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RELATIVE ENERGY RISK:
IS SOLAR ENERGY RISKIER THAN NUCLEAR?

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If operations research is, as the dictionaries define it, the integration of a wide variety of data over a great many fields, then risk analysis qualifies as a branch of operations research.

There are various definitions of risk analysis, but perhaps a simple one is "calculation of the damage to human health as a result of a given activity." Damage to human health can encompass accidents and disease, both fatal and non-fatal. In principle, any human activity can have its risk calculated; however, most risk analyses have concentrated on forms of energy production.

Risk analysis can be viewed as a branch of operations research primarily because it cuts across so many disciplines and fields of research. For example, an analysis may involve knowledge of accident rates in various industries; the time and manpower it takes to construct a solar panel; the ways in which materials such as glass and aluminum are transported; the lifetimes of an energy facility; and so on. The objective of assembling this array of knowledge is to calculate a "bottom line" for risk, i.e., the total number of deaths, accidents or diseases associated with a unit of energy production. In this way, risk analysis is somewhat different from environmental impact statements and related documents.

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It clearly would be out of the question to evaluate the risk of all energy systems in a paper of this type; in any case, many systems have not yet been evaluated in this way. The following discussion of risk analysis is divided into three parts: (a) a brief discussion of the methodology which can be used, (b) a listing of some of the major assumptions, and (c) the results of a comparison of eleven energy systems.

The energy systems considered here can be divided into two groups: conventional, i.e., those in fairly widespread use, like coal or nuclear, and non-conventional, i.e., all others, like solar and wind. In general, although some of these non-conventional systems have been described as "risk-free," they are not. In fact, compared to some conventional systems like natural gas and nuclear, technologies like solar and windpower have relatively high risk. The reason is simple. Because of the dilute nature of the energy they handle, solar and wind systems, when compared on the quantity of their energy production, require a considerable amount of apparatus as compared to other systems. In turn, this apparatus requires a large amount of material and construction labor to build and install. Associated with each ton of material and hour of labor is a definite number of accidents, diseases and deaths, according to labor statistics. When the risk is summed up in this way, we find that non-conventional systems generally have high risk. In particular, to answer the question posed in the title of this talk, solar energy seems to have a higher risk than nuclear power, when the methodology outlined below is used.

METHODOLOGY

We may divide the overall risk of an energy system into two parts: occupational and public. These two aspects are sometimes called voluntary and involuntary, respectively, although there is some doubt as to exactly what the latter two terms imply.

In calculating the overall risk attributable to an energy system, many analysts count not only the activities exclusively related to a particular system (e.g., uranium mining or roof repair to a solar collector), but also activities such as transportation, construction, etc., which are more general. Although one has the option of considering only the activities "exclusive" to a technology in evaluating energy risk, this is done only rarely.

In determining the risk to society of various energy alternatives, a variety of risk sources can be considered. These are indicated in Figure 1. Not included here are aspects which may have an indirect effect on health, such as resource depletion, weapons proliferation, climate change, etc. While important, they are not appropriate to the current discussion.

In terms of operations research, it will be seen from Figure 1 that a wide variety of data is needed to calculate risk. In terms of public health risk alone, this can arise from air pollution effects from many chemicals; reactor accidents; accidents at railroad crossings and on highways; and so on. The wide variety of data sources are subdivided into theoretical, based on mathematical approximations, and historical, based on what has happened in the past. Handling all the sources of data and combining them in an appropriate and fair manner demands the highest skills of the operations researcher.

All energy systems require raw materials; some may require fuel, like uranium, coal or oil. All systems require component fabrication, construction and maintenance. Raw materials, intermediate and finished products must be transported. All energy systems, as will be noted below, have some public health risks. Finally, the risk of waste disposition and deactivation has been calculated for nuclear power, although a case can be made that this source of risk is higher for other energy systems, such as coal. In particular, the coal tip accident in Aberfan, Wales, in the early 1960's was the largest single disaster associated with waste disposition in history.

Some of the risk components noted in Figure 1 pertain solely to particular energy systems, and others are more general. For example, since uranium has only limited civilian use outside of nuclear reactors, mining of this substance may be called an activity "exclusive" to the technology. On the other hand, steel is used in most energy systems. The total risk of an energy system is made up of both exclusive and non-exclusive activities.

