all cancers, White 1987.

BLACK MALES

BLACK FEMALES

Figure 6b. Remaining lifetime risk of dying of all cardiovascular diseases and all cancers, Black 1987.

OTHER MALES

OTHER FEMALES

Figure 6c. Remaining lifetime risk of dying of all cardiovascular diseases and all cancers, Other 1987.

WHITE MALES

WHITE FEMALES

Figure 7a. Remaining lifetime risk of dying of accidents, chronic obstructive pulmonary disease, pneumonia and influenza, and diabetes, White 1987.

BLACK MALES

BLACK FEMALES

Figure 7b. Remaining lifetime risk of dying of accidents, chronic obstructive pulmonary disease, pneumonia and influenza, and diabetes, Black 1987.

OTHER MALES

OTHER FEMALES

Figure 7c. Remaining lifetime risk of dying of accidents, chronic obstructive pulmonary disease, pneumonia and influenza, and diabetes, Other 1987.

WHITE MALES

WHITE FEMALES

Figure 8a. Remaining lifetime risk of dying of cardiovascular diseases by type, White 1987.

BLACK MALES

BLACK FEMALES

Figure 8b. Remaining lifetime risk of dying of cardiovascular diseases by type, Black 1987.

OTHER MALES

OTHER FEMALES

Figure 8c. Remaining lifetime risk of dying of cardiovascular diseases by type, Other 1987.

WHITE MALES

WHITE FEMALES

Figure 9a. Remaining lifetime risk of dying of cancers by type, White 1987.

BLACK MALES

BLACK FEMALES

Figure 9b. Remaining lifetime risk of dying of cancers by type, Black 1987.

OTHER MALES

OTHER FEMALES

Figure 9c. Remaining lifetime risk of dying of cancers by type, Other 1987.

Table 7. Estimated causes of death from cancer in the United States. ^a		
Cause	Percent	Range
Diet	35	10-70
Tobacco	30	25-40
Infection	?10	1-?
Sexual behavior	7	1-13
Occupation	4	2-8
Geophysical factors ^b	3	2-4
Alcohol	3	2-4
Pollution	2	<1-5
Medical treatment	1	0.5-3
Food additives	<1	-5 ^c -2
Industrial products	<1	<1-2
Unknown and other	?	?
<p>a. Reference 21.</p> <p>b. Only 1/3 of these could reasonably be considered "avoidable." Geophysical factors also cause a disproportional number of nonfatal cancers (up to 30 percent of all cancers) because of skin cancer from exposure to UV light.</p> <p>c. Allowing for a possible protective effect of antioxidants and other preservatives.</p>		

Figures 10a through 10i show breakdowns of remaining lifetime risks of dying of accidents, which are dominated by vehicle accidents and falls. Risk of dying in vehicle accidents declines rapidly after age 25 and that for fall increases rapidly after age 60. The differences between men and women are striking for vehicle accidents, poisoning, drowning and several of the less important types of accidents. Some of these differences are probably attributable to occupational accidents.

WHITE MALES

WHITE FEMALES

Figure 10a. Remaining lifetime risk of dying of accidents by type, White 1987.

BLACK MALES

BLACK FEMALES

Figure 10b. Remaining lifetime risk of dying of accidents by type, Black 1987.

OTHER MALES

OTHER FEMALES

Figure 10c. Remaining lifetime risk of dying of accidents by type, Other 1987.

WHITE MALES

WHITE FEMALES

Figure 10d. Remaining lifetime risk of dying of accidents by type, White 1987.

BLACK MALES

BLACK FEMALES

Figure 10e. Remaining lifetime risk of dying of accidents by type, Black 1987.

OTHER MALES

OTHER FEMALES

Figure 10f. Remaining lifetime risk of dying of accidents by type, Other 1987.

WHITE MALES

WHITE FEMALES

Figure 10g. Remaining lifetime risk of dying of accidents by type, White 1987.

BLACK MALES

BLACK FEMALES

Figure 10h. Remaining lifetime risk of dying of accidents by type, Black 1987.

OTHER MALES

OTHER FEMALES

Figure 10i. Remaining lifetime risk of dying of accidents by type, Other 1987.

3.2 SMALL RISKS

The mortality rates from the common and well-understood causes shown in the figures above are so large that, were they from a single, controllable cause other than drinking and smoking, they would long since have been reduced. The risks from modern technologies that are now candidates for reduction are orders of magnitude smaller, in the range of 1 in 10,000 (10^{-4}) to 1 in 1,000,000 (10^{-6}) per lifetime. These risks are similar in magnitude to risk of death from lightning or bites and stings (Table 3)

Even vehicular travel, the largest single source of technological risk, and a real killer, is responsible for "only" one death out of forty in the United States. Apart from that, technological risk simply doesn't find its way into the standard mortality tables.

H.W. Lewis, 1990¹⁷

Table 8 shows examples of some familiar causes of mortality of this severity in 1987; the table is not intended to be inclusive.

Table 8. Examples of low-level risks in the United States, 1987.		
LIFETIME RISK PER PERSON ^a		
10^{-4} 1 in 10,000 U.S. total 335/yr	10^{-5} 1 in 100,000 U.S. total 34/yr	10^{-6} 1 in 1,000,000 U.S. total 3/yr
Cystic fibrosis Alcoholic psychosis Encephalitis Male breast cancer Mental retardation Collapsed lung Kidney stones Blocked urethra Osteomyelitis Osteoporosis Nasal polyps Down's syndrome Fall from ladder Fall from chair or bed Trip/stumble Excessive heat Drown in bathtub Assault with blunt object	Gastric salmonella Ectopic pregnancy Helminthiasis Hemorrhage of pregnancy Toxemia of pregnancy Compression of vein Constipation Noncancerous breast disorders Ankylosing spondylitis Fall in or from train Accidental barbiturate poisoning Burning bedclothes Impact in sports Mining/drilling machinery Explosion of pressure vessel Assault by poisoning Legal execution	Typhoid, paratyphoid Tularemia Mumps Malaria Cancer of eye lid Vitamin A deficiency PKU Glaucoma Cataract Legal abortion Infected toe Infected finger Acne Cleft palate Object left during surgery Therapeutic radiation overdose
a. Assumes uniform risk over 70 year life span; total deaths from all causes in 1987 was 2,123,323; total population was 234,400,000.		

A quick scanning of this table makes one point clear -- few of us have much of a feeling for differences among risks of these magnitudes. Mostly we base our evaluation on familiarity or understandability/plausibility. Few of us would imagine, for example, that there is any risk at all of dying of acne, until we realize that this really means an out-of-control facial infection that reaches the brain. Would we guess that the risk of dying from falling out of bed is ten times as great as that from falling from a train? Or that the risk of drowning in a bathtub is equal to that of assault with a club?

Certainly, few understand the real significance to everyday life of risks as low as those in Table 8. We often see discussions of the acceptability or unacceptability of lifetime risks of 1 in a million (10^{-6}). But if this standard of acceptability were applied to the entire society, parts of our system might simply cease to function until alternative ways of doing things could be found.

Were we not to exceed the level of exposures implied by ...risk [of 1 in a million], ... cooks could not cook (benzo[a]pyrene and other "indoor" carcinogens), roads could not be paved (hot asphalt and products of incomplete combustion), dentists could not x-ray (x-rays), anesthesiologists could not anesthetize (halothane), and stone masons (thorium), plumbers (lead, fumes), painters (solvents, epoxides), carpenters (wood dust), and farmers (UV from sunlight) could not work.

P. Milvy, 1986¹⁸

There is evidence that most people are not able to discriminate among risks of this magnitude and simply lump together all risks lower than about 1 in a 1000 (10^{-3}) as "small."²⁴ While this may often be a useful heuristic for individual decision making, it tends to gloss over the differences between risks that are merely "small" and those that should realistically be treated as zero. As a result, the near-zero risks acquire from the lumping more perceived importance than they deserve for their magnitudes.

4. RISK REGULATION

4.1 STANDARD PRACTICE

Congress produces legislation that determines the goals and the structure of environmental regulations. But Congress is a political rather than scientific body; it focuses on issues as they arise. There are not always requirements for considering the place of an individual issue in the larger regulatory or economic systems.

Congress has been unclear on the goals of environmental statutes, other than to clean the environment without seriously harming the economy.²⁵ So the specific decisions on the relative importance of the various factors involved -- the definitions and value judgments -- are left to regulatory agencies. Lacking sufficient resources, the agencies tend to address short-term, dramatic, or newsworthy events. When possible, costs and technical feasibility are considered in detail, but often the most important considerations are the political pressures of the moment.²⁵ As a result, regulations are fragmented and inconsistent, sometimes contradictory and redundant.

Congress and the regulatory agencies have not enunciated comprehensive risk goals, but they have said enough to get themselves into trouble.

Byrd and Lave, 1987²⁶

Figure 11 illustrates the forces driving the environmental regulation system. Note that technical information on effects and cost of controls forms only a single and not especially well-connected part of this system.

Fischhoff has outlined three conditions that must be met to make standard setting an effective means of managing risks:²⁷

- o Setting standards must be preferable to case-by-case decisions, as when:
 - No choice among options is possible;
 - No choice among options is required;
 - Predictability is important;
 - Regulators hope to shape future options;
 - Competing technologies fall in the same jurisdiction;
 - Category members are homogeneous;
 - An explicit policy statement is attractive;
 - Value issues are sensitive;
 - Political resources are limited;

- Process is important; and
 - Awkward applications can be avoided.
- o Some general safety philosophy that balances risk and other factors must be justified on normative grounds, including:
 - Formal analysis of alternative standards;
 - Professional judgment;
 - Political process; and
 - Revealed preference.
 - o That philosophy must be translated faithfully into operational terms, which requires determination of:
 - What should be the range of application -- what aspects of which technologies should be included?
 - Where should be the locus of application-- to technology, to outcome, to consequences?

Table 9. Statutory approaches to control of toxic substances.^a

Statute	General approach(s)
Clean Air Act	Air toxics regulated under section 112: best-available-technology approach, also risk-based "ample margin of safety".
Clean Water Act	Toxic pollutants regulated under Section 307: best-available-technology approach, no-risk goal (complete prohibition).
Safe Drinking Water Act	Standards based on best available technology, goals are based on no risk.
Resource Conservation and Recovery Act	Best available technology generally required, some risk-based standards.
Superfund	Risk-based goals, some cost considerations.
Toxic Substances Control Act	Explicit cost-benefit balancing.
Pesticides Act	Explicit risk-benefit balancing.
Occupational Safety and Health Act	Risk and cost considerations.
a. Source: Reference 25.	

- How should compliance be measured -- features or aggregation of features to measure, measures of statistical variation and uncertainty, unit of observation, sampling scheme, surrogate measures?
- How should the standard be enforced -- interpretation, dealing with incomplete evidence, rigor of enforcement, correction factors for uncertainty or misrepresentation.

In practice, these necessary or desirable conditions are seldom all met.

Table 9 shows the general approaches to control of risks by various statutes, and Tables 10 and 11 show the outcomes with respect to levels of risk that have been determined by regulatory agencies to be "unacceptable" and "acceptable" under these statutes.

Figure 11. Forces in environmental policy making. (Source: Reference 25.)

- Process is important; and
 - Awkward applications can be avoided.
- o Some general safety philosophy that balances risk and other factors must be justified on normative grounds, including:
 - Formal analysis of alternative standards;
 - Professional judgment;
 - Political process; and
 - Revealed preference.
 - o That philosophy must be translated faithfully into operational terms, which requires determination of:
 - What should be the range of application -- what aspects of which technologies should be included?
 - Where should be the locus of application-- to technology, to outcome, to consequences?

Table 9. Statutory approaches to control of toxic substances.^a

Statute	General approach(s)
Clean Air Act	Air toxics regulated under section 112: best-available-technology approach, also risk-based "ample margin of safety".
Clean Water Act	Toxic pollutants regulated under Section 307: best-available-technology approach, no-risk goal (complete prohibition).
Safe Drinking Water Act	Standards based on best available technology, goals are based on no risk.
Resource Conservation and Recovery Act	Best available technology generally required, some risk-based standards.
Superfund	Risk-based goals, some cost considerations.
Toxic Substances Control Act	Explicit cost-benefit balancing.
Pesticides Act	Explicit risk-benefit balancing.
Occupational Safety and Health Act	Risk and cost considerations.
a. Source: Reference 25.	

- How should compliance be measured -- features or aggregation of features to measure, measures of statistical variation and uncertainty, unit of observation, sampling scheme, surrogate measures?
- How should the standard be enforced -- interpretation, dealing with incomplete evidence, rigor of enforcement, correction factors for uncertainty or misrepresentation.

In practice, these necessary or desirable conditions are seldom all met.

Table 9 shows the general approaches to control of risks by various statutes, and Tables 10 and 11 show the outcomes with respect to levels of risk that have been determined by regulatory agencies to be "unacceptable" and "acceptable" under these statutes.

Table 10. Lifetime individual risks of cancer determined to be "significant" by government agencies. ^a		
Statute	Substance	Risk
Occupational Health and Safety Act	Arsenic	0.4
	Ethylene dibromide	0.2
	Ethylene oxide	0.1
	Asbestos	0.06
	Coke oven emissions	0.0002
Clean Air Act	Arsenic from copper smelting	0.03
	Coke oven emissions	0.02
	Radionuclides from uranium mines	0.01
	Benzene from coke ovens	0.005
	Benzene from fugitive emissions	0.002
	Radionuclides from phosphate mines	0.001
	Arsenic from glass manufacturing	0.0008
	Radionuclides from DOE facilities	0.0008
	Radionuclides from NRC licensees	0.0001
Toxic Substances Control Act	Benzene from gas stations	> 0.0001 ^b
	Methylenedianiline	0.01
	Butadiene	0.01
a. Source: Reference 25 b. Clean Air Act Amendments of 1990.		

