Comparative risk analysis of different energy sources using utility theory

by

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A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
MASTER OF SCIENCE

Department: Chemical Engineering and
Nuclear Engineering
Major: Nuclear Engineering

Approved:

ersity
Ames, Iowa

1978

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ABSTRACT

A deterministic approach is devised to compare the safety features of various energy sources. The approach is based on multiattribute utility theory (MAUT). The method is used in evaluating the safety aspects of alternative energy sources used for the production of electrical energy.

Four alternative energy sources are chosen which could be considered for the production of electricity to meet the national energy demand. These are nuclear, coal, solar and geothermal energy. For simplicity, a total electrical system in each case is considered.

A computer code is developed to evaluate the overall utility function for each alternative from the utility patterns corresponding to twenty-three energy attributes, mostly related to safety. The model can accommodate for other attributes assuming that those are independent. The technique is kept flexible so that virtually any decision problem with various attributes can be attacked and optimal decisions can be reached.

The selected data resulted in preference of geothermal and nuclear energy over other sources and the method is found viable in making decisions on energy rise based on quantified and subjective attributes.

CHAPTER I. INTRODUCTION

Comparative risk analysis of different energy sources is a complicated problem which is subject to highly controversial debates and no model which can precisely and quantitatively deal with all the attributes concerning the issue. Components contributing to this complexity include environmental, social and difficult to quantify consequences that are crucial in selecting an alternative, and uncertainties about the overall impact of a particular alternative.

The purpose of this study is two-fold: to investigate the usefulness of multiattribute utility theory in evaluating safety aspects of alternative energy sources used for production of electricity; and to illustrate the techniques which will help the decision-makers in arriving at a conclusion to this end.

Four alternative energy sources have been chosen which are or which have the potential to become competitive for the production of electricity to meet the nations' energy demand. These are nuclear, coal, solar and geothermal energy. For simplicity a "total system" in each case has been considered. It is quite possible to extend the applicability of the theory to include situations in which a combination of any two, three or four energy sources are used to produce electricity. One may then compare different proportions of the combinations as to which could be the safest so far as environmental degradation, social cost, thermal pollution, effect on health and safety of the public and many different attributes are concerned. However, the model presented has its limitations (it will be described later) and care has to be taken to adhere to it for a more accurate result.

The description of the problem is given in Chapter II which specifies the various elements affecting the environment directly or indirectly due to coal-fired, nuclear, solar and geothermal power plants. Chapter III describes the general application of utility theory while the multiattribute utility model is presented in Chapter IV. The latter chapter also explains assumptions necessary for the applicability of the model. In Chapter V, twenty-three attributes have been selected and their range determined which were considered to be most effective on decision-making. The assumptions of the model, mentioned above, have been verified in Chapter VI. Chapter VII describes the method of determining the component utility function. The best fit for an exponential curve was obtained by a computer program and the coefficients for each attribute are listed. The scaling factors for the mathematical model are assessed in Chapter VIII. In Chapter IX the attribute levels are evaluated and the necessary assumptions and event trees are presented. The utility functions have been calculated by a specially developed computer program and are tabulated in Chapter X. The program is developed with a great degree of flexibility so that it can be used for solution of a variety of decision problems of the same nature as the problem analyzed here.

CHAPTER II. PROBLEM DESCRIPTION

Electricity has long been taken for granted, in an era of abundance, as the "stuff" that makes everything run. The power has always been there when it is wanted - for half a century. Few have stopped to consider that electric power, although the sine qua non of the modern society, is generated by a wasteful and almost primitive mechanical process - about two-thirds of the energy in the fuel which generate it is thrown away into rivers, lakes, and the atmosphere, in the form of heat.

Clean as the image of electricity may be, its production causes vast air and water pollution. Coal-fired power plants rank with the automobile as the nation's worst air polluter. According to the Department of Health, Education and Welfare, in 1968 which were responsible for 20% of all soot and ash, 50% of sulfur dioxide, and 20% of the nitrogen oxides emitted by all sources.

Fossil-fuel and nuclear power plants together also account for 80% of all U.S. water used for the cooling of industrial processes (an amount equivalent to over 10% of fresh water run-off in the entire nation), often causing thermal effects harmful to fish and water quality.

Nuclear Power Plants

Nuclear power has been originally envisioned as a never-ending nonpolluting power source. However, virtually every aspect of the nuclear power industry, from radioactive waste processing and disposal, to "routine" release of radioactivity from the power reactor itself has been of concern to some opposition groups who charge that current practices may increase the levels of radioactive exposure. Although the nuclear power industry has a very clean record of no major accident up until now, it is appropriate for the decision-maker to accommodate for public opinion even if the fear of the opponents is based only on speculations. Moreover, the Nuclear Regulatory Agency has yet to select a site for final multi-thousand-year storage of high-level wastes from today's plants.

Coal-fired Power Plant

An alarming problem is the projected tripling by the year 2000 of the burning of coal, which in 1970 was used to supply 49% of total electricity generation and accounted for well over four-fifths of the utility industry's air pollution. The trend in coal-fired plant construction is towards the "pyramiding" of power generating units at one site - each unit several times the size of an entire plant built 10 years ago, with multiple environmental problems to match. Despite the fact that current technology makes possible over 99% soot removal, several hundred pounds of microscopic ash particles may still escape into air hourly from large plants. Sulfur dioxide control techniques, only now moving into full commercial availability, are designed to remove at most 90% of the pollutants. Very little is even known about nitrogen oxide removal for coal burning. Methods of effectively cleaning coal before burning (coal gasification and solvent refining), overlooked during the period of optimism about nuclear expansion, will not begin to be commercially applied for about 10-15 years.

Nevertheless, coal-burning power plants, always a part of the landscape in the East, have recently spread to the huge coal fields of the Southwest, and are being developed in the Pacific Northwest as well. To get the coal out of the ground, vast areas in the West are going to be strip-mined; 35-year contracts have been signed in several states, and stripping has long since begun. A group of utilities has recently proposed construction of 90,000 megawatts of coal-fired capacity in and around the Rocky Mountains in Wyoming (1).

Solar Power Plants

There seems to be a general impression that solar energy technologies are socially and environmentally benign. For a mix of potential solar options to constitute a truly significant energy source, they will have to be used on a very large scale, on the order of tens of terawatts. It is now well-known that the use of any technology on a large scale produces unanticipated and sometimes unwanted impacts on both social and physical environments.

Most discussions of environmental impacts of solar facilities centers on the operating phase. However, the process of creating and operating a large industrial infrastructure to construct, operate, and dismantle facilities that might dominate hundreds of thousands or even millions of square kilometers of land and ocean will have a number of direct and indirect impact effects. For example, substantially more steel and concrete are required to produce a kilowatt hour (thermal) of electricity with the efficiency of solar technologies than with fossil and nuclear facilities.

> The power needs of the United States in the year 2000 could be met by mirrors covering between 65,000 and 80,000 square kilometers (25,000 to 30,000 square miles), the equivalent of 0.86 percent of the land area of the country. As a basis, solar insolation of 0.33 kilowatts per square meter per hour is assumed (this is only half the average sunshine that falls on places like Arizona, Southern New Mexico, Southern California and West Texas). To cover such an area with mirrors would require 130

> million tons of aluminum, well over thirty times America's annual production. To coat them would need four times more glass than the United States produced in 1970; to support them, it would take only slightly more steel than in all the automobiles on the road in America (2).

This in turn implies additional burdens of air and water pollution from increased requirements of the above mentioned material.

On a national average basis, the additional impacts appear very small. However, if large industrial facilities are constructed in arid regions to permit the most economic utilization of the major solar-thermal electric conversion (STEC) power plant components (optical elements), the local impacts may be far from negligible. (In fact, such operations may have difficulty meeting the provisions of the Clean Air Act in the United States.)

During the operating phase, many of the environmental problems associated with fossil fuel use are absent. In general, land-based solar facilities will not produce air pollution, and there are no radioactive materials considerations involved. In addition, the very serious potential problems associated with rapid increases in atmospheric carbon dioxide resulting from fossil fuel combustions are also completely avoided. There is a possibility that STEC facilities, however, might cause an increased level of atmospheric carbon dioxide. Present understanding indicates that the deeper ocean waters are the ultimate sink for atmospheric carbon, and by increasing the mixing rate, there will be a shift in the exchange rates of carbon dioxide between the atmosphere and the ocean surface. According to some studies, each 3 KWh generated from OTEC facilities will increase atmospheric carbon dioxide in an amount equivalent to that resulting from fossil fuel combustion that produces 1 KWh (that is, the STEC plants will have roughly one-third the carbon dioxide impact of conventional fossil plants) (3).

It is not clear that there will not be effects on weather and climate. For example, it is often claimed that solar conversion systems, such as STEC and photovoltaic power plants, will not add to the thermal burden of the earth. In reality, the presence of such machines will result in a change in the thermodynamics of a region. Studies have shown that the albedo, or the reflectivity, of a region containing either STEC or photovoltaic power plants of the type presently envisioned will be substantially modified. In arid desert regions, the albedo will be in the 0.2-0.3 range; local changes as much as 50% are possible in the presence of solar facilities (3).

In addition to effects caused by changes in reflectivity, there are other effects that generally have not been considered. For example, a large field of heliostats will increase the surface roughness length and will facilitate increased turbulent transfer of heat from the ground to the atmosphere. In nonarid regions, photovoltaic and other systems will change the local surface hydrology, especially if substantial surface preparation (including paving) is required.

Although detailed calculations on the effects of STEC facilities on ocean surface temperature have not been carried out, estimates of the local effects range from a decrease of 0.5°C to several degrees. It has been concluded by some investigators that large-scale STEC deployment (on the order of terawatts or greater) may have very strong effects on climate and that this issue will have to be investigated carefully if STEC plants turn out to be technically and economically viable as large-scale alternatives.

A concept such as putting huge solar panels into orbit and beaming power back to earth by microwaves, would be potentially hazardous. The consequences would be severe if a malfunction in the microwave transmitter caused it to beam, for example, 10,000 MW into a populated area. This possibility could be compared to the release of radioactivity from a nuclear power plant in case of a loss of coolant accident where the protection systems fail.

Geothermal Power Plants

Geothermal energy, the natural heat of the earths interior, is the largest energy reservoir that is directly accessible to man. Where nature delivers energy from its reservoir to earth's surface in the form of steam or superheated water capable of producing steam, its direct conversion to electricity has proven to be economical.

Still there are a number of environmental problems which have to be solved before its use is widely accepted. The most obvious items are embodied in the intrusion of an industrial operation into nonindustrial land areas. For example, a geothermal well is drilled in the same fashion as an oil well. Problems include noise and the appearance of drill rigs.

When developing a field yielding a steam/water mixture, there is the matter of disposal of surplus waters. In some instances, these wastes will be high in mineral content, and cannot be discharged into surface waters. Unless very well-mixed, even ocean discharge could lead to severe local effects, if the plant waste differed substantially from ocean water.

The more difficult problems arise when the geothermal wells produce hot water, rather than dry steam. In this case the water may be highly mineralized. As has been calculated for an equivalent electric plant of 1,000 MW size, salt water is produced at the rate of approximately 150 million gallons/day, or over 150,000 acre-feet annually. For 2% brine, 12,000 tons/day of salts would result if the water was evaporated away (4). This poses a monumental solid disposal problem, and constitutes a real environmental danger.

Before disposal, the water might be concentrated in evaporation ponds, or used as feedwater to a desalting plant. In either case, limits exist to the concentration factor, thus the disposal of the brines is a problem requiring careful consideration.

After overcoming original wellhead pressure, it is often found that the water is literally poured down the hole. This is often made easier by the greater density of the concentrated and cooled brine. One must take care to avoid aquifers that connect to areas where the waste will do harm, e.g., sources of agricultural or potable water. A potentially serious problem in injection well operation is the deposition of minerals from the water in the pores surrounding the well. Such deposition can cause rapid impediment to well flow.

A closely associated problem is that of land subsidence. If large quantities of fluids are removed from the underground reservoir, the land surface may sink, with sometimes disastrous consequences. This happened in the Wilmington oil field.

Experience in Colorado, and some on-going experiments there, have indicated that seismic activity can be stimulated by the injection of water deep underground.

Noxious gases are often a by-product of geothermal wells. At the Geyers, for example, the odor of hydrogen sulfide (H_2S) is prevalent. It exists in the steam with other gases, most notably carbon dioxide. The noncondensable gases contribute from 0.2 to 1.8% of the steam flow at the geysers. Of this 82.5% is CO_2, 6.6% methane, 1.4% hydrogen, 1.2% inerts, 4.5% H_2S and 3.8% ammonia. Some gases dissolve in the condensate. This is the case of H_2S, where a portion dissolves in the condensate and later escapes to the atmosphere when the condensate water is evaporated in the cooling tower. If we assume that only 1/2% of the steam flow, on the average, is noncondensable gas, the above figures indicate that H_2S is present in the steam to the amount of 225 parts per million (4).

A possibly significant environmental effect to be expected in routine operation of a geothermal power plant is heat rejection. The geothermal steam is available at low pressure and temperature, as compared to that from conventional boiler or nuclear plants. Thus, the heat rejection will be high. If air-cooled condensers are used, the reject energy will be larger and will go directly to heating the atmosphere. How this heated air would distribute itself and affect the local climate will require detailed consideration of local conditions. If water cooling towers are used, the temperature would be affected to a lesser extent, but substantial quantities of water would be evaporated, thus influencing the humidity and the climate.

In any well drilling operation involving high pressure fluids, the possibility of a well blowout must be taken into account. Blowout occurs in a variety of ways. The classic oil well blowout is one type. Such a blowout might flow as much as 10 acre-feet/day. Clearly, such a release of salt water in an agricultural area would pose a major environmental problem. Another type of blowout might occur when the formation through which the well passes is unstable.

Selection of Energy Source

It is thus clear that comparing the safety aspects of the four energy sources, described above, for the production of electricity involves a number of attributes. We can structure this decision problem as a mathematical optimization problem, but this can lead to a number of difficulties.

One such difficulty is that the optimization model may focus upon an objective that has little impact on the final decision problem. This often happens when the objective has a small range over the alternatives, even though the objective per se is important. For example, employment may be an important objective, but if the employment opportunity for alternative systems were all within a small range of each other, then other objectives would have more influence on the decision. Also, experience has indicated that in utility assessments, varying more than two attributes simultaneously, is extremely difficult for decision-makers.

This and other related problems provide the motivation to consider applying multiattribute utility models. Applications of mathematical decision-making models have, in the past, tended to use unidimensional and easily measurable objective functions. Common examples include maximizing profit, maximizing lives saved per dollar, minimizing the cost of an aircraft which meets certain minimum criteria or minimizing the average waiting time of customers receiving some service. The problem with this approach, of course, is that almost all decisions in fact involve multiple criteria, and these criteria are often subjective in nature, eluding easy quantification. The essence of good decision-making in such circumstances lies in trading off one goal against another.

Mathematical decision-making models can be properly applied in such situations only if these trade-offs can be expressed in quantitative form. Therein lies the value of multiattribute utility (MAU) models. Thus, in our case, the MAU theory provides a practical tool for the development of multi-dimensional objective functions.

In Chapter IV the MAU model which is suitable for the present problem will be explained. Before going to that the concepts of utility theory will be briefly described to provide the basic tool for understanding MAU model.

CHAPTER III. UTILITY THEORY AND ITS APPLICATIONS

Utility theory is a mathematical theory in which we attempt to measure people's attitude or preferences towards multiple objectives by means of numerical "utility functions" (5). The concept of utility has been borrowed in decision analysis to establish a scale for expected monetary values of lotteries or business ventures when there is an indifference in choice under uncertainties (6). Assessment of numerical utilities can be used for nonmonetary as well as monetary attributes (7).

Numerical utility functions are best explained in the context of monetary values. Let us consider gamble shown in Figure 1, which results in a payoff of \$0 or \$100 with equal probabilities of 0.5. The expected monetary value (EMV) is

$$\text{EMV} = \frac{1}{2}(\$0) + \frac{1}{2}(\$100) = \$50$$

The EMV of a gamble with several possible outcomes can be

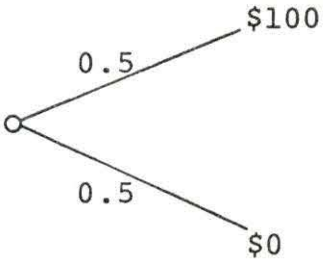


Figure 1. Gamble for expected monetary value

generally obtained by multiplying each possible cash outcome by its probability and summing these products over all possible outcomes (8).

In general for individuals who are not willing to base their decision merely on the basis of the EMV of the gamble (non-EMV'ers) the EMV would not be a good predictor of preferences between multiple choices. In this case, the monetary value must be appropriately expressed in different units to associate with each lottery its expected value and to choose the lottery that has the best showing on this new scale of expected values. These units may be called "utiles" which represent the expected utility of money for an individual. The utility function may be defined as the function that describes the actual indifference points of an individual between sets of two alternatives. If the basis is a risk-avert he or she may be indifferent (has no preference) to keep the lottery of Figure 1 or sell it, say, for $10 (8). Each individual has a personal utility curve which can be a priori plotted by sampling of situations and then used for decision-making in future gambles. To construct the curve, two reference points must be defined as boundary conditions. Additional points on the curve would be found by determining the preferences of the individual among other alternatives. Suppose, for a given person, the following two points are chosen

$$u(\$0) = 0 \text{ utiles}$$

$$u(\$100) = 5 \text{ utiles}$$

Then we can find out the utility for \$10, for Gamble I, as

$$\begin{aligned} u(\$10) &= 0.5 \times u(\$0) + 0.5 \times u(\$100) \\ &= 0.5 \times 0 + 0.5 \times 5 \\ &= 2.5 \text{ utiles} \end{aligned}$$

The principles and the method discussed here can be applied to the assessment of the utility functions for such things as health effects measured as the number of days lost from disability per capita per year, air emissions measured as daily sulfur dioxide concentrations, and mortality measured as number of fatalities (9, 10). In addition, the full dimensionality of the energy system alternatives has been treated by the use of utility theory (11). Application of the utility theory methods in the treatment of the variability of the number of fatalities which may result from accidents has been suggested for risk analysis for nuclear facilities (5).

CHAPTER IV. MULTIATTRIBUTE UTILITY MODEL

Most complex decisions require the decision-maker to make trade-offs between competing value objectives. Multiattribute utility theory provides a formal basis for describing or prescribing choices between alternatives whose consequences are characterized by multiple value relevant attributes (11). Thus, analytic work on such problems requires that one obtain an objective function involving multiple measures of effectiveness to indicate the degrees to which these objectives are met. Such an objective function specifies a preference ranking of consequences and allows one to identify the trade-offs between various combinations of levels of the different attributes. In a risk-free environment, one should choose the alternative course of action that maximizes (or minimizes) the objective function (12).

However, most real decision problems, such as that of ours, involve uncertainties - and these uncertainties need to be either considered formally or informally in analyzing the problem. If one chooses to do this formally, it is necessary to specify an objective function with special characteristics in order to make the analysis for solving the problem tractable. For this reason, it would be nice to be able to use the expected value of the objective function as a guide to identify the best alternatives. This is appropriate, given that one accepts the axioms of utility theory specified by Von Neumann and Morgenstern (13). The objective function is then a utility function. This utility function not only provides one with the necessary information to rank consequences and identify trade-offs between attributes, but it also follows from the aforementioned axioms that one should choose the alternative that maximizes the expected utility.

The utility concept is theoretically sound, and the mathematical details are not involved. However, as mentioned earlier, the difficulty comes when one tries to specify reasonable procedures for obtaining multiattributed utility functions. The general approach followed by many people has been to make assumptions about preferences and then derive the functional form(s) of the utility function satisfying these assumptions. For a real problem, if the assumptions are verified, the functional form can be used to simplify the requisite assessments needed to specify the utility function. Often these assumptions are so involved that it is unreasonable to expect a decision maker to ascertain whether or not they might be appropriate for a specific problem.

In the following lines, sufficient conditions will be stated to imply that a multiattributed utility function is either multiplicative or additive. The number of conditions required increases only linearly with the number of attributes.

None of the conditions requires the decision maker to consider trade-offs between more than two attributes simultaneously or to consider lotteries over more than one attribute. Furthermore, subject to the assumptions, the assessments needed to specify the n-attribute utility function completely are on one-attribute utility functions and on scaling constants.

The main assumptions we use concern the concepts of preferential independence and utility independence. We say $x_i \times x_j$ is preferentially independent of $x_{ij}-$ if one's preference order for consequences $(x_i, x_j, x_{ij}-)$, with $x_{ij}-$ held fixed, does not depend on the fixed amount $x_{ij}-$. This implies that the indifference curves over $x_i \times x_j$ are the same, regardless of the value of $x_{ij}-$.