As mentioned above, a minority of risk analysts consider only the "exclusive" activities in risk computation: uranium mining, repairing solar collectors, etc. However, this approach neglects sources of risk from activities necessary to produce energy from a given system. The analogy of producing automobiles might be drawn here. Some aspects of their production, like assembly lines, are exclusive to this industry. Others, such as making chrome, copper, aluminum and so on are not. If we want to determine the economic cost of a car, we have to consider both the exclusive and non-exclusive activities.

Figure 1 is a simple diagram. But how does one actually calculate each of the components? As might be expected, computation is more difficult than conceptualization. Before discussing the details, some explanatory notes and <u>caveats</u> must be given. Some of these have been given elsewhere. (1)(2)

(a) Risk cannot be considered in isolation, since the size of systems varies considerably. The risk of a massive coal-fired plant should not be compared to that of a small solar panel. Most analysts have calculated risk per unit energy output. This is usually taken as one megawatt-year or the annual output of a large coal or nuclear plant (around 700 megawatt-years). The unit used is not of great consequence as long as consistency is maintained.

(b) Component lifetime plays an important part in risk calculations. Some risk may be produced in capital construction (building a reactor or wind turbine) and some may be incurred as a running cost (operation and maintenance, or mining coal and uranium). To take account of both aspects, the total risk is divided by the total energy produced over the lifetime of the system.

The lifetimes of many systems are not accurately known. Often replacement is made, not because parts have worn out, but because of economic obsolescence. A lifetime of 30 years has been assumed for most of the systems discussed here. The major exceptions are solar space heating and windpower, with estimated lifetimes of 20 years, and hydroelectricity, at 50 years.

(c) Risk data are often given as so many deaths, accidents and diseases per unit energy. A natural question then arises: Can these be combined into an overall index of risk?

Physically, they cannot, but mathematically, they can. For example, the American National Standards Institute and occupational health bodies often use the value of 6000 man-days lost per death. Obviously, the value in particular cases will vary strongly, ranging from the premature death by a week of a 90-year old due to air pollution to the accidental death of a 20-year old in a coal mine. Nonetheless, this approximation can be a useful one.

(d) Some solar or wind systems may require energy storage capabilities. When the sun doesn't shine or the wind doesn't blow, the consumer still needs energy. Storage can take many forms -- rocks, liquids, batteries, pumped air or other systems. In the present work, a rock-and-oil system was assumed. This probably constitutes a lower limit to risk; risk attributable to manufacturing batteries is likely higher.

If the reliability aimed for in "baseload" electrical distribution (usually one hour of power loss in a year) is taken as a guide, the storage required to meet this guideline could be huge. To avoid these storage problems, a back-up, of ordinary electrical energy, must be available. This back-up can come from one particular source, such as coal-fired or nuclear plants, or from a "mix," based on the national proportions of electrical supply. The latter assumption is used here.

(e) The risk of transmitting energy, as well as producing it, could be considered. This can be accomplished by evaluating the risk of building and operating transmission lines or pipelines. In the case of both, the risk attributable to transmitting energy forms only a small fraction of the total risk of the system.(3)(4) As a result, this aspect of risk can be disregarded as a first approximation.

(f) Present-day conditions, not future expectations, were assumed for each system. For example, it might be contended that coal-fired plants of the future could produce less pollution than present ones, resulting in decreased health effects. Future steel mills might have a lower occupational risk than those which now exist. Future wind turbines might be more efficient than those which have been built to date. All of this might be true, and all of it might not. We know the present only imperfectly, and the future even less. As a result, it seems prudent to consider primarily today's energy systems with their associated risk, and re-calculate the values as new knowledge is generated.

(g) Most risk calculation is based on historical or actuarial data. For example, occupational risk in the steel industry is based on what has happened in the past, not what might be achieved in the future. Occupational risk has declined slowly if at all, with the exception of coal mining.(5)

In terms of catastrophic public risk, i.e., accidents which can harm more than a few people at a time, there exists, for all except one energy system, only historical data. For example, the risk of hydroelectric dam failure has not, as far as is known, been computed theoretically. As a result, the historical data for hydroelectricity, in which the total number of public deaths attributable to this source since 1890 are divided by the total hydroelectricity produced since that time, are used here.