Byrd and Lave outline various regulatory rationales for defining "trivial" (*de minimis*) and "significant" risks.²⁶ Trivial risks should be those so small that they are simply not worth worrying about. The concept of trivial risk includes an assumption that zero risk is impossible -- that the world is an inherently risky place. Note that it is possible to reduce many specific risks to zero by simply avoiding exposure. What is meant here is that there are tradeoffs among risks; in most cases, avoiding one kind of risk necessarily means accepting another kind associated with the avoidance behavior. At a minimum it means giving up the benefits associated with the risks avoided.

Trivial risks can be defined in absolute terms or as a proportion of one risk to all such risks. The Nuclear Regulatory Commission, for example, attempted to define a trivial risk to be an increase of 0.1 percent over background risk. For cancers in the United States, that would be about 1 in 510,000 or about 480 cancers per year, and for heart attacks it would be about 760 deaths per year. For other sources of risk, that proportion produces a much smaller total.

Table 11. Lifetime individual risks of cancer determined not to be "significant" by government agencies.^a

Statute	Substance	Risk
Occupational Health and Safety Act	Asbestos	0.02 ^b
	Arsenic	0.08 ^b
	Ethylene dibromide	0.008 ^b
	Ethylene oxide	0.003 ^b
Clean Air Act	Arsenic from primary lead smelting	0.002 ^b
	Arsenic from zinc oxide plants	0.001 ^b
	Benzene from fugitive emissions	0.0005 ^b
	Benzene from storage vessels	0.0004
	Arsenic from secondary lead smelting	0.0004
	Benzene from ethylbenzene plants	0.0001
	Benzene from gas stations	0.0001 ^c
	Benzene from maleic acid plants	0.00008
Toxic Substances Control Act	Formaldehyde from abrasives manufacturing	0.001
	Formaldehyde for apparel workers	0.0006
	Formaldehyde for funeral workers	0.0006
	Formaldehyde in conventional homes	0.0001
	Formaldehyde in mobile homes	0.0001
	Formaldehyde for college students	0.000003
<p>a. Source: Reference 26.</p> <p>b. Risk level after regulation.</p> <p>c. The Clean Air Act Amendments of 1990 establish a "benchmark" for "acceptable" risk from benzene exposure of 1×10^{-4} cancers per lifetime.</p>		

Absolute risk is harder to rationalize; the authors suggest perhaps an absolute risk of 1 in a million lifetimes, or about 3 to 4 per year could be defined as trivial. Others have proposed this level.

"Significant" risks should be defined in terms of observability; they should be large enough to be clearly distinguishable against the background variability of other risks. There is no question that "something should be done" about risks that are so large as to be clearly distinguishable. As a rule of thumb, the incidence of a condition must roughly double to be considered statistically significant.²⁶ Statistical observability depends heavily on the number of persons and the number of cases involved. Thus, it is much easier to detect significant changes in rare conditions than in common ones.

The authors suggest that one measure of "significant" risk might be the lowest total mortality for any age group, about 24 per year per 100,000 for children 5 to 9 years of age.

Doubling this risk for a lifetime yields a statistically observable increase in risk of 1.7 percent. Rates for specific conditions would be lower. Alternatively, Cohen and Lee have suggested that a risk perception threshold exists at about 1 in 1000, because people tend to treat all risks lower than that as being equal.²⁴

Between risks that are clearly significant and those that are clearly trivial lies an ill-defined area where judgment must be applied. In this area, decisions about risks must be made using a broader range of criteria than just magnitude. Usually, we add an evaluation of the costs and benefits of available methods for reducing the risks and broader measures of the characteristics of the risks as they influence perceptions of severities and acceptability of magnitudes (see below).

Congress has, for example, set stringent safety goals for food and cosmetics for two apparently opposite reasons -- food because it is essential and cosmetics because they are not. Cosmetics are held to stringent requirements because their social benefits are insufficient to outweigh any risks. In contrast, medicines are seen as having significant benefits that balance increased risks. It is the net effect of the increases and decreases in risks from use of medicines that must be acceptable.

Travis *et al.*^{28,29} and Milvy²³ examined the magnitudes of risks regulated by government agencies to determine whether or not regulators implicitly use any quantitative definitions of trivial and significant. It appears that for chemical carcinogens:

- o All risks greater than about 4×10^{-3} are regulated without regard to cost;
- o Few risk less than 10^{-6} are regulated at all.

It would appear, therefore, that the regulations establish defacto definitions of "significant" and "*de minimus*" risks at these levels.

There is also a significant relationship between levels of acceptable risk and the size of the population affected. For small populations, risks as high as 10^{-4} are accepted. Milvy proposes a formula for acceptable risk that is a function of the inverse square root of the population affected (Figure 12), and supports its development with some philosophical discussion of equity and fairness.

He presents an interesting illustration that hypothesizes a case in which 100 cancer deaths annually are caused nationwide by a carcinogen that can be eliminated by a processing plant in which 30 of 100 workers will die of cancer per year. The national savings is 70 cancers per year and the risk is a known (and presumably compensated) condition of employment, but the solution would be unacceptable to most people because of the distribution of risks and benefits and the inequity of the burden placed on those workers. In contrast, a second illustration hypothesizes another factory in which 1 worker of 100 will face a 10 percent additional lifetime risk of cancer, and the reduction in risk nationwide is

50 cancer deaths per year. This solution seems acceptable, even though it exposes that single worker to a risk 67 times greater than the general population.

So it is clear that the mortality rate, alone, is not enough to establish the acceptability of risk. We are uncomfortable committing even a single specific person to die in order to make others of us free from risk.

Byrd and Lave point out that in some cases, risk may be trivial, but the cost of reducing them is also trivial, so there is little reason not to reduce them. In such cases, the burden of proof should fall on those advocating expenditures to demonstrate that they are justified, not on the regulatory agencies to demonstrate that they are not.²⁶ In the opposite case, when risks are significant but costs of reducing them are excessive, the burden of proof should fall on the regulatory agencies.

Figure 12. Risk regulation a function of size of population at risk. (Source: Reference 23)

1. Accident, fatal—private sector 1982
2. —mining
3. —finance, insurance and real estate,
47 years (18–65)
4. —all, 1982 rate for 70 years
5. Acrylonitrile⁽¹⁰⁾
6. Alachlor—dietary⁽¹¹⁾
7. —flaggers⁽¹¹⁾
8. —farmers⁽¹¹⁾
9. —ground applicators⁽¹¹⁾
10. Amitraz—apple & pear sprayers⁽¹²⁾
11. —apple & pear consumers⁽¹²⁾
12. —apple, dietary⁽¹²⁾
13. —pears, dietary⁽¹²⁾
14. Arsenic—copper smelters—high⁽¹³⁾
15. —copper smelters—low⁽¹³⁾
16. —glass manufacturing⁽¹³⁾
17. —Inorganic, neighboring—population average
exposure^(12,13)
18. —maximum exposure⁽¹²⁾
19. Asbestos—occupational
20. —school: students & teachers
21. Benzene—fugitive emissions⁽¹³⁾
22. —coke by-product^(13,14)
23. —maleic anhydride⁽¹³⁾
24. —ethylbenzene/styrene⁽¹³⁾
25. —storage⁽¹³⁾
26. —Stage II gasoline market⁽¹⁴⁾
27. —urban⁽¹³⁾
28. —average population exposure—drinking water⁽¹⁶⁾
29. —average population exposure—air⁽¹²⁾
30. Beryllium⁽¹⁷⁾
31. Butadiene, 1,3—occupational⁽¹⁸⁾
32. Cadmium⁽¹⁹⁾
33. Captan—food consumption⁽²⁰⁾
34. Captofol—food consumption⁽²¹⁾
35. Carbon tetrachloride—urban⁽¹³⁾
36. Chlordane/heptachlor—food consumption⁽¹²⁾
37. Chlorobenzilate—citrus consumers⁽¹²⁾
38. —citrus applicators (assumed)⁽¹²⁾
39. Chloroform—urban⁽¹³⁾
40. Chromium—vicinity of large point sources^(19,24)
41. —urban⁽¹⁹⁾
42. Cigarette smokers—male
43. Coke ovens—average exposure for U.S. population at risk⁽¹²⁾
44. —occupational⁽¹²⁾
45. Daminoside—food consumption⁽²²⁾
46. 1,2-dichloroethane—urban⁽¹³⁾
47. Ethylene dibromide—occupational⁽¹³⁾
48. —immediate post-regulatory dietary⁽¹³⁾
49. Ethylene dichloride⁽²³⁾
50. Ethylene oxide⁽¹⁹⁾
51. Folpet—food consumption⁽²⁴⁾
52. Formaldehyde—urban ambient⁽¹³⁾
53. —production use release⁽¹³⁾
54. —resin manufacturing workers⁽¹³⁾
55. —apparel workers⁽¹³⁾
56. —mobile homes⁽²⁵⁾
57. —nonurea/foam. homes⁽²⁵⁾
58. Lindane—shelf paper⁽¹⁷⁾
59. —livestock applicators⁽¹⁷⁾
60. —pecan applicators⁽¹⁷⁾
61. —food⁽¹⁷⁾
62. MBOCA—indirect occupational exposure⁽¹³⁾
63. —direct occupational exposure⁽¹³⁾
64. —nonproduction workers (occupational)⁽¹³⁾
65. MDA—manufacturing workers⁽¹³⁾
66. —processing workers⁽¹³⁾
67. —all workers—OTS based⁽¹³⁾
68. —all workers—TLV based⁽¹³⁾
69. Nickel⁽¹⁹⁾
70. Nitrosamines—occupational exposure from metal-
working fluids⁽²⁶⁾
71. NTA—Public drinking water⁽¹²⁾
72. —formulators (occupational)⁽¹²⁾
73. PCB—dietary food⁽²³⁾
74. Pentachlorophenol—applicators/workers⁽²⁷⁾
75. —air⁽²⁸⁾
76. Radiation, ionizing—all workers in medicine and industry⁽²⁹⁾
77. —power reactor workers⁽²⁹⁾
78. —coal-fired boilers⁽³⁰⁾
79. Radionuclides—DOE facilities⁽³⁰⁾
80. —uranium mines⁽³⁰⁾
81. —elemental phosphorus plants⁽³⁰⁾
82. —phosphate industry⁽³⁰⁾
83. Radon—drinking water⁽³¹⁾
- 83a. —indoor⁽³⁶⁾
84. Styrene monomer—occupational⁽²⁸⁾
85. Tetrachloroethylene—urban population⁽³²⁾
86. —dry cleaners⁽³²⁾
87. Trichloroethylene—urban air⁽³²⁾
88. Uranium mill tailings—inactive sites⁽¹³⁾
89. —active sites⁽¹³⁾
90. Vinyl chloride—average exposure for population—Air⁽¹²⁾
91. —maximum exposure (occupational)⁽¹²⁾
92. —workers (occupational)⁽¹⁹⁾
93. —average exposure for population—water⁽¹⁶⁾
94. Volatile Synthetic Organic Compounds⁽²⁶⁾
- — Risk—fatal “white collar” accidents (finance,
insurance, real estate) for 70 years.
- — 10^{-6} risk

Figure 12. (KEY).

4.2 COSTS OF RISK REGULATION

We would all like to be able to spend whatever amount of money and other resources are necessary to reduce risks to whatever level we agree is acceptable. But the world has never been so perfect, and we have never had enough money to do all of the things we might otherwise do.

The cost of controlling environmental risks in the United States is enormous. It is currently estimated to be 185 billion dollars a year in direct costs to industry and government, nearly \$1700 per year per taxpayer,³⁰ and much more in indirect costs.³¹ So someone must decide how our finite budget for reducing environmental risk will be spent.

But it is not clear that anyone has been especially rational about how our money should be spent. Except for a few extreme cases, it appears that risk management mechanisms have more or less stumbled along following the path of least resistance -- resistance of many forms and from many directions. In the literature of decision making this is called "muddling through," and it is common in our form of government.³² It may be, in fact, that regulators prefer this approach to any more rational one based on information and rules of procedure. It may simply be easier for officials under political pressure to commit resources when ignorant.³³ Only recently have there been serious attempts to introduce quantitative analyses of cost-effectiveness in risk management. In 1981, Executive Order 12291 mandated that federal agencies must perform cost-benefit analyses on rulings projected to cost \$100 million or more.³⁴ Since that time, based in part on some of the more startling results of such analyses, it has become increasingly clear that we simply cannot afford to continue as we have. A more rational approach is required.

To that end, the U.S. Office of Management and Budget (OMB) has requested the U.S. Department of Energy and other federal agencies to develop an integrated cost- and health risk-estimating process that can be used to evaluate the relative cost-effectiveness of alternative risk-reduction activities.³⁵ Work is currently underway, but the Department of Energy has encountered many problems in implementing this effort in the consistent way required for policy assessment, and results are subject to an exceedingly high uncertainty.³⁶

A recent report of the EPA Science Advisory Board also concludes that a major restructuring is required of the way EPA manages its risk mitigation activities. Among the Board's recommendations are:⁴

- o EPA should target its environmental protection efforts on the basis of opportunities for the greatest risk reduction.
- o EPA should attach as much importance to reducing ecological risk as it does to reducing human health risk.
- o EPA should improve the data and analytical methodologies that support the assessment, comparison, and reduction of different environmental risks.
- o EPA should reflect risk-based priorities in its strategic planning processes.
- o EPA should reflect risk-based priorities in its budget process.
- o EPA -- and the nation as a whole -- should make greater use of all the tools available to reduce risk.
- o EPA should emphasize pollution prevention as the preferred option for reducing risk.
- o EPA should increase its efforts to integrate environmental considerations into broader aspects of public policy in as fundamental a manner as are economic concerns.
- o EPA should work to improve public understanding of environmental risks and train a professional work force to help reduce them.
- o EPA should develop and improve analytical methods to value natural resources and to account for long-term environmental effects in its economic analyses.