In a similar fashion, we say x_i is utility independent of x_i- if one's preference order over lotteries on x_i, written $(\tilde{x}_i, x_i-)$, with x_i- held fixed, does not depend on the fixed amount x_i-. This implies the conditional utility function over x_i, given x_i- fixed at any value, will be a positive linear transformation of conditional utility function over x_i, given x_i- fixed at any other value.

With these ideas, the main result can be stated as follows:

Let $x \equiv x_1 \times x_2 \times \ldots \times x_n$, with $n \geq 3$. If for some x_i, $x_i \times x_j$ is preferentially independent of $x_{ij}-$ for all $j \neq i$

and x_i is utility independent of $x_{\bar{i}}$, then either

$$U(x) = \sum_{i=1}^{i=n} k_i u_i(x_i), \tag{1}$$

or

$$1 + KU(x) = \prod_{i=1}^{i=n} [1 + Kk_i u_i(x_i)], \tag{2}$$

where U and the u_i are utility functions scaled from zero to one, the k_i are scaling constants with $0 < k_i < 1$, and k (> -1) is a nonzero scaling constant. Equation (1) is the additive utility function and Equation (2) is referred to as the multiplicative utility function.

The k_i can be interpreted as the utility u assigned to a consequence with all its attributes except x_i set at their least preferable amount and x_i set at the most preferable amount. The assessment procedure for k_i is given in Chapter VIII.

The value of K can be found from the values of the k_i. When $\Sigma k_i = 1$, then $K = 0$, and Equation (2) reduces to the additive form of Equation (1). When $\Sigma k_i \neq 1$, then $K \neq 0$ so that we can use Equation (2).

CHAPTER V. MEASURES OF EFFECTIVENESS

To evaluate the alternatives, one needs to specify some measures of effectiveness which explicitly describe possible impacts of each of the important alternatives concerned with the problem. As a result, a set of attributes were selected along with their ranges to be used in evaluating alternatives. The attributes serve to indicate the degree of impact each alternative will have on the environment. A summary of these attributes, labelled X_1, X_2, ..., X_{23}, is given in Table 1.

Many of the attributes are self-explanatory but some of them require clarification. These are as follows:

Symbol	Attribute	Explanation
X_1	Fatality	Includes only the mining and transport death
X_2	Chronic effect	Includes death due to disease due to the use of different energy sources, e.g., black lung, cancer, respiratory disease and heart trouble, etc.
X_3	Disability	Includes injury in mining, transport, and excess cases of black lung, cancer, etc.
X_{13}	Material damage	Corrosion of materials due to air pollution components particularly SO_2 and NO_x
X_{21}	Frequency (events/year)	This is the average frequency of accidents on the record or anticipated

Symbol	Attribute	Explanation
X_{22}	Insurability, third party liability	This is the probability of the third-party (nongovernment) insurance for the health and material safety of the public in case of accident
X_{23}	Degree-of-regulation imposition	This is the degree of environmental regulations that the utility has to obey as a precondition for its normal running. In some cases, e.g., coal-fired plants can choose to pay penalty for allowing the particulates, sulfur dioxide and nitrogen oxides to go into air without abatement, for economic reasons.

Table 1. Relative range of various attributes

Symbol	Attribute	Measure	Range	
			Best	Worst
X_1	Fatality (occupation)	Fatality-per-billion-MWh	0	15000
X_2	Chronic-effect (public)	Death/100 MW-plant/year	0	120
X_3	Chronic-effect (occupational)	Death/billion-MWh-supply	0	1500
X_4	Employment	Job/million-MWh	14000	0
X_5	Disability	Disability-days/million-MWh	0	3000
X_6	Global-temperature-change	Degree-fahrenheit (1980-2000)	0	2.4
X_7	Average-outage-of-power-plant	Percentage	0	100
X_8	Fuel-supply (from 1980)	Years	1000	0
X_9	Diversity	Mills/KWh	0	.01
X_{10}	Sabotage	Mills/KWh	0	.01
X_{11}	Vegetable-damage	Million-$/yr	0	500
X_{12}	Land-fill	Acres-100-ft-depth/yr	0	3000
X_{13}	Material-damage	Billion-$/yr	0	12
X_{14}	Land-use	Square-mile/yr/1000 MW-plant	0	60
X_{15}	Thermal-pollution	Percent-of-input-energy-dumped-in-water	0	100
X_{16}	Noise-pollution	dB(A)	0	90
X_{17}	Discomfort (physical)	Subjective	0	100

Table 1 (Continued)

Symbol	Attribute	Measure	Range	
			Best	Worst
X_{18}	Discomfort (psychological)	Subjective	0	100
X_{19}	Aesthetic-effect	Subjective	0	100
X_{20}	Accident	Magnitude (fatality/accident)	0	4500
X_{21}	Frequency (event/yr)	Events/year	1E-06	1
X_{22}	Insurability, - third-party-liability	Probability	1	0
X_{23}	Degree-of-regulation-imposition	Percentage	100	o

CHAPTER VI. VERIFICATION OF ASSUMPTIONS

Before we assess the utility function, the assumptions made for arriving at the MAU model, presented earlier, has to be verified for the present case. The technique used to verify the preferential independence assumptions are as follows:

As an example, consider whether fatalities (X_1) and employment (X_5) are preferentially independent of the other attributes. We started by assessing what the amount of fatality X_1 was, such that (X_1; 14,000) was indifferent to (1:3000). That is X_1 people killed in mining and transport and 14,000 people employed are indifferent to one person killed and 3,000 employed. We assess a figure 30 for X_1. Here the exact number is not important for verifying the assumptions, but what we want to know is if this number changes when other attributes are varied. Thus the other attributes were varied to undesirable magnitudes and tried to get X_1. We again arrive at the same number 30. In fact the same appears to be true for any trade-offs between fatality and employment. Hence, we concluded fatality and employment were preferentially independent.

Next we go to other attributes and see if the same thing is applicable for them. We verified that land-use (X_{14}) and average-outage-of-power-plant (X_7) are preferentially independent. In fact, going through a number of combinations we find that all attributes are preferentially independent of the remaining attributes.

Also it was necessary to verify the utility independence assumption. Here, again, the same general approach is applicable. We had essentially to verify that X_i was utility independent of x_i- for all i = 1,2,...,23. Let us see, for example, if thermal pollution X_{15} was utility independent of $X_{\overline{15}}$. The other 22 attributes were set at reasonable magnitudes, and the conditional utility function over thermal pollution (percentage of input-energy dumped in water) from 30% to 70% was assessed. It was found that 49% was indifferent to a 50-50 lottery yielding either 30% or 70%. Then the values of $X_{\overline{15}}$ attributes were changed to less desirable magnitudes. Again, it was found that 49% was indifferent to a 50-50 lottery yielding either 30% or 70%. In fact, we verified that this is valid for any fixed value of X_{15}. Thus we found that relative preferences for any lotteries and consequences involving uncertainties only about X_{15} would not depend on the other attributes. The conclusion is, therefore, that X_{15} is utility independent of the other twenty-two attributes.

By going through identical procedures, it was verified that all the remaining attributes are also utility independent.

However, it must be pointed out that these verifications are subjective and may vary from person to person. The preferences may also vary with time. At this time, these are our "best" preferences (A Delphi questionnaire method might be suitable for a general consensus of the preferences and is recommended for a future research) and therefore the assumptions are suitable for our problem.

CHAPTER VII. ASSESSMENT OF COMPONENT UTILITY FUNCTION

To find the utility function for each attribute, the method described in (14) was used. The technique is illustrated below.

From Table 1, where we have chosen the range for each attribute, we scale our utility function so that

$$u(\text{best}) = 1$$

$$u(\text{worst}) = 0 .$$

Thus, for X_{15}, $u(0\%) = 1$

and

$$u(100\%) = 0 .$$

To begin with, we find that 38 percent is indifferent to a lottery yielding either 0% or 100%, each with probability 0.5. Therefore, the certainty equivalent for the lottery is

$$\begin{aligned} u_{15}(38) &= 0.5\ u_{15}(0) + 0.5\ u_{15}(100) \\ &= 0.5 \quad \text{(refer to Figure 16)} \end{aligned}$$

Since 38 is less than the expected value of [0.5 x 0 + 0.5 x 100 =] 50, this original assessment indicates that the utility function might exhibit a gambler scenario.

In a similar way we can choose a few more points on the utility curve, e.g., we found 17% indifferent to 0% and 38%; and 59% indifferent to 38% and 100%, both for a 50-50 lottery, hence

$$u_{15}(17) = 0.5\ u_{15}(0) + 0.5\ u_{15}(38)$$
$$= 0.75$$

and

$$u_{15}(59) = 0.5\ u_{15}(38) + 0.5\ u_{15}(100)$$
$$= 0.3$$

Then a utility curve was smoothed through the empirically assessed points. In each case we considered at least five points.

This process was repeated for each attribute and the utility functions are fitted by an exponential function of the form

$$U(x) = A + B * \exp(CX)$$

The coefficients A, B and C for each attribute are given in Table 2. The utility functions are shown in Figures 2 through 24.

There is no proof that the utility functions obtained are "accurate", since this is again a matter of personal judgement. However, we strongly feel that there may not be a drastic change in the nature of the scenarios obtained here, e.g., a curve which is risk-averse will remain so; it is only the curvature which might, on the average, change from person to person. Hence, the results obtained from these utility function will be, within certain limits, a general representation of the preferences.

Table 2. Coefficients of utility function, $u(x) = A + Be^{Cx}$

Attribute	A	B	C
X_1	-0.0754	1.0754	-0.0001772
X_2	-0.0185	1.019	-0.0334
X_3	0.2566	1.257	-0.001059
X_5	-0.0309	1.031	-0.0008769
X_6	1.022	-0.0223	1.53
X_7	1.535	-0.5353	0.01054
X_8	1.003	-1.003	-0.00589
X_9	-0.0215	1.021	-38.61
X_{10}	-0.0215	1.021	-38.61
X_{12}	-0.2886	1.2886	-0.0005
X_{13}	-0.785	1.078	-0.2626
X_{14}	-0.0095	1.009	-0.0466
X_{15}	-0.6625	1.663	-0.0092
X_{16}	1.404	-0.4038	0.0083
X_{17}	1.078	-0.078	0.02626
X_{18}	1.078	-0.078	0.02626
X_{19}	1.23	-0.2301	0.01676
X_{20}	-0.1667	1.1667	-0.000432
X_{22}	-0.03765	0.03765	3.316
X_{23}	1.284	-1.284	-0.01508

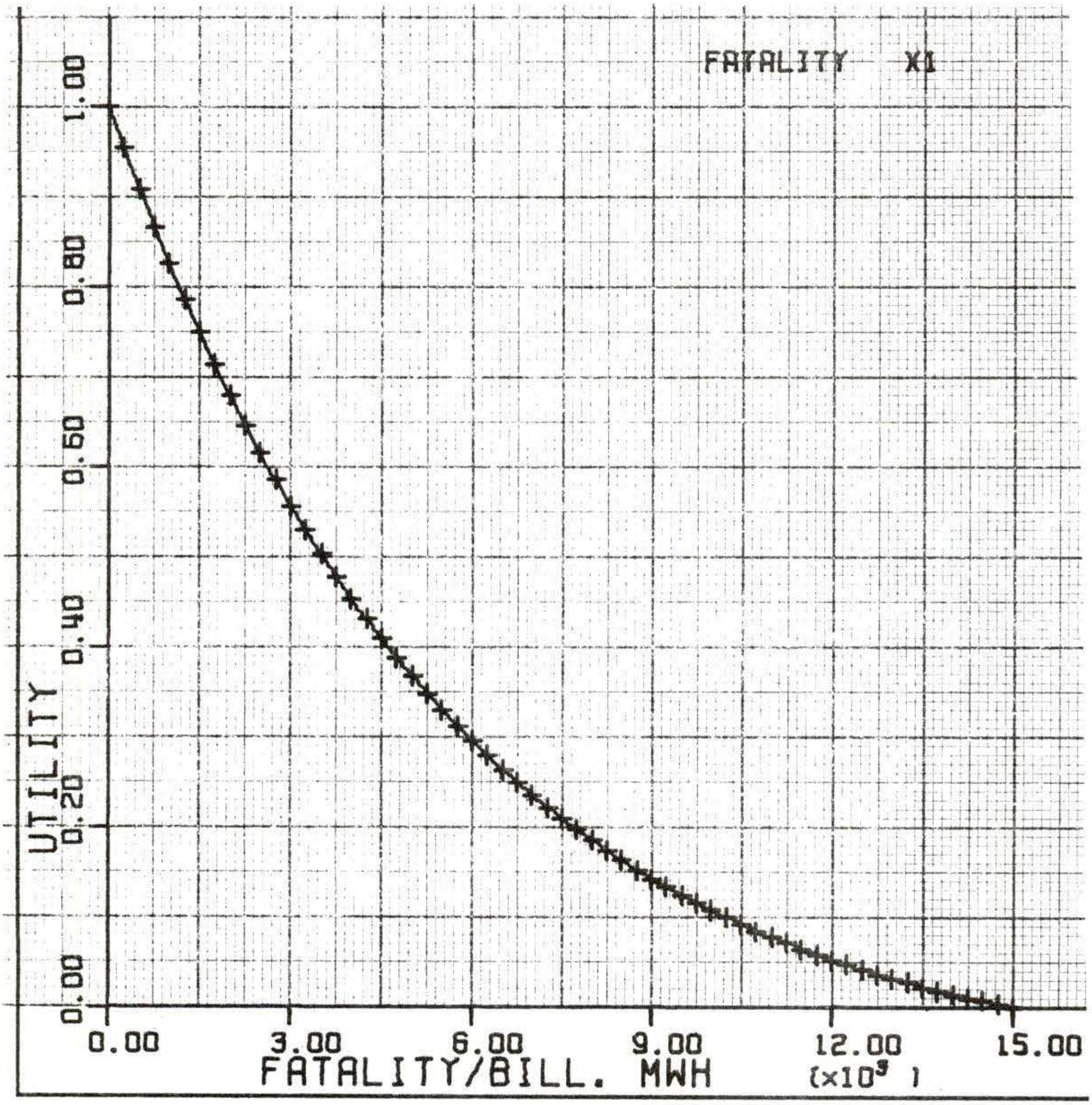


Figure 2. Component utility function for fatality

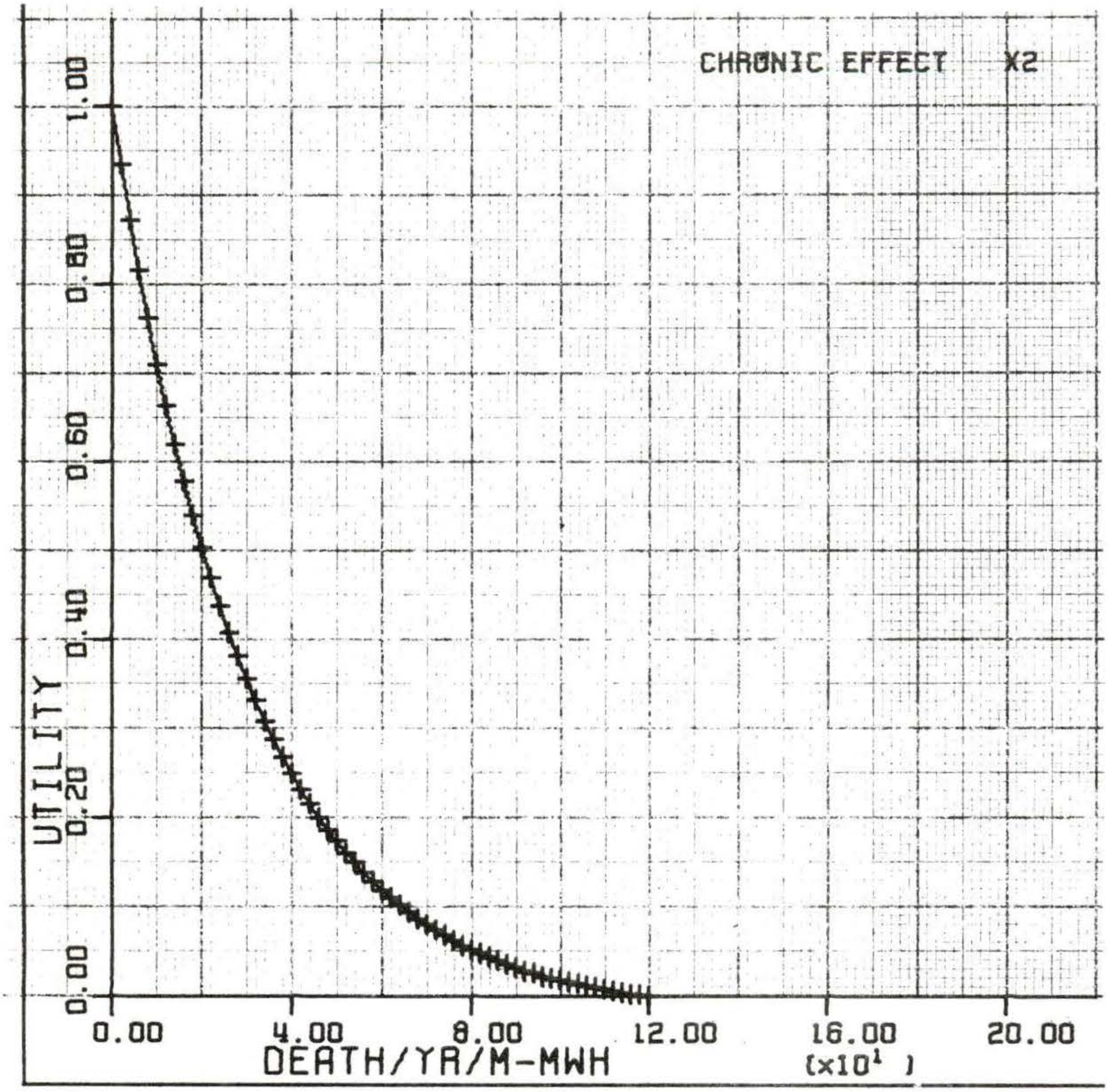


Figure 3. Component utility function for chronic effect (public)

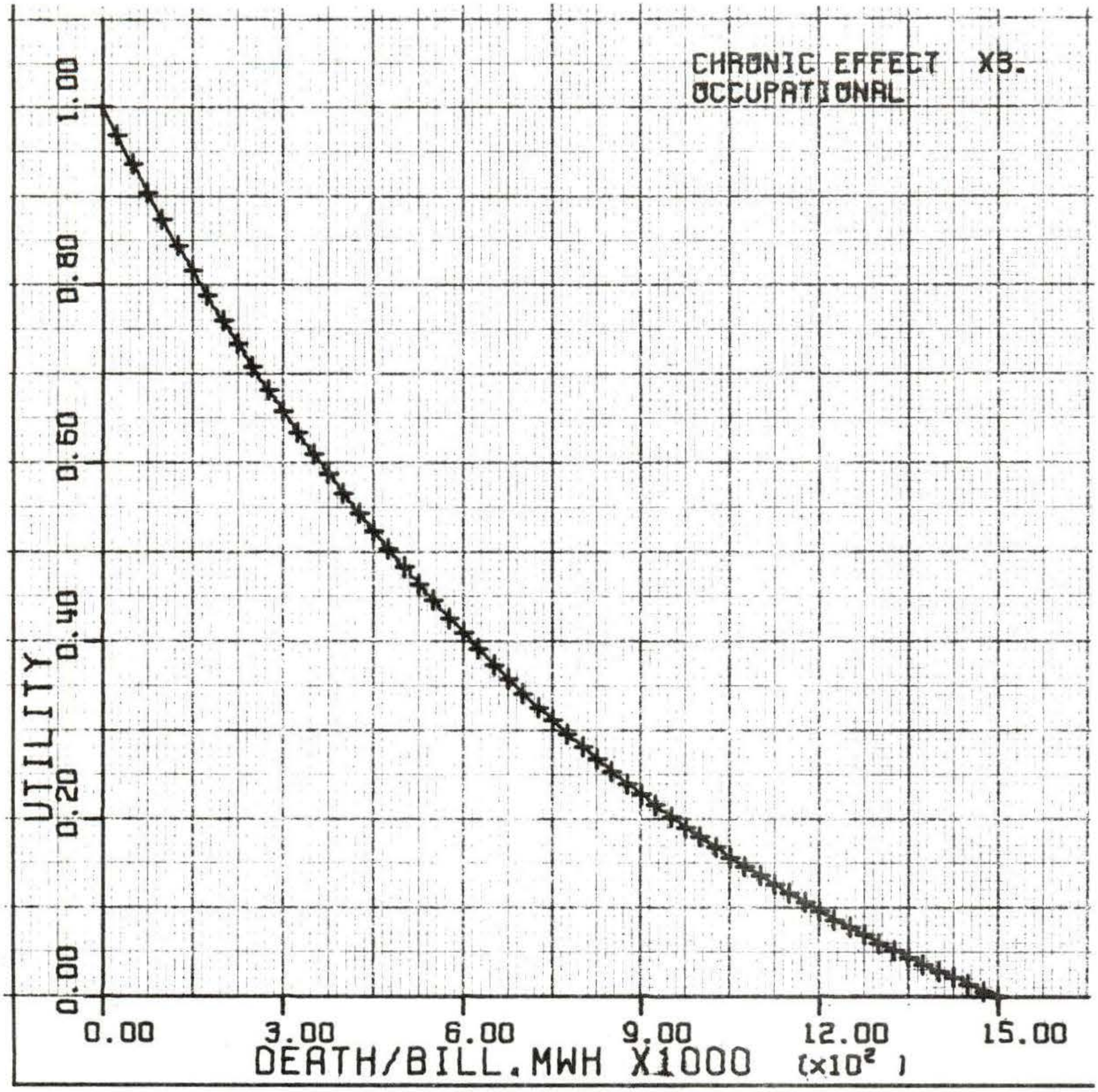


Figure 4. Component utility function for chronic effect (occupational)