The only system for which theoretical, as opposed to historical, calculations have been produced is nuclear power.(6)(7) These studies have attempted to calculate the probabilities of a range of accidents, from negligible to severe.

The Rasmussen report(6) went on to estimate, by integration over the probabilities, the average number of deaths to be expected per reactor-year of operation. The recent German Risk Study "more or less confirms" the results of the U.S. study.(7)

(h) The nuclear system considered is the light-water reactor (LWR) presently used in the United States and other countries.

(i) Geographical aspects play an important part in many aspects of risk, but have not been studied adequately up till now. For example, health effects from air pollutants from coal-fired plants will depend strongly on whether the plant is in a heavily populated area, the direction of winds, etc. The question of geography has been most extensively studied with respect to nuclear plants, but more work needs to be done.

(j) In order to avoid possible charges of pro-nuclear bias, nuclear risks were handled differently from those of the rest of the study. In general, they were "maximized," i.e., the highest values were chosen from a variety of literature sources. This procedure was not followed for other energy systems. For occupational risk, this maximization did not affect the results strongly, since different estimates are fairly similar. However, there seems to be differences of opinion in terms of public risk, with a few estimates being much higher than those commonly accepted. These former estimates can be termed "worst cases," and apparently have no experimental or historical basis. The values of Comar and Sagan(10) were used, as published in the Annual Review of Energy. The maximum values for public risk used by Comar and Sagan are much higher than both the average value calculated by Rasmussen(6) or the historical record (see above).

(k) Perhaps the most important caveat in this paper is that much of the data dealing with risk are imprecise, to say the least. Examples would fill pages, but a few must suffice: (i) the energy collected per unit area in a solar collector is variable; (ii) the man-hours per unit energy output in uranium mines will depend strongly on the ore grade; and (iii) the lifetime of windmills is still a matter of controversy.

As a result of these and many other uncertainties, the results presented here can only be taken as approximations. While the absolute values of risk shown later in this paper are subject to change as information is improved, the relative rankings have more validity. They can be used as a general guide to orders of magnitude of risk.

CALCULATIONS OF RISK

How is total risk calculated? As can be deduced from Figure 1, a variety of methods are employed. In terms of material acquisition, labor statistics give the number of deaths, accidents and illnesses per man-years worked. The number of man-hours required per operation is then multiplied by the deaths, accidents or disease per man-hour, yielding the occupational risk. The calculations are shown schematically in Figure 2.

As an example, suppose mining X tons of coal requires Y man-days. If the number of man-hours lost per day of work is Z, then the number of man-hours lost per ton of coal is YZ/X.

A similar analysis can be performed in terms of construction. With knowledge of the trades – roofing, electrical work, plumbing and so on – the man-hours of each required per unit energy output, and the risk per man-hour, a calculation similar to that for material acquisition can be performed. As mentioned above, knowledge of these various data forms constitutes a part of operations research.

Transportation risk poses a different problem. In principle, we should know the ways in which each material is transported – rail, truck, air or barge – the distance it is moved, and the risk per ton-mile for each of the transportation types. In practice, this information is difficult to find, so approximations have to be made.

Sand and other materials for making concrete are generally moved short distances, so the risk attributable to their transport is probably small. As a crude approximation, it can be assumed that non-sand materials are carried by train and are moved the same distance as coal.

Energy-related public health risk arises from a number of sources. Transportation accidents occur not only occupationally, but to members of the public as well. By far the largest effect on the public is due to pollutants produced by burning coal and oil. Values used here were originally generated by the National Academy of Sciences. In addition to these direct emission effects, there are indirect ones. The construction of almost all energy systems requires metals like steel and aluminum. To produce these metals, fuels must be burned, leading to air pollution and, in turn, potential health impacts. These health effects must be attributed to the systems requiring these metals, since without these materials the energy could not be produced.

There is also a risk to public health due to potential catastrophes such as nuclear accidents and hydro dam failures. The rationale behind calculating their effects was discussed above.

