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RADIOACTIVE WASTE

# COST/BENEFIT CONSIDERATIONS OF NUCLEAR POWER

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*A cost/benefit analysis has been used in an attempt to place the societal costs associated with nuclear power into perspective by comparing them with the costs associated with coal-fired plants. Generation of electricity from coal is assumed to represent an acceptable risk in our society.*

*The results of this qualitative evaluation indicate that nuclear power compares favorably with coal for the following costs: resource depletion, environmental insult, cost of power generation, voluntary occupational health risks, and involuntary public health risks associated with routine plant operation. Plant accidents, waste disposal techniques for both nuclear and coal-fired stations, and the nuclear safeguards issue are identified as the major areas requiring further risk evaluation.*

In today's advanced nations the public is, with increasing frequency, being called on to make decisions regarding technological options which can have a major impact on the society's quality of life. Such public decisions can be delivered directly, as in a vote on a bond issue for rapid transit, or indirectly, for example, when a nuclear moratorium issue is placed before a state legislature. It is the duty of the scientific community to see that the public is adequately informed of the potential societal costs and benefits associated with alternative technical systems.

Within the framework of societal decision making, cost/benefit analysis can be seen as a valuable tool for clarifying and comparing both the benefits and risks associated with alternative technical systems. Cost/benefit analysis can be broken down into the following stages. First, the public needs to have a clear understanding of the performance goal. Second, the technical alternatives must be defined in terms of both the potential costs and the probability of achieving the desired goal. Finally, the potential costs of each system must be put into a form that allows the public to compare them with costs of already existing systems. With this information, the public should be able to choose the optimum system.

Unfortunately, the real world presents the following limitations to performing straightforward analytical cost/benefit comparisons. First, there is no way to quantify absolutely the perceived benefits of a specified goal since one man's nirvana is another's disaster. Second, because all social costs do not have the same units of measure, they cannot be easily summed into one final total. Some costs can be described in financial terms, some in aesthetic terms, and some in terms of fatalities. Perhaps, with some imaginative manipulation, all costs could be reduced to a common unit of measure. While this approach is appealing, it is extremely difficult because of the subjective and socially controversial nature of the value judgments that must be used to convert, say, human life into economic terms.

These weaknesses are pointed out not because they invalidate the general approach but because they suggest how it can be modified to correspond more closely to the real world. This modified approach is as follows:

1. Explain the perceived benefits but do not attempt to quantify them. Instead, let each individual come to his own judgment as to their relative merits.

2. As before, define the technical alternatives in terms of both the potential costs and the probability of achieving the desired goal. However, this time we do not attempt to combine all costs but, instead, the costs are grouped according to logical categories. Thus, one category might contain all costs that can be expressed in monetary terms, while another may contain costs that can be expressed in terms of loss of human life.

3. Compare the costs of each technical option, category by category, with like costs of an existing societally accepted system.

4. The public is then asked to intuitively integrate the perceived costs and benefits and render a final judgment.

Now, before applying this approach to nuclear power in general and to the waste management issue specifically, I would like to point out two advantages it produces. First, it enumerates all major issues of concern and focuses attention on those areas that require further definition and analysis. Second, by grouping potential risks into logical categories which are analyzed in a uniform manner, it can force opponents to talk to the problem rather than around it.

For example, consider two scientists presenting the following arguments to convince the public of the safety or the danger of nuclear power. The first states that his reactor has a one in a billion chance per year of a class IX accident. The second states that several kilograms of plutonium if dispersed finely enough around the world could potentially produce several billion cancer fatalities per year. Technically, both might be right, but in effect they have only succeeded in confusing the public. Would not an approach that defines nuclear accidents in terms of the general risk of fatality associated with each event give the public a better basis for comparison?

Since risk is defined as the probability of an event times the expected magnitude, we would ask the first scientist how many people could be killed by his postulated accident and the second what the probability is of dispersing the plutonium finely enough to produce the postulated cancer induced fatalities. With this information, the risk associated with each argument can be compared through the common unit of measure—expected fatalities per year.

Let me now apply this cost/benefit approach to the issue of nuclear power. Public acceptance of nuclear power has become a key question which must be resolved before the full potential of this energy source can be realized. Before the public can be expected to endorse the use of nuclear power, it must first understand the following points: (a) the importance of energy in general, and of electricity in particular, to our quality of life; (b) the reasons why nuclear power could be a major energy source during the balance of this century; (c) the total societal cost of nuclear energy; and (d) the relationship of this cost to alternative sources of energy.

