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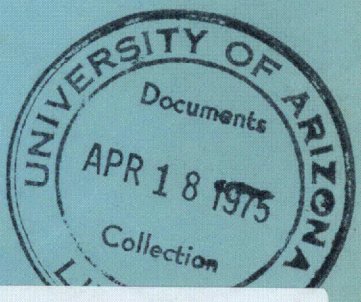
COMPARATIVE RISK-COST-BENEFIT STUDY OF ALTERNATIVE SOURCES OF ELECTRICAL ENERGY

A COMPILATION OF NORMALIZED COST AND IMPACT DATA FOR CURRENT TYPES OF POWER PLANTS AND THEIR SUPPORTING FUEL CYCLES

DECEMBER 1974

UNITED STATES ATOMIC ENERGY COMMISSION
DIVISION OF REACTOR RESEARCH AND DEVELOPMENT



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COMPARATIVE RISK-COST-BENEFIT STUDY OF ALTERNATIVE SOURCES OF ELECTRICAL ENERGY

A Compilation of Normalized Cost and Impact Data for Current Types of Power Plants and Their Supporting Fuel Cycles

December 1974

Office of Energy Systems Analysis
Division of Reactor Research and Development
United States Atomic Energy Commission

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PREFACE

This study is an attempt to quantify societal costs associated with the production of electrical energy by currently available alternative systems under routine operating conditions. Motivating the study was an awareness that societal costs of a given system cannot be judged in a vacuum. Costs of alternatives must be compared. Particular emphasis was placed on examining each energy system in its entirety -- both the power plant and its supporting fuel cycle. The study was initiated in a climate which lacked objective, factual, and quantitative inquiry. The charter of the study thus called for quantification of costs and impacts, supported by the most thorough documentation possible. At the outset, it was recognized that these goals would be approached rather than achieved.

The words "risk" and "benefit" in the report title are somewhat misleading. The word "risk" connotes rather severe unplanned events, such as large scale-low probability accidents, diversion of nuclear materials, and the like. In fact, the study is restricted to routine impacts -- including routine accidents whose frequencies can be established from historic data. "Risks" are translated into "costs" using frequencies and consequences of events inferred from past experience. Also, the title suggests that the reader may find a weighing of costs (including risks) against benefits. However, "benefit" is defined here as a quantity of electrical energy. Assigning an absolute societal value to electrical energy is left to the reader. With these definitions, the study reduces to an assessment of societal costs (external as well as internal).

Drafts of the study were issued for review in September 1972 and August 1973. As the study progressed it became evident that conditions were changing more rapidly than their effects could be factored into the analysis. For example, mine safety legislation has resulted in a factor-of-two reduction in coal mining fatality statistics used in this report. Similarly, the emergence of OPEC in late 1973, occurring in an already inflationary energy economy, severely escalated prices of energy in practically all forms.

While these rapid changes do not alter the central conclusions of the study, they do underscore the desirability of keeping data bases current of delineating statistics (past) from forecasts (future), and of maintaining a coherent format in which data elements can be periodically corrected with ease. For these reasons, the conceptual structure of this study and the documented track from raw data to derived quantities are as important as the quantitative results.

The study project leader and principal author of this report was Shelby T. Brewer, U.S. Atomic Energy Commission (AEC). Others who participated in the preparation of the report were Richard A. Livingston, formerly of the AEC, and William A. Buehring, formerly of Argonne National Laboratory (ANL). Some of the data used in this report was assembled by an ANL staff working under AEC direction and funded by an AEC contract. Principal contributors from the ANL staff were William A. Buehring, Kenneth A. Hub, and the late Paul F. Gast. Leonard L. Bennett and Howard I. Bowers of Oak Ridge National Laboratory provided plant capital, fuel cycle, and operating and maintenance costs.

CHAPTER 1

INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

The role of energy in sustaining and advancing civilization is fundamental and pervasive. It is difficult to identify a single artifact or activity of modern society which does not involve, either directly or indirectly, an expenditure of energy beyond that associated with man's muscular exertions.

In general, the production of a quantity of useful energy, such as a kilowatt-hour of electricity, involves several dimensions of cost:

(a) the diversion of conventional labor, material, and capital resources, all of which are normally reflected in the market price of energy;
(b) the consumption of a quantity of a nonrenewable fuel resource, thus precluding its use in the future;
(c) degradation of natural and manmade environments, including disruption of natural material, energy, and biological balances, and damage to man-made structures and materials.
(d) impacts on human health and safety.

Recently, popular attention has been drawn to the last two of these cost groupings, as evidenced by the staggering proliferation of energy and environmental studies in the past few years.

Concern over environmental impacts of producing electrical energy has often focused on very narrow aspects of individual electrical energy production systems,* such as thermal effects of discharge heat from power plants, mining impacts, and air pollution. For this reason, the quantitative environmental literature on electrical energy production is, to a large extent, fragmentary and redundant.

A more balanced and coherent view requires that costs and impacts throughout entire fuel cycles be identified, quantified, normalized and compared on a consistent basis. As part of a continuing analysis of the role of nuclear power in providing the Nation's energy requirements, the Division of Reactor Research and Development of the United States Atomic Energy Commission has undertaken such an assessment -- the "Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy."

*The terms "electrical energy production system" and "fuel cycle" are used synonomously in this report.

Purpose and Scope

The purpose of this study is to provide a quantitative basis for making comparisons of societal costs across and within alternate electrical energy production systems. The principal tasks in achieving this goal are to assign internal and external costs of the alternate systems to a common unit of electrical energy produced (kilowatt-hours) and to express such costs, where possible, in consistent units (dollars). Fuel cycle material balances provide the central format for assembling and normalizing data, and provide the quantitative link between an impact or cost anywhere in the system, and a corresponding quantity of electrical energy (benefit) produced.

Such information could provide a preliminary basis for numerous ancillary comparisons and cost-benefit tradeoffs, including: (a) comparisons of total costs (internal plus external) of producing electrical energy from alternate fuels; (b) comparisons of external and internal costs for each process step within each fuel cycle, in order to determine which steps are the most environmentally offending, and in order to measure the cost-effectiveness of abatement measures; (c) comparison of external costs of alternative methods for the same functional step in a given fuel cycle; and (d) comparison of the total costs associated with alternative energy strategies, or mix of fuels, to meet a given energy demand projection over a period of time; and (e) coherent judgements regarding abatement measures, which, while reducing an impact at one stage in an energy system, may increase impacts at another.

The following restrictions and assumptions serve to further define the scope of the Study.

. The study is confined to electrical energy. A more comprehensive assessment would include all forms of end use energy ("total energy"). Benefits and costs of substituting electrical energy for other forms are not addressed, although the coefficients developed in the course of this study can be useful in such analyses.

. The study is restricted to electrical energy production, and embraces entire fuel cycles, and their residuals. Questions regarding electrical energy use are not addressed, although alternative electrical energy use patterns may have significant environmental and economic differences.

. Attention is restricted to modern, commercial size, baseload power plants and their supporting fuel cycle facilities, and to those systems based on technologies whose commercial application is proven. The analysis includes only those systems expected to make major contributions to base load power production in the near term,

i.e. the next ten or fifteen years. Systems considered are those based on coal, residual fuel oil, natural gas, nuclear fission (LWR) fuels, and hydroenergy. Although two types of advanced nuclear fission reactors -- the HTGR and the LMFBR -- are expected to make significant contributions to base load power by the end of this century, these concepts are not addressed quantitatively in this report. Electricity generation using gasified coal is similarly excluded.

. The study is restricted largely to quantification of the environmental and human impacts of the energy systems under normal operating conditions. Certain classes of routine industrial accidents, for which reliable statistics are available, are treated, however. Large, hypothetical accidents at a nuclear power plant are excluded, since other concurrent USAEC studies are addressing this topic.

. "Benefit" in this study is defined as a quantity of electrical energy, e.g., one kilowatt hour. No attempt is made to determine the absolute societal value of electricity. That is, the question addressed is not whether a unit of electrical energy should be produced, but instead how it should be produced.

"Risks" are treated as "costs" in this study: the product of the probability of an undesirable event (per unit of electrical energy) times the consequences of the event.

"Costs" include both "internal" and "external" costs. Internal costs are those costs already borne by electricity consumers. Internal costs are already imbedded in the price of electricity (mills/kWhe) and include the conventional components -- labor, materials, and costs of capital. External costs are the environmental and human impacts not accounted for in the price of electricity.

With the definitions of benefit, risk, and cost established above, the study reduces to a comparison of total costs to produce electricity by alternative fuels.

. Much of the information assembled in this report is based on aggregate national data. In this sense, the assessment assumes a national homogeneous model, at the expense of displaying regional variations in unit costs, impacts, engineering and economic constraints, local utility company practice, site-specific considerations, and the like. For example, in order to properly burden a quantity of electrical energy with coal mining impacts, it is necessary to assume production fractions from surface and underground mining techniques. Although the unit impacts of production

methods are disaggregated and displayed separately in the body of the report and in other supporting materials,* production fractions representative of the current national pattern (∿50% underground, ∿50% surface) are assumed for the purpose of constructing summary tables. The same general approach was taken in several other elements of the assessment.

The bases for normalization of costs and impacts are 1000 MWe of electrical generating capacity, or the annual operation of one 1000 MWe unit at 75% capacity factor (6.57 billion kWhe).** All fuel cycle parameters are normalized to these quantities through equilibrium fuel material balances. The resulting evaluation is a static comparison of costs and impacts associated with alternate energy systems. It is recognized, however, that the overall problem of ranking alternatives is a time dependent one, and that alternatives must be regarded as changing mixes of energy sources or energy strategies, rather than as individual, isolated sources. The development of static impact coefficients, the central task of this study, is a prerequisite of the broader assessment of comparing energy strategies.

1.2 SUMMARY AND CONCLUSIONS

Summary

For purposes of making gross comparisons, representative costs and impacts of alternative electrical energy production systems† were assembled and normalized to 6.57 billion kilowatt hours (kWhe), the annual energy produced by one 1000-MWe unit operating at 75% capacity factor. Systems considered were those based on coal, oil, natural gas and nuclear fission fuels.†† Attention is restricted to modern, commercial size, baseload power plants and their supporting fuel cycle facilities, and to those systems based on technologies whose commercial application are proven. Although two advanced reactor types, the HTGR and the LMFBR, are expected to make significant contributions to base load power production by the end of the century, this study includes a quantitative appraisal only of the current generation of power reactors -- the LWRs. Emphasis of the report is on quantifying effects throughout the respective fuel cycles, from fuel extraction to power generation, as conceptualized

*and are available to the reader in substituting his own assumptions.
**Some impacts and costs are related to a unit of electrical energy produced (kWhe), while others are related to power capacity (MWe).
†The terms "electrical energy production system" and "fuel cycle" are used synonymously in this report.
††The hydro-energy system is discussed qualitatively in Chapter 3. Little quantitative information is developed, since relatively little additional hydro capacity is expected to be installed.

in Fig. 1.1. Where possible, non-conventional costs were reduced to a common basis (same unit of electrical energy produced) and to common units (dollars), thus rendering them comparable and, perhaps, additive.

The information assembled and normalized in this report emerged from an extensive literature survey aimed at quantifying numerous individual impacts and costs. In most cases, the individual impacts and costs displayed in this report are derived quantities. Individual items of data were rarely found in the desired format, that is, restricted to the particular impact or cost under consideration and normalized to a unit of electrical energy produced or to a unit of production capacity. For each item addressed, considerable manipulation -- disaggregation, interpretation, averaging, normalization -- was necessary to reduce the quantity to consistent and meaningful information. In several cases, only source terms, e.g., pollutant emission rates, are presented. Ideally, one would reduce all such quantities to ultimate impacts in consistent damage units to permit their display as added costs.

Table 1.1 summarizes comparative data for the alternate fuel cycles normalized to production of 6.57 billion kWhe or to a generating capacity of 1000 MWe.* The format of Table 1.1 warrants some explanation. First, much of the data represents sums over the individual fuel cycle process steps. Chapters 3 and 5 give similar data for each process step, permitting the reader to make comparisons among process steps of individual fuel cycles or among similar process steps (e.g., mining) across competing fuel cycles. Further, it is recognized that the organization of a table such as Table 1.1 can prejudice and distort a comparative assessment.** In this regard, great care was taken to present an objective set of impacts and costs, assembled in a coherent, but uncontrived, matrix. Entries in Table 1.1 are arranged to conform roughly to the four conceptual groupings of costs and impacts established in the Introduction: (a) conventional costs; (b) consumption of nonrenewable fuel resources; (c) environmental degradation; and (d) impacts on human health and safety.

The major categories of Table 1.1 are discussed briefly below.

Power Plant and Energy System Efficiencies

Power plant net thermal efficiencies for the fossil plants are essentially the same -- 38-39%. The LWRs, PWR and BWR, have somewhat lower net thermal efficiencies, ∿ 32%, owing to their coolant temperature limitations.

*Some impacts and costs are related to a unit of production, while others are related to system capacity.

**e.g., the grouping of data under descriptive headings, the selection of "typical" or "representative" parameters, the omission of impacts not quantifiable, etc.

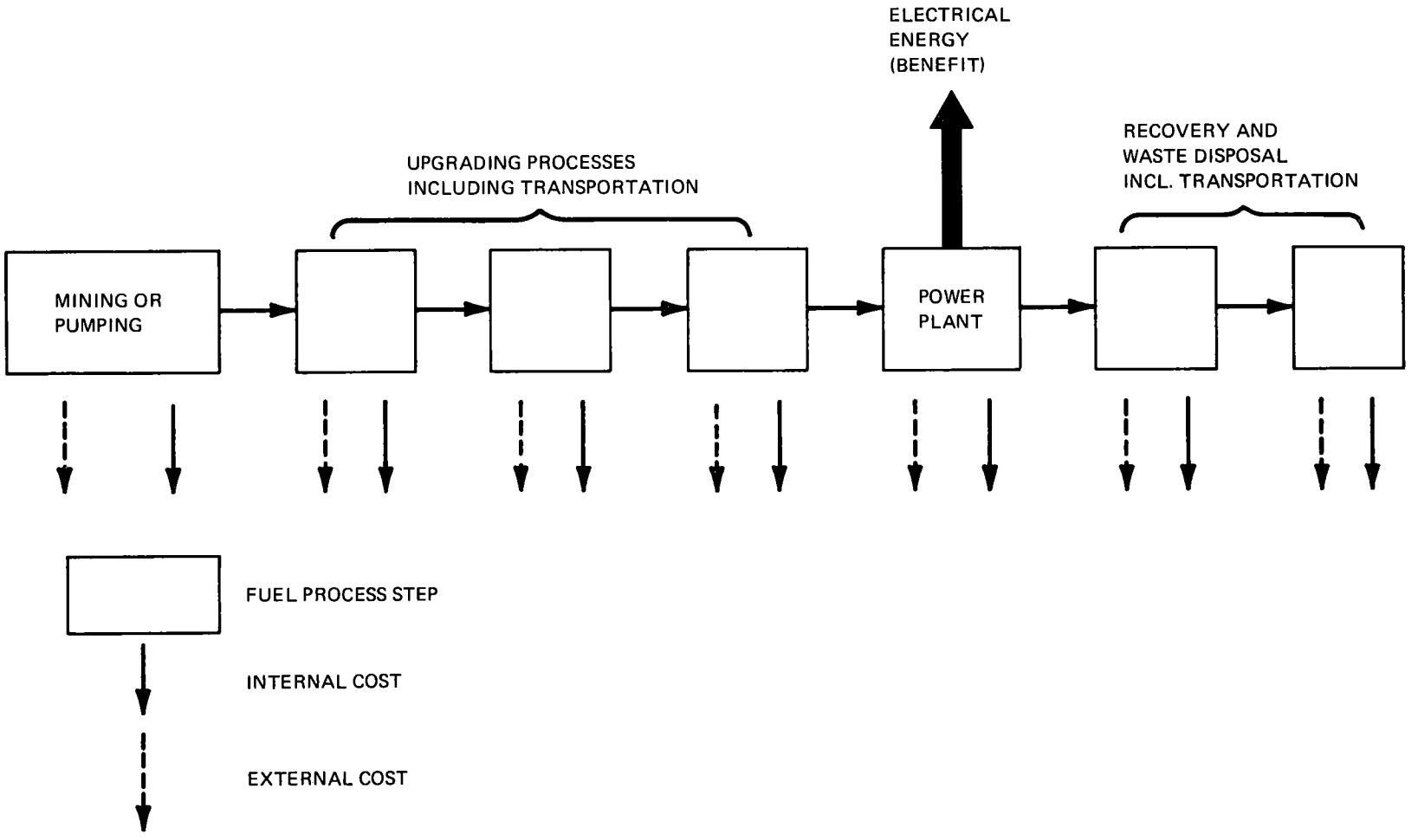

FIG. 1.1 SCHEMATIC OF A FUEL CYCLE (ENERGY PRODUCTION SYSTEM)

TABLE 1.1 COMPARISON OF COSTS AND IMPACTS OF ALTERNATE ELECTRICAL ENERGY PRODUCTION SYSTEMS*

Basis: 1000 MWe Power Plant, 75% CF
6.57×10^9 kWhe

	Coal	Oil	Gas	LWR
POWER PLANT AND ENERGY SYSTEM EFFICIENCIES				
Electrical Energy (billion kWhe/year)	6.57	6.57	6.57	6.57
Power Plant Heat Rate (BTU/kWhe)	8,900	8,830	9,110	10,850
Power Plant Thermal Efficiencies (kwe/kw_t, %)	38	39	38	32
Energy System Efficiency (kwh_e consumer/kwh_t input, %)	35	35	34	28
CONSUMPTION OF NON-RENEWABLE FUEL RESOURCES				
Power Plant Fuel Consumption (annual)	2.3M tons	10M barrels	64 B cubic ft.	~130 M tons U**
Fraction of Reserves Consumed (annual)	0.000006	0.0001	0.0004	0.0002
CONVENTIONAL COSTS (mills/kWhe)* **				
Plant	7.8	7.2	6.4	11.7
O&M	0.8	0.6	0.6	0.8
Fuel	9.8	27.4	36.0	6.0
Total	18.4	35.2	43.0	18.5
SELECTED ABATEMENT COSTS (mills/kWhe)* **	4.7	2.0	0.6	0.6
OCCUPATIONAL HEALTH AND SAFETY				
Occupational Health (MDL/yr)	600	U	U	480
Occupational Safety				
Fatalities (Deaths/year)	1.1	0.17	0.08	0.1
Non-Fatal Injuries (#/year)	46.8	13.1	5.3	6.0-7.0
Total Man-Days Lost (MDL/year)	9,250	1,725	780	900-1000
PUBLIC HEALTH AND SAFETY				
Public Health				
Routine Pollutant Release (MDL/year)	U	U	U	180-210

TABLE 1.1 CONTINUED

Basis: 1000 MWe Power Plant, 75% CF

	Coal	Oil	Gas	LWR
Public Safety				
Transportation Injuries				
Fatalities (Deaths/year)	0.55	U	U	0.009
Non-Fatal (Injuries/year)	1.2	U	U	0.08
Total Man-Days Lost (MDL/year)	3,500	U	U	60
ENVIRONMENTAL DEGRADATION				
Land				
Land Use, Inventory (acres)	22,400	~1,600	~3,600	~1,000
Land Use, Consumption (acres/year)	740	S	S	12
Air				
SO_2 release, w/o abatement (tons/year)	120,000	38,600	20	3,600
, w abatement	24,000	21,000	0	720
NO_x releases, w/o abatement (tons/year)	27,000	26,000	13,400	810
Particulate releases, w/o abatement (tons/year)	270,000	26,000	518	8,000
, w abatement	2,000	150	4	60
Trace Metals releases (tons/year)	0.5 Hg	1,500 V	U	S
Radioactivity releases (Ci/year)	0.02	0.0005	S	250-500 T
Thermal Discharge, power plant stack (billion kwh_t/year)	1.64	1.71	2.2	0
Water				
Cooling Water Use (billion gal./year)	263	263	263	424
Process Water Use (billion gal./year)	1.46	1.75	1.42	0.095
Radioactivity releases (Ci/year)	0	0	0	500-1000
Other Impacts (billion gal./year)	16.8	7.9	0	S
Thermal Discharge, power plant (billion kwht/year)	9	9	9	14

U ≡ Unevaluated; S ≡ Small; M ≡ Million; B ≡ Billion; T ≡ Thousand

*The number of digits shown is not generally indicative of precision. In many cases, several digits are retained merely for calculational purposes.

**About 99% of this figure is not irretrievably consumed; rather, it is available in the form of enrichment plant tails for use in breeder reactors.

***1980 dollars.

Overall energy system efficiencies include corrections for process heat and electrical energy requirements of the supporting fuel cycle operations. For all systems, process heat requirements for the supporting fuel cycle are negligible compared to the heat input at the power plant. Fuel cycle electrical energy requirements are also negligible, except for the diffusion-enrichment plant requirements for the LWR systems, which are of the order of 3 to 5% of the power plant output. Transmission losses are assumed the same for all systems.

The fossil fuel cycles have similar systems efficiencies -- ∿ 35%. The LWRs have lower system efficiencies, ∿ 28%, due both to their lower power plant efficiencies and their enrichment plant power requirements.

More detailed analyses of the overall fuel cycle energy balances are given in Chapter 5 and in the Appendix.

Consumption of Nonrenewable Fuel Resources

The availability of fuel at acceptable cost is a major consideration in selecting a power plant type. For example, fuel shortage offsets the environmental benefits of the natural gas system. Annual fuel consumption of each 1000 MWe plant is expressed in Table 1.1 as a fraction of reserves available for U.S. electric power production, at current extraction costs and with current extraction technology. Current alternative-use fractions were used to establish the reserve base available to the U.S. electricity production. Residual fuel oil (RFO) assumed to be available from Africa and Venezuela is included in the RFO reserve base.

Coal is seen to be the most abundant fossil fuel resource, natural gas the least. Foreign deposits place the RFO system on a par with the LWR systems.

Fuel resource data is given for each of the mineral fuels in Chapter 3, and reduced to equivalent quantities of electrical energy in Chapter 5.

Conventional Costs

Conventional costs are those definable costs already imbedded in the price of electricity to the consumer -- the costs for labor, materials, and use of money. They include the capital cost of power plant amortized over the life of the plant, plant operating and maintenance costs, and fuel costs. Fuel costs include costs incurred throughout the fuel cycle, including capital costs of fuel cycle facilities. These costs are ultimately transferred to the utility company and, together with utility company working capital changes associated with fuel, borne by the consumer.

Representative conventional costs, corrected for escalation to the year 1980, are shown in Table 1.1. The purposes of including conventional costs in this report are to show roughly the market competiveness of the alternate energy systems and to provide reference points for comparison of nonconventional costs. Where possible, costs associated with abatement and restoration measures have been separated from the conventional costs.

It should be recognized that conventional costs are quite sensitive to power plant location. Further, a number of factors cause such costs to vary with time -- routine inflation, abundance of fuel resources, capacity/throughput effects, legal and regulatory actions, technological maturity, etc.

Abatement Costs

Abatement costs in Table 1.1 include SO_2 removal from stack gases (coal), desulfurization of residual fuel oil, natural-draft evaporative cooling towers (all plants), near-zero radwaste systems (LWRs) and surface mined land reclamation. This is not, of course, a complete list.

Abatement costs in the coal cycle are the greatest, due to the large cost projected for SO_2 removal. The desulfurization of residual fuel oil is the dominant abatement cost in the oil cycle. The near-zero radwaste treatment systems add little to the LWR energy costs.

Environmental Degradation

Burden rates on the environmental receptors* -- land, air, and water -- are displayed in Table 1.1, with the intent of presenting crude measures of relative environmental impacts of the alternate energy systems. In most cases, these burden rates are merely source terms, i.e., emission rates normalized to a quantity of electrical energy produced. Ideally, these quantities would be reduced to incremental quantities of damage to ultimate receptors, such as natural flora and fauna, structural materials, crops, and the like. Dollar costs could then be assigned to units of damages. Owing largely to the lack of damage-function information for each pollutant-receptor combination, this procedure could not be followed rigorously.

Two aspects of land use are included in Table 1.1: land tied up or committed by the power plants and their supporting fuel cycle; and the land "consumed" annually, e.g.,

*Effects on human health and safety are frequently included in the term "environmental effects." In this study, human health and safety are considered separately. The next two sections deal, respectively, with occupational and public health and safety.

land disturbed by surface mining, land inundated by disposal of fuel cycle residuals. The coal fuel cycle has the greatest land impact, owing mainly to its mining operations and waste disposal. Inventory land requirements for the nuclear fuel cycles are magnified by exclusion-area requirements, but are still an order of magnitude less than that of the coal cycle.

Annual emissions of sulfur oxides, nitrogen oxides, particulates, radioactivity, heat, mercury, and vanadium to the atmosphere are shown in Table 1.1. The coal energy system releases greater quantities, per unit energy produced, of SO_2, NO_x, and particulates than do the other fossil systems. For purposes of comparison, electrical energy required for the gaseous diffusion enrichment of LWR fuel is assumed to be provided by a coal-fired plant, and prorated quantities of coal cycle pollutants are, accordingly, assigned to the LWR fuel cycle.* It is interesting to note that on this basis, the LWR cycle "emissions" of SO_2 and particulates are greater than those of the natural gas fuel cycle. Thermal releases to the atmosphere are about 15% of the total heat rejected by fossil power plants. There are, of course, no atmospheric thermal releases at nuclear power plants. Minute quantities of radioactive materials are routinely released from nuclear facilities to the atmosphere. These emissions are of primary concern to public health, and are discussed below, together with fossil pollutants, under the heading "Public Health and Safety."

Light water reactors, because of practical coolant temperature limitations, operate at lower thermal efficiencies and, therefore, reject more heat than modern fossil fuel plants of the same generating capacity. For this reason and because about 15% of the heat from fossil fueled plants is discharged into the atmosphere through the stack, LWRs discharge about 1/3 more waste heat to cooling water than do modern fossil fueled plants.

Process water use in the LWR fuel cycle is essentially negligible compared to that in fossil fuel cycles, due both to the nature of the processes themselves and to the relatively small masses and volumes of fuel materials involved. Chemical contamination of waterways is similarly small. Chemical contamination in the fossil system includes acid mine drainage in coal fields, black water from coal cleaning

*This is, of course, a purely arbitrary assumption, although the existing diffusion capacity is powered by coal-fired power plants. Notwithstanding recent publicity to the contrary, coal is not uniquely required for the production of enriched nuclear fuel. Some electricity (a few percent of the equivalent electrical energy yield of the nuclear fuel) is required, and any fuel which produces electricity will do.

plants; oil spills, ballast discharge, and refinery effluents in the oil system.

As discussed in Chapter 4, damage functions for each pollutant-receptor combination are not well established. Thus, any measure of damage costs, normalized to annual emission rate must be regarded as a gross preliminary estimate. Section 4.9 gives crude measures of the dollar costs imposed by damage from coal, oil, and natural gas plant SO_2 and particulate emissions. Section 4.10 presents estimates of dollar costs associated with impacts (largely consumptive water use) of waste heat rejection by natural draft wet cooling towers. Estimates of other damage costs -- associated with mine land disruption, oil spills and ballast discharge, and biological oxygen demand of refinery effluents -- are given in Section 4.11. All of these damage costs are summarized in Table 1.2. More detailed discussions are provided in the Appendix.

Occupational Health and Safety

Table 1.1 displays occupational health effects for coal and nuclear energy systems in units of man-days lost (MDL).

The dominant occupational health effect in the coal fuel cycle is coal workers' pneumoconiosis (CWP), or "black lung," a respiratory disease resulting from the accumulation of coal dust in the lungs of underground miners. An advanced stage of this disease is progressive massive fibrosis (PMF). Crude estimates of the frequency (normalized to 6.57 billion kWhe) of CWP cases, are compared to estimated occupational health effects in the light water reactor fuel cycles -- lung cancers among uranium miners due to inhalation of radon gas, and cancers resulting from occupational exposures at the reactor and reprocessing plants.*

It is estimated that on the order of one case of black lung can be attributed to the mining requirements associated with one 1000 MWe coal-fired plant per year.** By comparison, on the order of one malignancy would be expected in the light water reactor fuel cycles, per 1000 MWe plant, during the life of the plant ($\sim$ 30 years).

Occupational health is addressed in more detail in Sections 4.4, 4.6, 4.7 and in the Appendix.

Occupational injuries due to routine industrial accidents occur throughout the alternate fuel cycles. Table 1.1 gives injury rates, normalized to the annual operation

*6000 MDL is assigned to each malignancy; 1000 MDL is assigned to each case of simple CWP.

**Assumes 50% production in the power plant from underground mines. Also assumes that future U.S. coal mining health impacts, after implementation of the 1969 Act, will be similar to British experience.

of a 1000 MWe power plant. Injuries in the coal cycle exceed, by far, those in the other fuel cycles. About one occupational fatality per year can be attributed to each 1000 MWe coal fired plant. The dominant source of coal cycle injuries is underground mining.* The injury rates in the oil, gas, and LWR fuel cycles are roughly equivalent -- an order of magnitude below that of coal. Mining in the nuclear fuel cycles accounts for most of the injuries in these cycles. Because of the high energy content of nuclear fuels, nuclear fuel mining injury rates are much lower than those in coal mining.

Public Health and Safety

Public health effects of electricity production are extremely difficult to assess. Pollutant emission rates at the power plant or at a fuel process step in the supporting fuel cycle are first estimated. A thorough understanding of the process in question, and a careful description of the material flows involved in the process are normally sufficient to yield a fairly accurate emission rate, normalized to a given quantity of electrical energy produced. Transport of the pollutant through various pathways to man, or to alternate fates, must next be analysed. Factors involved in this step are local meteorology, hydrology, pollutant reconcentration mechanisms, pollutant loss mechanisms, biological uptake mechanisms, population distribution, and the life style, including diet, of the population. Human exposure levels and rates must then be assessed to determine dose. Finally, the health damage corresponding to this dose (using an appropriate dose-response function or coefficient) must be evaluated; and if warranted, a dollar cost may be assigned to the incremental health damage.

The establishment of dose-response relationships is at present the weakest link in this procedure. The relationships between health effects and pollutant concentrations (or dose levels) are generally established by epidemiological studies on statistical samples of the human population, or laboratory studies on animals. Animal studies require that results be scaled in some manner in order to estimate human effects.

Table 1.1 contains crude estimates of public health effects (in units of mandays lost)** of the routine radioactivity emissions from the nuclear fuel cycles. These figures are based on a very conservative dose-response coefficient of the order of ~0.0001 malignancy per rad, and the emission rates in curies per ton of fuel

*Occupational injury figures of Table 1.1 assumes 50% production from underground mines, 50% from surface mines.
**6000 MDL is assigned to each malignancy.

processed or per MWHe estimated in the present study. Section 4.4, the Appendix, and the footnotes of section 3.5 describe these calculations in more detail.

Unfortunately, human health hazards from fossil fuel pollutants are not as well understood and quantified as the health hazards from radiation. There is no dose-response data comparable in quality to therapeutic irradiation and atomic bomb casualty data and no linear dose-response model, both of which are so useful in estimating (however conservatively) radiation effects. Numerous measures of health effect have been investigated but no preeminent measure has emerged which is analogous to malignant neoplasm in the case of radiation. Toxicologic studies on animals have demonstrated that massive doses of specific chemicals such as sulfur dioxide may impair health. Likewise, chronic exposures of animals have demonstrated health effect. Correlations between various measures of human respiratory impairment, including death, and levels of air pollution have been observed during and following episodes of exceptionally high concentration of air pollutants. However, there is no information on the effect of individual exposure to specific pollutants during such episodes, and no dose-response relationship can be formulated. This same lack of exposure information plagues the attempt to establish pollutant-response correlations through study of chronic exposure. Several regression formulas have been developed which relate measures of mortality and morbidity to measures of general air pollution levels such as sulfur dioxide concentrations and concentrations of particulate matter. These formulae are of no use for the prediction of health effect as a function of pollution level because they have not been based on known and controlled populations, the exposure measures relate to concentrations made at several geographical locations but are not a measure of personal exposure, and the full spectrum of air pollutants is not represented in the equations. Although a quantitative comparison between radiation health effect and fossil air pollution health effect is an essential part of the comparison of nuclear and fossil fuel cycles, no quantitative estimate of fossil air pollution health effect, normalized to a unit of electrical energy produced, can be made at this time.

While it is not feasible, at this time, to normalize public health effects to a unit of energy produced, some perspective can be gained by comparisons of natural background levels, man-made exposures, regulatory standards, and broad ranges of pollutant concentrations known to result in some health effect. Figure 1.2 illustrates the comparisons for sulfur dioxide, nitrogen oxides, and whole body irradiation. The areas labeled "medically perceivable effects" are adopted from a recent University of California study.* Several tentative conclusions may be drawn from Figure 1.2.

*Hausknecht, D. Public Health Risks of Thermal Power Plants, University of California UCLA-ENG-7242 (May 1972).

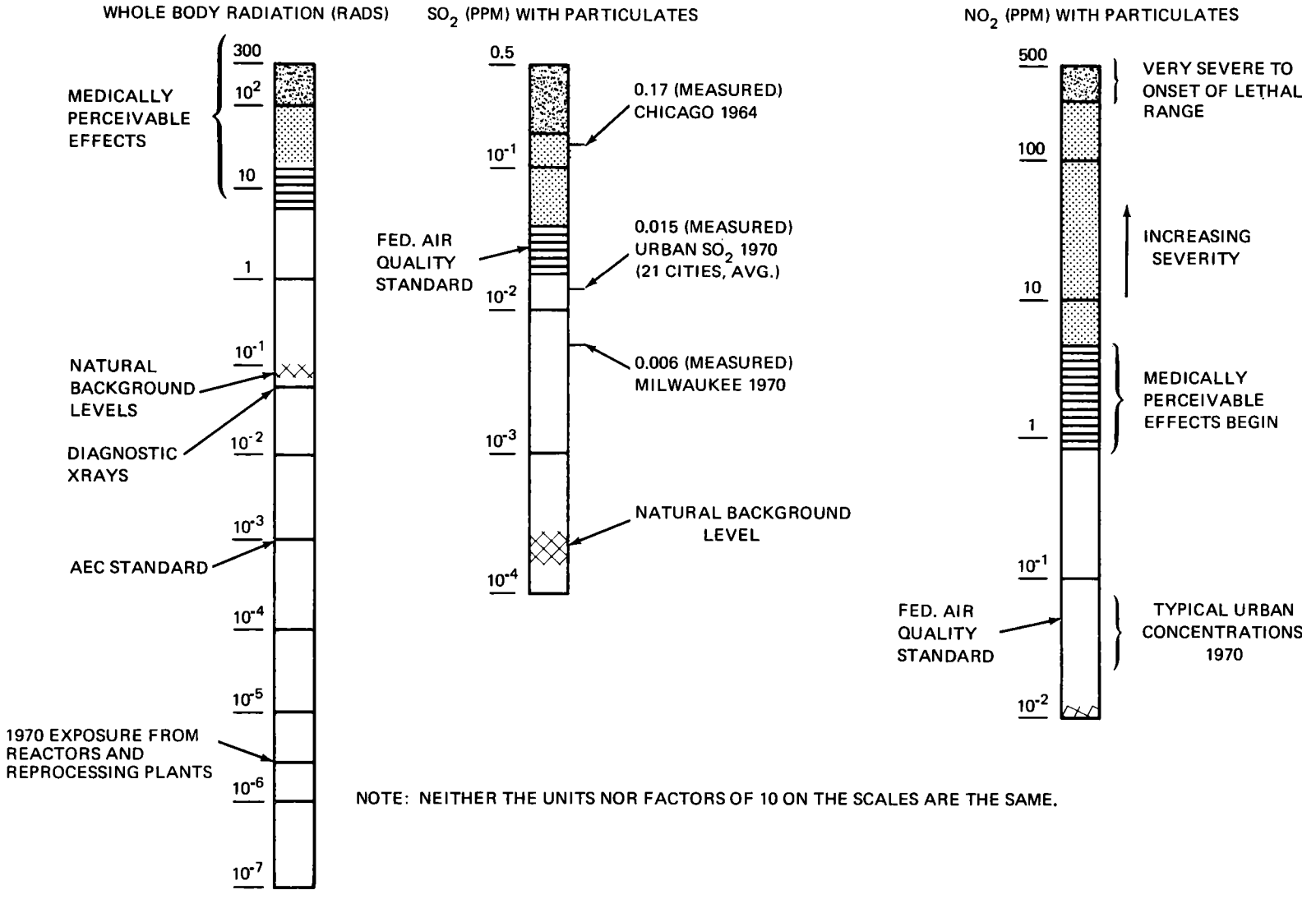

FIG. 1.2 COMPARISON OF POLLUTANT STANDARDS, BACKGROUND LEVELS, MANMADE EXPOSURES, AND HEALTH EFFECTS

(a) Environmental Protection Agency standards for SO_2 and NO_2, applicable to fossil-fired power plants and other man-made sources of these pollutants, are above natural background levels of these pollutants. Current USAEC regulations (10 CFR 20) for radiation exposure are about equivalent to doses from natural background sources. However, the new proposed "as low as practicable" guidelines (10 CFR 50, Appendix I), applicable to light water reactors, would restrict individual doses to orders of magnitude below that from natural sources.

When man-made and natural sources are added, the total levels permitted by regulations or guidelines are:

- about a factor of 100 over natural background for SO_2;
- about a factor of 4 over natural background for NO_2; and
- about a factor of 2 over natural background (10 CFR 20) or about a factor of 1.01 over natural background (10 CFR 50, Appendix I)* for radiation.

(b) As expected, ranges of medically perceivable effects are well above natural background levels for all three pollutants.

(c) With the exception of SO_2, the standards are well below the ranges of medically perceivable effects.

(d) Actual average annual radiation whole body exposures from nuclear power facilities in 1970 were several orders of magnitude below the existing standards (10 CFR 20) and natural background. Concentrations of fossil pollutants (together with background) were substantially above background levels in 1970.

The discussion above was restricted to effects on public health of routine pollutant releases from the energy system. Of concern also is public safety, more specifically, the hazards to the public from conventional accidents in transporting fuels.** Of the various process steps in the electricity production systems, fuel transportation is the dominant source of accident-risk to the public since it is in the transportation of fuel that the public comes in closest contact with the energy production system. Routine industrial accidents at power plants and fuel processing facilities usually affect only occupational personnel. Table 1.1 compares public injury rates associated with transporting fuel required for 1000 MWe coal-fired and LWR power plants.

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*Proposed.

**Hypothetical, large scale-low probability accidents at power plants and supporting facilities are not addressed in this study.

Radiological and chemical risks associated with transporting fuels, which are orders of magnitude below risks of conventional impact-injury,* have been excluded.

Because of the large masses and volumes of fuel involved, coal transportation imposes a much more severe public safety hazard than transportation of nuclear fuels. Public injury rates in coal transportation are, in fact, comparable to occupational injury rates in coal mining. The transportation of coal for a 1000 MWe plant results in a statistical public death about every two years -- this almost entirely due to accidents at railroad grade crossings. Thus, about one third of the total fatalities attributable to the coal fuel cycle are public fatalities, the other two-thirds being occupational fatalities largely in underground mining.

A more detailed treatment of conventional injury rates in fuel transportation is given in the Appendix.

Nonconventional Costs in Perspective

Although normalized to the same quantity of electrical energy produced or production capacity, the quantities in Table 1.1 are in a variety of physical and nonphysical units. Quantities along a single row are, however, in consistent units, so that comparisons can be made across competing energy systems. Ideally, one wishes to reduce all such quantities to the same dimension, e.g., dollars, in order to make dissimilar categories of impact within each energy system comparable, and perhaps, additive, making possible comparisons of total societal costs across competing energy systems. For example, one might wish to compare the occupational radiological health impact in the LWR system to the conventional costs of producing electrical energy in this system.

Efforts to assign dollar values to non-conventional costs are highly preliminary, subjective, and generally imperfect. However, in several specific cases, it is possible to make gross assessments useful in making order-of-magnitude comparisons.

Table 1.2 compares conventional costs of producing electrical energy and several categories of environmental and human impacts which were reduced to dollar costs. This table represents the highest degree of summation and condensation considered feasible, useful, and appropriate in this study. The table aggregates numerous quantities derived and presented in a labyrinth of supportive materials in the main report and the appendices. Further condensation could lead to misinterpretation and gradual vitiation through succeeding generations of studies.

*USAEC, Nuclear Fuel Transportation Study (to be issued).

TABLE 1.2 COMPARISON OF CONVENTIONAL COSTS AND SOME EVALUATED NON-CONVENTIONAL COSTS OF ALTERNATE ENERGY SYSTEMS

Basis: Annual operation of one 1000 MWe Power Plant and Supporting Fuel Cycle (6.57 billion kWhe). 1980 dollars.

		Coal	Oil	Gas	LWR
Conventional Costs	(10^6/yr)				
Capital Plant		51	47	42	77
Fuel Cycle		64	180	237	39
O&M		5.4	4.0	3.7	5.2
Rounded Totals		120	231	283	121
Abatement Costs	(10^6/yr)				
Cooling Towers		3.6	5.9	7.1	2.4
Sulfur/SO_2 Removal		25.9	4.9	NA	NA
Strip-mined Land Reclamation		0.1	NA	NA	S
Near-Zero Radwaste		NA	NA	NA	1.2-1.8
Rounded Totals		30	11	7	3-4
Conventional & Abatement	(10^6/yr)	150	242	290	125
Abatement Component	(%)	20	5	2	3
Safety	(10^6/yr)				
Occupational[a]		0.46	0.086	0.039	0.05
Public[b]		0.18	U	U	0.003
Subtotal		0.64	>0.086	>0.039	0.053
Health	(10^6/yr)				
Occupational		0.03[c]	U	U	0.024[d]
Public		U	U	U	0.01[e]
Subtotal		>0.03	U	U	0.034
Total Human Health & Accident Costs	(10^6/yr)	>0.67	>0.086	>0.039	0.087

TABLE 1.2 -CONTINUED

Environmental Effects	(10^6/yr)				
Water Base		0.4	0.4	0.4	0.6
Air Base		0.8	0.6	0.1	S
Land Base		0.2	S	S	S
Subtotal		1.4	1.0	0.5	0.6
Total Human & Env. Effects	(10^6/yr)	2.1	1.1	0.5	0.7
Percent of Conv.	(%)	3	1	0.5	0.9

Key: U = unevaluated; NA = not applicable; S = small

Footnotes:
(a) Conventional injuries in routine industrial accidents, including fatal and non-fatal injuries; 1 death = 6,000 MDL = $300,000
(b) Conventional injuries in accidents in transporation of fuels; 1 death = 6,000 MDL = $300,000
(c) Coal workers' pneumoconiosis (CWP)
(d) Radiological health effects, including lung cancers among uranium miners.
(e) Radiological health effects from routine emissions.

The limitations and uncertainties of the information displayed in Table 1.2 warrant further discussion. These qualifications do not, however, invalidate the major conclusions and findings of the study.

. Additive Costs

One of the tasks of the study was to reduce numerous quantities to a consistent basis (same unit of electrical energy produced) and to consistent units (dollars) in order to render them comparable and additive. All costs, internal and external, should be summed to obtain a total societal cost.

Adding any set of quantities to obtain a total requires that they not only be in consistent units, but also that they be (a) exhaustive and (b) mutually exclusive. Put another way, this means that one should include all of the costs, and that one should avoid counting something twice.

The categories and quantities of Table 1.2 are not exhaustive. One notable omission is the public health effect of airborne fossil pollutants, which, for reasons discussed in more detail in the text, could not be quantified. For this reason, the health subtotal for the coal system may be low by an order of magnitude.

Neither are the quantities of Table 1.2 mutually exclusive. For example, the conventional costs displayed may indeed contain components such as workers' compensation and insurance, tending to internalize occupational health and safety impacts. In many such cases an exact separation of costs could not be achieved.

Uncertainties

There are several degrees of uncertainty among the quantities presented in Table 1.2. Uncertainties increase, generally, as one moves from top to bottom and from left to right in Table 1.2. In general, it was found that small quantities were attended by the greatest uncertainty. This is understandable, since small quantities are frequently masked by large ones; the hazards of dealing with small differences between large numbers are well known among scientists and engineers. Fortunately, in the context of this report, small quantities are less important than large ones.

Conventional costs, the largest of the quantities presented, are the most accurately known. A band of plus or minus 15% is assigned to cover regional and local variances and uncertainties in escalating labor, materials, and money costs to 1980. Abatement costs, because they can be tied to specific equipment and procedures, are roughly as accurate as the conventional costs displayed.

Rates of occupational injuries in the coal cycle are considered quite accurate and representative. For example, statistical fluctuations in fatalities per million miner-hours appear very slight; the gradual reduction in mining injuries from 1955 to 1967 appears systematic, suggesting that such injuries may be regarded for practical purposes as deterministic and accepted. By contrast, injuries in uranium mining, because they are fewer, appear highly random. Accordingly, a broad confidence band of $\pm$ 50% is assigned to nuclear system injuries. Similar comments apply to public injuries in transporting coal and nuclear fuels.

Accidental injuries can be counted as discrete events and assigned to specific activities, e.g., mining, transportation, etc. By contrast, health effects are amorphous, difficult to define, and often impossible to assess quantitatively with current knowledge of dose-response characteristics. For this reason, health damage costs displayed in Table 1.2 should be regarded only as order-of-magnitude estimates based on the best available information. Radiological health impacts of nuclear power production are considered to be conservative, i.e., over-estimated, in that they are based on a linear dose-response extrapolation.

Life Values

Health and injury costs were assessed at $50 per man-day lost, leading to a life value of $300,000 if one assumes 6000 man-days lost per death. These are arbitrary figures, assigned to permit rough comparisons, and carry with them no implied comment on the absolute value of human life. The $300,000 per death figure is, however, in accord with several independent assessments. The reader may adopt his own values by scaling the health and accident costs of Table 1.2.

Summary of Limitations

To summarize, several limitations and shortcomings of Table 1.2 were discussed above:

. the costs tabulated do not form a complete set, nor are they mutually exclusive; for this reason, the table does not yield total social costs of producing electricity;

. in several categories, only very crude estimates of non-conventional costs could be made; in general it was found that small quantities are attended by the greatest uncertainty; and

. the unit costs of $50/MDL and $300,000/death, assigned more or less arbitrarily to permit comparisons of health impairment and injury costs with conventional costs, are highly subjective, and may be readily challenged on emotional and moral grounds.

None of these shortcomings, however, invalidate the major conclusions and findings of the study, reviewed in the next section. The salient point is that even drastic changes in the very small quantities in question will not propel these quantities to dominant importance.

Choice of life value, if applied consistently, will not distort the relative impacts of the competing energy systems. Further, whatever value is assumed, within reason, the health and injury costs will remain small compared to the conventional costs of producing electricity. Similarly, the large uncertainties in the environmental, health, and injury figures do not alter the conclusion that these costs are small compared to conventional costs. The same general argument could apply to overlaps and omissions in the Table.

Conclusions

1. Costs associated with human health and injury effects, both occupational and public, of new power stations and their respective prorated supporting fuel cycles, are small compared to conventional energy costs (less than 1%). This conclusion excludes public health effects of airborne fossil pollutants -- SO_2, NO_x, particulates, trace metals -- which could not be quantified.

2. Total non-conventional costs -- including health, injury, and environmental impacts -- are small compared to conventional energy costs (less than 3%).

3. In view of conclusions 1 and 2, ultimate fuel resource availability is apt to have greater influence, in making national choices among energy systems, than environmental considerations. Coal and nuclear fuels are the most abundant domestic fuels for electricity generation. This assumes that greater nuclear fuel utilization is achieved through the conversion of fertile nuclides to fissile nuclides, as in the fast breeder reactor. A host of factors affecting supply of residual fuel oil and natural gas make extensive, long-term base load use of these fuels doubtful.

4. Health and injury impacts are greater for occupational personnel than for the public.

5. Specific judgments concerning the cost effectiveness of various abatement measures cannot be supported by the data available. Although costs of abatement measures can be estimated with some degree of accuracy, corresponding incremental costs of damage avoided are difficult even to estimate by order of magnitude, owing to the lack of damage function (dose-response function) information.

6. The overall problem of ranking alternatives is a time-dependent one, and alternatives must be regarded as mixes of energy sources through time rather than as individual isolated sources. It is probable that all sources will be welcome to meet the rising demand for electrical energy. For this reason, a quantitative ranking or scoring among individual energy systems, based on static parameters, is unwarranted. However, some qualitative conclusions, based on the quantitative assessment summarized in preceding tables are in order.

. The natural gas system enjoys low plant capital costs, and incurs minimal environmental and human impacts. However, remaining domestic reserves are small, imports at acceptable costs are uncertain, and there is competition from alternate uses of this fuel, such as commercial and residential heating. Supply problems also face the residual fuel oil (RFO) system. Domestic yields of RFO are low (less than 10%) because of the incentive to maximize production of more valuable refinery ends; thus, a preponderant share of RFO consumed in the U.S. is imported, and foreign sources cannot be considered secure and permanent. Environmental and human impacts involved in the RFO system are large compared to those of the natural gas system, but substantially less than those of the coal system. Because of fuel supply related problems, and attending conventional costs, RFO and natural gas are expected to have diminishing roles in fueling new generating capacity after 1980.

. Coal, the most abundant of domestic fossil fuel resources, is the most severe environmental offender. This results largely from the sheer quantities -- masses and volumes -- of materials handled in the fuel cycle. Impacts of the coal energy system are more visible and, to some extent, more easily measured than those of other systems. In almost every category addressed, non-conventional (or external) costs are greatest in the coal system. Quantified external costs of producing electricity from coal are, however, less than 3% of conventional costs. Abatement costs, particularly SO_2 retention systems if proved feasible, may add as much as 20% to internal costs. However, the compelling fact is that coal is an abundant domestic fuel, and its environmental disadvantages are not likely to preclude its continued exploitation as a source of electrical energy.

. Nuclear fuels, including both fissile and fertile nuclides, are abundant domestic resources, and are expected to share, with coal, a major role in electrical energy production from 1980 through the year 2000 and beyond, provided reactors with substantially improved fuel utilization characteristics are introduced on a commercial scale. Gross, direct environmental impacts of extracting, processing, and transporting fuel -- so visible in the coal fuel cycle -- are essentially absent

in the nuclear fuel cycles, because of the high energy content (on a mass or volume basis) of nuclear fuels. Similarly, nuclear power plants do not discharge large, visible quantities of airborne pollutants. The current generation of nuclear power plants -- the light water reactors -- discharge about one-third more heat to the environment than do modern fossil plants. Though relatively small in mass and volume, material flows and residuals in the nuclear fuel cycles are not without very substantial potential hazard. For this reason, nuclear systems are designed, fabricated, and operated with numerous safeguards, high performance radwaste systems redundancies, and with increasingly vigilant quality assurance programs and standards.

CHAPTER 2
CONCEPTUAL FRAMEWORK

The central tasks of this study are to assemble all impacts and costs of each electrical energy production system, and to reduce them to a consistent basis in order to permit comparisons. The methodology adopted has purposely been kept as straightforward as possible. Elaborate models and computational methods, which can not be supported with quality input data, were avoided. The purpose of this Chapter is to establish a brief conceptual framework useful for organizing and simplifying a very complex subject.

2.1 DEFINITIONS

Benefit

"Benefit" in this study is defined as a quantity of electrical energy, e.g., one kilowatt hour (kWhe). Since a kWhe from system A is "as good as" a kWhe from system B, the study reduces to a comparison of the risks and costs attending the production of electricity in alternate energy systems (alternate fuel cycles).

No attempt is made in this study to determine the absolute societal benefit of electricity. Other investigators have related electricity (or, more broadly, energy) consumption to standard of living, gross national product, etc., and have concluded that increased electrical energy consumption is desirable. Still others have argued that increased energy consumption, from whatever means, is undesirable, because of dwindling resources and environmental burden.

Such questions are beyond the purview of this study. The question addressed here is not whether increased electrical energy consumption is desirable, but, rather, which system (or mix of systems) can produce the energy with minimum total costs.

Risk

"Risks" are treated as costs in this study. A risk may be translated into equivalent unit energy cost once (a) the probability, or frequency, and (b) the consequences of the undesireable event are assessed:

Energy cost associated with a risk	=	Probability of the event per unit of benefit (energy produced)	x	Consequences of the event

Risks addressed in this study are those for which statistics are available, e.g. routine industrial accidents, or for which frequencies can be extrapolated from those of similar industrial operations. The study is confined to routine operation

of the energy systems. Large consequence-low probability accidents are not considered.*

With these definitions of benefit and risk, the study reduces to a comparison of costs of producing electricity by alternate systems.

Cost

Several classes of costs are addressed in this study. Although a rigorous classification scheme is not followed throughout this report, it is useful to establish and examine the conceptual basis for the meanings of cost as exercised in this study.

Costs are classified as internal or external.

. Internal Costs. Internal costs of a product or service are those costs which are borne by the beneficiaries of the product or service in the monetary price of the product or service.

. External Costs. External costs are those additional costs which are not borne in the monetary price of the product or service. External costs, or "externalities," are generated when there are mismatches between those bearing the costs and those receiving the associated benefits. Conceptually, these mismatches may occur in both sectoral and temporal dimensions. As an example of a "sectoral" mismatch, workers engaged in energy industries may bear more than their share of the cost of electricity, if not fully compensated for their unique health and safety hazards. As an example of a "temporal" mismatch, future generations may pay for our current extravagant consumption patterns in terms of future scarcity of fuel resources and accumulated environmental impacts.

. Total Societal Costs. The total societal cost of producing electricity is the sum of internal and external costs.

Costs may be "internalized" by a number of mechanisms --- installation of abatement equipment which eliminates or reduces external damages caused by energy system residuals, workers' compensation for health impairment, insurance settlements, risk pay in hazardous occupations, etc. Such internalized costs are frequently referred to as "abatement costs," "avoidance costs," "restoration costs," depending on the mechanism involved. For simplicity, the term abatement cost is used in this study to denote all such costs.

*Another USAEC-sponsored study, recently published as WASH-1400, is concerned with large consequence-low probability accidents at reactor power plants.

Because of the difficulties in rigorously measuring external costs and in establishing the degrees of internalization, a more flexible classification scheme is adopted for this study. The two types of costs in this scheme are conventional costs and non-conventional costs.

. Conventional Costs. Conventional costs are the usual costs for labor, materials, and use of money. Conventional costs generated throughout a fuel cycle are ultimately transferred to the electric utility company, and borne, along with the utility company's costs of money associated with fuel, and station (capital plant, operating and maintenance) costs, by the electricity consumer. Thus conventional costs are entirely internal. Where possible, abatement costs are identified and displayed separately.

. Non-conventional Costs. Non-conventional costs are those costs not normally associated with, or not explicitly defined in, account structures, such as public and occupational health hazards. Non-conventional costs include identifiable abatement costs and any remaining quantifiable external costs. There are three broad categories of non-conventional costs: 1) environmental impacts; the distortion of natural material and energy cycles; 2) consumption of non-renewable resources; and 3) human health and safety effects.

Figure 2.1 illustrates the cost definitions established above.

2.2 NORMALIZATION OF FUEL CYCLE IMPACTS AND COSTS

General Approach

Electric power production involves a series of processes -- fuel extraction, upgrading, transportation, energy conversion (release of the fuel's energy at the power plant), and disposal of wastes. Such a series of processes is called a fuel cycle or an energy production system. The net product (or "benefit") of the system is electrical energy. Internal and external costs are generated at each process step of the fuel cycle.

For purposes of comparing alternate fuel cycles, all such costs, both internal and external, must be assigned to a given quantity of electrical energy (net) produced, that is, the costs must be "normalized." Internal costs throughout the fuel cycle are ultimately transferred to the utility company and borne by electricity customers in the price of electricity (mills/kWhe), along with amortized capital charges for the generating plant, the utility company's cost of money associated with fuel, operating and maintenance costs, and other utility costs.

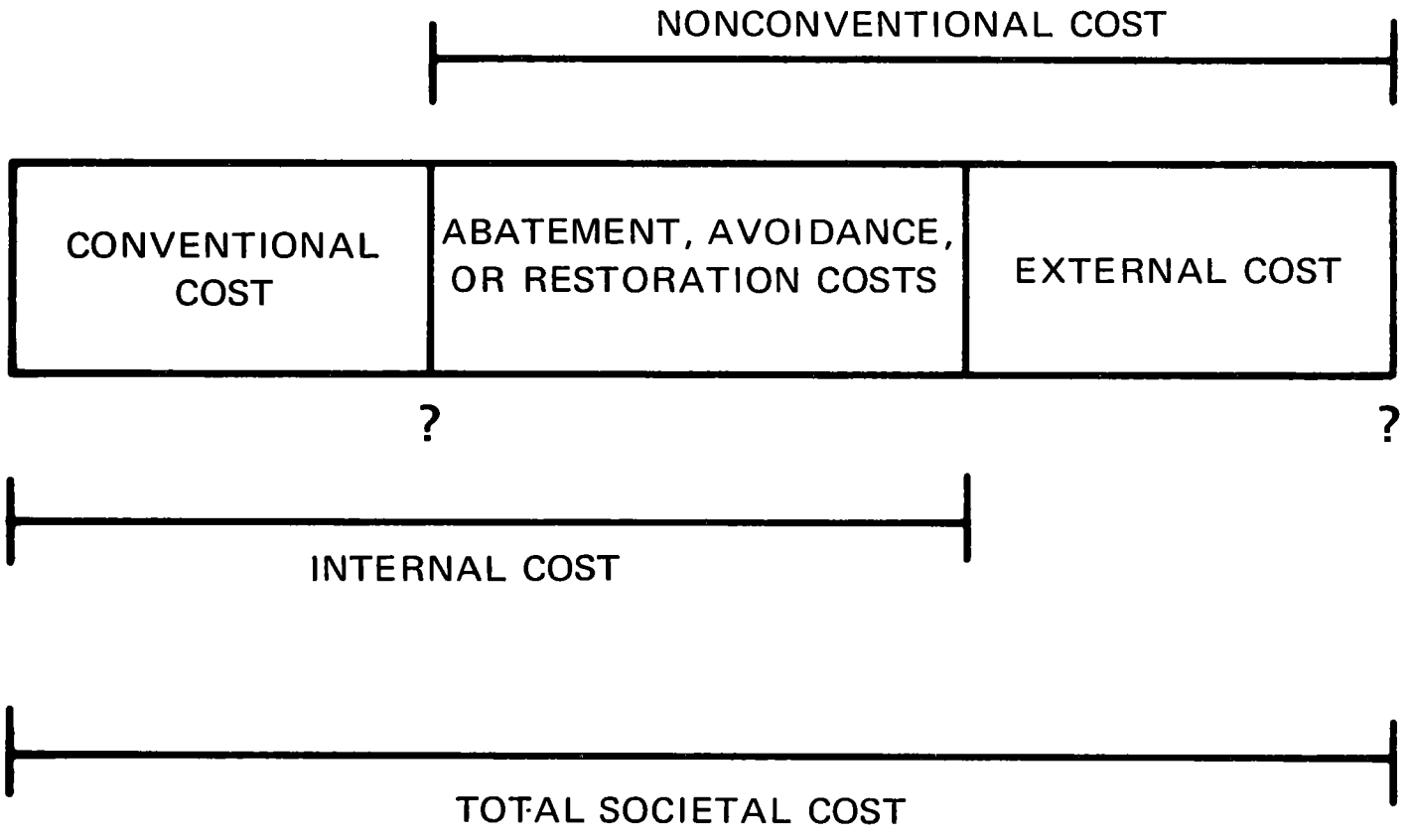

FIG. 2.1 ILLUSTRATION OF TYPES OF ENERGY PRODUCTION COSTS

The approach in this Study is straightforward: impacts and costs, where quantifiable, are tied to a unit of electrical energy via the equilibrium fuel cycle materials balance. Fuel cycle material flow sheets form the quantitative link between an impact or cost anywhere in the system, and a corresponding quantity of electrical energy (benefit) produced.