A rational approach to risk management requires decisions on measures of values of reductions in risk, in particular including the value of a life saved. This is an exceedingly difficult judgment to make at the individual level, because it forces us to place a value on our own lives and those of our friends and loved ones, which are priceless. Rescuers do not ask the cost of rescuing trapped miners, for example. They pay as long as there is hope of success, partly because they (and the rest of us) hope others will rescue them if they are the next to be trapped. But for unknown lives (as in private donations for medical research), and for our own lives in the abstract (as in installing smoke alarms), we clearly make such judgments all of the time. The difficulty is quantifying these judgments systematically in dollars.

The best measure of the value of a life is the amount people are willing to pay, including foregone income, for lifesaving when confronted with actual decisions involving known risks of different kinds. Formal studies of willingness-to-pay for reduced risk examine such things as wage premiums offered for risky jobs and tradeoffs between effectiveness and price of safety devices. Application of results of such studies assumes a level of understanding of the risks involved that is similar to that of the risks to which results will be extended. In many cases, that may mean almost no understanding.

A recent survey of this literature found credible estimates ranging from \$1.6 million to \$8.5 million per life saved, with more confidence placed on the lower end of the range.²⁰ In particular, the values above \$5.5 million are based on data of questionable quality. The authors suggest viewing these results as an "interim range."

While the uncertainty of these estimates is exceedingly high, and we clearly would not want to pick a single number as absolute, nevertheless, it is also clear that expenditures outside this range must be considered unreasonable with respect to public willingness-to-pay. The top of this range must be considered an upper limit to the cost-effectiveness of an acceptable risk-reducing regulation.

Of course, not all risk-management regulations are aimed solely at human risk; many are also intended to reduce environmental risk. In many cases the values of environmental benefits are easier to quantify than the values of human lives because they are sold on open markets. The value of improved water quality in a river, for example, can be quantified in part through the resulting decrease in cost of treatment of that water downstream, its increased recreational and real estate value, and perhaps increased production of food fishes dependent on the quality of that river. To the extent that such environmental benefits are quantifiable, they can be subtracted from the total cost of risk-management regulations.

Morrall³³ and Travis, *et al.*²⁹ have examined the literature on costs of regulation. In 1986, Morall examined 44 proposed, final, or rejected federal rules aimed at reducing death (as opposed to non-fatal accidents or illnesses) for which reasonably complete information was available on risks, benefits, and costs. Morrall's data were updated by the federal Office of Management and Budget in 1992.³⁸ These are shown in Table 12.

Travis, *et al.* included only chemical carcinogens. Because of a lack of data on costs, most of the chemicals included are from decisions made after 1981 Executive Order 12291. Table 13 shows the estimated cost per life saved and Figure 12 shows a plot of cost per life saved against individual risk. The results are widely variable, with little systematic relationship between level of risk and cost-effectiveness of regulations except the "significant" and "*de minimus*" limits of 4×10^{-3} and 10^{-6} as mentioned on page 48, and:

- o Between, 10^{-6} and 4×10^{-4} , risk are regulated provided the cost is not more than about \$2 million per life saved.

4.3 THE ROLE OF COST-EFFECTIVENESS IN RISK MANAGEMENT

Lacking an unlimited budget, risk managers must either muddle through, following the path of least resistance and parceling out available resources to the risks-of-the-month until they are exhausted, or attempt to allocate them among alternative risk-reduction measures in some reasonable way. Were risk reduction the only criterion, then the allocation would be relatively straightforward, subject primarily to uncertainties created by inadequate knowledge and data on the cost-effectiveness of alternative risk-reduction measures.

Table 12. Risks and Cost-Effectiveness of Selected Regulations.^a

Regulation ¹	Year Issued	Health or Safety?	Agency	Baseline Mortality per Million Exposed	Cost per Premature Death Averted (\$Millions 1990)
Unvented Space Heater Ban	1990	S	CPSC	1,890	0.1
Aircraft Cabin Fire Protection Standard	1985	S	FAA	5	0.1
Auto Passive Restraint/Seat Belt Standards	1984	S	NHTSA	6,370	0.1
Steering Column Protection Standard	1967	S	NHTSA	385	0.1
Underground Construction Standards	1989	S	OSHA-S	38,700	0.1
Trihalomethane Drinking Water Standards	1979	H	EPA	420	0.2
Aircraft Seat Cushion Flammability Standard	1984	S	FAA	11	0.4
Alcohol and Drug Control Standards	1885	H	FRA	81	0.4
Auto Fuel System Integrity Standard	1975	S	NHTSA	343	0.4
Standards for Servicing Auto Wheel Rims	1984	S	OSHA-S	630	0.4
Aircraft Floor Emergency Lighting Standard	1984	S	FAA	2	0.6
Concrete & Masonry Yes Standard	1988	S	OSHA-S	630	0.6
Crane Suspended Personnel Platform Standard	1988	S	OSHA-S	81,000	0.7
Passive Restraints for Trucks & Buses (Proposed)	1989	S	NHTSA	6,370	0.7
Side-Impact Standards for Autos (Dynamic)	1990	S	NHTSA	NA	0.8
Children's Sleepwear Flammability Ban	1973	S	CPSC	29	0.8
Auto Side Door Support Standards	1970	S	NHTSA	2,520	0.8
Low-Altitude Windshear Equipment & Training Standards	1988	S	FAA	NA	1.3
Electrical Equipment Standards (Metal Mines)	1970	S	MSHA	NA	1.4
Trenching and C Standards	1989	S	OSHA-S	14,310	1.5
Traffic Alert and Collision Avoidance (TCAS) Systems	1988	S	FAA	NA	1.5
Hazard Communication Standard	1983	S	OSHA-S	1,800	1.6
Side-Impact Stds for Trucks, Buses and MPVs (Proposed)	1989	S	NHTSA	NA	2.2
Grain Dust Explosion Prevention Standards	1987	S	OSHA-S	9,450	2.8
Rear Lap/Shoulder Belts for Autos	1989	S	NHTSA	NA	3.2
Standards for Radionuclides in Uranium Mines	1984	H	EPA	6,300	3.4
Benzene NESHAP (Original: Fugitive Emissions)	1984	H	EPA	1,470	3.4
Ethylene Dibromide Drinking Water Standard	1991	H	EPA	NA	5.7
Benzene NESHAP (Revised: Fugitive Emissions)	1988	H	EPA	NA	6.1
Asbestos Occupational Exposure Limit	1972	H	OSHA-H	3,015	8.3
Benzene Occupational Exposure Limit	1987	H	OSHA-H	39,600	8.9
Electrical Equipment Standards (Coal Mines)	1970	S	MSHA	NA	9.2
Arsenic Emission Standards for Glass Plants	1986	H	EPA	2,660	13.5
Ethylene Oxide Occupational Exposure Limit	1984	H	OSHA-H	1,980	20.5
Arsenic/Copper NESHAP	1986	H	EPA	63,000	23.0
Haz Waste Listing for Petroleum Refining Sludge	1990	H	EPA	210	27.6
Cover/Move Uranium Mill Tailings (Active Sites)	1983	H	EPA	30,100	45.0
Acrylonitrile Occupational Exposure Limit	1978	H	OSHA-H	42,000	51.5
Coke Ovens Occupational Exposure Limit	1976	H	OSHA-H	7,200	63.5
Lockout/Tagout	1989	S	OSHA-H	4	70.9
Asbestos Occupational Exposure Limit	1986	H	OSHA-H	3,015	74.0
Arsenic Occupational Exposure Limit	1978	H	OSHA-H	14,800	106.9
Asbestos Ban	1989	H	EPA	NA	110.7
Diethylstilbestrol (DES) Cattlefeed Ban	1979	H	FDA	22	124.8
Benzene NESHAP (Revised: Waste Operations)	1990	H	EPA	NA	168.2
1,2-Dichloropropane Drinking Water Standard	1991	H	EPA	NA	653.0
Haz Waste Land Disposal Ban (1st 3rd)	1988	H	EPA	2	4,190.4
Municipal Solid Waste Landfill Standard (Proposed)*	1988	H	EPA	<1	19,107.0
Formaldehyde Occupational Exposure Limit	1987	H	OSHA-H	31	86,201.8
Atrazine/Alachlor Drinking Water Standard	1991	H	EPA	NA	92,069.7
Haz Waste Listing for Wood Preserving Chemicals	1990	H	EPA	<1	5,700,000.0

a. Source: Reference 33

Figure 13. Cost-effectiveness of federal regulations for chemical carcinogens. (Source: Reference 29)

But the criterion normally faced by risk managers is actually reduction in **political pressure**, which arises from **fears** about risks, real or not. Trouble comes from mismatches between the magnitudes of risks and public fear of them, and risk managers' obligation to address all fears in some way, regardless of their basis in reality.

This requirement is reasonable. We need not look far into history to learn that information changes; concerns change. Some of the available analyses and data will turn out to be incorrect or misleading, some not. The current risk-of-the-month may turn out on closer examination to be insignificant. Proposed mitigation measures may do more harm than good. Some of the fears ignored by risk assessors as products of public ignorance may turn out to be real and important.

The mismatches between available information and public fears are often extreme. Some risks are known to be exceedingly high, but there is little public fear that forces action, or there may even be public resistance to mitigating actions (cigarette smoking). Other risks are clearly low, but with high public fear and pressure for mitigation (radiation).

Table 13. Estimated cost-effectiveness of regulated chemical carcinogens.^a

Chemical	Annual cancers prevented	Cost per life saved (\$ Millions)
REGULATED CHEMICAL CARCINOGENS		
Arsenic		
High-arsenic copper smelters	0.9-14.2	0.1-1.6
Low-arsenic copper smelters	0.06-0.96	10-160
Glass manufacturing	0.06-0.99	5-81
Drinking water	65	0.015
Asbestos		
Occupational exposure		
at 2.0 fibers/cc	40	3.4
at 0.5 fibers/cc	52	3.3
Public and occupational exposure	129	1.01
Benzene		
Fugitive emissions	0.31	1.2
Gasoline emissions		
Stage I controls	0.06	1500
Stage II-NA controls	0.41-0.83	63-150
Stage II-Nat. controls	1.1-1.9	76-95
Onboard controls	1.4-1.7	120-140
Total	3.3-4.4	110-160
Butadiene	20	0.065-0.17
Cadmium	7.7	1.0
Chromium	180	0.033
Chlorobenzilate	0.4	4-12
Dibromochloropropane		
Occupational exposure		
Peaches	0.063	4.9
Citrus	0.05	240
Pineapples	< 0.001	> 230
Soybeans	0.13	55
Cotton	0.001	530
Total	0.25	81
Ethylene Dibromide		
Occupational exposure	0.94-7.9	0.5-4.1
Public exposure		
Soil fumigation	61	0.43-0.67
Quarantine fumigation	330	0.09
Spot grain fumigation	790	0.004
Ethylene oxide	9.1-10	1.9-3.8
Formaldehyde		
U-F foam	23	0.55-2
Lead	0.35	1.4
Trihalomethanes	325	0.12
Vinyl chloride	10.5	6.7
^a . Source: Reference 28		

Table 13. (Continued.)		
Chemical	Annual cancers prevented	Cost per life saved (\$ Millions)
UNREGULATED CHEMICAL CARCINOGENS		
Alachlor Diet	2	406-634
Amitraz Pears	1.6-2.4	2.7-4.1
Arsenic Secondary lead smelters	0.09-0.8	17-150
Benzene Storage vessels	0.13-0.89	2.1-14
Maleic anhydride Process vents	0.27-0.43	5.8-9.2
Chlorobenzilate Citrus fruits	8	0.38-7.3
a. Source: Reference 28		

How should risk managers best address this poorly-linked assemblage of information, misinformation, and fears?

Given the current state of knowledge, it is clear that risk managers should attempt to mitigate risks high enough to pass a predefined cost-effectiveness criterion regardless of political pressures in opposition. In such cases, risk managers have a professional obligation, and for regulatory agencies perhaps also a legal obligation, to promote mitigating actions and to educate the opposition.

Managers should study risks failing the criterion to reduce uncertainty about the cost-effectiveness of mitigation, and educate the public to reduce misplaced political pressure. We should not ignore feared risks that current information suggests are low, but neither should we allocate large sums of money to mitigate them just to calm an excessively-fearful public. In such cases, risk managers should try to educate the public as to the low cost-effectiveness of mitigation, and to better ways the money might be spend to reduce risk. Inevitably, this means trying to shift public attention from things people care about to things they don't.

5. HEALTH RISKS OF ENERGY TECHNOLOGIES.

5.1 COMPARING RISKS OF ALTERNATIVE TECHNOLOGIES

In the 1970's and early 1980's there was a large effort to quantify and compare the health risks of alternative energy technologies.³⁹ The basic methods developed then were generalized and have now been adopted as a standardized approach to risk assessment for many kinds of activities.

The fundamental objective of comparative risk assessment is to generate a set of risk estimates that places all alternatives on an equal basis for comparison. This is easier for technologies with similar risk characteristics, such as coal-, gas-, and oil-fueled power plants, and harder for technologies that are very different, such as solar energy technologies. The risk characteristics of the latter are fundamentally different from the former. They occur to different people and in different parts of the energy system; accidents are more important in some, and routine operation are important in others.

To account for these differences, analysts expanded their risk estimates to include increasingly more of the energy system, until finally they arrived at "fuel cycle analysis" and "materials analysis", which trace fuels and materials from "cradle to grave", examining risks of all stages of the cycle from extraction of fuels and materials, through construction and operation of facilities, to final disposal of wastes and decommissioning of plants. Further attempts to avoid leaving out important differences in risks lead to assessments that evaluate the indirect impacts of building and maintaining the facilities of the energy system throughout the entire national economy using economic input-output analysis.³⁹ This is based on an assumption that the economic activity required to produce and maintain the facilities in operation would not otherwise have taken place and therefore is attributable to those facilities. There remains some question as to whether or not extending the analysis to the entire economy yields risks that are actually attributable to the energy technology alone.⁴⁰

Energy systems are disaggregated into subsystems which are assessed separately:

o Fuel extraction	o Equipment fabrication
o Fuel processing	o Facility construction
o Fuel transport	o Operation and maintenance
o Conversion	o Waste disposal
o Power transmission	o Decommissioning

Risks are assessed for workers and the general public, for routine operations and accidents. Figure 14 shows a typology of risks that should be included. Results are standardized to some unit of system output (e.g., GWe-yr of electricity produced, Btu of

heat consumed, worker-year), accounting for the efficiency of transfer of energy through each subsystem. Note that this is not the same as standardizing plant sizes, as was the tendency in the early days of comparative risk assessment.⁴¹ It is clearly inappropriate to pretend that all types of plants (base load, peaking, solar and wind cycling, etc.) must be the same size when they are not build and operated that way.