Finally, there is public health risk due to waste disposition and deactivation. Most recent publicity on this subject has concerned nuclear power, although a large number of people have died due to the coal waste accidents at Aberfan in Wales and Buffalo Creek in the United States. A number of recent estimates(8) have suggested that, with reasonable precautions, the public risk from nuclear waste disposition should be small. Only time can prove or disprove these contentions.

RESULTS

Using the methodology sketched out above, occupational and public risk can be calculated for a number of systems, both new and old. Results are shown in Figures 3–5.

Figure 3 shows that occupational risk is highest for methanol. A considerable amount of logging is required for this system, and logging is one of the riskiest occupations after mining.

Lowest is natural gas, because comparatively little labor is required in its production. Coal has a relatively high value, primarily because of the high relative risk of coal mining.

The six new or non-conventional systems to the right of the figures have relatively high values, ranging from 3–60 times that of natural gas (in terms of maxima). Depending in general on dilute forms of energy like sun- and wind-power, these systems require large collectors per unit energy output. In turn, building and operating these collectors requires large amounts of labor, which tends to produce substantial occupational risk. Each of these steps in the reasoning has exceptions, but the overall deductions are generally valid. Results are approximately similar to those of Hoy(9).

Figure 4 shows the public risk, again using the same units. For those systems assumed to require back-up, the risk is shown with and without back-up.

The highest values, by a substantial factor, are those of coal and oil, primarily due to pollution effects. Lowest again is natural gas, followed by nuclear. In the case of the latter system, a fairly pessimistic or high value was taken for the risk due to reactor accidents.

The six non-conventional systems to the right have some public risk, although much less than coal or oil. This is due to a number of factors: (a) some systems require back-up, which produces public risk; (b) materials requirements produces air pollution; and (c) transportation of materials produces public risk at railroad crossings.

Finally, Figure 5 shows the total risk, found by adding occupational and public risk. This is a purely optional step, designed to measure total effects on society. Others may wish to weight the two components unequally, or avoid the addition entirely.

As might be expected on the basis of Figures 3 and 4, natural gas and nuclear have the lowest total risk, with coal and oil the highest. In between are a "group of seven." There is not much reason to discuss the ranking within this group, since there is some uncertainty in the values calculated. However, it is seen that the new or non-conventional systems can have substantial risk to health if the entire energy cycle is evaluated.

SUMMARY

The methodologies of operations research can be used to find the total risk to human health of a variety of energy systems. The object of this study was to gather data from a great many sources, and use as consistent a methodology as possible to evaluate total risk. This could be used as a definition of operations research.

When the calculations are performed, we find, counter perhaps to some people's intuition, that some non-conventional energy systems have relatively high risk. Lowest of all are electricity produced from natural gas and nuclear power, contrary to the publicity given to pipeline explosions and reactor accidents, respectively. It is clear, however, that much is still not known about many energy systems, and that further knowledge will refine the estimates given here. The discipline of operations research can provide critical tools to the refinement of these estimates.