Basis

The quantity of electrical energy selected as a basis for comparing costs on impacts among systems, is largely arbitrary. Because much design literature uses 1000 MWe power plants as a basis, this nominal rating was adopted for the present study. A capacity factor (CF) of 75% is assumed. Thus the basis for comparisons in this study is the annual electrical energy delivered by one 1000 MWe power plant operating at 75% CF, i.e., 6.57 billion kilowatt hours. All supporting fuel cycle activities are normalized to this quantity.

It is recognized that because of variations, among the alternate systems, in economies of scale, the selection of a single unit rating may favor specific systems. Also, assumption of a large capacity factor, say 85%, would favor capital intensive plants, such as nuclear. Since comparison of conventional costs is not the main thrust of this study, such distortions, if they exist, are not thought to be important.

It is recognized that no single configuration for an individual energy system can be truly representative. Much of the data assembled is based on national aggregate quantities, statistics, and averages. For example, casualties in coal mining, attributable to the annual requirements of one 1000 MWe coal-fired plant, are calculated assuming 50% production from underground mines and 50% production from surface mining. These figures are typical of actual U.S. production statistics for bituminous coal in the late 1960s and early 1970s, although no single individual power plant may be supplied by this production distribution.

Normalization of External Costs

Although accounting practices vary widely among utility companies, accounting methods have been standardized[1] for purposes of making design comparisons, tradeoff studies, and the like. Highly structured methods do not exist, however, for allocating external costs, in either physical or monetary units, to electrical energy. Several classes of external costs were identified in this study. These classes are described below. While this classification scheme was not applied rigorously in this study, the scheme is useful in organizing one's thinking.

Class I. Throughput related impacts

Impacts or external costs in this category are directly proportional to fuel cycle throughout. These costs may be tied directly to a quantity of electricity energy produced, via the fuel cycle mass balance:

$$\frac{S}{E}\ \frac{\text{impact}}{\text{net electrical energy produced}} = \frac{S\ (\text{impact})}{F\ (\text{fuel throughput})} \times \frac{F\ (\text{Fuel throughput})}{E\ (\text{net electric energy produced})}$$

Most of the impacts identified in this report are of this type. Processing effluents and waste streams are of this type. Thermal discharges, for example, are directly proportional to fuel throughput, or electrical energy, as is the consumption of fuel resources.

Class II. Capacity related impacts

Impacts in this category are related to the energy industry level, or capacity, rather than fuel cycle throughput. The addition of generating or fuel processing capacity involves the investment of steel, concrete, etc., whose production imposes environmental and human impacts. The external costs associated with the production of capital equipment, if known, would be amortized over the life of the facility and, therefore, burdened to a very large quantity of electrical energy.

A second type of capital intensive impacts involves an inventory (or resources-tied-up) concept as opposed to irreversible consumption or irreversible damage. Land use is an example of this type. Power generating and fuel processing facilities occupy real estate acreage which is unavailable, during their useful lifetimes, for other uses.

Class III. Cumulative anomalous impacts

This class of impact is related to throughput and energy production but not in a directly-proportional manner, as in Class I. For example, an increment of damage from acid mine drainage cannot be assigned to a corresponding quantity of coal extracted. Rather, the current drainage impact from a given mine site is related to the total amount of coal mined to date.

Class III impacts require that assessed cumulative impacts over a long period of time be assigned to the corresponding total electrical energy produced. Class III impacts quantified in this report were treated on a case-by-case basis.

2.3 ASSESSMENT OF NONCONVENTIONAL COSTS

The discussion in Section 2.2 emphasized the necessity of using the fuel cycle materials balance as a central format for assembling, arranging and normalizing data. A thorough quantitative description of each fuel cycle process yields fuel cycle residual and effluent source terms, and other environmental and human impact data, corresponding to the production of a unit of electrical energy.

Although normalized to the same quantity of electrical energy produced or electrical power capacity, these quantities are in a variety of physical and nonphysical units --- dollars, mandays lost, tons of individual effluents, curies, acres, etc. Ideally, one wishes to reduce all such quantities to the same dimension, e.g., dollars, in order to render them comparable and additive.

Figure 2.2 illustrates the conceptual steps involved in evaluating the external cost associated with the release of an arbitrary pollutant from a power plant or from a supporting fuel cycle process facility. The pollutant generation rate is governed by the nature and activity level of the process itself. A careful description of the process materials and energy balances yields the pollutant generation rate on a per unit throughput basis. (This source term can be related directly to electrical energy production using an overall fuel cycle mass balance.) An abatement system, if present, serves to reduce the emission rate of the pollutant to the uncontrolled environment. Once released, some fraction of the pollutant may reach humans, structures, or flora and fauna where they may cause harm. The mechanisms by which pollutants move via air, water and food chain from the point of emission to affected populations or structures are exceedingly complex. The computational model must account for alternate pathways, alternate fates (loss or decay) of the pollutant, and the population distribution around the point of emission. Using ambient concentrations of pollutants established by the transport (dispersion) calculations, dose to man (or other subject) can be estimated. Resulting damage is assessed using a damage function (or dose-response function) if available. Finally the cost of the incremental damage may be converted to monetary units.

The last two steps -- application of a dose/response function to obtain damage and the assignment of dollar costs -- are the most difficult. In general, dose/response characteristics are poorly understood for low level exposures spread over a long period of time (this is discussed in Chapter 4), and only order of magnitude estimates of damage (e.g. health effects), based on conservative assumptions, can be made. Similarly, the assignment of dollar costs to human health impairment, including death, is highly subjective. A value of 50 dollars per manday lost (MDL), applicable to

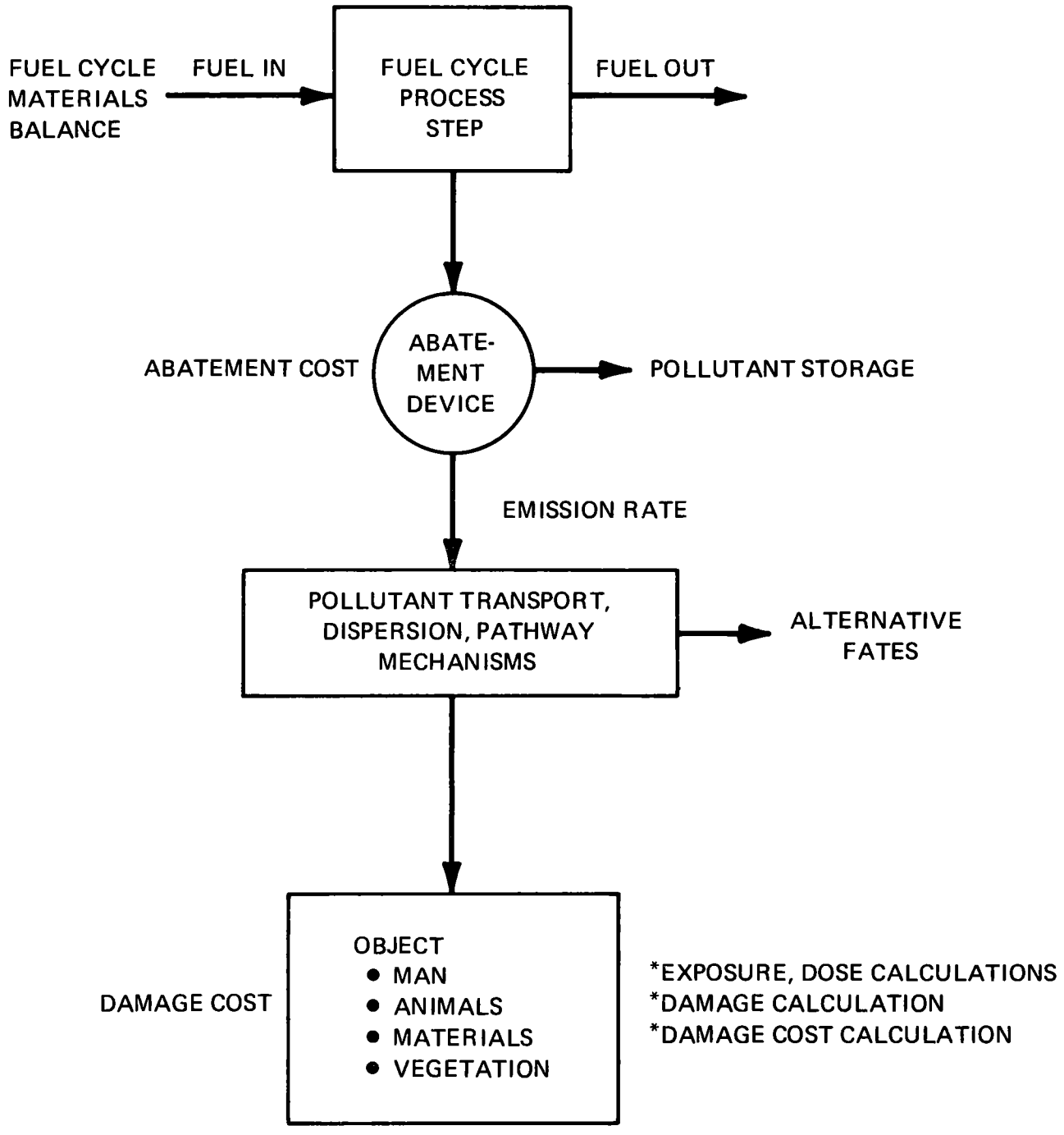

FIG. 2.2 ASSESSMENT OF EXTERNAL COSTS

occupational and public health and accident effects of all energy systems, was assumed for this study (Section 4.7). A death is assumed to correspond to 6000 MDL. Thus the assumed life value is $300,000. The reader is encouraged to substitute his own values. Mandays lost as well as their dollar value in each energy system are displayed in order that the effect of changing the dollars per manday lost figure is obvious to the reader.

The generic analysis implied by Figure 2.2 may be characterized as a "brute force" method of assessing external costs. Another gross measure of external cost is the abatement, compensatory, or restoration costs associated with preventing, compensating or repairing the damage. Ideally, the incremental cost of installing and operating abatement equipment, e.g., flue gas cleanup systems, would exactly match the incremental damage or externality prevented. This is illustrated in Figure 2.3. In practice, such cost/benefit tradeoffs have only recently been addressed by regulatory bodies, industry, and environmental groups. The reason is obvious: a rigorous cost/benefit analysis requires accurate damage function information which is simply not available for most pollutants. Further, abatement measures may simply replace one form of pollution with another, and may, indeed, be counterproductive. For example, an abatement device installed at a power plant generally decreases the plant efficiency. Thus environmental and human impacts throughout the fuel cycle are increased.

2.4 EQUILIBRIUM VS. TIME DEPENDENT CONSIDERATIONS

The procedure of assessment and normalization described above implements static comparisons across and within the alternate energy production systems. The larger problem, of course, is an assessment of total societal costs associated with alternate energy strategies, that is, alternate mixes of energy sources and production systems to meet a given, time dependent electrical energy demand over some specified period of time, say 1970-2020. The development of static impact coefficients, as discussed above and as performed in the present study, is a prerequisite of the larger assessment of comparing energy strategies.

The overall problem of comparing alternatives is time dependent for a number of reasons.

(a) Fuel resources are not equally abundant, and the depletion characteristic of a particular fuel resource locates its contribution in the time frame. Thus, for example, one might favor the natural gas fuel cycle on environmental grounds, but U.S. reserve estimates indicate that it will not be available in quantity beyond the end of this century.

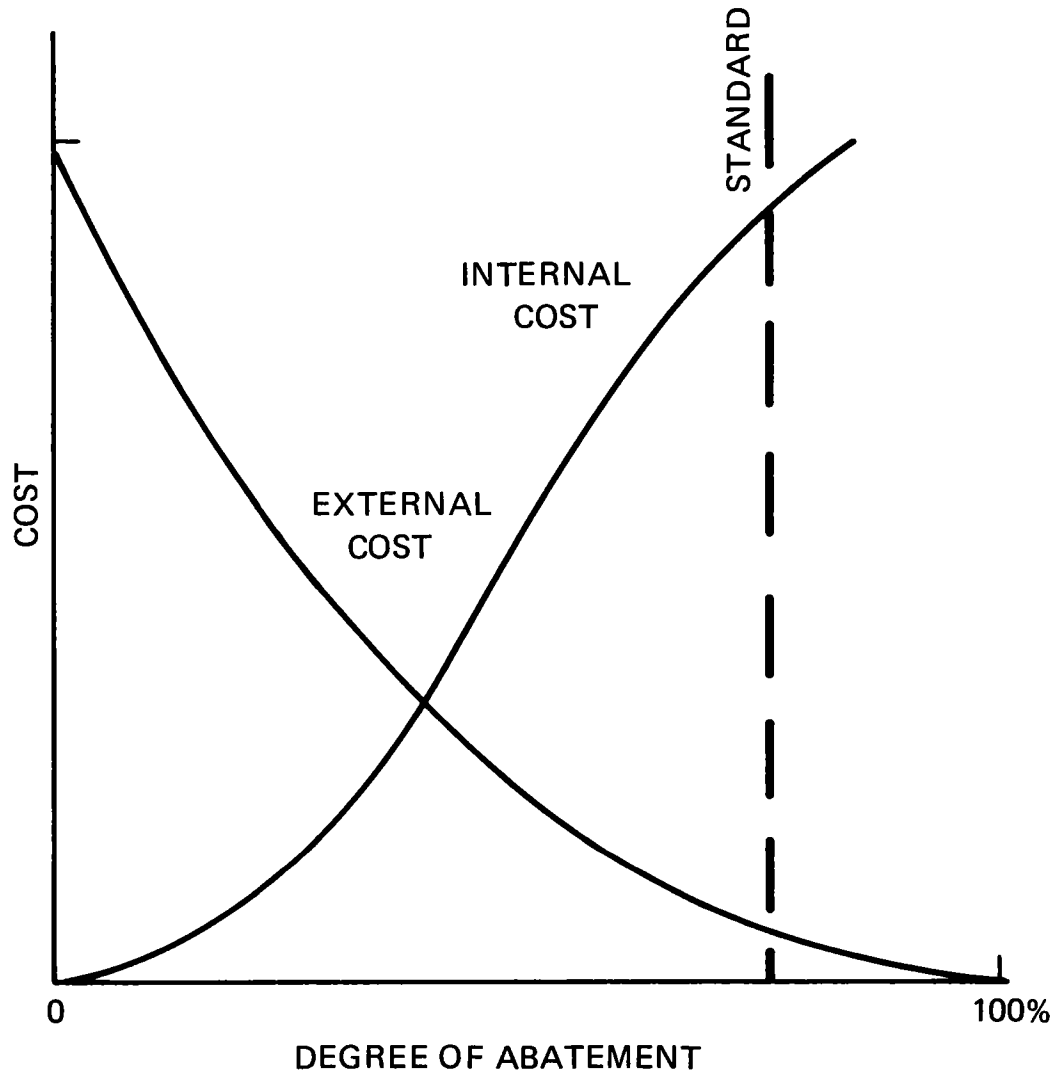

FIG. 2.3 RELATIONSHIP BETWEEN EXTERNAL AND INTERNAL COSTS

(b) The several energy technologies are in various stages of development and maturity. For example, nuclear fusion and natural gas energy cannot be regarded as competing alternatives in the same time frame.

(c) There is inertia in committing fiscal and other resources to development and installation of new energy technologies, resulting in significant time lags between conception and maturity of a new technology.

(d) The economic environment of each energy system changes with time; routine inflation of base labor and material prices may escalate energy costs preferentially; reductions in capacity/throughput ratios with system maturity, especially in the nuclear fuel cycle, tend to reduce costs, as do learning, gradual recovery of first of a kind costs, etc.

(e) Regulatory and legislative actions at discrete points in time affect the relative competitiveness and relative impacts of the energy systems.

(f) As control devices are introduced and improved, pollution rates per unit of electrical energy delivered are reduced.

(g) Impacts and costs change, or shift, as patterns of production change. For example, strip mining accounts for a much larger fraction of coal production now than it did ten or fifteen years ago, and thus the average impacts of electricity production from coal have changed in quantity and in character over this period.

(h) Environmental and human impacts may be proportional to quantity of electrical energy produced (kWhe), to the capacity of the energy production system (kWe), or to the produced energy integrated over a long period of time. There are time displacements between the production of a unit of electrical energy, or the addition of production capacity, and the appearance of an environmental or human impact.

For these and numerous other reasons, the overall problem of ranking alternatives is a time dependent one, and alternatives must be regarded as mixes of energy sources, or strategies, rather than individual sources.

Others have addressed time dependent assessments in various degrees of scope and in various degrees of detail.[2,3] A recent, highly publicized study performed at the

Massachusetts Institute of Technology[2] for the Club of Rome advertised a computer model intended to relate world population, industrial production, consumption of nonrenewable resources, and food production, and pollution. Although the modeling and quantitative results were rejected by the scientific community, the study did serve to popularize principles which have been recognized, at least qualitatively, since Malthus: that the resources of the earth are finite, and that population growth hastens their depletion, as well as multiplying environmental burden.

In a more narrow area, the U.S. Atomic Energy Commission has performed a number of studies directed at analysing the role of nuclear power in providing U.S. energy requirements.[4,5] More specifically, these assessments have examined the conventional costs and fuel cycle requirements of various mixes of nuclear reactor power plant types to meet a given electrical energy demand through the year 2020.

Incorporation of the impact coefficients (costs and impacts normalized to a given unit of electrical energy) determined in the present study, into existing computer programs [6,7,8,9] could extend these analyses to include annual and cumulative environmental burdens and other nonconventional costs through the year 2000 or beyond. Because of time and resource restrictions, this was not accomplished in the present study.

As noted in the statement of scope, this study is confined to those systems expected to make a nationally significant contribution to base load power production in the near term, i.e. the next ten or fifteen years. Only modern power plants, those added in this time span, are considered. The year 1980 is selected as a reference year, for purposes of establishing a consistent set of economic and technical ground rules in making comparisons of equilibrium fuel cycles. Plants scheduled to go in service in the late 1970's and early 1980's are currently in design, construction, and licensing phases, and there is abundant design literature* for these plants.

*Including Preliminary and Final Safety Analysis Reports and Environmental Impact Statements.

Footnotes and References for Chapter 2: Conceptual Framework

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(3) Austin, A. L. and J. W. Brewer, "World Population Growth and Related Technical Problems" IEEE Spectrum (Dec. 1970)

(4) USAEC, Potential Nuclear Power Growth Patterns, WASH-1098 (Dec. 1970)

(5) USAEC, Cost-Benefit Analysis of the U.S. Breeder Reactor Program - Updated (1970), WASH-1184 (Jan. 1972).

(6) Bloomster, C. H. et.al., PACTOLUS: A Code for Computing Nuclear Power Costs, BNWL-1169 Pacific Northwest Laboratories (Jan. 1970)

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(9) Welfare, F. G. et.al., The Oak Ridge Systems Analysis Code (ORSAC): User's Manual, ORNL-TM-3223 (May 1971)

CHAPTER 3
DESCRIPTIONS OF ALTERNATE FUEL CYCLES

3.1 INTRODUCTION

Purpose

A prerequisite of an environmental impact assessment of any industrial activity is a thorough, quantitative understanding of the fundamental technological processes involved in that activity -- all inputs and outputs of the activity, its burden on physical resources, the character and quantity of its effluents, and the efficiency with which the activity blends materials, energy, capital, and manpower into a product (benefit). For this reason, the first task of the Study was to lay out each of the competing fuel cycles, describing the basic physical processes of each step, and normalizing all quantities to a unit of electrical energy produced or to a unit of capacity (Appendix).

This chapter consists of abbreviated, qualitative descriptions of the major features of the alternate fuel cycles and tabular summaries of evaluated conventional and nonconventional costs. It is intended to acquaint an intelligent lay reader with processes and operations involved in producing electrical energy, as well as to report quantitative results of the assessment. Detailed information is provided in the Appendix.

Energy Systems Considered

The assessment is restricted to modern, base-load power plants and their supporting fuel cycles, and to those systems based on technologies whose commercial application is proven. This includes coal, oil, natural gas, nuclear (LWR), and hydro power systems.*

A number of potential sources have been excluded. Two emerging nuclear systems, the high temperature gas cooled reactor (HTGR) and the liquid metal cooled fast breeder reactor (LMFBR), were not included because widespread commercial scale deployment of these systems is projected to occur beyond the near term time frame of the study. Coal gasification, in the form intended for power plant use, also falls outside the time frame of the study. Potential sources such as geothermal, solar, and fusion power are similarly excluded.

*Hydroelectric power is included because it currently supplies a significant amount of electricity, although its role is expected to diminish over the next thirty years. Little quantitative information on hydro systems is developed in this study.

About this Chapter and Its Relationship to Other Parts of the Study

The information assembled and normalized in this report emerged from a rather extensive literature survey aimed at quantifying numerous individual impacts and costs. In most cases, the individual impacts and costs displayed in this report are derived quantities. Individual items of data taken from the literature were rarely found in the desired format, that is, restricted to the particular impact or cost under consideration and normalized to a unit of electrical energy produced. For each item addressed, considerable manipulation -- disaggregation, interpretation, aggregation, averaging, normalization -- was necessary to reduce the quantity to consistent and meaningful information. The Study, thus, has characteristics of both analysis and synthesis: analysis of individual elements of data, normalization to a consistent basis, then synthesis of the individual elements into a coherent framework.

For simplicity, much of the supporting technical material (derivations and documentation) for this chapter is contained in the Appendix and footnotes. In particular, more detailed and thorough descriptions of the coal, nuclear, oil and gas fuel cycles are to be found in the Appendix. Among other data, the Appendix presents process effluent source terms, appropriately normalized to unit fuel cycle throughput and thence to a given quantity of electrical energy produced. Chapter 4 and the Appendix address the problems of translating these source rates into ultimate impacts and costs.

In the present Chapter, effort was made to make the fuel cycle descriptions as parallel as possible, in fact, to squeeze the discussions into a standard format. This was neither possible nor meaningful, because of the inherent dissimilarities among the systems. Nevertheless, the mineral fuel sections have some rough similarities. Each of these sections contains two material flow diagrams. One of these displays a macroscopic view of the flow of the fuel resource through its respective national fuel and energy industry --- the sources of supply and ultimate dispositions, including non-electrical and non-energy uses, of the mineral. The second diagram shows the material flows through the fuel cycle process steps, normalized to 6.57 billion kilowatt hours, the electrical energy produced by one 1000 MWe power plant operating for one year at 75% CF. The fuel cycle flow sheets form the quantitative link between an impact or cost anywhere in the system, and a corresponding quantity of electrical energy (benefit) produced.

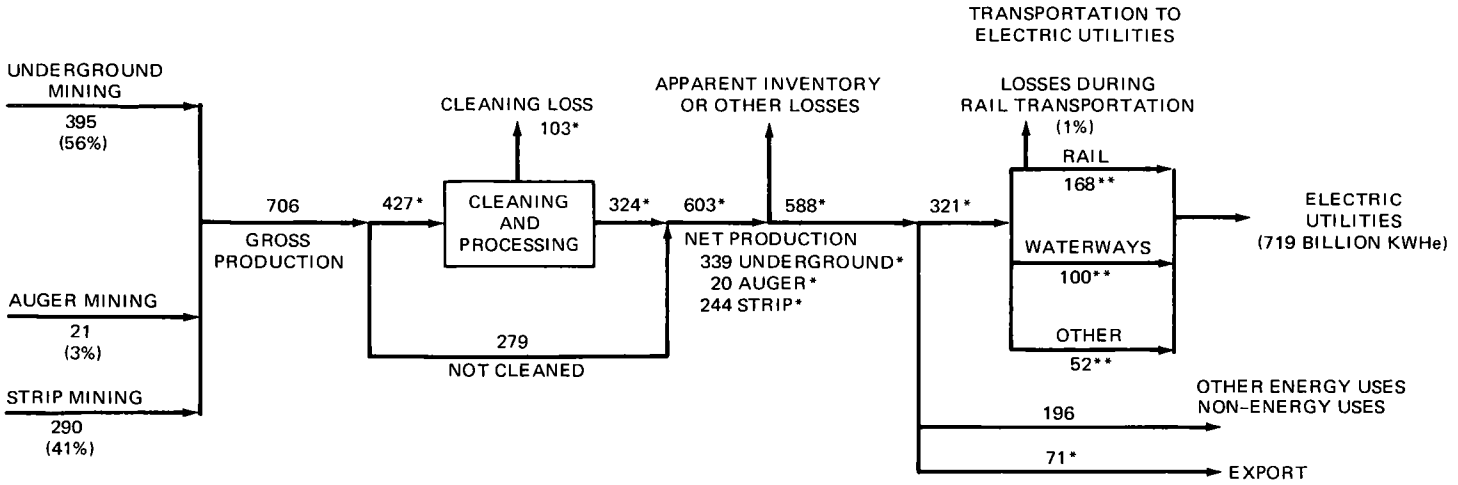
A summary table is presented at the conclusion of each section. These tables contain conventional dollar costs (materials, labor, capital), certain abatement costs, and environmental and human impact "source terms" -- all normalized to the production of 6.57 billion kilowatt hours. These quantities are arrayed by fuel process step, and are in a variety of physical and nonphysical units -- dollars, curies, tons of individual pollutants, acres, etc. To render these effects truly comparable and additive, they must be reduced to common dimensions, e.g., dollars; that is, they must be reduced to ultimate societal costs. Although efforts to accomplish this are quite preliminary and imperfect, it is possible in several specific cases, to make gross, order-of-magnitude assessments which are useful in gaining perspective and in making comparisons of alternatives. Section 3.7, the concluding section of this chapter, presents crude estimates of ultimate impacts and costs for the competing energy systems. These evaluated effects are quantified in one or both of two dimensions: dollars; and mandays lost. Again, the basis is the annual operation of one 1000 MWe power plant and its supporting pro-rated fuel cycle activities. Since quantification has not been possible for several impacts thought to be important, the tables presented in Section 3.7 do not comprise complete lists, and thus do not yield "total societal costs" for the respective energy systems.

3.2 THE COAL FUEL CYCLE

Electricity from Coal and the U.S. Coal Industry

In 1970, about 55% of the tonnage of coal produced in the U.S. was used in the generation of electricity.[1a] For the same year, coal-fired plants supplied about 46% of the electricity consumed[1b], including hydro electricity. Of the thermal plants (non-hydro), coal-fired generators accounted for about 54% of the electricity consumed.[1b] Although the relative coal contribution to thermal power generation is expected[2a] to diminish in the future (about 41% in 1980, and 30% in 1990), the demand for utility coal will continue to increase to meet increasing total electrical energy demand.[2b]

Figure 3.1 displays the production and disposition of bituminous coal in the U.S. in 1970, as inferred from National Coal Association (NCA) data.[45] The NCA's published production quantities, e.g., ~603 million tons in 1970, are the coal industry's net yield after cleaning. In 1970, about 60% of the gross raw coal production was cleaned, of which about 24% was lost in the cleaning process. Thus, cleaning losses accounted for about 15% of gross production.



*NOTE: NUMBERS ARE IN UNITS OF MILLIONS OF TONS OF BITUMINOUS COAL. NUMBERS WITH ONE ASTERISK (*) WERE OBTAINED FROM NATIONAL COAL ASS'N. (NCA), BITUMINOUS COAL DATA, 1971 ED. TRANSPORTATION FIGURES (**) WERE ESTIMATED FROM NCA, COAL TRAFFIC ANNUAL, 1970 ED. ALL OTHER FIGURES WERE INFERRED FROM BITUMINOUS COAL DATA, 1971 ED. SEE FOOTNOTE (45)

FIG. 3.1 U. S. PRODUCTION AND DISPOSITION OF BITUMINOUS COAL, 1970

Origins of Coal and U.S. Coal Resources

Coal consists primarily of the organic remains of swamp plants that lived over 200 million years ago. Under the influence of heat and pressure, the original peat-like material has been transformed into simple hydrocarbons. Not all coal has reached the final stage of metamorphosis known as anthracite, which is almost pure carbon. The next to last stage, bituminous coal, retains some hydrocarbon content and is widely used by utilities. The lower stages, lignite and subbituminous coals, have undergone less transformation, have lower heating values and are used only in areas where other fuels are not available.

In the United States, the major area of anthracite deposits is located in eastern Pennsylvania. However, the bulk of the nation's coal resources is composed of bituminous coals, found predominantly in Appalachia and the midwest, and lignite, located in the western states. The total tonnage of all types of coal estimated to underlie the U.S. down to a depth of 6000 ft. is 3.2 trillion tons[3], and the resources known to exist amount to 1.6 trillion tons, of which roughly one quarter is lignite. For various reasons involving economic and technological considerations, it is expected that much of this known resource base will never be mined. Under current conditions the actual amount that is actually available for production is in the range of 200-400 billion tons. Environmental legislation may further limit the supply through restrictions on sulfur content and strip mining practices. If only coal having one percent or less sulfur can be mined, the current reserves fall to the range of 50 to 115 billion tons. This can be compared against a current annual demand of approximately 600 million tons.

The Coal Fuel Cycle for Electric Power Production

Principle steps in the coal fuel cycle for the production of electrical energy are mining, cleaning, transportation, power generation (power plant), and disposal of residuals. Figure 3.2 shows a materials balance for a representative, modern coal-fired power plant and its supporting fuel cycle. The power plant is assumed representative of coal-fired plants coming on line in the year 1980.

Mining

Coal mining employs two major techniques: surface mining which removes the overburden to expose the coal seam, and underground mining which extracts the coal from under the overburden. Surface mining generally may be used when the seam is 100 ft. or less below ground. Otherwise, underground methods are indicated. At present about 55% of the coal industry output comes from underground mines, and the rest from surface mines.[4] Both methods are now highly mechanized, especially surface

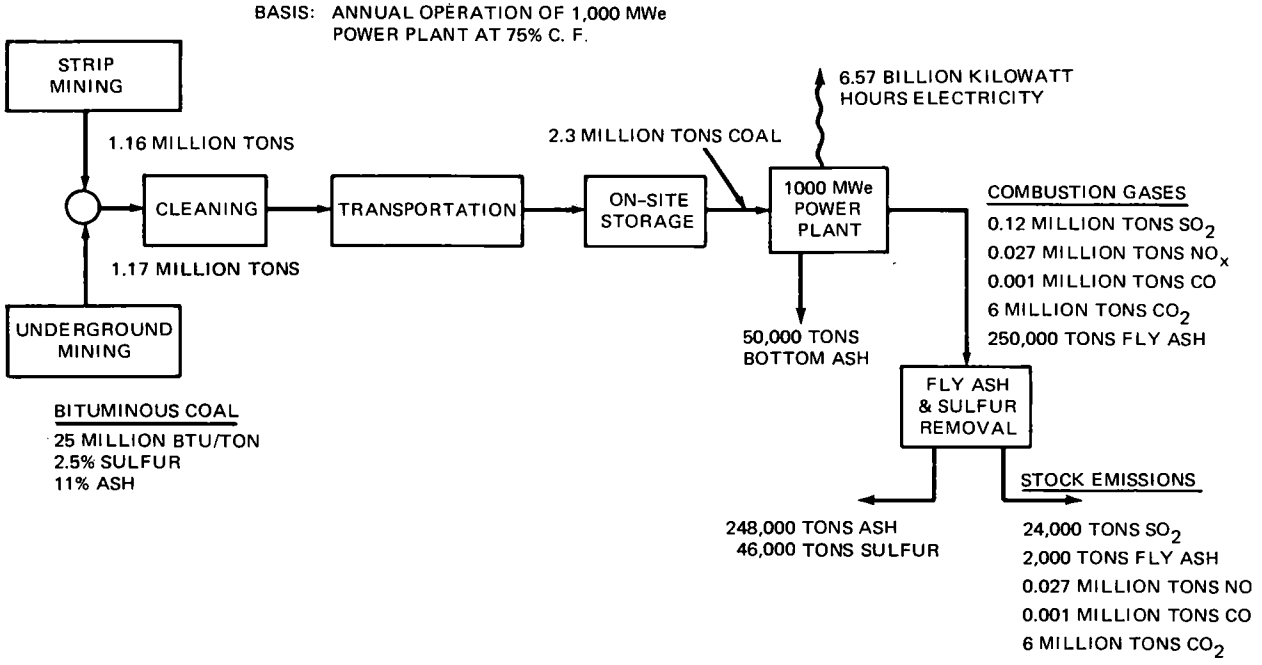


FIG. 3.2 THE COAL FUEL CYCLE FOR ELECTRIC POWER PRODUCTION

techniques which utilize enormous shovels and scrapers to load oversize trucks. Thus the productivity of the surface miner is extremely high, on the order of 5 tons per manhour. Underground mining is more difficult to automate, but presently almost all miners use machines for at least some cutting and loading. In the most advanced mines, the cutting, loading and conveying of coal is entirely mechanized in a continuous process. The productivity of the underground mines averages roughly 1.5 tons per manhour.[4]

The underground mine has a potential for serious accidents through explosions and fires due to methane and coal dust. Routine mechanical accidents also present serious hazards; annually 150-200 miners die in underground coal mines primarily because of falling rock and haulageway accidents.[27] The accident rate is much lower for surface miners, partly because less manpower is needed and partly because fewer accident causing conditions exist in surface mines.

The occupational disease of black lung, or coal workers pneumoconiosis (CWP), that afflicts many older miners develops from the accumulation of coal dust in the lungs. In some cases, the buildup of dust produces little or no disability, but in others it can trigger deterioration of the lungs that eventually renders the victim a bedridden invalid. Detailed British studies indicate that after at least 15 years exposure to coal dust, annually, 2 men out of 1000 will have a positive diagnosis for CWP, and 2 men in 10,000 will develop the acute form of the disease.[5] It is believed to occur primarily in underground mines where the men must work in confined areas with heavy concentrations of dust in the air.

Both methods of mining result in significant environmental impacts. Underground mining, by removing the support for the overlying strata produces cave-ins and subsidence at the surface. This can have little or no effect but at the other extreme it can disrupt water courses, cause collapse of buildings and prevent use of the land for agriculture, etc.[6] Although most mining operations leave behind pillars of unmined coal to support the roof, this is rarely a permanent solution to the subsidence problem, because coal is a poor structural material and grows weaker upon long exposure to air. Roughly 0.1 to 0.2 acre is subject to subsidence for every thousand tons of coal mined.[7]

The land disruption produced by surface mining comes directly from ripping up the overburden to get at the coal seam. A distinction should be made between area strip mining which is done on flat land and contour strip mining which is done along hill sides. The former tends to be ultimately less disruptive since the overburden which

is removed in one cut is usually dumped in the adjacent ditch left from the previous cut. In this fashion a large amount of the area strip mine can be filled in and reclaimed. In contrast, the contour strip operation dumps the overburden down the slope, destroying additional acreage and making it difficult to restore the land. While area stripping often takes place on farm land, which can be restored to its original use with proper reclamation practices, contour stripping frequently is done in wilderness areas which are very difficult to restore. It is estimated that about 0.15-0.3 acres are disrupted for every thousand tons of coal produced by surface mines.[9]

Coal mining causes significant amounts of water pollution. One major pollutant is acid mine drainage, composed principally of sulfuric acid and iron salts.[9] This is produced from the iron pyrites found in association with coal seams. Mining operations expose the pyrites to air, which in combination with ground waters flowing through the mine, generate the acidic drainage. When this polluted water flows into surface streams it can be toxic to most forms of aquatic life. Conditions for drainage formation are usually found in underground mines and the problem is especially severe in abandoned ones. Surface mines tend to be less significant as sources of acid mine drainage; however, the runoff from strip mine waste piles can contribute heavy silt loads to receiving bodies of water.

Mining operations create air pollution through dust releases, primarily from surface mines. Also, where coal seams have caught fire, noxious gases such as carbon monoxide, sulfur dioxide and hydrogen sulfide are released.

Cleaning and Processing

Following mining, about 60% of the total coal output of the U.S. is mechanically cleaned and processed[33,45] to reduce mineral content and to give a specified size distribution.[10] From Figure 3.1, about one quarter of the coal processed is lost; thus about 15% of the gross bituminous coal production is lost in cleaning. The principal impact of coal preparation is water pollution caused by the fine coal particles that remain suspended in the wash water. Unless the wash waters are impounded and treated, the waste water ("black water") will escape into the environment. Approximately 1.5 tons of waste water is produced for every ton of coal processed.[11]

In addition to water pollution, coal processing plants generate large amounts of solid wastes, which consists mostly of rock with a certain amount of carbonaceous material also present. Twenty percent of the weight of raw coal may be rejected

as waste during cleaning. The refuse heaps pose a land use problem, and a potential air pollution problem should the heaps catch fire.

A few cleaning plants use pneumatic methods to process the coal, generating large amounts of coal dust that must be controlled. Also, thermal drying methods may also release coal dust at some installations.

It is possible to burn raw coal in power plants or to clean the coal at the plant site rather than having it done at the mine. The choice depends upon the economics of transporting the waste contained in the raw coal versus paying higher prices for cleaned coal.

Transportation

Coal transportation plays an important role in the cycle because of the bulk of material that must be moved. A 1000 MWe coal fired power plant may require as much as 3 million tons of coal per year, which is roughly equivalent to 3 million cubic yards. The cost of transportation can amount to 40% or more of the cost of fuel to the utility.

Railroads carry 70% of the coal loaded at the mine mouth, although some is later transferred to other types of transportation. In the electrical utility sector, 52% of the coal arrives by rail, 34% by water and remainder by truck, conveyer belt and other means.[12] The average distance the coal moves between mine and power plant is 300 miles for both rail and waterway.

Because of the large volumes involved, some utilities have installed unit trains solely for the purpose of moving coal from the coal mine to a power plant. In some cases, the operation of the train is almost entirely automated.

Railroad fatality rates associated with coal movement are comparable to that of mining.[13] Each year about 2300 people die in railroad accidents, and since 25% of total tonnage carried by train is coal (half of which is intended for utility use), approximately 200 deaths per year may be attributed to its transportation for electric utility use. It should be noted that only 10% of these fatalities are employees. The majority occur when motor vehicles are struck at grade crossings.

In terms of energy consumption, the diesel fuel required to move coal by train or water is less than one percent of the energy content of the coal. The associated air pollution is also negligible compared to power plant emissions.

Electricity Generation

At the power plant, coal is burned in boilers to generate steam which then turns turbine generators. Individual coal-fired units range up to 1000 MWe and beyond in size. Many power plants have multiple units, with the older, smaller and less efficient boilers being phased out as larger, more modern units are installed. Because of the inherent limitations of the heat cycle used to convert coal's stored chemical energy into mechanical work, only about 40% of the energy is utilized, 10% escapes with the exhaust gases, and the remaining 50% of the heat must be rejected to the environment. The 1970 national average heat rate for coal-fired power plants was about 10,250 Btu/kWhre[14] and the average heating value of coal was about 11,300 Btu/lb.[15] Thus it requires about 0.91 lbs. of coal to generate a kilowatt-hour of electricity. The most efficient power plants have heat rates near 8900 Btu/KWhre.[16]

The largest power plants all use pulverized coal combustion systems which burn the fuel as a suspension of fine particles in air. This promotes complete combustion and allows flexibility in varying the power output of the plant. However, it also greatly increases the amount of fly ash that must be collected to prevent its release as air pollution. The ash content typically comprises ten percent of the weight of the coal. It is made up largely of mineral matter, usually alumina, silica and ferric oxide, although some unburned carbon may also be present. Large particles of fly ash will settle out near the power plant, while the finer particulates will remain suspended in the air. Particulates on the order of one to ten microns are opaque and cause the visual phenomenon of smoke. Much of the trace metal content of coal is carried off in the fly ash.

Aside from creating smoke and haze, particulates cause soiling of materials and increased cleaning costs. They are also suspected of accelerating the attacks of corrosive gases such as nitrogen oxides and sulfur oxides that are released by power plants.

Roughly 170 lbs. of fly ash may be produced from burning one ton of coal.[17] Control techniques such as scrubbing the exhaust gases with water sprays, collecting the particles with electric fields and using cloth filters can reduce particulate emissions by as much as 99%.[18]

Sulfur dioxide gas is formed by the burning of the sulfur content of the coal, which currently averages 2.5%.[19] Essentially, all the sulfur is oxidized; thus on the average 80 lbs. of sulfur dioxide is generated per ton of coal burned.

Sulfur dioxide causes corrosion and damage to plant life at the concentrations found in power plant exhaust gases. It is also suspected of causing or aggravating respiratory illnesses in humans, although it is unclear to what extent other factors such as particulates, cigarette smoking, etc. are also involved. Sulfur dioxide can be retained by various chemical processes, but, until the present, control methods were not installed at power plants. The most promising systems may achieve 90% efficiency in SO_2 removal, but the long term reliability of these systems has not been demonstrated.[20]

Nitrogen oxides in exhaust gases come largely from atmospheric nitrogen. They are corrosive and play a role in the formation of photochemical smog such as is prevalent in the Los Angeles area. Nitrogen oxides can be controlled by careful control of the combustion process and by keeping the maximum temperature of the furnace below 2800°F, the threshold for formation of NO_x.

Small amounts of hydrocarbons that have cancer causing potential may also be emitted from coal-fired power plants. Data from cigarette smoking research indicates that benso-alpha-pyrene (BAP) in particular may reach significant levels of concentration in the atmosphere of some urban areas.[21] However, coal-fired electricity generation is only one of the several sources (e.g., automobile) of this emission.

A variety of elements present in trace quantities in coal may be emitted during combustion. Trace elements that appear to be most important are mercury, lead, zinc and beryllium. Health authorities are concerned that these elements may produce toxic effects in humans after long exposures, either through direct exposure to air containing the elements or through reconcentration in the food chain.

Certain coals also contain measurable amounts of uranium and radium that yield radioactive decay products. However, the net exposure due to radiation from these decay products is negligible compared to that from natural background sources such as cosmic rays and granite.[22]

The ash that results from coal burning, including that part of the fly ash collected by pollution control devices, must be disposed of. Although this material may be utilized for such purposes as making cement, in most cases it is disposed of by dumping. The land used for this purpose at a 1000 MWe power plant is typically about 5 acres per year.[23] The wastes produced by some sulfur dioxide treatment methods may double this requirement.[23,24] The heat that must be rejected from the steam cycle is dissipated either to local bodies of water or to the atmosphere

by cooling towers. The former method requires careful design to avoid harming aquatic life. The cooling tower system may be objectionable from a visual standpoint because of the large bulk of the towers and the plumes of water vapor that are released.

Several factors might act to change the current picture of the coal fuel cycle. One of the most significant is the legislation concerning air pollution and mining health and safety. Due to the problems of achieving adequate sulfur dioxide control, especially for existing plants, utilities in urban areas have been converting coal-fired power plants to burn residual fuel oil, which has a sulfur content that is controllable. This trend reduces the overall demand for coal; however, the demand for low-sulfur coal has risen sharply while the usual grades of steam coal are no longer being utilized. The effect is an apparent shrinking of the reserves of coal that are economically feasible to mine. To counteract this, efforts to develop methods of coal gasification, which permit effective sulfur oxide control, are being actively pursued.[25]

The coal mine health and safety legislation will increase mining costs by requiring more safety equipment and more expensive operating procedures.[26] At some point in time, the mining companies will also become liable for compensation for miners afflicted with black lung. Since these costs are somewhat proportional to manpower, the mining companies may tend to increase productivity and reduce labor requirements through increased automation of the mines.

The resulting increase in capital investment will accentuate the existing pattern of change away from a large number of small, independent labor intensive mines, toward a smaller number of large, capital intensive operations financed by outside corporations. Also a shift toward surface mining is favored; however, this may be negated by pending legislation which will require more thorough reclamation of strip mined areas. Although U.S. coal resources are abundant, it will be increasingly difficult to mine because of the problems involved in finding deposits of suitable quality, which are near enough to the market, and that can be mined in an environmentally acceptable manner. Furthermore, increased capital costs and demands for coal in large quantities by individual consumers make it uneconomical to open or to continue operations at mines which are below a minimum annual capacity. Thus, there are difficulties in acquiring enough property to make it worthwhile to operate a mine at a given location.

Unit Impacts and Costs

Table 3.1 summarizes conventional costs (1000 dollars), and environmental and human impact data associated with the annual operation of a 1000 MWe coal-fired power plant and its supporting fuel cycle. A power plant capacity factor of 75% is assumed; thus, the quantities in Table 3.1 correspond to the production of 6.57 trillion kilowatt hours of electrical energy.

Footnotes and References for Section 3.2 - The Coal Fuel Cycle

(1a) *National Coal Association, Bituminous Coal Data, 1971 Edition, p. 77.*

(1b) *Refer to Figure 1.2 of this report, based on:*

Earl Cook, "The Flow of Energy in an Industrial Society," Scientific American (September 1971) and National Petroleum Council (1971), U.S. Energy Outlook, Washington, D. C.

(2a) *Federal Power Commission, The 1970 National Power Survey, Part 1 (December 1971), page I-1-19, Table 1.4.*

(2b) *Ibid, p. I-1-20, Table 1.5.*

(3) *Averett, Paul (1969), "Coal Reserves of the U.S. as of January 1, 1967," United States Geological Survey Bulletin No. 1275.*

(4) *Gallagher, J. J., and Westerstrom, L. W. (1970), "Coal-Bituminous and Lignite," Bureau of Mines Minerals Yearbook, U.S. Department of Interior.*

(5) *ACGIH (American Conference of Governmental Industrial Hygienists) 1969, "Synopsis of the Work Proceedings, Spindletop International Conference on Coal Workers Pneumoconiosis," Archives of Environmental Health, Vol. 21, p. 221.*

Gough, J., Testimony before Subcommittee on Labor on Coal Mine Health and Safety, 91st Congress (1st Session), Part 3.

(6) *Perry, Harry (1969), Environmental Aspects of Coal Mining, 136th Annual Meeting, AAAS, Boston, Massachusetts.*

(7) *This figure is based on an average coal seam thickness of about five feet, giving coal production of ~ 8000 tons/acre.*

Delson, J. K. and R. J. Frankel, Residuals Management in Mining Coal and Producing Power, Resources for the Future, Washington, D. C. (1971).

(8) *"Surface Mining and Our Environment," (1967), U.S. Department of Interior, U.S. Government Printing Office.*

(9) *Appalachian Regional Commission (1969), Acid Mine Drainage in Appalachia, Washington, D. C.*

(10) *Keystone Coal Manual, 1971, National Coal Association, Washington, D.C.*

TABLE 3.1

ANNUAL EFFECTS OF A 1000 MWe COAL-FIRED POWER PLANT AND ITS SUPPORTING FUEL CYCLE

BASIS: 6.57 Billion Kilowatt-hours (one year operation @ 75% CF)

		Mining	Transportation	Power Plant	Total
Conventional Costs ($10^6$$) (1980 dollars)	(28)				
Fuel		56	8		64
Plant Capital				51	51
O & M				5.4	5.4
Rounded Total					120
Abatement Costs ($10^6$$) (1980 dollars)	(43)				
Cooling Towers				3.6	
SO_2 Removal				25.9	
Strip-land Reclam.					
@ $300/acre		0.1			
@ $3000/acre		1.0			
Rounded Total					30
Occupational Accidents	(27)				
Deaths		0.98	0.055	0.03	1.1
Nonfatal injuries		40.5	5.1	1.2	46.8
Man-days lost		8330	570	350	9250
Mining Impacts					
Land disturbance by stripping (acres)	(32)	470			
Land subsidence, undergrd. mining (acres)	(32)	260			
Mine drainage (tons)	(35)	10,000			
Sulfuric acid in drainage (tons)	(35)	80			
Dissolved iron in drainage (tons)	(35)	20			
Public Accidents, Rail Transportation	(13)				
Public Deaths			0.55		
Public Injuries			1.17		
Public Days Lost			3,500		
Transportation and Handling Loss (tons)	(36)		10,000		
Occupational Health					
Coal workers pneumoconiosis	(44)				
Simple CWP (cases)		0.6			
Massive fibrosis (cases)		0.0006			
Effects at the Power Plant	(34)				
Fuel Consumption (tons)				2,300,000	
Bottom ash (tons)	(40)			50,000	
Fly ash retained (tons)	(34)			248,000	
Sulfur retained (tons)	(34)			46,000	
Waste storage area (acres)	(41)			5	
Thermal discharge (10^{10} kWh_t)				0.89	
Stack discharge (10^{10} kWh_t)				0.16	
Air emissions					
Fly ash (tons)	(34,37)			2,000	
Sulfur dioxide (tons)	(34,37)			24,000	
Carbon dioxide (tons)	(37)			6,000,000	
Carbon monoxide (tons)	(37)			1,000	
Nitrogen oxides (as NO2) (tons)				27,000	
Mercury (tons)	(39)			5	
Beryllium (tons)	(39)			0.4	
Arsenic (tons)	(39)			5	
Cadmium (tons)	(39)			0.001	
Lead (tons)	(39)			0.2	
Nickel	(39)			5	
Radium 226 (ci)	(38)			0.02	
Radium 228 (ci)	(38)			0.006	
Land Use	(32)				
Inventory (acres)		22,000		400	
Annual (acres/yr.)		736		5	

(11) Delson, J. K. and Frankel, R. J. (1971), Draft: Residuals Management in Mining Coal and Producing Power, Resources for the Future, Washington, D.C. (1/2 ton black H_2O produced/ton of coarse coal, 3 tons black H_2O produced/ton fine coal).

(12) Coal Traffic Annual, 1970, National Coal Association, Washington, D.C.

(13) Casualty rates, both occupational and public, associated with the transportation of all fuel materials considered in this report, are developed in more detail in Chapter 5. Some sources of statistical data on coal transportation are:

Federal Railroad Administration, Accident Bulletin No. 139.
U.S. Bureau of the Census, Statistical Abstract of the U.S., annual publication.
National Safety Council, Accident Facts 1971, Chicago, Illinois.
National Transportation Safety Board, Special Study: Fatality Rates for Surface Freight Transportation, 1963 to 1968.
Transportation Association of America, Transportation: Facts and Trends, Seventh Edition (April 1970), Quarterly Supplement (January 1971).
Interstate Commerce Commission, Freight Commodity, Statistics: Year Ended December 31, 1969.
Association of American Railroads, Yearbook of Railroad Facts, 1972 ed.
National Coal Association, Coal Traffic Annual, 1970 edition.
National Coal Association, Bituminous Coal Facts.

(14) Electrical World (March 15, 1972), "22nd Annual Statistical Survey."

(15) National Coal Association, Steam-Electric Plant Factors, 1971 Edition, Washington, D.C.

(16) Olmstead, Leonard M. (November 1, 1971), "17th Steam Station Cost Survey," Electrical World.

Also, Federal Power Commission, Problems in Disposal of Waste Heat from Steam Electric Plants, 1969.

(17) Smith, W. S. and Gruber, C. W. (1966), Atmospheric Emissions from Coal Combustion - An Inventory Guide, U.S. Department of Health, Education and Welfare, NAPCA No. AP-24, Washington, D.C.

Office of Science and Technology, Considerations Affecting Plant Site Selection, Washington, D.C. (1968).

(18) Reese, J. T. and Greco, Joseph (August 1968), "Experience with Electrostatic Fly-Ash Collection Equipment Serving Steam-Electric Generating Plants, Journal of Air Pollution Control Association, Vol. 18, No. 8.

(19) Smith, W. S. and Gruber, C. W. (1966), Atmospheric Emissions from Coal-Combustion - An Inventory Guide, U.S. Department of Health, Education and Welfare, NAPCA No. AP-24, Washington, D.C.

(20) Slack, A. V. and Falkenberry, H. L. (December 1971), "SO_2: More Questions than Answers," Electric World.

(21) Watson, Donald E. (1970), The Risk of Carcinogenesis from Long-Term Low Dose Exposure to Pollution Emitted by Fossil-Fueled Power Plants, UCRL-50937, Lawrence Radiation Laboratory, Livermore, California.

(22) Martin, James E., Harvard, Ernest D. and Oakley, Donald T. (1969), "Comparison of Radioactivity from Fossil Fuel and Nuclear Power Plants," in Hearings on Environmental Effects of Producing Electric Power, Part 1, Joint Committee on Atomic Energy, U.S. Government Printing Office, Washington, D.C.

(23) Office of Science and Technology (1968) Considerations Affecting Steam Power Plant Site Selection, U.S. Government Printing Office, Washington, D.C.

(24) TVA (1969) Sulfur Oxide Removal from Power Plant Stack Gas: Use of Limestone in Wet-Scrubbing Process, Clearinghouse for Scientific and Technical Information, 5285 Port Royal Road, Springfield, Virginia.

(25) Squires, Arthur M. (1971) "Capturing Sulfur During Combustion," Technology Review, MIT, Vol. 74, No. 2.

Resources for the Future, Energy Research Needs Washington, D.C. (1971).

(26) Straton, John W. (1971), "Effects of Safety Legislation on Productivity," presented at 1971 Coal Convention, American Mining Congress, Pittsburgh, Pennsylvania.

(27) Occupational injury and fatality rates, throughout each of the competing fuel cycles, are given on a consistent basis in Chapter 5. Coal figures shown assume 50% production in strip mining and 50% production in underground mining. The principal sources of data on coal cycle injury and fatality rates are liated below:

J. J. Gallagher and L. W. Westerstrom, "Coal-Bituminous and Lignite" Bureau of Mines, Minerals Yearbook, 1970, Department of Interior.
F. T. Moyer, "Coal-Mine Fatalities in 1970," Mineral Industry Surveys, p. 12.
F. T. Moyer, "Coal-Mine Injuries and Worktime, December and Annual Summary, 1970," Mineral Industry Surveys, p. 11.
National Coal Association, Bituminous Coal Facts, 1970:
p. 82, "Manpower and Safety"
p. 11, "Energy in the Seventies"
p. 18, "Transportation"
p. 91, "Transportation"
"Injury Experience and Worktime in the Mineral Industries," Minerals Yearbook, 1968, p. 137.
Association of American Railroads, Yearbook of Railroad Facts, 1972 ed., p. 24.
National Transportation Safety Boards, Fatality Rates for Surface Freight Transportation, 1963 to 1968, 1971, p. 10.
Transportation Association of America, Transportation Facts and Trends, 8th Edition, April 1971, p. 14.
Injury Rates by Industry, 1969, "Electric Companies and Systems," Bureau of Labor Statistics, No. 389.
"Injury Frequency Rates, Electric, Gas, Sanitary Services," Statistical Abstract of the U.S., 1970, p. 237.
See also footnote (13).

(28) Conventional costs exclude costs of abatement measures e.g., sulfur removal, cooling towers, surface mine land reclamation, etc. Conventional costs estimates of each of the energy systems are given in Chapter 5. They are included in this report in order to show roughly the dollar competitiveness among the energy systems and to provide reference points for the comparison of conventional, abatement, and external costs.

(29) See Section 4.10. These are costs beyond the "abatement cost" associated with installation and operation of a natural draft wet cooling tower, shown elsewhere in the table. The major component of this cost is consumptive use of water in the cooling tower, figured at 10 cents/1000 gallons.

(30) See section 4.9 and the Appendix.

(31) For a 75% capacity factor,

$$1000\ MWe \times 10^8 \frac{KWe}{MWe} \times 8760 \frac{hr}{yr} \times 0.75 = 6.57 \times 10^9 \frac{KWhe}{Yr}$$

Conventional Energy Cost (Generating), Coal-fired Power Plant;

$$\frac{120 \times 10^6\ \$/Yr \times 10^3\ mills/\$}{6.57 \times 10^9\ KWhe/Yr.} = 18.4\ mills/KWhe$$

Human Injury Cost, Coal-fired Power Plant

$$\frac{0.65 \times 10^6\ \$/Yr \times 10^3\ mills/\$}{6.57 \times 10^9\ KWhe/Yr.} = 0.099\ mills/KWhe$$

Other Non-conventional Costs, Coal-fired Power Plant

$$\frac{1.5 \times 10^6 \times 10^3\ mills/\$}{6.57 \times 10^9\ KWhe/Yr.} = 0.23\ mills/KWhe$$

(32) See Appendix for quantification of land use in the coal fuel cycle.

(33) A more detailed discussion of coal cleaning and processing may be found in Delson, J. S. and R. J. Frankel (Resources for the Future), Residual Management in Mining Coal and Producing Power (1971 Draft), page III-16 ff.

There are several methods for processing coal. Tonnages processed by various types of equipment are given by Bureau of Mines, Minerals Yearbook, 1969, Vol. II, page 348:

Types of Equipment	1968	1969
	(Millions of Tons)	
Wet Methods:		
Jigs	159	155
Concentrating Tables	47	45
Classifiers	5	3
Launders	4	5
Dense Medium Processes:		
Magnetite	71	72
Sand	27	24
Calcium Chloride	2	2
Flotation	9	10
Total, wet methods	324	316
Pneumatic Methods	17	19
Total for all Methods	341	335

(34) The following assumptions were made in obtaining the unit impact and emission data at the power plant:

a. Heating value of coal is 25 million Btu per ton.
b. Heat rate of the power plant is 8900 Btu/kWhe, yielding about 2900 kWhe per ton of coal.
c. Ash content of coal is 11%.*
d. Sulfur content of coal is 2.5%.**
e. For purposes of estimated trace element concentrations in flue gas, the representative pound of coal is assumed to have 0.75 pounds of carbon which, when burned with 30% excess air, results in one cubic meter of flue gas at standard temperature and pressure and 100 grams of coal burned.