The availability of energy governs modern nations' ability to improve the quality of life for their growing populations. In our modern industrial societies, energy has become as basic a commodity as food and raw materials. In fact, our food supply is itself dependent on massive man-created energy in the form of farm equipment and nitrogen fertilizer.

During the past half century, per capita energy consumption in the U.S. has roughly doubled, with a good part of that increase occurring in the last decade. Even given the most optimistic attempts at energy conservation and increased efficiency in end-use devices, it would be a very optimistic assumption to project no more than a doubling in the per capita energy consumption during the next half century. The economic welfare and social goals of our population are such that we are unlikely to do any better than this. Historically, electricity production has grown much more rapidly than total energy consumption, primarily because of the desirability of this particular energy form in terms of convenience and safety. While it is difficult to predict how fast future electricity demand will grow relative to total energy consumption, all the factors that have made it desirable in the past will probably continue to make it more so in the future. The key point is that the increased demand for electricity production is a prime requirement of our society, and the alternative of severely limiting the quality of life of our population in the future is not an acceptable basis for national planning.

The principal options likely to be commercially feasible in the next several decades for meeting these demands involve expansion of fossil-fueled (chiefly coal) and nuclear power stations. All other options, such as solar power, geothermal power, and fusion are either limited in their possible contribution or are in such early stages of development that they are not likely to be in commercial use within the next several decades. In view of pragmatic limitations on the ability to expand the installation of coal and nuclear stations, both options will have to be vigorously pursued in order to approach the projected demand for electricity.

In terms of the earlier discussion, a high probability of success should be assigned to coal and nuclear power stations and a low probability to advanced systems with respect to meeting our energy needs during the balance of this century.

Next, societal costs associated with the generation of electricity from nuclear power must be defined. Where possible, these costs should be expressed in terms of their impact on both this and future generations. Four societal costs can be identified: resource depletion, environmental insult, power generation costs, and public health risks. These costs can be arranged into three logical categories which define common units of measure. Resource depletion will be evaluated in a subjective manner; environmental insult can be measured in terms of the land which must be devoted to resource extraction; power generation costs will be evaluated in monetary terms; and public health risks will be described in terms of fatalities and days of disability.

The coal-fired power plant was selected as the technical system with which nuclear power will be compared. Coal and nuclear power plants are similar in both scope and size, and coal-fired plants have a reasonable degree of public acceptance. If it can be shown that the societal costs of nuclear power compare favorably with those of coal-fired plants, then the expected public response would be to accept nuclear power.

First consider resource depletion. Both coal and uranium are nonrenewable energy resources. As world oil supplies are depleted, converted coal could become an important source of raw materials for fertilizer, petrochemicals, and transportation uses. The world's growing demand for food alone precludes continued long-term reliance on fossil fuels as the nation's principal source of energy. However, unlike coal, the only nonmilitary application of uranium is the production of electrical energy. Further, the advent of the fast breeder reactor puts the need for uranium on a completely different basis. Fast breeder reactors extract on an average roughly 50 times more energy from a given amount of natural uranium than other nuclear reactors. This will extend the availability of our current uranium supply from decades to hundreds of years.

Resource depletion is listed as a subjective cost, because we cannot predict the degree to which future generations will need the coal which the next several generations will use in producing electricity. However, we can say that if coal becomes the primary electric utility fuel, future generations might be deprived of an important raw material.

The environmental insult resulting from coal and uranium mining can be measured by the amount of land that must be mined per year to fuel a 1000-MW(e) power plant. For Eastern open pit mines that yield 3500 tons of coal per acre, ~1500 acres/yr must be mined per 1000-MW(e) power plant. For a nuclear station the comparable open pit uranium mining requirement is 16 acres/yr. Thus, land use considerations favor nuclear over coal by a factor of ~90 for the example cited above.

Coal and uranium can be compared in terms of their financial impact with respect to power generation costs. The rising cost of energy can become a major handicap to worldwide societal improvement. The electrical generation costs of nuclear power is lower than a comparable coal-fired generation plant, and this gap should widen as the full impact of air quality and mining legislation is felt. The price of energy has important social connotations. Cheap and abundant energy is an indispensable tool for greater social justice. Freedom from back-breaking toil, shorter working hours, easier domestic work, added liberty of movement, education and recreation possibilities, more comfort, and better health are all tied to inexpensive energy. Raise the price of energy and who will be unable to afford the use of a car, the assistance of a power tool, the conveniences of home appliances, the enrichment of travel and recreation? The poor, of course, will be most deprived. Any shortage of any commodity in the world will hit the poor first.