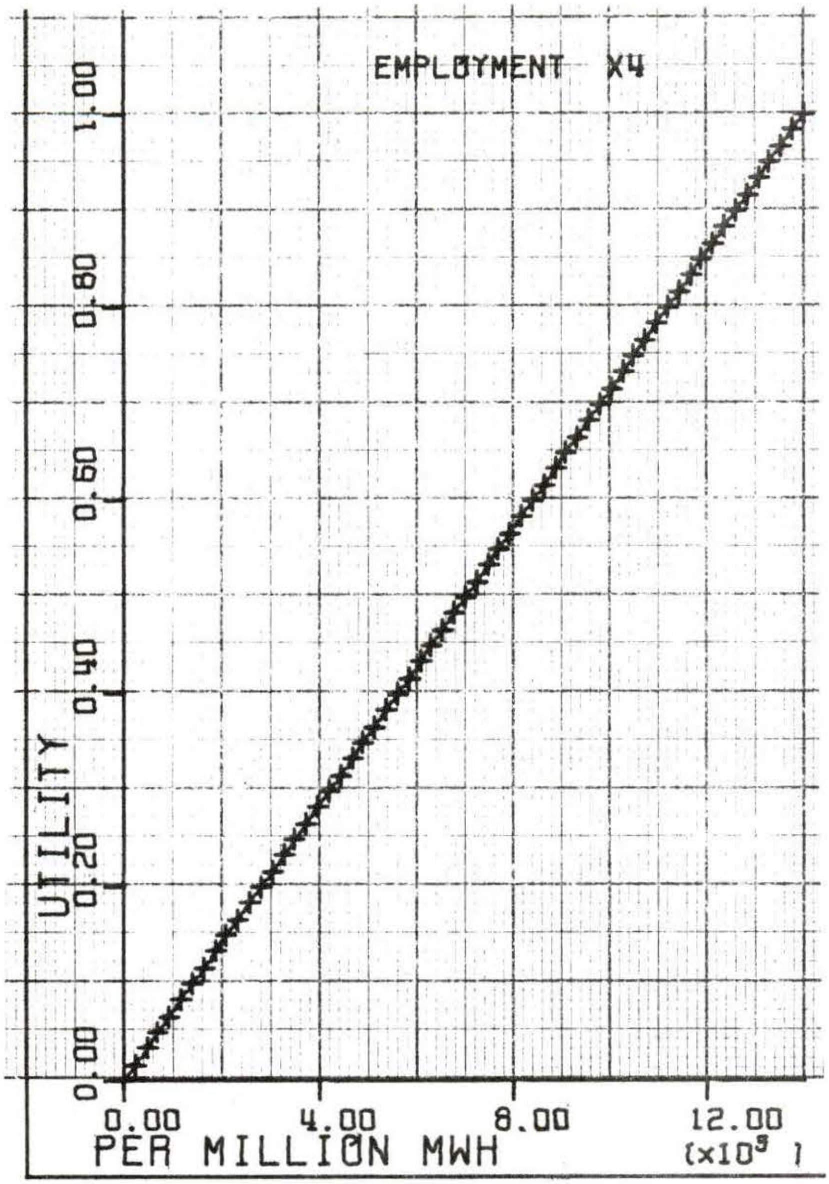


Figure 5. Component utility function for employment

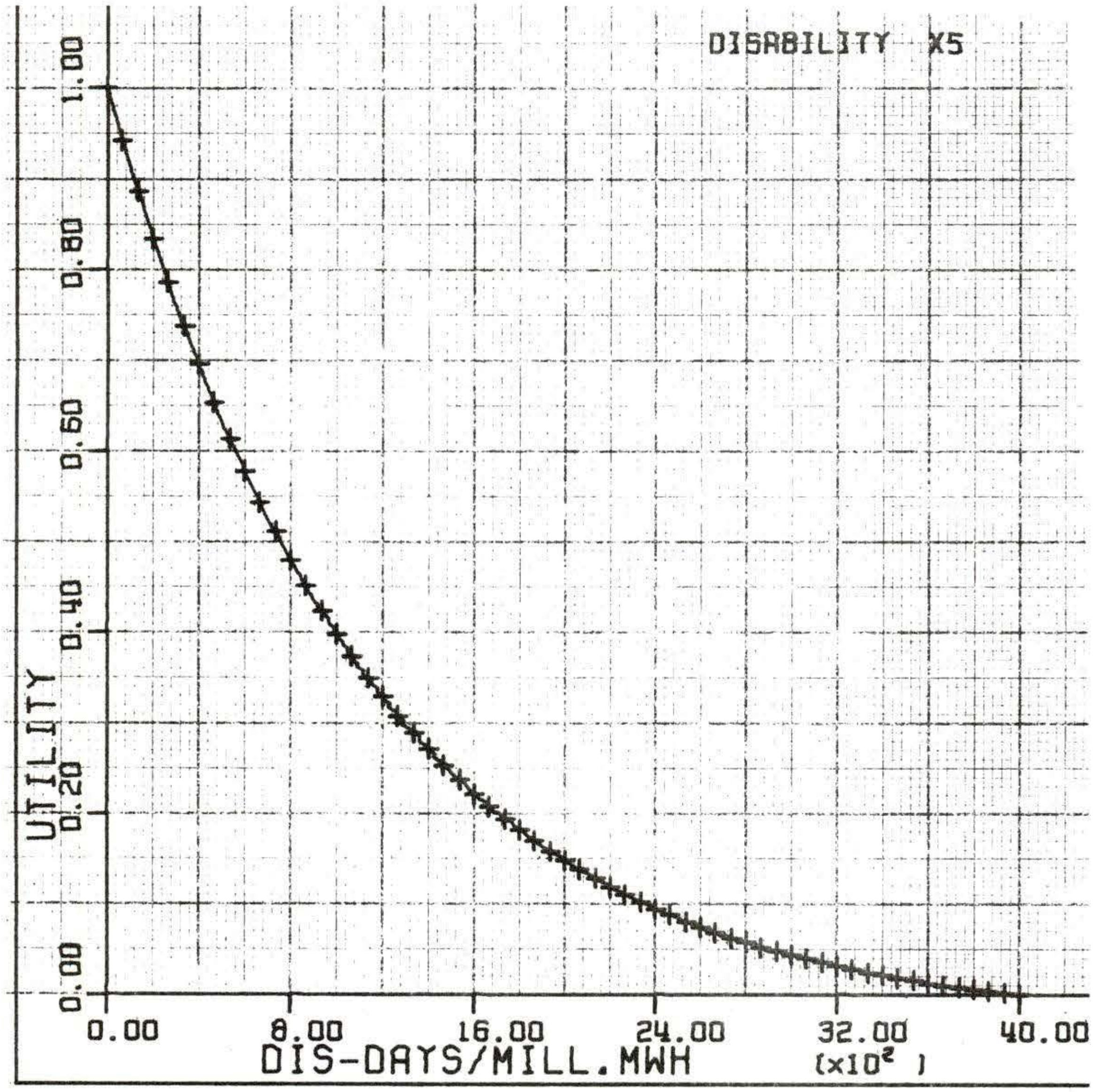


Figure 6. Component utility function for disability

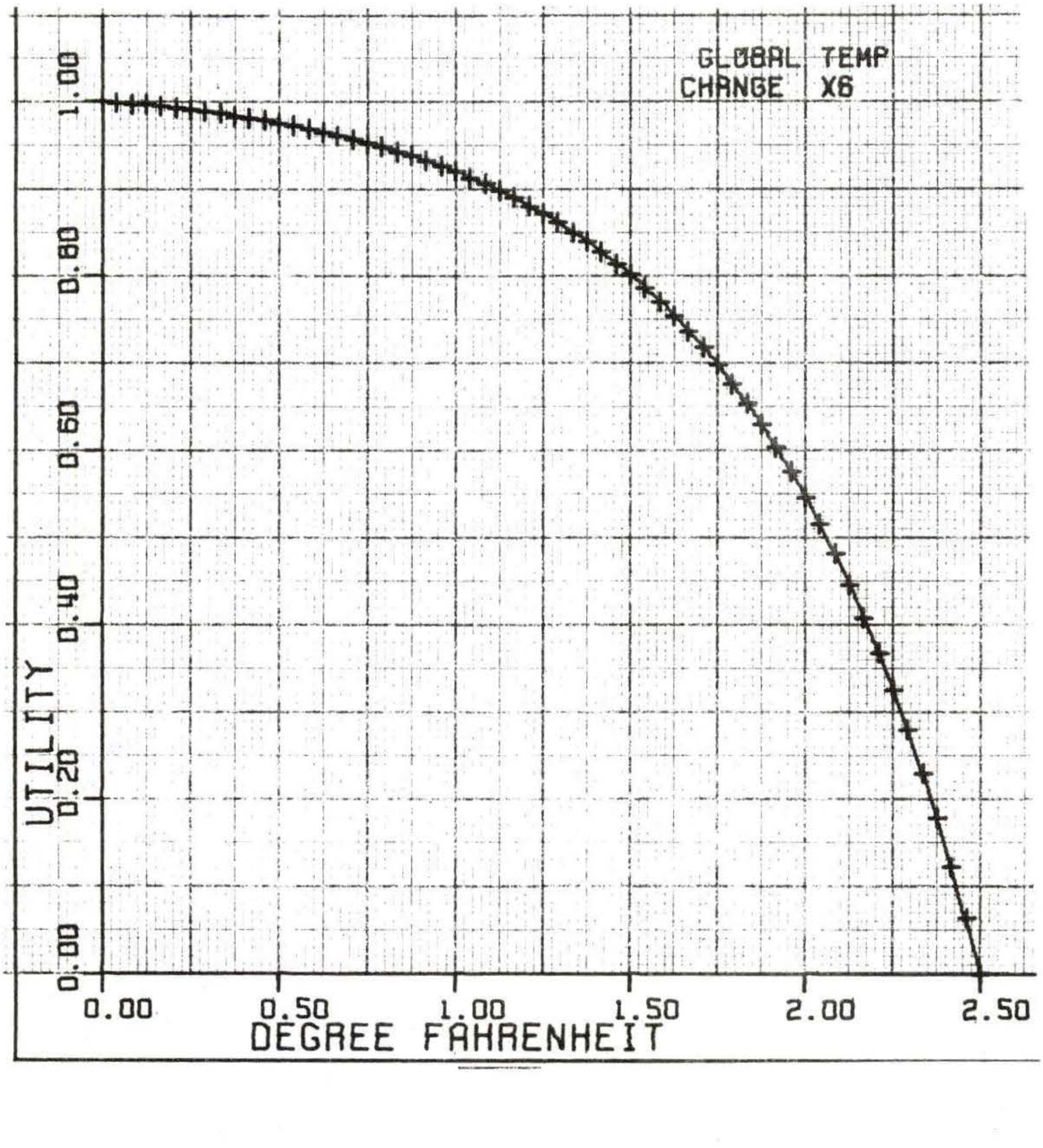


Figure 7. Component utility function for global temperature change

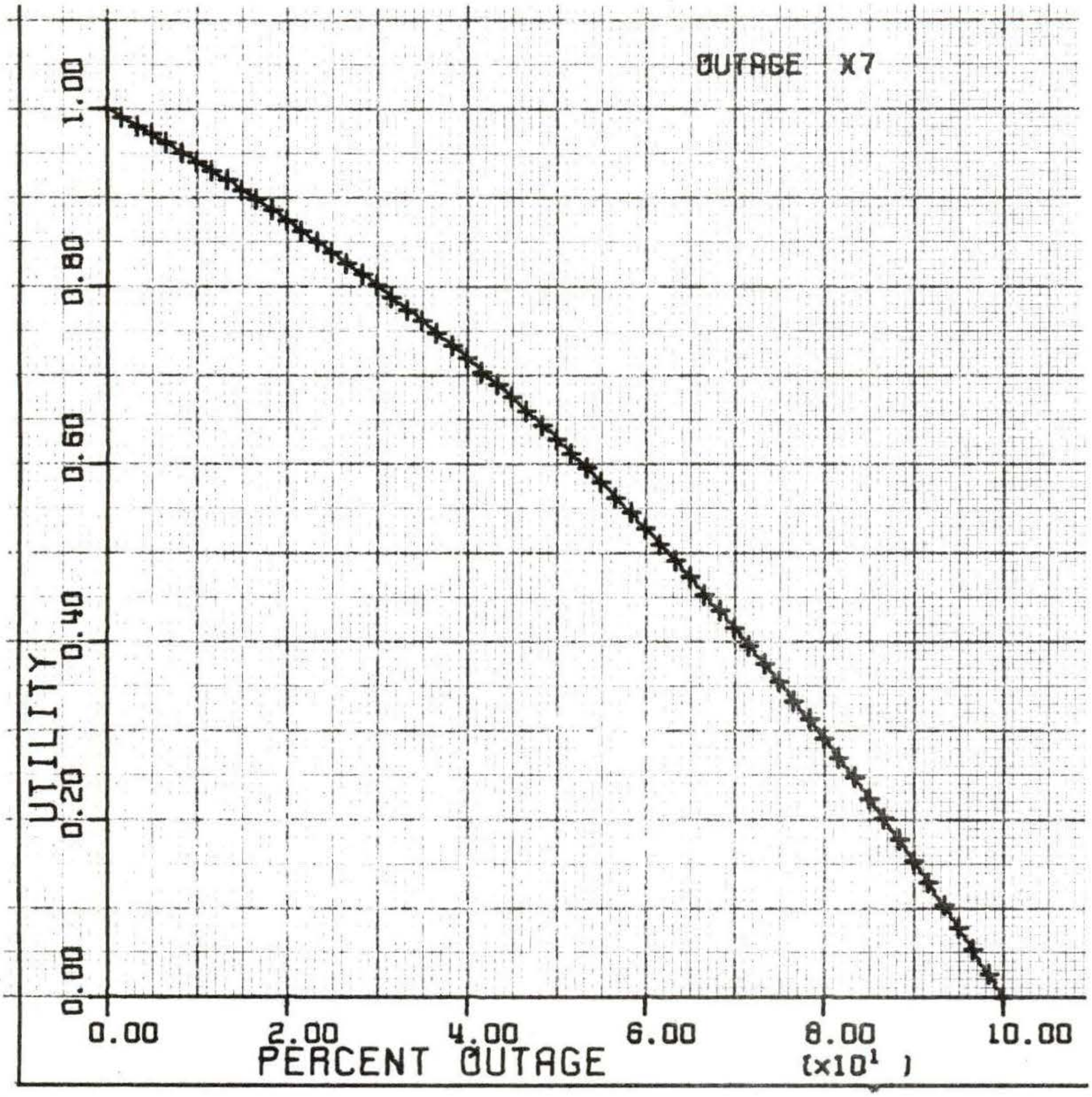


Figure 8. Component utility function for percentage outage

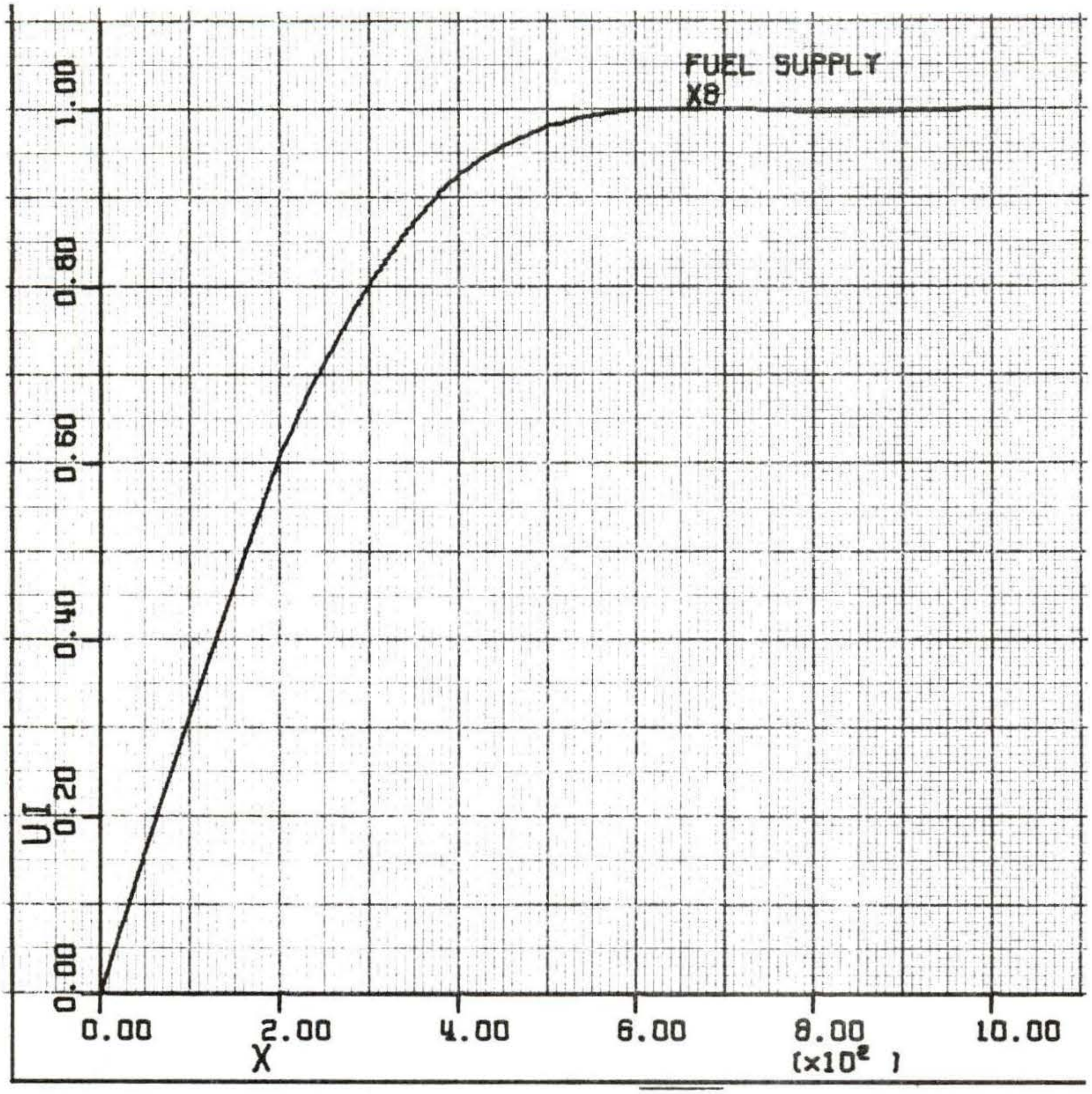


Figure 9. Component utility function for fuel supply

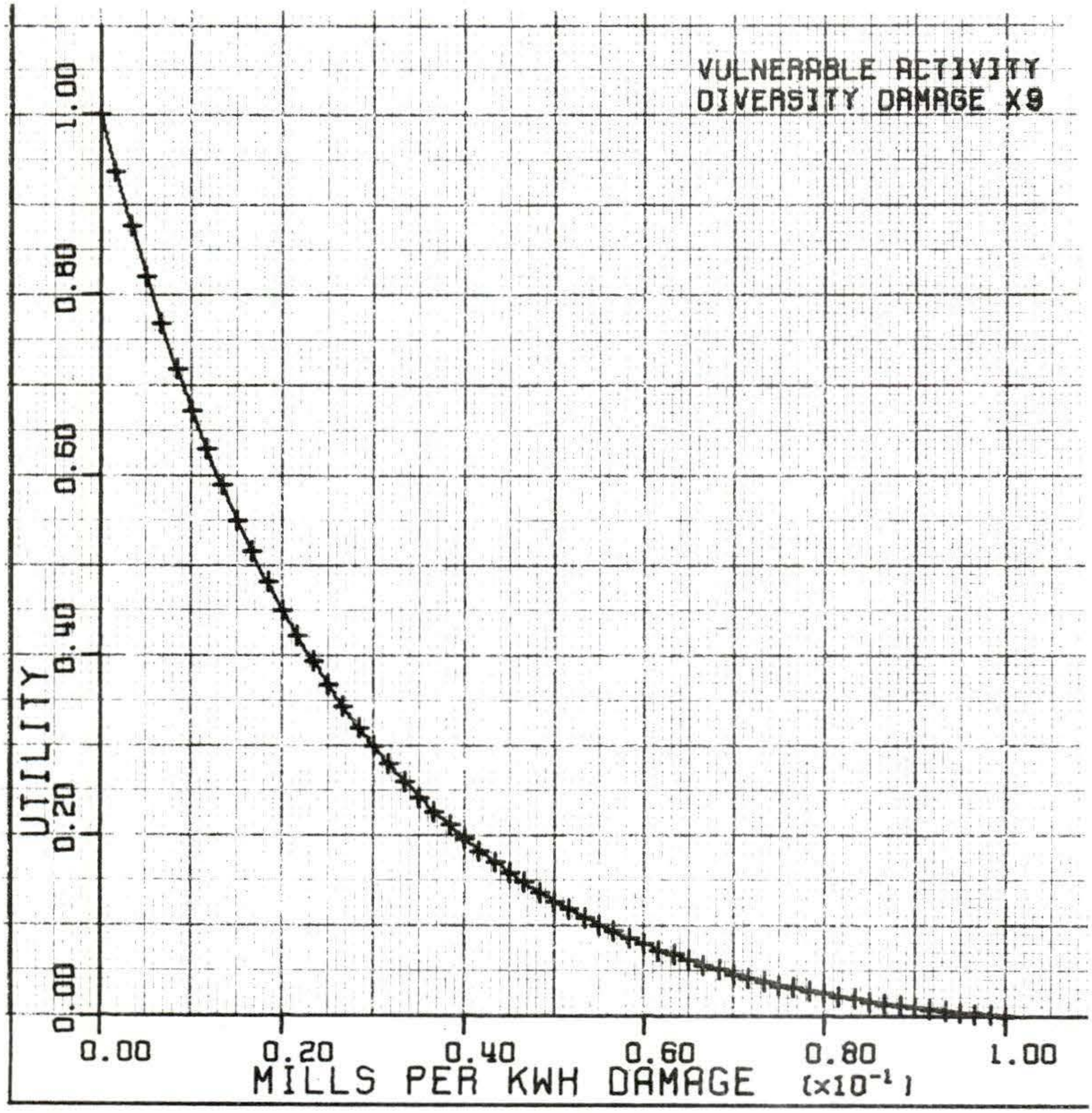


Figure 10. Component utility function for diversity

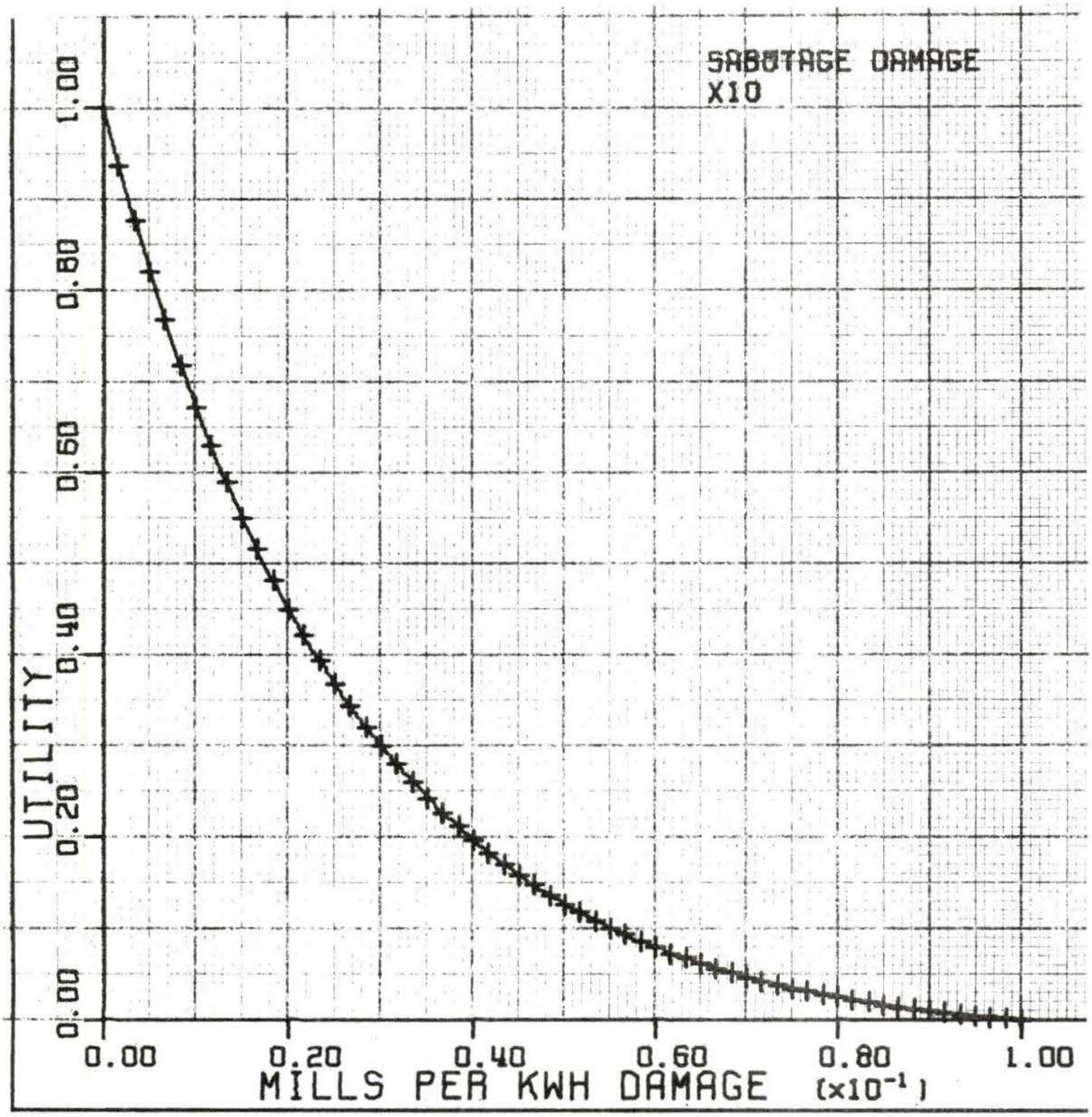