Different measures of risk can produce different relative results. Risk can be expressed as average societal risk per unit energy produced, average individual risk per unit energy produced for those directly exposed, or risk to the maximally exposed individual. Because of differences in workers required per unit energy produced, for example, it is possible that an alternative using few workers could have a low average societal risk per unit energy but a high individual risk per worker for the few workers involved. Similarly, average public exposures to pollutants could be low, but a few people nearby could have especially high exposures. These differences are significant to decision making, requiring judgments about the relative importance of risks to a few and risks to many. Similar judgments are required about risks now or to the current generation versus risks later, especially to future generations.

There is also a broad range of **kinds** of health and environmental risks, and the mixes of kinds of risks are different for different technologies. Kinds of risks (or sources of risks) are generally reported separately (e.g., fatalities, illnesses, lost workdays, resources consumed, tons of emissions), but there have been many attempts to make them commensurable in some rational and objective way -- to develop a common metric that allows direct comparison of mixes of different kinds of risks. This requires, for example, a way to determine how many dead ducks are equivalent to one sick sister. Attempts are usually based on studies of willingness-to-pay or willingness-to-be-compensated to have more or less of the value at risk. While such measures are possible in theory, they are often difficult to estimate in practice. One approach, called contingent valuation, is to ask people how much they would be willing to pay for situation A over situation B. The results of such studies have three weaknesses:

- o They contain a wide range of responses;
- o Responses vary with the way questions are asked; and
- o The credibility of the responses is questionable, because respondents don't actually have to pay the difference.

One suggested alternative is to use as a surrogate the dollar cost of reducing or mitigating all kinds of risks to *de minimus* levels.⁴¹ Examples might be the cost of emissions controls or the cost of restocking a damaged stream with fish. This surrogate has theoretical problems in that there is not necessarily any relationship between abatement or mitigation costs and risks, but it establishes an upper bound on peoples' willingness-to-pay, and the needed information can be developed at the current state of knowledge.

Some care must be taken in selecting the alternative energy systems and technologies to be compared. A valid comparison requires that the technologies be **exchangeable**. That is, they must be directly substitutable in the energy system -- in a utility's generation mix, for example, or in some end use. Thus technologies for generating base load power should not be compared with those for short-term peak loads; low-temperature home heating technologies should not be compared with high-temperature industrial heating technologies.

Similarly, most energy technologies are part of a system of interconnected parts. They should not be evaluated apart from the rest of the system without which they can not operate. For example, wind-powered electricity generation requires some way to adjust to mismatches between the supply of wind and the demand for electricity, so it must usually be part of a larger and more flexible system. Thus a windmill should not be compared directly with another source of electricity out of the context of the system in which it must operate; solar heating devices should include requirements for emergency or peak demand backup systems, perhaps electric or kerosene space heaters, which have high risk.

Risk assessors often forget that the health risks of energy technologies are not fixed. Rather they are variable functions of the resources expended to reduce them through emissions controls, safety equipment, and low-impact locations. We evaluate "generic" energy technologies for comparison, including comparison of costs. But there are always opportunities for reducing risks at increased expense. Technologies can be compared given some specified set of controls (e.g., current Federal, state, and local regulations) and a specific location, but the results will change if the degree of control or the location is altered. There are cases for which a site and specific fuel-technology alternatives have been identified. Comparisons can be made under such circumstances, but the results should not be generalized.

Another exceedingly difficult consideration is defining or assigning **attributable** risks. In general, the public health risks from normal operations of all energy sources are negligible at the level of a single plant. But plants do not operate individually, they are part of systems and contribute to background levels of the same risks from other sources. No single power plant produces acid rain, for example. Acid rain is a result of total emissions exceeding the assimilative capacity of the environment; many plants and many natural sources of emissions together produce acid rain. What then is the contribution of a single plant to the total? If the existing system does not exceed the assimilative capacity of the environment, but one more plant will, should all of the damage be attributed to the one new plant, which in fact will cause the damage, or should it be shared among all because of their contribution to the total? Analysts have not resolved satisfactorily how to treat the marginal effects of new facilities.

The uncertainties contained in most estimates of the health risks of energy technologies are immense -- routinely several orders of magnitude or more:⁴⁰

- o Artifactual uncertainties arise from the uncertainty of analysts about how raw data should be converted into risk estimates, including artifacts from data selection, processing, or interpretation, questions about how to define "generic" facilities and conditions for analysis, and deciding what risks are properly attributed to the energy technology rather than the economic system as a whole. For generic facilities, for example, there is a tradeoff between the specificity of the technology analyzed (precision) and the representativeness of the results (accuracy), that can not readily be resolved in any simple way
- o Observational uncertainties arise from inadequacies in the quality of the available data, including incomplete data and nonspecific data containing irrelevancies. Excessively aggregated data are a particularly large problem of this type, since it is common that analysts must rely on national statistics, which are usually organized and aggregated in ways that are suboptimal for health risk assessment. Huge uncertainties arise from inadequate understanding of the exact relationships between exposures to pollutants and resulting health effects at concentrations in

ambient air. Usually, the data on the effects expected to be most common and therefore most important, such as subclinical degradations in health from exposure to pollutants, are insufficient to be included in any assessment.

- o Random uncertainties arise from the normal variability of random processes, which have a statistical distribution of values about their means and are not expected to be a specific value. These include effects of location, time, weather, population distributions, and a broad range of similar natural conditions that have no fixed value.

For these reasons, small differences among estimated risks of generic technologies are not meaningful for decision making.

5.2 RECENT ESTIMATES OF HEALTH RISKS OF ENERGY TECHNOLOGIES

The human health impacts of energy technologies arise mostly from routine emissions of pollutants and from traumatic accidents, which may also release pollutants. The natures and magnitudes of the risks differ among technologies -- they are a lot different for some -- and so the differences must be included in any evaluation of their relative merits.

Based on the characteristics of their health risks, energy technologies can be classified into three groups:⁴²

- o The Fuels Group is characterized by use of large amounts of fossil fuels or biomass -- coal, oil, natural gas, wood, etc. -- the collection, processing, and transport of which have high accident rates that dominate occupational risks and the burning of which produces large amounts of air pollution and solid waste that dominate public risks.
- o The Renewable Group is characterized by use of diffuse renewable resources with low energy density -- sun, wind, water -- which are available in enormous quantities at no cost, but the capturing of which requires large areas and construction of expensive facilities capable of "concentrating" them into useful forms. Occupational risks are high and dominated by construction of the facilities. Public risks are low, mostly confined to low-probability accidents, such as dam failures, equipment failures, and fires.
- o The Nuclear Group includes nuclear fission technologies, which are distinguished by extremely high energy densities in the processed fuel, with correspondingly low quantities of fuel and wastes to process, but with low concentrations in the earth's crust, necessitating a large mining or collection effort. Occupational risks are, therefore, relatively high and dominated by mining and processing accidents. Public risks are small and dominated by routine operations of reactors. Special attention

must be given to public fears of risks from exposure to radiation from nuclear technologies -- fears which are relatively large per unit risk to health.

Within these technology groups, health risks are similar in form and magnitude. But among the groups they are quite different. They occur in different parts of the fuel cycle, to different people, and their characteristics are different with respect to public perceptions of their relative importance in decision making.

To compare the health risks of these different energy technologies on a common, rational basis, it is therefore necessary to consider entire fuel cycles, from their beginnings in extraction of fuels to their endings in disposal of wastes. Some analyses even include risks of providing materials for building and operating facilities.

It is also necessary to distinguish between effects on workers and on the general public, and between effects of routine operations and accidents. Hazards at work are normally accepted conditions of employment and are more or less controlled by safety regulations. Hazards to the general public are usually involuntary and poorly understood, often feared inordinately or ignored completely. Similarly, routine risks are subject to explicit or implicit acceptability criteria, but accidents are often too infrequent to be remembered and evaluated adequately. Frequent accidents (e.g., automobiles) soon become routine and accepted in the public mind; infrequent and severe accidents (e.g., airplanes) are especially feared regardless of their likelihood.

We would also like to be able to distinguish between kinds of health effects -- acute and chronic, fatal and nonfatal, short-term and long-term sequelae, etc. As is evident from public fears of radiation, all health risks are not equal. But because of problems with definitions and extensive overlapping in characteristics and severities among health effects of energy technologies, it is seldom possible to make such fine distinctions. Often studies include only risk of death for lack of other quantifiable endpoints for which useful data are available.

5.21 Health Risk Assessment

A valid comparison of health risks of alternative energy technologies should include the following.

- o Risks to workers.
 - Routine exposure to chemicals, radiation, noise, and stress.
 - Accidental trauma and exposure to chemicals, radiation, noise, and stress.

- o Risks to the general population.
 - Routine exposures.
 - Chemicals.
 - Radiation and electromagnetic fields.
 - Social factors (employment, population distribution, culture).
 - Accidents.
 - Physical and chemical trauma.
 - Inhalation or ingestion of harmful chemicals.
 - Exposure to radiation.
 - Indirect risks from changes in the environment
 - Disease vectors
 - Food crops and nutrition
 - Livelihood and lifestyle

Important analytical considerations that should be addressed in a valid comparison of energy technologies are:

- o Specification of technical boundaries of the system to be analyzed. Substitutability of technologies to be compared.
- o Specification of geographic and time scales of interest. Discount rates into the future.
- o Use of Mean estimates, confidence intervals and/or probability distributions. Content of confidence intervals.
- o Use of consistent coefficients among alternatives for emissions, accidents, and health effects.
- o Applicability of data from other countries.
- o Analysis of routine and/or accidental effects. Severity of accidents included.

There are no studies that include all of these health risks for all or even a large number of energy technologies. Rather, there are studies of most of these risks from some technologies and some of these risks for most technologies. The best information is available on the things people care about most; the rest we must infer however we can. And there are no studies that are consistent with respect to all of the analytical considerations.

5.22 History

In the 1970's many governments and institutions expended large amounts of resources assessing the health and environmental impacts of alternative energy sources to provide data for long-term energy planning. This work generated a broad range of reports and comparisons, each attempting to improve on the previous.⁴³

After that effort, work aimed at comparing alternative technologies declined until 1990, when a new wave of activity began in response to concerns about environmental

externalities and ways to include them in evaluating electricity-generating technologies. This new activity is described qualitatively below, but results are not summarized herein for two reasons:

- o Early estimates of externalities have been severely criticized by U.S. Department of Energy analysts and others. Presentation of those results would lend them credibility that the U.S. Department of Energy believes they do not deserve.
- o In 1990, the U.S. Department of Energy initiated a series of fuel cycle studies to provide better estimates of externalities, but these studies are not yet available.

Therefore, the quantitative results on the relative health impacts of energy technologies presented below is based on descriptions of technologies, environmental regulations and health effects information as they were 10 to 15 or more years ago, or on projections from that time of what they might look like in the future.

But times and technologies have changed. Some new technologies are available or developing rapidly; some promising technologies failed to meet expectations. Environmental controls have improved; attitudes have changed; regulations have become more stringent; new environmental concerns have developed. More studies of health effects of exposure to pollutants are available; in particular, it has become apparent that combustion products cannot be lumped together and treated the same for all technologies based on a single-pollutant (sulfur oxides) surrogate as we did in the past.⁴⁴ Finally, as required controls have reduced health risks of generating electricity, attention has shifted to other environmental impacts, particularly regional and global impacts of the collective emissions from all burning of fossil fuels. Examples are acidic deposition, regional haze, and changes in global climate.

This discussion, therefore, places limited emphasis on the details and magnitudes of the available estimates of health effects of energy technologies. The new studies externalities will produce more up-to-date estimates and will present them in new metrics (See Section 1990's, below).

We would get slightly different numbers were we to repeat the studies today. But the available data remain useful for comparisons among technologies, particularly for comparisons among the technology groups described above. The health effects of these groups are so different, and occur in such different places and to different people, that the small technology- and pollutant-specific details are of less importance.

5.23 Summary of Health Effects

The significant health effects of technologies for generating electricity are shown in Tables 14 through 16.

5.24 Comparisons of Health Effects

1970's.

Paskievici reviewed 15 important studies from the active period of the 1970's.⁴⁵ Some of these studies have been heavily criticized in the literature for methodological inadequacies and all are exceedingly inbred, one building on the results and assumptions of another (Figure 15). Yet their results vary by as much as a factor of 100 even for the same author in different studies. The numbers reported by Paskievici are also subject to heavy criticism because of exceedingly low quality control during extraction and conversion to standard units.⁴⁶ Appendices A-1 through A-8 show results from Paskievici's survey as partially recalculated and corrected by Brookhaven National Laboratory.⁴⁷ Given that the verification of Paskievici's results is incomplete, the primary usefulness of these numbers is to illustrate the exceedingly high uncertainty of such derivations.