Thus, in economic terms, the societal costs associated with the price of power both favor the use of nuclear energy over coal. Nuclear power's advantage is further increased if we consider the promise that the fast breeder reactor offers—more efficient power production, a great reduction in fuel requirements and costs, and corresponding reductions of the problems created by mining.

The last category for comparison is that of public health risks arising from the generation of electricity by nuclear and coal-fired plants. Here, the unit of measure will be annual fatalities and disability days resulting from the operation of a 1000-MW(e) power plant.

Public health risks must be separated into risks from voluntary and involuntary exposure. Here, voluntary risks refer only to occupational hazards that are incurred by workers during the extraction, transportation, and conversion of fuel into electric power. A recent study by Lave and Freeburg[1] suggests that the occupational health risks of producing electricity from coal are greater than the corresponding risks from nuclear power in terms of both chronic disease and accidental death.

Involuntary risks are defined as those hazards which are imposed by society and not easily modified by the individual. Involuntary public health risks arising from the generation of power must be evaluated both for normal and abnormal operations. And the risks to this and future generations must be considered.

Public risks from nuclear power arise from the release of radioactivity during normal operation, from accidents that can release radioactivity, from diversion of plutonium, and from the release of stored highly radioactive material.

Involuntary risks from coal-fired stations come from pollutants released during normal operation, boiler or tank explosions that release pollutants to the atmosphere, and the disposal of large quantities of fly ash and slag which contain varying amounts of pollutants.

To compare the relative involuntary risks of coal-fired and nuclear plants, we can consider the total integrated risk of potential fatalities and disabilities over the lifetime of the postulated hazard. For coal-fired plants, the public health risks arising from routine operation, plant accidents, and waste disposal would be integrated over the lifetime of the plant. For nuclear plants two integrals would be used. The first term integrates over plant lifetime the risks of routine operation, plant accident, plutonium diversion, and radioactive waste. The second term evaluates the waste disposal hazard from plant decommissioning to the time when the radioactive material no longer represents a health risk.

If the probability and magnitude for each of the risks described above were known, it would be a simple job to plug in the numbers and compare the total involuntary public health risk of coal and nuclear plants. Unfortunately, much work needs to be done in defining and quantifying many of the involuntary risks before a definitive statement can be made. However, it is possible to make some preliminary comparisons for several of the risk terms.

Work by Lave and Freeburg[1] indicates that the routine operation of a nuclear plant presents a significantly smaller public health risk than the routine operation of a coal-fired plant.

As reported by Starr et al.,[2] the public health risk due to accidental releases from either nuclear or oil-fired plants are of the same magnitude and about 100 000 times smaller than the risk from routine operation of the plants. A similar study needs to be made comparing coal-fired and nuclear plant accidents, but it seems reasonable to assume that the conclusions of the analysis by Starr et al. would not be altered significantly.

The problem of preventing the illegal diversion of plutonium presents a risk which is unique to nuclear power. This is clearly an area that requires more problem definition and risk evaluation. We might say that fissionable material must be of little value to the professional terrorist in comparison with other highly toxic substances that can be obtained with much less effort. However, the public needs more quantitative assurance that adequate safeguards are being taken. We need to know the level of security at which the energy expended by saboteurs to divert plutonium is greater than that required by alternative threats to create the same amount of havoc.

The final involuntary public health risk from both coal-fired and nuclear power plants is that of waste disposal. For coal, the disposal problem coincides approximately with the life of the plant, and involves many tons of fly ash and coal, with a low amount of toxic material per unit weight. For nuclear plants, the potential risk from disposal, which can last for hundreds of thousands of years, centers around relatively small solidified amounts of highly radioactive material. Much work needs to be done on both of these disposal issues before we can present society with the lowest risk approach to storing the wastes from nuclear and coal-fired plants. For the present, controlled surface storage appears to be adequate as a near-term solution for nuclear plant wastes.

Now, let us examine how the risk evaluation technique could be applied to evaluating the public health hazard associated with the disposal of radioactive wastes. The risk is evaluated over two time periods. The first, between times $t_1$ and $t_2$, corresponds to the plant lifetime of 25 to 30 years. The second interval, between $t_2$ and $t_3$, starts at plant decommissioning and extends to the time at which the radioactive material is not a public health risk. Thus,

total risk from waste disposal

$$= \int_{t_1}^{t_2} P_w M_w \, dt + \int_{t_2}^{t_3} P'_w M'_w \, dt \ , \qquad (1)$$

where

$P_w$ = probability per year of an uncontrolled release of a specified amount of radioactive waste

$M_w$ = the potential fatalities which this release can be expected to produce.