* Fly ash emissions to air assume fly ash retention of ~99%:

Ash Content: $0.11 \frac{\text{tons ash}}{\text{tons coal}} \times 2.3 \times 10^6 \frac{\text{tons coal}}{\text{year}} = 250{,}000 \frac{\text{tons ash}}{\text{Year}}$

Fly Ash Retained: $0.99 \times 250{,}000 \frac{\text{tons ash}}{\text{Year}} = 247{,}500 \frac{\text{tons ash}}{\text{year}}$

Fly Ash Emission: $250{,}000 - 247{,}500 = 2{,}000 \frac{\text{tons ash}}{\text{year}}$

** SO_2 emissions to air assume a sulfur retention of ~ 80%:

Sulfur content: $0.025 \frac{\text{tons S}}{\text{tons coal}} \times 2.3 \times 10^6 \frac{\text{tons coal}}{\text{year}} = 58 \times 10^3 \frac{\text{tons S}}{\text{Year}}$

Sulfur emissions: $24000 \frac{\text{tons } SO_2}{\text{Year}} \times 0.5 \frac{\text{tons S}}{\text{tons } SO_2} = 12000 \frac{\text{tons S}}{\text{Year}}$ emitted

Sulfur retained: $0.8 \times 58 \times 10^3 \frac{\text{tons S}}{\text{Year}} = 46{,}000 \frac{\text{tons S}}{\text{Year}}$ retained

(Numbers do not add exactly, due to rounding.)

(35) Data for normalized values relating to mine drainage were obtained from the following sources:
Delson and Frankel, Residuals Management in Mining Coal and Producing Power, RFF.
Federal Water Pollution Control Administration, Mine Drainage Pollution Control Research and Development Project, Dept. of Interior (1968)
Appalachian Regional Commission, Acid Mine Drainage in Appalachia (with Appendices in 5 separate volumes) (1969).

(36) Coal transportation and storage losses from Delson and Frankel, p. II-25.

(37) Some coal power plant flue gas emission data were obtained from following sources:
CO_2, SO_2 and NO_x (as NO_2) -- Delson and Frankel, p. II-27
CO, formaldehyde, hydrocarbons, and hydrochloric acid -- Smith, W. S. and C. W. Gruber, Atmospheric Emissions from Coal Combustion, An Inventory Guide, HEW (April 1966).

Fly Ash -- Midwest Research Institute, "Particulate Pollutant System Study, Vol. I -- Mass Emissions," Project #3326-C, page 50, Delson and Frankel, page II-27.

Another source of emission data, for all fossil pollutants is:
McGraw, M. J. and R. L. Duprey, Compilation of Air Pollutant Emission Factors, EPA, Triangle Park, N.C. (1971)

See also Footnote (34).

(38) Emissions of Radioactivity from Coal-fired Power Plants.
References:
Eisenbud, M. and H. G. Petrow, "Radioactivity in the Atmospheric Effluents of Power Plants that Use Fossil Fuels," Science, Vol. 144, page 288.

Martin, J. E. et.al., "Comparison of Radioactivity from Fossil Fuel and Nuclear Power Plants," from Environmental Effects of Producing Electric Power, Hearings Before JCAE, 91st. Congress, Oct. 28-Nov 7, 1969.

Aberneathy, R. F. and F. H. Gibson, Rare Elements in Coal, Bureau of Mines Information Circular 8163 (1963), pages 61, 62, 63; page 15; pages 13, 14; page 11.

Denson, N. M. Uranium in Coal in the Western U.S., U.S. Geo. Surv. Bull. 1055, page 1.

(39) Emissions of Trace Metals from Coal-fired Power Plants

a. Mercury

The average mercury content of 36 American coals analyzed by a mercury vapor detector is 3.3 ppm (Ref: Joensun, O.I., "Fossil Fuels as a Source of Mercury Pollution," Science, June 4, 1971, p. 1027). The result may be on the low side because of losses in purification steps. (From the results the author suggests that a conservative global value of 1 ppm is appropriate for the combustion of 3 billion tons of coal.) Most of the sample results are in the hundreds of parts per billion, indicating perhaps that less than the average applies to coal used in the U.S. A value of 2 ppm is chosen for the present study, giving 1.6×10^{-4} pounds per million BTU in coal. See also Delson and Frankel, p. II-34.

Almost all of the mercury is released in the flue gas. Over 90% was released in flue gas according to a test on a coal-fired power plant operating at 660 MW on 21% ash coal containing 0.3 ppm mercury. Ref: Billings, C. E. and W. R. Watson, "mercury Emissions from Coal Combustion" Science (June 16, 1972), p. 1232.

b. Beryllium

An average beryllium content in coal of 2.3 ppm is reported by Abernathy, R. F. and F. H. Gibson, Rare Elements in Coal, Bureau of Mines Information Circular 8163 (1963).

The Northern Great Plains regional value is 1.5 ppm, the eastern interior and appalachian regions' value is 2.5 ppm. Consideration is given to ash contents of about 13 ppm beryllium for eastern and interior province coals (Abernathy, R. F., et.al., Spectrochemical Analyses of Coal Ash for Trace Elements, Report of Investigations #7281, Bureau of Mines, July 1969, page 4). Average ash is about 10% of dry coal so that beryllium content on a coal basis is 1.3 ppm. The average of the two sources is rounded off to 2 ppm.

Somewhat more beryllium may be mobilized into the atmosphere than corresponds to the fraction of ash which is emitted from the power plant stack. Abernathy and Gibson, (Bu Mines IC 8163), p. 15 express the viewpoint the "beryllium now present in the coal probably is a result of accumulation by plants and/or by adsorption from solution by the organic matter in the coal-forming swamps to form metallo-organic complexes." Thus, beryllium is possibly released in coal combustion in a manner not directly associated with coal ash content. Assuming that beryllium is released from the vitrain

as molecular oxide, it would be captured by available surfaces which might well be mostly the very fine ash particles which preferentially escape electrostatic precipitation.

In assigning the beryllium stack release rate in the present study, 2 ppm beryllium in coal concentration and a 6 to 1 reduction (including ~ 90% ash recovery) are assumed, leading to a stack release rate of about 3×10^{-5} pounds per million BTU in coal.

c. Arsenic

The arsenic release rates of coal-burning power plants are based on 5 ppm in coal, a world-wide average given by Bertine, K. K. and E. D. Goldberg, "Fossil Fuel Combustion and the Major Sedimentary Cycle," Science, 173, July 16, 1971, page 233. Meager data in Abernathy and Gibson (Bu Mines IC 8163) pages 13, 14 are consistent with this average.

Also, information from Abernethy (Bu Mines Report of Investigation 7281) appears to be consistent with the 5 ppm average.

Arsenic is grouped with elements found in many but not all of most ash samples. The samples with 100 to 200 ppm of arsenic account for most of the samples with arsenic present. Thus, on a coal basis, 10 to 20 ppm may be in, say, 50% of the coal or 5 to 10 ppm as an average for arsenic content. One half of the arsenic is assumed to escape in the flue gas. With these assumptions, the stack emission rate is about 2.3×10^{-4} pounds per million BTU in coal.

d. Other trace elements

Concentrations in coal of trace elements not discussed above were taken from Abernathy, et.al., Spectrochemical Analyses of Coal Ash for Trace Elements, Bureau of Mines Report of Investigations #7281 (July 1969) and Abernethy and Gibson, Rare Elements in Coal, Bureau of Mines Information Circular 8163 (1963) page 11.

e. Summary

The table below summarizes the trace element emission coefficients of trace metals established for this study.

Element	Concentration in Coal (ppm)	Stack Emission (pounds/million BTU in coal)
Arsenic	5	2.3×10^{-4}
Barium	64	5×10^{-4}
Beryllium	2	3×10^{-5}
Boron	55	4.4×10^{-4}
Chromium	20	1.6×10^{-4}
Cobalt	12	1.0×10^{-4}
Copper	12	1.0×10^{-4}
Gallium	5	4×10^{-5}
Germanium	8	6.4×10^{-5}
Lanthanium	10	8×10^{-5}
Lead	9	7×10^{-4}
Lithium	40	3×10^{-4}
Manganese	30	2.4×10^{-4}
Mercury	2	1.6×10^{-4}
Molybdenum	6	5×10^{-5}
Neodymium	4	3×10^{-5}

Nickel	20	1.6×10^{-4}
Niobium	4	3×10^{-5}
Rubidium	25	2×10^{-4}
Samarium	1.6	1.5×10^{-5}
Scandium	8	6.4×10^{-5}
Selenium	3	3×10^{-5}
Strontium	85	7×10^{-4}
Tin	2	1.6×10^{-5}
Titanium	400	3×10^{-3}
Cerium	5	4×10^{-5}
Vanadium	33	2.6×10^{-4}
Yttrium	12	1.0×10^{-4}
Zinc	40	3×10^{-4}
Zirconium	76	6×10^{-4}

(40) Bottom ash in coal-fired power plants:
Delson, J. K. and R. J. Frankel, Residuals Management in Mining Coal and Producing Power, Resources for the Future (1971), page II-27.

(41) Waste storage area at a coal-fired power plant.
The ash disposal requirement for Commonwealth Edison's Kincaid plant is assumed to be typical. Ref.: Jonelis, R. E. and R. F. Scheibel, "Kincaid Station Reservoir Development and Plant Design Features," Proc. of Amer. Power Conf., Vol. 28 (1956), page 370.

For Kincaid, 33 million tons of ash require 560 acres or about 60,000 tons per acre. For ~ 300,000 tons of ash per year per 1000 MWe plant (~50,000 tons bottom ash plus ~ 250,000 tons of collected fly ash), about 5 acres per year are required.

(42) Delson, J. K. and R. J. Frankel, Residuals Management in Mining Coal and Producing Power, Resources for the Future (1971), p. II-25.

Land disturbance figures assume 50% production from strip mining and 50% production from underground mining.

(43) See Chapter 5 of this report.

(44) Occupational Health
The most prominant occupational health hazard in the coal fuel cycle is coal workers pneumoconiosis or "black lung". British studies[5] have estimated the incident rate of the disease in typical coal dust concentrations: ~2 cases/1000 man year. The inverse productivity in underground coal mining is about 2.5×10^{-4} man-yr./ton of coal. Assuming that half of coal mined for the representative 1000 MWe power plant comes from underground mines (~1.2 million tons = 0.5 x 2.3 million tons), the expected number of cases associated with annual fuel requirements for the plant is ~0.6.

The advanced stage of the disease (massive fibrosis) occurs with an incidence rate about 100 times less. Thus, the corresponding rate for massive fibrosis is about 0.006.

See Section 4.6.

(45) The construction of Figure 3.1 (U.S. Production and Disposition of Bituminous Coal, 1970) was not straightforward. The National Coal Association (NCA), Bituminous Coal Data, 1971 ed., reports production

figures after cleaning operation. They do not list gross, mining production. The fraction of coal cleaned is given by NCA as the fraction: cleaned coal/net production (after cleaning).

In Figure 3.1, numbers indicated with one asterisk (*) were taken directly from the NCA tabulations. Other figures were inferred, as shown below. All figures are in units of millions of tons of coal, and refer to the year 1970.

a. Net Production: 603 (p. 8, NCA, Bituminous Coal Data, 1971 ed.)*
b. Raw Coal to Cleaning Plants: 427 (p. 63)*
c. Coal Obtained in Cleaning: 324 (p. 63)*
d. Cleaning Losses: 103
e. Percent of Production Cleaned: 53.6 (= c/a) (p. 9)*
f. Coal not cleaned: a - c = 279
g. Gross Production: f + b = f + c + d = a + d = 706
h. Gross production figures by method (underground, anger, strip) were obtained by ratio from NCA's net production figures (p. 13). This assumes that the same fractions of gross production by each method are cleaned.
i. The discrepancy between NCA's net production figure (603, p. 8) and their domestic consumption plus export figure (588, p. 8) is apparently a net to inventory.
j. Consumption by electric utilities: 321 (p. 77)*
k. Total domestic consumption: 517 (p. 9)*
l. Other than electric utility use: k - j = 196
m. Exports: 71 (p. 9)*

3.3 THE RESIDUAL FUEL OIL CYCLE

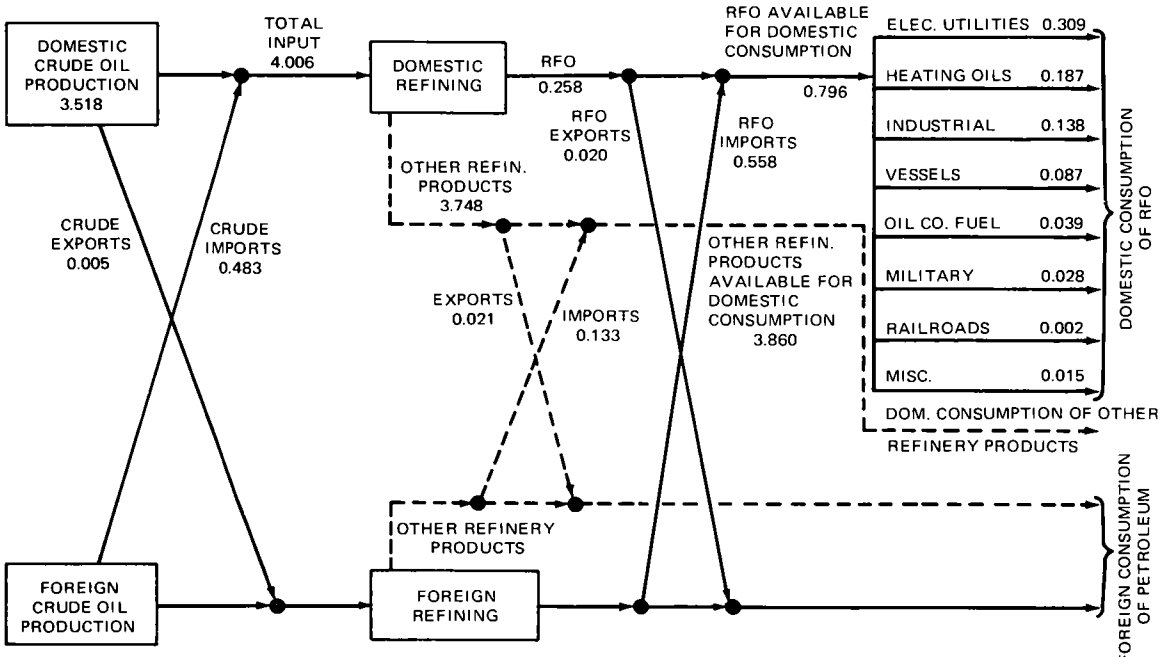
The U.S. Petroleum Industry and Electricity from Residual Fuel Oil

In 1970, power plants firing residual fuel oil (RFO) supplied about 12% of the electricity consumed in the U.S., including hydro-electricity. Of the thermal plants oil-fired generators accounted for about 14% of the electricity produced.[16] Although the relative contribution of RFO to electric power production is expected to diminish[17] after 1980 (about 14% in 1980, and 9% in 1990), the gross demand by utilities for RFO may continue to increase due to increasing total electrical energy demand.[18]

Complexity of the Petroleum Industry

In several respects, the RFO fuel cycle for the production of electrical energy is more difficult to analyze (for the purposes of this study) than those of coal and nuclear fuels. RFO production and disposition must be regarded in the context of the entire petroleum industry. Figure 3.3 displays the U.S. consumption of petroleum, including utility RFO, and sources of supply for the year 1970. The complexity of the industry is evident from this figure.

The petroleum industry is a multi-product industry. RFO is but one of a large number of energy and nonenergy products of petroleum refineries; indeed, RFO is generally considered a byproduct, if not a waste product, of U.S. refineries.



NOTE: ALL FIGURES ARE IN UNITS OF BILLIONS OF 42-GALLON BARRELS. FIGURES MAY NOT BE ADDITIVE DUE TO ROUND-OFF, NET CHANGES IN STOCK AND LOSSES. LIQUIFIED NATURAL GAS (LNG) IS EXCLUDED. THIS FLOW SHEET WAS CONSTRUCTED FROM DATA TABULATED IN ANNUAL STATISTICAL REVIEW, AMERICAN PETROLEUM INSTITUTE (MAY 1972). SEE FOOTNOTE (22).

FIG. 3.3 U. S. CONSUMPTION AND SOURCES OF SUPPLY OF RESIDUAL FUEL OIL (RFO), 1970

Costs and impacts in the petroleum industry, up to and including the refinery step, should be distributed appropriately among the multitude of petroleum products. The correct procedure for so burdening RFO is not clear, since RFO commonly has sales values lower than crude oil. Similarly, many wells produce both crude oil and natural gas. The correct procedure for dividing costs and impacts between the two is not established.

A further difficulty in analyzing the RFO fuel cycle is that significant fractions of crude oil and refinery products are imported. Foreign production and refinery technologies and practices may vary considerably from domestic technologies and practices. It is not clear how, if at all, domestic consumption of RFO (and other petroleum products) should be burdened with environmental impacts incurred abroad. Other complicating features are: the complexity of corporate structure in the petroleum industry, the varying degrees of corporate integration in the petroleum fuel cycle(s); legal, regulatory and subsidy conditions affecting the industry, such as prorationing, the oil import program, and depletion allowances; the high degree of substitutability of petroleum products, and the ability of the industry to respond to short-term changes in market conditions; and the inherent complexity and sophistication of the industry's technology.

Characteristics of RFO and the General Pattern of RFO Supply for U.S. Consumption

The production, refining and transportation of the oil consumed in the generation of electric power forms a pattern that has characteristics distinct from the rest of the petroleum industry in the United States. The particular grade of oil usually burned at power plants is known as residual fuel oil (RFO) since it comes from the residue that is left behind after the lighter fractions have been distilled during the first step of refining.[19] Residual fuel oil's low heating value and thick consistency make it undesirable for use in transportation and home heating markets, which constitute the major part of the U.S. consumption. Consequently, its sales value is traditionally below that of the crude oil from which it came. This low price makes residual attractive to utilities and other industrial users who burn fuel in sufficient quantities to justify the additional capital expenditures for the added equipment needed to handle residual. The U.S. refiners, on the other hand, regard it as a waste product and attempt to convert as much of it as possible to more profitable forms such as gasoline and petroleum coke. Thus, the yield of RFO per barrel of crude oil has dropped to below 10%, and will continue to fall as U.S. refineries install more complex processing equipment.[1]

In the absence of an adequate supply of domestic RFO, the bulk of it comes from foreign sources, predominantly refineries situated in the Caribbean which process crude from Venezuela. In 1970, the Venezuela/Netherlands Antilles area supplied about 28% of imported crudes, about 65% of imported heavy fuel oils, about 39% of imported other petroleum products, and about 46% of all imported petroleum.[23]

Caribbean refineries yield 50 to 60% RFO per barrel of crude,[2] partly because Venezuela petroleum tends to have a higher residuum content than that from U.S. wells, and partly because the economic situation in the region permits the construction of relatively simple refineries that can produce RFO profitably.

Another characteristic that sets RFO apart from other petroleum fuels is its viscosity, which is so great that it is not economical to transport RFO by pipeline for great distances. Economics also work against other modes of overland transportation such as trucks and tank cars. As a result, it is used primarily at locations that are accessible by water transportation. The consumption of RFO is concentrated in the Eastern seaboard and to a much lesser extent the Pacific and Gulf Coasts.

Hence the general pattern of the residual fuel oil industry consists of production of crude oil in Venezuela, refining and desulfurization in Caribbean refineries, transportation by tankers to east coast ports, where it is distributed to nearby industrial consumers. Electric utilities consume about 39% of the total (See Figure 3.3).[3,22]

Origins of Petroleum

The exact origin of petroleum has not been entirely resolved although the evidence points to organic material such as plant and animal remains that have come into contact with salt water. After being covered over in sediment, this material is changed into oil by the action of heat and pressure. In some cases, the oil may remain finely dispersed through the source rock. In more favorable conditions the rock is porous enough to permit the oil to migrate through the strata until it collects in suitable geological formations to form pools. The oil bearing deposits in Venezuela are primarily limestone dating from 50-100 million years, and the most productive fields are located in the Lake Maracaibo basin and the coastal area around the Orinoco River delta.[5]

Crude Petroleum and Inferred RFO Resource Bases

U.S. Petroleum Resources

Estimated U.S. crude oil reserves available at current prices and technology are about 460 billion barrels, including offshore fields.[24] Presently, the yield of RFO in domestic refineries is about 6% (see Fig. 3.3). Assuming that this yield persists indefinitely, the domestic resource base of RFO is tentatively set near 27 billion barrels. Carrying this extrapolation further, the electric utility portion of this (based on 1970 consumption patterns, Fig. 3.3) is about 10 billion barrels. Similarly, ultimate U.S. crude oil resources are estimated to be about 2800 billion barrels, or potentially 165 billion barrels of RFO.[24] With current consumption patterns, this would correspond to about 65 billion barrels available for electricity generation.

Foreign Petroleum Resources

A significant fraction of petroleum consumed in the U.S. is imported. Figure 3.3 shows[20] that about 24% of the petroleum used in the U.S. in 1970 came from foreign sources. This figure includes imported refinery products (including RFO) and imported crude. Similarly, about 72% of the U.S. RFO consumption was provided by imported RFO together with RFO from imported crude refined domestically.[20] Furthermore, oil import rates are expected to rise significantly in the future. The National Petroleum Council estimates that over 50% of the oil consumed in the U.S. in 1985 will come from foreign sources.[21] Because of the importance of foreign supply, it is important to consider foreign reserves in measuring petroleum resources presumed available for U.S. consumption.

A major source of both crude oil and refinery products for U.S. use is Venezuela, as noted above. Current known and probable crude reserves there are estimated at 69 billion barrels.[4] With an RFO yield in Caribbean refineries of 60%, this amount of crude represents an RFO resource base of about 41 billion barrels. The ultimate resource base in Venezuela has been estimated at 800 billion barrels, or potentially 480 billion barrels of RFO.[4]

Other foreign sources directly contributing to the U.S. RFO supply are in Africa, principally Nigeria and Libya. Crude oil from these nations is shipped to Caribbean refineries where it is refined into low sulfur RFO, among other products. The combined proven reserves of these two countries is 36 billion barrels or potentially 22 billion barrels of RFO.[14] The ultimate resource base may be 1100 billion barrels of crude, or equivalently, 650 billion barrels of RFO.

The RFO Fuel Cycle for Electric Power Production

Steps in the RFO fuel cycle for the production of electrical energy are crude oil production, oil storage and transportation, refining, and electrical energy generation. Production includes exploration, drilling, and production (pumping) activities. Figure 3.4 displays a materials balance for a representative modern RFO-fired power plant and its supporting fuel cycle.

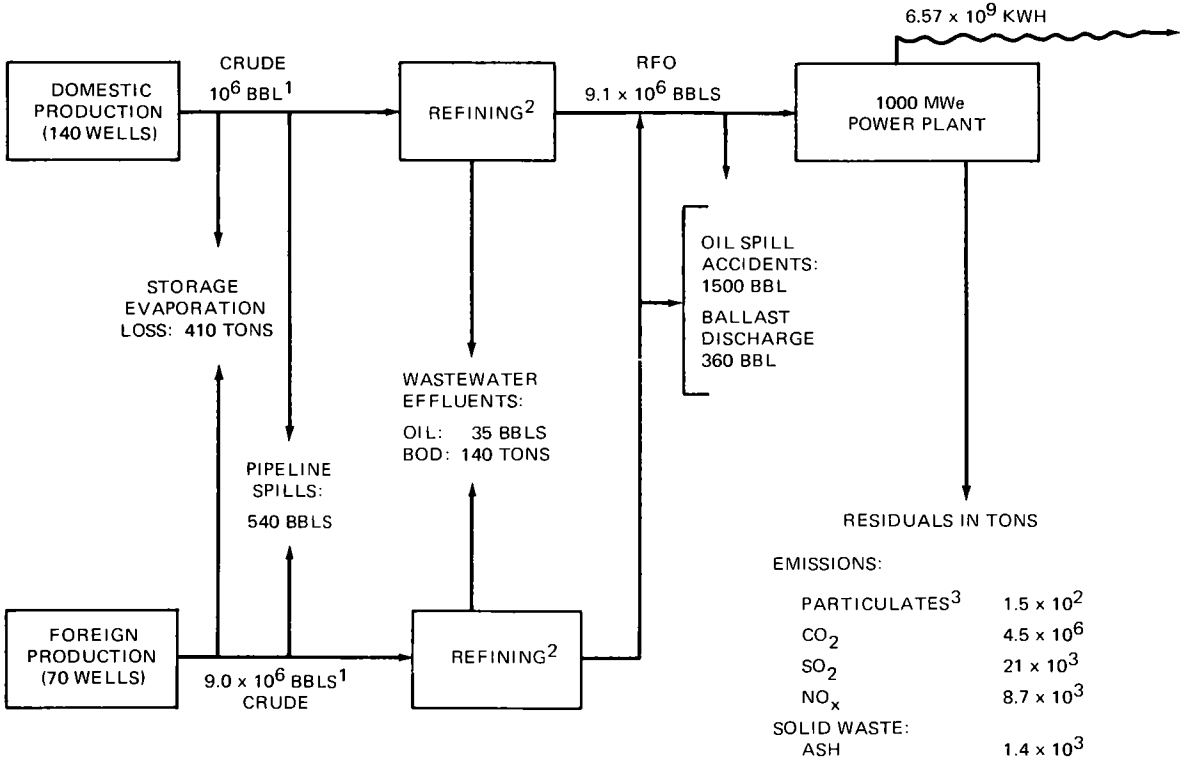
The crude oil refinery inputs shown in Figure 3.4 have been determined on a BTU-equivalent basis and represent only that portion of refinery input attributable to residual fuel oil production. The numbers of foreign and domestic producing wells shown in the diagram are based upon present United States and Venezuelan well outputs of 18.5 and 370 barrels per day.[25] If crude supplies from Persian Gulf countries were utilized, considerably fewer wells would be required. For example, at current levels of output, only six Kuwait producing wells are necessary to support the foreign crude oil stream.

Crude Oil Production

Oil is removed from the ground at wells. The rate of flow from a given well depends upon numerous factors including the viscosity of oil, its distribution in the strata, the porosity of the oil-bearing rock, and the pressure in the pool. Generally, not all the oil contained in a reservoir can be extracted; between 20 to 80% may remain after the natural driving pressure on the reservoir is exhausted. The fraction left behind depends upon a number of variables including well spacing and the amount drawn from each well. Additional secondary production from a depleted reservoir can be achieved by pumping water or gas down into the reservoir to restore the driving force.

As old wells are exhausted, new ones must be drilled, both to extend existing fields and to develop new ones. The almost universal technique of drilling uses a special bit rotating at the bottom of a line of steel pipe. The actual cutting is done by an abrasive fluid that circulates down through the pipe. The fluid cools the drill bit and then returns to the surface, carrying with it the rock cuttings.

There are a number of potential environmental hazards associated with oil production. The drilling fluid, or "mud", contains chemical agents that may be a source of water pollution. The brine that is often found in association with oil deposits may also be a pollutant. When the well strikes oil, there is the hazard of explosions and fire. After the well goes into production, oil leaks and spills can occur that



[1]PORTION OF REFINERY INPUT ATTRIBUTABLE TO RESIDUAL FUEL OIL PRODUCTION: CALCULATED ON A Btu EQUIVALENT BASIS.

[2]RESIDUAL FUEL OIL YIELD OF U. S. REFINERIES, 10%; FOREIGN REFINERIES, 40 TO 50%.

[3]ASSUMES A 90% COLLECTION EFFICIENCY FOR ELECTROSTATIC PRECIPITATORS.

FIG. 3.4 THE RFO CYCLE FOR ELECTRIC POWER PRODUCTION

may cause serious environmental impacts. Drilling and production is the most dangerous part of the cycle, based on U.S. experience. The fatality rate in the production steps is ten times higher than the other steps of the cycle. In some areas, so much fluid has been removed from underground that the land has subsided.

Refining

Most refining to RFO for U.S. consumption takes place in several large refineries sited in Venezuela and nearby Caribbean islands, namely Trinidad, Aruba and Curacao. There the crude oil is heated and distilled into individual components. The residual yield of the typical refinery averages about 50%.(6) The distillate products undergo little or no further processing; in some installations, on the order of ten percent of the throughput goes through cracking to increase the yield of lighter products, but generally speaking, the major sources of RFO are much simpler installations than those in the U.S., which produce primarily gasoline and other light distillates.

Venezuelan crude tends to have a high sulfur content, and most of it ends up in the residual fraction after distillation. The limits on sulfur content that have been imposed by the U.S. as an air pollution control measure make it necessary to reduce the sulfur level in the residual before it can be used. The simplest method consists of blending Venezuelan RFO with low sulfur residual from other regions, principally Libya and Nigeria. However, most of the refineries in the Caribbean are installing desulfurization plants in order to avoid reliance on Eastern Hemisphere producers.(7)

Desulfurization of all of the residual oil is impractical because the trace quantities of metals such as vanadium and nickel that are present will contaminate the catalyst used in the process. Instead, the residuum is put through a vacuum distillation unit, in which a fraction of it is distilled off,(8) leaving the trace metals behind in the remaining fraction. This distillate is then treated to yield a minimum sulfur content, and the two fractions are recombined, producing an overall sulfur level that meets the legal restrictions.

Refinery operations generate a multitude of pollutants. Air pollution comes both from burning fuel in the boilers to provide heat for various processes and from hydrocarbon vapors emitted from the petroleum being treated. Water pollution results from process water as well as oil leaks. In addition, a large amount of cooling water is needed. Some processes result in heavy sludge formation which constitutes a solid waste disposal problem.(9)

Storage and Transportation

The tankers used to transport the RFO from the refinery to the consumer are usually specially designed for the purpose, and have heating coils to reduce the viscosity of the oil. These residual tankers are small compared to the super tankers that carry Middle East crude: 50,000 deadweight tons compared to 300,000 for the super tanker.

The amount of RFO imported daily on the Eastern Seaboard is currently about 1,500,000 barrels per day and utilities are assumed to account for 39% of this or 590,000 barrels per day. This is equivalent to 93,000 tons/day or approximately two tanker loads per day. There is a potential for oil spills due to this traffic, both from ordinary operations such as transfers between ship and shore, and bilge and tank cleaning, and from major accidents. Statistics suggest that at least one major tanker accident per year may occur in this traffic and it will most probably happen near shore. Aside from making beaches unusable for recreation purposes, spilled oil kills marine life and water fowl.

Electricity Generation

RFO currently supplies about 15% of the energy used in steam electric power plants. Following the enactment of strict air pollution regulations, utilities with coal-fired power plants in urban areas have shown a trend to conversion to oil. On a nationwide average, a gallon of residual fuel oil will generate 13 kwhrs.[10] As with other steam-electric plants, oil-fired systems must discard approximately 60% of the fuel's energy content as waste heat. Ten percent of the heat produced by oil combustion is carried off by the exhaust gases, the remaining 50% is rejected to the condenser cooling system which may use either a body of water or a cooling tower as a heat sink.

Air pollutants emitted by oil includes sulfur dioxide, nitrogen oxides, particulates. Compared to pollutants released from coal, oil emits roughly equal amounts of nitrogen oxides per BTU, about one-quarter the amount of SO_2, and one hundredth the amount of particulates, all prior to control devices. These three pollutants are judged to be the most hazardous to human health and to be the cause of extensive property damage, although quantitative relationships between levels of concentration in the air and the resulting impact have not yet been firmly established. In addition, oil combustion releases small amounts of hydrocarbons that may have cancer causing potential. Finally, residual fuel oil, especially from Venezuela, has significant amounts of trace metals, notably vanadium and

nickel. These metals are known to be hazardous in sufficiently large concentrations, but at the levels of exposures due to fossil fuel combustion, there appears to be no danger.[11]

Because RFO is the result of chemical processing at a refinery, it is feasible to reduce air pollution from RFO by chemical treatment of the fuel before combustion to remove the sources of pollutants such as sulfur. As mentioned earlier, an extra refining step can be added to reduce the sulfur content to suitable levels. However, this added treatment increases the fuel cost by approximately 50¢ per barrel.[12] Some utilities have found it preferable to convert coal-fired boilers to burn this low sulfur oil, rather than install stack gas cleanup devices to control the emissions from coal combustion.[13]

The ash disposal problem from oil-fired power plants is negligible in comparison to that of coal.

Among possible technological developments that may affect the future of RFO as an electric utility fuel are lower cost techniques for desulfurization. Also being researched are methods of reducing its viscosity to permit piping[14] it over long distances, thus allowing its use farther inland. Another possibility is the production of synthetic liquid fuel from coal.

The major question concerns the adequacy and reliability of future RFO supplies. Estimation of oil reserves tends to be inaccurate; however, it appears that in contrast to the situation in the United States, overall world reserves will be adequate to meet future needs. The fact that almost all RFO comes from foreign sources introduces a great deal of uncertainty due to political and diplomatic complications. Petroleum imports have a significant impact on U.S. balance of payments. The U.S. Oil Import Quota system has been important in establishing the current petroleum industry patterns. Also, in the past oil supplies have been seriously disrupted by wars in the Middle East and Civil War in Nigeria. The major oil producing countries, which have historically worked at cross purposes and tried to undercut each other, have recently joined to form a solid front in negotiating crude oil prices with the major international oil companies. The result has been higher taxation and partial nationalization of company assets.[15]

Unit Impacts and Costs

Table 3.2 displays representative conventional costs (1980 dollars), abatement

TABLE 3.2

ANNUAL EFFECTS OF A 1000 MWe RFO-FIRED POWER PLANT AND ITS SUPPORTING FUEL CYCLE

Basis: 6.57 Billion Kilowatt-hours (one year operation @ 75% CF)

	Production	Refining	Transportation & Storage	Power Plant	Totals
Conventional Costs ($10^6$$) (1980 dollars)					
Fuel				180	180
Plant Capital				47	47
O&M				4.0	4.0
Rounded Total				231	231
Abatement Costs ($10^6$$) (26) (1980 dollars)					
Cooling Towers				5.9	5.9
Desulfurization		4.6			4.6
Rounded Total					11.
Occupational Accidents (27)					
Deaths	0.063	0.042	0.030	0.037	0.172
Non-Fatal Injuries	7.5	3.0	1.1	1.5	13.1
Man-days Lost	735	420	220	350	1725
Air Pollutant Emissions (10^3 tons)					
Particulates	-	0.06	-	0.15	0.21
SO_2	-	0.09	-	21	21
NO_x	-	0.3	-	8.7	9.0
CO	-	-	-	7.5	7.5
CO_2	-	-	-	4500	4500
Hydrocarbons	-	-	0.41	0.93	1.3
Aldehydes	-	-	-	0.19	0.19
Radioactive releases (10^{-6} Ci)					
Ra-226	-	-	-	150	150
Ra-228	-	-	-	380	380
Waste Water Effluents					
Saltwater brine (10^9 bbls)	20	-	-	-	20
Oil (bbls)					
Spills	-	-	1500	-	1500
Pipeline loss	-	-	540	-	540
Operational Discharge	-	35	360	-	400
BOD (tons)	-	140	-	-	140
Solid Waste, ash (10^3 tons)	-	-	-	1.4	1.4
Thermal Discharge (10^{10} kWht)	-	≈0	-	0.87	0.87
Stack Heat Discharge	-	-	-	0.17	0.17
Fuel Consumption					
Crude Oil (10^6 bbls)	92	-	-	-	-
Residual Fuel Oil (10^6 bbls)	-	-	-	9.2	9.2
Land Use (28)					
Land Inventory (acres)	1424	75	α	80	1579
Annual Incremental (acres/yr)	S	S		S	

α Land use associated with storage of petroleum and RFO is included in the production, refining, and power plant figures.

costs (1980 dollars), and environmental and human impact data associated with the annual operation of one 1000-MWe RFO-fired power plant and its supporting fuel cycle.

Footnotes and References for Section 3.3 - The Residual Fuel Oil Cycle

(1) *Southwest Legal Foundation, Exploration and Economics of the Petroleum Industry, Matthew Bender & Co., NY, NY (1969), Table 3, page 186.*

(2) *Oficina de Economia Petrolera, Petroleo Y Otros Datos Estandisticos 1969, Caracas.*

(3) *National Coal Association, Bituminous Coal Data, 1971 Edition, Washington, D.C. (1972).*

(4) *See (2), (6), (22.1), (22.2).*

(5) *Lieuwen, Edwin, Petroleum in Venezuela - A History, Russell & Russell, NY (1954), page 2.*

(6) *Creole Petroleum Corp., Data on Petroleum and Economy of Venezuela, Caracas (1971), page 18.*

See also (2).

(7) *Hutchinson, K. E., "Big Is the Word for Creole's New Desulfurizer at Amuay," World Petroleum, (Jan. 1971).*

(8) *National Petroleum Council, Environmental Conservation, Vol. 1 (1971), page 95.*

(9) *Beychok, Milton, Aqueous Wastes from Petroleum and Petrochemical Plants, William Clowes & Sons, London & Beccles, Great Britain (1967), page 267.*

(10) *Edison Electric Institute, Statistical Year Book of the Electric Utility Industry for 1971, NY, NY (1972).*

(11) *McGraw, M. J. and R. L. Duprey, Compilation of Air Pollutant Emission Factors, EPA, Triangle Park, N.C. (1971).*

(12) *Federal Power Commission, The 1970 National Power Survey, Part II, USGPO, Washington, D.C., page II-4-18.*

(13) *Resources for the Future, Energy Research Needs -- A Report to the National Science Foundation, (1971), pages 1-18, 19.*

(14) *See (22.1), (22.2).*

(15) *Resources for the Future, Energy Research Needs -- A Report to the National Science Foundation, (1971), pages X-84, 85.*

(16) *Refer to Fig. 1.2 of this report, based on:*

Earl Cook, "The Flow of Energy in an Industrial Society," Scientific American (Sept. 1971) and
National Petroleum Council (1971), U.S. Energy Outlook.

(17) Federal Power Commission, The 1970 National Power Survey, Part 1 (Dec. 1971), page I-1-19, Table 1.4.

(18) Ibid, p. I-1-20, Table 1.5.

(19) Crude petroleum consists of a mixture of several thousand hydrocarbon compounds of various molecular weights and hydrogen-carbon ratios. The compounds with the lowest specific gravity tend to have the highest heating value due to a higher hydrogen content. The boiling point of each compound is related to its specific gravity, and this fact is used to separate the crude into products of a given specific gravity, such as gasoline or diesel fuel, by distillation at selected boiling temperatures. Above 600°F, most hydrocarbons start to decompose; thus it is general practice in refineries to keep the maximum temperature of the crude below this limit in the initial distillation process, referred to as reactivation or topping. The fraction that does not evaporate at this temperature is the source of residual fuel oil. For some extremely heavy Venezuelan crudes, the fraction that remains as residual at 550°F is 90 percent in contrast to less than 30% for some U.S. crude.

(20) Petroleum Imports

Fractions of U.S. petroleum consumption from imports are computed below. Refer to Figure 3.3, which was constructed from 1970 data presented in API, Annual Statistical Review: U.S. Petroleum Industry Statistics 1956-1971, (May 1972).

All numbers are in units of billions of 42-gallon barrels,

. U.S. Domestic Consumption

RFO		0.796	(A)
Other Refinery Products (ORP)		3.860	(B)
Total		4.656	(C)

. Imports (Net)

RFO	0.558 - 0.02 =	0.538	(a)
ORP	0.133 - 0.021 =	0.112	(b)
Total		0.65	(c)
Crude	0.483 - 0.005 =	0.478	(d)

Apportion imported crude to U.S. refinery products:

0.065 x 0.478 = 0.03107	(e)	
.538	(a)	
0.569	(f)	Effective RFO Import.
(1-0.065)x 0.478 = 0.447	(g)	
.112		
0.559	(h)	Effective ORP Import.

Total Import = (f)+(h) = 1.128 (i)

. Import Fractions

Total Petroleum, (i)/(C)	24%	(j)
RFO, (f)/(A)	72%	(k)
Other Ref. Prod. (h)/(B)	15%	(l)

(21) National Petroleum Council, U.S. Energy Outlook: An Initial Appraisal 1971-1985, (July 1971), page 13.

(22) Construction of Fig. 3.3, U.S. Consumption and Sources of Supply of Residual Fuel Oil.

Fig. 3.3 was constructed from 1970 data given in or derived from the American Petroleum Institute reference (22.1). Numbers may not add exactly, due to rounding. References (22.2), (22.3), (22.4), (22.5) are other sources of statistics relating to petroleum production, refining, and consumption.

(22.1) American Petroleum Institute, Annual Statistical Review: U.S. Petroleum Industry Statistics 1956-1971, (May 1972).

(22.2) American Petroleum Institute, Petroleum Facts and Figures, 1971 Edition, (May 1971).

(22.3) Bureau of Mines, U.S. Dept. of the Interior, International Petroleum Annual, 1970, (March 1972).

(22.4) National Coal Association, Bituminous Coal Data, 1971 Edition (May 1972).

(22.5) Creole Petroleum Corporation, Data on Petroleum and Economy of Venezuela 1970, (July 1971).

(23) Reference (22.5), page 26.

Reference (22.5) is used here because the API (22.1, 22.2) displays only the crude oil imports by country of origin (22.1 p. 9). Imports of refinery products and RFO are not presented by country of origin.

(24) U.S. Crude Oil Resources

The figure of 460 billion barrels of U.S. crude, available at current prices and technology, was obtained from reference (24.1), as follows:

	U.S. Crude Oil Resources (billion barrels)		
	OnShore	OffShore	Totals
Proved Reserves	34	5	39
Indicated reserve plus undiscovered resources producible with current economics and technology	246	171	417
	280	176	456

The ultimate U.S. resource figure of 2800 billion barrels of crude was obtained from ref. (24.1), as follows:

U.S. Crude Oil Resources
(billion barrels)

	OnShore	Offshore	Totals
Available with current economics and technology	280	176	456
Undiscovered resources not discoverable and discovered resources not producible under current economics and technology	1100	1180	2280
	1380	1356	2736

Source:
(24.1) U.S. Dept. of Interior, U.S. Energy: A Summary Review, (Jan. 1972) p. 27.

(25) Oil and Gas Journal, (December 27, 1971).

(26) See Chapter 5 of this report.

(27) Occupational Injuries in the RFO Cycle

Raw statistics relating to injuries in the oil and natural gas industries were taken from reference (27.1).

Several difficulties are encountered in assigning injuries to a unit of electrical energy produced from residual fuel oil:

(a) the statistics presented in (27.1) aggregate oil and natural gas production activities;

(b) the injuries attributable to oil must be distributed appropriately among the refinery products;

(c) the statistics tabulated in (27.1) refer only to domestic production, transportation and refining; foreign injury statistics are not available; this problem is relevant because most RFO consumed in the U.S. is imported.

Problem (a) was resolved by attributing injuries according to dollar values of production. Well-head values for crude oil and natural gas production in 1971 were $11.9 billion and $4.0 billion, respectively. Thus, 75% of the injuries relating to production activities are assigned to oil production.

Problem (b) was resolved by distributing production, transportation, and refining injuries to refinery products on a BTU - equivalent basis. Assume that the heating values of crude oil and residual fuel oil are 5.8×10^6 BTU/barrel crude and 6.3×10^6 BTU/barrel RFO respectively (ref. 27.2). Assume further that refinery yield of RFO are 10%, that is 10 barrels of crude oil yield 1 barrel of RFO plus other refinery products. (Domestic yields are currently about 6%). Thus one BTU (crude oil) yields ~0.11 BTU (RFO), that is, RFO accounts for about 11% of the fuel energy output of the refinery, and 11% of the impacts, such as occupational injuries, at and before the refinery are attributed to RFO.

Problem (c) was resolved by assuming that foreign occupational injury rates are similar to those in the U.S.

The following sample calculation for oil production fatalities illustrates the method.

A. U.S. 1969 Production (exploration, drilling and pumping) fatalities in oil and natural gas industries = 28 fatalities (CO+G) (ref. 27.1).

B. Fatalities attributable to oil production = 0.75 x 28 = 21 fatalities (CO)

C. U.S. 1969 crude oil production = 3.2×10^9 bbls CO

D. Fatality rate = $21/3.2 \times 10^9 = 6.59 \times 10^{-9}$ fatalities (CO)/bbls CO

E. Annual fuel requirements of one 1000 MWe RFO-fired power plant
   Heat rate = 8830 BTU/KWHe
   Cap. Factor = 75% (Electrical Energy = 6.57×10^9 KWHe/yr)
   Annual Heat = $8830 \times 6.57 \times 10^9 = 58 \times 10^{12}$ BTU/yr.
   RFO Req't = 58×10^{12} (BTU/yr)/6.3×10^6 (BTU/bbl RFO) = 9.21×10^6 bbl RFO/yr.

F. Crude oil refinery input to yield this ammount of RFO:
   9.21×10^6 (bbl RFO/yr)/0.10 (bbl RFO/bbl CO) = 9.21×10^6 bbl CO/yr

G. Corresponding number of crude oil production fatalities
   = 92.1×10^6 bbl Co/yr x 6.59×10^{-9} fat./bbl Co = 0.61 fat/yr

H. This figure must be weighted by the factor 0.11, as explained above, crude oil production fatalities attributable to annual RFO requirements of one 1000 MWe power plant = 0.61 x 0.11 = 0.067 fatalities/year.

   This figure assumes 100% domestic supply of RFO. From Fig. 3.3, only about 32.4% of U.S. RFO consumption (1970) came from domestic sources. This domestic fatality rate is

   0.067 x 0.324 = 0.022 fatalities/yr.

I. The foreign production fatality rate, attributable to the annual RFO requirements of one 1000 MWe power plant, is computed in a manner similar to steps A-H above. The following assumptions are made:

   - RFO import fraction is 1-0.324 = 0.676 (See Fig. 3.3)
   - Foreign fatality rates on per unit barrel produced basis is same as for U.S., as given in Step D.
   - RFO yield in foreign refineries is ~ 50%
   - Heating values of crude oil and RFO are the same as assumed for U.S. oils.

   With these assumptions, the foreign production fatalities attributable to a U.S. RFO-fired power plant are = 0.0445 fatalities/yr

J. From step H and I above, the total (domestic and foreign) fatality rate is = 0.067 fatalities/yr.

This procedure was repeated for transportation and refining steps in the fuel cycle. Average 1968-69 injury rates, e.g., fatalities per barrel, derived from ref. (27.1) were used to obtain values for fatalities and non-fatal injuries presented in Table 3.3.1.

(27.1) U.S. Dept. of Interior, Bureau of Mines, Mineral Industry Surveys (1970) "Disabling Work - Injury Experience of the Oil Industry (All Activities) and Natural Gas Industry (Excluding Distribution Activities) in the United States, 1969."

(27.2) American Petroleum Institute, Annual Statistical Review (May 1972), page 60.

(28) See Appendix for quantification of land use in the RFO cycle.

3.4 THE NATURAL GAS FUEL CYCLE

The U.S. Natural Gas Industry and Electricity from Natural Gas

Natural gas supplies energy for the generation of about one-fourth of the central station electricity produced in the U.S.(17) Approximately one-sixth of the total natural gas is used in the electric power industry. The remainder is used in the petrochemical industry, industrial process heat, residential and commercial heat, refrigeration, and air conditioning. Figure 3.5 displays the production and disposition of natural gas in the U.S. in 1970.(18)

In the early years of oil exploration, the discovery of natural gas was considered a byproduct in the search for oil. Natural gas was disposed of in the field, either by burning or by venting to the atmosphere. As late as the mid-1930s, a gas-only well was considered little better than a dry hole.(19)

It was not until the development of thin-walled, high tensile strength pipe that the natural gas industry matured. Following World War II, long distance pipelines opened up the northern markets to gas supplies from producing wells in the Southwest. As demand for gas increased, gas became a product in its own right and ceased being a byproduct of oil production. The enhanced status of gas was reflected in the reorganization which occured within many producing companies as gas production departments were established separate from oil production departments. Over the past two decades, companies have continually increased the portion of their exploratory effort devoted to the search for gas.

Origin and Occurrence of Natural Gas

The most commonly accepted explanation for the origin of natural gas is that it was formed from organic matter in the same manner and in the same time frame as oil. A similar process can be observed in the formation of "swamp gas" where small quantities of flammable gas bubble up through stagnant water. The natural gas reserves in use today exist below ground or sea and are covered by impermeable rock. Most natural gas in tested reservoirs has been found at depths of 1000 to

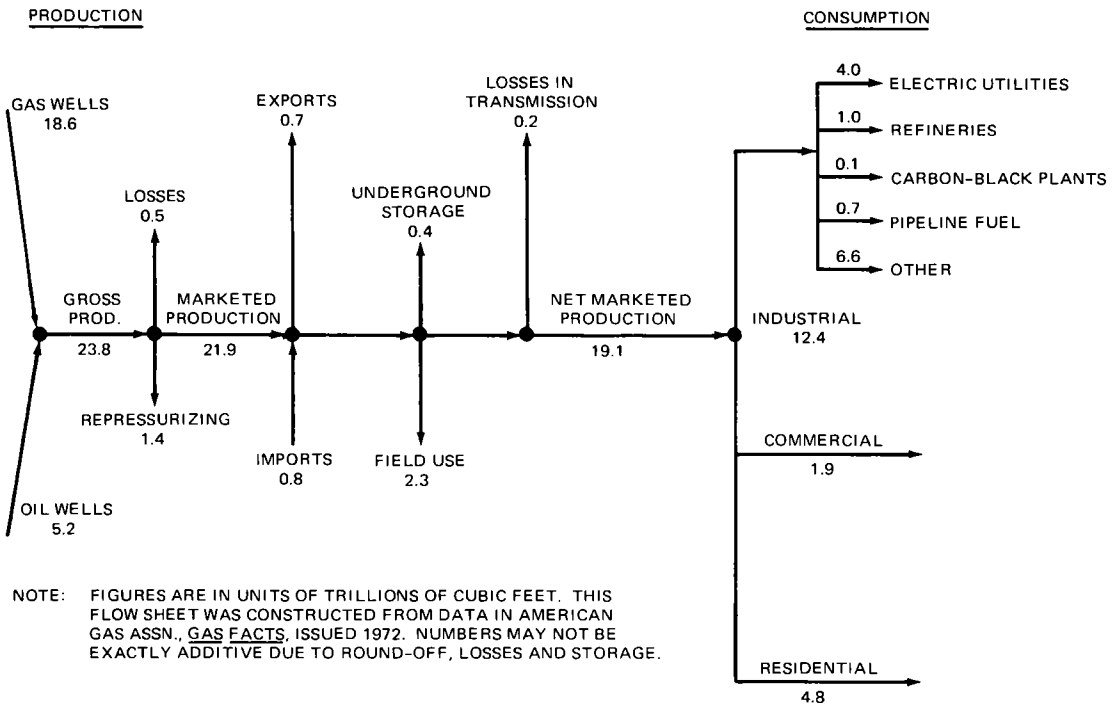


FIG. 3.5 PRODUCTION AND DISPOSITION OF NATURAL GAS IN THE U. S., 1970

18,000 feet below the surface of the earth; the deepest successful well drilled was 24,453 feet. Gas deposits may be found with pressures as high as 10,000 psi. The geography of the natural gas production industry is closely allied with that of the crude oil industry. The bulk of domestic production is concentrated in the Texas-Louisiana-Gulf Coast, Texas Panhandle, and West Texas-East New Mexico regions.

Gas Supply and the Price of Natural Gas

Natural gas is one of the least polluting forms of energy available. Unfortunately, proved reserves of this fuel have been declining both in absolute and relative terms for the past several years. At the end of 1971, proved reserves stood at 278 trillion cubic feet, only 12 1/2 times the present rate of consumption. The availability of gas at acceptable prices is the overriding consideration in judging the merits of natural gas as a viable alternate source of electrical energy. For this reason, most of the discussion below centers on natural gas supply and demand, i.e., conventional economics and costs, rather than environmental impacts.

Gas Supply

It is now generally recognized that past government policy has favored the pricing of natural gas at too low a level.* The result has been an over-development of the markets for this fuel and underdevelopment of new sources of supply. Overcoming the present supply "crunch" is the overriding problem facing natural gas companies and their state and federal regulators.

It is unlikely that gas energy will be available either in sufficient quantity or at low enough prices to make it a competitive energy source for baseload power plants coming on line in 1980. Although new sources of gas energy, such as imported liquified natural gas (LNG) and substitute natural gas (SNG, produced from coal, LP-gas, and petroleum naptha) will be available in significant quantities by the end of this decade, it is likely that these new supplies will be reserved for the residential and commercial markets. In any event, the high delivered cost ($1.10 - $1.50 per million Btu) of these fuels will preclude their use in baseload power plants.

Given the present supply-demand imbalance for natural gas produced from wells and the high cost of alternative sources of gas energy, simple economics dictates that

*The Federal Power Commission regulates the price of natural gas sold in interstate commerce. The Commission's regulatory stance has been largely determined by court interpretation of the Natural Gas Act. See References (1) and (2).

the price of gas will increase. The FPC, in fact, has recently proposed that the field price of new-contract gas sold in interstate commerce be essentially decontrolled. Whether significantly higher or even free-market prices can be justified under provisions of the Natural Gas Act, however, remains to be seen. Also uncertain is the shape of natural gas supply curve as a function of price. At what price would the supply-demand balance be restored?

New Sources of Natural Gas Supply

New supply sources include: (1) additions to conventional sources, that is, gas from the lower forty-eight states, southern Canada, southern Alaska, and the continental shelves off the Gulf and West Coasts; (2) gas from Alaska's North Slope and Canada's northern frontier territories; (3) imported liquified natural gas (LNG) from Algeria and other overseas sources; (4) synthetic natural gas (SNG) processed from coal and from petroleum products; and possibly (5) gas produced by nuclear stimulation from tight reservoirs in the Rocky Mountain states.

Conventional Sources. Domestic reserves of natural gas have been declining in recent years and now stand at about 280 trillion cubic feet, roughly 12-1/2 times domestic production during 1971. The difference between domestic consumption of 23.7 trillion cubic feet during 1971 and domestic production of 22.8 trillion cubic feet was made up by net imports of 0.9 trillion cubic feet. Most of the imported gas originated in the Canadian Province of Alberta.

A recent staff study conducted by the Federal Power Commission forecasts a peak in U.S. gas production of about 25 trillion cubic feet in the mid-1970's followed by a decline to about 20 trillion in 1980 and to 18 trillion in 1990.[3] Reserve additions in the lower forty-eight states for the period 1971-1990 are estimated at 325 trillion cubic feet, roughly 20 to 40% of current estimates of the ultimate undiscovered potential of the region. Higher natural gas prices are expected to lead to improved reserve additions in most of the major producing regions of the country. South Louisiana additions should increase from 5.6 trillion cubic feet in 1970 to 8.6 trillion cubic feet in 1975. Texas Gulf Coast additions will rise from 1.1 trillion in 1971 to 1.4 trillion in 1975, while Permian Basin additions will increase from 1.2 trillion cubic feet in 1971 to 1.6 trillion in 1975. Hugoton-Anadarko additions are projected to be flat at about 1.5 trillion from 1971 through 1975. Texas Gulf Coast, Hugoton-Andarko, and Permian Basin reserve additions are expected never to recover to their 1966-67 highs. Production in South Louisiana, the Texas Gulf Coast, and the Rocky Mountains is expected to

increase through 1975, while the Hugoton-Andarko, Permian Basin, and other Southwest regions are expected to peak out in 1973.

If FPC projections are correct, by 1980 domestic consumption of gas will exceed the supply from conventional sources by some 9 trillion cubic feet. This short-fall will have to be made up by some combination of arctic gas, imported LNG, SNG manufactured from coal and petroleum products, and by gas released from tight reservoirs by nuclear stimulation.

. Arctic Sources. Recent exploratory drilling in the Alaskan and Canadian arctic indicate the presence of vast reserves of natural gas. Exploration until now has been mainly centered in three regions: (1) the Prudhoe Bay area of Alaska's North Slope, (2) the Mackenzie Delta of the Beaufort Sea Region, and (3) the Ellef Ringness-Ellesmere Island area.

Proved reserves in the Prudhoe Bay fields are already sufficient to justify construction of a natural gas pipeline. Most of these reserves, however, consist of associated and dissolved gas so that production cannot begin until a market outlet is established for the crude oil. Delays in commencement of construction of the trans-Alaska crude oil pipeline have delayed construction of a natural gas pipeline. The cost of transporting gas produced from the Prudhoe Bay fields east to the Mackenzie Delta and then south down the Mackenzie River Valley to Midwestern markets is estimated to be $0.81 to $1.00 per thousand cubic feet (Mcf).(4)

Unlike reserves in the Prudhoe Bay area, natural gas reserves so far discovered in the Mackenzie Delta consist mainly of nonassociated gas. Imperial Oil has conducted most of the search in this region and has reported a number of gas strikes along the Beaufort Sea coastline.(5,6) The oil company has recently signed an agreement with two Midwestern pipeline companies, committing up to 10 trillion cubic feet of "potential natural gas reserves in the Mackenzie Delta area of the Northwest Territories."(7) The two pipeline companies will make advance payments of $40 million dollars to accelerate development and production of gas reserves. Imperial Oil Company estimates that proved reserves of 15 trillion cubic feet are required to justify a pipeline. The company is confident that this figure will soon be reached. A recent Gulf-Mobil strike some 40 miles south of Beaufort Sea coastline has greatly extended the potential gas-bearing area in the Mackenzie Delta.(6)

Panarctic Oils Ltd., has made major gas discoveries in the Arctic Islands (roughly in the region 78° - 80° north latitude and 84° - 112° west longitude). Gas

reserves of 25 - 30 trillion cubic feet will be needed to support a pipeline out of the region. It appears likely that these reserves will be proved within one or two years. Four United States gas companies have pledged $75 million advance payments with an additional $75 million payable upon the laying of a pipeline.(8)

The ultimate potential of the arctic fields is unknown; however, it is likely that each of the three regions discussed above will be producing one trillion cubic feet annually by 1980. U.S. "city-gate" costs of natural gas from these sources will be approximately $1.10 per Mcf with transportation representing three-fourths of total cost.

Liquified Natural Gas. The American Gas Association predicts that by 1980 the United States will be importing 2 trillion cubic feet of natural gas annually. El Pase Natural Gas Company's proposal to import one billion cubic feet daily from Algeria is the first officially approved by the Federal Power Commission.(9) Other proposals include one by Indiana Standard and People's Gas to import gas from Trinidad, another by Tenneco and Texas Eastern Transmission for imports from the Soviet Union, and an assortment of others by gas utilities and pipeline companies for imports from overseas sources in Ecuador, Venezuela, and Nigeria.

In approving the El Pase Natural Gas Company's import plan, the FPC set initial rate ceilings of 85¢ per Mcf for deliveries to Columbia Gas' Chesapeake Bay terminal and 94¢ per Mcf at Southern Energy's terminal near Savannah, Georgia. A one cent per year escalation was allowed for deliveries after 1980.* The total capital cost of the receiving, storage, and transportation facilities associated with the receiving terminals is estimated at $270 million. These costs will add approximately 15¢ to the delivered cost of the gas. The estimated $630 million cost of liquification facilities in Algeria and tanker costs of approximately $750 million are covered by the import rates to be charged by El Paso Natural Gas Company.