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CAPTIONS

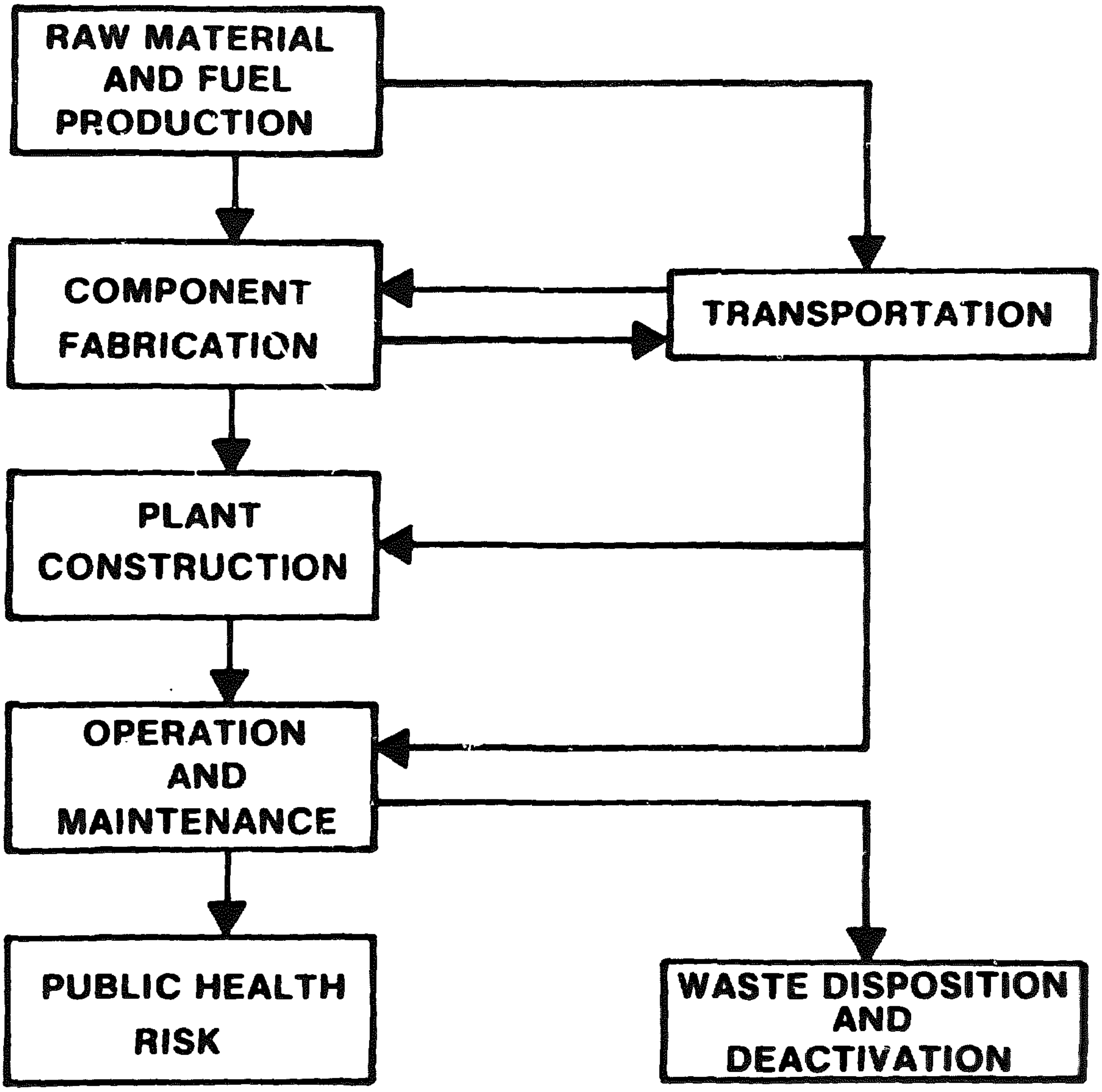
Figure 1. Sources of Risk in Energy Production. The relative importance of the components depends on the energy system. For some systems, energy back-up and storage may be required to increase reliability. Transportation is shown as interacting with a number of components.

Figure 2. Risk from Material Acquisition. Each of the raw materials which go into an energy system has an associated risk, dependent on the accident, illness and death rate per unit weight. Dashes indicate that other materials are used.

Figure 3. Occupational Man-days Lost per Megawatt-year. The top of the bars indicates the upper end of the range of values; the dotted lines within the bars, the lower. Those bars to the right of the vertical dotted lines indicate values for technologies less applicable to Canada. Solid and dashed jagged lines refer to the maximum and minimum values, respectively, if low-risk or no back-up is assumed. These jagged lines are not shown in this figure because occupational risk changes little when no back-up is assumed; however, they are shown in Figs. 4 and 5. Each death is counted as 6000 man-days lost. Note the logarithmic scale.

Figure 4. Public Man-days lost per Megawatt-year (see explanation in caption to Figure 3). Natural gas-fired electricity has the lowest value. Coal and oil have the highest values, due to air pollution effects.

Figure 5. Total Man-days lost per Megawatt-year (see explanation in caption to Figure 3). Quantities here are found by adding occupational and public risk. Natural gas and nuclear have the lowest values.