An uncontrolled release of radioactive waste can be initiated by one or more of the following events:

1. technological malfunction ($T$)
2. natural disasters ($D$)
3. actions of man ($M$)
   a. carelessness
   b. sabotage
   c. war.

Using these three risk initiators, the final expression becomes

risk from uncontrolled waste release

$$= \int_{t_1}^{t_2} (P_T M_T + P_D M_D + P_M M_M) \, dt$$

$$+ \int_{t_{22}}^{t_3} (P'_T M'_T + P'_D M'_D + P'_M M'_M) \, dt \ . \qquad (2)$$

In applying this concept of risk to retrievable surface storage and nonretrievable permanent geologic storage, the two most discussed disposal techniques can provide some interesting, if somewhat speculative, insights. Retrievable surface storage stresses man's responsibility for safeguarding the waste material. Since the material is recoverable, this approach is attractive because it leaves all future options open. Permanent storage, on the other hand, assumes little faith in future generations' ability to accept this responsibility; in doing so, it forecloses future options for managing the radioactive material.

After looking at Eq. (2), the following observations can be made about retrievable surface storage for the period $t_1$ to $t_2$ (~25 to 30 yr):

1. Technological Malfunction. Careful engineering and constant surveillance and maintenance should reduce the probability and magnitude of an uncontrolled release to an acceptable level.

2. Natural Disasters. The judicious selection of a site should eliminate all but the most infrequent natural disasters (such as the once in a million year earthquake or volcanic eruption) from being a major concern. However, the probability of the once in a million year disaster occurring during the short span of thirty years is sufficiently remote that even if a large magnitude release is postulated, the resulting risk should be within the acceptable range.

3. Actions of Man. Sufficient technological safeguards and security precautions could be designed into a retrievable surface storage facility to reduce this risk to an acceptable level.

As a long-term option, from $t_2$ to perhaps several hundred thousand years in the future, retrievable surface storage appears to be an uncertain alternative, because it depends on a high level of responsibility in each one of the thousands of generations that succeeds us. A decision would have to be made by each generation as to a shift to permanent storage.

Likewise, permanent storage appears to be an unattractive option in the immediate future because of the as yet unknown risks of technological malfunction and natural disaster. However, as a long term solution to the waste management problem, permanent storage appears feasible, given sufficient time and money for analyzing the options. It should be pointed out that the current estimates for waste disposal costs place them at <1% of the total generation cost.[3] Thus, the costs of both waste management and ultimate disposal technique should not be a limiting factor in achieving an acceptable waste disposal system.

The most likely waste disposal scenario appears to use retrievable surface storage from time $t_1$ to $t_2$ and permanent storage from $t_2$ to $t_3$. Two final observations can be made about this formulation of the total risk. First, the obvious way to reduce the integrated risk is to shorten the time during which the material remains highly radioactive. This could be accomplished by chemically separating the actinides and then eliminating them by transmutation or extraterrestrial disposal. Elimination of the actinides will reduce the time of radioactive waste management from a million years to less than 1000 years.

Second, by varying time $t_2$, the time at which the waste is transferred from temporary to permanent storage, in Eq. (2) we can determine the time that results in minimum total risk from both retrieval and permanent storage.

In conclusion, a cost/benefit approach has been presented which could assist the public in selecting the optimum system or systems to provide for our future energy needs. But before this analysis can be implemented, every risk must be quantified and compared.

Using this cost/benefit technique the societal costs of nuclear power were compared with those of coal-fired power plants. Generation of electricity from coal was assumed to represent an acceptable risk within our society. The results of this qualitative evaluation suggest that nuclear power compares favorably with that of coal for the following societal costs: resource depletion, environmental insult, the economic costs of power generation, voluntary occupational health risks, and involuntary public health risks associated with routine plant operation.

Plant accidents and waste disposal techniques for both nuclear and coal-fired stations and the nuclear safeguards issue have been identified as the societal costs requiring further risk assessment.

These issues appear to have feasible and publicly acceptable solutions. And, I believe that final public acceptance and endorsement of nuclear power will come when these risks have been clearly defined, quantified, and compared with the societal costs of coal-fired plants.

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