. Synthetic Natural Gas. According to National Petroleum Council projections, production of synthetic pipeline gas should reach one-half trillion cubic feet by 1980.(10) Most of the synthetic gas will be produced from naptha and LP-gas with production ultimately limited by the availability of imported feedstock. Because of its high cost, synthetic natural gas is usually considered as an emergency

*El Paso has indicated that it considers the rate ceilings too low and has applied for an increase.

energy source by pipeline and gas utility companies unable to arrange for new supplies of well gas. Construction time for SNG plants is only about two years.

The Columbia Gas Systems project at Green Springs, Ohio will produce synthetic gas from Canadian LP-gas at an estimated cost at the plant of $1.12 per Mcf. Algonquin Gas Transmission Company estimates the cost to its customers of gas produced at its naptha-based plant in Freetown, Massachusetts, will be $1.80 per Mcf.* The Office of Emergency Preparedness lists twenty-two companies with proposals to build SNG plants based on imported petroleum feedstock.(5)

Production of synthetic pipeline gas from coal is not likely to represent a significiant source of gas supply before 1985. Although feedstock costs for a coal-based plant are considerably lower than for petroleum-based plants, capital and environmental costs are considerably greater, yielding a gas product of comparable overall cost. A recent staff study by the Federal Power Commission forecasts 0.3 trillion cubic feet of synthetic gas from coal in 1980 and 1.4 trillion in 1985.

. Nuclear Stimulation. It has been estimated that 300 trillion cubic feet of natural gas could be freed by nuclear stimulation from tight reservoirs in the Rocky Mountain area at a wellhead cost of less than 50¢/Mcf.(11) The 300 trillion cubic feet estimate is based upon extensive geological data for the region in question and upon test results from Atomic Energy Commission projects Gasbuggy, Rulison, and Miniata.

Given a 65¢/Mcf wellhead price in 1985, a Cities Service Company study indicates that nuclear stimulation of low productivity reservoirs could yield 6.2 trillion cubic feet per year by 1985 and 11 trillion cubic feet per year by 1990.

Major problems associated with nuclear stimulation are the local effects of seismic shocks and the risk of radioactive contamination of underground water supplies. Development of gas reserves on a scale comparable to that projected by the Cities Service study will depend upon the timely resolution of problems associated with these external effects.

*SNG costs in cost-of-service rate applications to the FPC for base-load plants have ranged between $1.12 and $1.42/Mcf, cost-of-service rates for peak shaving projects have ranged from $1.60 to $1.80.

Price of Natural Gas

Given the high transportation costs for natural gas originating in remote areas, the high costs of SNG, and the likelihood that free market prices will prevail for gas produced from conventional sources, it seems likely that the price of natural gas in 1980 will be several times 1972 interstate price ceilings. In 1980 the average new-contract price for gas delivered to Midwest markets is estimated to be at least 85¢ per million BTU (roughly 90¢ per Mcf).* At this price, natural gas will continue to penetrate the electric utility market as a fuel for gas turbine peaking operations. As a fuel for boilers designed for base-load operations, however, it will be at a significant disadvantage.

The Natural Gas Fuel Cycle for Electric Power Production

Figure 3.6 is a flow diagram of the natural gas fuel cycle for electric power production. The estimated quantities of gas produced from oil and gas wells are based on present national-average production statistics.(12) Average U.S. gas-well output in 1969 was roughly 3-1/2 times the gas output from all oil wells.

Power plant emissions are based upon recently compiled EPA emission factors.(13) The particulate matter and SO_2 emissions correspond to rates from uncontrolled sources and are within the EPA standards for large steam generators.** Under the assumption that improved nitrogen oxide control techniques will be applied by 1980, the NO_x emission rate has been set at a value corresponding to the federal standard.

Residuals flows from gas plant operations have not been determined, because the internal and external costs of natural gas processing are properly attributed to the production of natural gas liquids. (The value of one year's production of natural gas liquids, evaluated at the gas plant, is currently about 40 percent of the total annual wellhead value of natural gas.) The gas plant sulfur output is based on the current U.S.-average rate of 0.043 lbs per 1000 cubic feet of gas processed.(15)

*Covers a Gulf Coast wellhead price of 65¢ per mcf and a transportation cost of 25¢ per mcf.

**Since there are no SO_2 standards for gas-fired boilers, the SO_2 emission rate can be compared with the standard for oil-fired boilers. See Reference (14) for the federal standards proposed for stationary sources.

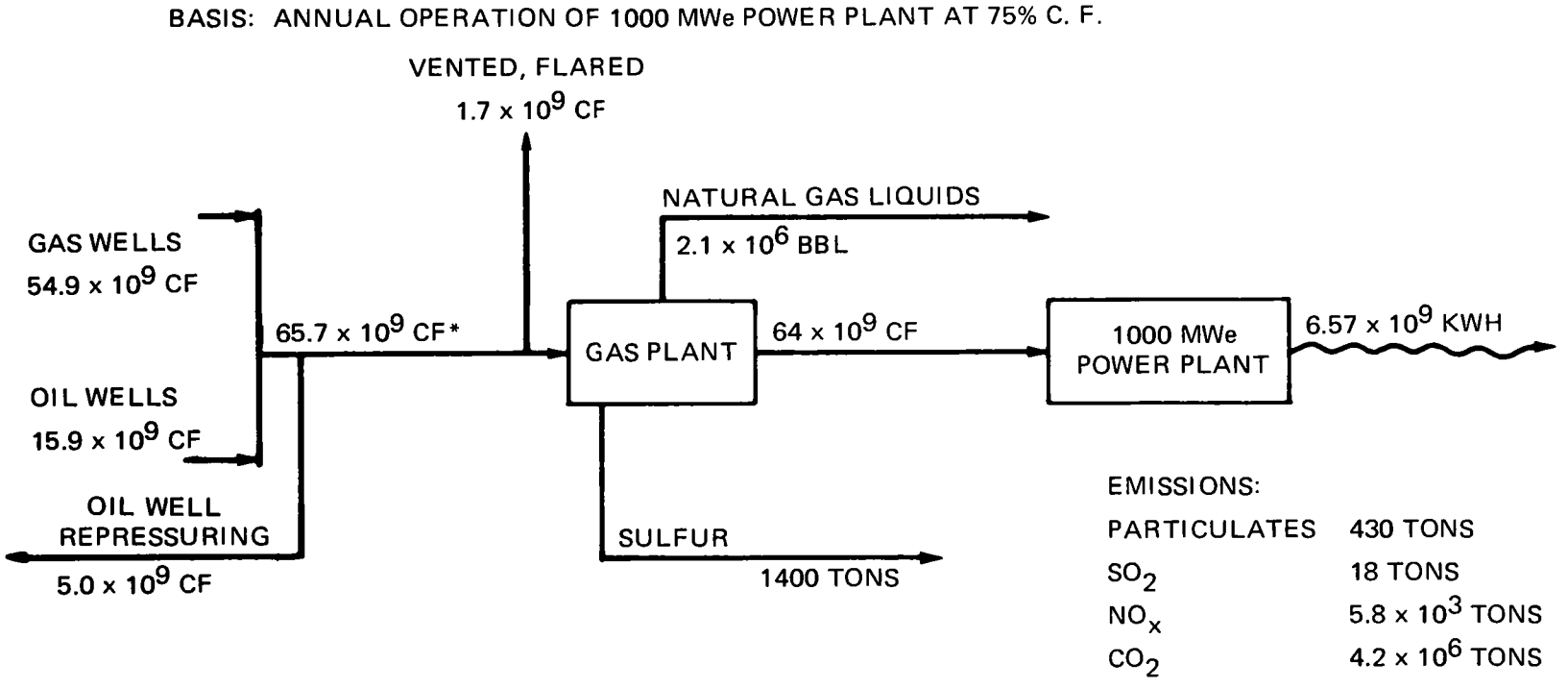


FIG. 3.6 THE NATURAL GAS FUEL CYCLE FOR ELECTRIC POWER PRODUCTION

Unit Impacts and Costs

Table 3.3 lists the annual expenditures and effects associated with the operation of a 1000 MWe natural gas energy system.

The occupational injury rates given in Table 3.3 are based on Bureau of Mines data and were estimated in the same manner as those for the oil energy system discussed in Section 3.3 above.[16] Injury rates associated with gas plant operations have been computed, but are not entered in the summary totals; these and other gas plant costs are properly charged against natural gas liquids production.

Footnotes and References for Section 3.4 - The Natural Gas Fuel Cycle

(1) *Resources for the Future, U.S. Energy Policies: An Agenda for Research, Johns Hopkins Press, Baltimore, Md., (1968).*

(2) C. A. Hawkins, *The Field Price Regulation of Natural Gas, Florida State University Press, Tallahassee, Florida, (1969).*

(3) "FPC Sees U.S. Gas Deficit Soaring," *Oil & Gas J. (Mar. 6, 1972).*

(4) "Arctic Gas-Line Cost Rises to $5 Billion, *Oil & Gas J. (Mar. 6, 1972).*

(5) *Oil & Gas J. (Feb. 14, 1972).*

(6) *Oil & Gas J. (Feb. 28, 1972).*

(7) *Oil & Gas J. (Apr. 3, 1972).*

(8) *Oil & Gas J. (Jan. 10, 1972).*

(9) *Wall Street Journal (June 29, 1972).*

(10) *National Petroleum Council, U.S. Energy Outlook: An Initial Appraisal 1971-1985, Volume One, (July 1971).*

(11) *Oil & Gas J. (July 12, 1972).*

(12) *American Petroleum Inst., Petroleum Facts and Figures, 1971 Edition.*

(13) M. J. McGraw and R. L. Duprey, *Compilation of Air Pollutant Emission Factors, EPA, Triangle Park, N.C., (1971).*

(14) U.S. EPA, "Standards of Performance for New Stationary Sources: Notice of Proposed Rule Making," *Federal Register, Vol. 36, No. 2 (August 1971).*

(15) "1971 Survey of Gas-Processing Plants," *Oil & Gas J. (July 12, 1971).*

(16) Bureau of Mines, *Disabling Work-Injury Experience of the Oil Industry (All Activities) and the Natural Gas Industry (Excluding Distribution Activities) in the United States, 1969, Mineral Industry Surveys, U.S. Dept. of the Interior, (1970).*

TABLE 3.3

ANNUAL EFFECTS OF 1000 MWe GAS-FIRED POWER PLANT AND ITS SUPPORTING FUEL CYCLE

Basis: 6.57 Billion Kilowatt-hours (one year operation 75% CF)

	Production[a]	Gas Plant[b]	Trans-portation	Power Plant	Total
Conventional Costs ($10^6$$)					
Fuel				237	237
Capital				42	42
O&M				3.7	3.7
Rounded Total				283	283
Abatement Costs ($10^6$$) (1980 dollars)					
Cooling Towers				7.1	7.1
Rounded Total				7	7
Occupational Accidents					
Deaths	0.021	0.006	0.024	0.037	0.082
Nonfatal Injuries	2.5	0.56	1.3	1.5	5.3
Mandays Lost	250	90	180	350	780
Effects at the Power Plant					
Air Pollutant Emissions (10^3 tons)					
Particulates				0.43	0.43
SO_2				0.018	0.018
CO				0.012	0.012
Hydrocarbons				1.1	1.1
NO_x				5.8	5.8
Aldehydes				0.085	0.085
Organics				0.115	0.115
CO_2				4,200	4,200
Thermal Discharge (10^{10} kWht)				0.88	0.88
Stack Discharge (10^{10} kWht)				0.22	0.22
Land Use					
Inventory (acres)	300	4	3,200	100[c]	3,600
Fuel Consumption (10^9 c.f.)	1.7[d]			64	66

a/ Includes exploration, drilling, and production activities.
b/ Gas plant effects not included in "Total" column. See text.
c/ One-half the acreage required for a site with two 1000 MWe generating units.
d/ Gas loss - flaring, venting.

(17) Refer to Figure 1.2.

(18) Figure 3.5 was constructed from data from American Gas Assn, Gas Facts, issued 1972.

(19) Katz, David L., et al, Handbook of Natural Gas Engineering, McGraw Hill, NY (1959), p. 1.

3.5 NUCLEAR FUEL CYCLES

Introduction

The first useful power obtained from nuclear fission energy was at the Experimental Breeder Reactor I in 1951. Since that time, various nuclear systems for producing electricity have been developed. In 1970, about 1.5% of the electrical energy produced in the U.S. was from nuclear sources.(1) This percentage is expected to rise to over 25% by 1980 and to continue to rise rapidly after that.(2) Thus, nuclear energy sources are expected to play an increasingly important role in meeting the U.S. electrical energy demand.

Nuclear and fossil energy systems differ in several obvious, but important respects. It is instructive to consider these, qualitatively, at the outset.

- Aside from military applications, nuclear energy is consumed almost entirely in the form of electricity, whereas coal, petroleum, and natural gas serve other energy needs, such as process heat, transportation and nonenergy needs. Alternative uses (other energy uses and nonenergy uses) of nuclear resources are small and competitive pressures for these resources are practically nil.* In this respect, the nuclear energy economy is less complex than that of fossil energy.

- Quantities (volumes and masses) involved in the nuclear fuel cycles are characteristically small, due to the high energy content of nuclear fuels. The potential energy contained in one pound of fissionable material, assuming all of the material and its conversion products are fissioned, is about 0.36 billion British Thermal Units (BTU). The same quantity of energy is contained in about 1400 short tons of bituminous coal, or 6000 barrels of residual fuel oil, or 35 million standard cubic feet of natural gas.

- Although the flow of fuel is relatively small, the sequential steps in the nuclear fuel cycles are more numerous and more complex than in fossil fuel

*However, process heat applications of nuclear energy are currently under consideration.

cycles. Processes involved in extracting fission energy are inherently "more technical" than their combustion energy counterparts. Industries associated with nuclear energy are commonly characterized as "high-technology" industries. Nuclear energy technology, the youngest of the viable energy technologies, has enjoyed a large share of the world's scientific and engineering resources, and potential hazards associated with nuclear fission energy have been given more attention than comparable hazards in other energy industries.

The types of nuclear power reactors examined in this report are the pressurized water reactor (PWR) and the boiling water reactor (BWR). Both reactors use light water as coolant and moderator and are referred to generically as light water reactors (LWRs). Light water reactors are expected to dominate the nuclear power economy for much of the remainder of the century. Two advanced reactor types -- the liquid metal cooled fast breeder reactor (LMFBR) and the high temperature gas cooled reactor (HTGR) -- are expected to reach commercial maturity by the end of the century. Since this study is confined to current commercially-applied technology, only the LWRs are treated in this report.

The source of energy in these plants is the fission process--the splitting of a heavy nucleus. In nuclear power reactors, fission occurs principally as a result of collisions of neutrons and heavy nuclei. Neutrons are emitted in the fission process; thus, the process can be made self-sustaining. There are two classes of fissionable material: "fissile" material, which can be fissioned by incident neutrons of any energy; and "fertile" material, which can be fissioned only by incident neutrons of very high energy. Very little of the energy released in power reactors results from the fissioning of fertile species. However, fertile nuclides may be transformed to fissile nuclides (the more readibly fissionable species) through the non-fission capture of a neutron.

Two fissionable elements occur in nature - uranium and thorium - and thus comprise the ultimate resource base for nuclear power generation. The dominant isotope in natural uranium is the fertile nuclide uranium-238 (U-238). Less than one percent of natural uranium is the fissile nuclide U-235, which is the only fissile nuclide found in nature. Thorium occurs in nature only in the form of fertile material, thorium-232 (Th-232). The two preponderant naturally occurring fertile species, U-238 and Th-232, can be converted to fissile Pu-239 and U-233, respectively, by neutron capture in a nuclear reactor.

Power reactors may use available fissionable materials in a variety of modes. Light water reactors (PWR and BWR) use uranium enriched tto a few percent in fissile U-235. The principle fissioning species in LWRs is U-235; some fertile U-238 is also fissioned and some U-238 is converted to fissile plutonium during reactor operation. The HTGR uses both uranium and thorium. Uranium input to HTGRs is highly enriched in U-235 (~ 93%). Some fertile Th-232 is converted to fissile U-233 during reactor operation. The principal fissile species in LMFBRs is Pu-239. As in the LWR, the LMFBR converts fertile U-238 to fissile Pu-239. The LMFBR, however, generates more fissile material than it consumes. Table 3.4 lists the principal fuel species used in LWRs, HTGRs and LMFBRs.

TABLE 3.4

PRINCIPAL FUEL SPECIES IN NUCLEAR REACTORS

	Fissile		Fertile
LWR (PWR & BWR)	U-235* Pu-239	⟶	U-238*
HTGR	U-235* U-233	⟶	Th-232*
LMFBR	Pu-239	⟵	U-238*

*Occur naturally.

The fuel cycles associated with LWRs, HTGRs, and LMFBRs may be interrelated and made complementary in a number of ways, as indicated in Figure 3.7. The enrichment plant tailings, a waste product in the LWR and HTGR fuel cycles, may be used as resource input to the LMFBR fuel cycle. The plutonium produced by LWRs, as well as the excess plutonium produced by LMFBRs, can be used to start up new LMFBRs, or it can be recycled in the LWRs to reduce LWR natural uranium makeup requirements. U-233 produced in HTGRs can be recycled to reduce the natural uranium requirement of that fuel cycle.

Light Water Reactors and Their Supporting Fuel Cycles*

More than 100,000 MWe of light water reactors (LWRs) have been ordered by utility companies in the United States.[3] The heat generated in the reactor core is removed by circulating ordinary water through it. The water serves not only as a coolant but also as a moderator; that is, it slows the neutrons to the desired low energy at which most fissions take place.

*A more detailed treatment of LWRs and their fuel cycles may be found in the Appendix.

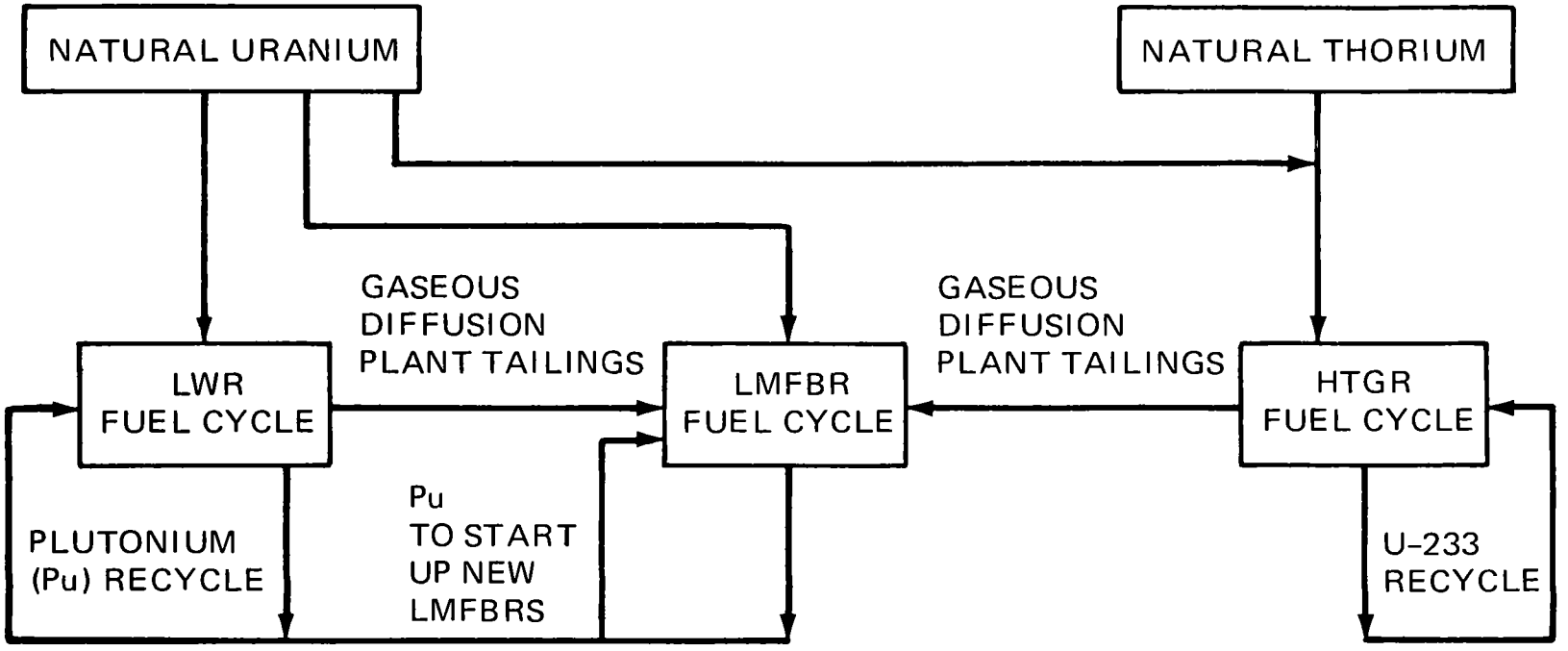


FIG. 3.7 FLOWS OF FUEL MATERIALS IN THE U. S. NUCLEAR POWER INDUSTRY

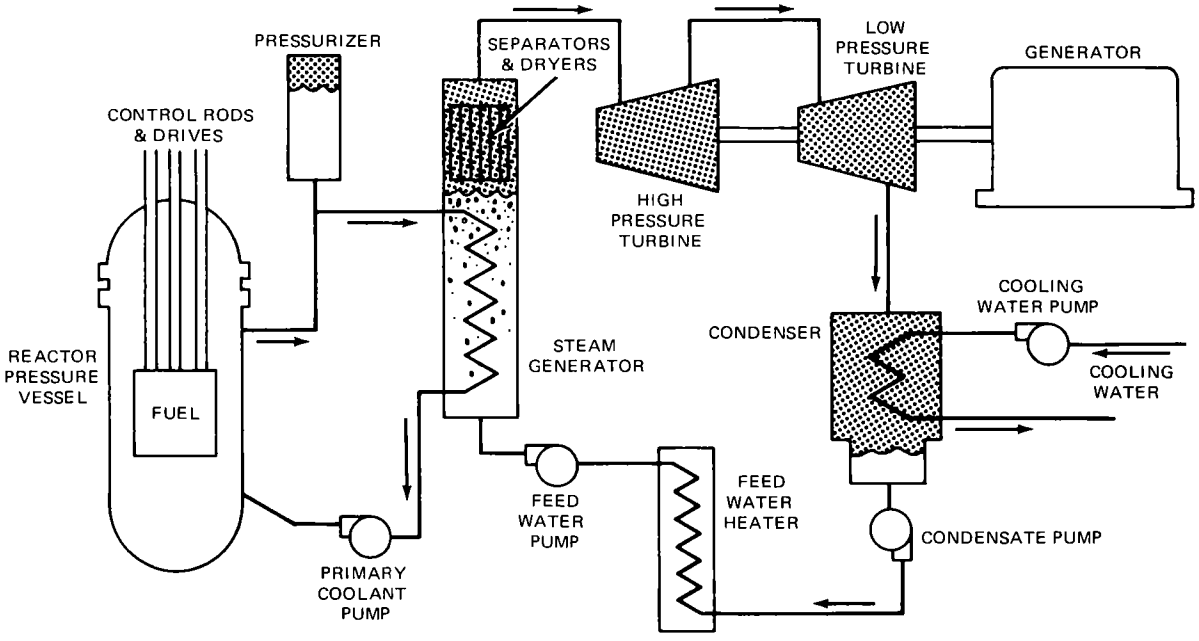
The two types of LWR are the pressurized water reactor (PWR) and the boiling water reactor (BWR). Water under pressure is circulated through the PWR core (Figure 3.8) at a pressure high enough to prevent the water from boiling. The heated pressurized water is then passed through a steam generator where the heat is transferred to water in a secondary system. The pressure in the secondary system is somewhat lower, thus allowing the water to boil. The steam which is formed is then routed to the turbine. The BWR (Figure 3.9), as its name implies, allows boiling to take place directly in the reactor core, thereby eliminating the need for a secondary water system between the primary coolant and the turbine.

The uranium fuel for these reactors moves through several processes before and after productive use in the reactor core. These processes are in general quite similar for PWR and BWR fuel and will therefore be described for both reactor fuel cycles simultaneously. Steps in the LWR fuel cycles are: mining, milling, conversion, enrichment, preparation and fabrication, electricity generation (reactor power plant), reprocessing of spent fuel, waste disposal, and transportation between fuel cycle steps. Figure 3.10 displays material balances for the fuel cycles assumed representative of LWRs going on line in 1980.

For each step in the LWR fuel cycle, information on direct human impacts (such as mining-related injuries), radionuclide releases to the air and water, radioactive wastes which are sent to permanent storage, resource requirements, and other cost factors (cost as defined in Chapter 2), have been assembled and normalized to the production of 6.57 billion kilowatt hours of electrical energy, the energy generated by one 1000 MWe power plant operating for one year at 75% capacity. Some of this information, such as radionuclide release to the air, does not represent a final impact. The methods for transforming the basic information obtained by direct examination of the fuel cycles into final impacts are discussed in Chapter 4 and in the Appendix and footnotes of this report. The Appendix also contains more detailed and quantitative descriptions of the LWR power plants and their fuel cycles and deals with the public and occupational radiological health impacts associated with production of electrical energy by LWR systems.

U.S. Uranium Resources

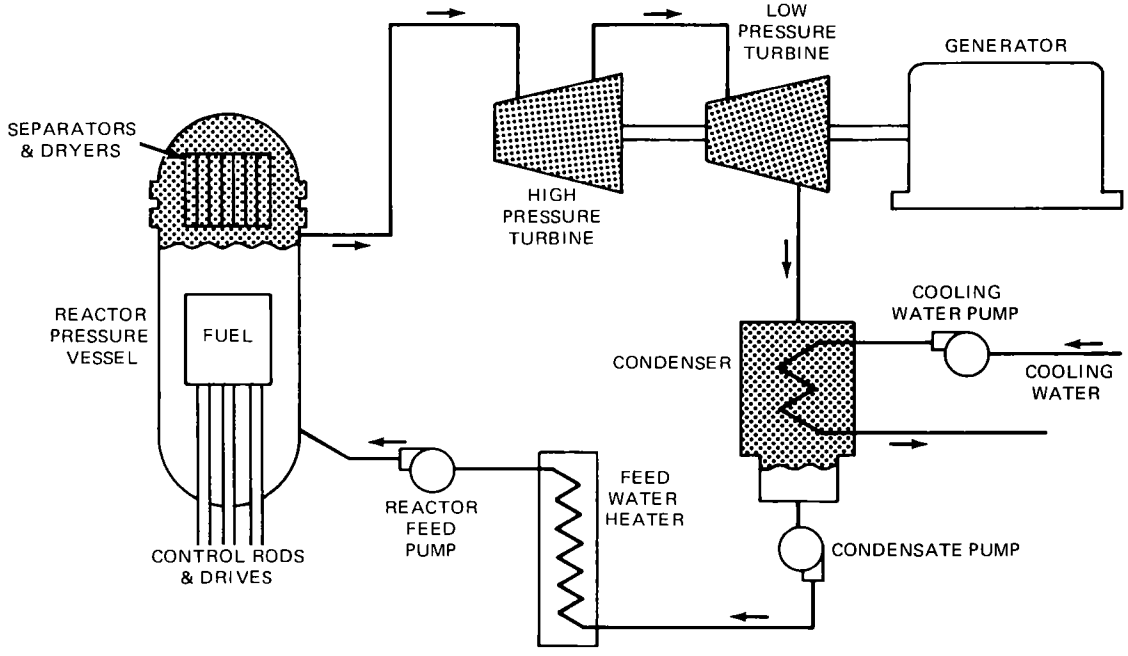
The U.S. reserves of uranium recoverable at $10 or less per pound of U_3O_8 [4] were estimated to be about 1,130,000 short tons of U_3O_8 as of January 1974. About 340,000 tons are reasonably assured in conventional deposits, and 90,000 tons are thought to be available as a byproduct from phosphate and copper mining. Estimated



BABCOCK & WILCOX
COMBUSTION ENGINEERING
WESTINGHOUSE

FUEL: SLIGHTLY ENRICHED URANIUM OXIDE CLAD WITH ZIRCONIUM ALLOY
MODERATOR: WATER
COOLANT: WATER
PRESSURE OF PRIMARY SYSTEM 2,250 POUNDS PER SQUARE INCH
REACTOR OUTLET TEMPERATURE 605° F

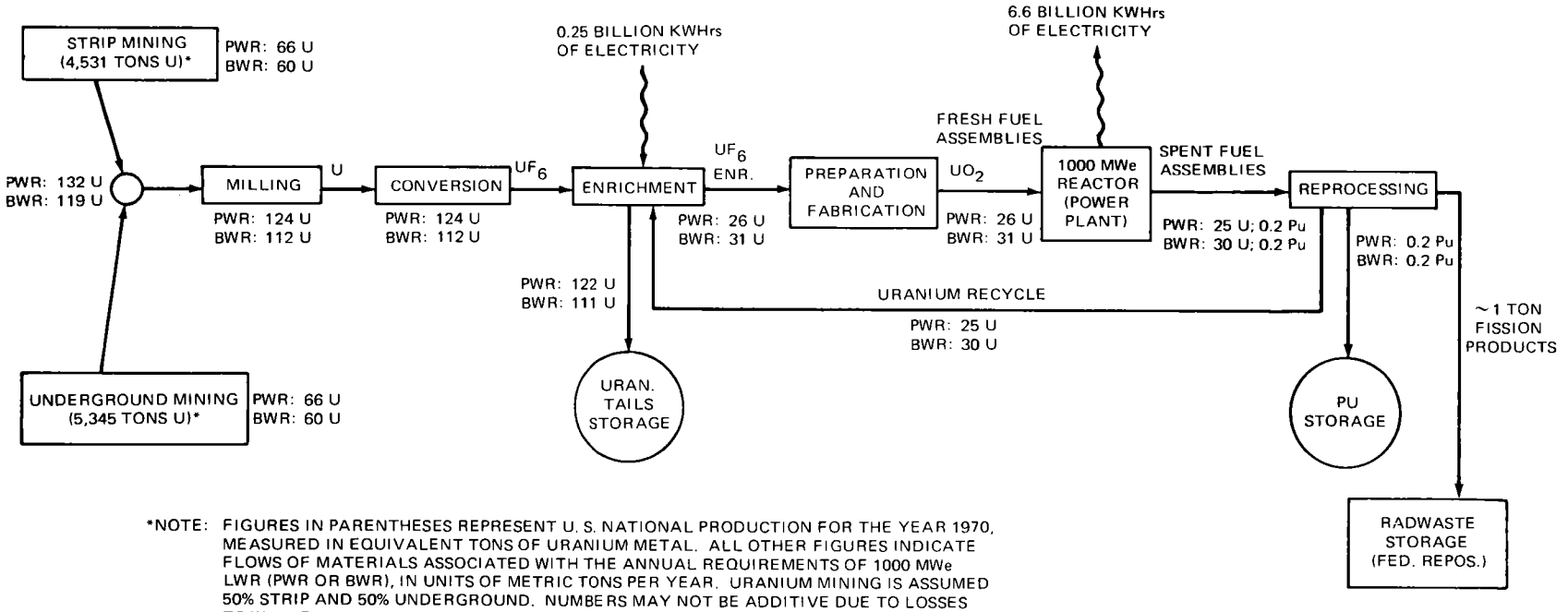
FIG. 3.8 PRESSURIZED WATER REACTOR POWER PLANT



GENERAL ELECTRIC

FUEL: SLIGHTLY ENRICHED URANIUM OXIDE CLAD WITH ZIRCONIUM ALLOY
MODERATOR: BOILING WATER
COLLANT: BOILING WATER
PRESSURE OF PRIMARY SYSTEM 1,000 psi
OUTLET TEMPERATURE 550° F

FIG. 3.9 BOILING WATER REACTOR POWER PLANT



*NOTE: FIGURES IN PARENTHESES REPRESENT U. S. NATIONAL PRODUCTION FOR THE YEAR 1970, MEASURED IN EQUIVALENT TONS OF URANIUM METAL. ALL OTHER FIGURES INDICATE FLOWS OF MATERIALS ASSOCIATED WITH THE ANNUAL REQUIREMENTS OF 1000 MWe LWR (PWR OR BWR), IN UNITS OF METRIC TONS PER YEAR. URANIUM MINING IS ASSUMED 50% STRIP AND 50% UNDERGROUND. NUMBERS MAY NOT BE ADDITIVE DUE TO LOSSES TO WASTE, ROUND-OFF, BURNUP AND PRODUCTION.

KEY: PWR - PRESSURIZED WATER REACTOR BWR - BOILING WATER REACTOR
U - URANIUM Pu - PLUTONIUM

FIG. 3.10 THE LIGHT WATER REACTOR (LWR) FUEL CYCLE

additional resources at or below $10 per pound are 700,000 tons.[5] Table 3.5 gives USAEC estimates[5] of U.S. uranium resources as of January 1974, as a function of extraction cost.[6] The resource base for LWRs and the LWR fuel utilization characteristics are discussed in more detail in Chapter 5.

Mining

Uranium is mined by both underground and surface (pit) techniques. Over 60% of the 1973 domestic uranium production was from open pit mines. Technological advances have tended to increase the depths at which open pit mining can be economical, and over 40% of the domestic reserves are thought to be minable by this method. Stripping the overburden may be a large part of the cost of mining, and the depth that may be reached depends on the deposit's character and accessibility.

Underground uranium mines use many mining methods and variants since the ore bodies are erratic in shape, size, attitude, and grade. On the Colorado Plateau 85% of the production is from deep shaft mines and open pits. However, many mines are still simple adits or inclined entries driven into a canyon wall or sloping ground to recover small deposits of uranium ore.

Workers in the uranium mining industry for the past several years have experienced roughly the same risk (on a per million manhour basis) of fatal and nonfatal injury as workers in the coal mining industry.[7] The productivity of uranium miners is not as high as coal miners, partly due to uranium deposits often being small and hard to develop and partly due to the difference in mechanization and development of the two industries.[7] For this reason, injury rates on a per million ton output basis are higher in uranium mines.[7] However, the ore requirement to produce a given quantity of electrical energy is smaller by orders of magnitude in the nuclear system, owing to the high energy content of nuclear fuels. Thus, on an energy basis, injury rates in uranium mining are significantly lower than in coal mining. Close to one coal mining fatality per year associated with the fuel requirements of one 1000 MWe power plant can be expected. On the same basis, the fatality rate in uranium mines is roughly one-tenth of this.[8]

Radon gas is produced from the natural decay of radium, which is itself a member of the uranium decay chain. Since uranium is present in low concentrations in rocks, oceans, and building materials, the gaseous radon which escapes and is dispersed in the atmosphere exposes us all to very low concentrations. The difficulty arises in underground uranium mining where a relatively small quantity

TABLE 3.5

U.S. URANIUM RESOURCES[6]

January 1, 1974

Cost Cut Off $/lb U_3O_8	Tons U_3O_8 Reasonably Assured (Reserves)	Estimated Additional (Potential)	Totals
$ 8	277,000	450,000	727,000
10	430,000	700,000	1,130,000
15	610,000	1,000,000	1,610,000
30	790,000	1,700,000	2,490,000
50	4,800,000	3,700,000	8,500,000
100	8,800,000	8,700,000	17,500,000

of air is available for dilution. Some of the radon-222 escapes directly to the mine atmosphere from exposed rock surfaces, while some of the radon trapped inside is released as rocks are broken during mining operations. The decay of radon in the mine atmosphere results in deposition of daughter isotopes on dust particles. Statistical studies have shown that exposure to high concentrations of radon gas and its alpha-decay products leads to an increased probability of developing lung cancer during some future time period.[9.1, 9.2] The etiological factor of occupational origin is alpha radiation from the decay of Ra-222 daughter products which lodge in the miners' lungs. The legal limit for annual exposure to radon and its decay products has been reduced to a level which is much lower than that which existed in some uranium mines in the past.

It has been estimated that several times as many underground uranium miners would die from accidents in one year's time than would die from future lung cancers resulting from exposure during that year to radon and its daughters at the annual limit. Some procedures to reduce exposure to radon and its daughters include increased ventilation, filtration, and the use of respirators.

Because of concern among some medical authorities, an epidemiological study of the U.S. uranium miners was begun by Heuper in 1948 and later continued by the U.S. Public Health Service. This study provides the most comprehensive single body of knowledge on lung cancer incidence in miners exposed to airborne radon daughter products. The PHS study, along with other supportive research[9] on U.S. uranium miners, forms the basis of the dose-response characteristic assumed for the present study.

Data recorded, analyzed, and interpreted by Lundin, et.al.[9.1] suggest that the excess risk of death, to age 80, resulting from radiogenic lung cancer, among white male uranium miners, is of the order of 0.0001 per man per working-level-month (WLM).[10] Assuming an annual exposure of 4 WLM per year,[13] and productivity of 3 metric tons of U_3O_8 per miner per year, the group occupational dose is about 1.3 miner-WLM per metric ton of U_3O_8. The annual fuel requirement of one 1000 MWe LWR is about 160 metric tons of U_3O_8. About half of this, or 80 metric tons is assumed produced by underground mines. Thus, the occupational group dose corresponding to the annual 1000 MWe LWR mining requirements is about 104 miner-WLM. Using the risk coefficient cited above, the expected number of cases of radiogenic lung cancer associated with the annual fuel requirements for a 1000-MWe LWR is about 0.01. The reader is warned of the large uncertainties contained in this computation, resulting from the uncertainity in the risk estimate of Lundin.[9.1] The result should be viewed only as an order-of-magnitude estimate.

Milling

Only about four pounds of U_3O_8 are present in one ton of ore from the mine. Thus, there is an incentive to locate the mill, in which the U_3O_8 is separated from the ore, near the mine in order to keep down the cost of transporting the ore containing 99.8% waste material.

The three main steps in uranium milling are ore preparation, concentration, and product recovery. The ore preparation involves crushing and grinding with the objective of getting the ore down to a particle size small enough that the uranium is liberated or exposed. Concentration is achieved by a leaching process, generally using sulfuric acid, which results in practically all of the uranium going into solution. The insoluble materials are then separated and a solvent extraction or an ion exchange process is used to upgrade and purify the clarified pregnant solution. Uranium is then precipitated from the solution. The product is filtered and dried; the result, called "yellowcake," contains about 80% U_3O_8. Overall uranium recovery from ore to finished product is generally about 95%.

Radon gas is released from the ore during the crushing and grinding steps. It enters the mill ventilation system and is discharged from the gaseous effluent stack. Ventilation and filtration are used to reduce airborne wastes.

The insoluble materials left after the leaching process are sent to a tailings impoundment area. These tailings contain most of the radioactive species other than uranium and radon gas which were present in the ore. Since only about 0.2% of the ore has been removed, these radionuclides are present in practically the same concentration in the tailings as they were in the original ore. The tailings piles are generally covered with earth to reduce radon release and to minimize release of other radionuclides by erosive processes.

The liquid effluent flowing offsite may carry small quantities of uranium, thorium, or radium. Current practice at most uranium mills is to recycle liquids so that fresh water intake just offsets evaporative and seepage losses; other mills precipitate any nuclides of concern from the liquid flowing offsite.

Conversion

The next stop for the U_3O_8 is the conversion plant where the uranium is converted to gaseous uranium hexafluoride (UF_6) by reduction, hydrofluorination, and fluorination processes. A very small amount of uranium from offgas scrubber solutions is discharged through limestone to waterways.

Enrichment

The UF_6 is then shipped to the gaseous diffusion plants which receives natural uranium having about 0.7 weight percent U-235 and produces a product stream of uranium having from two to four weight percent U-235 for LWR fuel and a tails stream which is stored. The tails stream is known as depleted uranium since it has only 0.2 to 0.3 weight percent U-235. Very small amounts of gases containing uranium are released from the waste gas treatment system to atmosphere. Even smaller amounts of uranium are discharged from the uranium recovery plant into waterways through a holding pond, which receives ashes of solid wastes, uranium solutions, and recovered uranium materials.

Preparation and Fabrication

The enriched UF_6 is then sent to the preparation and fabrication plant where the UF_6 is converted to uranium dioxide pellets, which are placed in the zirconium alloy tubes that make up the finished fuel assembly. Small amounts of uranium pass through the treatment systems and are released to the atmosphere or the liquid effluent. Due to the high quality standards in the industry, a relatively large amount of solid waste is generated. Since the uranium is of such high value, there is an economic incentive to recover the uranium carried along with the scrap materials. This low-hazard-potential solid waste, which generally consists of paper trash, packing material, broken glassware, protective clothing, and contaminated equipment, is sent to commercial burial grounds for surface burial. Laboratory research and geologic and hydrologic studies have shown that carefully packaged low level wastes such as these can be safely buried at carefully selected and operated surface burial facilities.

Electricity Generation

The fabricated fuel is then delivered to the reactor power plant where the electrical generation takes place. As the uranium fissions in the reactor core, some pinholes or defects in the fuel cladding may develop which allow some of the fission products to escape to the coolant water. The releases to the coolant are in proportion to the number of rods which have leaks. The reactor gaseous and liquid waste treatment systems are designed to capture or hold up for natural decay most of the radionuclides before they are released to the environment. The PWR and BWR have different types of radwaste systems so they will be described separately. The PWR gaseous radioactive wastes result mainly from degassing the reactor coolant, displacement of cover gases as liquids accumulate and sampling operations and automatic gas analysis for hydrogen and oxygen in cover gases. These gases are

collected, compressed, and dehumidified. The water is sent to the liquid radwaste system while the gases typically are stored for 45 days or more in decay tanks before release to the environment. Kryton-85 makes up about 90% of the radioactivity remaining in the decay tanks after 45 days of storage. Since Kr-85 has a half-life greater than 10 years, there would be no appreciable decrease in its activity if the holdup time were doubled or tripled. Cryogenic or other systems can be used to further reduce releases of krypton and other noble gases.

Release of the noble gases from a typical PWR after 45 day holdup produces site boundary doses which are small with respect to the proposed AEC standards, which are in turn small compared to the natural background radiation.

The PWR liquid radwaste system collects and processes radioactive liquid wastes generated from various sources throughout the plant. The degree of treatment which a batch of liquid wastes receives depends on its activity. Some very low level wastes will need no processing at all and will be discharged from the plant. Some high level wastes will be evaporated; the residues will be packaged for offsite burial at commercial burial grounds of the type described earlier. Other liquid wastes will be treated by demineralizers which use an ion exchange treatment. Treated liquids may then be discharged from the plant, recycled through the plant, or given further treatment.

The activity actually released in the liquid effluent from a PWR is expected to total less than one curie per year, exclusive of tritium. Tritium (H-3) is formed by ternary fission (a fission in which three elemental fission products result instead of the usual two) and by neutron interaction with boron, lithium, and deuterium in the water. The main source from the latter three is production from boron, which is placed in the circulating water for control purposes. The ternary fission production is actually much greater than any of these other sources, but about 99% of the tritium formed from fission is expected to remain inside the fuel tubes.

Since tritiated water, HTO, is chemically identical to ordinary water, separation of the tritiated water from ordinary water is difficult. No practical method is currently available for such a separation at power reactors. About 600 curies of tritium are expected to be released from a 1000 MWe PWR plant per year. However, most of the tritium inventory remains with the fuel; thus most tritium releases in the LWR fuel cycle occur at the reprocessing plant, i.e., ~ 16,000 Ci/yr per 1000 MWe LWR, in the form of gaseous release to the atmosphere. It

should be noted in passing that the current world-wide environmental inventory of tritium is estimated to be from 25 to 80 million curies produced by natural processes and one to two billion curies from atmospheric nuclear detonations.

Gases accumulate in the typical BWR coolant system from radiolytic decomposition of reactor water into hydrogen and oxygen, air leakage into the system, and radioactive noble gases released through defects in the cladding of the fuel. Relatively large volumes of noncondensable gases are drawn from the main condenser through steam jet air ejectors. The gases are then heated and sent to a catalytic recombiner, where the hydrogen and oxygen are combined to yield water vapor. Next, the water vapor and steam are removed by condensation, and the gases left are sent to a holdup pipe for delay of from 30 minutes to several hours. This allows many of the short-lived xenon and krypton isotopes to decay. The gases are then put through some additional moisture control procedures and passed through high efficiency filters before entering a series of charcoal beds. Xenon and krypton are adsorbed by the charcoal and are therefore subjected to an additional delay time before filtering and discharge to the atmosphere.

The typical system described above is expected to reduce the design basis release level (measured in curies per unit time) by a factor of 50. Variation of this system is common. At least one U.S. utility plans to cool the gases entering the charcoal beds to 0°F to increase the delay time the noble gases experience. The practical application of systems such as cryogenic distillation is also being investigated.

Another source of gaseous emissions in the BWR is the offgas system for the gland seal. The gland seal system for the turbine shaft bearings permits a small fraction of primary steam to flow into a separate off-gas system. These gases are released to the environment through the chimney after about a two minute holdup. The radioactivity in this gas is mainly due to krypton and xenon isotopes with half-lives on the order of minutes. At least one utility is planning to reduce these emissions by providing clean steam as backflow into the turbine gland seal.

A BWR utilizing room temperature charcoal beds and two minute holdup for gland seal exhaust would be expected to release the same amount of long-lived Kr-85 and greater amounts of short-lived krypton and xenon isotopes than a PWR with 45 day holdup.

The BWR liquid radwaste system has many of the same components as the PWR system. The liquids are collected and treated as necessary by demineralizing, evaporating, filtering, and further storage. Tritium release from a BWR plant is expected to be less than for a PWR since there is no burnable poison (boron) source in the BWR. However, the small fraction of ternary-fission-produced tritium which is released from the fuel to the coolant must be assumed to be the same in the BWR as in the PWR. This results in about 100 curies of tritium release per year for a 1000 MWe BWR.

Radiation doses to the general public due to normal releases of radionuclides at LWRs and in the associated fuel cycle facilites are estimated in the Appendix. An abbreviated discussion is provided in footnotes (17), (18), (19). The Appendix also deals with occupational doses in the LWR fuel cycle.

Both types of reactors produce some solid wastes which are carefully packaged and sent to commercial surface burial facilities as is the solid waste from fabrication. Some typical sources of this waste are filter sludges and spent resins, concentrated wastes, air filters from off gas and radioactive ventilation systems, contaminated clothing, miscellaneous paper, rags, etc. from contaminated areas, and contaminated equipment which cannot be economically decontaminated. The total production of this solid waste from a 1000 MWe reactor is expected to be from 2000 to 5000 cubic feet per year.

Reprocessing

Following exposure in the reactor, the fuel is removed from the core and allowed to sit in storage pools for more than 100 days. During this time the radioactivity of the discharged fuel elements decreases rapidly as the short-lived fission products decay away. The spent fuel is then shipped to the chemical reprocessing plant to recover the materials of value. Recovered uranium and plutonium can be recycled. The waste materials of the recovery process contain the fission products which were separated from the uranium and plutonium.

Krypton-85 and tritium make up more than 99% of the activity released from the reprocessing plant since, as discussed earlier, practical systems for capture of these two radionuclides have yet to be demonstrated. The release at the reprocessing plant annually amounts to almost 300,000 curies of Kr-85 and 16,000 curies of tritium from the fuel received from one 1000 MWe LWR.

Some of the low level wastes produced at the reprocessing plant are shipped to the commercial burial grounds for surface burial. These wastes are of the low level, nontransuranic type.

The high level wastes are primarily the fission product concentrates. Current plans are to store these wastes for about five years as solutions at the reprocessing plant to let the relatively short-lived radionuclides decay which in turn reduces heat generation and radioactivity per unit volume of liquid. The wastes are then solidified and shipped to a federal repository no later than ten years after reprocessing.

Other types of waste material produced at the reprocessing plant may also be shipped to the federal repository. These include the zirconium alloy cladding hulls, intermediate level waste, and waste contaminated with plutonium and other transuranic isotopes.

The anticipated increasing use of nuclear power to meet the electrical generating demands in the U.S. results in a need for a carefully considered waste disposal policy. Some of the wastes described earlier need to be isolated for thousands of years. Thus, the need for a facility such as a federal repository is evident. Recognizing that a truly permanent solution to the problem is required, the AEC in consultation with the National Academy of Sciences and Members of the Geologic Community has sponsored work over the past 15 years to examine the suitability of bedded salt formations as a final repository for these materials.

Salt has a number of characteristics which makes it particularly well suited for this purpose, most important of which is that bedded salt deposits are completely free of circulating ground waters and are isolated from underground aquifers by essentially impermeable shale. This situation tends to be preserved because any fractures that might develop are healed by plastic deformation and recrystallization of the salt.

Disposal as solids in surface vaults is also being studied. The AEC has proposed that surface vaults for the engineered storage concept be designed, built, and tested at the same time as a pilot plant program for storage in underground salt beds is tested. These facilities could be available for use by 1980 and would allow for easy retrieval should this be required. Depending on the experience gained in operation of the engineered surface storage facilities and the pilot operation in a geologic formation, decisions would be made by the mid-1980's on

which concept should be expanded. However, evaluation studies on the feasibility of other concepts are also planned.

Transportation of Nuclear Materials

Transportation of materials is required between all of these steps in the nuclear fuel cycle. In most cases the materials are transported by truck although rail facilities are expected to handle some shipments of spent fuel between reactors and reprocessing plant and all shipments of waste to the federal repository.

Most concern about transportation of materials in the nuclear fuel cycle is generally centered on shipments of spent fuel and high level waste materials. However, one must not forget all the other shipments in the nuclear fuel cycle because the total vehicle miles logged in these other shipments is not a negligible quantity in comparison with waste and spent fuel shipment miles.

Shipping containers are designed according to the value and potential hazard of the cargo. U_3O_8 is shipped in 55 gallon drums while spent fuel shipped by rail will travel in 200,000 pound casks which are designed to withstand fire, impacts, and submergence in water without leaking.

Unit Impacts and Costs

Tables 3.6 and 3.7 display representative conventional costs (1980 dollars), abatement costs (1980 dollars), and environmental and human impact data associated with the annual operation of 1000 MWe light water reactors and their supporting fuel cycles. Fuel cycle effects are, of course, prorated to the annual fuel requirements of a 1000 MWe power plant. Since a plant capacity factor of 75% is assumed, the quantities in Tables 3.5 and 3.6 correspond to the production of 6.57 billion kilowatt hours of electrical energy.

Footnotes and References for Section 3.5: Nuclear Fuel Cycles

(1) *Refer to Figure 1.2 of this report.*

(2) *Federal Power Commission, The 1970 National Power Survey, Part 1 (December 1971), page I-1-19, Table 1.4.*

(3) *U.S. Atomic Energy Commission, Nuclear Reactor Built, Being Built, or Planned in the U.S.*

(4) *Although uranium occurs in several chemical forms in nature, uranium resource estimates are commonly given in equivalent units of mass of* U_3O_8. *One ton of* U_3O_8 *contains about 0.85 tons of uranium.*

TABLE 3.6

ANNUAL EFFECTS OF A 1000 MWe PWR AND ITS SUPPORTING FUEL CYCLE

Basis: 6.57 Billion kilowatt hours (one year operation @ 75% CF)

		Mining	Milling - Fabrication[c]	Reactor Power Plant	Reprocessing & Transportation[b]	Totals
Conventional Costs ($10^6$$) (1980 dollars)						
Fuel		6.2	17.2	10.3[a]	5.5	39
Plant Capital				77		77
O&M				5.2		5.2
Rounded Total						121
Abatement Costs ($10^6$$) (1980 dollars)	(16)					
Cooling Towers				2.4		2.4
Near-Zero Radwaste				1.2		1.2
Rounded Total						4
Occupational Accidents	(11)					
Deaths		0.09	0.005	0.01	0.002	0.1
Non-fatal Injuries		3.6	1.5	1.3	0.12	6.5
Man-days Lost		762	88	110	15	975
Mining & Milling Impacts						
U(natural) for GDP feed (MTU)		132				
Strip Mining of uranium & Mill tailings (acres)		9	2.2	-	-	11
Tailings produced @ Mill (10^3MT)	(14)	-	79	-	-	79
Public Accidents in Transportation of Nuclear Fuels (Excl. exposures to radioactivity)						
Deaths		-	-	-	0.009	0.009
Non-fatal Injuries		-	-	-	0.08	0.08
Man-days Lost		-	-	-	60	60
Occupational Health						
Miners radiation Exposure (miner-WLM)	(13)	104	-	-	-	104
Other Occupational Exposure (man-rad)	(12)	-	15	300	30	345
Solid Radioactive Waste Disposal	(15)					
Volume (10^2ft^3)			77	22	13	110
Burial Area (acres)			0.15	0.04	0.31	0.5
Land Use (20)						
Inventory (acres)		~500	~100	100	100	~1000
Consumption (acres/yr)		9	2	-	1	12
Effects at the Power Plant						
Thermal discharge (10^{10} kWht)				1.4		1.4
Net destruction of Uranium (MTU)				1.1		1.1
Net production of Plutonium (MTPu)				~0.2		~0.2
Routine Radioactive Releases to Atmosphere (Ci)	(17)					
H-3		-	-	-	16000	16000
Kr-85		-	-	5500	280,000	290,000
I-129		-		-	0.0003	0.0003
I-131		-		-	0.004	0.004
Xe-131m		-		180	50	230
Xe-133		-		580	-	580
Cs-134		-		-	0.007	0.007
Rn-222		-	44	-	-	44
U-234		-	0.006	-	~0	0.006
U-238		-	0.002	-	0	0.002
Total U		-	0.009		~0	0.009
Pu-241		-	-	-	0.003	0.003
Total Pu		-	-	-	0.003	0.003
Others		-			0.2	0.2
Routine Radioactive Releases to Waterways (Ci)						
H-3		-	-	580	350	930
I-129		-	-	-	0.0002	0.0002
I-131		-	-	0.03	0.00002	0.3
Cs-134		-	-	0.01	0.01	0.02
U-234		-	0.1	-	0.002	0.1
U-238		-	0.04	-	0.0007	0.04
Total U		-	0.2	-	0.003	0.2
Others		-	0.0008	0.1	3.	3.
Population Exposure from Routine Release of Radionuclides	(18)					
.Global Model: All-time commitment, long-lived nuclides						
World (whole body man-rad)						
Kr-85		-	-	~3	127	130
H-3		-	-	-	22	22
Total World						152
U.S. Only (whole body man-rad)						
Kr-85		-	-	~0.1	6	6.1
H-3		-	-	-	2.4	2.4
Total U.S.						8.5
.Local Model: Airborne short-lived noble gases and tritium						
Total Man-rem within 50 miles						
High Population Assumption						42
Medium Population Assumption						4.2
Low Population Assumption						0.6

a. Working capital charges (fuel)
b. Includes all transportation steps
c. Milling, Conversion, Enrichment, and Preparation and Fabrication

TABLE 3.7

ANNUAL EFFECTS OF A 1000 MWe BWR AND ITS SUPPORTING FUEL CYCLE

Basis: 6.57 Billion kilowatt hours (one year operation @ 75% C.F.)

		Mining	Milling - Fabrication[c]	Reactor Power Plant	Reprocessing Transportation[b]	Total
Conventional Costs ($10^6$$) (1980 dollars)						
Fuel		5.6	16.1	10.3[a]	6.7	39
Plant Capital				77		77
O&M				5.2		5.2
Rounded Total						121
Abatement Costs ($10^6$$) (1980 dollars)	(16)					
Cooling Towers				2.4		2.4
Near-Zero Radwaste				1.8		1.8
Rounded Total						4
Occupational Accidents	(11)					
Deaths		0.09	0.005	0.01	0.002	0.1
Non-fatal Injuries		3.3	1.4	1.3	0.14	6.1
Man-days Lost		696	81	110	16	903
Mining & Milling Impacts						
U (natural) for GDP feed (MTU)		144				
Strip Mining of Uranium & Mill Tailings (Acres)		9.0	2.0	-	-	11
Tailings produced @ Mill (10^3MT)		-	72	-	-	72
Public Accidents in Transportation of Nuclear Fuels (Excl. exposures to radioactivity)						
Deaths		-	-	-	0.009	0.009
Non-fatal Injuries		-	-	-	0.08	0.08
Man-days Lost		-	-	-	60	60
Occupational Health						
Miners' radiation exposure (Miner-WLM)	(13)	~100	-	-	-	~100
Other Occupational exposure (Man-rad)	(12)	-	15	300	30	345
Solid Radioactive Waste Disposal	(15)					
Volume (10^2 ft^3)		-	93	44	14	150
Burial Area (acres)			0.19	0.09	0.31	0.6
Land Use	(20)					
Inventory (acres)		~500	~100	100	100	~1000
Consumption (acres/yr)		9	2	-	1	12
Effects at the Power Plant						
Thermal Discharge (10^{10} kWht)		-	-	1.4	-	1.4
Net destruction of Uranium (MTU)		-	-	1.1	-	1.1
Net production of Plutonium (MTPu)		-	-	~0.2	-	~0.2
Routine Radioactive Releases to the Atmosphere (Ci)	(17)					
H-3		-	-	-	16000	16000
Kr-85		-	-	5500	280,000	290,000
I-129		-	-	-	0.0003	0.0003
I-131		-	-	0.002	0.004	0.006
Xe-131m		-	-	580	50	630
Xe-133		-	-	130,000	-	130,000
Cs-134		-	-	-	0.007	0.007
Rn-222		-	40	-	-	40
U-234		-	0.006	-	~0	0.006
U-238		-	0.002	-	~0	0.002
Total U		-	0.009	-	~0	0.009
Pu-241		-	-	-	0.003	0.003
Total Pu		-	-	-	0.003	0.003
Others				120,000	0.2	120,000
Routine Radioactive Releases to Waterways (Ci)						
H-3		-	-	85	350	440
I-129		-	-	-	0.0002	0.0002
I-131		-	-	0.1	0.00002	0.1
Cs-134		-	-	0.001	0.01	0.01
U-234		-	0.1	-	0.002	0.1
U-238		-	0.05	-	0.0007	0.05
Total U		-	0.2	-	0.003	0.2
Others		-	0.0008	0.2	3.0	3.0
Population Exposure from Routine Release of Radionuclides	(18)					
.Global Model: All-time commitment, long-lived nuclides						
World (whole body man-rad)						
Kr-85		-	-	~3	127	130
H-3		-	-	-	21	21
Total World						151
U.S. Only (whole body man-rad)						
Kr-85		-	-	~0.1	6	6.1
H-3		-	-	-	2.3	2.3
Total U.S.						8.4
.Local Model: Airborne short-lived noble gases & tritium						
Total man-rem within 50 miles						
High Population Assumption						310
Medium Population Assumption						25
Low Population Assumption						4.4

a. Working capital charges (fuel)
b. Includes all transportation steps
c. Milling, Conversion, Enrichment, and Preparation and Fabrication

(5) USAEC, Statistical Data of the Uranium Industry, January 1, 1974, GJO-100. Personal Communication, John Patterson, Div. of Production and Materials Management, USAEC.