RAW MATERIAL AND FUEL PRODUCTION
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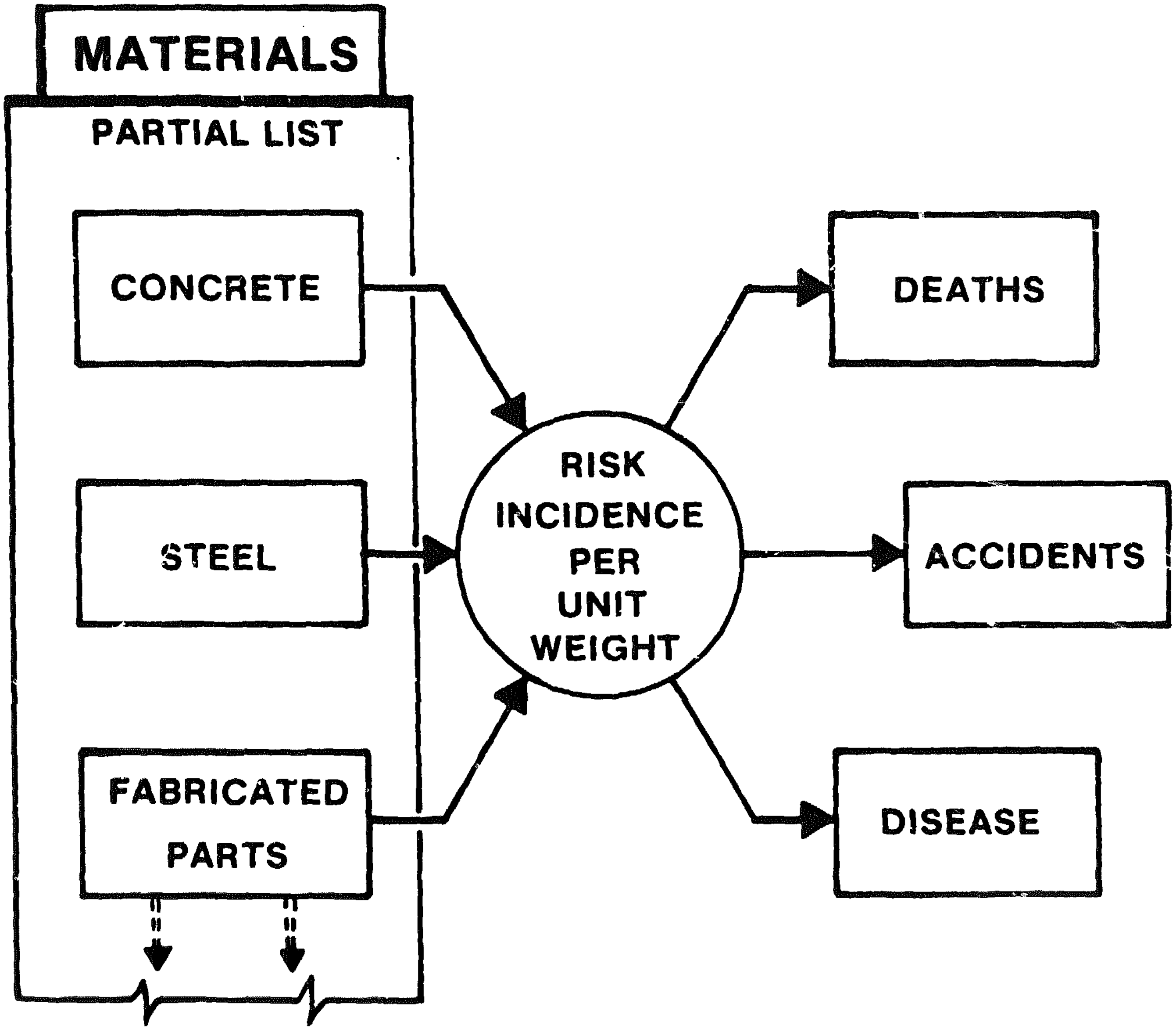
TRANSPORTATION
PLANT CONSTRUCTION
OPERATION AND MAINTENANCE