Figure 11. Component utility function for sabotage damage

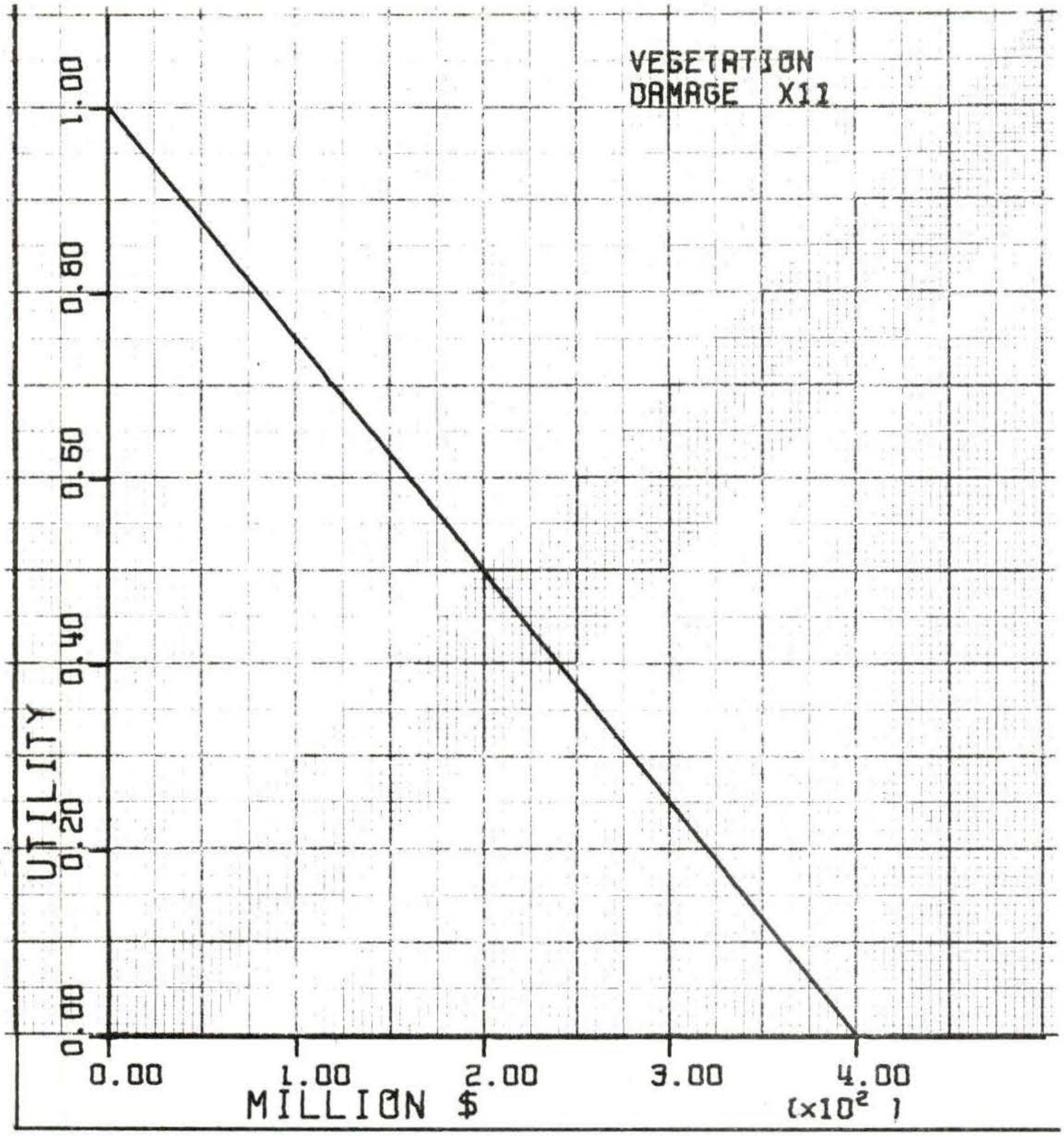


Figure 12. Component utility function for vegetation damage

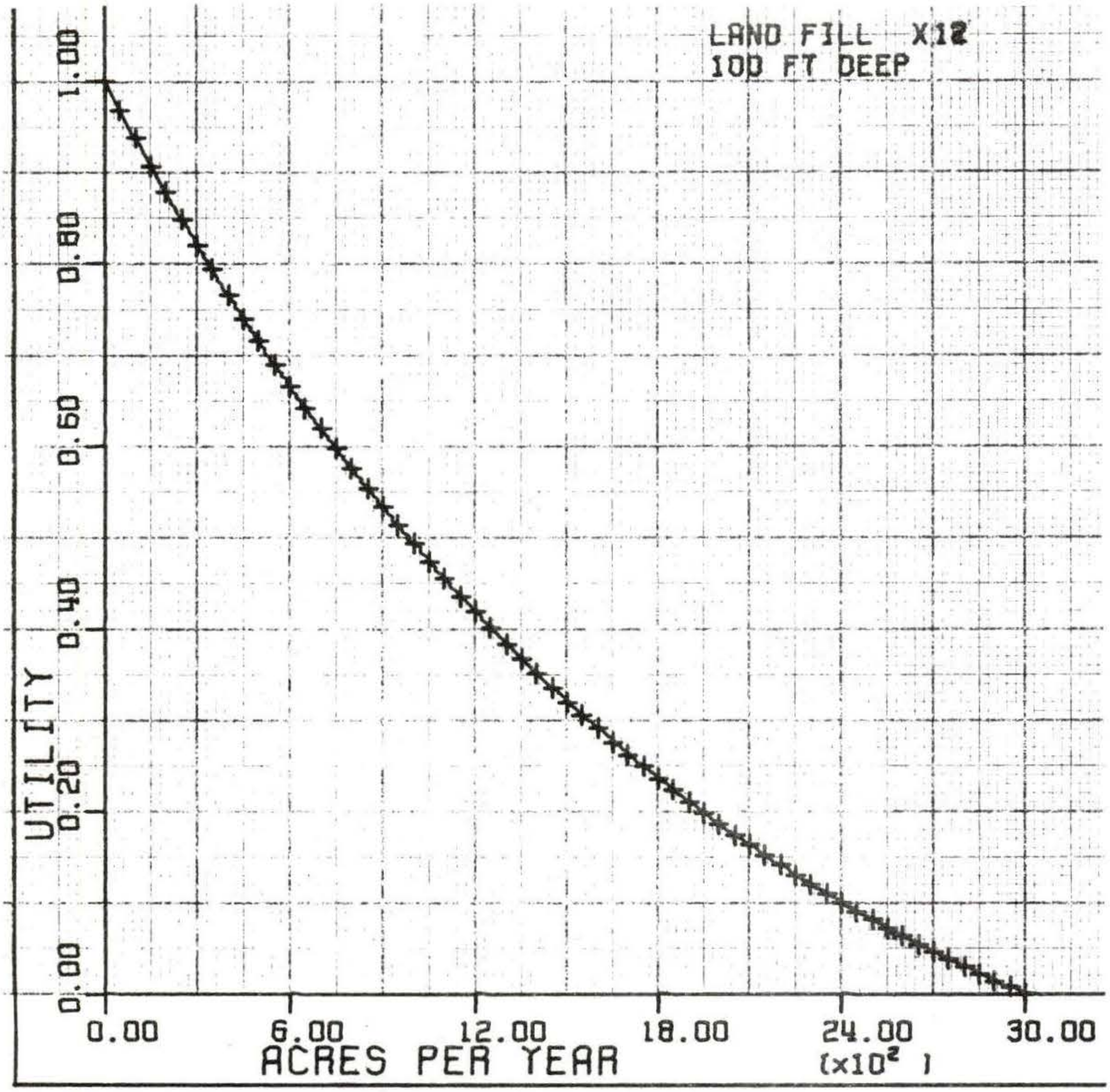


Figure 13. Component utility function for land fill

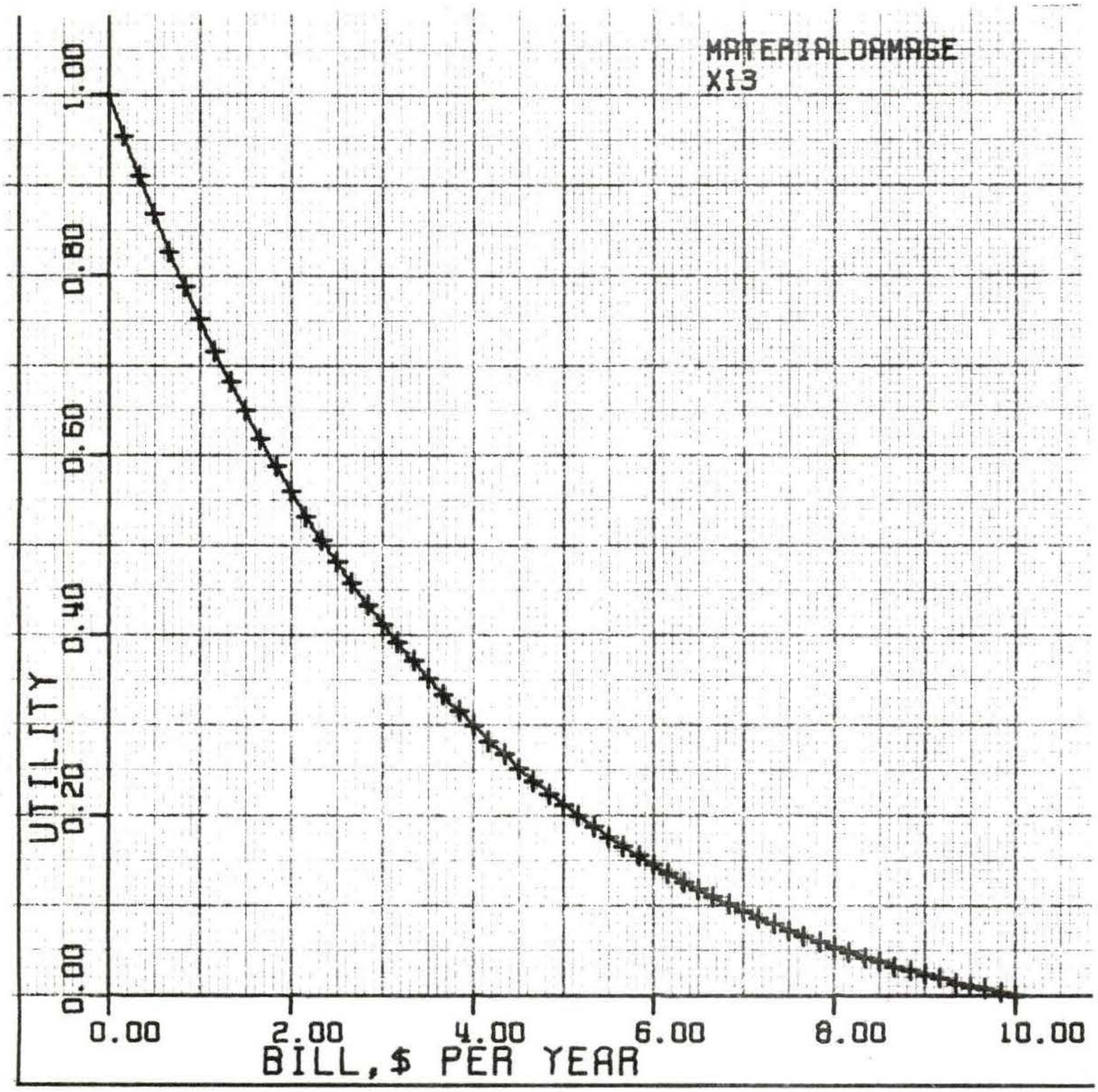


Figure 14. Component utility function for material damage

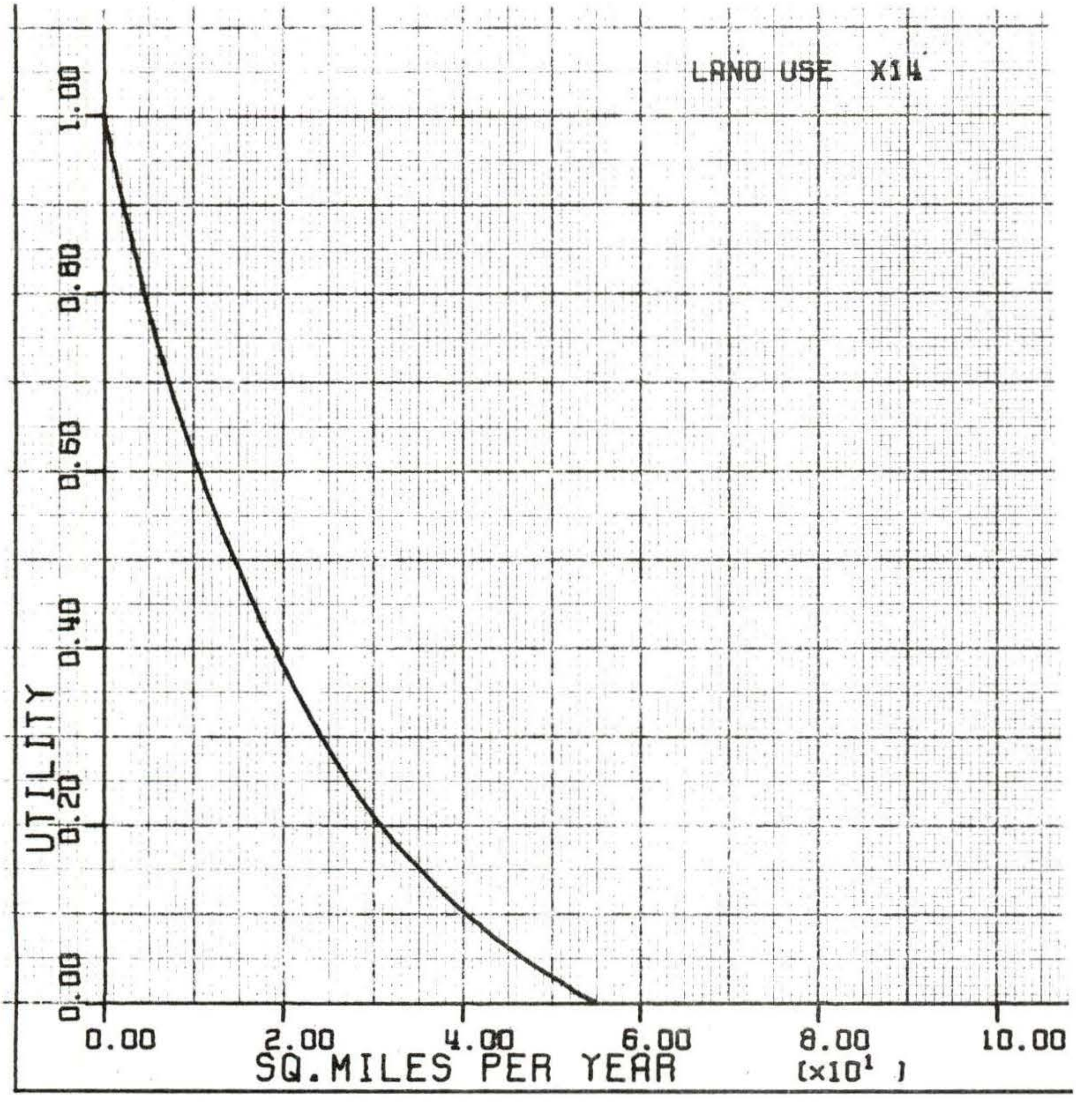


Figure 15. Component utility function for land use

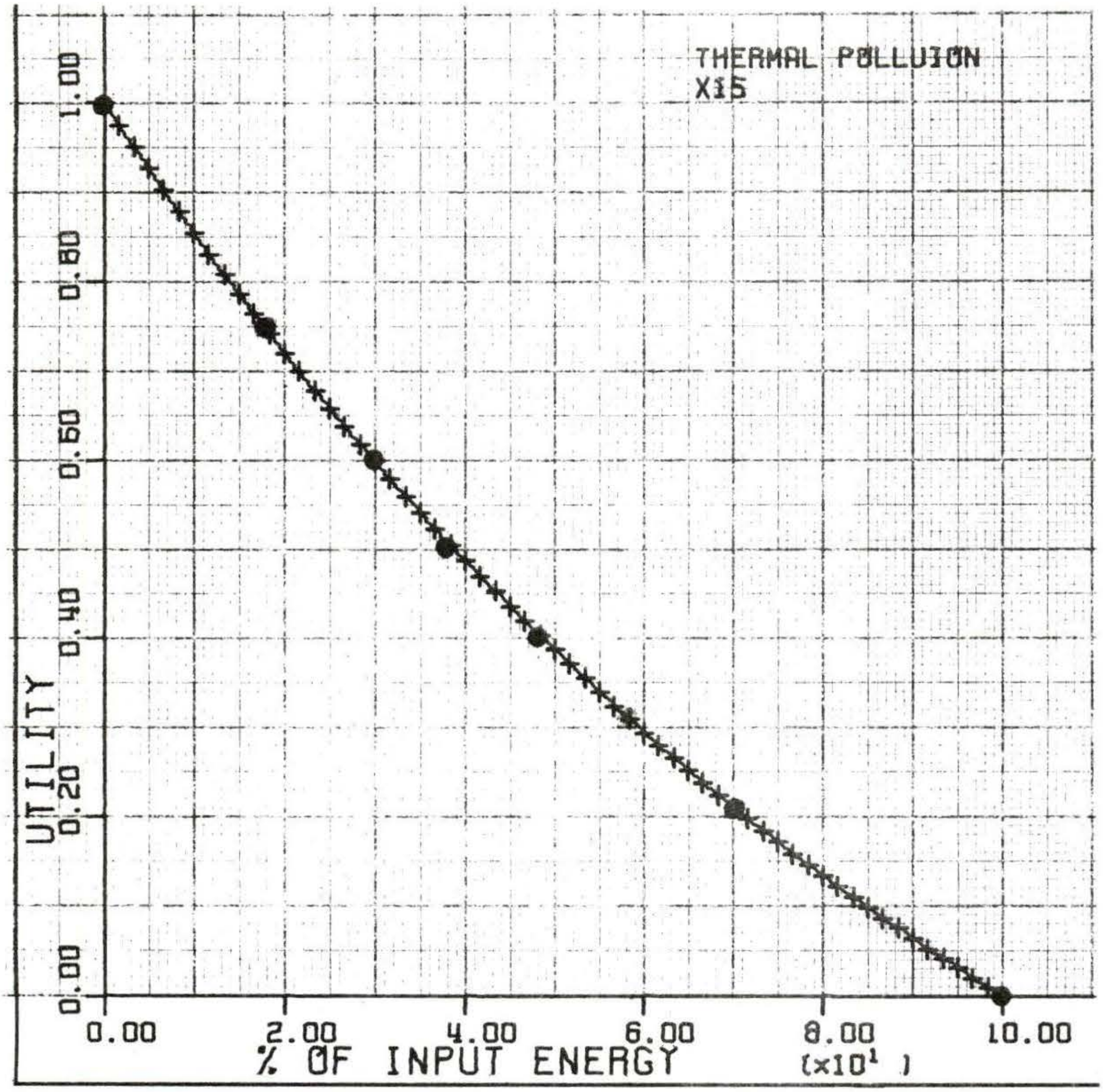


Figure 16. Component utility function for thermal pollution (percentage of input energy dumped into water)