(6) The estimates of reasonably assured reserves are made by the USAEC from basic data provided by private uranium companies. In order to qualify in the reserve category, the material must have been demonstrated to exist by sample data and shown to be profitably recoverable based on actual production experience. Forward operating and capital costs have been used to estimate reserves at a given price. Ore cutoff grades are based on operating costs only, but the average grade of ore produced must be adequate to allow recovery of all operating and forward capital costs. The average grade of the reasonably assured resources in conventional deposits recoverable at up to $10 per pound is about 0.17% U_3O_8.

(7) Injury Rates in Uranium and Coal Mines

The table below compares injury statistics in coal and uranium mining for the period 1964-1969. Figures aggregate injuries from both strip and underground mining methods.

Note that coal and uranium injury rates on a per million manhour basis are similar, but that rates on a per million ton output basis are higher for uranium, due to lower productivity rates in uranium mining.

COMPARISON OF COAL AND URANIUM MINING ACCIDENT RATES*

	Injury Rates Per Million Man-Hours				Injury Rates Per Million Tons of Output			
	Uranium		Coal		Uranium Ore		Coal	
Year	Fatal	Nonfatal	Fatal	Nonfatal	Fatal	Nonfatal	Fatal	Nonfatal
1964	0.51	44.6	0.96	43.9	0.75	65.9	0.48	22.0
1965	1.62	45.4	1.04	44.7	2.28	59.4	0.49	21.1
1966	1.18	35.3	0.96	42.9	1.61	48.6	0.43	19.1
1967	0.74	46.2	0.92	41.8	0.95	59.1	0.29	18.0
1968	0.71	37.0	1.22	40.4	0.92	48.4	0.56	17.0
1969	1.54	31.4	0.85	41.8	2.03	41.5	0.36	17.4
Ave.	1.02	39.2	1.01	42.6	1.39	53.4	0.45	19.0

*Sources: (7.1), (7.2), (7.3), (7.4), 7.5).

Data were also obtained showing the injury rates for underground versus open pit uranium mining.(7.5) Underground mining had a higher fatality and nonfatal injury rate by a considerable margin as shown in the table below. These rates have been showing a downward trend as the uranium industry becomes more sophisticated. For example, the inclusion of fatalities from 1960 through 1963 raises the average underground fatality rate to 2.30 deaths per million tons. However, 1960 was a particularly bad year as 29 underground miners died while the underground mining production was less than 5.6 million tons of ore.

URANIUM MINING ACCIDENT DATA

	Underground Mining			Open Pit Mining		
Year	Production 10^3 tons ore	Fatalities	Nonfatal Injuries	Production 10^3 tons ore	Fatalities	Nonfatal Injuries
1964	3760	4	326	1537	0	23
1965	3133	10	250	1243	0	10
1966	2966	7	187	1332	0	23
1967	3678	3	291	1593	2	21
1968	4082	5	303	2366	1	9
1969p	3731	12	220	2173	0	25
1964-69 Ave Accident Rates Per 10^6 tons of ore		1.92	73.9		0.29	10.8
Rate per 10^6 kg U_3O_8*		1.06	40.6		0.16	5.9

*Assuming 0.2% U_3O_8 content in ore.

p means preliminary

Source: (7.5)

Assuming 0.2% U_3O_8 content in ore and that 50% of the mining production is by the open pit method, the fatality rate for all uranium mining is 0.61 deaths per million kg of U_3O_8 mined, while the nonfatal injury rate is 23.2 injuries per million kg of U_3O_8. Using 6000 man-days lost per death and 55 man-days lost per nonfatal injury (ave. of 1964 through 1968 data from Ref. 7.1) gives 4940 man-days lost per million kg of U_3O_8 mined.

Sources:

(7.1) Bureau of Mines, Minerals Yearbook - 1968

(7.2) National Coal Association, Bituminous Coal Facts -- 1970

(7.3) Bureau of the Census, Statistical Abstract of the U.S., Annual Publication.

(7.4) Bureau of Mines, Coal Mine Injuries and Worktime -- December and Annual Summary, 1970, Issued May 24, 1971.

(7.5) R. L. Faulkner, Dir., USAEC, Div. of Raw Materials, Personal communication, Oct. 29, 1971.

(8) The following crude calculation supports this statement. A more refined treatment of occupational casualty rates in the alternate fuel cycles is given in Chapter 5 and the Appendix.

Coal
Annual requirement of 1000 MWe power plant: 2.3×10^6 short tons.
Fatality rate in Mine (7): 0.45 fatalities per 10^6 short tons.
Thus, 0.45 (fatalities/$T0^6$ST) x 2.3 (10^6ST/Yr) = 1.0 (fatality/Yr) per 1000 MWe plant.

Uranium
Annual requirement of 1000 MWe power plant: ~130 metric tons U/Year
Assume: U_3O_8 concentration ~0.2%.
Fatality rate in mine (7): 1.39 fatalities per 10^6 short tons (ST)

Thus, 1.39 (fatalities/10^6 ST ore) x 10^{-6} (10^6 ST ore/ST ore)
x 1/0.002 (ST ore/ST U_3O_8) x 1/0.85 (ST U_3O_8/ST U)
x 1.1 (ST U/M.T. U) x 130 (MT U/Yr)
≈ 0.1 (fatalities /Yr)

(9) Major references on lung cancer risk among uranium miners, due to radon daughter inhalation, and on related matters, are listed below. The present study made heavy use of reference (9.1), the most recent report of the Public Health Service study.

(9.1) Frank E. Lundin, Jr., Joseph K. Wagoner, and Victor E. Archer, "Radon Daughter Exposure and Respiratory Cancer, Quantitative and Temporal Aspects," U.S. Department of Health, Education and Welfare, Public Health Service, National Inst. for Occupational Safety and Health, Natl. Inst. of Environmental Health Sciences Joint Monograph No. 1, June 1971.

(9.2) W. C. Hueper, "Occupational and Environmental Cancers of the Respiratory System," Section C.11, Springer-Verlag, New York, 1966.

(9.3) Frank E. Lundin, Jr., J. William Lloyd, and Elizabeth M. Smith, "Mortality of Uranium Miners in Relation to Radiation Exposure, Hard-Rock Mining and Cigarette Smoking--1950 Through September 1967," Health Physics 16 pp. 571-578 (1969).

(9.4) Joseph K. Wagoner, et al, "Radiation as the Cause of Lung Cancer Among Uranium Miners," New Eng. J. Med. 273 pp. 181-188 (1965).

(9.5) Joseph K. Wagoner, et al, "Cancer Mortality Patterns Among U.S. Uranium Miners and Millers, 1950 Through 1962," J. Nat. Cancer Inst. 32 pp. 787-801 (1964).

(9.6) Federal Radiation Council, Radiation Protection Guidance for Federal Agencies, Memorandum for the President, December 27, 1968. Reprinted in ref. 11, appendix 1.

(9.7) "Underground Mining of Uranium Ore, Radiation Protection Guidance for Federal Agencies," Environmental Protection Agency, Federal Register, 36 pp. 9480-9482 (May 25, 1971).

(9.8) "Federal Metal and Nonmetallic Mine Safety Act of 1966," Public Law 89-577, 89th Congress.

(9.9) Code of Federal Regulations, Title 30 (mineral resources), part 57, Federal Register Office, National Archives and Records Serv., General Services Administration, Washington, D.C.

(9.10) Aurel Goodwin, Chief, Health Division, U.S. Bureau of Mines, Arlington, Virginia, personal communication, April 5, 1972.

(9.11) Joint Committee on Atomic Energy, Radiation Standards for Uranium Mining, Hearings before the Subcommittee on Research, Development, and Radiation of the Joint Committee on Atomic Energy, Congress of the United States, Ninety-First Congress, first session, March 17 and 18, 1969. U.S. Govt. Printing Office, Washington, 1969.

(9.12) Joint Committee on Atomic Energy, Radiation Exposure of Uranium Miners, Hearings before the Subcommittee on Research, Development, and Radiation of the Joint Committee on Atomic Energy, Congress of the

United States, Ninetieth Congress, first session, May 9,10,23, June 6,7,8,9, July 26,27 and August 8 and 10, 1967. Parts 1 and 2. U.S. Govt. Printing Office, Washington, 1967.

(9.13) "Radiation Exposure of Uranium Miners," a report of an Advisory Committee from the Division of Medical Sciences: National Acad. of Sciences--Natl. Research Council--Natl. Acad. of Engineering. Federal Radiation Council, Washington, D.C., August 1968. Reprinted as ref. 11, appendix 3.

(9.14) "Epidemiologic Studies of Uranium Miners," National Acad. of Sciences--National Research Council, report of the Ad Hoc Committee, Advisory Committee to the Fed. Radiation Council, Jan. 27, 1971. This report may be seen at the Headquarters and at the 10 Regional Offices of the Environmental Protection Agency. Addresses are given in ref. 7.

(9.15) Robley D. Evans, "Radiation Protection of Uranium Miners," U.S. Dept. of Labor, Bur. of Labor Standards. Hearings on safety and health standards, Nov. 20, 1968. Reprinted as ref. 11, appendix 6.

(9.16) Geno Saccomanno, et al, "Histologic Types of Lung Cancer Among Uranium Miners," Cancer 27 pp. 515-523 (1971).

(9.17) Geno Saccomanno, et al, "Lung Cancer of Uranium Miners on the Colorado Plateau," Health Physics 10 pp. 1195-1201 (1964).

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(9.19) "Vital Statistics of the United States 1967," U.S. Dept. of Health, Education and Welfare, Public Health Service, Wash. D.C., 1969.

(9.20) Geno Saccomano, "Radiation Exposure of Uranium Miners," U.S. Dept. of Labor Bur. of Labor Standards, Hearings on safety and health standards, Nov. 20, 1968. Reprinted as ref. 11, appendix 5.

(9.21) "Probable Numbers and Costs Through 1985 of Lung Cancer Cases Among Uranium Miners," Feb. 2, 1967. Reprinted as ref. 12, part 2, appendix 7.

(9.22) Charles F. Eason, Asst. Dir. for Workmen's Compensation and Radiation Records, U.S. Atomic Energy Commission, personal communication, April 13, 1972.

(9.23) Opinion of the Supreme Court of Utah in Garner vs. Hecla Mining Co. (1967). Reprinted as ref. 12, part 2, appendix 16.

(9.24) Oswald C. Abernethy, Supervising Referee, State of Colorado, Dept. of Labor and Employment, Div. of Labor, Workmen's Compensation Section, Denver, Colorado, personal communication, May 4, 1972.

(9.25) Occupational Safety and Health Act of 1970, Public Law 91-596, 91st Congress, S.2193, Dec. 29, 1970, Section 27 (d)(1).

(9.26) Office of Workmen's Compensation and Radiation Records, Office of the General Manager, USAEC, Washington, D.C., personal communication, May 1, 1972.

(10) Basis for lung cancer risk estimate among uranium miners is given in the table below.

Lung Cancer Deaths Expected to Age 80, Among 10,000 White Men Who Mine Uranium Between Ages 20 and 50

	Expected with no radiation exposure	Expected with exposure at 4 WLM/year	Expected with exposure at 12 WLM/year
Total deaths[a]	353	512	684
Excess deaths	0	259	331
Excess deaths/miner/WLM		1.3×10^{-4}	0.92×10^{-4}

Lifetime probability/WLM of death from radiogenic lung cancer adopted for use in this report: Order of 10^{-4}.

(a) From Lundin, et al (9.1, Table 44.

(11) Occupational Accidents in the LWR Fuel Cycles

a. Sources of injury rates in uranium mining are given in footnote (7).

b. Elsewhere in the LWR fuel cycle, base data were taken from:
   - Bureau of Labor Statistics, Work Injuries in Atomic Energy, 1968 -- A Survey of Privately-Owned and Operated Establishments, BLS Report #378, and from
   - Bureau of Labor Statistics, Work Injuries in Atomic Energy, 1969, BLS Report #385.

The following injury rates are averages of 1967 through 1969 data:

	Fatalities per Million Manhours	Nonfatal Injuries Per Mil. Manhours	Severity Rate Mandays Lost Per Million Manhours
A. Production of feed materials	0.03	3.5	266
B. Fuel element fabrication & recovery	0.01	6.4	199
C. Power reactor operation & maintenance	0.04	5.1	400

Category A represents both the conversion and enrichment steps, while Category B represents both the fabrication and reprocessing steps. In the lack of more detailed data, these composite rates are assumed to be the same for each activity in the category.

Since the desired rates are in injuries per unit throughput, the inverse productivity figures in manhours per unit output are required. The table below summarizes the calculations of inverse productivity figures.

	Employment	U.S. 1980 Throughput	Manhours Per Unit Output
Conversion			60 mh/ton U
Enrichment	5,468	25.6×10^{6} SWU	0.429 mh/SWU
Fabrication	3,600	4500 MTU	1.6×10^{3} mh/MTU
Reactor O & M	17,000	8.5×10^{11} KWH	4.0×10^{-5} mh/KWH
Reprocessing	825	3,400	4.85×10^{2} mh/MTU

The 1980 employment and throughput figures were taken from Data for Preliminary Demonstration Phase of the "Environmental Quality Information and Planning System (EQUIPS)," BNWL-B-141, 1971. The conversion process was estimated to require 60 manhours per ton of uranium.

Combining the derived inverse productivity data with the injury rates, the following rates, related to fuel cycle throughput, were obtained:

	Fatality Rate	Nonfatal Injury Rate	Severity Rate (mandays lost)
Conversion	1.8×10^{-6}/ton U	2.1×10^{-4}/ton U	1.6×10^{-2}/ton U
Enrichment	1.3×10^{-8}/SWU	1.5×10^{-6}/SWU	1.1×10^{-4}/SWU
Fabrication	1.6×10^{-5}/MTU	1.0×10^{-2}/MTU	3.2×10^{-1}/MTU
Reactor O & M	1.6×10^{-12}/KWH	2.0×10^{-10}/KWH	1.6×10^{-8}/KWH
Reprocessing	4.8×10^{-6}/MTU	3.1×10^{-3}/MTU	9.7×10^{-2}/MTU

The rates calculated above were then normalized to a unit of electrical energy using the appropriate (PWR or BWR) fuel cycle materials balance.

c. Injury rates for uranium milling operations were calculated using data from:

- Bureau of Mines, Minerals Yearbook -- 1968, and from
- Bureau of the Census, Statistical Abstract of the U.S., annual publication.

The average of 1964 through 1968 data was:
2×10^{-8} fatalities per kg U_3O_8 milled,
6.3×10^{-6} nonfatal injuries per kg of U_3O_8, and
4.1×10^{-4} man-days lost per kg of U_3O_8.

There was only one death in the five year period, while there were 290 nonfatal injuries and 18,821 mandays lost. The severity rate steadily improved from 2,142 mandays lost per million manhours in 1964 to only 85 mandays lost per million manhours in 1968. All ore mined in those years was assumed to be milled during that five year period.

(12) Occupational Exposure to Radiation in the LWR Fuel Cycles Under Normal Operating Conditions (Excl. Uranium Mines)

a. Internal Doses

In contrast to data on external exposure, compilations of internal exposure data are rare in the available literature. Three compilations (12.9, 12.10, 12.17) were found which gave internal exposure data, but not in sufficient detail to permit a quantitative assessment. Kiefer (12.17), et al, did comment, however, that contribution to the total occupational dose from internal emitters was small compared to external exposure.

b. External Dose

Compilations of occupational external exposure data are abundant. Unfortunately, the occupational groups are seldom explicitly defined in terms of work responsibilities. Also, visitors are monitored at some nuclear installations and their exposure data are included with that for personnel. Finally, there appears little relationship between occupational group dose and production level of a nuclear facility, e.g., man-rads per year and power produced by a

reactor, making normalization to electrical energy delivered difficult. The broad ranges of occupational doses reported for similar facilities indicates differences in manning level, operating procedure, and facility design.

Reactors

From ref. (9.13), average annual occupational doses for four LWRs are:

Reactor	Period	Average Man-rad Per Year
Indian Point 1	1962-69	173
Big Rock Point	1962-70	135
Shippingport	1965-69	180
Dresden	1960-70	185
	Arithmetic Average	~ 170

Power ratings of these plants range from 70 to 200 MWe.

The number of people required to operate, maintain, and refuel a nuclear power plant is not a linear function of reactor power, but depends on the operating practice of the utility. TThe man-rads at a 1000 MWe facility would be approximately the same as at a 200 MWe facility, which roughly represents the size for the 170 man-rad per year given previously, if similar health physics practices are employed and if the manhours required for operation, refueling, and maintenance at the large reactor are equal to that of the smaller reactor. It is expected, however, that the exposure hours due to refueling and maintenance might be a factor of two higher. In this manner, a value of 300 man-rad has been selected as representative of annual staff dose at a 1000 MWe reactor operating at 75% capacity during the 1980 to 1990 period. There is a large uncertainty associated with this number. In the first years of operation, a new reactor at a new site might be expected to show lower total exposures. In later years the exposure might increase as radiation levels build up. The 1970 exposures of more than 1000 man-rad at Indian Point 1 (12.13) and Douglas Point (12.7) probably approximate upper bounds for occupational exposure at the reactor.

Reprocessing Plant

The AEC has gathered data on the external exposure of monitored individuals at the one U.S. fuel reprocessing plant in operation (12.15). The throughput of this plant has been about 100 metric tons uranium (MTU) each year in the recent past (12.23). Occupational doses for the monitored population at this facility are presented below and are normalized to fuel throughput. The average is calculated by summing the staff dose for the various years and dividing by the total throughput.

Year	Man-Rad (12.23)	Man-Rad/MTU
1968	600	6.0
1969	857	8.6
1970	1100	11
	Average	8.5

As the case of power reactors, a relationship between occupational dose and product output has not been demonstrated for nuclear fuel reprocessing facilities.

The data given above apply to a reprocessing plant operated at less than half of its nominal capacity of one MTU/day, which is currently being raised to

3 MTU/day. By 1980, at least two other reprocessing plants are expected to be in operation, with one of them having a nominal capacity of six MTU/day. Improvements in technique, the use of the large capacity plant, and the availability of large quantities of fuel to be reprocessed are all factors which will tend to improve the productivity in terms of MTU per manyear employment at the reprocessing plant. In fact the EQUIPS study[12.26] shows a factor of six improvement in industry productivity between 1967 (120 MTU and 170 employees) and 1980 (3400 MTU and 825 employees). The occupational dose at the reprocessing plant has been estimated in this study by using the 1980 EQUIPS[12.26] productivity and conservatively assuming each worker receives the maximum allowable annual average dose of 5 rads. This gives a value of 1.2 man-rad per MTU which is in reasonable agreement with the observed data given above when one accounts for the projected improvement in productivity. However, if the 1980 productivity estimate turns out to be correct, then the estimated 1.2 man-rad per MTU should be high since not all workers would be expected to receive the maximum annual average dose as has been assumed.

Other Fuel Cycle Steps

The occupational dose delivered in the remaining steps in the fuel cycle except mining, has been grossly estimated to be about 15 man-rem. From data in reference [12.6], the mean annual exposure for 62,090 employees of Atomic Energy Commission licensees is 212 mrem, in the industrial category (13,331 employees) it is 160 mrem, in fuel processing (6,637 employees) it is 328 mrem, and in packing and transport (335 employees) it is 65 mrem. Based on productivity rates given in footnote (11), it is estimated that milling, conversion, enrichment, and fabrication total about 80 man-years of employment for the 1000 MWe PWR or BWR. If the average exposure were 200 mrem, the BWR or PWR total would be 16 man-rem. Transportation exposure at 65 mrem per manyear would not add significantly to the total.

c. References

[12.1] Khalid Faroog Mirza and Walayat Khan Malik, "Average Exposure to Radiation Workers in Pakistan," Health Physics 18 p. 569 (1970).

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(12.7) R. Wilson, "Man-Rem, Economics and Risk in the Nuclear Power Industry," Nuclear News 15 (2), pp/ 28-30 (1972).

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(13) Exposure Levels in Uranium Mines

One "working level" (WL) is any combination of short lived radon daughter products in one liter of air, which upon complete decay will yield 1.3×10^5 Mev. A miner is exposed to one working level month (WLM) if he works for 170 hours in an atmosmosphere in which the air concentration of radon daughters is 1 WL.

The current limit on the average concentration of radon daughter products is 1 WL (9.9) and the limit on miner exposure is 4 WLM per year. The 1 WL mine air limit is currently under review (9.10). The U.S. Department of Interior has the authority under the Federal metal and Nonmetallic Mine Safety Act of 1966, to establish and enforce mine air concentration and miner exposure limits (9.8).

Assuming miners are exposed to the limit, that the productivity is 3 metric tons of U_3O_8 per miner per year, and that half of the annual 1000 MWe LWR makeup fuel[8] is underground-mined, the annual miner group exposure level is:

$$\frac{4\ (\text{WLM/Yr}) \times 160\ (\text{MT-}U_3O_8\text{/Yr}) \times 0.5\ (\text{MT-}U_3O_8\ \text{Undergrd.-mined/ MT}U_3O_8)}{3\ (\text{MT-}U_3O_8\text{/miner-yr})}$$

$$\approx 104\ (\text{miner-WLM/Yr})$$

(14) *Tailings Produced at Uranium Mills*

The mass of ore tailings produced at uranium mills associated with the annual operation of one 1000 MWe PWR is approximated as follows:

$$\frac{124\ (MTU/Yr)}{0.85\ (MTU/MTU_3O_8)} \times \frac{1}{0.002}\ \frac{MT\text{-}ore}{MT\text{-}U_3O_8} \approx 73{,}000\ \frac{MT\text{-}ore\ tails}{Yr}$$

(15) *Disposal of Solid Radioactive Wastes in LWR Fuel Cycles*

Solid radioactive wastes generated throughout the LWR fuel cycle will be stored at Federal Repositories and Commercial burial grounds. Volumes generated, normalized to annual operation of one 1000 MWe LWR (BWR or PWR) and its supporting fuel cycle, are given below:

Basis: 1000 MWe LWR Annual Operation @ 75% C.F. (6.6 billion kilowatt hours of electricity)

Type	PWR	BWR
High Level Waste[a]	85 ft^3	85 ft^3
Cladding Hulls[b]	60	65
Int. Level Waste[c]	788	788
Transuranium Waste[d]	361	433
Nontransuranium Waste[e]	9,855	13,797
	11,142 ft^3	15,168 ft^3
Burial Area[f]	0.52 acres	0.59 acres

a. 10,000 MWD(t) yields one cubic foot, ref. (15.1)
b. 2.1 cubic feet per metric ton fuel, ref (15.1)
c. 10,000 cubic feet per metric ton Pu processed. Compacted by a factor of three before shipment ref. (15.1)
d. 14 cubic feet per metric ton of fuel processed. This number only accounts for waste produced at the reprocessing plant. ref. (15.1)
e. PWR: 2500 cubic feet per year at reactor plus fabrication waste at 300 cubic feet per MTU, ref. (15.2, 15.3)
BWR: Quad Cities Unit 1 will produce roughly 5000 ft^3 per year, ref. (15.4), plus fabrication waste at 300 ft^3/MTU, ref. (15.2, 15.3)
f. 50,000 cubic feet solid waste per acre of burial ground except for solidified high level waste which requires approximately one acre per 300 cubic feet of waste, ref. (15.1).

(15.1) Oak Ridge National Laboratory, Siting of Fuel Reprocessing Plants and Waste Management Facilities, ORNL-4451 (1970).

(15.2) USAEC, The Nuclear Industry - 1970, and The Nuclear Industry - 1971.

(15.3) Battelle, Data for Preliminary Demonstration Phase of the "Environmental Quality Information and Planning System (EQUIPS)", BNWL-B-141 (1971).

(15.4) Environmental Report for Quad Cities Units 1 and 2, AEC Dockets 50-254 and 50-265, Nov. 16, 1970.

Environmental Impact Assessment: Supplemental Information to the Quad Cities Environmental Report, prepared for Commonwealth Edison Co. by Battelle-Columbus Laboratories, November 1971, and supplements.

(15.5) USAEC, Nuclear Fuel and Waste Shipping Study (to be issued).

(16) See Chapter 5 of this report.

(17) Routine Radioactive Releases

Routine release rates were estimated from a number of references (listed below), normalized to fuel cycle throughtput, and to electrical energy produced.

Uranium milling	(17.1)
Conversion	(17.1)
Enrichment	(17.1)
Preparation/Fabrication	(17.1)
Reprocessing	(17.1, 17.2)
Reactor Power Plant	(17.3, 17.4, 17.5, 17.6, 17.7, 17.8, 17.9, 17.10, 17.11, 17.12, 17.13, 17.14)

(17.1) Battelle, Data for Preliminary Demonstration Phase of the "Environmental Quality Information and Planning System (EQUIPS)," BNWL-B-141 (1971).

(17.2) Allied Gulf Nuclear Services, Environmental Report for Barnwell Nuclear Fuel Plant (November 5, 1971)

(17.3) Commonwealth Edison Co., Environmental Report for Zion.

(17.4) Indiana and Michigan Electric Co., Environmental Report for Donald C. Cook Nuclear Plant (February 1971).

(17.5) Stewart, J. E. and A. F. Desar, "Cryogenics: A Solution to Radioactive Pollution," Electrical World (November 15, 1971).

(17.6) Van Hollen, H. J. and W. A. Webb, "PWR Nuclear Power Plant Systems for Reducing Radioactive Releases," Proc. American Power Conference, Volume 33 (1971).

(17.7) TVA, Draft Environmental Statement for Watts Bar Nuclear Plant, Units 1 and 2 (May 1971).

(17.8) Indiana and Michigan Electric Company, Final Safety Analysis Report Donald C. Cook Nuclear Plant, Volume 4, Section 11.1.3.

(17.9) Commonwealth Edison Company, Final Safety Analysis Report, Zion Nuclear Plant, Volume VI, Appendix 14A.

(17.10) Commonwealth Edison Company, Environmental Report for Quad Cities Nuclear Plant.

(17.11) Commonwealth Edison Company, Safety Analysis Report for Quad Cities, Volume II, Section 9, Radioactive Waste System.

(17.12) Testimony of James M. Smith, General Electric, before the Illinois Pollution Control Board, May 24, 1971, PCB 71-20.

(17.13) Smith, James C. and C. E. Kent, "Nuclear Plant Environmental Control," Proc. American Power Conference, Volume 33 (1971).

(17.14) TVA, Draft Environmental Statement for Browns Ferry Nuclear Plant Units 1, 2, and 3 (July 14, 1971) and supplements.

(18) *Radiation Dose to the General Population from Routine Releases in the Nuclear Fuel Cycle*

Tables present estimated annual radioactivity release rates (curies/year), by radionuclide, from nuclear power plants and their associated fuel cycles (prorated). Calculated population doses (man-rad/year), corresponding to these releases, are also given in these tables. The source quantities (Ci/Yr) and population dose quantities (man-rad/yr) are related through computational models which:

- *describe the transport (dispersion) of radionuclides through the environment, yielding environmental concentrations (e.g., curies/liter of air) of the radionuclides; and which*
- *estimate population dose (man-rad) resulting from these environmental concentrations.*

The computational modeling must recognize geographical distributions of population in the vicinity of nuclear facilities (in the case of short-lived nuclides) and national and world population growth characteristics (in the case of long-lived nuclides). Various pathways to man - air, water, food chain - must be included. Further, there are a variety of exposure modes: transpiration, inhalation, ingestion, submersion in water, and many sub-varients. Local meteorology, hydrology, and population pattern must be considered. For all of these reasons, community dose calculations may be quite complex. Results can be quite sensitive to small changes in obscure variables. When simplifying assumptions are introduced, they are normally selected to be conservative, that is, leading to higher dose figures. Results should be treated as order-of-magnitude estimates only.

Population dose calculations performed in the course of this study are discussed in Chapter 4 and described in more detail in the Appendix. Two models were established: the global model, which yields U.S. and worldwide population dose commitments (all time) due to releases of long-lived isotopes (H-3 and Kr-84) during one year's operation of a 1000 MWe nuclear power plant, and its supporting fuel cycle (prorated); and a local model, which yields population doses within a 50-mile radius of nuclear facilities, due to release of relatively short-lived isotopes. Major assumptions are listed below.

Major Assumptions

a. *Global Model*

a.1. Radionuclide: Tritium (H-3)

Source: All H-3 released from the fuel cycle is released at the reprocessing plant in the form of a gaseous effluent.

Distribution: Ultimate reservoirs of H-3 are the surface waters of the world. H-3 is instantaneously dispersed according to the current distribution pattern of environmental tritium, i.e., one curie of H-3 released contributes ~ 3×10^{-10} pCi/liter to surface waters between 30° and 50° north lattitude, and ~ 3×10^{-11} pCi/liter to surface waters throughout the rest of the world.

Human Uptake: Concentration of tritium in human body water follows that of environmental tritium instantaneously.

Dose Rate: The total body dose rate corresponding to an H-3 concentration of 1 nCi/liter in human body water is 0.11 mrad/year. The total dose commitment (all time) per individual is the initial dose rate multiplied by the mean half-life of H-3, 17.7 years.

Population: To account for U.S. and world population growth over the mean half-life of H-3, the exposed population is taken to be that ten years after the release of the tritium.

b. Local Model

b.1. Radionuclides: Short-lived noble gases and tritium.

Sources: All releases throughout the fuel cycles are assumed airborne and released from a single stack. Year 2000 Study results have shown that dose from water-borne releases are insignificant.

Distribution: Exposed population is that within 50-mile radius of the point of release. Atmospheric transport is described by the Gaussian plume model. Meteorological data, effective stack heights, etc., are given in the discussion of Chapter 4.

Human Uptake: Inhalation and transpiration. Only the total body dose were calculated.

Dose Rate: Dose rate factors for submersion in air were assumed as follows:

Dose Factors For Submersion in Air
(mrem/hr per pCi/m^3)

H-3	2.5 - 03
Kr-83m	~0
*Kr-85m	1.1 - 03
Kr-85	2.3 - 05
*Kr-87	1.1 - 02
*Kr-88 + Rb-88	1.8 - 02
Kr-89	1.6 - 02
*Xe-131m	2.4 - 05
*Xe-133m	2.4 - 04
*Xe-133	2.2 - 04
*Xe-135m	3.1 - 03
*Xe-135	1.8 - 03
Xe-137	1.2 - 03
*Xe-138	1.1 - 02
*Cs-138	1.6 - 02

*From The Year 2000 Study.

A.A - BB means A.A x 10^{-BB}

Population: To demonstrate the sensitivity of integrated population dose to population distribution around the facility, three population distributions were assumed. Dose calculations were performed for each distribution.

Population Distributions Used for Dose Calculations For 1980

Annulus	High	Medium	Low
0-1 mile	2,200	170	0
1-2	18,000	350	0
2-3	40,000	1,270	0
3-4	20,000	680	0
4-5	30,000	1,105	20
5-10	190,000	11,845	508
10-20	1,100,000	68,680	55,792
20-30	3,100,000	79,200	50,680
30-40	5,500,000	310,700	33,000
40-50	8,400,000	2,246,000	73,700
Total	18,400,000	2,720,000	213,000

Data obtained from environmental reports (some Indian Point data estimated from Figures 2.2-7 and 8 of the LaSalle County Station Environmental Report). The distribution is representative of Indian Point, the Medium distribtuion of Calvert Cliffs in 1970, and the Low distribution of Hanford in 1980.

(19) *Radiological Health Effects* - LWR Energy Systems

Assumptions:

- *Dose-response coefficient: Individual probability of malignancy (Chapter 4)* ..... 2×10^{-4}/rad or 2×10^{-4} cases/man-rad
- *Time lost* ..... 6000 MDL/case
- *Cost* $50/MDL

PWR Energy System (6.57 billion kWhe)

Occupational

- *Occupational Group Exposure (Excl. U-mines), from Table 3.5.2 and footnote (12)* ..... 345 man-rad
- *Time Lost:* $345 \times 2 \times 10^{-4} \times 6000$ ..... 414 MDL
- *Cost:* 414×50 ..... $0.02 \times 10^6$$

Public

- *Population Exposure (Table 3.5.2):*
  - 152 man-rad — World Kr-85 and H-3
  - 4.2 — Local, medium population assumption
  - 156 man-rad — Total
- *Time Lost:* $156 \times 2 \times 10^{-4} \times 6000$ ..... ≈190 MDL
- *Cost:* 190×50 ..... ≈$0.095 \times 10^6$$

BWR Energy System (6.57 billion kWhe)

Occupational

- *Approximately same as PWR* ..... 414 MDL, $0.02 \times 10^6$$

Public

- *Population Exposure (Table 3.5.3):*
  - 151 man-rad — World, Kr-85 and H-3
  - 25 — LLocal, medium population assumption
  - 176 man-rad
- *Time lost:* $176 \times 2 \times 10^{-4} \times 6000$ ..... ≈210 MDL
- *Cost:* 210×50 ..... ≈$0.011 \times 10^6$$

(20) *See Appendix for quantification of land use in the nuclear fuel cycles.*

3.6 HYDROELECTRIC POWER

Water head is one of the oldest sources of electrical energy. Hydropower's versatility provides many advantages including the ability to start quickly, adjust to rapid changes in load, provide spinning reserve, maintain frequency control and particularly to furnish peaking power. Hydro plants are sturdy, relatively simple, require little maintenance, assure high reliability, and have a long service life.

Among all of the methods available for economic production of electric power, hydropower is the only one utilizing current energy inflow from the sun. Fossil fuels and uranium are nonrenewable resources, which, once expended, are gone forever. The natural, downhill flow of water is continuously renewed through the evaporation and precipitation of water.

Although the development of hydropower sources may have significant environmental impact, those effects of greatest concern for fossil fueled and nuclear plants are absent. Hydropower plants do not discharge chemical pollutants to the atmosphere, nor do they produce radioactive wastes which must be carefully disposed of, nor is there any production of waste heat. However, the availability of developable sites in the continental U.S. for additional production of hydropower is severely limited and this is the principal disadvantage of this energy source within the context of future planning.

The Federal Power Commission reports almost 52 million kilowatts of installed conventional hydroelectric capacity in the contiguous 48 states, which in 1970 produced 253 billion kilowatt hours or 16.4 percent of the electric energy of the contiguous states.

By 1990, the FPC projects 82 million kW of conventional hydro producing 319 billion Kwh, or only 5.4 percent of the Nation's electric energy. The 60 percent rise in capacity accompanied by a rise of only 25 percent in energy output shows the trend toward using hydro primarily for peaking duty, dependable capacity and spinning reserves.(1)

In the same report, the FPC estimates that the Nation's installed pumped storage capacity will rise from 3.6 million kW in 1970 to 70 million kW in 1990, anticipating taking advantage of low incremental cost, off-peak nuclear energy for pumping.(2) Pumped storage plants and nuclear plants are complementary and on occasion are planned as a development unit.

At any potential hydropower site, the power that can be developed is proportional to the product of the available hydraulic head and the flow rates. The head, or difference in elevation between the water level upstream of the turbines and the level downstream of their discharge, may be provided by the existence of a natural waterfall but is more frequently created by the construction of a dam. In the U.S., Niagara Falls is the only waterfall site providing major amounts of power.

As the available head decreases, larger flow rates must be handled to provide a fixed amount of energy, and this requires either larger turbines or more units with consequent increases in costs. As a rule of thumb, heads of less than 30 ft. are not developable. Low head developments are usually multipurpose projects where substantial benefits to navigation and flood control are obtained.

Waterfall plants have the distinction of producing very limited environmental impact. The aquatic life forms in the river are already adapted to the effects produced by the falls. The provision of an alternate flow path from the upper to the lower river does not significantly alter conditions. The major environmental effect is an aesthetic one rising from the decrease in the flow rate over the falls and from the interposition of manmade structures in a natural setting. In the case of Niagara Falls, these effects have been minimized by limiting major water diversion to the nighttime hours and by locating the power plant out of sight of visitors to the Falls area.

Two major types of hydraulic turbines are used in U.S. installations. For higher heads, Francis turbines are used. These are similar to a centrifugal pump. In fact, in pumped storage installations, these machines are used both as pumps and turbines. In the usual form of this machine, water is distributed from a spiral casing, flowing radially inward through the runner, and is discharged downward near the axis of the machine. These machines are used when the available heads are in the range from 100 to 1500 ft.[3]

For lower heads, Kaplan turbines are used. These machines resemble giant-sized ship's propellers. The range of application overlaps somewhat that of the Francis turbines with design heads up to 120 ft. Most turbines of this type are equipped with variable pitch blades which permit more efficient operation over a range of loads.

The machines are operated at constant speed to provide AC power at closely regulated frequency. Load following is achieved by varying the water inflow through changes in guide vane settings for both types and through changes in the pitch of the runner blades in the Kaplan type. Efficiencies of both types are around 95 percent when operated at their design points. Efficiency declines when the load varies in either direction from the design point. Hydro turbine-generator sets usually have a stretch capability for operation up to about 15 percent above nameplate rating, the limit being set by the generator windings.

There are several phases of development of river basins as power supply systems. Neglecting earlier phases, when the hydro potential is only partially developed, the three major phases are: 1) system predominantly hydro with some undeveloped potential for increased annual kilowatt hours; 2) no additional annual kilowatt hours available from hydro, but peaking capability still being increased, growing base load requirements must be met from thermal plants; and 3) system predominantly thermal, hydro used mainly for peaking.

The Columbia River Basin is presently in the first phase. Power supply in the Pacific Northwest is almost entirely hydro. The composite annual plant factor for the large plants of the Pacific Northwest is 75 percent. There are a few areas on the major rivers and their tributaries where developable head has not yet been exploited and at developed sites a significant amount of river flow during high flow seasons is passed over the spillways. Nevertheless, projections of load growth indicate that in the next decade some of the base load will have to be supplied from thermal plants.(4)

The second phase is typified by the upper Missouri River. The available head from central Montana down through the Dakotas to the Nebraska border is fully exploited by six dams. With the exception of the last downstream dam, 99.75 percent of the water released was utilized for power generation from 1966 to 1970. A major function of the last downstream dam, Gavins Point, is to smooth out the flow to facilitate navigation on the lower river which requires some releases without power production. The composite plant factor for the system is 50 percent and peaking operation is an important function. About 40 percent of the annual energy generated in the service area is supplied by lignite burning steam plants which have assumed a major part of the base load. Projected growth in demand is such that additions of 1200 MW to the hydro-turbine capacity of the system are planned. Since no additional energy is available, the plant factor for hydro will fall to 30 percent. Growth of base load will be met by additional thermal plants.(5)

The third phase is typified by the TVA system. Here, the hydropower energy generation and peaking capability have been developed. Less than 20 percent of the annual Kwh are supplied by hydro. All future additions to the system will be thermal plants.(6)

With the exception of Alaska, the potential for increased base load hydroelectric power in the U.S. is limited. A twenty-year plan for the development of the Pacific Northwest projects an increase of only 3,789 MW of firm hydropower

during that period.[7] Possibly twice this much exists for the entire Nation, excepting Alaska. Peaking capacity potential is much less limited.

The impact of water development projects on the environment consists of a mixture of benefits and costs. Multiple purpose project benefits may include flood control, navigation, irrigation, hydroelectric power, domestic water supply, recreation, and fish and wildlife enhancement. Tradeoffs exist. Land and forests lost to the reservoir may result in protecting downstream cities and lands from disastrous floods. A detrimental effect on the fishery may be offset by building a hatchery. On the other hand, severe floods are damaging to fish, hence a degree of flood control can benefit the fishery.

Direct adverse effects on human health and safety are confined to accident situations: accidents to workers during construction; accidents to employees during operation; and accidental releases of large volumes of water, including major dam failures. The accident rate for employees is expected to be similar to that for the electrical generating industry as a whole; that is, six injuries per million manhours and 0.1 fatal accidents per million manhours.[8]

Major failures of large dams have occurred from time to time with resultant loss of lives and destruction of resources. However, the completeness and accuracy of the record allows only a rough estimate of the probabilities of such failures. Lessons learned from past disasters reduce the probability of future ones. The adequacy of the design from the safety standpoint, including the nature of the foundation rock, is examined as part of the Federal Power Commission licensing process, and a periodic inspection program has been established. Some state governments have also established dam safety programs.

While major dams are designed to withstand earthquakes, geologists now also include in their site studies a seismic history of the area and an investigation of the deep foundation characteristics such as rock stress, water table, and permeability. Recent seismological literature suggests that earthquake activity has increased at several large dams and reservoirs, including Kremasta Dam in Greece, Kariba in East Africa, Koyna in India, and Hoover Dam. Some articles suggest seismicity increases with reservoir loading. Earthquakes of magnitude 6 have occurred at Kariba, Koyna, and Kremasta.[9-12] The number of these dams is small considering the thousands of dams in existence. One authority in India challenges the presumption of a relationship between dam building and seismic activity, particularly at the Koyna Dam.[13] The more recent concensus is that a combination of weak

subsurface foundation conditions coupled with injection of reservoir water under pressure accounts for the seismic activity in the cases cited. The latest literature suggests careful geological surveys of subsurface foundation conditions at the sites of proposed dams and in the proposed reservoir area.[14-15]

Because of the small number of people involved, the displacement of the human inhabitants of the area to be flooded is an additional impact of somewhat less significance. This effect has been regarded as fully covered by the costs of land acquisition.

The environmental impacts of a hydroelectric plant start with the construction of the dam and the flooding of land to make a reservoir. Considerable acreage is thus taken out of use.

In some cases, the impoundment of water will affect its quality. The large surface area of a reservoir promotes evaporation, and this may produce an increase in the salinity of the discharged water, making it less usable for some purposes downstream.

Some rivers carry a heavy sediment which may be dropped in the still waters behind the dam, thus ultimately filling the reservoir with silt. On the other hand, some ocean beaches require an annual deposit of river sediment to make up for erosion losses caused by winter storms. When dams are built upstream, blocking the natural flow of sediment, the beaches have to be rebuilt every year by other methods.

Public attention has often been focused on dams as barriers to upstream migration of adult fish. However, fish passage facilities have been generally successful and have created few problems for potential spawners.[16] In the absence of dams, these migrants would cover the same distance and "climb" to the same altitude to reach their spawning grounds and would in many cases face more difficulty from natural falls and rapids than are presented by the manmade facilities.

Under some conditions, passage of water over spillways can produce nitrogen supersaturation in waters downstream. This condition has adverse effects upon both adult and juvenile fish.[17] Effects can be reduced by use of slotted gates in empty turbine bays rather than spillways for the release of surplus water. Ultimately as upstream storage projects regulate stream flow, the spillways will have much less overflow.

Impounding of water in the reservoirs creates a condition of temperature stratification with little mixing of surface waters into the deeper layers. Water drawn from lower layers may be deficient in dissolved oxygen. This condition may confuse migrating fish.

Temperatures in a staircase of reservoirs tend to be higher than in a free flowing river. However, selective release of deeper reservoir water can aid in lowering river temperatures.

Migrants going downstream face considerable hazard from natural predation by species of fish resident in the river. These hazards are increased by reservoirs which are favorable habitats for predators and which also increase the migration time and thus the time of exposure to predation. The mean velocity of downstream migration is the same as the river flow velocity. The migrants are also subjected to the hazards of passage through turbines. Nitrogen supersaturation and oxygen deficiencies are also injurious to juveniles. These hazards occur primarily on a reservoir-dam passage basis and are only loosely related to the power produced.(17)

Footnotes and References for Section 3.6: Hydroelectric Power

(1) *Federal Power Commission, The 1970 National Power Survey, Vol. I, page I-18-29.*

(2) *Ibid, page I-18-1.*

(3) *T. H. Carr, Electric Power Stations, Chap. 24 -- Hydroelectric Plants, Chapman & Hall 1955.*

(4) *Annual Reports, Bonneville Power Administration.*

(5) *Creighton W. Becket, "Additional Power Developments at the Missouri River Main Stem Dams," Proc. Amer. Pwr. Conf. 33, 1971, pp. 842-847.*

(6) *Power Annual Report 1970, Tennessee Valley Authority.*

(7) *The Hydro-Thermal Power Program: A Status Report, Bonneville Power Administration, December 1971.*

(8) *1970 Injury Rates, Major Industries, National Safety council.*

(9) *"Seismology - Responsibilities and Requirements of a Growing Science," Part II Problems and Prospects, 1969 National Research Council, Academy of Sciences, Wash., D.C. See page 34 on man triggered earthquakes.*

(10) *"Some Discriminatory Characteristics of Earthquakes Near the Kariba, Kremasta, and Koyna Artificial Lakes," Bulletin Seismological Society of America, Vol. 62n2, pp 493-507, April 1972.*

(11) *"Seismic Investigations in the Boulder Dam Area 1940-1944 and the Influence of Reservoir Loading on Earthquake Activity," Bulletin Seisomological Society of America, Vol. 35, pp 175-192, 1945.*

(12) "Study of the Koyna Earthquake of December 10, 1967," Bulletin Seismological Society of America, Vol. 59n3, pp 1149-1162, June 1969.

(13) "December 10, 1967 Koyna Earthquake and Reservoir Filling," Bulletin Seismological Society of America, Vol. 62n2, pp 661-662, April 1972.

(14) Four papers presented at the International Symposium on Man-Made Lakes, Scientific Committee on Water Research, International Council on Scientific Unions, Knoxville, Tennessee, May 1971.

(15) Seismic Activity at Man-Made Reservoirs, Proceedings, The Institution of Civil Engineers, 50, Paper No. 7416, Sept. 1971, 15-24.

(16) F. A. Davidson, The Effect of a Succession of Dams on the Columbia River on the Upstream Movement of the Blueback Salmon Runs, Public Utility District of Grant County, Ephrata, Washington, January 1967.

(17) F. A. Davidson, The Survival of the Downstream Migrant Salmon at the Power Dams and in Their Reservoirs on the Columbia River, Public Utility District of Grant County, Ephrata, Washington, November 1965.

3.7 ULTIMATE IMPACTS AND COSTS

In the preceding sections summary tables for each of the alternate energy systems were presented. These tables contained conventional costs, abatement costs, and environmental and human impact data normalized to the annual operation of a single 1000 MWe power plant (75% C.F.) and its supporting fuel cycle activities. Thus, the quantities given in these tables are costs and impacts associated with the production of 6.6 billion kilowatt hours of electrical energy.

Although normalized to the same quantity of electrical energy or electrical power capacity, these quantities are in a variety of physical and nonphysical units - dollars, man-days lost, tons of individual effluents, curies, man-rads, acres, etc. These quantities were derived from a "direct inspection" of the respective energy systems, and, in many cases, merely represent appropriately normalized "source" terms for pollutants and other environmental burdens.

Ideally, one wishes to reduce all such quantities to the same dimension, e.g., dollars, in order to render them comparable and, perhaps, additive. Efforts to accomplish this are highly preliminary, subjective, and generally imperfect. However in several specific cases, it is possible to make gross assessments, useful in making order-of-magnitude comparisons.

Tables 3.8 through 3.12 below display evaluated effects, or ultimate impacts and costs, of the coal, oil, natural gas, PWR, and BWR energy systems. These evaluated effects are quantified in one or both of two dimensions: dollars, and mandays lost.

TABLE 3.8

EVALUATED EFFECTS OF A 1000 MWe COAL-FIRED POWER PLANT AND ITS SUPPORTING FUEL CYCLE

BASIS: 6.57 billion kilowatt-hours (one year operation @ 75% CF)

Category	Comment	Costs $10^6$$	Costs MDL*
Conventional Costs (1980 dollars)			
Capital	Entirely internal	51	
O&M	Entirely internal	5.4	
Fuel	Entirely internal	64	
Total (28)		120	
Abatement Costs (1980 dollars)			
Cooling Towers		3.6	
SO_2 Removal		25.9	
Land Reclamation		~ 0.1	
Total		30	
Mining & Transportation Impacts			
Strip	50% of production. 470 acres. External cost taken to be $300/acre.	0.1-0.2	
Underground	50% of production. 260 acres. Assume cost of subsidence negligible.		
Mine Drainage	$3.5 million for 500 billion gallons of drainage. For 2.4 million gallons, the cost is $20.	0.000020	
Transportation			
Loss of coal	10,000 tons at $9/ton	0.09	
Non-employee accidents	Assumes one MDL is equivalent to $50.	0.18	3500
Power Plant			
Thermal Discharge	1.3 million KWt to cooling water.	0.4	
Pollution Damage	SO_2 and particulates. Includes only damages to property and materials. Human health effects not evaluated.	0.8	
All Occupational Accidents			
Strip Mining	Assumes one MDL is equivalent to $50.	0.065	1300
Underground Mining		0.35	7000
Transportation		0.03	600
Power Plant		0.02	350
Total		0.47	9250

*MDL - Mandays Lost.

TABLE 3.9

EVALUATED EFFECTS OF A 1000 MWe RFO-FIRED POWER PLANT AND ITS SUPPORTING FUEL CYCLE

Basis: 6.57 Billion Kilowatt-hours (one year operation @ 75% CF)

Category	Comment	Cost $10^6$$	MDL
Conventional Costs (1980 dollars)			
Capital	Entirely internal	47	
O&M	Entirely internal	4.0	
Fuel	Entirely internal	180	
Total	Entirely internal	231	
Abatement Costs (1980 dollars)			
Cooling Towers		5.9	
Desulfurization		4.6	
Total		11	
Occupational Accidents	Assumes $50 per MDL	.09	1725
Refinery and Transportation Impacts			
BOD	See Section 4.11	.06	
Ballast Discharge		.04	
Oil Spills		--	
Power Plant Impacts			
Pollution Damage	SO_2 and particulates. Includes only damages to property and materials. See section 4.9	0.6	
Thermal Discharge	Largely consumptive use of water in natural draft wet cooling towers @ 10¢/1000 ga.	0.4	

TABLE 3.10

EVALUATED EFFECTS OF A 1000 MWe GAS-FIRED POWER PLANT AND ITS SUPPORTING FUEL CYCLE

Basis: 6.57 Billion Kilowatt-hours (one year operation @ 75% CF)

Category	Comment	Costs	
		$10^6$$	MDL
Conventional Costs (1980 dollars)			
Capital	Entirely internal	42	
O&M	Entirely internal	3.7	
Fuel	Entirely internal	237	
Total	Entirely internal	283	
Abatement Costs (1980 dollars)			
Cooling Towers		7.1	
Total		7	
Occupational Accidents	Assumes $50 per MDL.	0.04	780
Power Plant			
Pollution Damage	SO_2 and particulates. Includes only damages to property and materials. See section 4.9	0.1	
Thermal Discharge	Largely consumptive use of water in natural draft wet cooling towers, @ 10¢/1000 gal.	0.4	

TABLE 3.11

EVALUATED EFFECTS OF A 1000 MWe PWR AND ITS SUPPORTING FUEL CYCLE

Basis: 6.57 billion kilowatt hours (one year operation @75% CF)

Item	Comment	Costs $10^6$$	Costs MDL
Conventional Costs (1980 dollars)			
Capital	Entirely internal	77	
O&M	Entirely internal	5.2	
Fuel	Entirely internal	39	
Total		121	
Abatement Costs (1980 dollars)			
Cooling Towers	Entirely internal	2.4	
Near-Zero Radwaste	Entirely internal	1.2	
Total		4	
Occupational Accidents	Assumes $50 per MDL. Assumes 50% uranium production from underground mining. Excl. radiological hazards.	0.049	975
Public Accidents During Transportation	Excl. radiological hazards. Assumes $50 per MDL.	0.003	60
Occupational Health			
Miners' Radiation Exposure	Assumes 6000 MDL per case of lung cancer and $50 per MDL.	0.003	60
Other Occupational Radiation Exposure	Assumes 0.0002 cancers per man-rad, 6000 MDL per cancer, and $50 per MDL	0.02	414
Population Radiation Exposure	Assumes 0.0002 cancers per man-rad, 6000 MDL per cancer, and $50 per MDL.	0.009	190
Thermal Discharge	Largely consumptive use of water in natural draft wet cooling towers @ 10¢/ 1000 gal.	0.6	

TABLE 3.12

EVALUATED EFFECTS OF A 1000 MWe BWR AND ITS SUPPORTING FUEL CYCLE

Basis: 6.57 billion kilowatt hours (one year operation @ 75% CF)

Item	Comment	Costs	
		$10^6$$	MDL
Conventional Costs (1980 dollars)			
Capital	Entirely Internal	77	
O&M	Entirely Internal	5.2	
Fuel	Entirely Internal	39	
Total		121	
Abatement Costs (1980 dollars)			
Cooling Towers	Entirely Internal	2.4	
Near-Zero Radwaste	Entirely Internal	1.8	
Total		4	
Occupational Accidents	Assumes $50 per MDL. Assumes 50% uranium production from underground mining. Excl. radiological hazards.	0.045	903
Public Accidents During Transportation	Excl. radiological hazards. Assumes $50 per MDL.	0.003	60
Occupational Health			
Miners' Radiation Exposure	Assumes 6000 MDL per case. of lung cancer and $50 per MDL.	0.003	60
Other Occupational Radiation Exposure	Assumes 0.0002 cancers per man-rad, 6000 MDL per cancer, and $50 per MDL.	0.02	414
Population Radiation Exposure	Assumes 0.0002 cancers per man-rad, 6000 MDL per cancer, and $50 per MDL.	0.011	210
Thermal Discharge	Largely consumptive use of water in natural draft wet cooling towers @ 10¢/1000 gal.	0.6	

Since quantification has not been possible for several impacts thought to be important, these tables do not comprise complete lists, and thus do not yield "total societal costs." The reader is cautioned, in interpreting these evaluated effects, that these are preliminary estimates intended for comparative purposes. In many cases, comparative conclusions based on these tables are valid only if quantities differ by one or more orders of magnitude.

Chapter 4 and the Appendix deal in more detail with the effort to assign ultimate cost values to the various classes of impacts for which "source terms" were established in the present chapter. Thus much of the support for the figures presented in the tables below is to be found in Chapter 4, as well as in the footnotes, and in the Appendix.

Discussion

It is not feasible at this stage to determine exactly what fractions of non-conventional costs are, in fact, already internalized. For example, it is not known to what extent costs of occupational injuries are included in energy costs, through such mechanisms as insurance, miners' compensation, safety regulations, and the like. However, from a comparative viewpoint, the exact partition between internal and external portions of total social costs appears unimportant:

> Tables 3.8 through 3.12 show that, for all of the competing energy systems, the nonconventional costs evaluated -- excluding abatement costs -- are small compared to conventional costs.

For the coal energy system, the conventional cost is 120 million dollars per year, or about 18 mills per kWhe. Total injury costs, figured on a mandays lost basis ($50 per MDL) is about 0.65 million dollars, or about 0.1 mills per kilowatt hour. This is less than 1% of the conventional cost. Other nonconventional costs evaluated, excluding abatement costs, amount to about 1.5 million dollars, or about 0.2 mills per kilowatt hour. Total nonconventional costs evaluated, excluding abatement costs, are thus about] to 2% of conventional costs. Similarly, for the RFO-fired, natural gas-fired, and nuclear systems, the evaluated nonconventional costs, exclusive of abatement costs, are 1% or less of their respective conventional costs.

Ideally, an incremental abatement or restoration cost balances the corresponding incremental damage cost. External costs are internalized in this manner. The abatement (or restoration) measures considered in this study are those for which technical and economic data are available: cooling towers to dispose of waste heat at each

of the five alternate power plants, SO_2 removal from coal-fired power plant stack gases, "near-zero" radwaste treatment systems for light water reactors, desulfurization of residual fuel oil, and reclamation of surface-mined land. This, of course, is not a complete list, nor do the incremental abatement costs assembled here correspond precisely to the various categories of damage costs given in Tables 3.8 through 3.12. One notable omission, among the abatement costs considered, is the cost associated with improving occupational health and safety conditions, and various forms of workers' compensation for health impairment and injury. Likewise, costs associated with health effects of fossil plant effluents have not been evaluated, although SO_2 abatement costs -- flue gas treatment for coal-fired plants, and RFO-desulfurization -- do appear in the tables. For these reasons, abatement costs cannot be matched and compared on a one-to-one basis with other nonconventional costs listed in Tables 3.8 through 3.12.

Nevertheless, some insight can be gained by comparing abatement or restoration costs to conventional costs. Abatement costs are greatest in the coal energy system -- about 25% of its conventional cost. Control of flue gas SO_2 emission accounts for most of this. The RFO-cycle abatement costs are near 5% of its conventional cost. Nuclear system abatement measures (cooling towers and near zero radwaste systems) would add 3% to conventional costs. The natural gas cycle enjoys the least relative abatement cost -- about 2-1/2% of its conventional cost.

Costs and impacts are compared further -- across and within fuel cycles -- in Chapter 5.

CHAPTER 4

ASSESSMENT OF IMPACTS AND COSTS

4.1 INTRODUCTION

The purpose of this chapter is to bridge the gap between descriptions of the alternate energy systems (Chapter 3) and the display of ultimate impacts or costs on a consistent basis (annual operation of one 1000 MWe power plant and prorated fuel cycle activity) and in common units (dollars). Fuel cycle descriptions yield data on activity levels, throughput, resource requirements, residuals, and effluent source terms associated with the production of a unit of electrical energy or the addition of unit of system capacity -- that is, data resulting from a direct inspection of each of the alternate energy production systems. The aim of this Chapter, and the supporting Appendix, is to answer the questions: So what? What are the ultimate, non-conventional costs, and how may they be defined and measured?

For example, Chapter 2 identified several conceptual steps in assessing external costs associated with pollutant emissions:*

(1) determination of pollutant emission rate from a process operation;
(2) description of the transport of the pollutant through various pathways (air, water, food chain) to the subject (human, animal, vegetable, structural material, etc.);
(3) estimation of the dose of the pollutant to the subject taking into consideration the subject's population distribution;
(4) estimation of the damage done to the subject by the dose, using an appropriate dose-response relationship (damage function) for the particular subject-pollutant pair in question;
(5) placing a monetary value on the resulting amount of damage.

A careful description of an energy production system's material and energy flows yields the emission rates, or source terms, for step (1). This was accomplished in Chapter 3 and the Appendix. In general this Chapter and supporting sections of the Appendix are concerned with the remaining steps. The weakest parts of the assessments are found to be those corresponding to step (4); in most cases, knowledge of dose-response characteristics for the low-level-long-term exposures addressed here is not sufficient to support a rigorous quantitative analysis.

*Similar steps could be devised to assess impacts other than those associated with pollutants, or residuals.

This Chapter and supporting sections of the Appendix are attempts to assemble the best available damage function information and to examine its limitations.