PUBLIC HEALTH RISK
WASTE DISPOSITION AND DEACTIVATION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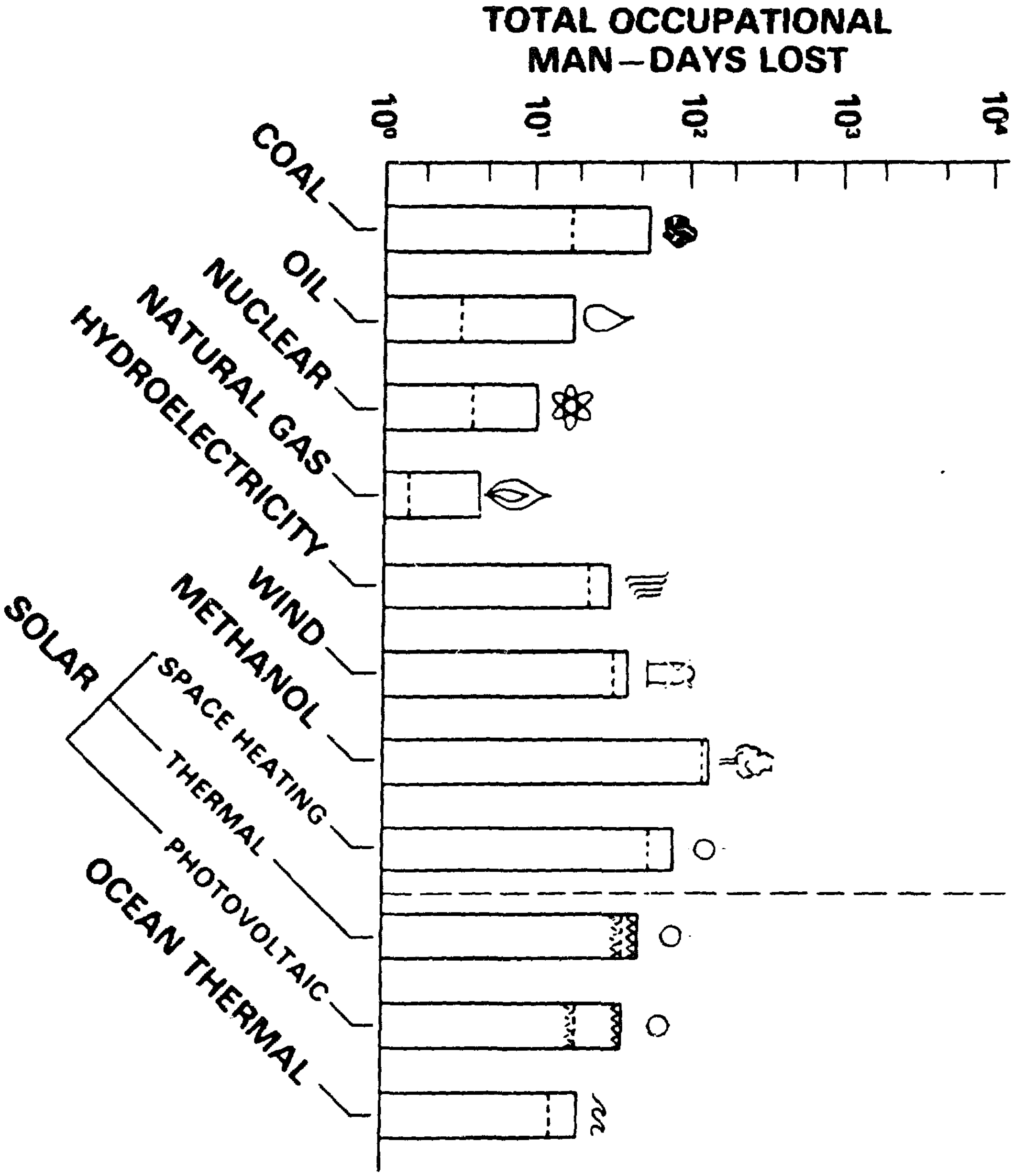
ACCIDENTS
DISEASE