With respect to the uncertainty of the estimates, Paskievici concluded:

- o Differences in dose-effect model can produce variations of a factor of 100;
- o Differences in postulated antipollution equipment can produce variations of a factor of 25;
- o Differences in location of the facility can produce variations of a factor of 10.
- o Differences in the distances over which exposures are estimated (e.g., < 50 mi, > 50 mi) can produce variations of a factor of 10;
- o The nuclear fuel cycle is better understood and better quantified than the other fuel cycles; and
- o Much of the variability in these estimates reflects our limited knowledge of the physical, chemical, and biological reactions that connect emissions of pollutants to health effects;

Table 14. Significant health effects of technologies for generating electricity -- Fuels Group.^a

Technology	Health effects	
	Occupational	Public
Coal	Black lung disease Trauma from mining accidents Trauma from transport accidents	Air pollution health effects Trauma from transport accidents
Oil	Trauma from drilling accidents Cancer from exposure to refinery organics	Air pollution health effects Trauma from explosions and fires
Oil shale	Brown lung disease Cancer from exposure to retorting emissions Trauma from mining accidents	Cancer from exposure to retorting emissions Air pollution health effects
Natural gas	Trauma from drilling accidents Cancer from exposure to refinery emissions	Air pollution health effects Trauma from explosions and fires
Tar sands	Trauma from mining accidents	Air pollution health effects Trauma from explosions and fires
Biomass	Trauma from accidents during gathering and processing Exposure to hazardous chemicals and biological agents from processing and conversion	Air pollution health effects Diseases from exposure to pathogens Trauma from house fires
a. Source: Reference 48		

Table 15. Significant health effects of technologies for generating electricity -- Renewable Group.^a

Technology	Health effects	
	Occupational	Public
Geothermal	Exposure to toxic gases - routine and accidental. Stress from noise. Trauma from drilling accidents	Disease from exposure to toxic brines and hydrogen sulfide. Cancer from exposure to radon
Hydropower, conventional and low-head	Trauma from dam failures.	Trauma from construction accidents. Disease from exposure to pathogens.
Photovoltaics	Exposure to toxic materials during fabrication - routine and accidental.	Exposure to toxic materials during fabrication and disposal - routine and accidental.
Wind	Trauma from accidents during construction and operation.	
Solar thermal	Trauma from accidents during fabrication. Exposure to toxic chemicals during operation.	
a. Source: Reference 48.		

Table 16. Significant health effects of technologies for generating electricity -- Nuclear Group.^a

Technology	Health effects	
	Occupational	Public
Fission	Cancer from exposure to radiation during uranium mining, ore/fuel processing, power plant operation, and waste management Trauma from industrial accidents during mining, processing, power plant construction and operation, and waste management	Cancer from exposure to radiation during all stages of the fuel cycle - routine and accidental Trauma from transport accidents
a. Source: Reference 48.		

Readers should not place a great deal of weight on the ranges included in the various tables herein. They are not derived from a consistent basis, but rather represent those portions of the total uncertainty the analysts were able or willing to include in the analyses. In some cases they represent the range of other analysts' estimates, which depend a great deal on their assumptions. Although some assumptions are becoming "standardized" by default from repeated use, there are few rules that assure consistency. Often the ranges include only one or two variables for which the analysts were unable to specify a "best estimate" on some rational basis.

This is not necessarily bad with respect to the usefulness of the results for policy analysis and decision making. Were all of the sources of uncertainty contained in an estimated included, the range of the result would be so large as to be essentially meaningless and therefore useless. It is better to constrain the estimate to a specified set of circumstances that are easy to understand than to include all circumstances and produce a result that is not understandable. Differences between what is analyzed and the real world can be dealt with intuitively. Therefore, consistency is more important than completeness.

The health risk estimates are, therefore, much more uncertain than is indicated by their ranges. How much more uncertain can be seen from Paskievici's comparison. Paskievici separated diseases from normal operations from effects of accidents, diseases and trauma. He selected his "best estimate" of the risks of diseases from normal operations based on his review (Table 17); "best" appears to be mostly subjective judgment. From these he concluded the following.

- o The total risk of occupational diseases is negligible for the oil and natural gas fuel cycles and similar for the coal and uranium fuel cycles. Major risks of occupational diseases in the coal cycle occur during extraction; those in the uranium cycle occur at power plants and reprocessing facilities.
- o The risk of fatalities in the general population is negligible for the natural gas cycle, relatively low for the uranium cycle, and relatively high for the coal and oil cycles.
- o The risk of fatalities in the general population is lower than that of occupational fatalities for the uranium cycle, but higher for the coal and oil cycles.
- o The risk of occupational diseases is negligible in the natural gas cycle, and higher in the oil, uranium, and coal cycles, in that order.
- o The total risk of non-fatal diseases is much higher for the coal and oil cycles than for the uranium cycle; the natural gas cycle has practically no health effects.

Table 17. "Best estimates" of health effects of fuel cycles, not including accidents, Paskievici, 1980.^a

Fuel Cycle	Workers		Population		Total	
	Deaths	Diseases	Deaths	Diseases	Deaths	Diseases
Coal	0.1 (5)	1.5 (2)	3 (10)	1000 (20)	3 (10)	1000 (20)
Oil	~0	~0	3 (10)	1000 (20)	3 (10)	1000 (20)
Natural gas	~0	~0	~0	~0	~0	~0
Uranium	0-0.2	0-0.2	0-0.1	0-0.1	0-0.3	0-0.3

a. Source: Reference 45. Estimated uncertainty factors are given in parentheses.

Table 18. "Best estimates" of health effects of accidents in fuel cycles, Paskievici, 1980.^a

Fuel Cycle	Workers		Population		Total	
	Fatal	Non-fatal	Fatal	Non-fatal	Fatal	Non-fatal
Coal	1.40 (1.5)	60 (1.5)	1.0 (1.5)	1.8 (2.0)	2.4 (1.5)	62 (1.5)
Oil	0.35 (1.5)	30 (1.5)	?	?	0.35 (1.5)	30 (1.5)
Natural gas	0.20 (1.5)	15 (2)	0.009 (1.5)	0.005 (1.5)	0.21 (1.5)	15 (2)
Uranium	0.20 (1.5)	15 (2)	0.012 (1.5)	0.11 (2)	0.21 (1.5)	15 (2)

a. Source Reference 45. Estimated uncertainty factors are given in parentheses.

Paskievici also selected subjective "best estimates" for health risks of accidents (Table 18). These include only statistics on real accidents, not hypothetical ones, and in most cases do not include accidents during construction and dismantling of facilities. No public risks from nuclear accidents are included, as there were no data from real accidents when the report was written.

He concluded the following.

- o Estimates of health risks of accidents are less uncertain than those of routine operations. Results of different studies agree within a factor of 2. Differences are attributable to assumptions about working conditions and interpretations of statistical data.
- o The risks of occupational fatalities in the natural gas and uranium cycles are very small; those for the oil and coal cycles are two and seven times larger, respectively.

The risks in the coal cycle are mostly from mining; those from the nuclear cycle are more evenly distributed.

- o The risk of fatalities in the general population from accidents is essentially negligible for the oil, natural gas, and uranium cycles. It is about 100 times greater for the coal cycle. In all cases, public risk arises from transport of fuel.
- o The risks of occupational injuries have the same distribution as occupational fatalities -- lowest for the natural gas and uranium cycles, two times higher for oil, and four times higher for coal.
- o The risk of injuries in the general population is very low, with the coal cycle being an order of magnitude higher than the natural gas and uranium cycles.

1980's.

We know of only three large integrated studies done in the 1980's that attempt to compare energy technologies on a uniform, consistent basis for complete fuel cycles, one by the United Nations Environment Program,⁵⁰ another done specifically for conditions in Switzerland,⁵¹ and one by the Electric Power Research Institute which includes mostly occupational health risks.⁴⁰ In spite of their more recent publication dates, however, most of the data used was taken from the earlier studies from the 1970's, and at best only a few technologies have been updated to account for changes in conditions.

Fritzsche. The most recent comparison is by Fritzsche for alternative energy systems in Switzerland.⁴² Fritzsche critically reviewed the literature on comparative risk assessments for energy technologies, with emphasis on more recent studies, and renormalized the results to represent conditions in Switzerland and the Federal Republic of Germany with respect to pollution emissions, population density, and the environment. He believes that the results are representative of new large modern power plants that could be built now in Europe. Note that the origin of these estimates is a report written in German, and we have not had an opportunity to evaluate its quality. There are suggestions that the assumptions and methods used may not be standard (e.g., high public risks from chronic diseases in the Renewable Group [Fig. 3]).

Figures 16 and 17 show Fritzsche's results for acute and chronic health effects to workers and the public for routine operations and accidents. The sloping ends of the bars represent the range of the estimates; the dotted shading indicates results of higher quality for well-studied systems. The scale is logarithmic, which tends to de-emphasize differences among technologies.

Figures 18 and 19 show Fritzsche's summary of results for severe accidents (more than 10 simultaneous deaths) world-wide (Table 19), which he assesses separately because of special public concern.

Figure 16. Occupational mortality risks of energy production from all stages of the fuel cycle, without severe accidents. (Source: Reference 42.)

Figure 17. Public mortality risks of energy production from all stages of the fuel cycle, without severe accidents. (Source: Reference 42.)

Figure 18. Frequency of acute fatalities per GWe-y electricity production from severe accidents in the nuclear and fossil-fuel systems. (Source: Reference 42.)

Fritzsche concludes that the health risks of production of electricity are relatively well known, even with respect to the probability of unlikely but potentially serious accidents. The technologies of the Fuels Group generally have high routine risks to the persons who collect the fuel and, except for natural gas, high routine risks to the public from inhalation of combustion products. The technologies of the Renewables Group have high routine risk to workers from construction of facilities, and "nonnegligible" routine risks to the public. The technologies of the Nuclear Group have "nonnegligible" routine risks to miners and operators of facilities and very low routine risks to the public.

Fritzsche also concludes that the probability of a severe accident is relatively high for the Fuels Group, low for the Nuclear Group, and, except for dam failures, essentially inconceivable for the Renewables Group.

Figure 19. Frequency of acute fatalities per GWe-y electricity production from severe accidents in hydraulic dams. (Source: Reference 42.)

UNEP. The second study was a massive, multi-year effort by the United Nations Environmental Program that attempted to incorporate and generalize essentially all of the quantitative health and environmental risk information available in the literature at that time.⁵⁰ Any effort of such size and scope is inevitably vulnerable to criticism for inconsistencies and procedural inadequacies that make the results highly uncertain. Nevertheless, this study is the largest, most complete, and most recent of those available. Virtually all of the results of this study are summaries of those from the reports of the 1970's.

Results from the United Nations Environment Program project are shown in Appendix B-1. Since the entire fuel cycle is not included for all technologies, the estimates of health risks are not completely comparable in every case.

Table 19. Severe accidents world-wide in the period 1969 to 1986. ^a					
Energy option	No. Severe accidents	Cause	Stage	Acute fatalities per event	Average per year
Coal	62	Mine accident	Coal mine	10-434	> 200
Oil	6	Capsizing	Oil platform	6-123	
	15	Fire/explosion	Refineries, tank farms	5-145	~ 25
	42	Fire/explosion	Transport	5-500	> 90
Natural gas	24	Fire/explosion	Various	6-452	> 80
Water	> 8	Over-topping	Dams	11-2500	> 200
Nuclear	1	Meltdown	Chernobyl	31	
a. Source: Reference 42.					

Figures 20 and 21 show total occupational fatalities for electricity and large-scale heating fuel cycles. The highest occupational risks are associated with technologies involving much intermediate processing (coal gasification, coal liquefaction, oil shale). Direct combustion of fuels has lower occupational risk (excepting natural gas), with the specific level of risk being related to the energy density of the fuel. High-technology systems (nuclear, renewables) plus natural gas have the lowest occupational risks. The ratios of deaths to injuries are not constant among technologies.

EPRI. The study by EPRI reviews important past studies that assesses methodologies and presents a state-of-the-art general "risk accounting" methodology for health risk assessment, which was applied to a comparative risk assessment of eight energy systems for generating electricity. This report provides considerable detail on basic methodologies and their limitations for inter-technology comparisons.

- o Risk levels of alternative technologies are not fixed, but are functions of the resources expended to reduce them. Allocation of resources is a policy decision.
- o Even though estimates of occupational health risks are easiest to obtain and have the best quality of supporting data, the range of plausible results is nevertheless orders of magnitude. This range is an inevitable result of the level of disaggregation of the data from which the basic calculations are made, and of ambiguities in specifications of processes. We cannot expect to do better with currently available data.

Figure 20. Occupational health risks of different energy cycles for generating electricity. (Source: Reference 50.)

Figure 21. Occupational health risks of different energy cycles for large-scale generation of heat. (Source: Reference 50.)

Table 20. Summary of estimated public health risks from routine emissions and transport of fuel for selected energy technologies (Reference 40).

Technology version	Risks to public health and safety from routine emissions	Fatalities per GWe-Y from transport of primary fuel^a
Coal-fired steam plant	Possibility of cardiopulmonary and respiratory symptoms from SO ₂ pollution. Possible cancers from hydrocarbons.	0.66
Wood biomass	Possibility of mild symptoms from NO ₂ and SO ₂ pollution in the vicinity of plant under worst-case conditions.	< 1.5
Oil fuel cell plant	Negligible, except for possible carcinogenic effects of hydrocarbon emissions.	Negligible (< 10 ⁻⁶)
Gas fuel cell plant	Negligible, except for possible carcinogenic effects of hydrocarbon emissions.	6x10 ⁻⁶ - 6x10 ⁻⁴
Nuclear PWR	Possibility of latent cancer fatalities from radiation.	4.3x10 ⁻⁴
<p>a. Only public health risks from routine emissions of SO_x, NO_x, particles, and radionuclides are included. Risks from other fuel processing stages, and from acidic precipitation, climatic modifications, fires, explosions, and other kinds of accidents are not included.</p>		

Results from the EPRI study are summarized in Figure 22 and Table 20. The study concludes:

- o Results for different technologies should not be compared unless they are directly substitutable one for another (e.g., a peaking plant should not be compared with a base-load plant).
- o Public health risks are more difficult to estimate than occupational risks. Risks from pollution emissions are particularly difficult to quantify. Some useful results are available for specific plants; results for "generic" technologies are probably not useful.

Key:

Operations and Maintenance Risks

Construction Risks

Dots within the range of estimated risk correspond to point estimates

Cautionary Note: Comparison of risks between technologies cannot be made meaningfully unless the technologies are substitutable.