4.2 DIFFICULTIES OF DETERMINING DAMAGE FUNCTIONS

There are several problems connected with finding a quantitative relationship between the occurence of any pollutant and its resulting damage. As opposed to acute damage caused by large amounts of toxic chemicals or radiation, environmental pollution is characterized by low concentrations of pollutants acting for long periods of time on large numbers of subjects. In the case of acute exposure the cause and effect relationship is readily apparent, but for chronic, low-level exposures the effect may be masked by other factors.

A fundamental difficulty concerns the correct measurement of pollutant concentration in the environment. The levels of interest of some pollutants such as mercury may be so low that they are beyond the measuring ability of scientific instruments. Although this problem is now being corrected, partly through the introduction of new techniques such as the use of lasers and neutron activation, the result is the absence of a complete set of data describing historic environmental pollutant levels. This lack of historic data frustrates efforts to correlate pollutant levels and health effects.

Similar problems exist in measuring the consequences of pollution. Chronic exposure to low levels of some substances will eventually produce definite symptoms of a specific disease. "Mad-hatters" disease is identified with exposure to mercurous chloride vapors, "black lung" with breathing coal dust for long periods of time, and the causes of several other specific diseases are also known, at least qualitatively.

However, other pollutants do not lead to exclusive, characteristic illnesses. Radiation, for instance, may cause cancer, but so does a large number of other agents, man-made as well as natural. Thus, given a case of cancer, it is impossible to state a priori that it was caused by radiation as opposed to some other cause. The same situation occurs for air pollution from fossil plants, which is suspected of causing respiratory illnesses. Yet these illnesses can also result from other agents such as viruses and cigarette smoke. The impact of air pollution, therefore, cannot be equated simply to the number of cases of respiratory illnesses.

Further, the role of natural repair mechanisms of a subject is not well understood. The duration of an exposure is important. A given dose, which if received in a short

period of time may be lethal, can be harmless if received at lower levels of exposure over a longer period.

The overall problem is that a pollutant, in amounts that are unknown or difficult to measure, may be affecting (with unknown severity) some subjects, the number of which is clouded by other factors. In dealing with this problem researchers usually take one of three approaches.

The first method uses controlled experiments under laboratory conditions. This enables the researcher to administer measured doses of a pollutant to a set of subjects and compare the subsequent response to that of a control set of subjects kept under identical conditions except for exposure to the pollutant under examination.

However, this method still may not yield conclusive results. A major drawback with studying pollutants in low concentrations levels is the consequent low probability of a pollution related illness or death appearing before other natural causes affect the subject. Thus, in order to get statistically significant data it is necessary to use large numbers of subjects. For instance, to see significant effects from low level radiation, it is estimated that an experimental population of hundreds of thousands of mice is required. The expense and manpower needs of an experiment of this size tends to rule it out for most applications.

In addition, results from laboratory animals like mice may not be applicable to humans because of differences in biological makeup. However, laboratory experiments on human subjects are not attempted for ethical reasons.

Finally, studies conducted in a controlled environment may leave out an essential factor that accounts for the impact of a pollutant. For instance, it appears that sulfur dioxide and particulate air pollution work in combination to cause respiratory illness. When either one is tested by itself under controlled conditions, the results prove to be inconclusive. For these reasons, data from laboratory experiments can only approximate the actual behavior of the pollutant in the environment and may miss some significant effects completely. Results from actual environmental exposures are preferred.

The most unambiguous information comes from exposures under peak or unusually high conditions. For instance, deaths due to air pollution become evident during extended smog episodes. Effects from radiation are known principally from the results of a

few abnormal situations. Much of the data has come from a few groups of people, such as the survivors of the Hiroshima and Nagasaki bomb blasts, or pioneer researchers in the field of X-rays and radioactivity. However, these data refer to the impact of exposure to a high level of pollutant working over a short period of time. There is evidence that suggests that when the same total exposure is due to low concentrations acting over long periods of time, biological defense mechanisms work to repair the damage. Consequently, the impact from low-level exposures may be much less than would be expected based on information from peak exposures.

The third approach, epidemiology, attempts to measure directly the effect of low-level exposures by analyzing vital statistics of populations exposed to such low levels. This method depends upon accurate records kept over long periods of time describing pollution concentrations and concurrent health effects. However, accurate pollution monitoring equipment is just now beginning to be installed. Thus, adequate historical data for pollutant concentrations do not exist.

Furthermore, the vital statistics for an area do not reflect individual exposure histories. Families move into the area as others move out, and the population may shrink or expand greatly during the time period under analysis. Thus even if records of pollution concentrations are in existence it is difficult to relate them to long term exposures to a definable group of subjects.

Finally, other factors that affect public health complicate the interpretation of mortality and morbidity figures. Factors like cigarette smoking or economic status appear to be far more important in determining a person's life span and well-being than exposure to pollution.

The discussion above pertains largely to human health effects, although the same general considerations may be applicable when the subjects are animals, plants, or materials. A further difficulty in impact assessment is the sheer numbers of pollutants and subject types. If there are O objects (humans, animals, plants, materials) and P pollutants, then the minimum number of damage function pairs to be addressed is O x P.

The difficulties discussed above are most apparent when dealing with mobile objects. Impacts on plants are generally easier to determine than on humans and animals. Effects on materials can be measured with some degree of accuracy.

Table 4.1 is intended to provide a more or less subjective feel for the current state of knowledge of damage functions. Generally, the damage function information is most adequate for materials, and least for humans.

4.3 STANDARDS AND GUIDELINES

As pointed out in Section 4.2, the facts regarding the impact of pollution are not known well enough to support a rigorous quantitative analysis. However, protection of public health and safety demands that government regulatory bodies act to restrict exposures to levels that will minimize harm. This means that the required standards and guidelines are set on the basis of incomplete knowledge, and under these circumstances it is common to make conservative assumptions. The standard-setting procedure involved has several aspects of a cost-benefit analysis and the resulting standards would ideally represent the optimum tradeoff between internal and external costs.

Standards may or may not be legally binding. The air and water quality standards administered by the Environmental Protection Agency put limits on various emissions from the industries covered by Federal legislation. Any operation found exceeding the standards may involve criminal charges. Other standards, usually established by industry associations, may be in the form of recommended guidelines that members of the industry may choose to comply with voluntarily. These may become legally binding, indirectly, since in civil court suits an operation that exceeds guidelines may be found negligent and liable for resulting harm.

The standards generally work in one of two ways, either by prescribing ambient quality or by restricting emissions of a pollutant from a given source. The ambient quality standard is designed to restrict the exposure of the subject* to pollution in the environment. Examples include standards for chemicals in drinking water and the limits on amounts of hazardous metals in the air breathed by workers. Emission standards, on the other hand, are designed to prevent or constrain hazardous substances from reaching the environment by restricting their emission rate. Examples include restrictions on release of sulfur dioxide from power plants and on release of radioactivity.

In theory the emission standards should be consistent with ambient standards. That is, the amount of pollutants released by each source should be fixed so that the total amount of pollutants in the environment does not exceed the concentrations as

*Human, animal, vegetable, or material.

TABLE 4.1
STATE OF KNOWLEDGE OF DAMAGE FUNCTIONS

SUBJECT	TYPE OF EXPOSURE	POLLUTANT									
		SO_2	NO_x	PARTICULATE	ACID MINE DRAINAGE	OIL SPILLS	RADIATION	THERMAL EFFECTS	COAL DUST	TRACE METALS	WASTE HEAT
Humans	Long Term Low Level	?	?	?	?	?	?	?	T	D	NA
	Peak Levels	D	D	D	D	D	T	D	D	T	NA
	Laboratory Studies	D	D	D	D	?	?	D	?	D	NA
Animals	Long Term Low Level	?	?	?	NA	?	D	NA	?	D	NA
	Peak Levels	?	?	?	NA	?	T	NA	?	T	NA
	Laboratory Studies	T	T	T	NA	?	C	NA	?	C	NA
Plants	Long Term Low Level	T	T	T	NA	D	T	NA	?	T	NA
	Peak Levels	T	T	T	NA	D	T	NA	?	T	NA
	Laboratory Studies	C	C	C	NA	D	C	NA	?	C	NA
Fish	Long Term Low Level	NA	NA	NA	D	?	D	D	?	D	?
	Peak Levels	NA	NA	NA	D	D	T	D	?	D	D
	Laboratory Studies	NA	NA	NA	T	T	C	T	?	D	D
Aquatic Plants	Long Term Low Level	NA	NA	NA	D	D	T	D	?	D	D
	Peak Levels	NA	NA	NA	D	D	T	D	?	D	D
	Laboratory Studies	NA	NA	NA	T		C	T	?	T	D
Materials	Long Term Low Level	T	T	T	T	T	T	D	?	D	NA
	Peak Levels	C	C	T	C	C	C	D	?	D	NA
	Laboratory Studies	C	C	C	C	C	C	D	?	D	NA

Symbols:
C = confirmed relationship
T = tentative relationship
D = data exists
? = partial or no data
NA = not applicable

set forth by the ambient standard. Thus, ambient quality should be determined first, and the emission standards should then be calculated from ambient standards. Unfortunately, uncertainties inherent in dispersion of pollutants and measurement of their effects, as described in the previous section, make this approach extremely difficult.

In practice the two types of standards are set independently using different criteria. For ambient quality the basis is minimizing harm, by reducing the presence of a given pollutant to below some safe level.

Exactly what constitutes a safe level is a matter of controversy especially since adequate data is usually unavailable. The level is set at a point somewhere between that known to be harmful and zero, based upon the judgment of experts in the field. Controversy arises over whether to assume a linear relationship between exposure and damage, or to assume a threshold effect.

A linear relationship implies that the presence of a pollutant in <u>any</u> concentration will always result in <u>some</u> damage, even as levels approach zero. Consequently, standards should be set as low as practicable to minimize harm.

A threshold effect is observable for some pollutants. A threshold effect means, simply, that below a certain concentration level, or threshold, no damage occurs. As applied to standard setting, it suggests that any level below the threshold is a safe level.

In the absence of a proven threshold effect, a linear relationship is generally assumed. If in fact a threshold does exist, the assumption is conservative in the sense that it overestimates damages at levels below the threshold. Because of the lack of accurate data about most pollutants, the linear relationship is generally used.

The concept of background level may also be used in setting ambient quality standards. This recognizes that many pollutants already exist in nature, such as the radiation due to cosmic rays and natural radioactivity in rocks. If the manmade contribution is quantitatively and qualitatively negligible compared to this background level, then the damage attributable to manmade releases will also be negligible compared to that due to unavoidable natural causes. This is the philosophy used in setting ambient radiation standards.

Emission standards, on the other hand, tend to reflect technological considerations. To sustain activity, the typical industrial operation must dispose of its waste products, which in the environment become pollutants. In many cases it is possible to reduce the emission of wastes, but impossible to eliminate emission completely, without shutting down the plant. Thus, emission standards are based to a certain extent on the requirements of the process involved and upon the available technology for abatement.

Table 4.2 displays radiation exposure standards established by the U.S. Atomic Energy Commission. Estimated actual U.S. per capita 1971 exposures from all sources -- medical, natural background, and nuclear power generation -- are also shown for comparison. The table shows that total man-made sources in the U.S. contribute about as much to received dose as do natural sources. Medical doses dominate the man-made category; doses related to nuclear power production in 1971 are negligible by comparison. Current USAEC limits (10 CFR 20) are of the same order of magnitude as background and medical doses. However, the proposed "as low as practicable" limits (10 CFR 50, Appendix I), currently under review, would be about two orders of magnitude below current limits, or about two orders of magnitude below background and medical doses.

Table 4.3 shows emission limits, established by the Environmental Protection Agency (EPA), applicable to new fossil power plants. Table 4.4 summarizes EPA national ambient air quality standards.

4.4 RADIOLOGICAL HEALTH IMPACT OF NUCLEAR POWER PRODUCTION

Since radiation from natural sources has always been present on earth, it seems reasonable to assume that over the course of billions of years of evolution, living organisms, including humans, have adapted themselves to a certain constant background level. However, after x-rays and other forms of radiation were discovered around the turn of the century, much more intense sources of radiation were developed, without appropriate consideration of its harmful effects. When a consistent pattern of cancers and early death became evident among such groups as radium workers and x-ray operators, steps were taken to limit radiation exposure and to investigate its effects on health. The development of information on radiation exposure began in the 1920's, decades before the development of nuclear power. The accumulation of knowledge on the subject makes it one of the few pollutants whose effects are relatively well known.

TABLE 4.2

U.S. RADIATION DOSES AND PROTECTION STANDARDS

a. Summary of Annual Whole-body Doses per Capita in the U.S.*

Radiation Source	Dose (rem/yr)
Medical	
Diagnostic	0.103
Therapeutic	.006
Radiopharmaceutical	.002
Occupational	.0008
Environmental	
Global fallout	.004
Worldwide H-3 and Kr-85	.00005
AEC installations	.00001
Nuclear power reactors	.000002
Fuel reprocessing	.0000008
Miscellaneous	.0026
Total of Manmade Sources	0.118
Natural Background in U.S.	0.130

* [Estimates for Year 1971 by the U.S. Environmental Protection Agency given in "Nuclear Power and the Environment," prepared by the IAEA in cooperation with WHO.]

b. Radiation Protection Standards

Maximum Individual Dose (Public)	
10 CFR 20	0.5 rem/yr
10 CFR 50 App. I (proposed "As low as practical" standard for LWRs)	0.005
Average Individual Dose (Public)	
10 CFR 20	0.17 rem/yr
10 CFR 50, App. I (proposed "As low as practical" standard for LWRs)	0.001

TABLE 4.3

EPA EMISSION STANDARDS APPLICABLE TO NEW POWER PLANTS

(pounds discharged to the atmosphere per million Btu heat input)

Maximum 2-hour average

Fuel	SO_2	Particulates	NO_x*
Coal	1.2	0.2	0.7
Oil	0.8	0.2	0.3
Gas	-	0.2	0.2

*Expressed as NO_2

TABLE 4.4
NATIONAL AMBIENT AIR QUALITY STANDARDS*

Pollutant	Primary Standard		Secondary Standard	
	Annual Mean	Max. Concentration Not To be Exceeded More Than Once Per Year	Annual Mean	Max. Concentration Not To Be Exceeded More Than Once Per Year
Sulfur Dioxide (SO_2)	80 (ug/m^3) .03 (ppm) (arithmetic)	365 (ug/m^3) .14 (ppm) 24-hr.	60 (ug/m^3) .02 (ppm) (arithmetic)	260 (ug/m^3) .10 (ppm) 24-hr. 1300 (ug/m^3) .5 (ppm) 3-hr.
Particulate Matter	75 (ug/m^3) (geometric)	260 (ug/m^3) 24-hr.	60 (ug/m^3) (geometric)	150 (ug/m^3) 24-hr.
Nitrogen Dioxide (NO_2)	100 (ug/m^3) .05 (ppm) (arithmetic)		Same as Primary	
Carbon Monoxide		10 (mg/m^3) 9.0 (ppm) 8-hr. 40 (mg/m^3) 35.0 (ppm) 1-hr.	Same as Primary	
Hydrocarbons		160 (ug/m^3) .24 (ppm) 3-hr. (6-9AM)	Same as Primary	

*Environmental Protection Agency, Regulations on National Primary and Secondary Ambient Air Quality Standards, 40 CFR 50, 36 FR 22384, Nov. 25, 1971.

Radiation interacts with all materials by colliding with the atoms present and exchanging some of its energy. This results in alterations in the atomic and molecular structure of the material. The nature of the collision is probabilistic and it is possible for a radio-particle to pass through an object without experiencing any collisions at all.

When the material is living tissue, the collisions result in the disruption of the molecular structure of the cells. Depending upon which molecules are hit and the energy involved, a cell may either die or reproduce abnormally. In the case of very intense radiation dose, so many cells are killed that the result resembles a burn extending throughout the exposed region of tissue. If large portions of the victim receives radiation burns, the result is death within a short time after exposure.

Lesser doses do not produce immediate effects but may lead to cancer in later years due to abnormal cell reproduction. Also, other effects characteristic of deterioration of tissue may be observed such as cataracts, reduction of fertility, defective growth and development, and early death. It should be emphasized that these results are from exceedingly high doses as compared to that from background or from nuclear power generation.

In addition, if the genetic material of the reproductive cells is affected, descendants of the person irradiated may show mutations. These mutations may be lethal, resulting in still births or death in early childhood. A nonlethal mutation may manifest itself in subtle ways that lead to decreased chance of survival for the affected individual. It has been observed that when populations of laboratory animals are irradiated, the birth rates of succeeding generations decline while the death rates increase, and this is taken as demonstrating the genetic effects of radiation.

Man-made chemical compounds also are suspected of causing mutations. Aside from artificial mutagens, a natural spontaneous background of genetic damage occurs, presumably due to mutagens naturally present in the environment, possibly including cosmic radiation. Since the average dose to a member of the general population due to the generation of nuclear power, is orders of magnitude below that from natural background radiation, presumably it will not affect the spontaneous mutation rate.

Estimation of Radiation Effects

Two general groups of people at risk are considered in this report: (1) the population at large and (2) occupational personnel employed in the energy system. The goal is to arrive at an order-of-magnitude estimate of the health damage to both groups resulting from routine radioactive exposure occasioned by the production of a unit of electrical energy, e.g., 6.57 billion kilowatt hours.

Public Health

Assessment of public health effects of radioactive releases involves several conceptual steps: (a) determination of the release rates (source terms) normalized to a unit of electrical energy produced; (b) description of the transport of the radionuclides through air, water, and biological pathways; (c) computation of dose to humans based on concentrations of the radionuclides in air, water, and food and population distributions; and (d) assignment of an increment of damage associated with the dose using a dose-response (risk) function.

Step (a) is accomplished in the Appendix. There, source terms in units of curies per year by radionuclide, are established for individual steps in each of the nuclear fuel cycles. The Appendix also describes in detail the computations corresponding to steps (b) through (d), for hypothetical but representative facilities. The assessment is discussed briefly below.

Radiological Dose-Response Coefficients (Risk)

Estimates of risk to man following radiation exposure are available for various categories of cancer and for genetic effect. From an extensive detailed review of the literature* the risk estimates of Table 4.5 are established for the purposes of this study. These estimates are considered to be based on the best available data.

The linear dose-response theory for radiation effects as exercised in this report predicts a certain quantity of response per unit population dose (man-rad) independent of the magnitude of the dose to particular individuals and independent of the rate at which individuals receive the dose. Thus, the same total radiation effect would be predicted for a group of one million people receiving 0.1 rad per person in one hour as for a group of one hundred million people receiving 0.001 rad per person in one year. The dose-response coefficients have been determined by assuming a linear

*See Appendix.

TABLE 4.5

RISK OF RADIATION HEALTH EFFECT FOLLOWING TOTAL BODY EXPOSURE[a]

A. Somatic effect

Probability per rad of total body dose, that an individual, irradiated at a specified age, will develop a radiogenic malignant tumor during a specified age span following irradiation.

Age at irradiation	Age span for which malignancy predicted	Class of malignant tumor[b]	Probability per rad
Adult	Lifetime	Leukemia	$O(2 \times 10^{-5}/rad)$[c]
		Thyroid cancer	$O(3 \times 10^{-5}/rad)$
		Total Malignancies	$O(20 \times 10^{-5}/rad)$
Infant less than 6 months of age	Lifetime	Thyroid cancer	$O(10 \times 10^{-5}/rad)$
In utero child	Before age of 10	Total Malignancies	$O(60 \times 10^{-5}/rad)$

B. Genetic effects[b]

Probability per rad of total body dose, that a genetic death will occur among the descendants of an individual who is exposed to total body irradiation before the end of his reproductive lifespan. The irradiated individual is assumed to be a member of a population of constant size and all of his descendants are assumed to remain within the population.

Age at irradiation	Probability per rad
Before the end of reproductive life span	$O(2 \times 10^{-3}/rad)$

[a] The dose in the various organs at risk is assumed to be equal to the average total body dose.

[b] The organs at risk are: (1) leukemia--red marrow, (2) thyroid cancer--thyroid gland, (3) total malignancies--total body, (4) genetic effects--gonads.

[c] The notation O(r) indicates that r is an order of magnitude estimate.

extrapolation from data in the high dose range. The estimation of biological effects in the low dose range using such risk values is, therefore, subject to considerable uncertainty. It has been suggested that risk values based on linear extrapolation be thought of as order of magnitude estimates; such an attitude is adopted here and emphasized in Table 4.5 through the use of the notation O(r) to indicate that risk r is order of magnitude.

Transport and Dose

Two models were established for computing public doses resulting from nuclear system releases: (1) a global model, which yields U.S. and world-wide population dose commitments (all time) due to routine releases of long-lived isotopes (H-3 and Kr-84) during one year's operation; and (2) a local model which yields population dose within a 50-mile radius of nuclear facilities, due to routine releases of relatively short-lived nuclides, during one year's operation. In both cases, of course, releases are normalized to energy system output of 6.57 billion kilowatt hours, i.e., one year's operation of one 1000 MWe nuclear power plant and its supporting fuel cycle requirements. Results are summarized in Table 4.6. Source terms are developed in the Appendix.

The global model dose represents an estimate of the world-wide population whole body dose commitment resulting from all long-lived krypton (Kr-85) and tritium (H-3) released as a result of one year's operation of the nuclear energy system. The calculation thus relates the population dose to the electrical energy generation responsible for that dose. It is assumed that the released isotope becomes widely distributed throughout an identifiable and well specified reservoir. For H-3 the reservoir is the surface water of the world, and for Kr-85 the reservoir is the entire atmosphere. The Kr-85 is assumed to spread through the atmosphere uniformly; 50% of the tritium is assumed to remain between 30° and 50° north latitude as has been observed for tritium produced from bomb tests. For conservatism all of the Kr-85 produced in fission is assumed released.

Based on a computerized Gaussian plume calculation, the local model accounts for whole body dose to people living within 50 miles of a hypothetical facility that releases through its stack all the fission product noble gases and tritium which are released to the environment at the reactor and reprocessing plant of a 1000 MWe energy system. An examination of numerous environmental statements for U.S. reactors and reprocessing plants together with the results of the Year 2000 Study has indicated that the whole body dose from noble gases and tritium from such a hypothetical facility would be the primary contributors to population whole body dose

TABLE 4.6

PUBLIC RADIATION DOSES FROM NUCLEAR ENERGY SYSTEMS*
(man-rad)

	Energy System**	
	PWR	BWR
Global Model (man-rad)		
World		
Krypton-85***	130	130
Tritium	22	21
Rounded Total	150	150
U.S. Only		
Krypton-85***	6.1	6.1
Tritium	2.4	2.3
Rounded Total	8.5	8.4
Local Model (man-rad)		
High Population Assumption	42	310
Medium Population Assumption	4.2	25
Low Population Assumption	0.6	4.4

*The number of digits shown is not indicative of precision. Two digits are retained merely for calculational purposes. All doses are whole body doses.
**"Energy system" includes the reactor power plant and its supporting fuel cycle. For practical purposes, all but the power plant and reprocessing plant releases may be ignored in computing public dose.
***Assumes all of the Kr-85 produced is released.

in the region of the facility. A more detailed study would include an examination of specific site conditions which could cause the dose from drinking water, eating fish, etc. to become large with respect to the local model dose displayed in Table 4.6. It is noteworthy that the local model population dose estimate itself turned out to be small with respect to the global model population dose thereby indicating that the inclusion of the neglected doses would not significantly change the estimated total man-rad received by the general population.

Part of the dose determined from the local model is due to Kr-85 and H-3. This population dose can be added to the man-rad determined using the global model because, in the absence of a holdup mechanism, only a small fraction of the Kr-85 and H-3 would be expected to decay before crossing the 50 mile radius used in the local model.

Only whole body dose has been calculated although it should be recognized that doses to specific organs may be more important in some cases and would be considered in a more detailed evaluation. The dose response function for total malignancies given in Table 4.5 is for whole body dose, and that is the dose which has been determined.

Occupational Health

Two groups of nuclear energy-system workers are considered in this report: (a) uranium miners (underground), and (b) employees in the remainder of the nuclear fuel cycle, including the power plant.

The extensive study of lung cancer in American uranium miners carried out by the U.S. Public Health Service has allowed the estimation of the probability that lung cancer will follow exposure to airborne radon and its daughter products in the air of underground uranium mines. The order of magnitude estimate for the lifetime probability of death from radiogenic lung cancer which has been adopted for use in this report is 10^{-4} per Working Level Month (WLM)* of exposure. The total WLM exposures, normalized to the annual mining requirements of the respective systems, are given in Table 4.7. The man-WLM figures given in Table 4.7 have been estimated assuming that 50% of the uranium ore is from underground mining and that each miner receives the legal limit of 4 WLM per year. The latter assumption tends to cause an overestimate of miners' exposure. A more detailed treatment of radiological health in underground uranium mining is given in the Appendix.

TABLE 4.7

OCCUPATIONAL RADIATION DOSE IN LIGHT WATER REACTOR ENERGY SYSTEMS*

Miners' Exposure (man-WLM)	104
All Other fuel cycle steps (man-rad)	345

*The number of digits shown is not indicative of precision. Two or three digits are retained merely for calculational purposes.

For occupational personnel throughout the rest of the nuclear fuel cycles, data are available on the annual exposure to external penetrating radiation (x-ray, γ-rays, and neutrons) of individuals who are routinely monitored. The monitored occupational populations are not well defined. They may include a variety of job categories and often include visitors to nuclear installations. Because of this, occupational population dose rather than individual dose has been adopted as the measure of exposure (man-rad/year). The size of the labor force varies with the amount of power produced, and production factors (e.g., MTU/year) have been used to normalize the population exposures. The normalized population exposures are combined with risk factors for the individual to provide a measure of health effect for the exposed population.

*One WLM is 170 hours exposure to air in which a liter of air contains short-lived Rn-222 daughter products which will yield 1.3×10^{-5} MeV of alpha particle energy upon total decay.

The expected man-rad for the steps in the nuclear fuel cycle other than mining is shown in Table 4.7. The exposures are essentially the same for all fuel cycles with an estimated 300 man-rad occurring at the reactor. The estimates are based on past experience and expected future conditions. Especially in the case of commercial fuel reprocessing plants, there is little operating experience and the experience of recent years may produce changes in operation which reduce the radiation exposure. The application of the measures of health effect to the projection of health damage to personnel as a result of future operation must be made with the knowledge that the nuclear power industry is in a period during which changes will likely affect personnel exposure.

A more detailed treatment of occupational doses excluding miners' exposure is given in the Appendix.

Summary

The risk coefficient $O(20 \times 10^{-5})$ malignancies per man-rad, from Table 4.5, is assumed. For uranium miners, a risk coefficient of $O(10^{-4})$ lung cancers per miner-WLM is assumed. Combining these coefficients with the normalized public and occupational dose figures of Tables 4.6 and 4.7, the expected number of cancer cases, for all time, attributable to one year's operation of the energy system are obtained as summarized in Table 4.8.

TABLE 4.8

EXPECTED NUMBER OF MALIGNANCIES ATTRIBUTABLE TO THE ANNUAL OPERATION* OF NUCLEAR ENERGY SYSTEMS

	PWR	BWR
General Population		
Global Model**	.03	.03
Local Model ***	.0008	.005
Rounded Total	.031	.035
Occupational Personnel		
Miners	0.01	0.01
All Other Fuel Cycle Steps	0.069	0.069
Rounded Total	0.08	0.08
Rounded Total (malignancies)	0.1	0.1

*Basis: Annual Operation of one 1000 MWe reactor power plant @ 75% CF and supporting fuel cycle requirements.
**Assumes all of the Kr 85 produced is released.
***From dose using medium population assumption. See Table 4.6.

4.5 HEALTH IMPACTS OF AIRBORNE FOSSIL POLLUTANTS

Gross Pollutants

The human health hazards from fossil fuel plant emissions, such as sulfur oxides, nitrogen oxides, hydrocarbons and particulates, are not as well understood as the health hazards from external whole body irradiation. This is due to the large number of possible deleterious substances in the air, including their interactions, to the existence of non-air-pollutant causative agents, to the lack of well-defined dose data for studying past exposures, to the lack of disease response data considering age, sex, aand disease latency periods for the receptor, and to possible synergistic and chemical co-agent accelerator effects. In general, air pollution causes undesirable health effects, but quantizing these effects and the delineation of causative agents are extremely difficult. There is no dose-response data comparable in quality to the therapeutic irradiation and atomic bomb casualty data and no linear dose-response approach, both of which are so useful in estimating radiation effects.

Numerous toxicological studies of animal response to general air pollution and to specific air pollutants have been carried out in an effort to gain insight into the levels at which pollution is harmful and into which pollutant combinations produce the most severe response at a given level of exposure.[1,2,3,4] Although toxicological studies on animals are an invaluable aid to the study of human response, they cannot yet be used as a basis for human dose-response relationships because no extrapolation of animal response to human response can be made with confidence. Thus predictions of human response to pollution and to specific pollutants must be based on direct observation of human beings. Although toxicological experiments are performed in laboratory settings under controlled conditions and thus yield well defined results, the range of toxicological studies on human beings, which can be made, is severely restricted by scientific ethics. Thus most of our knowledge of human response to air pollution comes from epidemiological studies of the exposure of human beings in the real environment.

There is a large variety of air pollutants simultaneously present in urban atmospheres. The epidemiological researcher cannot limit the exposure of his study group to just one or a few pollutants of interest such as those generated by fossil fueled power plants. The epidemiologist must deal with air pollution as a whole and thus epidemiological studies are poorly suited to the study of the effects of specific pollutants on man. Thus epidemiological studies for the most part examine the relationship between health effect and general air pollution.[1] Two different

types of general air pollution are recognized by air pollution epidemiologists: (1) a reducing type, an example of which is London smog, and (2) an oxidizing type, an example of which is Los Angeles smog. The reducing type is characterized by high levels of SO_2 and particulates, and finds its primary source in the burning of fossil fuels. In a general sense the air pollution which evolves from the operation of fossil fuel power plants is of the reducing type and information on the health effects that are related to the operation of fossil fuel plants can be obtained by studying human health in relation to reducing air pollution. Sulfur dioxide and some measure of particulate matter are normally used as air pollution variables when studying the relationship between health and levels of reducing-type air pollution. These variables are normally interpreted as indices of reducing-type air pollution and not as specific causative agents.

Epidemiological studies seek to establish relationships between health effect and variables such as air pollution which are thought to play a role in causing health effects. However, epidemiological studies alone are incapable of establishing that a cause-effect relationship exists between health effect and specific variables. The reason for this is that, although they may establish statistically significant associations between health effect and specific variables, the existence of an association does not imply that the specific variables under study cause health effects; they may merely be indices of the true causative variables. Thus, SO_2 and particulates, as they are normally used in epidemiological analyses are thought of as indices of the agents or combinations of agents in reducing-type air pollution, which cause health effects. These agents and combinations of agents are themselves unknown. In the absence of evidence to the contrary, however, strong associations may be compelling evidence for the existence of a cause-effect relationship between health effect and the given variables.

In the most thorough epidemiological studies the investigation is not limited to the relationship between health effect and air pollution but includes study of the relationship between health effect and several environmental and socioeconomic variables. Such analyses are often performed using multivariate regression analysis, and one product of such an analysis is a regression equation that relates the health effect to the various variables.[5,6,7,8] The associations between health effect and some or all of the variables are often statistically significant. Typical of non-air pollution variables are meteorological variables such as temperature and socioeconomic variables such as percentage of the population of a study group with annual income below a certain level. Some of these variables,

such as temperature, may be true causative variables but others, especially socio-economic variables, are only indices of true causative variables. These indices may or may not be statistically accurate indicators of the true causative variables. Since these latter variables are unknown, one does not know whether the indices are accurate. However, some regression equations have been formulated that explain almost all of the variation in the data, i.e., a graph of the regression equation would pass near the data points. If the data points to which the equation is fit can be assumed to be devoid of measurement error, then one can interpret such equations as containing variables which are accurate indices of all or nearly all of the true causative variables.[7,8] If this interpretation is adopted, then the regression equation may be used to predict health effects for the given sets of values of the variables. Such a substitution of values is, however, incapable of answering the question that is implicitly asked when a dose response relationship is sought: What is the change in health effect which accompanies a given change in an air pollution variable, when all other variables are held constant? This question cannot be answered because statistically significant correlations exist between the air pollution variables and other independent variables in the regression equation so that it is impossible to change the air pollution variable without simultaneously changing other variables. In effect, these correlations mean that some of the variables are indices of other variables. Also, some variables are possibly indices of a set of causative variables that is not included in the regression equation. The regression equation thus fails to separate the effect of air pollution from the effects of other variables.

Usually no quantitative treatment of measurement error is attempted in formulating regression equations. However, specific estimates of the measurement error should be made so that it is known how much of the variation in the data is due to variables which cause health effect and how much is due to the error of measurement. Two examples of variables that may contain large measurement errors are health effects variables and air pollution variables. For example, when death due to a specific cause is used to measure health effect and a death certificate is used to determine cause of death, error may arise because of incorrect recording of the cause of death on the certificate, incorrect diagnosis, different diagnostic criteria being employed in different locales, or because several equally important competing causes may have been present at the time of death, but only one is recorded on the certificate. Air pollution concentrations are measured at monitoring stations and a person is often assumed to be exposed to the air pollution level at the monitoring station nearest his home. However, normal activities may take a person to areas where air pollution levels are quite

different from the levels at the monitoring station nearest his home. The air pollution levels inside of the buildings where he works and inside of his house will be different from the monitoring station levels and may be higher or lower depending on such factors as his occupation and the integrity of his home heating system. The presence of error in the measurement of variables and the lack of quantitative estimates of the effect of such error on predictions made with regression equations cast doubt on the usefulness of the regression equations for quantitative prediction of health effects.

As epidemiological studies employing regression analysis have become more comprehensive, a number of studies have emerged which account for a large portion of the variation in the data and which demonstrate statistically significant association between SO_2 and particulates and health effect. However, one still is unable to be certain that the change in health effects associated with a specific change in SO_2 level in the regression equation, is valid. Indeed one is unable to quantify the health effects from general air pollution caused by the generating plants. Fossil fuel combustion products are believed to cause health effects. For a specific disease, lung cancer, the following quotation by the Committee on Biologic Effects of Atmospheric Pollutants, Division of Medical Sciences, National Research Council, displays a partial basis for this belief:[9]

> "The POM (Polycyclic Organic Matter) found in high concentration in cigarette smoke causes cancer of the lung and other organs in experimental animals; it is also present in the industrial environment, in which lung cancer rates are high, and is found generally in the air of urban communities. Examination of epidemiologic studies shows that, although a major factor in the causation of lung cancer in man is cigarette smoking, it does not account completely for the increased incidence of this disease. It appears that the incidence of lung cancer among urban dwellers is twice that of those living in rural areas; and within urban communities, the incidence is even greater where fossil-fuel products from industrial usage are highly concentrated in the air."

Because of the impossibility of isolating the effect of air pollution from other variables in regression equations and because of the uncertainty in the precision of regression equation predictions due to the neglect of measurement error, no quantitative estimates of the health effect that results from the air-borne emissions from fossil-fuel plants are made in this report.

Trace Metal Emissions

Trace metal emissions from fossil-fired power plants have been roughly estimated because a large fraction of the fly ash is in the respirable dust range and because some metals, occurring in coal particularly, probably display more mobility into the atmosphere than corresponds to fractional escape of fly ash. Mercury is the most volatile, followed by arsenic and its compounds; a few percent of the beryllium content in coal is assumed to escape regardless of the degree of removal of particulate matter from stack gas. The rest of the thirty or more elements including radium isotopes are assumed to follow the efficiency of fly ash recovery. Concentrations in the coal were averaged to represent total production in the United States. Based on the above considerations and an assumed effective atmospheric dilution factor of ten thousand, only beryllium among the toxicologically important or suspect elements might approach its suggested limiting community ambient concentration level within a factor of ten; the estimated level of 0.002 $\mu g/M^3$ is a factor of 5 below the recommended community limit of 0.01 $\mu g/M^3$. The radium 226 stack gas concentration corresponding to 0.02 curies per year from a 1000 MWe plant in 1980 is an order of magnitude below the maximum permissible concentration in air. This generalized estimate may not be appropriate for considering combustion of some low grade western coals where elements of health significance, beryllium, arsenic, and uranium sometimes occur in concentrations 100 to 1000 times greater than the national averages used in this rough estimating.

The perspective on trace elements has been broadened in the study by a review of health aspects of trace metals in the environment; this work supports the view that much more research is needed on the toxicology of low levels of atmospheric pollutants.

Health Impacts of Airborne Pollutants From Fossil Fired Power Plants

Because the health effects of combustion-related air pollution are so poorly understood, it is not meaningful or possible at this time to associate an increment of health damage with an increment of electrical energy production. Some perspective, however, can be gained by comparing man-made, combustion pollutant concentrations with natural background levels, with standards imposed by regulatory agencies, with a broad range of concentrations considered by experts to result in perceivable medical effects, and with similar quantities related to radiation releases from nuclear systems. This comparative material, based largely on a recent study by the University of California[10], is presented in Section 4.8.

Footnotes and References for Section 4.5 - Health Impacts of Airborne Fossil Pollutants

(1) The Sources of Air Pollution and Their Control, Public Health Service Publication No. 1548 (1968).

(2) Air Quality Criteria for Sulfur Oxides, Natl. Air. Poll. Control Admin. Publication No. AP-50 (1969).

(3) Air Quality Criteria for Particulate Matter, Natl. Air. Poll. Control Admin. Publication No. AP-49 (1969).

(4) Air Quality Criteria for Nitrogen Oxides, Air Poll. Control Office Publication No. AP-84 (1971).

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(9) National Academy of Sciences, Particulate Polycyclic Organic Matter, Division of Medical Sciences, National Research Council, NAS, Washington, D.C. (1972), page 245.

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4.6 RESPIRATORY DISEASES AMONG COAL MINERS

In addition to the safety hazards to be found in underground coal mines, the miner is exposed to disease causing conditions. The cold, damp atmosphere underground leads to high rates of chronic bronchitis and emphysema, and the presence of coal dust causes coal workers' pnemoconiosis (CWP), more commonly known as "black lung". This is defined as "the accumulation of (coal) dust in the lungs and the tissue reaction to its presence."[4]

Simple CWP is the buildup of dust in the lungs which may affect breathing. About 15 years of underground exposure are required for the development of CWP.[3] In progressive massive fibrosis (PMF), an advanced form of CWP, the lung tissue reacts to the coal particles, forming fibers which spread through the lungs, reducing respiratory capacity. Once a certain degree of simple pneumoconiosis is present, the development of PMF does not require further exposure to dust. Thus it can appear in miners who have left the mines.[15] PMF implies total disability according to the 1969 Act criteria.[11]

Random samples of U.S. miners show that 10% have CWP and one third of these have PMF.[3] About 2% of simple pneumoconiosis cases develop PMF each year.[17] It is difficult to connect these statistics with past mine conditions since records of U.S. dust concentrations have not been kept or reported. Results of recent measurements are, however, available. It was reported at a 1969 meeting that the average dust concentration in U.S. mines was about 7 mg/M^3 and that in some mines the average concentration was between 3 and 4.5 mg/M^3.[17] Extensive measurements made in 1968, 1969 and 1970 have been reported.[18] They show wide variations in dust exposure for various job categories in large underground bituminous coal mines. A significant number of job categories receive exposures greater than 2.9 mg/M^3. In a survey of strip mines, auger mines, and preparation plants, 88% of all workers had exposures less than 2 mg/M^3.

British data reflect the impact of an extensive program to abate the disease. Statistics for the program kept over a ten year period indicate that the annual incidence of CWP has dropped from 6 per thousand men to 2 per thousand.[1a, 7] British studies show that about 1% of the cases of simple CWP develop PMF per year[3] and about 5% of the PMF cases progress. The British dust standard for bituminous mines is 700 ppcc.[1b] While there is no simple conversion of this figure to milligrams per cubic meter (mg/M^3), it has been suggested that 700 ppcc could be equivalent to more than 10 mg/M^3.[1b]

Although the British recognized CWP as an occupational disease in 1943 and began programs of treatment and prevention at that time, the disease went officially unrecognized in the U.S. until recently. Several states have passed legislation providing compensation for miners disabled by CWP. In addition the Federal Coal Mine Health and Safety Act of 1969 contains a provision for paying compensation where none is available from the State.[16,10,11] The Act also contains standards limiting the concentration of coal dust in the mine air. The upper limit of the average concentration of respirable dust, set by the Act, is 2 milligrams per cubic meter (2 mg/M^3).

Quantification of CWP Health Impact

As with other impacts considered in this report, an attempt is made to estimate the CWP health impact associated with the mining of coal to produce a given quantity of electrical energy, i.e., 6.57 billion kilowatt hours. This effort encountered several difficulties enumerated below.

. The connection between CWP, which is diagnosed radiologically, and disability, which is diagnosed by clinical symptom and lung function test, is not known. Definitions of both CWP and CWP disability have recently been established in the U.S.[10,11,4] but legal and technical viability of these definitions is still subject to dispute.[5,4,3,9]

. Epidemiological data for CWP in the U.S. is lacking because adequate records and statistics have not been kept. For this reason heavy reliance is placed on British experience. The applicability of British studies to U.S. conditions - past and future - is tenuous. For example, the British dust concentrations are given in units of particles per cubic centimeter, as determined by a micrographic count method, while U.S. concentrations are measured in milligrams per cubic meter. There is no simple conversion factor between the two units.[1b] Moreover, the British mine conditions (dust concentrations) and the mechanics of the British regulatory programs may be vastly different from those in the U.S. The prevention of CWP as practiced in Britain involves dust abatement, and periodic examinations of the miners. Any who show a tendency toward CWP are given jobs in non-dusty locations.

Current CWP incident rates in the U.S. reflect past conditions before the 1969 Act went into effect. The average miner is now about 55 years of age and has seen long service under dusty conditions. Because CWP results from cumulative exposure and because no statistical information is available for

average 2 mg/M^3 exposures, the time-response and degree of the reduction in CWP incidence, resulting from the 1969 Act, is speculative.

U.S. Experience

In 1970 there were roughly 90,000 men working underground producing 339 million tons of coal in the U.S. The productivity of U.S. underground coal miners is thus about 4,000 tons per man-year, One 1000 MWe coal fired power plant consumes about 2.3 million tons of bituminous coal annually.

Half of this, or about 1.2 million tons, is assumed produced in underground mines and requires about 300 man years of labor. Assuming 10% of the underground miners have CWP and that 2% of these develop PMF per year, then 0.2% of the underground mining work force incur PMF per year. Thus, about 0.002 x 300 ≈ 0.6 cases of PMF are attributed to the annual underground mining requirements of a 1000 MWe coal-fired power plant. This corresponds to mine conditions and health monitoring procedures prior to the implementation of the 1969 Act, i.e., a national average mine dust concentration of, say, 7 mg/M^3, considerably in excess of the 2 mg/M^3 standard set by the 1969 Act.

British Experience

As noted above, British statistics show the result of a vigorous program for preventing CWP. Incidents of CWP in Britain have been reduced by a factor of three or more over a period of ten years. In 1967 about 2 new cases per 1000 men were reported. Thus about 0.6 new simple CWP cases are attributable to the annual mining requirements of a 1000 MWe coal fired power plant. About 1% of the British CWP cases develop PMF, so that about 0.006 new PMF cases per year are assigned to the 1000 MWe plant, a factor of 100 below the U.S. figure.

As discussed above, future CWP and PMF incident rates (after full implementation of the 1969 Act) are difficult to forecast. For the purposes of this study, it is assumed that the U.S. experience will be similar to that of the British. Table 4.9 summarizes the normalized results, based on British statistics.

TABLE 4.9

CASES OF COAL WORKERS PNEUMOCONIOSIS ATTRIBUTABLE TO THE ANNUAL REQUIREMENTS OF ONE 1000 MWe COAL-FIRED POWER PLANT

	Cases per Year
Simple CWP	0.6
PMF	0.006

Footnotes and References for Section 4.6 - Respiratory Diseases Among Coal Miners

(1) Hearings before the Subcommittee on Labor of the Committee on Labor and Public Welfare, U.S. Senate, on Coal Mine Health and Safety, Part 3 (February, March, May 1969).

a. Testimony of Jethro Gough (United Kingdom), May 1969, including tthe following UK report appended: National Coal Board, Medical Service and Medical Research, Annual Report 1967-68, Hobart House, London, S.W.1.

b. Report appended May 2, 1969 by Senator J. Randolph page 1017: "Discussion of CWP by James Hooley, Veteran British Mining Engineer and Coal Mine Manager."

(2) Hearings before the General Subcommittee on Labor of the Committee on Education and Labor, House of Representatives, on Coal Mine Health and Safety, (March, April, May 1969).

(3) American Conference of Governmental Industrial Hygienists (ACGIH), "Synopsis of the Work Proceedings" Spindletop International Conference on Coal Workers Pneumoconiosis, Archives of Environmental Health, Vol. 21 (Aug 1970) page 221.

(4) Gross, P. and R. DeTreville, "Black Lungs" Archives of Environmental Health, Vol. 20 (Apr. 1970) page 450.

(5) Hardy, H. J. "Comments in 'Black Lungs'" (Letters to the Editor), Archives of Environmental Health, Vol. 21 (Nov 1970), page 697.

(7) Appalachian Regional Commission, "The Safety and Health of Coal Miners," Appalachia Vol. 2 #5 (Feb. 1969).

(8) Hearings before the Subcommittee on Labor of the Committee on Labor and Public Welfare, U.S. Senate, on Health and Safety in the Coal Mines (June, August 1970).

(9) Hearings before the Subcommittee on Labor of the Committee of Labor and Public Welfare, U.S. Senate, on Black Lung Legislation (Dec. 1971, Jan., Feb. 1972).

(10) "Title IV -- Black Lung Benefits" Federal Coal Mine Health and Safety Act of 1969, Public Law 91-173, 91st Congress, S.2917, Dec. 30, 1969.

(11) Part 410 -- Federal Coal Mine Health and Safety Act of 1969, Title IV -- Black Lung Benefits, Federal Register 35, pp. 5623-5626 (April 7, 1970).

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W. S. Larnhart, et al., "Pneumoconiosis in Appalachian Bituminous Coal Mines," U.S. Dept. of Health, Education and Welfare, Public Health Service, Bur. of Occupational Safety and Health, Cincinnati, Ohio 1969.

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(15) Pendergrass, Eugene P. "Some Considerations of Coal Workers' Pneumoconiosis," Archives of Environmental Health, Vol. 20 (1970) p. 545.

(16) Hume, Brit, Death and the Mines, Grossman Publishers, NY (1971).

(17) Lee, D. "Coal Workers Pneumoconiosis -- State of Knowledge and Research Needs," J. Occupational Medicine, Vol. 13 (1971), pp. 183-192.

(18) Schlick, D. P. and N. L. Fannick, "Coal in the U.S." in Pulmonary Reactions to Coal Dust, A Review of U.S. Experience, M. M. Key et al. (Eds.) Academic Press, NY, NY (1971).

4.7 DOLLAR COSTS OF HEALTH AND ACCIDENT IMPACTS

Other parts of this report have attempted to quantify health and accident effects in the alternate energy systems. In Chapter 5 and the Appendix, occupational injury rates, throughout each of the alternate energy systems, are compiled and normalized to a unit of electrical energy produced. The Appendix also addresses occupational and public injuries due to conventional accidents in the transportation of coal and nuclear fuels. Radiological health impacts -- both public and occupational -- of the nuclear fuel cycles are treated in detail in the Appendix and summarized in Section 4.4 of this chapter. The Appendix also quantifies the incidence of radiologically induced lung cancer among uranium miners. Section 4.5 of this chapter deals, without success, with the problem of quantifying public health effects of airborne fossil pollutants.

In all cases the basis for normalization is the annual operation of one 1000 MWe power plant at 75% CF, i.e., 6.57 billion kilowatt hours of electrical energy. Health and accident effects, where quantifiable, are displayed in various units:

- fatalities, non-fatal injuries, severity for occupational accidents;
- cases of cancer, coal workers pneumoconiosis, etc. for occupational and public health impacts.

To render such quantities comparable and additive, one wishes to reduce them to consistent units. A unit of health and accident impact adopted for this study, following practices used in reporting industrial accident statistics, is the man-day lost (MDL). Ultimate health and accident impacts, based on MDL, are in dollar units.

Assessment of Man-Days Lost

The measurement of accident severity in terms of disability days (called man-days lost here) is common industrial practice. The American National Standard Method of Recording and Measuring Work Injury Experience[1] lists the estimated number of

man-days of time lost for various injuries. A few examples of the loss of time assessed for some permanent injuries are given below.

Type of Injury	Man-Days Lost
Death	6000
Permanent total disability	6000
Loss of or loss of use of	
Arm, at or above elbow	4500
Arm below elbow	3600
Hand	3000
Thumb	600
One eye, loss of sight	1800
Both eyes, loss of sight	6000
One ear, loss of hearing	600
Both ears, loss of hearing	3000

The three injury statistics which are often given per million man-hours of labor are the number of deaths, nonfatal injuries, and severity (man-days lost). Since the types and numbers of nonfatal injuries vary from industry to industry, there is no single value which can be used for man-days lost per nonfatal injury as there is for death or permanent total disability. Severity rates used in preparation of this report have been obtained from sources such as the Bureau of Labor, Bureau of Mines, and the Bureau of Railroad Safety.

The man-days lost concept has been used in this report as a measure of severity not only for occupational accidents but also for occupational radiation exposure, public radiation exposure, accidents causing injuries to members of the public (e.g., a coal trains runs over a person at a grade crossing), and coal workers' pneumoconiosis. This extension of the man-days lost concept allows a comparison among energy systems of the total human health and safety effects which have been quantified in this study. It must be recognized that quantification could not be accomplished for many items thought to have significant impacts on human health and safety.

The quantification of occupational and public health effects has been accomplished by using dose-response relationships discussed elsewhere in this chapter and in the Appendix. For conservatism all neoplasms and all cases of progressiv massive fibrosis are assumed to result in 6000 man-days lost, the value given above for accidental death. There is no non-fatal injury category given here for health

effects, since precision of the data used elsewhere in the calculations do not justify such finesse.

The procedure described above suffers many obvious flaws. Conceptually, the incremental health impact associated with the operation of an energy system in a given year will, in most cases, appear in succeeding years. For example malignancies (considered equivalent to death here) occuring after the year 19XX due to radiation exposure resulting from nuclear power plant operation during 19XX are accounted for in the same manner as accidental deaths occurring during 19XX. Neither present worth factors nor escalation factors are applied. Moreover, the cost to society in terms of productivity for, say, the accidental death of a young coal miner could very well be greater than the cost for a death of a uranium miner from lung cancer after 30 years of exposure to radon gas in underground mines. One should take into account such factors as the age distribution of the people affected and any latent period between cumulative exposure and the human impact to determine the productive man-days lost per death. In a more detailed study an investigation into the various categories of man-days lost, including non-fatal impairment, would ideally result in refined sets of numbers accounting for age, latency period, type of health effect, and the like.

Dollars Per Man-Day Lost

The societal cost of the man-days lost due to the operation of the energy system depends not only on the category of loss, i.e., injury, sickness, or death, but also on the occupations of the individuals involved and their ages. A model of the event that includes the descriptive parameters might be established. At this time, however, the obtaining of a consensus for values of men's health as a function of the numerous variables involved is beyond the work scope. Rather, an attempt is made to find a reasonable cost that may be applied to all man-days lost and this cost should be in a range that is compatible with the value system of concerned individuals and with the society.

Trying to assess the man-days lost due to a death from the objective view of society as was done here is different from commenting on the pricelessness of an individual's life. In line with the objective approach of this study an attempt was made to find a reasonable cost ($) that could be applied to all man-days lost. Use of this dollar figure allows the human health and safety effects of an energy system to be compared with other costs incurred by the system. However, the man-days lost as well as their dollar value in each energy system are displayed in all the tables of results in order that the comparison of human health and safety effects can be made with ease

and so that the effect of changing the dollars per man-days lost figure is obvious to the reader.

A rough estimate of a man-day value can be made by dividing the gross national product by the number of people-days in the U.S. for one year; this gives a value of ∿ $15 per man-day. The wages and salaries paid to workers per day worked is about twice this value. The medical and funeral expenses for health and accidents must be included in the analysis to obtain a value of dollars per man-day lost. A rigorous analysis would also require adjustments for the time effect of the incurred expense due to any latency period between the time of emission and the appearance of health effect. Other adjustments such as those for effects on family life are also needed depending on the category of the health or accident detriment. For the purposes of this study, $50/man-day lost is selected as a representative value. The selection of this value is somewhat arbitrary, reflecting the difficulties of dealing quantitatively with abstract detail. A review of the study results shows that conclusions drawn from the study are probably not altered if 25 or 100 $/man-day lost is assumed.

Dollars per man-day lost can be related in a numerical fashion to the cost of a life lost or to an agent causing health effects. The cost of a life lost in terms of dollars has been estimated by others;[8,9] still others have reported on the cost of radiation health damage.[2,3,4,5,6,7,10] Cohen and Higgins[7] have tabulated the estimates of dollars per man-rad made by a number of authors. Otway[10] has collected similar information. His tabulation ranges from $10 to 600. A similar tabulation,[10] inferred from life value estimates, range from $135 to $980/man-rad.

Neglecting the low value ($10/man-rad) and the high value ($980/man-rad), the range is much the same as that derived by Lederberg,[6] $100 to $600/man-rad. A value of ∿ $200/man-rad is close to the most prevalent estimate. From Otway's figure of one death per 10^3 man-rads (which is a higher rate than the estimate in this report) the value of life is ∿ $200,000. Otway argues that this may be a subconscious assessment of the value of life, based on a survey of recollections of catastrophic events. When the ratio of property damage to number of lives lost exceeded $200,000, the individuals surveyed tended to remember the property damage rather than loss of life.

The parameter assumed for the present study is $50/MDL. In Bureau of Labor statistics a loss of life is equivalent to 6000 MDL.[1] Thus, the life equivalent cost, used in this study, is $300,000.

Summary of Quantified Health and Accident Effects

The MDL ratings/event and $/MDL factors are applied to health and safety effects, normalized to 6.57 billion kilowatt hours, derived elsewhere in the report. Results are summarized in Table 4.10. The reader is reminded of cautionary remarks made throughout the discussion of the quantification of these impacts. In general the results displayed should be regarded as order-of-magnitude estimates based on best available data.

Footnotes and References for Section 4.7 - Dollar Costs of Health and Accident Impacts

(1) American National Standards Institute, American National Standard Method of Recording and Measuring Work Injury Experience, ANSI Z16.1-1967.

(2) Cohen, J. J., "PlowShare: New Challenge for the Health Physicist," Health Physics, (Nov. 1970).

(3) Hedgran, A. and B. Lindell, "PQR -- A Special Way of Thinking," Health Physics, (July 1970).

(4) Bergstrom, Stig O. W. "Environmental Consequences from the Normal Operation of an Urban Nuclear Power Plant," Health Physics Society Topical Symposium, Idaho Falls (Nov. 1970).

(5) Dunster, H. J. and A. S. McLean, "The Use of Risk Estimates in Setting and Using Basic Radiation Protection Standards," Health Physics (July 1970).

(6) Lederberg, J. "Squaring an Infinite Circle: Radiobiology and the Value of Life: (1971).

(7) Cohen, J. J. and G. H. Higgins, "The Socioeconomic Impact of Low-Level Tritium Releases to the Environment," in Proceedings of the Tritium Symposium, SWRHL, Las Vegas, Nevada (Aug. 1971).

(8) Rice, Dorothy and Barbara Cooper, "The Economic Valve of Human Life," American Journal of Public Health, 57 (1967) pp. 1954-1966.

(9) Carlson, J. W., "Valuation of Life Saving" Ph.D. Thesis in Economics, Harvard University (1963).

(10) Otway, H. J., "The Quantification of Social Values" in Risk vs Benefit: Solution or Dream, LA-4860-MS (February 1972).

TABLE 4.10

HUMAN (OCCUPATIONAL AND PUBLIC) HEALTH AND SAFETY IN ELECTRIC POWER PRODUCTION[d]

	Effect		Man-Days Lost[c]	Dollars[a] (Thousands of Dollars)
Occupational Accidents	F[b]	NFI[b]		
Coal	1.1	46.8	9250	460
RFO	0.17	13.1	1725	86
Natural Gas	0.08	5.3	780	39
PWR	0.1	6.5	975	49
BWR	0.1	6.1	903	45
Public Injuries in Transportation of Fuel	F	NFI		
Coal	0.55	1.17	3500	175
LWR (PWR, BWR)	0.009	0.08	60	3
Radiological Health Effects (Occupational)	M[b]			
LWR (PWR, BWR)	0.08		480	24
Radiological Health Effects (Public)				
PWR	0.031		186	9.3
BWR	0.035		210	10.5
Coal Worker's Pneumoconiosis (CWP)	C[b]			
Simple CWP	0.6		600	30
PMF	0.006		36	1.8

a. 1 MDL = $50
b. F ≡ accidental fatalities; NFI ≡ accidental non-fatal injuries, M ≡ malignancy cases; C ≡ CWP cases
c. Accidental Fatality ≡ 6000 MDL; Malignancy ≡ 6000 MDL; Simple CWP ≡ 1000 MDL; PMF ≡ 6000 MDL
d. Basis: . Power Plant and supporting fuel cycle, 1000 MWe, 75% CF (6.57 billion kilowatt hours)

4.8 FOSSIL AND NUCLEAR SYSTEM POLLUTANTS: NATURAL BACKGROUND, STANDARDS, ACTUAL MAN-MADE EXPOSURES, AND HEALTH EFFECTS

Attempts were made in this study to normalize each impact to a quantity of electrical energy produced or to a unit of electrical production capacity and to display each impact in consistent units such as dollars. As discussed in Section 4.5, this was not possible in the case of public health effects of airborne pollutants from fossil-fired power plants. In spite of the failure to quantify these effects some gross perspective can be gained by comparing natural background concentrations to regulatory standards, to actual man-made exposures or concentrations, and to broad ranges of perceived medical effects. Figure 4.1 illustrates the comparisons for sulfur dioxide, nitrogen oxide, and whole body radiation. The areas labeled "medically perceivable effects," which cover very large ranges (several orders of magnitude), are adopted from a recent University of California Study.(1) The study cited did not normalize health effects with respect to durations of exposure at the respective exposure level.(2) Several tentative conclusions may be drawn from Figure 4.1.

(a) Environmental Protection Agency standards for SO_2 and NO_2, applicable to fossil-fired power plants and other man-made sources of these pollutants, are above natural background levels of these pollutants. Current USAEC regulations (10 CFR 20) for radiation exposure are about equal to doses from natural background sources. However, the new proposed "as low as practicable" guidelines (10 CFR 50, Appendix I), applicable to light water reactors, would restrict individual doses to orders of magnitude below that from natural sources.