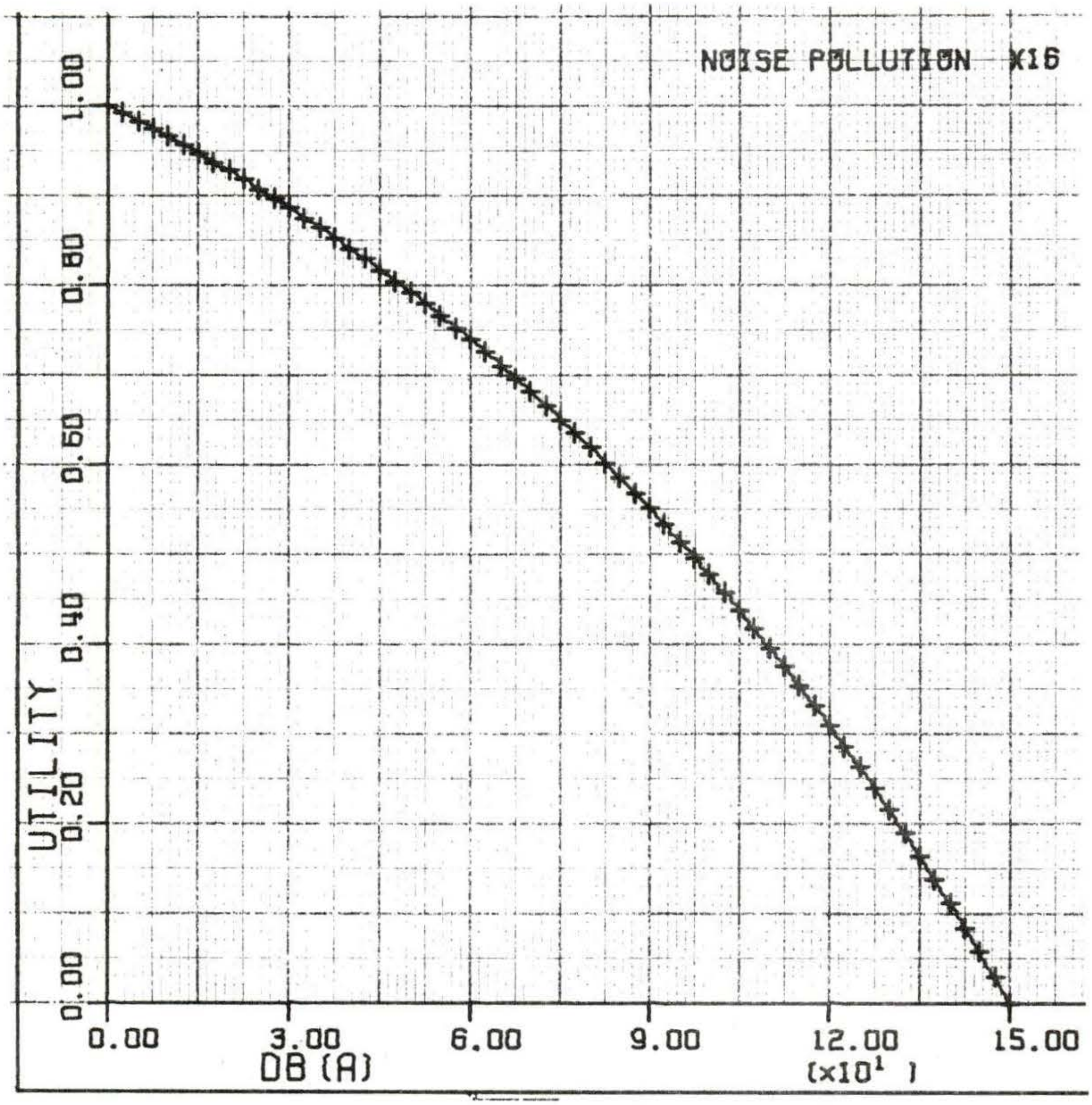


Figure 17. Component utility function for noise pollution

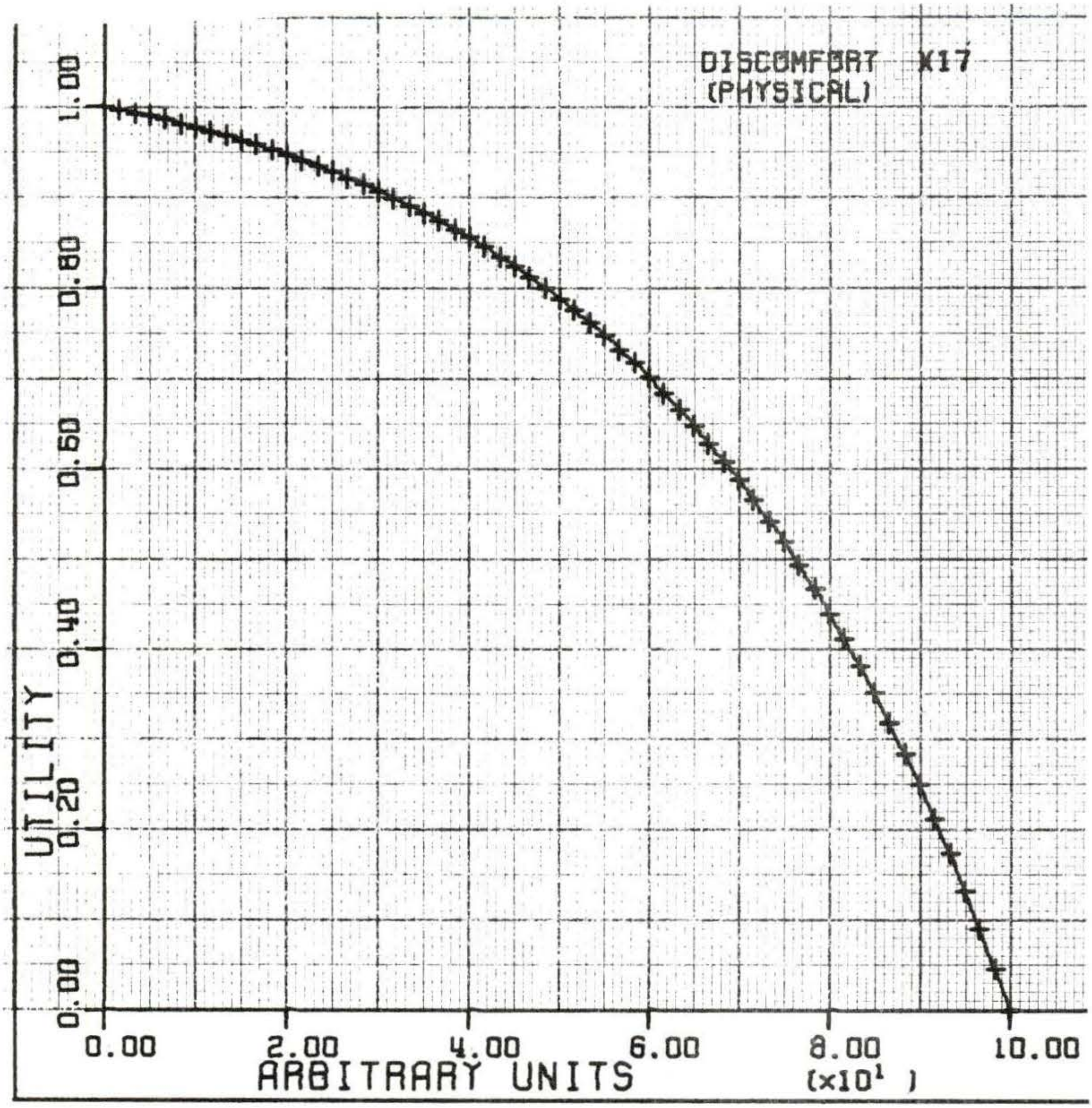


Figure 18. Component utility function for physical discomfort

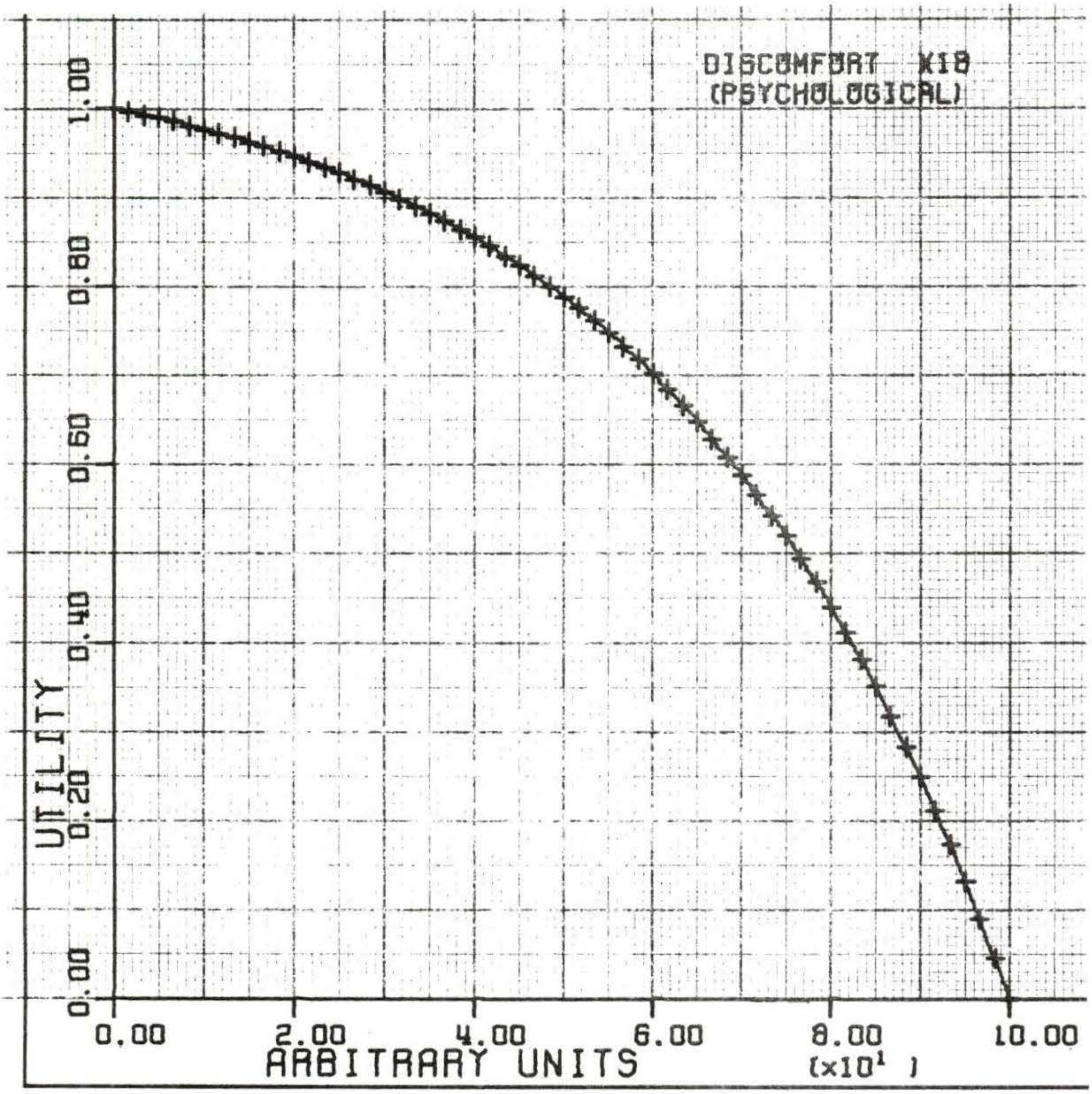


Figure 19. Component utility function for psychological discomfort

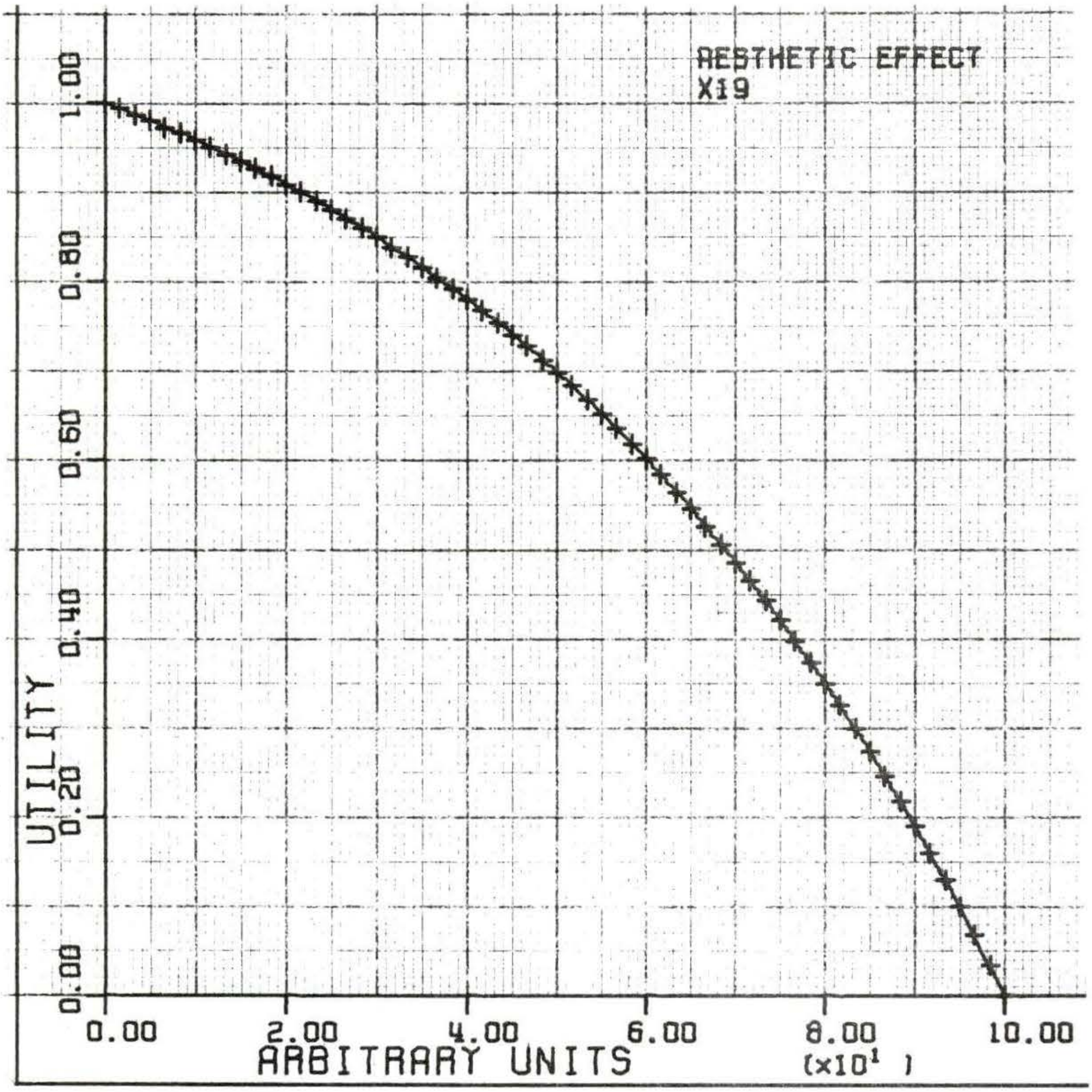


Figure 20. Component utility function for aesthetic effects

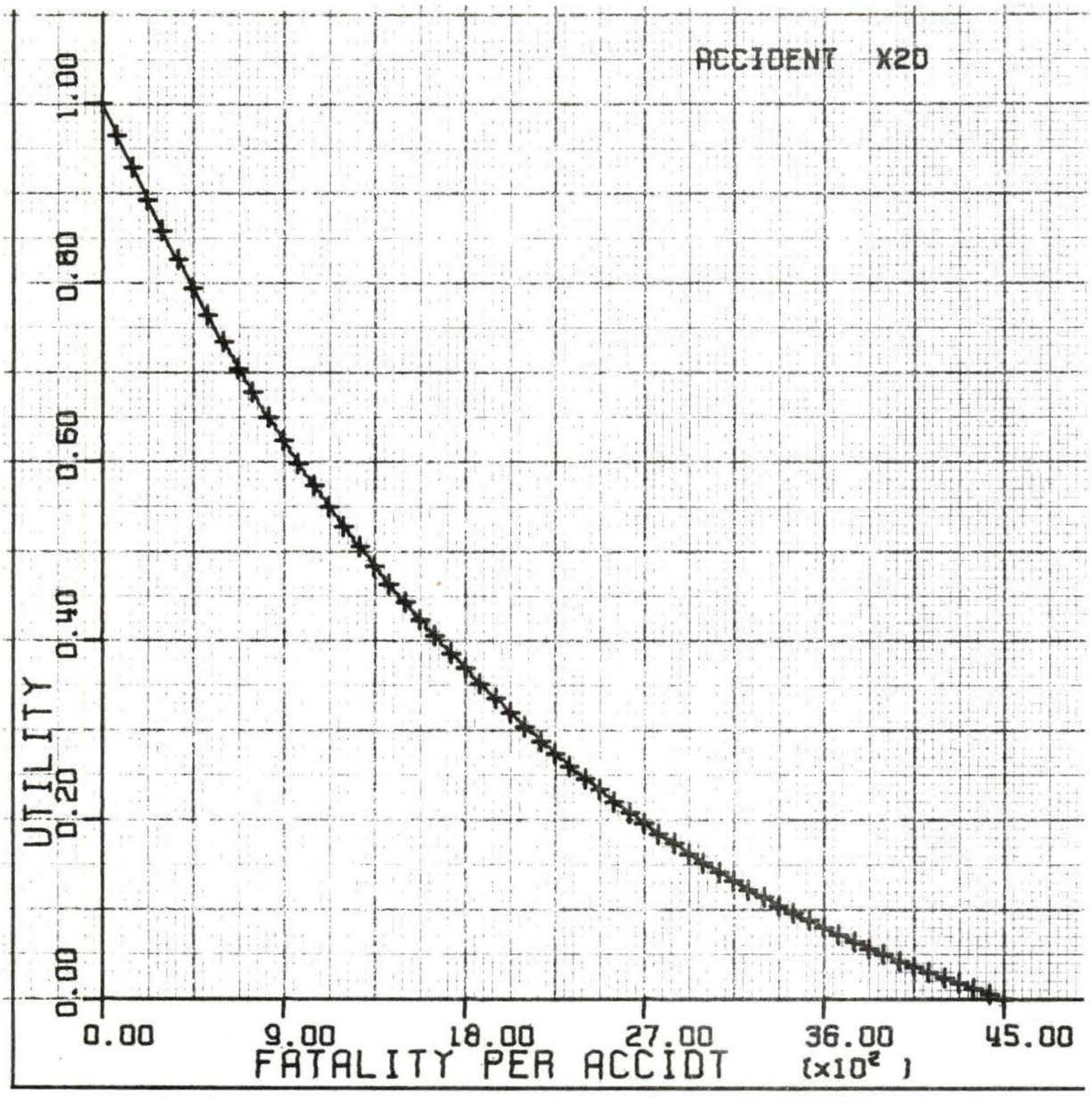


Figure 21. Component utility function for accident

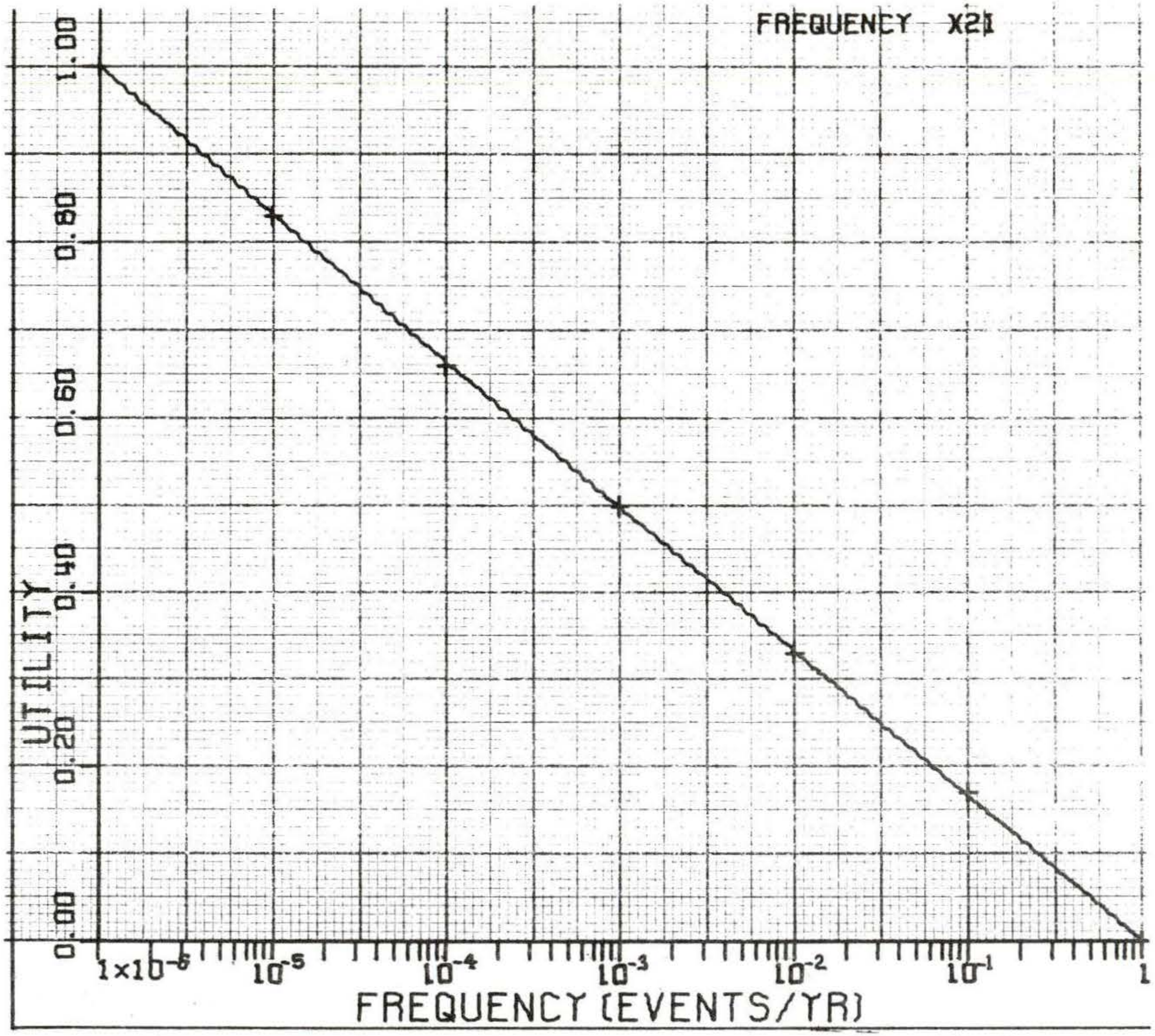


Figure 22. Component utility function for frequency of accidents

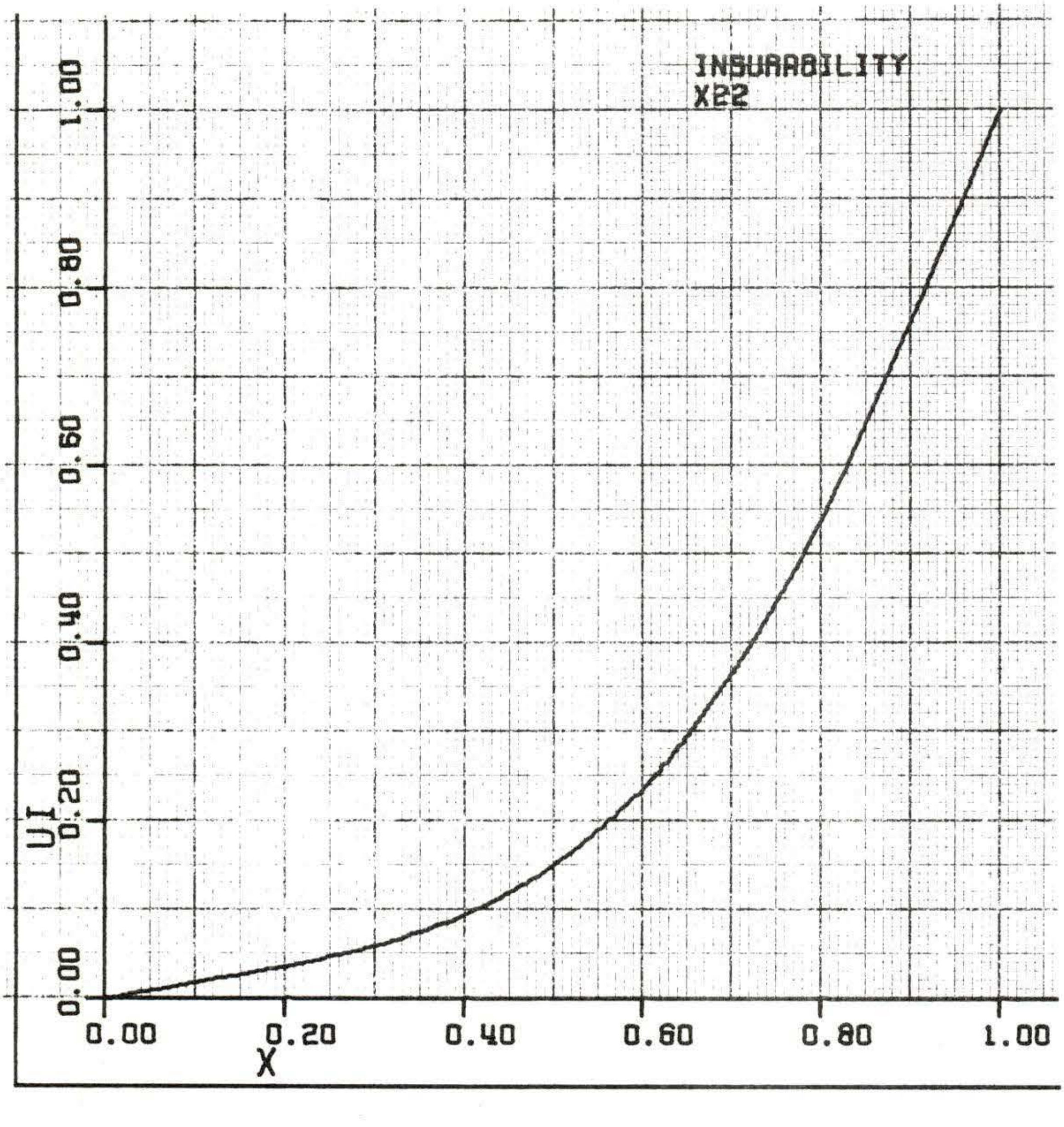


Figure 23. Component utility function for insurability in case of accident

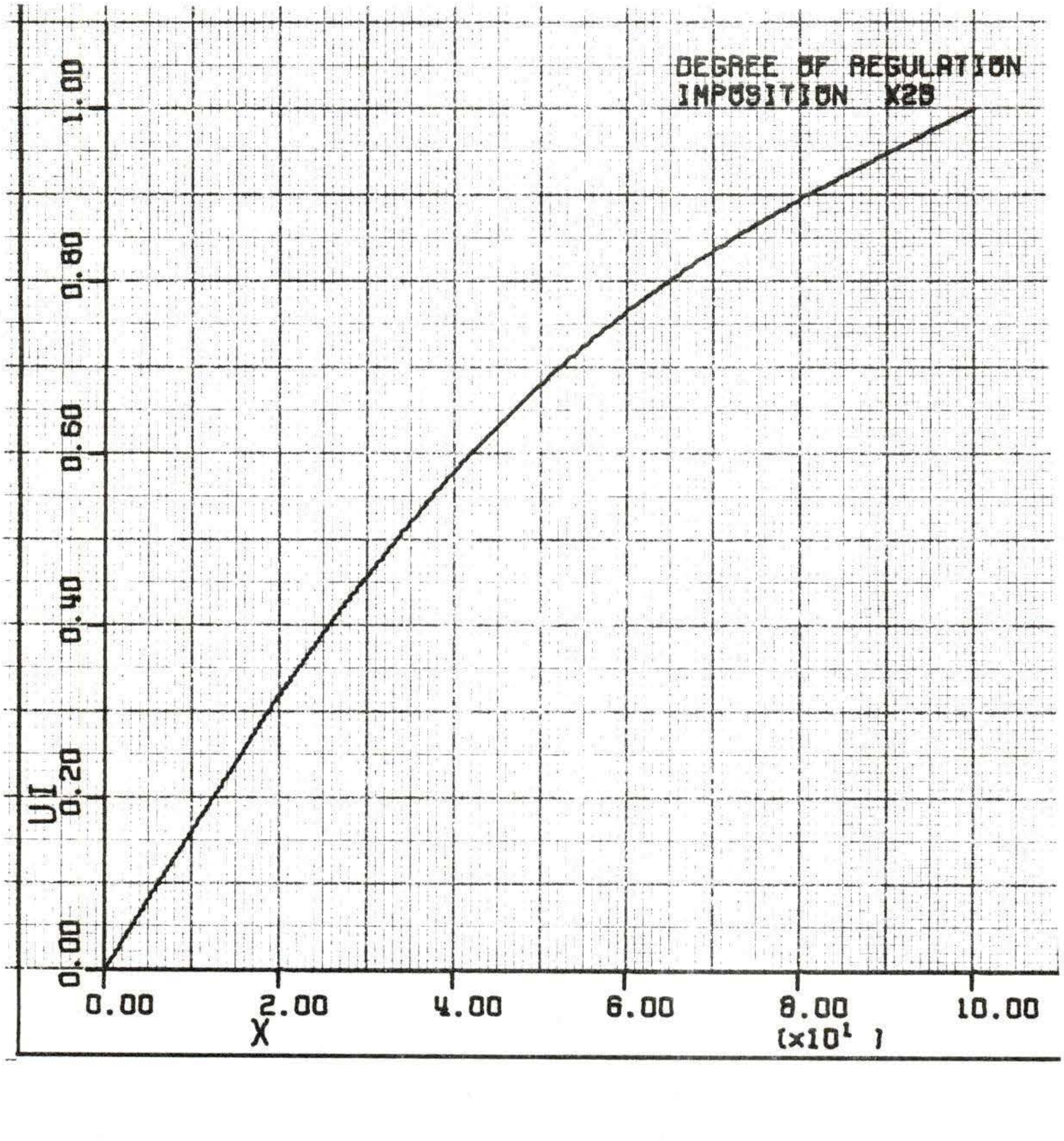


Figure 24. Component utility function for degree of regulation imposition

CHAPTER VIII. ASSESSMENT OF SCALING FACTORS, k_i

To illustrate the technique for assessing the k_i, scaling factor, let us take fuel supply (x_9) as an example. We compared a consequence with fuel supply at its most preferred amount, and all the attributes at their least preferred amount, to a lottery yielding the consequence with all attributes at their most preferred amount with probability p or the consequence with all attributes at their least preferred amount with probability (1-p). The object is to find a value p_1 of p such that the decision maker is indifferent between the lottery and the consequences. This utilizes Raiffa's "Indifference probability procedure" (6) which can be expressed, in general, as follows:

Let X^* and X_* denote the best and the worst possible outcomes, respectively, and let X_i be any other outcome. Arbitrarily, we set

$$U(X^*) = 1$$

and

$$U(X_*) = 0.$$