Figure 22. Expected range of occupational fatalities per GWe-y from construction, operation, and maintenance of energy facilities. (Source: Reference 40.)

- o Two particularly important methodological gaps are highlighted.
 - The more precise is the definition of a technology, the better the quality of the results, but the less general are the conclusions that can be made from them.
 - When there are "risk externalities" arising from multiple plants or end uses, joint production, or combined emissions, it is not clear how the share of the total risk -- the attributable risk -- should be estimated.

1990's

State regulatory authorities often approve the selection of technologies and fuels for new and repowered electricity generating plants based on a comparison of costs, with the least-cost alternative selected. In addition, some States seek to estimate economic values for "externalities" - or those external costs not considered by private decision makers - and include these costs along with the engineering cost to arrive at a total cost for each alternative. In these States, an attempt is made to include the economic value of health and environmental damages when selecting the least-cost alternative. In 1990, the U.S. Department of Energy initiated an effort to quantify risks and damages attributable to various electricity generation technologies.⁵⁵ In this study, the metric used for comparison of costs is mills per kilowatt-hour.

The two methods used to estimate values of external costs are (1) revealed preferences,⁵² and (2) damage functions.⁵³ The revealed preference method simply compiles the cost-effectiveness of regulatory requirements at the federal, state, and local levels. For air pollutants, this yields a range of values in \$/ton removed. External costs are obtained by multiplying the expected emission rate of each alternative by some number from within the range of \$/ton and dividing by the electricity production rate.

While the revealed preference method is easy to use, its validity depends on assumptions that:

- o Past regulations correctly estimated and weighed the various risk factors discussed above and
- o Selection of a value from the "revealed" range of \$/ton can be done rationally.

These assumptions are so tenuous that the U.S. Department of Energy is in favor of the damage function method, which is more robust.

The damage function method is similar to "fuel cycle analysis" discussed above, but with the additional step of estimating monetary values of risks and damages. This is the theoretically correct approach, but it is difficult and costly to implement. In the case of air pollutants, four steps are necessary in the estimation:

- o Amount of emissions;
- o Effects of emissions on air quality (source-receptor modeling);
- o Effects of air quality on health and the environment (damage functions); and
- o Economic costs of the effects.

Each step introduces additional uncertainties, particularly the last two, so that total uncertainty overall is orders of magnitude.

Nevertheless, emerging interest in least-cost energy planning that includes health and environmental externalities, and dissatisfaction with the values of externalities estimated in the available literature has led the U.S. Department of Energy and the Commission of European Communities to sponsor a new series of fuel cycle studies. The U.S. Department of Energy study is being done by Oak Ridge National Laboratory and Resources for the Future.⁵⁴ When completed, this effort will update the findings reviewed above to include more recent technologies, regulators, and environmental concerns.

In the latter, one way to approach the consideration of externalities is to let external costs affect the choice of technology and fuel given the degree of regulation. Determination of whether or not an external cost is significant to a decision depends on its value relative to the engineering costs of that alternative (both in mils/kw-hr). This approach provides (at least in theory) a criterion for deciding whether or not an environmental impact is important.

An example illustrates how the externality concept works, and may assist readers in evaluating the estimates of public deaths from alternative energy technologies provided in the Appendix. Suppose a new coal-fired powerplant would increase the public mortality rate by 1 death/GW-yr, and a public death is valued at \$2 million. This is about 0.2 mils/kw-hr. The engineering cost of a coal-fired powerplant is about 40 mils/kw-hr. Clearly an additional 0.2 mils/kw-hr will make little difference when coal is compared with other electricity-generating alternatives. But 100 public deaths/GW-yr would increase the cost of electricity by 20 mils/kw-hr -- a substantial additional cost.

Unfortunately, the uncertainties involved in current estimates of externalities preclude definitive results in many cases. Nevertheless, this approach has several virtues:

- o If the high end of the uncertainty range of an externality is small compared to engineering costs, then that externality can be ignored in the selection of technology and fuel;
- o The relative importance of the many externalities associated with fuel cycles are highlighted by the damage function method; and
- o Externalities that are potentially important but highly uncertain in degree and/or value can be identified for further study.

For the foreseeable future, some external costs will have ranges of uncertainty that span the decision space from unimportant through important. Since we assume that scientific knowledge has been exhausted in estimating the range of uncertainty, selection of a specific value must be a political decision. Research can narrow, but not eliminate ranges of uncertainty, so the role of politics in environmental protection appears to be secure so long as some ranges span the decision space.

5.25 Evaluation

The literature contains quantitative estimates of occupational and public health risks of energy technologies that can form a general basis for policy analysis and decision making. These results are technically slightly out of date, but not by so much as to be useless.

The results indicate that the risks of different technologies are different, often significantly so with respect to the bearers of the risk. But taken as a whole, for entire fuel cycles and energy systems, the differences among alternatives are not especially large compared to the uncertainty of the estimates. The latest round of fuel cycle studies will reexamine and may revise this conclusion.

The quality of the available information is inadequate to support detailed, quantitative, resource optimization studies based on estimated levels of health impacts. Instead, it can be used to provide general insights and some confidence that whatever energy technologies are selected for other reasons, there are not likely to be any future surprises with respect to the actual health risks of providing energy. Risks that seem unacceptably high based on these estimates can be studied in more depth and resources can be allocated to reducing them if it seems appropriate.

6. SUMMARY AND CONCLUSIONS

- o For a broad range of reasons, it is hard to think rationally and quantitatively about risks from any source. But it is especially hard to think about scary ones. We are all more or less subject to biases in perception or risks related to:
 - Misperceptions of randomness;
 - Overvaluation of small samples or unreliable data;
 - Neglect of base rates;
 - Availability of information;
 - Hindsight;
 - The "certainty illusion;"
 - Anchoring of opinions;
 - Failure to recognize regression; and
 - Desire for too much or redundant information.

The perceived magnitude of risk may, therefore, be significantly different from the "real" magnitude of risk as estimated by the standard methods of risk assessment.

- o The acceptability of a risk is a complicated function of a range of characteristics, only one of which is the "real" magnitude of morbidity or mortality. A large portion of acceptability is determined by its capability to create a feeling of "outrage" among those affected. Outrage is a function of:
 - Voluntariness;
 - Control;
 - Fairness;
 - Trustworthiness of source;
 - Ethicality;
 - Naturalness;
 - Familiarity; and
 - Memorability.

Other important characteristics related to the specific nature of the hazard are:

- Immediacy;
- Observability;
- Understandability;
- Fatality; and
- Dreadness.

- o Although we fear obscure risks, 90 percent of all deaths are from familiar causes -- first cardiovascular disease and cancer (65 percent), then accidents, chronic obstructive lung disease, pneumonia and influenza, and diabetes (25 percent). All other causes of death are much less common. Few of us have much understanding of differences among risks less than about 0.1 percent per year (1 in 1000). All such risks tend to get lumped together as "small" in peoples' judgments, and differences of several orders of magnitude are simply ignored. This causes people to give undue attention to risks much smaller than 0.1 percent that should realistically be treated as zero.
- o Congress has been unclear on the goals of environmental statutes. Therefore, because of political forces and time pressures, there is much confusion and inconsistency in the regulations. Fischhoff outlines three conditions that must be met to make standard setting an effective means of managing risks:
 - Setting standards must be preferable to case-by-case decisions;
 - Some general safety philosophy that balances risk and other factors must be justified on normative grounds; and
 - That philosophy must be translated faithfully into operational terms.

These conditions are not often met.

Risks determined to be "significant" and therefore worthy of regulation range from 1 in 10,000 to 4 in 10. Risks specifically estimated and determined not to be "significant" range from 3 in 1,000,000 to 2 in 100. Number of persons at risk is an important variable in determining the level of risk that has been determined to be "significant."

- o The costs of regulating these risks is enormous -- \$185 billion per year in direct costs alone, and much more in indirect costs. The costs have become so high that it is now essential that we begin using more rational methods of determining how much to spend on which risks. The federal government is moving in this direction, but it may be many years before a realistic approach to cost-effective risk management can be implemented. For EPA, the Science Advisory Board recommends:
 - EPA should target its environmental protection efforts on the basis of opportunities for the greatest risk reduction.
 - EPA should attach as much importance to reducing ecological risk as it does to reducing human health risk.
 - EPA should improve the data and analytical methodologies that support the assessment, comparison, and reduction of different environmental risks.
 - EPA should reflect risk-based priorities in its strategic planning processes.
 - EPA should reflect risk-based priorities in its budget process.
 - EPA -- and the nation as a whole -- should make greater use of all the tools available to reduce risk.

AIIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

2 of 2

- EPA should emphasize pollution prevention as the preferred option for reducing risk.
 - EPA should increase its efforts to integrate environmental considerations into broader aspects of public policy in as fundamental a manner as are economic concerns.
 - EPA should work to improve public understanding of environmental risks and train a professional work force to help reduce them.
 - EPA should develop and improve analytical methods to value natural resources and to account for long-term environmental effects in its economic analyses.
- o The methods of estimating risks of technologies and costs of mitigation are well established, but not especially well applied, mostly because of lack of information and needs for assessing generic rather than specific technologies. Uncertainties of total estimated risk are high -- routinely several orders of magnitude or more.
 - o Lacking an unlimited budget, risk managers must allocate resources cost-effectively. But they must also respond to political forces. Problems arise when there are large mismatches between available technical information on risks and public fears of those risks. It is clear that risk managers must promote mitigation measures meeting established criteria for cost-effectiveness. But risks that cannot meet these criteria also cannot be ignored. The best approach in this case is to:
 - Reduce the uncertainty of risk estimates through additional study;
 - Educate the public as to the low cost-effectiveness of mitigation measures; and
 - Promote other more cost-effective measures of reducing risks.
 - o The literature contains quantitative estimates of occupational and public health risks of energy technologies that can form a general basis for policy analysis and decision making. Some of these results are slightly out of date with respect to technologies, but not so much as to be useless.
 - o These results indicate that the risks of different energy technologies are different, often significantly different, especially with respect to the bearers of the risk. But taken as a whole, for entire fuel cycles and energy systems, the differences among alternative technologies are not significant compared to the uncertainty of the estimates.
 - o Recent studies of health risks of energy technologies conclude:
 - The technologies of the Fuels Group generally have higher routine risks than other groups to the persons who collect the fuel and, except for natural gas, higher routine risks to the public from inhalation of combustion products.

- The technologies of the Renewables Group have higher routine risks than other groups to workers from construction of facilities, and "nonnegligible" routine risks to the public.
 - The technologies of the Nuclear Group have "nonnegligible" routine risks to miners and operators of facilities and very low routine risks to the public.
 - The health risks of production of electricity are relatively well known, even with respect to the probability of unlikely but potentially serious accidents. Estimates of health risks of accidents are more certain than those of routine operations. Results of different studies agree within a factor of 2. Differences are attributable to assumptions about working conditions and interpretations of statistical data. The probability of a severe accident is relatively high for the Fuels Group, low for the Nuclear Group, and, except for dam failures, essentially inconceivable for the Renewables Group. Most of the public risk arises from transport of fuels.
 - The risk of injuries in the general population is very low, with the coal cycle being an order of magnitude higher than the natural gas and uranium cycles.
 - The total risk of non-fatal diseases is much higher for the coal and oil cycles than for the uranium cycle; the natural gas cycle has practically no health risks.
 - The risks of occupational fatalities in the natural gas and uranium cycles are very small; those for the oil and coal cycles are two and seven times larger, respectively. The risks in the coal cycle are mostly from mining; those from the nuclear cycle are more evenly distributed.
 - The risks of occupational injuries have the same distribution as occupational fatalities.
 - The risk of occupational diseases is negligible in the natural gas cycle, and higher in the oil, uranium, and coal cycles, in that order. Major risks of occupational diseases in the coal cycle occur during extraction; those in the uranium cycle occur at power plants and reprocessing facilities.
- o A new round of fuel cycle studies began in 1990, including a combined effort by the Department of Energy and the European Commission.⁵⁵ These studies will update estimates of risks of electricity-generating technologies and incorporate costs of regional and global health and environmental impacts (externalities). These costs will be expressed in mills/kw-hr so as to be directly comparable with estimates of engineering costs. The results will have substantial uncertainties given the current state of the art of the methodology.

7. REFERENCES

- 1 Sandman, P.M. Explaining Environmental Risk. Office of Toxic Substances, U.S. Environmental Protection Agency, Washington, DC, November 1986.
- 2 Wildavsky, A. No risk is the highest risk of all. *Am. Scientist* 67:32-37 (1979).
- 3 Thomas A.W. Miller and Edward B. Keller, The Roper Organization. Public opinion polls on 27 environmental risks, 1988-1990. *EPA Journal* 1991.
- 4 Science Advisory Board. Reducing Risk: Setting Priorities and Strategies for Environmental Protection. SAB-EC-90-021. U.S. Environmental Protection Agency, Washington, DC. September, 1990.
- 5 Kahneman, D., P. Slovic, and A. Tversky (Eds.). Judgment Under Uncertainty: Heuristics and Biases. Cambridge University Press, New York, 1982.
- 6 Slovic, P. Perception and acceptance of risk for energy systems: a behavioral scientists perspective. Presented at the American Public Health Association Annual Meeting, Los Angeles, CA, November 1981.
- 7 Greenberg, M.R., D.B. Sachsman, P.M. Sandman, and K.L. Salomone. Network evening news coverage of environmental risk. *Risk Analysis* 9:119-126 (1989).
- 8 U.S. Department of Health, Education, and Welfare. Smoking and Health: A Report of the Surgeon General. U.S. Government Printing Office, Washington, DC, 1979.
- 9 National Center for Health Statistics. Vital Statistics of the United States, 1987, vol II, Mortality, Part A. U.S. Public Health Service, Washington, DC, 1990.
- 10 Fischhoff, B., P. Slovic, S. Lichtenstein, S. Read, and B. Combs. How safe is safe enough? A psychometric study of attitudes towards technological risks and benefits. *Policy Sciences* 8:127-152 (1978).
- 11 Hance, B.J., C. Chess, and P.M. Sandman. Improving Dialogue with Communities: a Risk Communication Manual for Government. Submitted to the New Jersey Department of Environmental Protection, New Brunswick, NJ, 1988.
- 12 Slovic, P. Perception of risk. *Science* 236:280-285 (1987).
- 13 Slovic, P., S. Lichtenstein, and B. Fischhoff. Modeling the societal impact of fatal accidents. *Management Science* 30:464-474 (1984).
- 14 Fischhoff, B., S.R. Watson, and C. Hope. Defining risk. *Policy Sciences* 17:123-139 (1984).