When man-made and natural sources are added, the total levels permitted by regulations or guidelines are:

- about a factor of 100 over natural background for SO_2;
- about a factor of 4 over natural background for NO_2; and
- about a factor of 2 over natural background (10 CFR 20) or about a factor of 1.01 over natural background 10 CFR 50, Appendix I)* for radiation.

(b) As expected, ranges of medically perceivable effects are well above natural background levels for all three pollutants.

*Proposed.

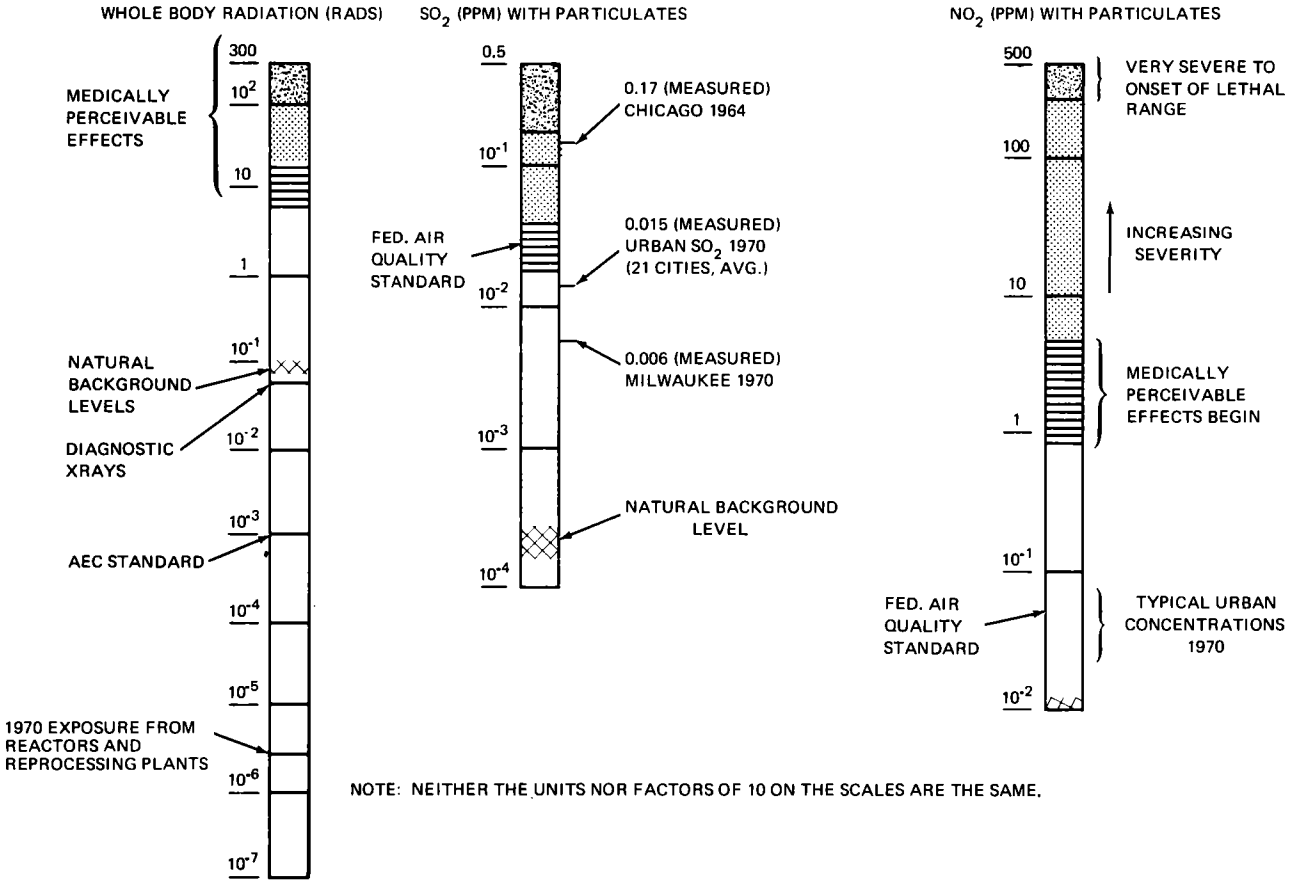

FIG. 4.1 COMPARISON OF POLLUTANT STANDARDS, BACKGROUND LEVELS, MANMADE EXPOSURES, AND HEALTH EFFECTS

(c) With the exception of SO_2, the standards are well below the ranges of medically perceivable effects.

(d) Actual average annual radiation whole body exposures from nuclear power facilities in 1970 were several orders of magnitude below the existing standards (10 CFR 20) and natural background. Concentrations of fossil pollutants (together with background) were substantially above background levels in 1970.

Footnotes and References for Section 4.8 - Fossil and Nuclear System Pollutants: Natural Background, Standards, Actual Man-Made Exposures, and Health Effects

(1) *Hausknecht, D., Public Health Risks of Thermal Power Plants, University of California UCLA-ENG-7242 (May 1972).*

(2) *The lethal level of 300 rads for whole body radiation, used in the University of California Study, is a representative value for short-duration, single event-type exposures. The probability of cancer, resulting from long term low level irradiation, adopted for the present study, is of the order of 10^{-4} per rad. See Section 4.4 and the Appendix.*

4.9 PROPERTY AND MATERIAL DAMAGES FROM AIRBORNE FOSSIL POLLUTANTS

One part of the external cost of power is the loss imposed on property and materials in the area around the plant as a result of exposure to emissions from the plant into the air. An attempt was made to quantify this loss for fossil-fuel plants based on available information about the effects of air pollution. Although data limitations make a precise estimate impossible, the figures developed are useful in indicating the order of magnitude of the loss. In addition, the sensitivity of damage to the choice of plant location, fuel, and emission controls was examined. A more detailed description of this part of the study is given in the Appendix.

Estimates of pollution costs associated with a single power plant in an urban area are made using two different methods. One estimate used a method based on figures for corrosion rates and maintenance expenditures of 53 common materials presented in a study by Richard L. Salmon.(1) He estimated (1) the difference in productive lifetimes of materials between urban and rural environments and (2) the total value of materials in urban areas exposed to pollution. From the two figures he made an estimate of national pollution-related corrosion costs. To this was added an expenditure which would be required to keep non-industrial property in urban areas at a given level of cleanliness. In the present study, the same general approach was taken, using (a) an estimate of the value of property exposed to pollution in a single urban area in which a hypothetical power plant is located, and (b) an estimate

of the proportion of urban air pollution attributable to the power plant. The result was an estimate of costs associated with shortening of productive lifetimes of materials and more rapid soiling caused by air pollution from SO_2 and particulates for a single fossil fueled electric power plant.

Calculations were made for a 1000 MWe coal-fired plant that had annual average daily emissions of 66 tons of SO_2 and 5.5 tons of particulates. These emissions are representative of a plant burning coal of 2.5% sulfur and 11% ash for 75% of each day and having SO_2 and ash removal efficiencies of 80 and 99%, respectively. For an urban site, the annual damage amounts to about 4 million dollars (in 1980 dollars) -- about 1 million dollars associated with material deterioration and about 3 million associated with soiling. This amounts to about $1 per person per year in the exposed area. Another view of the damage cost would be to express it in terms of the recipients of the plant output; with an assumed average use of 1.4 kW per person in the U.S., the damage is about $6 per person per year. The damage is not of uniform intensity around the plant; maps have been made to indicate the areas of principal geographic concentration of pollution, and hence loss, in relation to the plant location.

For comparison, another estimate of the loss was calculated using a method based on observed relationships between air pollution and residential property values. The principal study cited is by R. J. Anderson, Jr. and T. D. Crocker.[2] They used regression analysis to investigate the relationship between median values of owner-occupied housing for census tracts in 1960, and eight explanatory variables including concentrations of particulates and sulfur dioxide at the same locations. The same method was used for rental housing. A depressing effect of air pollution on property values and rents was noted. Their estimate of the quantitative relationship was applied to figures for property values in an urban area around a hypothetical coal-burning electric plant with the same characteristics as those assumed in the direct analysis of corrosion and soiling. Conceptually, the resulting estimate of cost should differ from the first estimate because it includes location-specific costs other than those associated with materials and also because it is restricted to residential property alone. This estimate gives damages of about 6 million dollars -- in rough agreement with the Salmon methods.

The property value method was used in addition to estimate the loss under a number of different assumptions about fuel type and quality, plant location, and emission controls. A wide range of figures is noted. The loss for the hypothetical coal-burning plant described above is shown to be of the same order of magnitude as for

an oil-burning plant using 0.7% sulfur oil with no SO_2 emission controls on the stack. The loss for a gas-burning plant with no stack controls is shown to be two orders of magnitude lower than for either the coal or oil alternatives. Finally, the loss is noticeably reduced if the plant is relocated to the edge of an urban area.

The results from both estimates indicate that the damages caused by fossil-fueled plants in the non-urban setting are less than 10 million dollars per year. Despite the reasonable agreement in results by both estimating methods, the relative damage by SO_2 and particulates is not consistent; in one method the major damage is caused by the SO_2 and in the other by the particulates. Based on this observation, an average collective damage was calculated for a non-urban setting. This averaging method raises the damage estimate for gas-fired plants by an order of magnitude. The results for the 1000 MWe plants were:

. Coal fired	0.8 million dollars/year
. Oil-fired	0.6
. Gas-fired	0.1

Concerning completely rural locations, it was noted that some vegetation is sensitive to SO_2 ambient levels in the air and to sulfur contents of soils: some effects are damaging, others may be veneficial. Limited literature on agricultural damage from SO_2 indicates a loss substantially less for a plant located in a wholly rural setting than the figures cited for an urban coal-burning plant.

Footnotes and References for Section 4.9 - Property and Material Damages From Airborne Fossil Pollutants

(1) *Salmon, R. L., Systems Analyses of the Effects of Air Pollution on Materials, Midwest Research Institute, 1970.*

(2) *Crocker, T. D. and R. J. Anderson, Air Pollution and Housing: Some Findings, Krannert Graduate School of Industrial Administration, Purdue University, Paper No. 264, January 1970.*

4.10 IMPACTS AND COSTS ASSOCIATED WITH WASTE HEAT

The impacts of waste heat are common to all of the energy production systems considered in this study, except hydro power production. A more detailed and thorough discussion of comparative impacts and costs is given in the Appendix.

All forms of energy harnessed by man - "useful" energy as well as "wasted" energy - ends up as dispersed thermal energy in the environment. Regarding the electrical energy production systems under consideration, heat is dissipated or rejected

throughout each of the alternate fuel cycles. Each supporting fuel cycle activity involves energy inputs, energy dissipation, and energy rejection, but the major point of energy release is at the power plant, as demonstrated by the overall system energy balances displayed in Section 5.4 and the Appendix. Thus, in the consideration of impacts and costs associated with energy release in electric power production attention is focussed on waste heat at the power plant because it is relatively large and localized.

As a consequence of fundamental laws of thermodynamics, all steam power plants, fossil as well as nuclear, reject (or waste) a fraction of the energy input. This energy is rejected in the form of heat to a "heat sink." Generally water is used as the environmental medium for heat rejection either in once-through systems, where it is taken from a natural body and returned at a higher temperature, or closed systems where cooling is accomplished by evaporating some of the water in a cooling tower or cooling pond. Some systems combine both methods, using, for example, cooling towers to lower discharge water temperatures sufficiently to meet thermal standards at the discharge. Another alternative, now being considered for some large power plants, is the rejection of heat directly to the air in a dry cooling tower.

About four-fifths of our electrical energy is generated using steam as a working fluid, where heat is rejected through a condenser to cooling water. To date, most of this heated water is returned to the natural water body in an open (once-through) cycle. The trend, however, is toward greater use of man-made, closed-cycle heat-dissipation facilities. This trend is motivated by two general considerations:

- Use of closed cycle facilities may be necessary to meet local water quality (temperature) standards; and

- Use of closed cycle facilities, by reducing intake water requirements by as much as 50-fold, makes siting of electrical power plants somewhat more flexible.

Global and Regional Considerations

Concern has been expressed over several gross effects of thermal discharge, including: its impact on the global energy balance, and its contribution to global temperature; effects on regional weather patterns; and effects on natural hydrological cycles, more particularly, the withdrawal and partial consumptive use of water in electric power generation.

Regardless of cooling method, the waste heat from the generating plant increases the local air temperatures as well as contributes, although in a very minor way at present, to gross temperatures on the planet. The ultimate disposition of this heat is by radiation to outer space. The sun's heat that is absorbed by the planet contributes in a very large fashion to the gross temperatures and has the same ultimate disposition. By way of comparison, a 3100 MW light water reactor power plant installation, which has an efficiency of ∿ 32%, would generate 1000 MW of electrical power and reject 2100 MW of thermal power directly to the environment. Ultimately, of course, the electrical energy also appears in the environment as thermal energy. The sun at our latitude inputs 3100 MW to the surface of the earth over an area of about 4 square miles as averaged for a day in June or July. Not all of the incident energy is absorbed. Some of the sun's energy is reflected, the amount reflected depending on the nature of the receiving surface. The average energy from the sun for a day in December and January is about 1/3 that for June and July because of the decrease in the hours of sunshine in a day and the change in angle of incidence of the solar flux.

On an annual basis, the conterminous states of the United States in 1970 had a net electrical energy generation of about 1600 billion kWhe. Assuming a 32% average efficiency for all generating plants excluding all hydro generation, and using an area of 3 million square miles for the U.S., the equivalent steady waste heat load from the generation of this electrical energy was 0.18 MW per square mile. This compares with a value of about 500 MW per square mile as the yearly average incident power from the sun. Thus, the sun input is about 3000 times that from electrical power generation. The total thermal energy consumption in the U.S. for all energy sources is about four times that of the electrical energy industry. On this basis, the U.S. had, in 1970, a man-contrived energy consumption rate, excluding food, of about 0.1% of the sun's input. This is a small percentage and has little effect on gross temperatures. With worldwide man-made heat releases of 0.25% in our net solar input, an overall warming of about 0.1°C plus a small increase in cloudiness would be expected.[1] Gross weather patterns would probably not be upset with this amount of man-made heat.[1]

These relative heat loadings of our environment by the sun and by man-made sources are gross effects. Concern has also been expressed for environmental consequences on a regional basis of the large heat inputs in metropolitan or megalopolitan areas, e.g., New York or Boston-Washington complexes. In these regions, local weather patterns might be significantly influenced by the large heat releases, which could be a sizable fraction of the sun's input energy in the year 2000. Local weather

effects have been reported downwind from Chicago and St. Louis due to heat and aerosol releases.[2] The major concern is not with gross man-made effects, but with regional and local effects and what happens as demands for all energy and, in particular, electrical energy growth in the future. Because water has been used as temporary heat sink for the discharge heat, some overall numbers on the water supply are worth reviewing before considering local and regional effects and other details of thermal discharge.

Whereas the thermal energy from the electrical generating plant adds to the energy source from the sun and results in increased temperatures, water for power plant use comes from a relatively fixed water runoff. Our average annual equivalent rainfall is $\sim 4 \times 10^{12}$ gallons per day. Nearly 70% of this rainfall is evaporated from wetted surfaces and transpired by vegetation. Of the natural runoff of 1.2×10^{12} gallons per day, about 22% was withdrawn for man's use in 1960.[3] The majority of the water withdrawal is returned to the water courses; however, some is lost (mainly by evaporation) and the water returned is often at a higher than the original temperature, which results in more losses in the water courses. These losses, or consumption, of water and the withdrawal are of concern for the future. The steam-electric plant consumptive usage is relatively small compared to such usage in agriculture. In the year 2000, it is believed, that water losses from steam-electric plants will be about 3/4% of the annual runoff. Consumptive water use in the generation of electrical energy is expected to be a small fraction of total consumptive use in the U.S. in the next 30 years.[4]

Alternate Cooling Methods

While the above discussions of gross temperature and water effects are relevant in placing quantities of energy released in perspective, the selection of cooling methods is governed by local and regional conditions, i.e., conditions at the power plant site. Various site conditions -- including meteorology and hydrology -- favor various cooling methods.

Major cooling methods and some of the attending environmental impacts, are described qualitatively below.

Once-Through Cooling

The cooling water passing through a condenser experiences typically a 10-20°F. temperature rise, which for a modern 1000 MWe fossil fuel plant implies a total flow of about 2000 cfs. and for a nuclear plant $\sim$ 3000 cfs. Although this is not

strictly a consumptive use of water, it would be a major diversion of flow for many water bodies. Such quantities, however, would not be noticeable for very large rivers, large lakes, and the oceans, and overall, the amount of heat added to such large water bodies would be negligible compared to the natural heat balance due to incoming solar radiation and cooling by evaporation losses. Evaporative losses resulting from thermal discharges to small rivers may result in a noticeable reduction in water for use downstream.

In the immediate area around the discharge, however, there will be a temperature elevation with the maximum temperature occuring at the point of discharge. The heated water will usually be observed as a plume extending from the discharge outward to where it is cooled to nearly the original temperature of the water body. The exact shape and size of the plume depends upon many factors including volume of flow, initial temperature difference, wind and current conditions, bottom shape and type and velocity of discharge. Generally, the greatest dimension of the plume, i.e., from discharge to where the temperature elevation is less than one degree, is about 1/2 mile. The excess temperature drops off rapidly away from the discharge, and most of the area of the plume consists of water only slightly warmer (1-3°F) than the ambient.

The environmental impact of heated waters under such circumstances is difficult to assess. It is known that different species of aquatic life have differing temperature tolerances that change with age. Fish and other mobile organisms generally avoid unfavorable temperatures if possible. Immobile organisms which cannot tolerate the higher temperatures will eventually be replaced by those that can.

Since most forms of life can accustom themselves to higher than normal temperatures if the rise is gradual enough, some experts maintain that the rate of change of temperature may be more important than the steady state temperature. The startup and shutdown operations of power plants may cause sudden temperature changes in the vicinity of the discharge. However, large natural fluctuations also occur due to changing current or weather conditions, which may be of equal or greater magnitude to start up and shut down operations.

In addition, fish may be drawn into the inlet of the cooling water system and killed on the screens used to prevent floating trash from entering the condensers. The accumulated debris on the screens is periodically removed and may be dumped into the discharge, where the dead fish may be assumed to have died from high temperatures. Where the inlet velocities are high and large fish populations are present around

it, fish kills at the inlet may be extensive. The total count may be increased by the carcasses of fish which have died elsewhere of natural causes being swept into the screens by the cooling water flow.

Cooling Ponds

Where local natural water bodies do not have enough capacity to handle the discharge, cooling ponds may be created as a form of closed cycle cooling. The heated water is discharged into the pond where it is cooled by natural processes of evaporation, radiation, and conduction. The cooled water then is recirculated through the condenser.

Roughly one acre of pond is needed for every megawatt of capacity; thus a 1000 MW plant requires over 1000 acres. Cooling ponds for the largest power plants tend to have multiple uses such as flood control, irrigation and hydroelectric power. Cooling ponds have water conservation (storage for low flow conditions) and recreational advantages.

Aside from land use the environmental impacts of cooling ponds involve possible increased evaporative losses which will result in less water for use downstream and increased total dissolved solids. The cost of cooling pond involves intake structures, discharge structures, and land. The price of land and the amount of excavation necessary will vary widely from site to site. Additional costs (above once-through cooling) may range from $2 to $15 per kilowatt of capacity. The pond area can be greatly decreased by using spray systems to improve heat transfer to the atmosphere. Improvements in performance of up to a factor of 20 over ordinary ponds have been demonstrated. However, the reduction in cost of land may be offset by the additional capital costs of the spray system and the increased power requirements for pumping. Thus, the costs of spray pond will be in the same general range as ordinary cooling ponds, but one method may have a cost advantage over the other for a given site. In addition to the environmental effects noted for the ordinary pond, spray ponds may also cause local fog and icing, and there may be objectionable drift.

Wet Cooling Towers

Wet cooling towers cool the circulating water by evaporation. Makeup water is required to replace that consumed in evaporation. The water is sprayed from the top of the tower into a counter-flowing or cross-flowing stream of air. In mechanical draft towers the air is drawn through by fans, while natural draft

towers use natural buoyancy forces to set up a flow as in chimneys. The heat of evaporation of water is great enough so that only 1-2% of the circulated water needs to be evaporated to give sufficient cooling, but the minimum temperature obtainable in wet cooling towers is set by the wet bulb temperature of the air. Thus, the use of cooling towers will generally result in reduced plant efficiency.

Natural draft towers are larger structures than mechanical draft towers and cost roughly 10-15 $/kWe, while the mechanical draft towers cost roughly 4-12 $/kWe. The actual cost is heavily dependent upon local conditions at the site. The mechanical draft systems require more power to run fans and thus have higher operating costs.

Although cooling towers are mostly operated on a closed cycle, some water must be withdrawn and discharged from the system in order to keep dissolved salts at a manageable level. This blowdown water will contain various chemicals used in water conditioning such as algaecides, chromates, etc. and may have to be treated before release to the environment.

A major impact of wet cooling towers is visual. Both natural and mechanical draft systems will emit large plumes of water vapor under the proper meteorological conditions. With mechanical draft towers, which are lower, the plumes may obscure visibility on roads in the vicinity and cause local icing. The plumes from natural draft towers are released sufficiently high that this does not occur, but the bulk of the tower itself--400 to 500 ft. or more high and 400 ft. in diameter--may be objectionable. A certain amount of the cooling water spray may be blown out of the tower. This drift will contain the salts present in the system and in the case of salt water or brackish water towers, may harm local vegetation.

Dry Cooling Towers

Dry cooling towers evaporate no water and thus can be used in arid regions where even wet towers cannot be used. However, the heat transfer is directly to air and is less effective than evaporative methods, thus requiring large heat transfer surfaces. Also the lowest attainable temperature is the dry bulb temperature, which reduces plant efficiency.

Both natural draft and mechanical draft dry towers have been built, and the capital costs may be roughly double those of comparable wet towers. For this reason, few power plants have dry towers. They may eventually be utilized in regions such as

the Western U.S. where location near a mine mouth is more economical than locating the plant near scarce sources of cooling water. Major environmental impacts of dry towers include the amount of land they occupy and the noise which may be generated.

Comparative Impacts and Costs

Table 4.11 compares impacts of alternative cooling methods, based on a more detailed analysis presented in the Appendix. Whether incremental abatement costs are matched by a reduction in environmental impacts was not determined in the course of this study. Ideally, one would display individual costs and impacts of each combination of power plant type and cooling method. The results would further be permuted to show relative advantages and disadvantages at various representative sites for each combination. Such a massive detailed undertaking was beyond the resources available for this study.

On the basis of the analysis presented in the Appendix, a reference cooling method was selected from the types of closed cooling systems included in Table 4.11. It is recognized that no single waste heat rejection system can be representative and optimum for the total United States and for each power plant type. However, as noted above, without this attempt to narrow down the options the work would have been unmanageable. The criteria for selection of the reference method included low environmental impact, low dollar cost, an active trend in utility acceptance, and wide applicability in most utility systems. A natural-draft wet cooling tower system was selected as the reference. Table 4.12 displays additional costs of natural draft wet cooling towers for the alternate energy systems as developed in Chapter 5. The figures are based largely on cost studies performed for the Division of Reactor Research and Development, USAEC, by United Engineers and Constructors.[5]

The abatement costs for natural draft wet cooling towers given in Table 4.12 are assumed to internalize the environmental impacts associated with once-through cooling. Several categories of costs, however, remain external. These include consumptive use of water, the slight decrease in water-base activities, fogging and icing, deposition of salts on surroundings due to drift, and effects on biota of cleaning chemicals discharged with blowdown to natural water bodies.

With the exception of the dry cooling tower, water is required for the heat rejection system to account for evaporation and blowdown. The drift of the water in the towers and spray canal also is another, but much smaller, source of water use. The drift from the well-designed towers is in the range of about 0.1 to 1.0% of the amount of water lost in evaporation.

TABLE 4.11

SUMMARY COMPARATIVE IMPACTS OF ALTERNATE COOLING METHODS

	Units	Mech. Draft Wet Tower	Natural Draft Wet Tower	Spray Canal	Artificial Lake	Forced Draft Dry Tower
Resource						
Land	Acres/MW_t	0.01	0.01	0.04	.5 to 1	0.015
Water	Gal/kWh_t	.3	.3	.3	.4	
	($/$kW_t$)	(1.2)	(1.2)	(1.2)	(1.6)	None
Air	--	--	--	--	--	--
Other	Consumption of Materials	Medium	Slightly > Mech. Wet Tower	Medium	Lowest	Highest
Populations						
Terrestrial	Local changes in diversity & dominant species.	Small	Small	Small	Small	Unknown
Aquatic		Small	Small	Small	Small	None
Man & His Activities						
Man						
Aesthetics	Appearance	Poor	Poor--Fair	Good	Good	Poor--Fair
Noise	Level	Noticeable	Slight	Slight	None	> Mech. Wet Tower
General	Interaction	Fog and ice in some locations could cause transportation hazards.			Favorable	Slight
Recreation	Opportunities	Slight decrease	Slight decrease	Slight decrease	Usually an increase	Probably a slight decrease
Commerce	Interaction	Fog and ice in some localities could cause transportation hazards a few times/year. Some farming could be adversely affected.			Slight	--

TABLE 4.12

ADDITIONAL (ABATEMENT) COSTS FOR ALTERNATE ENERGY SYSTEMS
WITH NATURAL DRAFT WET TOWERS
(1980 Dollars)

	Coal	RFO	Nat. Gas	LWR
		(10^6 per year)		
Additional Costs				
Capital	1.95	1.95	1.95	1.20
O&M	0.36	0.36	0.36	0.45
Fuel	1.28	3.60	4.74	0.78
Rounded Totals	3.6	5.9	7.1	2.4

Basis: Annual Costs per 1000 MWe Power Plant, 75% CF (6.57 billion kilowatt hours); 15% fixed charge rate.

The amount of blowdown from the mechanical and natural draft wet towers, the spray canal, and the artificial lake depends on equipment performance and on the allowable dissolved solids concentration in the receiving water body. In addition, the temperature of water returned to some sources must be reduced, or the blowdown must be well-mixed with the receiving water to meet the water quality standards.

Water use is normally not accounted for in conventional power plant economics. In a real sense water is used when the operation of a facility causes evaporation to occur; this water is lost to use by others in the watershed. The value of raw water to the user who withdraws from streams and lakes varies widely in the U.S. Water in the past was treated as a free good; however, with increased demand water rights based on various principles came about.(6) Water has become an even more valuable commodity. Prices charged for water withdrawn from water courses varies from none to a few cents per 1000 gallons. To quantify this water use, a cost of 10¢ per 1000 gallons consumed is assigned to represent the water value in 1980. This assignment is arbitrary, but reasonable. In many cases water uses by the power plant do not interfere with other water uses; however, with greater water use in the future, water charges may be prevalent. To capitalize the water operating change, a 75% annual capacity factor of equivalent full power operation and 15% annual charge for capital are assumed. This gives a coefficient of about $4-hours per gallon. When this coefficient is multiplied by the water loss expressed in terms of gallons per kWh of rejected heat, the equivalent capital cost per thermal kilowatt rejected is obtained. For example, with a water loss of 0.3 gal per kWht, the cost is 1.2 dollars per kilowatt of reject heat.

The consumption of water in natural draft wet cooling towers, from Table 4.11, is about 0.3 gal/kWht of rejected heat. Thus the equivalent capitalized charge is about 1.2 dollars per kilowatt of reject heat. For the purposes of this study, a round figure of 2 dollars per kilowatt of reject heat is assigned. This figure is assumed to include not only water consumption, but the other impacts identified for natural draft wet cooling towers. Table 4.13 gives annual costs of water consumption and other external effects, for the alternate energy systems.

Footnotes and References for Section 4.10 - Impacts and Costs Associated With Waste Heat

(1) *Weinberg, A. M., paper #49/P-033, 1971 Geneva Conference on the Peaceful Uses of Atomic Energy.*

(2) *Huff, F. A., et al, Effect of Cooling Tower Effluents on Atmospheric Conditions in Northeastern Illinois, Ill. State Water Survey Circular 100 (1971).*

TABLE 4.13

EXTERNAL COSTS ASSOCIATED WITH REJECT HEAT FROM ALTERNATE POWER PLANTS USING NATURAL DRAFT WET COOLING TOWERS

	Coal	RFO	Gas	LWR
Net Thermal Efficiency, %	38	39	38	32
Net Electrical Energy, 10^{10} KwHe/yr.	0.66	0.66	0.66	0.66
Stack Heat Discharge, 10^{10} KwHt/yr.	0.16	0.17	0.22	0
Reject Heat, 10^{10} kWht/yr	0.89	0.87	0.88	1.4
10^{6} kWt	1.3	1.3	1.3	2.1
External Cost, 10^{6}\$/yr.	0.4	0.4	0.4	0.6

Basis: 1000 MWe power plant, 75% CF
15% Fixed Charge Rate.
External Cost = 2\$/kWt, including ~ 1.2\$ for water consumption, based on ~ 10¢/1000 gal.

(3) *Piper, A. M. Has the United States Enough Water? Geo. Survey Water-Supply Paper 1797, USGPO (1965).*

(4) *Wollman, N. and G. W. Bonem, The Outlook for Water, Johns Hopkins Press (1971).*

(5) *United Engineers and Constructors, "Summary of Power Plant Cost Studies," presented to USAEC, August 1971.*

(6) *Post, R. G. and R. L. Seale (Eds) Water Production Using Nuclear Energy, Univ. of Arizona Press, Tucson (1966).*

4.11 OTHER DAMAGES: MINING, OIL SPILLS, AND REFINERY EFFLUENTS

Coal Mining

Damage and reclamation costs associated with environmental disruption in coal mining are normalized to the annual mining requirements of one 1000 MWe power plant. Coal is assumed produced by contour, area strip, and underground mines in the fractional amounts 0.1, 0.4, and 0.5 respectively.

Contour Mining

Some insight on the ways in which contour strip mining in eastern Kentucky affects social and economic conditions are highlighted in James Branscome's symposium speech on Coal and Environment and are not restated here.(1) For the purposes of this study, it has been assumed that the annual amount of coal from contour mining comes from a seam of about 60 acres in area and a little over 2 feet thick. In general, the costs of reclamation of surface mining can vary from a few hundred dollars per acre to over $5000/acre.(2) In West Germany where "brown" coal is being surface mined, the cost is estimated at $3000 to $4500 per acre. In a discussion of the economics of strip mining for West Virginia, an estimate of acceptable reclamation was from $1200 to well over $2000 per acre.(3) In this same general reference another author gave a breakdown of anticipated cost according to category:

planting	$225 to 250/acre
grading	$150 to 175/acre
drainage control	$200 to 215/acre
diversion ditch construction	$2000/mile
slide damage repair	$2000 to 1500/mile
haul road repair	$3000/mile
stream channel repair	$300 to 325/acre
pond stabilization	$10 to 20/acre
high wall access construction	$700/mile

elimination of hazardous conditions	$100/acre

For the purposes of this study, a value of $2000/acre is the assumed reclamation cost, although it is recognized that substantial reclamation of contour mined land is very difficult or almost impossible. The cost for the sixty acres amounts to ~$120,000, which is charged to the annual operation of the energy system.

In addition to the reclamation costs are the costs due to uprooting families. If one assumes that the families affected come from a much larger area than that directly mined, five families is a reasonable number. The welfare costs and replacement living quarter costs are assumed to result in an externality of about $100,000.

Area Strip Mining

Roughly 250 acres are strip mined to supply 40% of the coal required by the 1000 MWe plant. The dust or erosion effects, damage to roads by coal trucks, explosive damage, 24 hour per day noise level, and degraded real estate value all contribute to the external cost. In general, the average external cost for area strip mining is expected to be significantly less under 1980 regulations than the cost for contour mining. Considering the costs stated above, a cost of $500/acre is selected to represent the externalities caused by area strip mining. The annual cost is $125,000.

Underground Mining

It is assumed that the mine depth, geology, and operational methods are such that the cost of any subsidence is essentially zero.

Assuming that the mine drainage is 2.4 million gallons per year, and that the cost of 500 billion gallons of mine drainage is $3.5 million,[4] the operation of the underground mine is assumed to cause no significant external cost to mine drainage.

Uranium Mining

Uranium mining for the PWR and BWR energy systems may contribute a small external cost of the type being discussed in this section. The amount of land required for mining and mill tailings is small: less than 10 acres per year. Approximately 50% of the uranium comes from surface mines, the rest from underground mines. If a projected general damage for mining and tailings land use of $2000/acre (which is

the amount assigned for external cost in contour mining of coal) is assigned, the external cost is $20,000.

Oil Spills, Ballast Discharge

The effects of oil spillage have been examined by a number of investigators.[5,6,7,8] A social cost analysis of the Santa Barbara spill indicated that the oil companies bore most, if not all, of the social costs of the spill[6] Studies have shown that the cleanup costs for near-shore spills generally lie in the range $40 to $120 per barrel spilled. A social cost of $50 per barrel is attached to those ballast-water discharges. By 1980 the oil companies should bear most of the social costs associated with accidental oil spills.

Biological Oxygen Demand of Refinery Effluents

The external damage costs associated with refining biological oxygen demand (BOD) effluents were obtained by relating the marginal costs of removing BOD from municipal waste streams with the marginal benefits of removal. At the level of secondary treatment, the marginal costs of BOD removal are approximately $300 per ton of BOD removed.[9] If it is assumed that treatment to the secondary level is "optimal" (in the sense of equating marginal benefits and costs as they are now understood), then the incremental damage costs of an additional ton of BOD must also be $300. This method of assessing damage costs provides only a rough estimate; it neglects many important aspects of the problem, particularly the location-specific nature of the damage function.

Footnotes and References for Section 4.11 - Other Damages: Mining, Oil Spills, And Refinery Effluents

(1) *Branscome, J. "Coal and the Environment" Symposium of Coal and Public Policies, Univ. of Tenn. (Oct. 1971).*

(2) *Council for Environmental Quality, Annual Report on Environmental Quality - 1972*

(3) *Miernick, W. H., "The Economics of Strip Mining" The Strip Mining of America, Sierra Club (July 1971).*

(4) *Appalachian Regional Commission, Acid Mine Drainage in Appalachia (1969).*

(5) *Gaines, T. H., "Pollution Control at a Major Oil Spill," J. Water Pollution Control Fed., 43 #4, p. 651 (1971).*

(6) *Mead, W. J. and P. E. Sorenson, "The Economic Cost of the Santa Barbara Oil Spill," Santa Barbara Oil Symposium, Univ. of Cal., Santa Barbara, (Dec. 1970).*

(7) Mitchell, C. T. et.al., "What Oil Does to Ecology" J. Water Pollution Control Fed., 42 #5, p. 821 (1970).

(8) "Oil Spills: An Environmental Threat," Environmental Science and Technology, 4 #2, (1970).

(9) The cost of $300 per ton corresponds to a secondary treatment cost of 20¢ per 1000 gallons and a waste water BOD concentration of 150 ppm. The figure 20¢ per 1000 gallons is based on data in Reference (9.1) after an upward revision of the capital charge to 12% per annum.

(9.1) Smith, R., Cost of Conventional and Advanced Treatment of Wastewaters U.S. Department of the Interior, FWQA, Advanced Waste Treatment Branch, Div. of Research, Cincinnati Water Research Laboratory, Cincinnati, Ohio (1968).

CHAPTER 5
COMPARISONS ACROSS AND WITHIN ALTERNATE ELECTRICAL ENERGY PRODUCTION SYSTEMS

5.1 INTRODUCTION

Chapter 3 contained semi-quantitative descriptions of the alternate fuel cycles for the production of electrical energy. Tabular summaries of evaluated costs and impacts associated with the respective fuel cycles were also presented. Chapter 4, together with the Appendix, provided supportive material for evaluating ultimate impacts and costs - that is, for reducing non-conventional costs to consistent units such as dollars or man-days lost.

The purpose of the present Chapter is to summarize, display, and compare cost and impact information in parallel fashion for the respective fuel cycles. Much of the information assembled here has been developed (quantified and normalized) in previous chapters, and the present chapter merely rearranges this material into a format permitting rapid comparisions across and within the competing fuel cycles. Some new material is, however, developed in this chapter. This "new" material involves cost and impact considerations common to all of the energy systems -- conventional costs, fuel consumption and fuel resource bases, overall system energy balances, conventional occupational injuries, and the like. In each of these areas, it was convenient and practical to locate the discussion in one position in the report to assure uniform treatment of the subject across the competing fuel cycles.

Normalization is the same here as elsewhere in the report: costs and impacts related to fuel cycle throughput (or electrical energy produced) are normalized to 6.57 billion kWhe, the energy produced annually by one 1000 MWe power plant operating at 75 percent capacity factor, and those related to system capacity are normalized to the requirements of one 1000 MWe power plant or its prorated fuel cycle capacity.

5.2 CONVENTIONAL COSTS

Conventional or internal costs are those costs borne by the electricity consumer in the price of electricity. In this section, conventional costs for the competing energy systems, corrected to the year 1980*, are assembled. Where possible, abatement costs have been excluded. The main objectives of providing this cost

*Plant startup in 1980.

information are to show roughly the dollar competitiveness among the energy systems and to provide reference points for the comparison of conventional, external, and abatement costs.

It is difficult to arrive at representative values of costs, even for purely illustrative purposes. Costs vary widely with plant location and with time. Plant capital costs are sensitive to construction, labor, and material cost variations from region to region. Fossil fuel transportation costs are, of course, highly dependent on location. A multitude of factors causes costs to vary with time: inflation; the capacity versus activity level effect in new fuel cycle industries; improved technology; scarcity of resources; and legal and regulatory actions. All of these factors can alter the cost competitiveness of the alternative energy systems as location and time of starting operation are changed.

Three major components of electricity generation costs are (a) plant capital costs, (b) fuel costs, and (c) operating and maintenance costs.

Plant Capital Costs

Plant capital costs are those costs associated with the construction of the power plant, i.e., the acquisition of land and its preparation, the construction of buildings, and the purchase and assembling of equipment.

Table 5.1 compares 1000 MWe plant costs[1], in dollars per installed kilowatt of capacity, for plants commencing operation in 1980 and located at a hypothetical site called Middletown, USA.[2] Abatement costs have been excluded.

Also shown in Table 5.1 are the annual costs ($/year) and energy costs (mills/kWhe) resulting from amortizing the plant costs over the energy-producing life of the plant. An annual fixed charge rate of 15% is assumed. This includes depreciation, interest on bonds, return on equity, local, state and federal taxes, interim replacements, and conventional property insurance. A capacity factor of 75% is assumed.

Plant costs vary significantly with plant location. The variation may amount to as much as ±10% around the Middletown values. Location variations are also given in Table 5.1 in $/kWe.

TABLE 5.1

POWER PLANT CAPITAL COSTS*

(1980 Startup)

		Coal	Oil	Gas	LWR
Direct	$/kWe (1973 $)	162	150	132	226
Contingency & Spares	$/kWe	12	11	10	17
Subtotal	$/kWe	174	161	142	243
Indirect	$/kWe	30	28	25	61
Total	$/kWe	204	189	167	304
EDC&IDC (to 1980)**	$/kWe	133	124	110	202
Total	$/kWe (1980)	337	313	277	506
Rounded Total	$/kWe	340	310	280	510
Regional Variations	$/kWe	± 34	± 31	± 28	± 51
Annual Cost @ 15% Fixed Chg. Rate	10^6 $/yr	51	47	42	77
Energy Cost @ 75% Capacity Factor	mills/kWhe	7.8	7.2	6.4	11.7

* See footnotes (1) and (2). Costs are based on a two unit station, each unit with a net capacity of 1000 MWe.

** EDC - Escalation during construction.
IDC - Interest during construction.

Operating and Maintenance Costs

Estimated annual operating and maintenance costs[3], for plants going on-line in 1980 are summarized in Table 5.2. The values shown are levelized values for the first 10 years of power operation.

Fuel Costs

Costs incurred throughout a fuel cycle are ultimately transferred to the utility company and borne by the electricity customer, along with the utility company's working capital charges associated with fuel cycle transactions. The carrying charges of the fuel cycle industries, i.e., depreciation of processing facilities, cost of money, taxes, etc., are included in fuel cycle prices, and appear as direct costs to the utility.

Fossil fuel costs vary with power plant location, owing to the high transportation component of cost. Also, a variety of factors including inflationary pressures, regulatory actions, short-term scarcity, constrictions in the fuel supply and transportation capacities, and market place effects have resulted in drastic increases in fossil fuel prices over the past several years.

The cost of transporting nuclear fuel is a relatively minor component of fuel costs, and thus nuclear fuel costs are practically independent of power plant location. Improvement in fuel cycle technology and increased utilization of fuel cycle processing capacity should tend to decrease nuclear fuel costs, while ultimate depletion of low cost ores, increases in enrichment charges, and routine escalation will tend to increase fuel costs in light water reactor systems.

Figure 5.1 displays national-average fuel cost trends for coal, oil, gas, and nuclear (LWR) for 1969-71.[4] Table 5.3 demonstrates the broad variation of fossil fuel costs over the nation.[4]

Estimated fuel costs, representative of a plant going on-line in 1980, are summarized in Table 5.4. The projected costs of coal and oil were derived from Ref. (5) and were escalated from 1974 to 1980 at 8% per year. The price of natural gas is a very rough estimate of that which may be reached with price deregulation. Nuclear fuel costs are based on essentially the same economic ground rules used in Ref. (6). These represent the economic conditions expected to exist during the first 10 to 15 years of nuclear plant operation. Nuclear fuel costs were escalated from 1974 to 1980 using an overall escalation rate of 8% per year. Economies of scale may lead

TABLE 5.2

ANNUAL OPERATING AND MAINTENANCE COSTS FOR 1980*

(Thousands of Dollars per Year)**

	Coal	Oil	Gas	LWR
Staff	1500	1300	1200	1700
Fixed Maintenance	1900	1300	1200	1500
Variable Maintenance	1000	700	600	500
Supplies & Expenses	600	400	400	500
Administrative and General	400	300	300	400
Nuclear Insurance	-	-	-	600
Total 1980 Costs (10^3\$/yr)	5400	4000	3700	5200
Energy Cost (mills/kWhe)	0.82	0.61	0.56	0.79

* See footnote (3). Costs are for one 1000 MWe unit of a two-unit 2000 MWe station.

** Levelized over first 10 years of power operation.

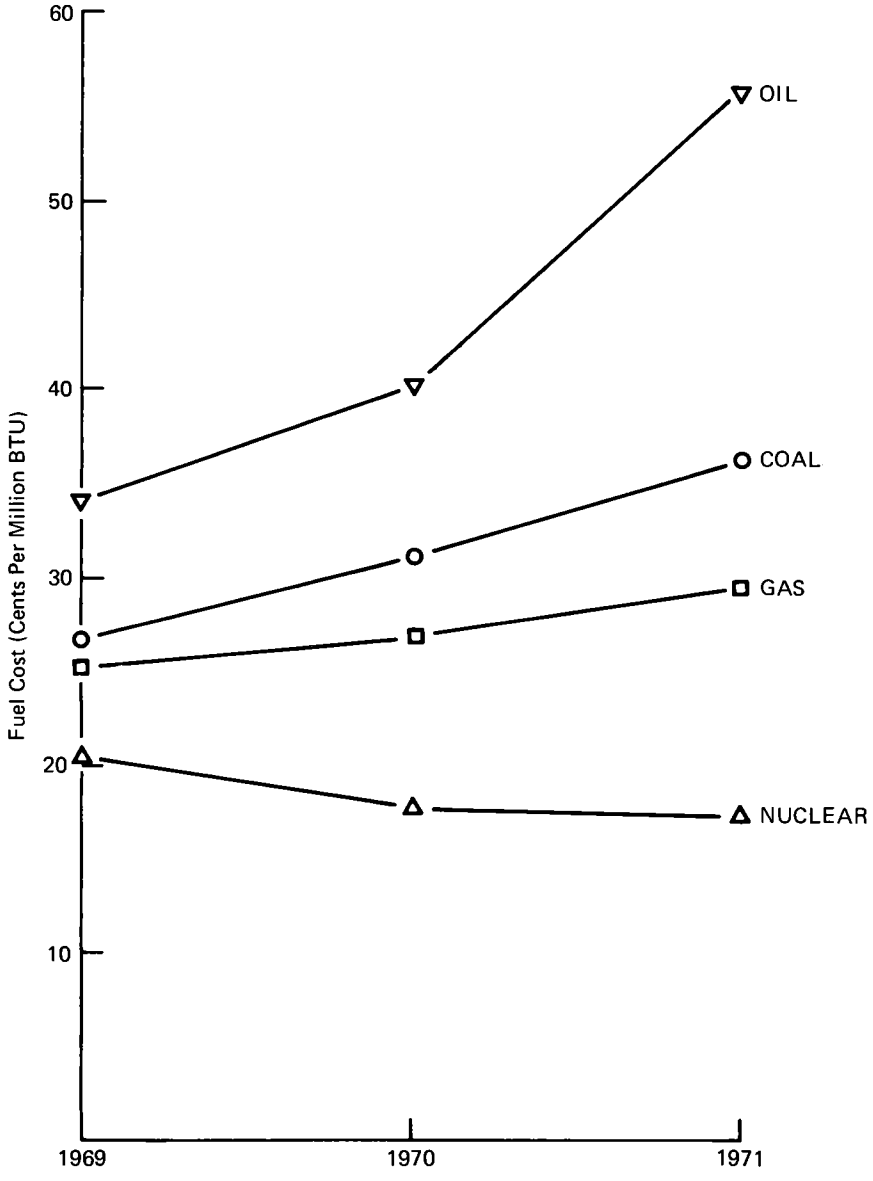

Figure 5.1 STEAM–ELECTRIC FUEL COSTS, U.S. (1969–1971)

TABLE 5.3

FUEL COSTS BY REGION*

(1969-71)

	(Cents per Million BTUs)								
	COAL			OIL			GAS		
	1969	1970	1971	1969	1970	1971	1969	1970	1971
New England	36.9	41.9	62.5	29.9	35.6	49.3	33.7	35.3	46.4
Middle Atlantic	30.0	36.1	41.6	34.7	42.6	59.2	35.6	38.3	45.3
E. No. Central	26.4	30.4	35.3	68.6	63.7	74.6	31.6	37.1	46.4
W. No. Central	26.2	28.2	32.1	57.1	65.1	76.8	24.9	25.6	28.0
So. Atlantic	28.4	36.1	41.3	33.0	34.8	45.7	31.6	34.7	40.3
E. So. Central	21.1	23.6	29.6	49.5	50.5	51.4	24.3	25.3	26.6
W. So. Central	None	40.1	None	37.7	44.9	66.4	20.5	21.1	22.2
Mountain	20.6	19.8	22.2	27.5	28.5	39.5	27.3	29.3	33.7
Pacific	None	None	14.0	36.4	39.0	54.6	31.2	32.4	34.1

*See footnote (4)

TABLE 5.4

POWER PLANT FUEL COSTS (1980 DOLLARS)

	Coal	Oil	Gas	LWR
Net Heat Rate (BTU/kWh)	8900	8830	9110	10850
Fuel Cost (¢/10^6BTU)	110	310	395	55
Annual Fuel Cost* ($10^6$$/yr)	64	180	237	39
Fuel Energy Cost (mills/kWhe)	9.8	27.4	36.0	6.0

*At 75% capacity factor

to cost improvements partially offsetting escalation, but these economies were not included in this cost estimate.

Total Conventional Costs

The total conventional costs for generating electricity--the sums of plant, operating and maintenance, and fuel energy costs--are given in Table 5.5.

TABLE 5.5
SUMMARY: CONVENTIONAL ENERGY COSTS

Estimated Total Electricity Generating Costs (1980 Dollars)

(mills/kWhe)

	Coal	Oil	Gas	LWR
Plant	7.8	7.2	6.4	11.7
O&M	0.8	0.6	0.6	0.8
Fuel	9.8	27.4	36.0	6.0
Total	18.4	35.2	43.0	18.5

Footnotes and References for Section 5.2 Conventional Costs

(1) *Plant capital costs presented in this section are based on capital costs studies performed by United Engineers and Constructors, Inc., and by Oak Ridge National Laboratory. UE&C has estimated plant capital costs for the PWR, BWR, Coal, and Oil type power plants in some detail. The UE&C base costs, together with ORNL data, have been assembled by ORNL as input information for use in the computer code CONCEPT, developed by ORNL.*

(1.1) *Current Status and Future Technical and Economic Potential of Light Water Reactors*, USAEC Report WASH-1082, March 1968.

(1.2) *Trends in the Cost of Light Water Reactor Power Plants for Utilities*, USAEC Report WASH-1150, May 1970.

(1.3) *Guide for Economic Evaluations of Nuclear Reactor Plant Designs*, USAEC Report NUS-531, NUS Corporation, January 1969.

(1.4) *1000 MWE Central Station Power Plant Investment Cost Study: Pressurized Water Reactor Plant*, USAEC Report WASH-1230 (Vol. I), United Engineers & Constructors Inc., June 1972.

(1.5) *1000 MWE Central Station Power Plant Investment Cost Study: Boiling Water Reactor Plant*, USAEC Report WASH-1230 (Vol. II), United Engineers & Constructors Inc., June 1972.

(1.6) *1000 MWE Central Station Power Plant Investment Cost Study: Coal-Fired Fossil Plant*, USAEC Report WASH-1230 (Vol. III), United Engineers & Constructors Inc., June 1972.

(1.7) *1000 MWE Central Station Power Plant Investment Cost Study: Oil-Fired Fossil Plant*, USAEC Report WASH-1230 (Vol. IV), United Engineers & Constructors Inc., June 1972.

(1.8) CONCEPT: A Computer Code for Conceptual Cost Estimates of Steam-Electric Power Plants - Status Report, USAEC Report WASH-1180, April 1971.

(1.9) R. C. DeLozier, L. D. Reynolds, and H. I. Bowers, CONCEPT: Computerized Conceptual Cost Estimates for Steam-Electric Power Plants - Phase I User's Manual, USAEC Report ORNL-TM-3276, Oak Ridge National Laboratory, October 1971.

(1.10) H. I. Bowers, et al., CONCEPT II: A Computer Code for Conceptual Cost Estimates of Steam-Electric Power Plants - Phase II User's Manual, USAEC Report ORNL-4809, Oak Ridge National Laboratory, April 1973.

(1.11) H. I. Bowers and I. T. Dudley, Multi-Unit Power Plant Cost Models for the CONCEPT Code, USAEC Report ORNL-TM-4300, Oak Ridge National Laboratory, March 1974.

(1.12) M. L. Myers, Cost Estimate for the Limestone-Wet Scrubbing Sulfur Oxide Control Process, USAEC Report ORNL-TM-4142, Oak Ridge National Laboratory, July 1973.

(1.13) Power Plant Capital Costs: Current Trends and Sensitivity to Economic Parameters, USAEC Report WASH-1345, October 1974.

(1.14) Heat Sink Design and Cost Study for Fossil and Nuclear Plants, USAEC Report WASH-1360, December 1974.

(2) NUS Corporation, Guide for Economic Evaluation of Nuclear Plant Designs, NUS-531 (January 1969).

(3) M. L. Myers and L. C. Fuller, Operating and Maintenance Cost Estimating Procedure for Steam-Electric Power Plants, ORNL-TM-4556 (to be published).

(4) Fuel cost data for Figure 5.1 and Table 5.3 were extracted from the following sources:

a. Coal and gas costs for 1969 and 1970, from: National Coal Association, Steam-Electric Plant Factors. (NCA obtains its data from annual utility reports submitted to the Federal Power Commission.)

b. Oil costs for 1969 and 1970, from: Edison Electric Institute, Analysis of Fuel for Electric Generation By the Electric Utility Industry - Fuel Burned Under Boilers and By Internal Combustion Engines.

c. Nuclear fuel costs for 1969 and 1970, from: Federal Power Commission, Steam-Electric Plant Construction Cost and Annual Production Expenses.

d. Coal, oil, gas, and nuclear fuel costs for 1971 were obtained by aggragating data from annual utility reports submitted to the Federal Power Commission (FPC) and on file in the FPC Public Document Room.

(5) *Federal Power Commission, News Release No. 20707, September 22, 1974.*

(6) *The Nuclear Industry - 1974*, USAEC Report WASH-1174-74.

5.3 CONSUMPTION OF EXHAUSTIBLE FUEL RESOURCES: FUEL RESOURCE BASES AND UTILIZATION CHARACTERISTICS OF ALTERNATIVE ENERGY SYSTEMS

Introduction

Most of the material assembled in this report concerns the environmental and human impacts of producing electrical energy. To place these nonconventional costs in perspective, some representative conventional costs* are cited also.

Environmental, human (health and safety), and conventional costs do not alone constitute a basis for making choices among alternative national energy strategies. Other major constraints in formulating energy policy are the fuel resource bases associated with the competing energy production systems and the relative efficiencies of the competing systems (or potential systems) in transforming these resources into useful energy. For example, if choices were made on environmental considerations alone, natural gas might be the preferred system. However, the current known U.S. resource base for natural gas will be exhausted in about twelve years at current consumption rates, without additional discoveries.

The purpose of this section is to provide gross comparisons of the coal, oil, natural gas, and uranium resource bases in terms of equivalent quantities of electrical energy. These results serve as figures of merit reflecting both the extent of various energy resources and the efficiency of utilization by the respective electrical energy production systems.

Difficulties

Several difficulties plague attempts to determine resource bases and to reduce them to comparable form:

. First, there is no widely accepted standard terminology, applicable to all energy fuels, designed to qualify the abundance of fuel resources. Each fuel industry has adopted its own unique set of conceptual describers, e.g., "reserves", "resources", "known reserves", "proven reserves", "estimate of proven recoverable reserves", "ultimate resources", "remaining resource", "estimated additional," and

*Internal costs less any identifiable abatement costs.

the like. While a given set of terminology and definitions may be meaningful to a specialist in one energy technology, the same word sets and concepts may not be acceptable to his colleague in another technology. Resource bases change with time due to a host of factors, including depletion of reserves and new discoveries. The aim in the computations below is to establish, however crudely, bases comprised of the present known reserves and estimated additions through the next several decades.

. Knowledge of extent of resources varies considerably among the competing fuels. For example, uncertainties in estimates of oil resources are, in general, greater than estimates of coal resources because coal is a solid and is found relatively near the surface.

. Grades of fossil fuel resources vary according to heating value, sulfur content, and other characteristics. A thorough compilation of fuel resource bases would include such delineations.

. To render resource figures comparable, limitations imposed by extraction technology and economics must be carefully defined and normalized. In many cases, it is physically impossible to extract all of the resources from a known deposit. For instance, as oil is removed from a pool the pressure in the pool decreases, and eventually a point is reached where the driving forces on the remaining oil are too low to cause it to flow up the well. Even with pumping and other techniques of increasing flow, an average of only 30% of the oil in a pool is extracted. Similarly, pillars of unmined coal must be left in place in underground coal mines to support the roof over the working area. In some circumstances, the pillars are pulled down as the mine is worked out. However, the average recovery of coal is only 60% of the amount present in the seam.

Moreover, comparative resource assessments must explicitly recognize extraction costs. In general, as a given resource base is progressively consumed and as deposits of lower concentrations are exploited, extraction costs (per unit contained energy) rise.

Indeed, extraction costs may make the entire energy production system uneconomic. Further, the economics or diseconomics of a resource base are determined not only by extraction costs but also by all remaining components of energy costs. For example, if an energy system is advantaged by low power plant capital costs, higher extraction costs per unit energy can be afforded, resulting in an "extension" of its resource base. Thus, a rigorous comparative assessment of resource bases would

require establishing parity or breakeven extraction costs of each fuel as functions of all components of energy costs of all competing fuels. This, of course, would be a very formidable undertaking, particularly in a climate of rapid escalation of fossil fuel costs and all plant capital costs. Fortunately, most of the major conclusions vis-a-vis relative resource bases and fuel utilization characterizations can be reached using very gross calculations.

. Legal, regulatory, and subsidy conditions affect the relative resource bases. For example, limitations on sulfur content of coal burned in power plants tend to shrink the coal resource base.

. Further, it must be recognized that not all of the energy resources are available for electrical energy production. There are, for example, competing uses for coal, RFO, and natural gas.

In the computations below, resource bases associated with electrical energy production were assigned according to 1970 production - consumption statistics, i.e., the following percentage of the respective total resource bases were assigned to electrical energy production: coal, 54%; residual fuel oil, 39%; natural gas, 21%; and nuclear fuels, 100%. These fractions will, of course, change with time in accordance with market conditions, technological advances, legal and regulatory constraints, and a host of other factors. Use of 1970 statistics is, therefore, somewhat arbitrary.

. The electrical energy equivalent of a given resource base depends, of course, on the conversion technology attached to it. Thus, as improvements in an existing energy production system (the entire fuel cycle, including the power plant) are made or as new conversion technologies are developed, the resource base may expand or contract.

Coal

The total amount of coal in the U.S. with overburden depths to 6,000 feet has been estimated, without reference to extraction economics, to be about 3.2 trillion tons.* Since the deepest U.S. mines go down only 2,000 feet, a number more closely approaching the economic reserves would be about 1.1 trillion tons. Total reserves, determined by mapping and exploration, for overburdens to 3,000 feet, are estimated to be about 1.5 trillion tons, of which about 0.67, 0.43, and 0.45 trillion are

*Averitt, Paul, Coal Reserves in the U.S. as of January 1, 1967.

bituminous, subbituminous, and lignite grades, respectively.* Most of the coal presently consumed by utility companies is bituminous.

Current recovery rates are about 60 percent for underground mining and about 80 percent for surface mining.** Ignoring sulfur limitations, the reserves corresponding to current extraction economics and technology, for the purpose of this study, are set at 200-400 billion tons.

In 1970 about 54 percent of the marketed coal was used in generating electricity. The resource base for coal fired electric power plants is thus taken as 100-200 billion tons. A modern 1000 MWe coal fired power plant produces about 2800 kWhe per ton of coal burned.*** Thus the coal resource base, for current extraction economics and technology is equivalent to 300-600 trillion kilowatt hours of electrical energy.

Residual Fuel Oil

Estimation of an RFO resource base for U.S. consumption by electric utilities is complicated by several factors: a) RFO is one of many refinery products; the ultimate resource is, of course, crude oil, and the yield of RFO per barrel of crude depends on the economic environment, location (domestic or foreign) of the refinery, etc.; and b) a significant portion (about 72 percent) of RFO consumed in the U.S. is imported or is produced in domestic refineries from imported crude; the amounts of foreign crude or foreign RFO available to the U.S. in the long term future is unknown.

U.S. crude reserves at current prices and technology are estimated at about 460 billion barrels, including offshore fields. Assuming an RFO yield of 6 percent in domestic refineries, this is equivalent to about 27 billion barrels of RFO. Current known and probable crude reserves in Venezuela, a major supplier of U.S. crude and RFO, is about 69 billion barrels. Caribbean refineries yield about 60 percent RFO, so that the Venezuelian reserve is equivalent to about 41 billion barrels of RFO. Other sources of U.S.-consumed RFO are two African countries, Nigeria and Libya, most of whose crude is refined in Caribbean refineries. The combined proven crude reserves of these two countries is 36 billion barrels or potentially 22 billion barrels of RFO.