To assign a utility to outcome $(X_i^*, X_{i\bar{*}})$ i.e., the consequence when x_i is at the most preferable amount and all the other attributes at their least preferable amount, the decision-maker must specify a probability p_i such that the lottery represented by Figure 25 is satisfied. The summary of the symbols used in Figure 25 and subsequently in Figure 26 are given in Table 3.

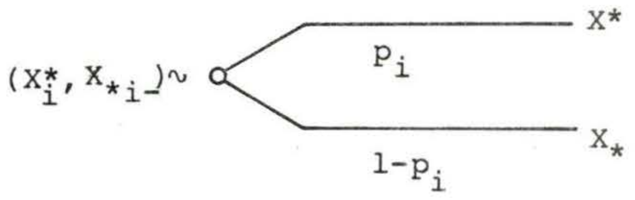


Figure 25. Lottery to determine the indifference probability p_i

Table 3. Summary of the symbols for scaling factor lottery

Symbol	Explanation
x_i^*	ith attribute raised to its best level
x_i^*	ith attribute at its worst level
x_{i*}^-	All other attributes except ith attribute at their worst level
p_i	Probability of getting all attributes at their best level for the lottery pertaining to the ith attribute
k_i	Scaling factor for the ith attribute
$\sim$	Indifferent to

Assuming the decision-maker is an expected utility maximizer,

$$U(X_i) = p_i U(X^*) + (1-p_i) U(X_*) = p_i .$$

Thus, the indifference probability p_i provides an appropriate utility measure. It can be easily shown (12) that k_i must be equal to p_i.

It is, however, advisable in assessing the k_i to order their magnitude. To do this, we set all 23 attributes given in Table 1 at their worst levels, and asked, "if only one could be raised to its best level, which one would be preferred?" The response was attribute X_1. This implied that k_1 must be the largest of k_i. Had there been indifference between moving either X_i or X_j to its best level, then k_i would equal k_j (15). After several adjustments, the result is in the following order

$$k_2 = k_{21} = k_{22} > k_9 > k_4 > k_8 > k_3 = k_1 > k_5 >$$
$$k_6 = k_7 > k_{17} > k_{10} = k_{16} > k_{18} = k_{19} > k_{11} > k_{20} >$$
$$k_{12} > k_{24} > k_{13} > k_{14} > k_{23}$$

After relative scaling factors had been established among k_i, their numerical values were calculated. The lottery for each is given diagrammatically in Figure 26 for a better understanding.