- 15 United States Government, Budget for 1992.
- 16 Wilson, R. and E. Crouch. Risk assessment and comparisons: An introduction. *Science*, 236:267-270 (1987).
- 17 Colburn, D. The risky lives of young black men. *Washington Post Health*, December 18/25, p. 7 (1990).
- 18 Wilson, R., and E. Crouch. Risk-Benefit Analysis. Ballinger Press, Cambridge, MA 1982. Tables 7-2 and 7-5.
- 19 Cohen, B.L. Catalog of risks extended and updated. *Health Physics*, 61:317-335 (1991).
- 20 National Center for Health Statistics. Vital Statistics of the United States, 1987, vol II, Mortality, Part A. U.S. Public Health Service, Washington, DC, 1990.
- 21 Doll, R., and R. Peto. The causes of cancer: Quantitative estimates of avoidable risks of cancer in the United States today. *J.N.C.I.* 66:1192-1308 (1981).
- 22 Lewis, H.W. Technological Risk. W W Norton & Company, New York, 1990.
- 23 Milvy, P. A general guideline for management of risk from carcinogens. *Risk Analysis* 6:69-79 (1986).
- 24 Cohen, B., and I.S. Lee. A catalogue of risks. *Health Physics* 36:707-722 (1979).
- 25 Lave, L.B., and E.H. Malès. At risk: The framework for regulating toxic substances. *Environ. Sci. Technol.* 23:386-391 (1989).
- 26 Byrd, D., and L.B. Lave. Narrowing the range: A framework for risk regulators. *Issues in Science and Technology* (4):92-100 (1987).
- 27 Fischhoff, B. Setting standards: A systematic approach to managing public health and safety risks. *Management Science*, 30:823-843 (1984).
- 28 Travis, C.C., S.A. Richter, E.A.C. Crouch, R. Wilson, and E.D. Klema. Cancer risk management. *Environ. Sci. Technol.* 21:415-420 (1987).
- 29 Travis, C.C., S.R. Pack, and A. Fisher. Cost-effectiveness as a factor in cancer risk management. *Environment International* 13:469-474 (1987).
- 30 Office of the President of the United States. Budget of the United States Government. Fiscal year 1992. Part Two, p. 371. U.S. Government Printing Office, Washington, DC, 1992.

- 31 Hohenemser, C., R. Kasperson, and R. Kates. Causal structure: A framework for policy formulation. IN C. Hohenemser and J. Kasperson (Eds.), *Risk in the Technological Society*, p. 109-139. Westview Press, Boulder, CO, 1982.
- 32 Lindblom, C.E. The science of muddling through. In: *Public Administration*, (R.T. Golembiewski, F. Gibson and G.Y. Cornog, Eds.), Rand McNally & Company, Chicago, IL, 1966.
- 33 Morrall, J.F., III. A Review of the Record. *Regulation*, November/December:25-34 (1986).
- 34 Federal Register, 46:13193 (1981).
- 35 Regulatory Program of the United States Government, April 1, 1990 -- March 31, 1991. U.S. Office of Management and Budget, Washington, DC., 1991
- 36 Development of Cost and Risk Estimate Process (Draft). U.S. Office of Management and Budget, U.S. Department of Energy, Washington, DC. September 1991.
- 37 Fisher, A., L.G. Chestnut, and D.M. Violette. The value of reducing risks of death: A note on the new evidence. *J. Policy Analysis and Management*, 8:88-100 (1989).
- 38 See, for example, Hamilton, L.D. Health and environmental risks of energy systems. IN *Risks and Benefits of Energy Systems*, Proc. IAEA/UNEP/WHO International Symposium, Jülich, 9-13 April 1984. International Atomic Energy Agency, Vienna, 1984.
- 39 See, for example, Ricci, P.F., and M.D. Rowe (Eds.) *Health and Environmental Risk Assessment*. EPRI EA-4114-SR. Pergamon Press, NY, 1985.
- 40 Cox, L.A., Jr., J. Fiksel, and A.S. Kalelkar. Analysis of Routine Occupational Risks Associated with Selected Electrical Energy Systems. EA-4020. Electric Power Research Institute, Palo Alto, CA, July 198
- 41 Environmental Externalities: An Overview of Theory and Practice. EPRI CU/EN-7294. Electric Power Research Institute, Palo Alto, CA. May 1991.
- 42 Fritzsche, A.F. The health risks of energy production. *Risk Analysis* 9:565-577 (1989).
- 43 See the reports reviewed by W. Paskievici, *Health Hazards Associated with Electric Power Production: A comparative Study*. Presented at the 4th Annual Meeting of the International Scientific Forum on Geopolitics of Energy, Fort Lauderdale, FL, November 10-14, 1980.

- 44 Fischer, H., L.D. Hamilton, S.C. Morris, P.D. Moskowitz, J. Nagy, and M.D. Rowe. Health Effects of Conventional Energy sources: A Health and Environmental Effects Document. Brookhaven National Laboratory, Upton, NY. September, 1983.
- 45 Paskievici, W. Health Hazards Associated with Electric Power Production: A comparative Study. Presented at the 4th Annual Meeting of the International Scientific Forum on Geopolitics of Energy, Fort Lauderdale, FL, November 10-14, 1980. Paskievici reviewed the following reports:

U.S. Atomic Energy Commission. Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy: A Compilation of Normalized Cost and Impact Data for Current Types of Power Plants and their Supporting Fuel Cycles. WASH-1224, 1974.

Hamilton, L.D. The Health and Environmental Effects of Electricity Generation -- A Preliminary Report. BNL-20582. Brookhaven National Laboratory, Upton, NY, 1974.

Hittman Associates, Inc. Environmental Impacts, Efficiency and Cost of Energy Supply and End Use. NTIS Report No. PB-239. Prepared for the National Science Foundation, the Environmental Protections Agency, and the Council on Environmental Quality, 1974.

Smith, K.R., *et al.* Evaluation of conventional Power Systems. ERG 75-7. University of California, 1975

Comar, C.L.. and L.A. Sagan. "Health effects of energy production and conversion." Annual Review of Energy, 1:581-600 (1976).

Pochin, E.E. Estimated Population Exposure from Nuclear Power Production and Other Radiation Sources. Nuclear Energy Agency, Organization for Economic Co-operation and Development, Paris, France, 1976.

MITRE Corp. Accidents and Unscheduled Events Associated with Non-nuclear Energy Resources and Technology. NTIS Report PB-265-398. Prepared for the U.S. Environmental Protection Agency, Washington, DC, 1977.

Morris, S.C. Comparative Effects of Coal and Nuclear Fuel on Mortality. BNL-23579. Brookhaven national Laboratory, Upton, NY, 1977.

WHO, Health Implications of Nuclear Power Production. Report of a Working Group. World Health Organization regional Office for Europe, Copenhagen, 1978.

Inhaber, H. Risk of Energy Production. AECB-1149 revised. Atomic Energy control Board, Ottawa, Canada, 1978.

Institute for Energy Analysis, ORAD. Economic and Environmental Impacts of a U.S. Nuclear Moratorium, 1985-2000. The MIT Press, Boston, 1979.

AMA Council on Scientific Affairs. "Health evaluation of energy-generating sources." J. Amer. Med. Assoc. 240:2193-2195 (1978).

U.K. Health and Safety Commission. The Hazards of Conventional Sources of Energy. Her Majesty's Stationary Office, London, England, 1978.

Ramsay, W. Unpaid costs of Electrical Energy: Health and Environmental Impacts from Coal and Nuclear Power. John Hopkins University Press, Baltimore, MD, 1978.

Schurr, S.H., *et al.* Energy in America's Future. The Choices Before Us. Resources for the Future National Energy Strategies Project. Johns Hopkins University Press, Baltimore, MD, 1979.

Morris, S.C., K.M. Novak, and L.D. Hamilton. Databook for the Quantitation of Health Effects from Coal Energy Systems (Draft). Brookhaven National Laboratory, Upton, NY, 1979.

Inhaber, H. Risk of Energy Production. AECB/REV-3. Atomic Energy Control Board, Ottawa, 1980.

Belhoste, J.F., B. Durant, and C. Maccia. Risques Sanitaires et Écologiques de la Production d'Énergie Électrique. Cycle Nucléaire (PWR), Fuel, Charbon. Présentation Des Scénarios, Centre d'études sur l'évaluation de la protection Dans le domaine Nucléaire, Fontenay-aux-Roses, France, 1979.

Committee on Nuclear and Alternative Energy systems (CONAES). Alternative Energy Demand Futures. U.S. National Academy of Sciences, 1980.

- 46 Hamilton, L.D. Personal communication. Brookhaven National Laboratory Upton, NY. August 29, 1990.
- 47 BEAD. Unpublished analysis and correction of Paskievici's results. Brookhaven National Laboratory Upton, NY. August, 1982.

- 48 Hamilton, L.D. Presentation to the IAEA Advisory Group on Comparative Environmental and Health Impacts from Different Energy Sources. March 5-9, 1990 International Atomic Energy Agency, Vienna, Austria.
- 49 OECD. Environmental Effects of Energy Systems. The OECD Compass Project. Organization for Economic Co-operation and Development, Paris, France. April 1983.
- 50 UNEP. The Environmental Impacts of Production and Use of Energy. Part IV: The Comparative Assessment of the Environmental Impacts of Energy Sources (3rd Draft). United Nations Environment Program, Nairobi, Kenya. January 1985.
- 51 Fritzsche, A.F. Gesundheitsrisiken von Energieversorgungssystemen. Von der Kohle bis zu Energien der Zukunft und den Rohstoffen bis zur Entsorgung, Verlag TÜV Rheinland, Köln. 1988 (in German).
- 52 Pace University Center for Environmental Legal Studies. Environmental Costs of Electricity. Prepared for the New York State Energy Research and Development Authority and the U.S. Department of Energy. Oceana Publications, Inc., New York, NY, 1990.
- 53 Valuation of Environmental Externalities for Energy Planning Operations. Tellus Institute, 1990
- 54 Cantor, R.A., *et al.* The External Costs of Fuel Cycles: Background Document to the Approach and Issues. Oak Ridge National Laboratory, Oak Ridge, TN, 1992.
- 55 U.S. Department of Energy. U.S.-ec Fuel Cycle Study: Background Document to the Approach and Issues. Oak Ridge National Laboratory and Resources for the Future. November 1992.

8. APPENDICES

Appendix A-1. Summary of estimated occupational fatalities per GWe-yr from accidents, BEAD, 1982. ^a				
Study	Coal	Oil	Gas	Uranium
WASH-1224, 1974	1.5	0.21	0.11	0.14
Hamilton, 1974	0.46	1.63	0.21	0.35
Hittman, 1974	1.7	0.11	0.086	0.18
Smith, et al., 1975	2.4-7.5	0.11-0.18	2.6-7.4	0.14-0.31
Comar and Sagan, 1976	0.71-1.9	0.2-1.8	0.76-0.37	0.09-0.55
OECD, 1976				0.69
MITRE, 1977	1.4	0.47	0.27	
Morris, 1977	0.53-0.93			0.14-0.29
WHO, 1978				0.55
Inhaber, 1978	2.3-6.6	0.19-1.9	0.08-0.40	0.10-0.60
IEA, 1979	0.19-1.4			
AMA, 1978	0.72-4.3		0.08-0.37	0.027-0.55
UK, 1978	1.8	0.3		0.25
Ramsay, 1978	0.48-1.5			0.09-0.31
Schurr, et al., 1979	0.4-1.3			0.08-0.27
Morris, et al., 1979	0.77-0.80			
Inhaber, 1980		0.30-2.0	0.16-0.48	0.14-0.60
CEPN, 1979	2.1	0.31		0.19
CONAES, 1980		0.47	0.27	0.27
a. Values in bold have been recalculated and accepted or corrected by BEAD (Reference 47), the remainder are directly from Paskievici (Reference 45).				

Appendix A-2. Summary of estimated non-fatal occupational accidents, BEAD, 1982. ^a				
Study	Coal	Oil	Gas	Uranium
WASH-1224, 1974	62	18	6.7	
Hamilton, 1974	34	110	19	
Hittman, 1974	86	9.1	7.3	
Smith, et al., 1975	56-170	5.2-15	58-160	
Comar and Sagan, 1976	34-100	16-120	5.8-32	
OECD, 1976			24	
MITRE, 1977	71	43		
Morris, 1977				
WHO, 1978				
Inhaber, 1978	56-83	18-140	6-35	
IEA, 1979	15-100			
AMA, 1978	34-140	16-120	5.3-32	
UK, 1978				
Ramsay, 1978				
Schurr, et al., 1979				
Morris, et al., 1979	58-62			
Inhaber, 1980	72-74	29-150	13-41	
CEPN, 1979	1400	24		
CONAES, 1980	55-150	43	24	
a. Values in bold have been recalculated and accepted or corrected by BEAD (Reference 47), the remainder are directly from Paskievici (Reference 45).				