TOTAL OCCUPATIONAL MAN—DAYS LOST
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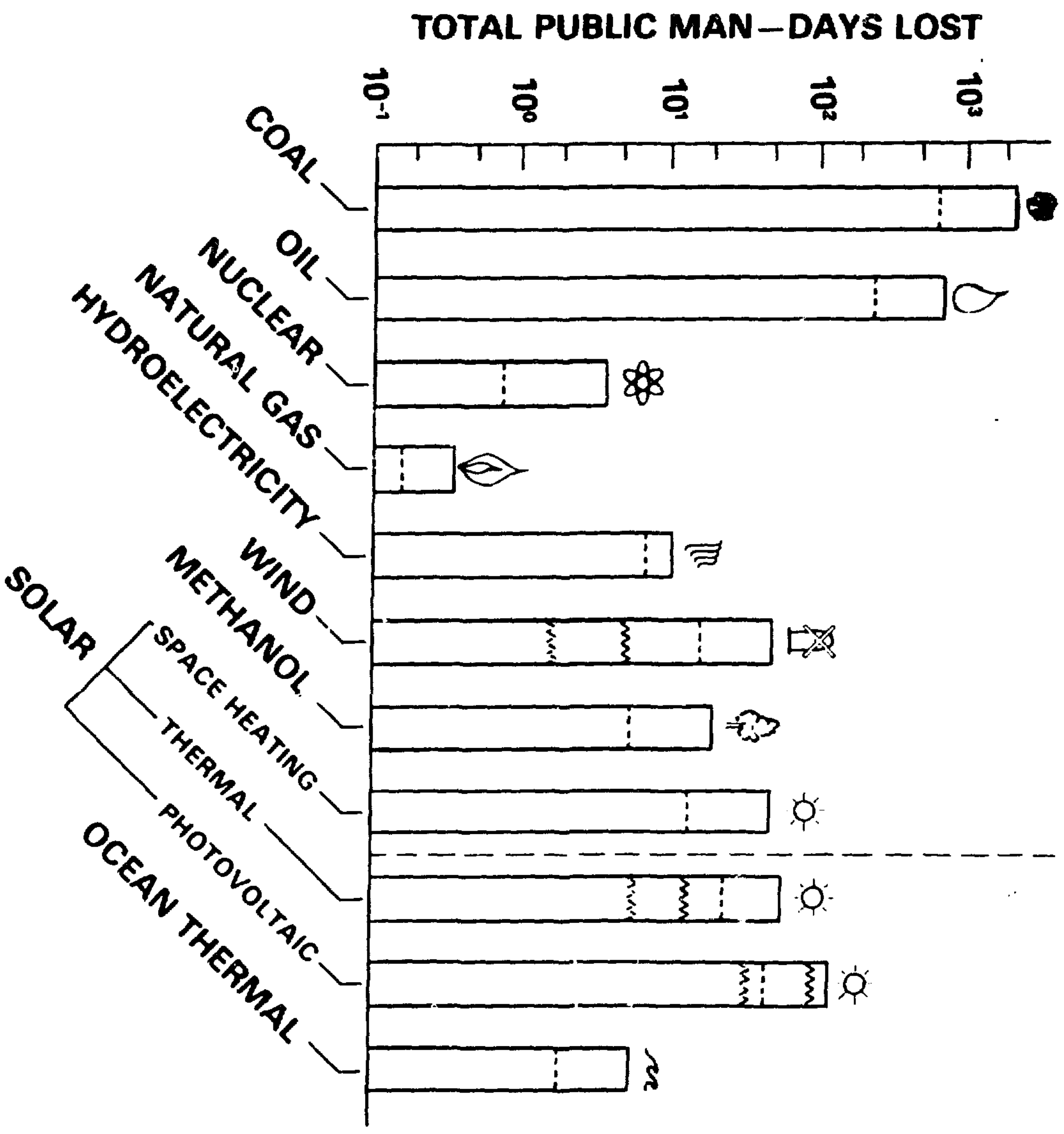
10^1
10^2
10^3
10^4
COAL
OIL
NUCLEAR
NATURAL GAS
HYDROELECTRICITY
WIND
METHANOL
SOLAR
SPACE HEATING
THERMAL
PHOTOVOLTAIC
OCEAN THERMAL



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