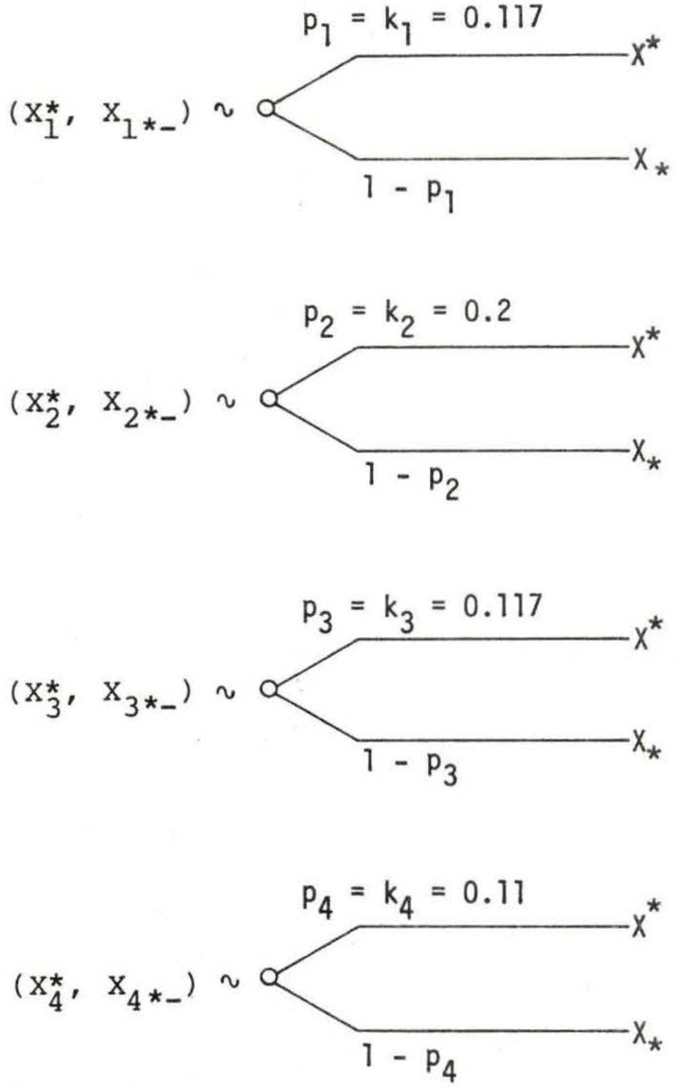


Figure 26. Lotteries for determining the component scaling factors, k_i

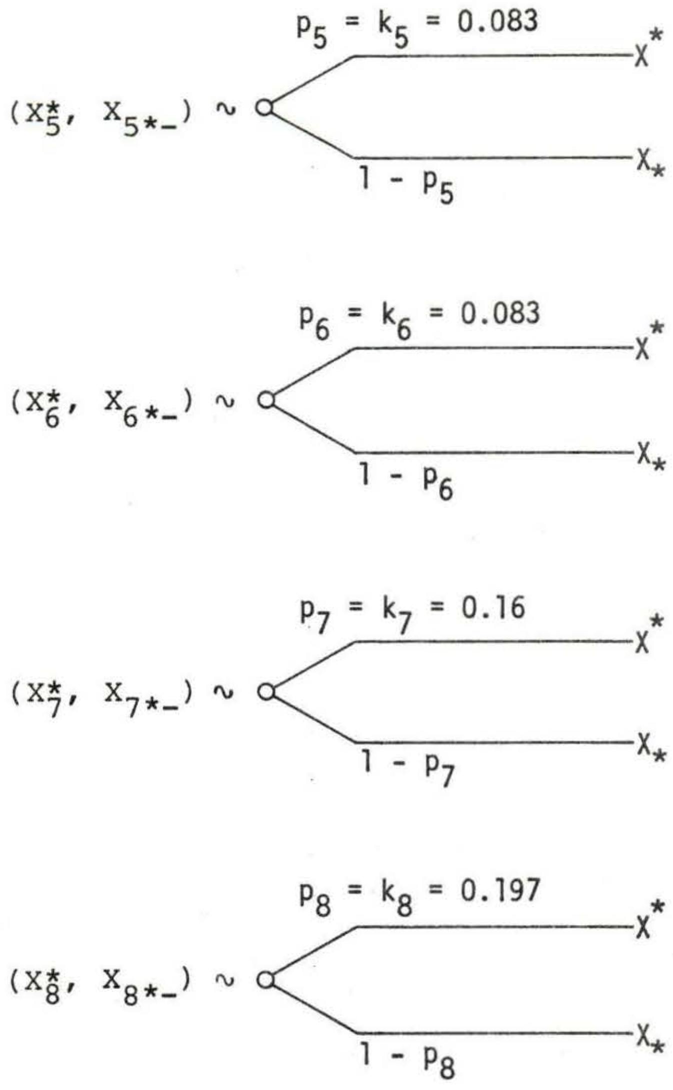


Figure 26 (Continued)

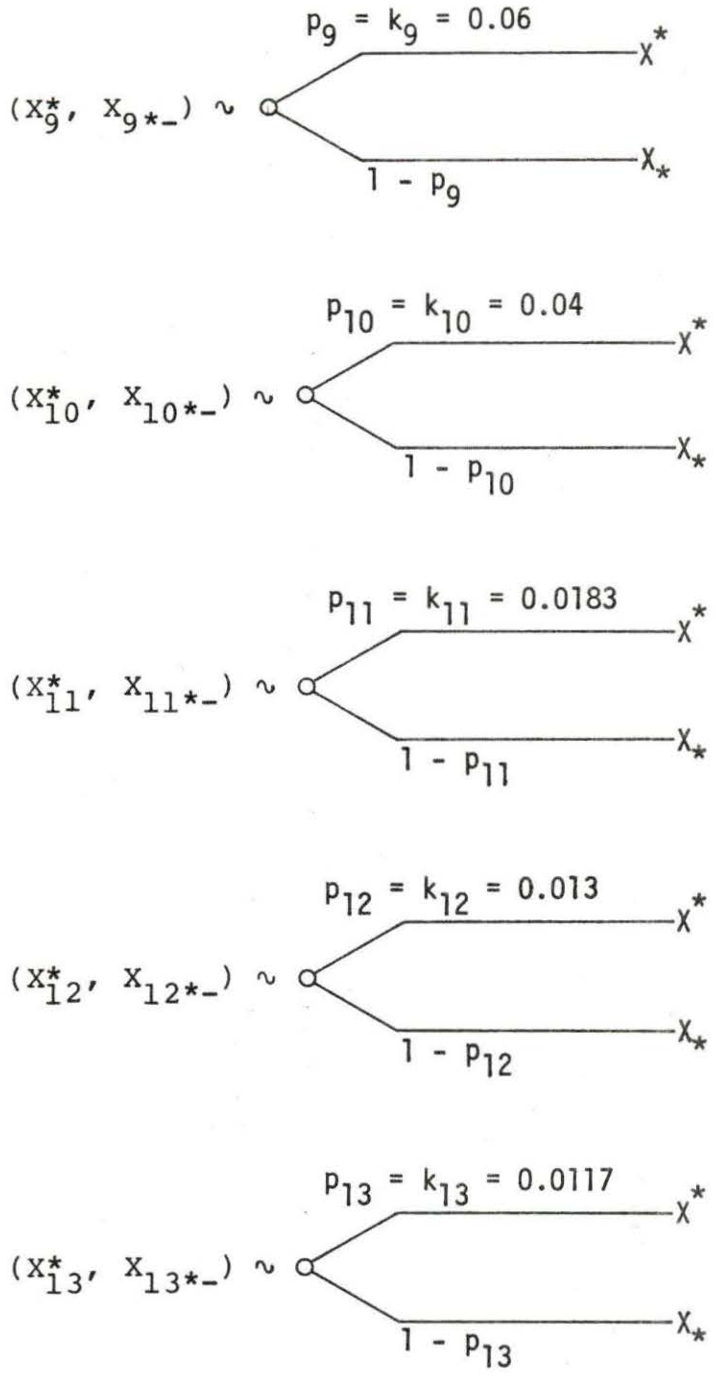


Figure 26 (Continued)

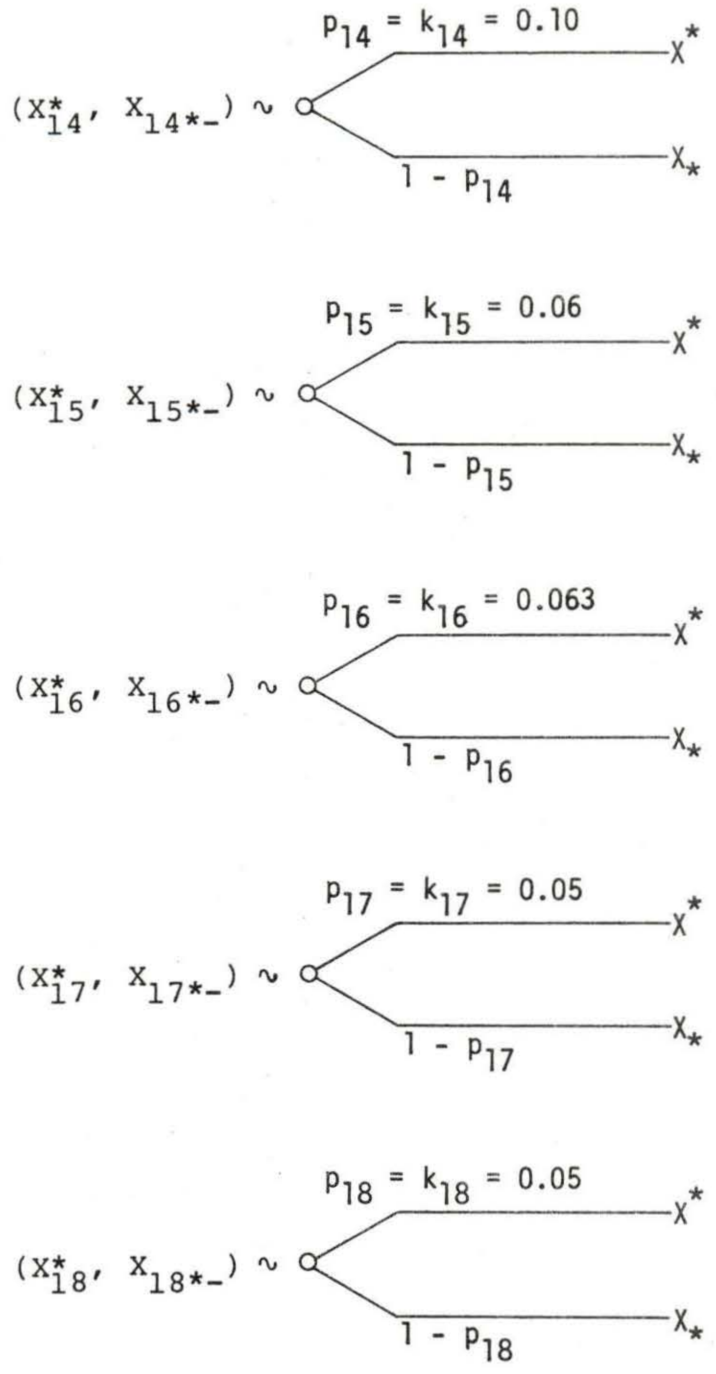
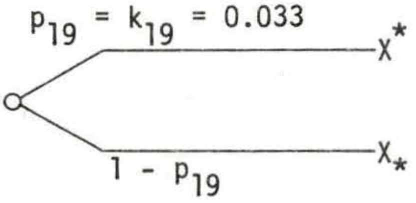
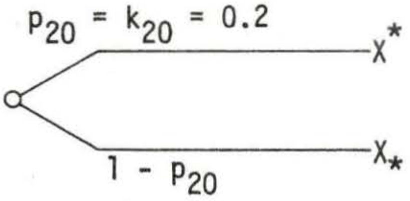


Figure 26 (Continued)

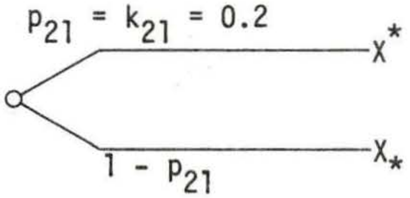
$(X^*_{19}, X_{19*-}) \sim$



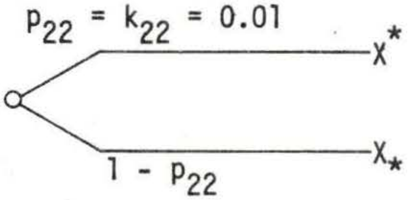
$(X^*_{20}, X_{20*-}) \sim$



$(X^*_{21}, X_{21*-}) \sim$



$(X^*_{22}, X_{22*-}) \sim$



$(X^*_{23}, X_{23*-}) \sim$

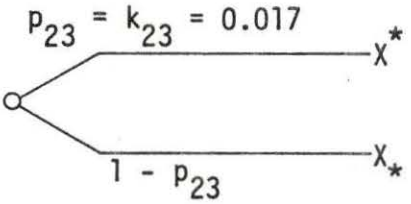


Figure 26 (Continued)

Assessing Parameter K

Since the sum of k_i is greater than one, we know the utility function is multiplicative rather than additive, is is additive only if $\Sigma k_i = 1$. Therefore, the value of K in Equation 2 must be determined by evaluating it at $(x_1^*, x_2^*, \ldots, x_{23}^*)$ where x_i^* is the most preferred amount of X_i. This gives us

$$KU(x_1^*, x_2^*, \ldots, x_{23}^*) + 1 = \prod_{i=1}^{23} [Kk_i u_i(x_i^*) + 1].$$

But

$$u(x_1^*, x_2^*, \ldots, x_{23}^*) = 1$$

and

$$u_i(x_i^*) = 1.$$

Hence,

$$K + 1 = (Kk_1+1)(Kk_2+1) \; . \; . \; . \; (KK_{23}+1).$$

Since

$\Sigma K_i > 1$, it can be shown (12) that

$$-1 < K < 0 .$$

By a simple computer program using iterative procedure we obtained

$$K = -0.77 .$$

CHAPTER IX. EVALUATION OF ATTRIBUTE LEVELS FOR EACH ALTERNATIVE

The attribute levels or the degree to which a particular alternative contributes in evaluating the utility function is given in Table 4.

The calculation and sources from which these levels have been chosen are being given in the following paragraphs. Care has been taken to represent the levels within reasonable range. Although in many of the cases these levels are subjective, we believe the levels are representative of the "true" situation.

X_1 Fatality (occupational):

Lave and Freeburg (16) investigated the data for 1969 when 54.3% of mined coal was used to generate 705 million MWh of electrical power, and about 3.06% of the mined uranium was used to generate 14 million MWh of nuclear power. There were 8 fatalities in uranium mining (plus an average of 1 fatality in 5 years in uranium ore milling). Since 1909, no less than 88,000 miners have died in American coal mines, and even now there are some 200 fatal accidents per year in coal mines, plus another 100 in transporting the coal to power plants. The average number of fatal coal mining accidents for 5 years 1965-1969 was 246 per year (17).

Table 4. Attribute levels for alternative systems

Attribute	Alternative Systems			
	I[a]	II[a]	III[a]	IV[a]
X_1	388.0	20.0	14752.0	0.40
X_2	40.0	0.02	0.001	7.50
X_3	1000.0	20.0	0.10	1.90
X_4	4470.0	4470.0	1490.0	894.0
X_5	1639.0	157.0	2640.0	282.0
X_6	0.80	0.05	0.80	0.50
X_7	31.0	30.0	60.0	30.0
X_8	420.0	60.0	1000.0	100.0
X_9	0.0	0.004	0.004	0.0
X_{10}	0.002	0.047	0.534	2×10^{-6}
X_{11}	120.0	0.0	0.0	0.0
X_{12}	2124.0	3.5	1.5	1.0
X_{13}	4.75	0.0	0.0	0.6
X_{14}	23.0	2.0	50.0	1.5
X_{15}	46.0	67.0	85.0	75.0
X_{16}	30.0	10.0	10.0	70.0
X_{17}	80.0	10.0	20.0	50.0
X_{18}	15.0	90.0	0.0	5.0
X_{19}	80.0	5.0	10.0	10.0
X_{20}	2450.0	1000.0	1000.0	280.0

[a] I = coal, II = nuclear, III = solar, IV = geothermal.

Table 4 (Continued)

Attribute	Alternative Systems			
	I^a	II^a	III^a	IV^a
X_{21}	0.17	10^{-6}	10^{-4}	0.02
X_{22}	1.0	0.0	0.50	1.0
X_{23}	40.0	100.0	30.0	60.0

From these figures we calculate for mining the death per billion MWh electrical generation for coal fired plants to be 189 and for nuclear power plants to be 18 (Table 2). For coal transportation the figure is 199. This is considering 75% plant capacity factor with 1.3 deaths per 1000 MWe-year plant (18). The transportation death for nuclear power plants are comparatively very small and can be safely neglected.

The fatality in case of solar energy utilization would depend heavily on falls from the roof tops, where the facilities are likely to be installed. We assume 10% of the population using solar cells for an "all solar system", the probability of fall 1 in 1000 climbs, 5 persons utilizing the facility installed per house and that for cleaning and maintenance purposes two climbs are necessary per month. Then death per million MWh was calculated to be 14,752.

The fatality due to transporting the solar cell equipment to the individual houses was calculated by the following assumptions. Transportation distance from the factory to individual houses is 400 miles, and accident rate 3.4×10^{-6} death/mile-year. Total death comes to 5,440.

X_2 Chronic effect (public):

For coal-fired plants, the number of excess deaths due to respiratory disease is between 20 and 100 per 1000 MW coal-fired plant per year (19). In (20) the figures are 40-100 excess deaths per 1000 MW coal-fired plant per year. Figures of the same order are in (16) and (21).

A figure of 40 excess deaths/year for a 1000 MW plant per year appears to be reasonable.

Estimate of cancer deaths from various causes including those of a U.S. nuclear industry of 300 power plant sites by the year 2000 is 3 deaths/year. Then death per 1000 MW plant per year was estimated to be 0.02 (22, 23).

X_3 Chronic effect (occupational):

For coal we take 1000 deaths by Black Lung among coal miners per billion MWh of electrical energy consumed (24).

For nuclear we consider 20 deaths by excess lung cancer among uranium miners (24).

Cohen assumed that the wastes from a fully nuclear U.S.

electrical capacity were to be buried at depth of 2,000 ft., utterly at random - perhaps under children's schools, water supplies or any other place where blind chance happened to put them. The results of Cohen's calculations, are based on what natural radioactive deposits are known to do, give the expected (average) number of eventual deaths per year: 1.1 deaths for the first 200 years, declining to 0.4 deaths thereafter (25).

The mean number of Americans killed by ingesting uranium or its daughters from natural sources is 12 per year (25).

X_4 Employment:

For coal-fired and nuclear power plants, for each 1 million MW increase in the production of electrical energy, the increase in employment is estimated to be 4,470 (26).

For solar plants we estimate that solar power increase by the same amount would have only 1/3rd impact on employment compared to that of nuclear or coal-fired plants. The reasons are that: a) the solar power plants have to be off-sited and difficult to build at load centers which means less capability to support large industrial load, and b) it has the inherent defect of being dependent on the climatical and geographical conditions.

For geothermal power plants the impact on employment was estimated to be only 1/6th as that of coal or nuclear power plants.

X_5 Disability:

For coal the injury from mining is taken to be 1545 disability days among coal miners for coal-fired plants per million MW of electrical energy consumed (18). Also the injuries from transportation is 94 disability-days. We consider 1639 injuries per million MWh (27).

For nuclear we take 157 disability days among uranium miners per million MWh of electrical energy consumed.

According to the assumptions made earlier, the disability-days per billion MWh electrical production comes out to be 2640 for solar power plants.

X_6 Global temperature change:

For coal-fired plants we consider total increase in temperature of the atmosphere as 0.8°F due to joint effect of CO_2 and dust loading from human activity, for 20 years as density time for dust loading (28, 29).

We estimate nuclear to have little impact (0.05°F) on global temperature change, due to the absence of both carbon dioxide and particulate emission.

In solar plant cases, because of its very low efficiency, the impact could be considered to be at least as high as coal-fired power plants.

X_7 Average outage of power plants:

The average outages considered for different power plants are as follows (30):

coal 31%, nuclear 30%, solar 60%, geothermal 30%.

X_8 Fuel supply (from 1980):

The fuel supply situation we favored are as follows (30):

coal - 420 years
nuclear - 60 years
solar - nondepletable
geothermal - 100 years

X_9 Diversion:

For coal power plants the social cost for diversion in this case is estimated to be almost negligible.

For nuclear power plants computing expected values yields an expected annual loss from plutonium diversion of \$2.5 million per year, or \$25,000 per reactor year. This is roughly 0.004 mills/KWh (30).

The social cost of diversion for 100 solar plants each 1000 MW was calculated (from the event tree in Figure 27), to be 0.0045 mills/KWh.

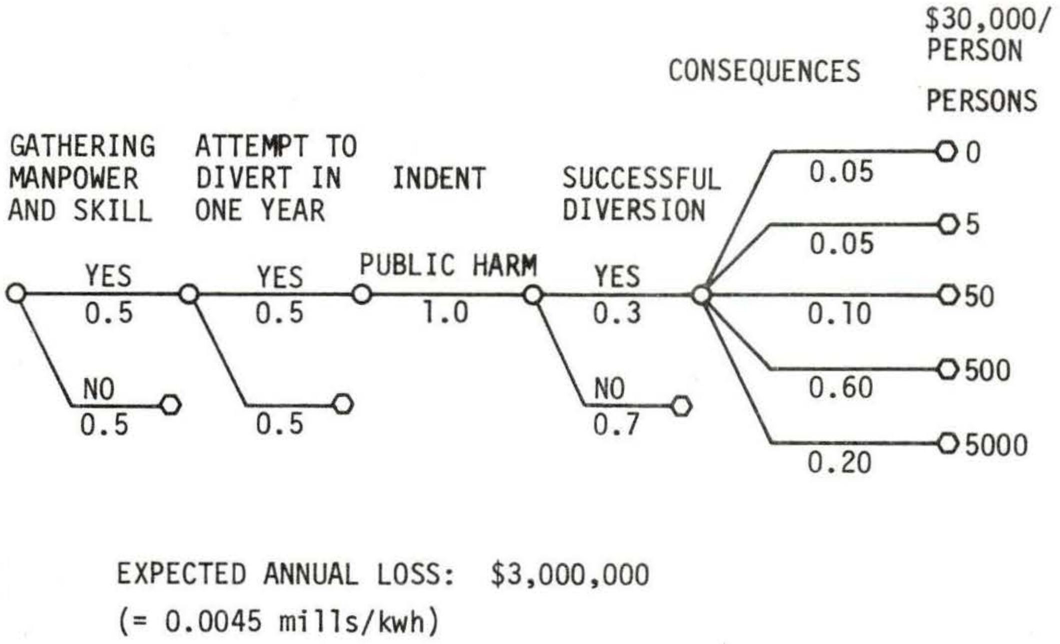


Figure 27. Illustrative model for solar diversion for 100 solar power plants each of 1000 MW

The microwave transmission to earth from the satellite may be "diverted" to a population which can cause disaster. This diversion can be done electronically by wave interference or by sending proper wave signals to the satellite. The potential damage is enormous and the capability required to cause this harm may not be great. A group of people with adequate electronic skill can do it even though they are far away from the territory. What is more important is that they can do it without much risk and can remain unknown and at large after the harm is done.