Appendix A-3. Summary of estimated public fatalities from accidents, BEAD, 1982. ^a				
Study	Coal	Oil	Gas	Uranium
WASH-1224, 1974	0.73			
Hamilton, 1974	1.6			
Hittman, 1974	4.1			
Smith, et al., 1975	0.73			
Comar and Sagan, 1976	0.73-1.7			
OECD, 1976				
MITRE, 1977	3.1			
Morris, 1977	0-5.3			
WHO, 1978				
Inhaber, 1978	0.8-1.9			
IEA, 1979	3.1			
AMA, 1978	0.73-1.7			
UK, 1978				
Ramsay, 1978	0.84-2.1			
Schurr, et al., 1979				
Morris, et al., 1979	0.53-1.3			
Inhaber, 1980	0.8-1.9			
CEPN, 1979	0.71			
CONAES, 1980	0.67-3.1			
a. Values in bold have been recalculated and accepted or corrected by BEAD (Reference 47), the remainder are directly from Paskievici (Reference 45).				

Appendix A-4. Summary of estimated non-fatal public accidents, BEAD, 1982. ^a				
Study	Coal	Oil	Gas	Uranium
WASH-1224, 1974	1.6			
Hamilton, 1974	13			
Hittman, 1974	87			
Smith, et al., 1975	1.6			
Comar and Sagan, 1976				
OECD, 1976				
MITRE, 1977	31			
Morris, 1977				
WHO, 1978				
Inhaber, 1978	1.6			
IEA, 1979	31			
AMA, 1978				
UK, 1978				
Ramsay, 1978				
Schurr, et al., 1979				
Morris, et al., 1979	5.3-7.0			
Inhaber, 1980	1.6			
CEPN, 1979				
CONAES, 1980	1.8			
a. Values in bold have been recalculated and accepted or corrected by BEAD (Reference 47), the remainder are directly from Paskievici (Reference 45).				

Appendix A-5. Summary of estimated occupational fatalities from disease, BEAD, 1982.^a

Study	Coal	Oil	Gas	Uranium
WASH-1224, 1974	0.008			0.11
Hamilton, 1974	0-4.7			0.18
Hittman, 1974				
Smith, et al., 1975	0-0.059			0.11-0.20
Comar and Sagan, 1976	0-4.7			0.52-0.60
OECD, 1976				0.65
MITRE, 1977				
Morris, 1977	0.13-8.7			0-0.09
WHO, 1978				0.22-0.33
Inhaber, 1978	0-3.5			0.13-0.72
IEA, 1979				
AMA, 1978	0-6.4			0.18-0.57
UK, 1978	1-2			
Ramsay, 1978	0-4.4			0.09-0.18
Schurr, et al., 1979	0-5.3			0.05-0.27
Morris, et al., 1979	0.11 (0-0.75)			
Inhaber, 1980	0.11 (0-0.75)			0.24-0.81
CEPN, 1979	~0			0.21
CONAES, 1980				0.32

a. Values in bold have been recalculated and accepted or corrected by BEAD (Reference 47), the remainder are directly from Paskievici (Reference 45).

Appendix A-6. Summary of estimated non-fatal occupational diseases, BEAD, 1982. ^a				
Study	Coal	Oil	Gas	Uranium
WASH-1224, 1974	0.8			
Hamilton, 1974	13-60			
Hittman, 1974				
Smith, et al., 1975	0.55-0.82			
Comar and Sagan, 1976	0.8-64			
OECD, 1976				
MITRE, 1977				
Morris, 1977				
WHO, 1978				
Inhaber, 1978	0.55-0.82			
IEA, 1979				
AMA, 1978	0.8-64			
UK, 1978				
Ramsay, 1978				
Schurr, et al., 1979				
Morris, et al., 1979	9.8-19			
Inhaber, 1980	4.2-8.4			
CEPN, 1979	0.78-4.8			0.97
CONAES, 1980				
a. Values in bold have been recalculated and accepted or corrected by BEAD (Reference 47), the remainder are directly from Paskievici (Reference 45).				

Appendix A-7. Summary of estimated public fatalities from disease, BEAD, 1982. ^a				
Study	Coal	Oil	Gas	Uranium
WASH-1224, 1974				0.021
Hamilton, 1974	4-150	1.3-130		0.067
Hittman, 1974				
Smith, et al., 1975	0.2-49	0.04-36		0.001-0.015
Comar and Sagan, 1976	1.4-14	1.3-130		0.013-0.21
OECD, 1976				0.22
MITRE, 1977				
Morris, 1977	0-320			0.21
WHO, 1978				0.07-0.10
Inhaber, 1978	1.5-150	1.4-140		0.03-0.23
IEA, 1979	1.2-3.7			
AMA, 1978	1.5-400			0.01-0.21
UK, 1978				
Ramsay, 1978	0.32			0.09-0.41
Schurr, et al., 1979	0-11			0.09-0.41
Morris, et al., 1979	0-24			
Inhaber, 1980	33-110	12-35		0.074-0.53
CEPN, 1979	0.34	0.31-0.62		0.11
CONAES, 1980				0.20
a. Values in bold have been recalculated and accepted or corrected by BEAD (Reference 47), the remainder are directly from Paskievici (Reference 45).				

Appendix A-8. Summary of estimated non-fatal public diseases, BEAD, 1982. ^a				
Study	Coal	Oil	Gas	Uranium
WASH-1224, 1974				
Hamilton, 1974	13-130	13-133		
Hittman, 1974				
Smith, et al., 1975	(1-220)x10 ³	(0.2-220)x10 ³		
Comar and Sagan, 1976				
OECD, 1976				
MITRE, 1977				
Morris, 1977				
WHO, 1978				
Inhaber, 1978	(1-220)x10 ³	(0.2-220)x10 ³		
IEA, 1979	(5.3-15)x10³			
AMA, 1978				
UK, 1978				
Ramsay, 1978	(1.2-120)x10 ³			
Schurr, et al., 1979	(0.34-34)x10³			
Morris, et al., 1979				
Inhaber, 1980	(190-570)x10 ³	(70-210)x10 ³		
CEPN, 1979	37	110		
CONAES, 1980				
a. Values in bold have been recalculated and accepted or corrected by BEAD (Reference 47), the remainder are directly from Paskievici (Reference 45).				

Appendix B-1. Health risks of energy technologies, UNEP 1985.^a

Technology	Occupational Deaths	Risks (per GWe-y) Occupational Injuries/ Diseases (WDL)	Public Deaths
FUELS -- ELECTRICITY			
Coal			
Surface mining	0.0016	9.4	
Underground mining	0.031	80.	
Coal cleaning	0.00091	2.4	
Power plant	0.00039 - 0.0057	1.9 - 2.8	0.059
Oil			
Onshore wells	0.0072	13.	
Offshore wells	0.0072	13.	
Refinery	7.8x10 ⁻⁵	21.	
Power plant	0.00017 - 0.00026	0.32 - 3.5	0.030
Natural gas			
Onshore and offshore production	0.0013 - 0.0021	4.7 - 5.0	
Purification	5.2x10 ⁻⁶ - 3.9x10 ⁻⁵	0.011 - 0.032	
Power plant	0.00011 - 0.00022	0.25 - 3.5	1.3x10 ⁻⁵
Gasification of low calorie coal			
Surface mining	0.0019	11.	
Underground mining	0.030	94.	
Coal cleaning	0.0014	4.8	
Gasifying power plant	0.0017	6.8	1.3x10 ⁻⁵ - 0.26 ^d
Gasification of high calorie coal			
Surface mining	0.0051	30.	
Underground mining	0.0796	110 - 260	
Coal processing	0.0048	2.3	
Power plant	0.00011 - 0.0017	0.98 - 3.6	1.3x10 ⁻⁵
Indirect liquefaction of coal			
Surface mining	0.13	790	
Underground mining	2.1	6700	
Fuel processing			
Power plant	0.0017	0.94	0.030

Appendix B-1. (Continued) ^a			
Technology	Occupational Deaths	Risks (per GWe-y) Occupational Injuries/ Diseases (WDL)	Public Deaths
Direct liquefaction of coal			
Surface mining	0.11	620	
Underground mining	1.6	5300	
Fuel processing			
Power plant	0.0017	0.94	0.030
Oil shale			
Surface mining			
Underground mining			
Retorting	0.19	24.	
Refining	7.8×10^{-5}	21.	
Power plant	0.00017 - 0.00026	0.32 - 3.5	0.0297
Tar sand			
Surface mining			
Underground mining			
Fuel processing			
Refining	7.8×10^{-5}	21.	
Power plant	0.00017 - 0.00026	0.32 - 3.5	0.023
Wood			
Plantation	0.023	160	
Power plant	0.0046	2.5	
Peat			
Extraction	0.010 - 0.011	85. - 110	
Processing and power plant	0.0011	3.0	
Biogas			
All stages	0.00047	17.	

Appendix B-1. (Continued) ^a			
Technology	Occupational Deaths	Risks (per GWe-y) Occupational Injuries/ Diseases (WDL)	Public Deaths
FUELS -- LARGE-SCALE HEATING			
Coal			
Surface mining	0.00076	4.4	
Underground mining	0.012	38.	
Coal cleaning	0.00042	1.2	
Heat generation	0.00013 - 0.0027	0.91 - 1.4	
Oil			
Onshore drilling	0.0034	6.2	
Offshore drilling	0.0034	6.2	
Refining	3.7×10^{-5}	9.9	
Heat generation	8.1×10^{-5} - 0.00012	0.15 - 1.7	
Natural gas			
Drilling	0.00059 - 0.0010	2.2 - 2.4	
Gas purification	1.8	0.0053 - 0.016	
Heat generation	5.5×10^{-5} - 0.00011	0.12 - 1.7	
Gasification of low calorie coal			
Surface mining	0.00090	4.9	
Underground mining	0.014	45.	
Coal cleaning	0.00065	2.3	
Gasifying heat generator	0.00081	3.2	9.7×10^{-5} - 0.00011
Wood			
Plantation	0.0114	84.	
Heat generation	0.0023	1.3	
Peat			
Extraction	0.0049 - 0.0055	40. - 51.	
Processing and heat generation	0.00054	1.4	
Biogas			
All stages	0.0023	8.2	

Appendix B-1. (Continued)^a

Technology	Occupational Deaths	Risks (per GWe-y) Occupational Injuries/ Diseases (WDL)	Public Deaths
FUELS -- TRANSPORTATION			
Gasoline			
Onshore drilling	1.8x10 ⁷	3.2	
Offshore drilling	1.8x10 ⁷	3.2	
Refining	1.9x10 ⁵	5.1	
Vehicles	2.9x10 ⁷	36.	
Diesel			
Onshore drilling	430	7.6	
Offshore drilling	430	7.6	
Refining	4.6	12.	
Vehicles	2.3x10 ⁷	36.	
Ethanol			
Grain production			
Fermentation	4.9x10 ⁵	1.0	
Vehicles	2.3x10 ⁷	36.	
Gasohol			
90% gasoline + 10% ethanol	3.9x10 ⁷	43.	
RENEWABLES -- ELECTRICITY			
Geothermal			
All stages	0.0043	0.51	
Hydropower			
All stages	7.4x10 ⁻⁵ - 0.00038	0.0023	
Tidal power			
All stages	7.4x10 ⁻⁵ - 0.00037	0.0023	
Wind			
All stages	0.0011	21.	
Photovoltaics			
All stages	0.00047	5.4	
Solar thermal			
All stages	0.0084	31.	

Appendix B-1. (Continued) ^a			
Technology	Occupational Deaths	Risks (per GWe-y) Occupational Injuries/ Diseases (WDL)	Public Deaths
RENEWABLES -- LARGE-SCALE HEATING			
Geothermal All stages	0.00094	0.11	
Solar thermal All stages	0.0023	8.3	
NUCLEAR -- ELECTRICITY			
LWR Fission			
Surface mining			
Accidents	0.00065	1.21	
Radiation	0.0039 - 0.0130		0.00026
Underground mining			
Accidents	0.0022	1.9	
Radiation	0.00039 - 0.0013		0.00026
Milling			
Accidents	0.00017	0.89	
Radiation	0.00047		6.5x10 ⁻⁵
Conversion			
Accidents	5.5x10 ⁻⁶	0.31	
Radiation	5.3x10 ⁻⁶		1.3x10 ⁻⁵
Enrichment			
Accidents	7.8x10 ⁻⁶	4.3	
Radiation	6.8x10 ⁻⁶		8.0x10 ⁻⁸
Fabrication			
Accidents	8.6x10 ⁻⁵	0.82	
Radiation	1.3x10 ⁻⁴		
Power plant			
Accidents	0.00017	0.28	
Radiation	0.0017	0.034	0.00023
Catastrophe			0.0013
Waste management			
Radiation	6.1x10 ⁻⁶	0.00011 ^b	0.00010

Appendix B-1. (Continued)^a

Technology	Occupational Deaths	Risks (per GWe-y) Occupational Injuries/ Diseases (WDL)	Public Deaths
NUCLEAR -- LARGE-SCALE HEATING			
LWR Fission			
Surface mining			
Accidents	0.00024	0.44	
Radiation	1.1×10^{-5}		9.6×10^{-5}
Underground mining			
Accidents	0.00081	0.68	
Radiation	0.00046		9.6×10^{-5}
Milling			
Accidents	6.4×10^{-5}	0.33	
Radiation	0.00017		2.4×10^{-5}
Conversion			
Accidents	1.9×10^{-5}	0.11	
Radiation	1.9×10^{-6}		4.6×10^{-6}
Enrichment			
Accidents	0.00029	1.6	
Radiation	2.5×10^{-6}		3.0×10^{-8}
Fabrication			
Accidents	3.1×10^{-5}	0.30	
Radiation	4.6×10^{-5}		
Heat generation			
Accidents	6.3×10^{-5}	0.10	
Radiation	0.00063	0.013	8.0×10^{-5}
Catastrophe			0.00046
Waste management			
Radiation	2.2×10^{-6}		3.8×10^{-5}
<p>a. Source: Reference 50</p> <p>b. Some of these diseases might be nonfatal radiation-induced cancers.</p> <p>c. Non-fatal radiation-induced cancers.</p> <p>d. This large range arises from the uncertainty of the health effects estimate for emissions of sulfur oxides from the gasifier.</p>			

DATE

FILMED

7/26/94

END