X_{10} Sabotage:

To evaluate the social cost of sabotage for coal-fired plants, the event tree shown in Figure 28 is developed.

Total expected annual loss for 100 coal-fired power plants is $1,300,000. This gives social cost of sabotage as 0.002 mills/KWh.

The social cost of sabotage for nuclear fuel cycle element calculated in (30) is 0.045 mills/KWh.

The social cost of sabotage for solar power plants was estimated from the event tree developed, Figure 29, and was found to be 0.534 mills/KWh.

The social cost of sabotage for geothermal power plants was calculated by the event tree developed, Figure 30, and was found to be 2×10^{-6} mills/KWh.

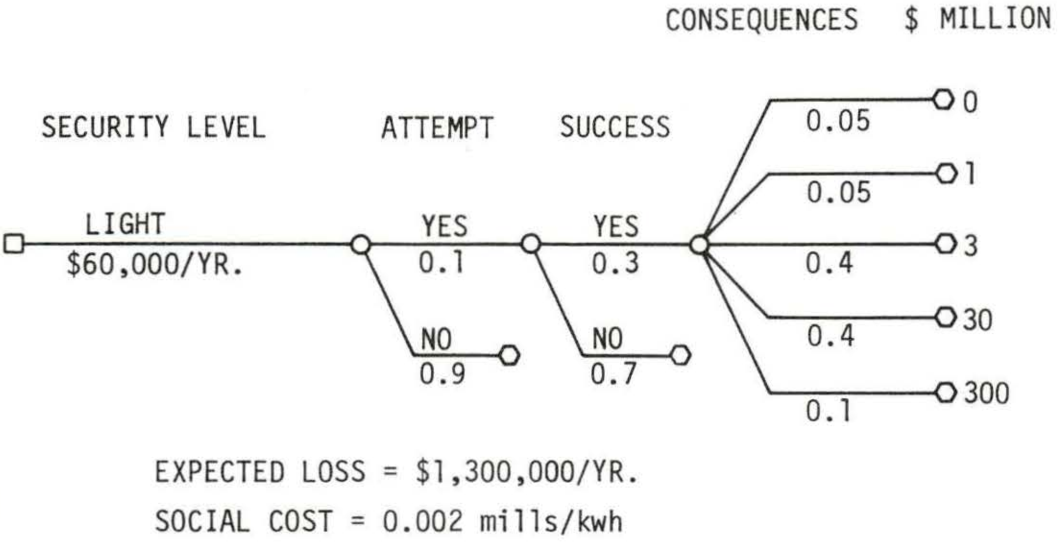


Figure 28. Illustrative model of coal-fired plant sabotage (100 plants)

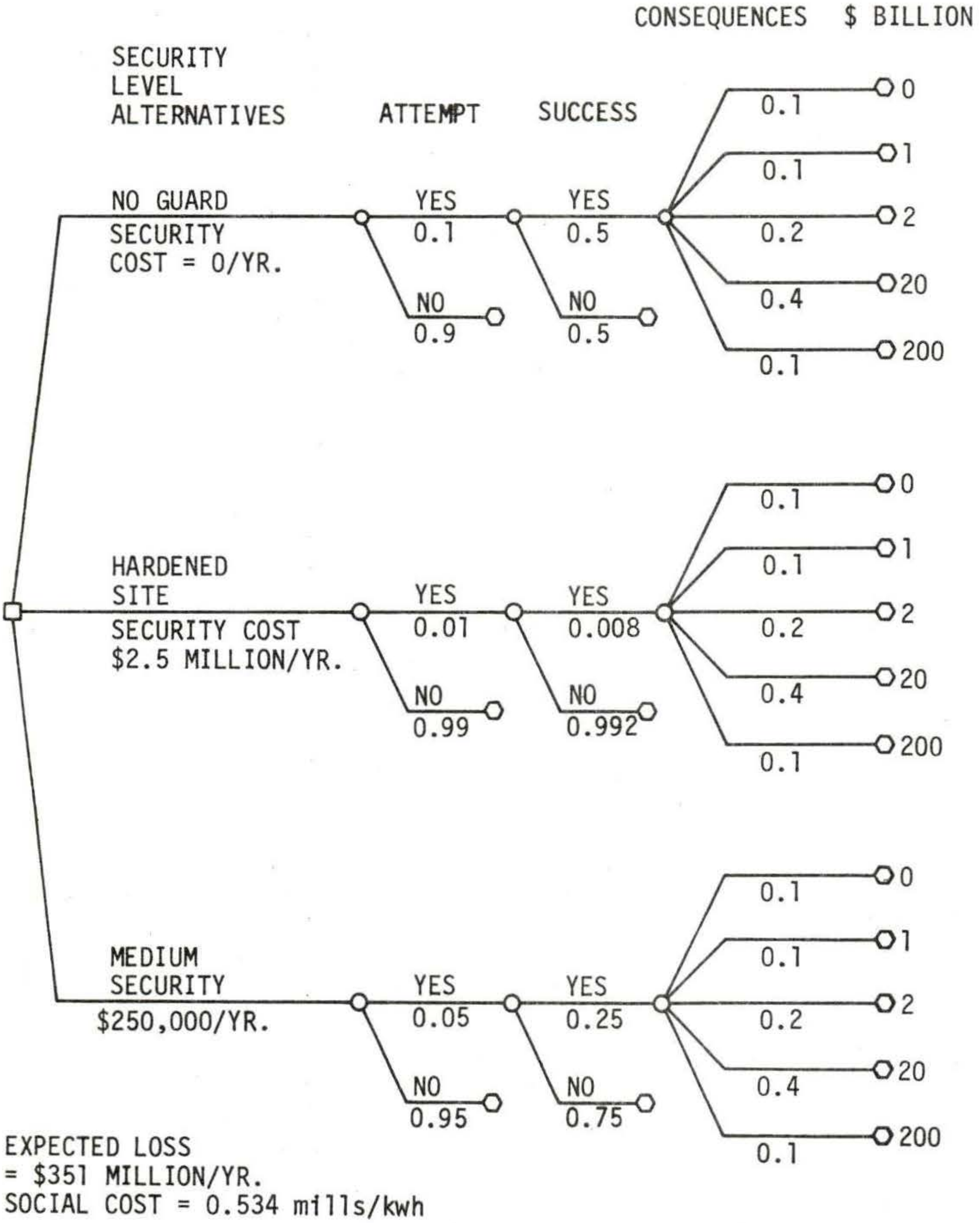


Figure 29. Illustrative model of solar power plant sabotage (100 plants)

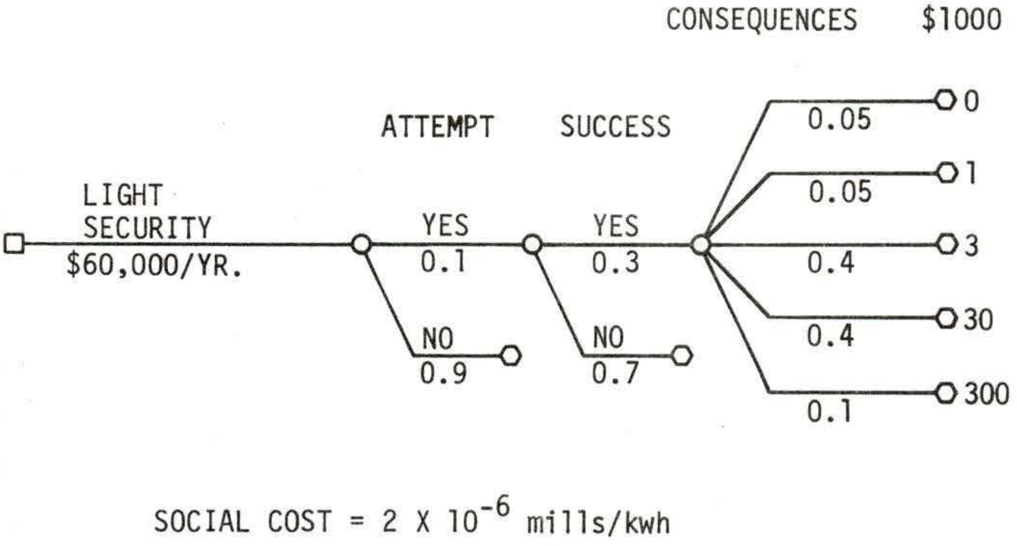


Figure 30. Illustrative model of geothermal power plant sabotage (100 plants)

X_{11} Vegetable damage:

It was estimated in (31) that average social cost of vegetable damage for coal-fired plants is $120 million per annum.

Nuclear, geothermal and solar power plants were considered to have negligible effect on vegetable damage.

X_{12} Land fill:

Coal: Current production (assuming 15% waste from extraction and cleaning, and 15% ash content) would yield 1/6th billion tons of waste per year in providing 25% of current U.S. energy needs. This would cover 1000 acres to a depth of 100 feet annually (32).

Hence for 53.1% energy demand we calculate land fill as 2124 acres surface area and 100 feet deep.

Nuclear: For a nuclear plant of 1000 MW capacity, the annual amount of solid discharge can be taken away in 60 truckloads. If 1000 MW plant is coal-fired, the annual amount of ash taken from the plant to the dump amounts to not less than 36,500 truckloads (17).

Hence from the ratio 60/36500, we get land fill for nuclear plant as 3.5 acres surface area and 100 feet deep.

X_{13} Material damage:

For coal, material damage due to SO_2, NO_x and particulates has been estimated in (31), to be $4,752 million per year.

We consider no material damage due to nuclear or solar plants, while that due to geothermal plant is taken as 0.6 billion dollars due to hydrogen sulfide gas (31).

X_{14} Land use:

The annual environmental impact of coal in land use for 1000 MW coal-fired plant (load factor 75%), is 9,120 acres if coal is deep-mined, and 14,010 acres if it is surface-mined; plus, 161 acres for processing, 2,213 acres for transport, and 696 acres for conversion (including 117 acres for ash storage, 13 acres for coal storage, and land effected by thermal discharges). About half of U.S. coal is surface-mined, so that the grand total is 14,635 acres (17).

For a nuclear plant with the same power and load factor, the annual acreage used in mining is 785 acres, 314 acres for conversion, 9.19 acres for processing, and acreage used for transportation is almost negligible (17).

The average size of a solar electric power plant of 1000 MW capacity would be anywhere between 15 to 50 sq. miles depending upon its design and efficiency.

X_{15} Thermal pollution:

The thermal-pollution is considered here in terms of the percentage of waste heat dumped in water. They are as follows:

coal - 46%
nuclear - 67%
solar - 85%
geothermal - 75%

X_{16} Noise pollution:

Noise pollution levels used were as follows (33):

coal - 30 dB(A)
nuclear - 10 dB(A)
solar - 10 dB(A)
geothermal - 70 dB(A)

X_{17} Discomfort (physical):

In this case a subjective unit of 0 to 100 was used which, in our judgement, are as follows:

coal - 80
nuclear - 10
solar - 20
geothermal - 50

X_{18} Discomfort (psychological):

Again the unit is subjective, 0 to 100.

coal - 15
nuclear - 90
solar - 0
geothermal - 5

X_{19} Aesthetic effect:

Here also a subjective unit was used:

coal - 80
nuclear - 5
solar - 10
geothermal - 10

X_{20} Accident:

Coal: The intense air pollution "episodes" which occurred in areas such as Belgium's Meuse Valley (1930); Donora, Pennsylvania (1948); London (1952) -- 4000 deaths; and New York City (1953, 1963 and 1966) (1), which resulted in a large number of deaths, will be considered here in the category of accidents. A table of such accidents is given below (16).

Time	Place	SO_2 level (ppm)	Excess deaths
Dec. 1952	London	1.5	3,900
Nov. 1952	New York	0.2	360
Jan. 1956	London	0.51	1,000
Jan. 1959	London	0.2	200
Dec. 1962	London	1.0	850
Dec. 1962	Osaka	0.1	60
Nov. 1966	New York	0.51	168

From the above data we consider a maximum expected number of deaths per accident as 2450.

Nuclear: The number of deaths per accident (with probability 10^{-6}), as calculated in the Rasmussen Report (34), is chosen here. It is 1000 deaths/accident.

Solar: Accidents can happen in solar microwave transmission from satellite which may lead to its focusing on a populated area (also see p. 74).

We estimate that a major accident of this nature has the potential of killing 1000 persons (10,000 MW beam focused on a populated area).

Geothermal: Total number of mine blowups in 1971 to 1974 is 4 and number of persons killed is 111 (35). Hence, persons killed/accident = $111/4 \simeq 28$. For "all-geothermal" power case - if we assume that the number of deaths is 10 times the above figure - then we take 280 as the number of deaths per accident, a conservative figure.

X_{21} Frequency (events/year):

Coal: From the figures given on page 82, we estimate the frequency of accidents per year as 1/6 or 0.17.

Nuclear: Frequency of accidents in case of nuclear power plants was taken from Rasmussen Report (34) as 10^{-6}/year.

Solar: The frequency of accidents which will kill 1000 persons would at least be more by two orders of magnitude compared to nuclear power plants. This assumption was made considering the following points:

1. The electronic system safeguards (microwaves) can not be as precisely achieved as by the cables used in nuclear power plants (one order of magnitude).

2. When an accident has occurred in the directional error of the microwave, it cannot be controlled by a means as reliable as a containment of nuclear power plant (another order of magnitude).

Hence, we choose 10^{-4} as the frequency of accidents in this case.

X_{22} Insurability, third-party-liability:

Probability of third-party-liability from coal-fired plants was taken as 1.0, for nuclear 0.0, for solar 0.5, and for geothermal 1.0.

X_{23} Degree of regulation imposition:

Its percentage estimates are as follows:

coal - 40%
nuclear - 100%
solar - 30%
geothermal - 60%

CHAPTER X. CALCULATING UTILITY FUNCTIONS

The utility function for each alternative was calculated from Equation (2) by the computer program given in the Appendix. The value of the utility for each of the alternative systems are given in Table 5. The most desirable system is the one that corresponds to the highest utility value. Thus we note that nuclear power plant system has higher utility than solar power plant system. Geothermal energy utilization has highest utility while coal-fired power plants have the lowest utility.

Table 5. Utility value for alternative systems

System	Utility Value
I Coal	0.7262
II Nuclear	0.8210
III Solar	0.7835
IV Geothermal	0.8430

CHAPTER XI. CONCLUSIONS AND RECOMMENDATIONS

This study is an attempt to give a methodology to the concerned decision-makers towards a rational approach in selecting planning alternatives for the energy system utilization using multiattribute utility theory. Four alternative energy systems have been chosen. The utility function is evaluated for each alternative over 23 attributes. The result indicates that the geothermal energy is the least risky one while nuclear, solar and coal-fired power plants have the risk (or environmental impact) in the ascending order. The most striking conclusion is that coal-fired power plants have the most severe environment impact. The nuclear power plants have environmental impact less than solar or coal-fired power plants.

This study is of a preliminary nature. A more refined study of the alternative energy planning decision based on this technique could be done. The following recommendations may be considered for future work.

1. A more specified target for the planning and its inclusion in the multiattribute utility model.
2. A thorough study regarding the selection of various attributes, verification of the assumptions imposed on the model and the evaluation of the attribute levels.

3. Evaluation of scaling factors for individual utility function by taking the views of a number of experts. The Delphi technique or the random response approach may be of great help for this purpose.

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ACKNOWLEDGMENTS

I would like to thank Dr. Abdelfattah A. Husseiny, my major professor, for suggesting this research and for his advice throughout the work.

I would also like to thank the other members of my committee, Dr. R. A. Danofsky, Dr. D. N. Roberts, Dr. Z. A. Sabri and Dr. H. J. Weiss for their kind encouragement. In particular, I would like to thank Professor R. A. Danofsky, Chairman of Nuclear Engineering, for his frequent and helpful advice concerning all aspects of my graduate program.

Gratitude is expressed to the Engineering Research Institute of Iowa State University for making financial assistance available.

APPENDIX: COMPUTER PROGRAM

Table A1. Computer program

```
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      COMPUTER CODE FOR RISK ANALYSIS
C      OF DIFFERENT ENERGY SOURCES
C      USING MULTIATTRIBURE UTILITY
C      THEORY
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
C              THIS PROGRAM FINDS
C                     (1) THE VALUE OF SCALING CONSTANT K
C                     (2) THE COMPONET UTILITY LEVEL FOR EACH
C                         ATTRIBUTE, AND
C                     (3) THE OVEALL UTILITY FUNCTION FOR
C                         EACH ALTERNATIVE CONSIDERED
C
C              THE PROGRAM USES MULTIATTIBUTE UTILITY THEORY
C              FOR A COMPARATIVE DECISION MAKING AMONG
C              VARIOUS ALTERNATIVES.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
C              EXPLANATION OF THE TERMS
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C           NN= NO. OF ATTRIBUTES
C           SKI= THE SCALING FACTOR FOR EACH ATTRIBUTE
C           NK= THE NO.OF ATTRIBUTES THAT CAN BE
C                     REPRESENTED IN THE EXPONENTIAL FORM
C
C                     U=A+B*EXP(C*X)
```

Table A1 (Continued)

```
C
C           A= CONSTANT   IN THE EXPONENTIAL
C           B= CONSTANT   IN THE EXPONENTIAL
C           C= CONSTANT   IN THE EXPONENTIAL
C
C           BK=  THE SCALING FACTOR
C           NA= NO.OF ALTERNATIVES FOR DECISION MAKING
C
C           X=  ATTRIBUTE LEVES
C
C           UI= COMPONENT UTILITY FUNCTION FOR ATTRI-
C                     BUTES NOT REPRESENTED IN EXPONENTIAL
C                     FORM.
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C  PROGRAM TO CALCULATE MULTIATTRIBUTE UTILITY FUNC.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      DIMENSION A(25), B(25), C(25), UI(25), X(25),
     1    SKI(25), S(25), Z(25)
      READ(5,1) NN
      WRITE(6,200) NN
  200 FORMAT('NUMBER OF ATTRIBUTES, NN=',I2,5X,'SKI',/)
    1 FORMAT(I2)
      READ(5,2) (SKI(J),J=1,NN)
    2 FORMAT(8F10.0)
      WRITE(6,201) (SKI(I),I=1,NN)
 201  FORMAT(12X,10E12.3)
C
C
C
```

Table Al (Continued)

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C        ITERATION TO CALCULATE VALUE OF
C        SCALING CONSTANT,  BK.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      DO 100 I=2,1001
      BK=(FLOAT(I)-1.0)*(-0.001)
      Y=BK+1.
      DO 20 J=1,NN
      UI(J)=SKI(J)*BK+1.
   20 CONTINUE
      R=1.
      DO 30 K=1,NN
      R=UI(K)*R
   30 CONTINUE
      DIFF=ABS(Y-R)
      IF (DIFF.LT.0.0001)GO TO 7
  100 CONTINUE
    7 WRITE (6,8)
    8 FORMAT(' VALUE OF OVERALL SCALING FACTOR,BK')
      WRITE(6,2) BK
      READ(6,1) NK
      READ(6,2) (A(IA),IA=1,NK)
      READ(6,2) (B(IB),IB=1,NK)
      READ(6,2) (C(IC),IC=1,NK)
      READ(6,1) NA
      DO 500 NS=1,NA
      READ(6,2) (X(ID),ID=1,NK)
```

Table Al (Continued)

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C       ITERATION TO CALCULATE THE
C       COMPONENT UTILITY FUNCTION, UI
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      DO 35 IX=1,NK
      Z(IX)=C(IX)*X(IX)
      UI(IX)=A(IX)+B(IX)*EXP(Z(IX))
      WRITE(6,18)
   18 FORMAT(' THE COMPONENT UTILITY FUNCTION')
      WRITE(6,21)UI(IX)
   21 FORMAT(5X,G21.5)
   35 CONTINUE
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C       ITERATION TO CALCULATE THE
C       OVERALL UTILITY FUNCTION, U
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      NK1=NK+1
      READ,(UI(JL),JL=NK1,NN)
      DO 58 N=1,NN
      S(N)=BK*SKI(N)*UI(N)+1.
   58 CONTINUE
      RR=1.
      DO 31 L=1,NK
```

Table Al (Continued)

```
    RR=S(L)*RR
 31 CONTINUE
    U=RR/BK -1./BK
    WRITE(6,40)U
 40 FORMAT('0THE OVERALL UTILITY VALUE',5X,G15.8)
500 CONTINUE
    STOP
    END
```