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* Averitt, Paul, Open File Report 1968, Geological Survey, Dept. of the Interior.
** FPC, The 1970 National Power Survey, Part I, page I-4-4 (Dec. 1971).
*** Assumes plant net thermal efficiency of ~ 40 percent and coal heating value of ~ 25 million BTU/ton.

All of the foreign potential RFO reserves mentioned (Venezuela, Nigeria, Libya) are assumed available for U.S. consumption. These potential RFO reserves, together with the domestic potential RFO resource base, total about 90 billion barrels. Electric utilities presently account for about 39 percent of RFO consumption in the U.S. Thus 35 billion barrels of RFO (about two-thirds of which would be imported) is taken as a rough estimate of the RFO available for electricity generation.

A modern 1000 MWe RFO-fired power plant produces about 720 kWhe per barrel of RFO.* Thus the RFO resource base assumed available for U.S. electricity generation is equivalent to about 25 trillion kWhe.

Natural Gas

Estimated proved recoverable reserves of natural gas as of December 31, 1970 were about 260 trillion cubic feet in the lower 48 states and about 31 trillion cubic feet in Alaska, totaling about 291 trillion cubic feet** -- about fifteen times the current annual consumption rate. The Federal Power Commission forecasts reserve additions of about 325 trillion cubic feet in the 1971-1990 period (lower 48).*** The ultimate remaining natural gas resource base may be between one and two thousand trillion cubic feet.****

For the purposes of this comparative assessment the natural gas resource base is assumed to be 616 trillion cubic feet, the estimated proved recoverable reserves plus assumed new finds in the 1971-1990 period. In 1970 about 21 percent of the marketed natural gas was consumed in the generation of electricity. Thus, reserves of about 130 trillion cubic feet are assumed available for electric power production. From Figure 3.6 about ten cubic feet of natural gas are required to generate one kilowatt hour of electrical energy in a modern gas-fired power plant. Thus the natural gas resource base available to electric energy production is equivalent to about 13 trillion kilowatt-hours of electrical energy.

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* Assumes plant net thermal efficiency of ~ 40 percent and a heat content of 6.3 million BTU per 42-gallon barrel of RFO.

** American Gas Association, Gas Facts (1971 Data).

*** "FPC Sees the U.S. Gas Deficit Soaring," Oil and Gas Journal (March 6, 1972).

**** Federal Power Commission, The 1970 National Power Survey, Part I (December 1971), p. I-4-15

Uranium

Two potentially fissionable* nuclides occur in nature, uranium and thorium. Natural uranium contains only 0.71 percent of fissile U235, the remainder being essentially all fertile U238, which may be converted to fissile Pu by parasitic capture of neutrons. LWRs and LMFBRs operate on uranium fuel cycles. Thorium occurs only in fertile form, Th232, and may be converted to fissile U233 by neutron capture. The HTGR uses both uranium and thorium.

The discussion below is restricted to uranium resources and the utilization of these resources in LWRs and LMFBRs. Uses of these resources other than in the production of electrical energy are assumed negligible.

LWR Fuel Resource Base and Fuel Utilization

Two sources of makeup uranium for LWRs are a) economically extractable uranium still in the ground and b) the uranium concentrate stockpile. The extraction cost cutoff representative of "current extraction economics and technology" for the LWR is taken to be 10 dollars per pound of U_3O_8. About one million short tons of unmined U_3O_8 are estimated available at 10 dollars or less per pound -- about 0.4 million in reasonably assured reserves and about 0.6 million estimated additional potential.** The concentrate stockpile as of the beginning of fiscal year 1973 was about 40 thousand short tons U_3O_8*** -- essentially negligible compared to the economic unmined resource. For the purpose of this study one million short tons of U_3O_8 is assumed.

Figure 5.2 contains an abbreviated form of the eequilibrium LWR-fuel cycle material balance. uantities are normalized to one kilowatt-hour of electrical energy produced. About one ton of U_3O_8 must be mined to produce 40 million kWhe. Thus if all of the $10 (or less) U_3O_8 is consumed in LWRs, the electrical energy produced would be about 40 trillion kWhe.

In the computation just described, no energy credit was given for the plutonium output of the cycle. Plutonium produced by light water reactors may either be stored to provide startup inventory for LMFBRs or it may be recycled in LWRs. If

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* There are two types of fissionable nuclides: fissile and fertile. Fissile nuclides are fissionable by neutrons of all incident energies, but are more readily fissioned by low energy neutrons. Fertile nuclides can be fissioned only by very high energy neutrons but can be converted to fissile material by non-fission capture of a neutron.

** As of January 1, 1974. Personal communication, J. Patterson, USAEC.

*** Nucleonics Week, Vol. 12 #11 - March 18, 1971.

the plutonium is recycled, the makeup uranium requirements may be reduced by as much as 25 percent, extending the equivalent electrical energy (from LWRs) of $10 or less U_3O_8 to about 50 trillion kWhe.

Another way of measuring the fuel utilization efficiencies of nuclear systems is to conceptually assign an energy equivalent to each stream of fissionable material entering or leaving the fuel cycle. Fertile material, as well as fissile material, is assigned an energy value. Energy released per fission is roughly independent of the nuclide species fissioned. Also, corrections for atomic weights are small, so that masses of fissionable material may be used in the calculation, rather than equivalent energies.* Fuel utilization is the mass fissioned plus the mass of plutonium produced (stored), divided by the mass of makeup uranium. The result, for the LWR, is about 0.0092, or about 1 percent. This method explicitly credits the light water system with its plutonium production, even though it is assumed in Figure 5.2 that Pu is not recycled in the LWR system. The potential energy content** of one million short tons of U_3O_8 is about 1.7×10^{16} kWh (heat) or 5.8×10^{19} BTU. Applying the fuel utilization efficiency of about 1 percent to this figure, one obtains about 156 trillion kWh (heat). The net thermal efficiency of the LWR power plant is about 32 percent, so that the corresponding quantity of electrical energy is 50 trillion kWhe, the same figure estimated above for the case of Pu recycle in LWRs.

The computations above restrict the LWR uranium resource base to $10 (or less) per pound U_3O_8, and AEC resource estimates as of January 1, 1974, were used. Several factors could, of course, alter this picture, such as the possible discovery of vast new quantities of uranium at this price, or the enhanced competitiveness of uranium-based energy due to rise in fossil prices, or, conversely, the decreased competiveness of nuclear plants due to rising capital costs.

The salient point with regard to uranium use in the LWR system is that most (about 98 percent) of the potential energy of the resource base ends up as enrichment plant tails (see Figure 5.2). The LWR, alone, is not an efficient user of uranium resources. Further, because the LWR system uses relatively large quantities of natural uranium, energy costs of this system are relatively sensitive to natural uranium costs, thus restricting the economic resource base of the LWR system.

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* About one megawatt-day is released in the complete fission of one gram of fissionable fertile or fissile) material. Another useful conversion is 2.205×10^{10} kWh (heat)/metric ton.

** As if 100 percent of the uranium atoms, fertile as well as fissile, were fissioned.

LMFBR Fuel Resource Base and Fuel Utilization

By producing more fissile plutonium (from fertile U238) than it consumes, the breeder reactor will extend uranium resources indefinitely. An equilibrium LMFBR (1000 MWe) fuel cycle material balance shows an annual uranium makeup requirement of about one metric ton, assuming recycle of uranium. Without uranium recycle, the makeup requirement is about 19 tons. About 0.2 metric tons of excess plutonium* are generated per year which may be used as inventory for new LMFBRs in an expanding nuclear power economy, or burned in LWRs, or other nonbreeders, should the nuclear energy demand flatten out.

Depleted uranium tails from enrichment plants, a byproduct of LWR fuel cycles, will be the source of uranium for many decades after the commercial introduction of breeders. Annual tails from one 1000 MWe LWR fuel cycle would supply the annual makeup requirement of about one hundred 1000 MWe LMFBRs, assuming uranium recycle in LMFBRs (or about five LMFBRs, assuming no recycle). When the tails stockpile (plus additions from concurrent LWR operation) is exhausted, uranium for LMFBRs will, of course, have to be mined. Because the uranium makeup requirements of the breeder are small, breeder energy costs are quite insensitive to uranium costs. Thus essentially all of the estimated uranium resource base, regardless of its price structure, is economically available for the LMFBR. Further, since the LWR system rejects about 98 percent of mined uranium, essentially all of the uranium "consumed" by LWRs remains available for LMFBRs. Thus the LMFBR resource base "overlays" the LWR resource base.

For the purpose of this assessment three components are assumed to comprise the LMFBR resource base: the current depleted tails stockpile, the current concentrate stockpile, and all of the remaining unmined uranium up to, arbitrarily, 100 dollars per pound U_3O_8. The concentrate stockpile and a portion of the unmined uranium may indeed be used as input to the LWR system, but as noted above all but about 1 or 2 percent remains available for the breeder.

The unmined resource base to $100 per pound U_3O_8 is about 17 million short tons U_3O_8.** The concentrate stockpile as of the beginning of FY 1973 was about 40 thousand short tons U_3O_8, negligible compared to the unmined resource. The current depleted tails stockpile is classified, but it is possible to infer an upper bound

* Excess Pu over that recycled in the LMFBR.

** As of January 1, 1974. Personal communication, John Patterson, Division of Production and Materials Management, USAEC.

for this stockpile from the open literature. AEC purchases of concentrate between FY 1948 and 1971 total 173,665 short tons U_3O_8.* Some of this may be included in the concentrate stockpile, and some may exist as enrichment plant tails from the submarine program, from civilian nuclear power, and from the U235 weapons program. An unknown amount has been consumed in production reactors to obtain plutonium for the weapons program and is thus unavailable as breeder fertile material. In any case, the upper bound of the current depleted tails stockpile should be about 135 thousand metric tons of uranium.** Compared to the 17 million tons U_3O_8 unmined, this quantity is negligible. For the purposes of making gross comparisons of resource bases among the energy fuels 17 million short tons of U_3O_8 is assumed to be the resource base of the breeder.

Figure 5.2 contains an abbreviated form of an LMFBR fuel cycle materials balance, normalized to one kilowatt hour of electrical output. About 2.5×10^{-10} ST U_3O_8 (or about 1.9×10^{-10} MTU depleted tails) is required as makeup in producing one kilowatt hour of electrical energy. The LMFBR resource base of 17 million ST U_3O_8 corresponds, then, to about 6.8×10^{16} kWhe of electrical energy. This computation gives no energy credit to the excess plutonium bred.*** To credit the system with excess plutonium, a fuel utilization efficiency is computed in a manner consistent with that applied to the LWR system above; the mass fissioned plus mass of plutonium produced, divided by the mass of uranium makeup. Using the quantities shown in Figure 5.2, the result is about 75 percent. The potential energy content of 17 million short tons U_3O_8 is about 29.0×10^{16} kWh (heat) or about 10^{21} BTU. Applying the fuel utilization efficiency of 75 percent to this figure, one obtains about 22.0×10^{16} kWh (heat). The net thermal efficiency of the LMFBR power plant is about 40 percent, so that the corresponding quantity of electrical energy is 9×10^{16} kWhe.

Summary

Table 5.6 summarizes the comparative information developed above. More detailed information is displayed schematically in Figure 5.2.

* USAEC, Statistical Data of the Uranium Industry, Jan. 1, 1972, GJO-100.
** 174,100 (ST U_3O_8) x 0.909 (MT/ST) x 0.85 (MTU/MTU$_3O_8$).
*** This is plutonium in excess of that which is recycled in the equilibrium LMFBR fuel cycle.

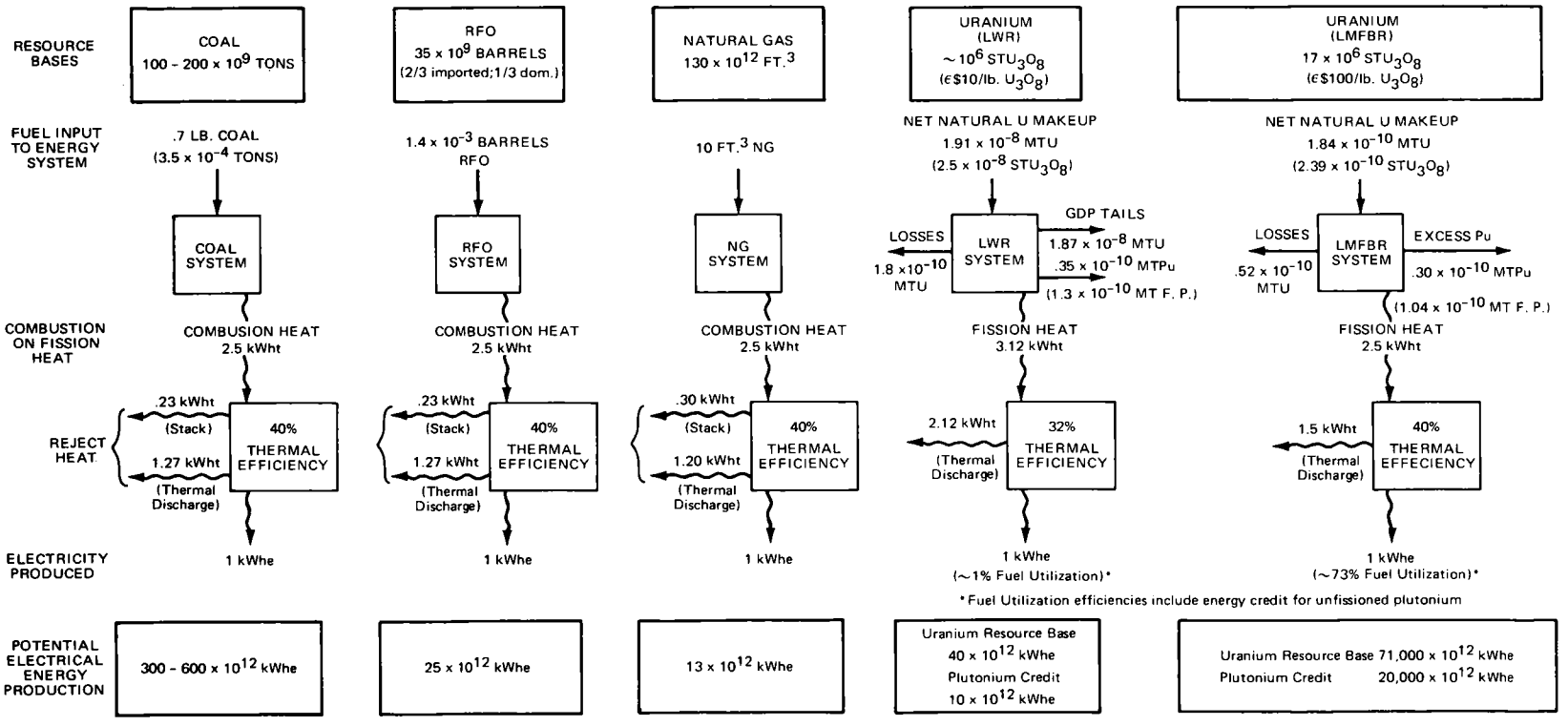

Figure 5.2 FUEL RESOURCE BASES AND UTILIZATION CHARACTERISTICS OF ALTERNATE ELECTRICAL ENERGY PRODUCTION SYSTEMS

TABLE 5.6

RELATIVE RESOURCE BASES FOR PRODUCTION OF ELECTRICAL ENERGY*

Fuel	Estimated Remaining Resources, @ Current Extraction Economics and Technology	Equivalent Electrical Energy Producable with Current Conversion Technology**
	(Conventional Units)	(trillion kWhe)
Bituminous Coal	200-400 x 10^9 short tons	300-600
Residual Fuel Oil	27 x 10^9 bbls (U.S.) 41 (Venezuela) 22 (Africa) 90 x 10^9 bbls (Total)	25
Natural Gas	616 x 10^{12} scf	13
Uranium		
LWR	1 x 10^6 short tons U_3O_8	50
LMFBR**	17 x 10^6 short tons U_3O_8	90,000

*See text for assumptions.

**While the LMFBR is not considered "current conversion technology" (commercial introduction is expected in the 1990s), its fuel resource base is included for purposes of comparison.

5.4 FUEL CYCLE ENERGY REQUIREMENTS AND OVERALL SYSTEM EFFICIENCIES

Processing and transportation steps in the various fuel cycles require energy in the form of heat or electricity. This is illustrated, for an arbitrary fuel cycle, in Figures 5.3 and 5.4. The total heat energy input to the system, including the heat released from the fuel at the power plant, is H. Of this energy, R_h is rejected as thermal energy, including the heat rejected at the power plant, R_e (=e) is dissipated in the fuel cycle electrical load, and T is lost in transmission, leaving E as the quantity of useful, delivered electrical energy. Thus it is possible to speak of an overall energy system efficiency, defined, for the purposes of this study, as E/H.

Figure 5.5 displays the energy balances for representative coal, residual fuel oil, natural gas, and nuclear fuel cycles. Quantities are normalized to a quantity of useful, delivered electrical energy E in arbitrary units.

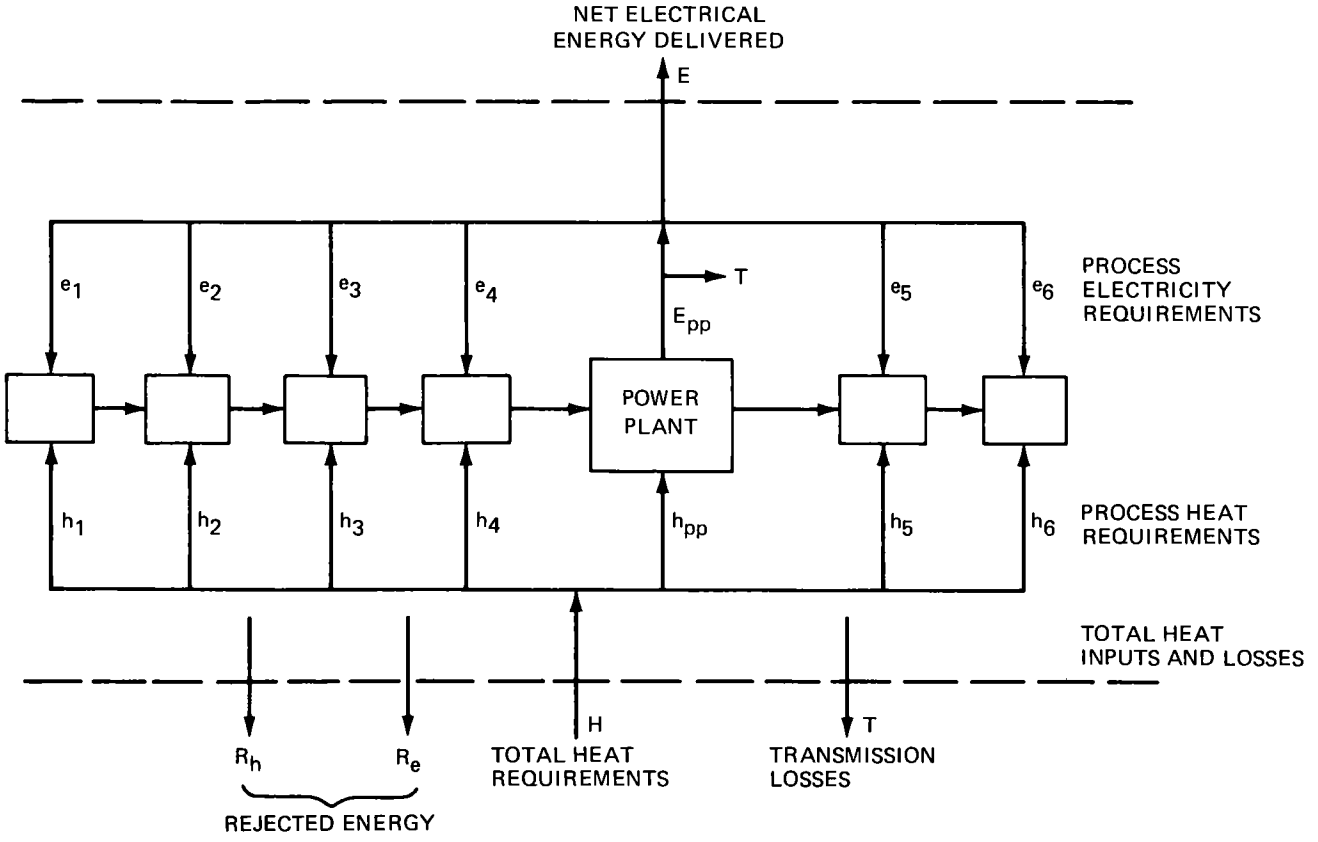

Figure 5.3 SCHEMATIC ENERGY BALANCE FOR A TYPICAL FUEL CYCLE

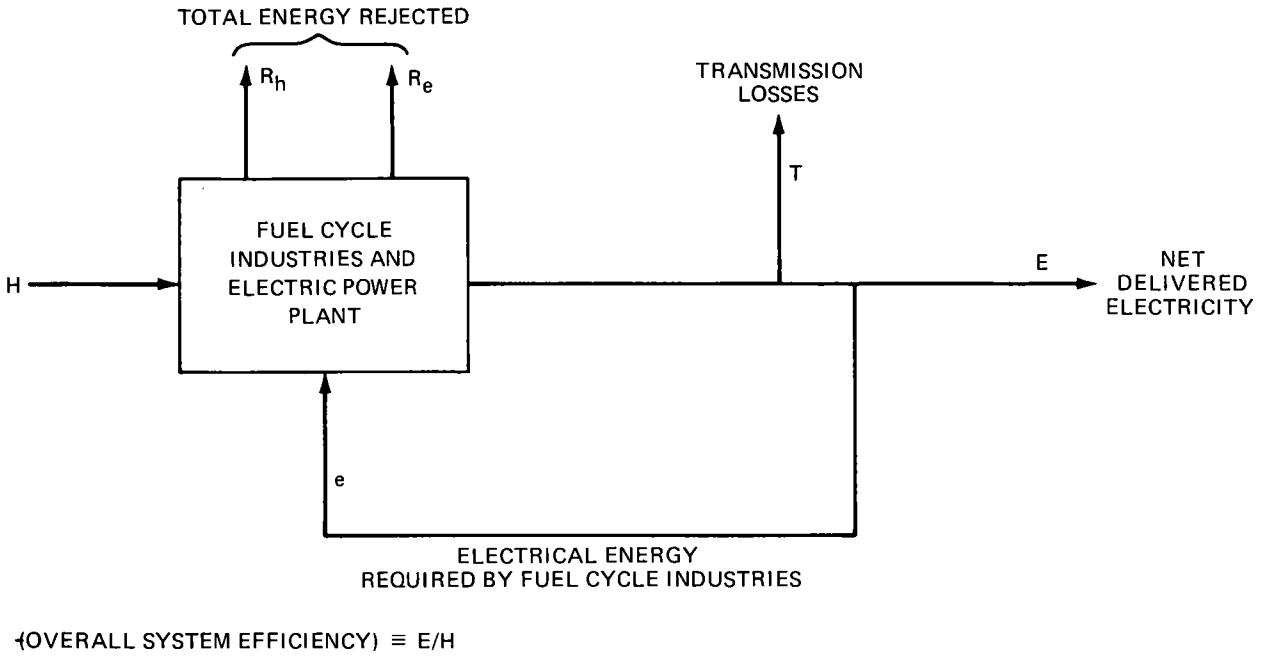

Figure 5.4 SCHEMATIC DEFINITION OF OVERALL SYSTEM EFFICIENCY

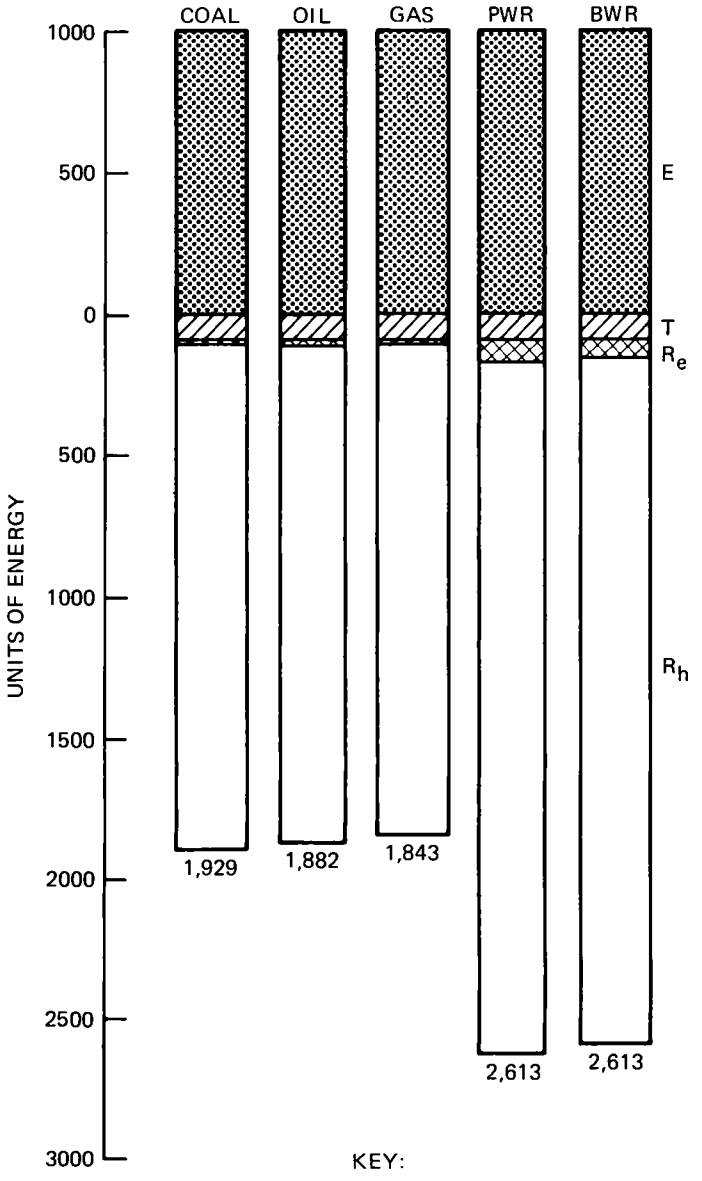

Figure 5.5 ALLOCATION OF ENERGY TO PROVIDE 1,000 UNITS OF NET ELECTRICAL ENERGY AT POINT OF USE

Tables 5.7 and 5.8 show the fuel cycle energy requirements, by process, normalized to 6.57 billion kWhe, the annual electrical energy generated by a 1000 MWe plant with a 75% capacity factor. Table 5.9 summarizes this energy balance data and gives values of the overall system efficiencies. Supporting material for this section is given in the Appendix.

Several conclusions may be drawn from the data assembled above.

1. Process heat requirements for all fuel cycle processes are negligible compared to the heat input at the power plant. Most of the heat rejection occurs at the power plant.

2. With the exception of LWR fuel cycles, the process electrical energy requirements are negligible. For the LWR cycles, the electrical load at the enrichment plant is about 3% of the power plant output.

3. The LWR cycles reject significantly more energy at the power plant than do the other cycles, which, together with their higher process electrical energy requirement, results in lower overall system efficiencies.

5.5 HUMAN HEALTH AND SAFETY

This section summarizes the relative impacts of the operation of alternate electrical energy production systems on human health and safety. Two general groups of humans at risk are considered: the population at large, that is, the public; and those who are employed in an energy system, that is, occupational personnel.

Occupational Safety

Figure 5.6 and Tables 5.10 - 5.12 present comparisons of occupational injury rates across and within the competing energy systems. Injuries considered in this analysis are those incurred in conventional, industrial-type accidents, and are of a mechanical, thermal, or electrical nature. Health effects resulting from exposure to toxic or radioactive materials released in accidents are excluded.

Figure 5.6 displays a comparison of occupational mandays lost due to conventional accidents in the alternate power plant types and their supporting fuel cycles. Tables 5.10 - 5.12 show deaths, nonfatal injuries, and mandays lost by fuel cycle steps. Data are normalized to the operation of a 1000 MWe plant for one year at 75% capacity factor, that is, to 6.57 billion kilowatt-hours of electricity.

TABLE 5.7

PROCESS HEAT REQUIRED IN THE INDIVIDUAL STEPS OF THE FUEL CYCLES

[billions kWht per year]

	Coal	Oil	Gas	PWR	BWR
Mining	0.14	0.10	0.10	0.0	0.0
Milling	-	-	-	0.014	0.012
Conversion	-	-	-	0.004	0.004
Diffusion Plant	-	-	-	0.0	0.0
Preparation	-	-	-	0.0	0.0
Fabrication	-	-	-	0.0	0.0
Reprocessing	-	-	-	0.011	0.013
Transportation	0.068	0.13	0.12	0.001	0.0019
Desulfurization	0.287	0.066	0.0078	-	-
Cooling Tower Penalty	0.5	0.5	0.5	0.63	0.63
Power Plant Operation	16.44	16.44	16.44	20.38	20.38
Total	17.44	17.24	17.17	21.04	21.04

Basis: 1000 MWe Generating Plant

75% Annual Capacity Factor

6.57 billion kWhe

TABLE 5.8

ELECTRICAL ENERGY REQUIRED IN THE INDIVIDUAL STEPS OF THE FUEL CYCLES

(billions kWhe per year)

Step	Coal	Oil	Gas	PWR	BWR
Mining	0.0078	0.011	0.011	0.0008	0.0008
Milling	-	-	-	0.0015	0.0014
Conversion	-	-	-	0.0012	0.0011
Diffusion Plant	-	-	-	0.264	0.216
Preparation	-	-	-	0.0028	0.0034
Fabrication	-	-	-	0.0002	0.0005
Reprocessing	-	-	-	0.0031	0.0037
Transportation	0.0	0.0	0.0	0.0	0.0
Desulfurization	0.094	0.056	0.0001	-	-
Total	0.10	0.067	0.011	0.27	0.23

Basis: 1000 MWe Generating Plant
75% Annual Capacity Factor
6.57 billion kWhe.

TABLE 5.9

ANNUAL ENERGY FLOWS FOR THE ENERGY SYSTEMS

Energy System	Net Elec. Output of Pwr. Plant, billions kWhe	Trans-mission Losses, billions kWhe	Process Heat Required billions kWht	Electrical Energy Required billions kWhe	Net Cycle Output, billions kWhe	Net Cycle Efficiency %	Rounded Net Cycle Efficiency Used in This Study, %
Coal	6.57	0.53	17.44	0.10	5.94	34.0	34
Oil	6.57	0.53	17.24	0.067	5.973	34.6	35
Gas	6.57	0.53	17.17	0.011	6.029	35.1	~ 35
PWR	6.57	0.53	21.04	0.27	5.77	27.4	~ 28
BWR	6.57	0.53	21.04	0.23	5.81	27.6	~ 28

Basis: 1000 MWe Generating Plant

75% Annual Capacity Factor

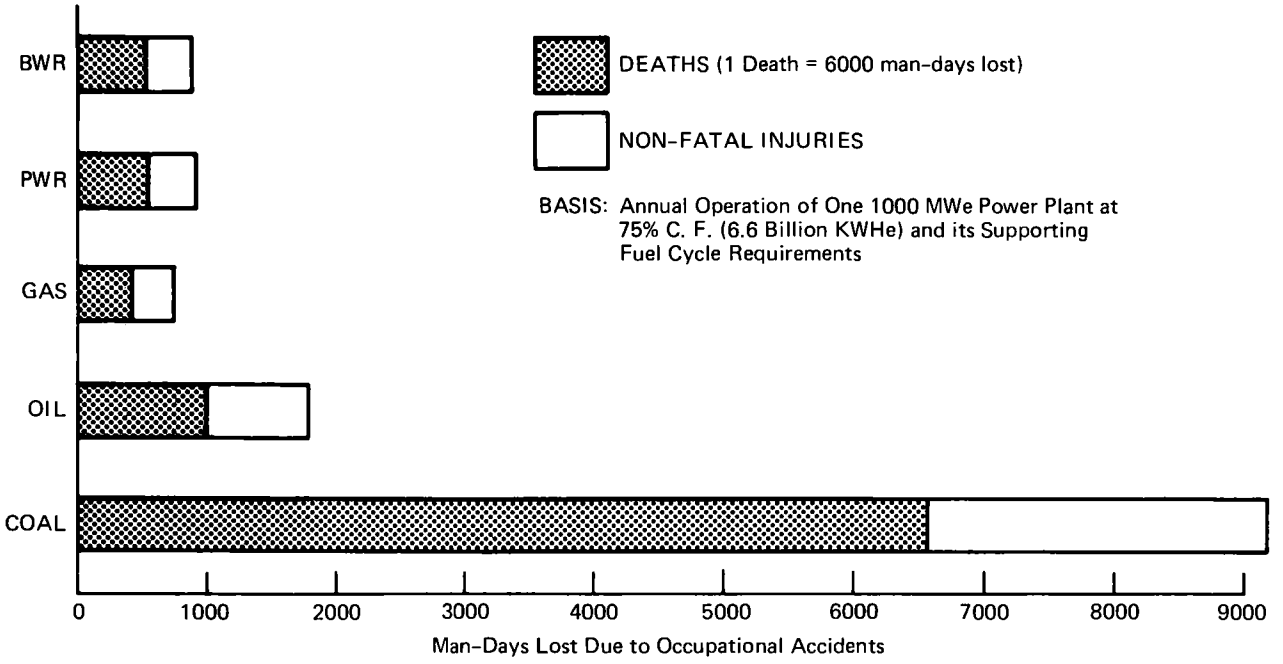

Figure 5.6 ANNUAL OCCUPATIONAL INJURIES IN THE ALTERNATE ENERGY SYSTEMS

TABLE 5.10

OCCUPATIONAL FATALITIES DUE TO ACCIDENTS

	Coal	Oil	Gas	PWR	BWR	
Mining/Pumping	0.96*	0.06	0.02	0.09*	0.09*	Mining
Fuel Processing	0.02	0.04	S	0.003	0.003	Milling
				0.0003	0.0002	Conversion
				0.001	0.001	Enrichment
				0.0004	0.0005	Fabrication
				0.0001	0.0001	Reprocessing
Waste Disposal	NA	NA	NA	NA	NA	Waste Disposal
Transportation	0.055	0.03	0.02	0.002	0.002	Transportation
Power Plant Operation	0.03	0.03	0.03	0.01	0.01	Power Plant Operation
Totals	1.1	0.16	0.07	0.1	0.1	Totals

Basis: 1000 MWe Power Plant
75% Capacity Factor

*Assumes 50% production from underground mines.

TABLE 5.11

OCCUPATIONAL NONFATAL INJURIES DUE TO ACCIDENTS

	Coal	Oil	Gas	PWR	BWR	
Mining/Pumping	39.8*	7.5	2.5	3.6*	3.3*	Mining
Fuel Processing	0.7	3.0	-	0.99	0.85	Milling
				0.028	0.026	Conversion
				0.18	0.16	Enrichment
				0.26	0.31	Fabrication
				0.079	0.092	Reprocessing
Waste Disposal	NA	NA	NA	NA	NA	Waste Disposal
Transportation	5.1	1.1	1.3	0.045	0.045	Transportation
Power Plant Operation	1.2	1.2	1.2	1.3	1.3	Power Plant Operation
Totals	46.8	12.8	5.0	6.5	6.1	Totals

Basis: 1000 MWe Power Plant
75% Capacity Factor

*Assumes 50% production from underground mines.

TABLE 5.12

OCCUPATIONAL MANDAYS LOST DUE TO ACCIDENTS

	Coal	Oil	Gas	PWR	BWR	
Mining/Pumping	8,186	735	250	762*	696*	Mining
Fuel Processing	144	420	90	63	58	Milling
				2.2	2.0	Conversion
				14	11	Enrichment
				8.5	9.9	Fabrication
				2.4	2.9	Reprocessing
Waste Disposal	NA	NA	NA	NA	NA	Waste Disposal
Transportation	570	220	180	13	13	Transportation
Power Plant Operation	350	350	350	110	110	Power Plant Operation
Totals	9,250	1,725	780	975	903	Totals

Basis: 1000 MWe Power Plant
75% Capacity Factor

*Assumes 50% production from underground mines.

These normalized injury rates are inferred from published statistics (past experience). Injury statistics are commonly reported on a per million man-hour basis, i.e., events per million man-hours of labor. Using labor productivity rates in each of the fuel cycle stages, e.g., tons per man-hour, and the fuel cycle material balance, the injuries can be allocated to a quantity of electrical energy produced.

Injury rates in mining coal and uranium are normalized to annual operation of respective 1000 MWe coal-fired and LWR power plants by assuming 50% production by underground mining and 50% production by surface mining. Injury rates in the RFO cycle up to and including the refinery are based on a BTU-equivalent method, and assume 10% volume yield of RFO in domestic refineries and 50% yield in foreign refineries. The import fraction is assumed to be 68%. Oil and gas production injuries at wells producing both oil and gas are separated according to dollar values of production (75% oil, 25% natural gas).

In Figure 5.6 and Table 5.12, 6000 mandays lost are assigned per death. There is no such conversion assigned nonfatal injuries, since the average severity (mandays lost per accident) of accidents varies from industry to industry.

Detailed supporting material for the occupational injury analysis is given in the Appendix.

The above results show that, on a per unit energy basis, far more injuries are incurred in the coal fuel cycle than in the oil, gas, and nuclear fuel cycles. Most of these injuries occur in underground coal mines. Assuming 50% production by underground mining, about one mining fatality per year can be attributed to one 1000 MWe coal-fired power plant. The large difference in injury rates, between the coal based system and competing energy systems, reflects the large amount of material that must be handled, per unit of electrical energy delivered, in the coal system.

Occupational Health

Like workers in other industries, employees of energy industries are routinely exposed to substances (chemicals, particulates, radionuclides, toxic metals, etc.) and to working conditions (heat, confinement, etc.) which singularly or in combination are potentially harmful to their health. As discussed in Chapter 4, human dose-response characteristics are not well known for most agents at low levels of exposure and under a wide variety of conditions. Thus, in most cases only order-of-magnitude estimates of potential health impact can be made.

TABLE 5.13

OCCUPATIONAL HEALTH IN THE LWR ENERGY SYSTEM

	Occupational Dose	Normalization Factor[4]	Normalized Occupational Dose	Risk	Expected Occurances Per 1000 MWe Reactor per Year (order of magnitude)
LWR Plant	0.4 man-rad/ MWe-Yr	750 MWe-Yr	300 man-rad	0.0002 malignancy/rad[1]	0.06 malignancies
Reprocessing Plant	1 man-rad/ MTU	30 MTU	30 man-rad	0.0002 malignancy/rad [1]	0.006 malignancies
Other Fuel Cycle Steps	-	-	15	0.002 malignancy/rad[1]	.003 malignancies
Uranium Mine	1.3[2] man-WLM/ MT-U_3O_8	80[3] MT-U_3O_8	104 man-WLM	0.0001 lung malignancy/ WLM	0.01 lung malig.

(1) Whole body dose

(2) 4 WLM/year; 3 MT U_3O_8/miner-year

(3) 160 MTU_3O_8 required for one 1000 MWe LWR per year; 50% underground mining.

(4) Basis: Fuel cycle requirements are those of one 1000 MWe plant operating for one year at 75% load factor.

TABLE 5.14

OCCUPATIONAL HEALTH IN THE COAL ENERGY SYSTEM

	Incident Rate	Inverse Productivity	Normalization Factor(1)	Expected Cases Per 1000 MWe Plant per Year
Simple Pneumoconiosos	2 cases/1000 man-yr	2.5×10^{-4} man-yr/ ton coal	1.2 million tons	0.6
Massive Fibrosis	0.02 cases/1000 man-yr	2.5×10^{-4} man-yr/ ton coal	1.2 million tons	0.006

(1) Basis: Coal requirements for one 1000 MWe coal-fired plant operating for one year at 75% load factor. Assume 50% of coal from underground mining.

TABLE 5.15

OCCUPATIONAL HEALTH AND SAFETY IN THE LWR AND COAL FUEL CYCLES

	Health Effects		Injuries			Total MDL*
	Cases	MDL	Fatalities	Nonfatal Injuries	MDL	
LWR FUEL CYCLE:						
Uranium Mine	0.01 malignancies (lung)	60	.09	3.5	750	810
All Other Fuel Cycle Steps	0.07 malignancies	420	~.01	~3	225	650
Totals (incl. other fuel cycle steps)	~0.08 malignancies	480	0.1	6.5	975	~1,500
COAL FUEL CYCLE:						
Coal Mine	0.6 cases simple pneumoconiosis 0.006 cases massive fibrosis	600 36	0.98	41	8,330	~9,000
Totals (incl. other fuel cycle steps)	0.6 cases simple pneumoconiosis 0.006 cases massive fibrosis	600 36	1.1	47	9,250	~10,000

*Health Effects and Injuries

The occupational health effects considered in this report are coal workers' pneumoconiosis, lung cancer among uranium miners, and somatic effects of exposure to radiation by workers throughout the remainder of the light water reactor fuel cycle (including the power plant). As in other parts of the study, attempts are made to normalize these effects to a given quantity of electrical energy produced, i.e., 6.57 billion kWhe, the electrical energy produced by one 1000 MWe power plant operating for one year at 75% C.F. Detailed supportive material for the quantification and normalization of occupational health effects is given in Chapter 4 and the Appendix. Occupational health effects in the coal and LWR systems are summarized in Tables 5.13 - 5.15.

Public Safety and the Transportation of Fuels

Considerations of safety are restricted in this report to conventional injuries of a mechanical, thermal, or electrical nature. Health effects resulting from accidental exposure to chemicals or radioactivity are excluded. (Health effects of routine and accidental exposures are addressed under the headings "Occupational Health" and "Public Health.")

The major source of conventional public injury in an energy system is that activity in which the public comes in closest contact with the system -- the transportation of fuel. Rates of human injuries attributable to the annual fuel transportation requirements of 1000 MWe coal-fired and LWR power plants are assessed in the Appendix. The results are shown in Table 5.16.

TABLE 5.16
TRANSPORTATION INJURIES IN THE COAL AND LWR FUEL CYCLES

	Coal	LWR
Public		
Fatalities	0.55	0.009
Nonfatal Injuries	1.2	0.08
Mandays Lost	3500	60
Occupational		
Fatalities	0.055	0.002
Nonfatal Injuries	5.1	0.045
Mandays Lost	600	13

Public Health

As in other parts of the study attempts were made to normalize public health effects of energy production to the annual operation of 1000 MWe power plants and their supporting fuel cycles. Section 4.4 summarizes conservative estimates of health impact resulting from routine releases of radionuclides from light water reactor systems. More detailed discussion of these computations is given in the Appendix. The public health effect of LWR system operation is conservatively estimated at 200 man-days lost per year per 1000 MWe.

Parallel estimates for fossil systems were not possible with the current state of knowledge of fossil pollutant dose-response characteristics. In lieu of a comparison of normalized health impacts of nuclear and fossil systems, comparisons of regulatory standards, background levels, actual manmade exposure levels, and ambient concentrations corresponding to broad ranges of perceived health effects were presented in Section 4.8.

5.6 ENVIRONMENTAL BURDEN

5.6.1 Land

Two concepts of land use are used in this report: (a) "inventory" land use and (b) "annual" land use. Tables 5.17 and 5.18 display inventory and annual land use parameters, by fuel cycle process step, normalized to the requirements of 1000 MWe coal, oil, gas, and LWR power plants.

Annual land use is related to the actual electrical energy produced. It is the incremental amount of land "consumed" in producing a given quantity of electrical energy, e.g. 6.57 billion KWHe, the electrical energy generated annually by one 1000 MWe power plant operating at 75% CF. Two prominent examples of such land use are land disruption due to mining operations and land inundated by fuel cycle wastes and residuals.

Inventory land use is related to energy system (power plant and supporting fuel cycle) capacity, e.g. 1000 MWe, and to commitment of land resources, used incrementally, for the duration of power plant life. The capacity-related component is simply the land occupied by the power plant (site) and supporting fuel cycle facilities, including exclusion areas, parking lots, etc. This land is "tied up" and unavailable for other uses during the life of the system. The commitment component refers to the commitment of land for incremental disruption (annual land use) over the lifetime of the power plant. In most cases the figures derived in this report

TABLE 5.17

INVENTORY LAND USE

(Acres per 1000 MWe Power Plant)

	Coal	Oil	Gas	LWR	
Mining/Pumping[3]	21,700	1,425	90	500	Mining[3]
Fuel Processing	300	75	30	100	Milling[4]
				50	Conversion
				10	Enrichment
				4	Fabrication
				73	Reprocessing
Waste Disposal	(1)	S	S	(2)	Waste Disposal
Transportation	NA	NA	3,200	NA	Transportation
Power Plant Operation	400	80	100	100	Power Plant Operation
Totals	22,400	~1,600	~3,600	~1,000	Totals

Basis: 1000 MWe Power Plant
75% Capacity Factor

S = Small
NA = Not applicable

(1) Coal ash waste disposal area committed for 30 year power plant life is included in Power Plant Operation.

(2) Radwaste disposal area committed for 30 year power plant life is included in Reprocessing.

(3) Land disturbance - commitment for 30 year power plant life is included.

(4) Land commitment for U-mine tailings for 30 year power plant life is included.

TABLE 5.18

ANNUAL LAND USE

(Acres per Year per 1000 MWe Power Plant)

	Coal	Oil	Gas	LWR	
Mining/Pumping	730	S	S	9	Mining
Fuel Processing	6	S	S	2	Milling
				S	Conversion
				S	Enrichment
				S	Fabrication
				S	Reprocessing
Waste Disposal	(1)			< 1	Waste Disposal
Transportation	NA	NA	NA	NA	Transportation
Power Plant Operation	5	0	0	0	Power Plant Operation
Totals	741	S	S	12	Totals

Basis: 1000 MWe Power Plant

75% Capacity Factor

S = Small

NA = Not applicable

(1) Coal ash waste disposal is included in power plant operation.

for the capacity-related component and the commitment component are not mutually exclusive; that is, they are not additive. The capacity-related component frequently includes land commited for incremental use. Both parameters are displayed, however, for sake of completeness.

For both measures of land use - inventory and annual - the land use parameters associated with supporting fuel cycle activities are normalized to the requirements of a 1000 MWe power plant.

To summarize, "inventory" land use includes land use related to capacity of the fuel cycle, and is land tied up by fuel cycle facilities and the power plant independent of the amount of electrical energy actually produced. It also involves land committed for disruption in winning the fuel resource from its natural habitat and land committed to the disposal of residual wastes. Units of "inventory" land use are acres. "Annual" land use, on the other hand, includes only the land disruption or inundation associated with the production of 6.57 billion kWhe of electrical energy. Units of "annual" land use are, of course, acres per year.

5.6.2 Air

As discussed previously, releases of air pollutants from one source will disperse and mix with those from other sources according to local conditions so that at the point of interest it is difficult to assign the amount of exposure due to a given source. Furthermore, the effect of such exposures has not yet been quantitatively determined. Thus, the actual impact of air pollution cannot be calculated. Therefore, for purposes of comparison the quantitities of pollutant emitted at the stacks will be used, since these numbers can be calculated fairly accurately.

The pollutants considered are SO_2, particulates, NO_x, trace metals, and radioactivity. Tables 5.19 through 5.23 compare source terms for these pollutants in the various fuel cycles. For purposes of comparison no emission controls are assumed for the fossil pollutants, and the advanced "near-zero" radwaste systems have been omitted from the LWR system. In the LWR fuel cycle, a range of fossil pollutants is given, the upper limit corresponding to the assumption that power for uranium enrichment is supplied by a coal-fired power plant.

With the exception of some dust releases in coal cleaning plants, the most significant source of air pollution occurs at the power plant for the fossil fuels. Coal is clearly the most prominent source of SO_2 and particulate emissions, while NO_x emission depends more on combustion conditions than choice of fuel.

TABLE 5.19

SO_2 RELEASES*
(Tons per Year)

	Coal	Oil	Gas	LWR	
Mining/Pumping	S	S	S	S	Mining
Fuel Processing	S	S	S	S	Milling
				S	Conversion
				0-3,600**	Enrichment
				S	Fabrication
				S	Reprocessing
Waste Disposal	NA	NA	NA	NA	Waste Disposal
Transportation	S	S	S	S	Transportation
Power Plant Operation	120,000	38,600	20	0	Power Plant Operation
Totals	120,000	38,600	20	3,600	Totals

Basis: 1000 MWe Power Plant
75% Capacity Factor

S = Small
NA = Now applicable

*Without abatement
**Zero emission corresponds to an all-nuclear power source for the gaseous diffusion plants. Upper limit is based on coal-fired power source.

TABLE 5.20

NO_x RELEASES*
(Tons per Year)

	Coal	Oil	Gas	LWR	
Mining/Pumping	S	S	S	S	Mining
Fuel Processing	S	S	S	S	Milling
				S	Conversion
				0-810**	Enrichment
				S	Fabrication
				S	Reprocessing
Waste Disposal	NA	NA	NA	NA	Waste Disposal
Transportation	S	S	S	S	Transportation
Power Plant Operation	27,000	26,000	13,400	0	Power Plant Operation
Totals	27,000	26,000	13,400	810	Totals

Basis: 1000 MWe Power Plant
75% Capacity Factor

S = Small
NA = Not applicable

*Without abatement
**Zero emission corresponds to an all-nuclear power source for the gaseous diffusion plants. Upper limit is based on coal-fired power source.

TABLE 5.21

PARTICULATE RELEASES
(Tons per Year)

	Coal	Oil	Gas	LWR	
Mining/Pumping	S	S	S	S	Mining
Fuel Processing	3,000	S	S	S	Milling
				S	Conversion
				0-8,000*	Enrichment
				S	Fabrication
				S	Reprocessing
Waste Disposal	NA	NA	NA	NA	Waste Disposal
Transportation	S	S	S	S	Transportation
Power Plant Operation	267,000	26,000	518	0	Power Plant Operation
Totals	270,000	26,000	518	8,000	Totals

Basis: 1000 MWe Power Plant
75% Capacity Factor

S = Small
NA = Not applicable

*Zero emission corresponds to an all-nuclear power source for the gaseous diffusion plants. Upper limit is based on coal-fired power source.

TABLE 5.22

TRACE METAL RELEASES
(Tons per Year)

	Coal(1)	Oil(2)	Gas	LWR(3)	
Mining/Pumping	S	S	S	NI	Mining
Fuel Processing	S	S	S		Milling
					Conversion
					Enrichment
					Fabrication
					Reprocessing
Waste Dispsoal	NA	NA	NA		Waste Disposal
Transportation	S	S	S		Transportation
Power Plant Operation	5	1,500	S		Power Plant Operation
Totals	5(1)	1,500(2)	S	NI	Totals

Basis: 1000 MWe Power Plant
75% Capacity Factor

S = Small
NA = Not applicable
NI = Not included

(1) Mercury. Mercury is the element of greatest concern in coal.

(2) Vanadium. Vanadium is the element of greatest concern in RFO.

(3) Trace metals in the nuclear fuel cycles are treated as radioactive material.

TABLE 5.23

RADIOACTIVITY RELEASES TO AIR

(Curies per Year)

	Coal	Oil	Gas	PWR	BWR	
Mining/Pumping	___	___	___	___	___	Mining
Fuel Processing	___	___	___	50	50	Milling - Fabrication
				250,000	250,000	Reprocessing & Transportation
Power Plant Operation	0.02	$5X10^{-4}$		5,000	250,000	Power Plant Operation
Totals	~0.02	$\sim 5X10^{-4}$	~0	~250,000	~500,000	Totals

Basis: 1000 MWe Power Plant
75% Capacity Factor

The trace metals comparison merely gives an idea of the relative magnitudes of emissions, and it is difficult to rank the competing energy systems for this particular class of emission impact. First, only two of the fifty or more relevant elements have been considered: mercury from coal firing, and vanadium from RFO firing. Second, mercury is known to be a toxic element, while vanadium is relatively harmless.

Very crude radioactivity release estimates are given in Table 5.23. These estimates are presented only to permit rough order-of magnitude comparisons of radiological sources in the alternative fuel cycles. A valid comparison of radiological impacts of the various fuel cycles requires that each of a large number of radionuclides be treated separately. The decay losses, ultimate fates, pathways to man and other receptors, dose, and dose-effects associated with each radionuclide should be accounted for in order to make valid comparisons.

5.6.3 Water

Water quality is affected by the various fuel cycles in a number of ways. One is the release to the environment of water that has acquired undesirable characteristics through natural processes. In this category are acid mine drainage and brine water from oil wells. Another type of impact involves direct dumping (accidental or deliberate) of foreign, and possibly toxicc, material into surface waters. Oil spills and mine spill dumps are examples. Another category involves the use of water for various process applications with the result that its quality is degraded as a direct result of the process. Examples would be the production at coal cleaning plants of water containing suspended fine coal particles and oily water from refinery applications. Also, water may be drawn from the environment for some use that does not affect the chemical characteristics of it, but may produce undesirable changes in its physical quality. The most important case is the temperature rise experienced by water used for cooling condensers. Finally, some water may be withdrawn and not returned to the source body of water, thus reducing the quantity available for other uses downstream. In some situations this may simply be a case of the plant intake being located on one body of water and its discharge on another. In other cases the water evaporates in uses like a wet cooling tower, and while it is no longer available for use downstream, it is not removed from circulation in the overall hydrologic cycle. However, there are circumstances where amounts of water are effectively withdrawn permanently from the environment. Examples include chemical processes that utilize the hydrogen or oxygen content of the water molecules. This situation can work in reverse, since the combustion of fossil fuel results in the

formation of new molecules of H_2O at the rate of 1 to 2 lbs. of water vapor per pound of fuel. Other processes do not chemically dissociate the water, but do remove it from circulation. For instance coal mine refuse and coal ash slurries have a residual moisture content acquired during processing. In some oil fields water is injected into underground strata to increase recovery of petroleum. In light water reactors, the water in the primary coolant loop becomes radioactive and remains stored on the plant site. Generally speaking, these permanent withdrawals and additions to the hydrologic cycle are negligible compared to other water flows in the fuel cycle.

For purposes of comparison the water used in each fuel cycle is classified under one of four categories.

The first is water used for cooling purposes. For simplicity it is assumed that the amount of any chemicals added to this water is negligible. Thus, the impact of this use consists of the diversion of surface waters and the possible release of heated water, depending on whether or not closed cycle cooling methods are used. Comparison of cooling water requirements are presented in Table 5.24.

The second category includes all water that is involved in process operations and thus undergoes some degradation in quality. The number of different pollutants involved ranges up in the thousands if organic chemicals and life forms such as bacteria are counted. The severity of the pollution depends not only on the specific types of pollutants involved but also on the concentrations in the waste water, the total amount discharged, and on conditions in the receiving body of water. Lacking the resources to make a sufficiently detailed analysis of the environmental impact of each discharge, the comparison here uses only the volumes of process water, thus implicitly assuming that any use that degrades water quality is no better or worse than any other. This drastic simplication must be kept in mind in considering the results shown in Table 5.25.

Table 5.26 lists releases of water polluted by natural processes, the third category. The need for a separate table listing these items arises from the fact that while cooling water and process water needs are directly related to the production of energy, the impacts included in this category depend upon local conditions and external factors that may bear no predictable relation to energy production. Acid mine drainage is determined primarily by local rainfall conditions, geology, and groundwater flow. Hence, two mines with identical outputs of coal may produce completely different quantities of acid water. Similarly, major oil spills depend

TABLE 5.24

COOLING WATER USE

(Millions of Gallons per Day)

	Coal	Oil	Gas	LWR	
Mining/Pumping	S	S	S	S	Mining
Fuel Processing	S	S	S	S	Milling
				S	Conversion
				S	Enrichment
				S	Fabrication
				S	Reprocessing
Waste Disposal	NA	NA	NA	NA	Waste Disposal
Transportation	NA	NA	NA	NA	Transportation
Power Plant Operation	720	720	720	1,162	Power Plant Operation
Totals	720	720	720	1,162	Totals

Basis: 1000 MWe Power Plant
75% Capacity Factor

S = Small
NA = Not applicable

TABLE 5.25

PROCESS WATER USE

(Millions of Gallons per Day)

	Coal	Oil	Gas	LWR	
Mining/Pumping	NA	2.8	S	NA	Mining
Fuel Processing	0.2	0.8	1.7	0.12	Milling
				S	Conversion
				0.14	Enrichment
				S	Fabrication
				S	Reprocessing
Waste Disposal	(1)	(1)	(1)	S	Waste Disposal
Transportation	NA	NA	NA	NA	Transportation
Power Plant Operation	3.8	1.2	1.2	0	Power Plant Operation
Totals	4.0	4.8	3.9	0.26	Totals

Basis: 1000 MWe Power Plant
75% Capacity Factor

S = Small
NA = Not applicable

(1) Included in Power Plant Operation

TABLE 5.26

OTHER WATER IMPACTS[1]

(Millions of Gallons per Day)

	Coal	Oil	Gas	LWR	
Mining/Pumping	14.2[2]	8.5[4]	NA	NA	Mining
Fuel Processing	31.9[3]	NA	NA		Milling
					Conversion
					Enrichment
					Fabrication
					Reprocessing
Waste Disposal	NA	NA	NA		Waste Disposal
Transportation	NA	13.2[4]	NA		Transportation
Power Plant Operation	NA	NA	NA		Power Plant Operation
Totals	46.1	27.7	NA	NA	Totals

Basis: 1000 MWe Power Plant
75% Capacity Factor

NA = Not applicable

(1) Water flows are equivalent volumes needed to dilute the impact to Federal water Quality standards.

(2) Acid mine drainage.

(3) Water wastes from coal cleaning plants.

(4) Oil spills.

upon the hazards to shipping rather than on factors related to oil consumption. Generally speaking, the items in this category are environmental impacts that may be caused by a given cycle, but are not willingly or routinely incurred by production of that fuel. Again, only volumes of water affected are compared, not severity of pollution.

The fourth category involves degradation of water quality by emissions of process wastes into water bodies. This category differs from the second category in that water is not used in the fundamental process, but rather serves as a receptor of wastes. Again, the number of potential chemical and radiological pollutants is great, and ultimate damage-function information is not available for each. Table 5.26A gives crude estimates of radioactivity releases to water. The units are in quantities released, in this case curies per year, rather than volume of water involved as in Tables 5.24 - 5.26. The estimates given in Table 5.26A are extremely crude and are presented only to permit order-of-magnitude comparisons of radiological sources in the alternate fuel cycles. The reader is admonished against misapplying the contents of this table. A valid comparison of radiological impacts of the various fuel cycles requires that each of a large number of radionuclides be treated separately. The decay losses, ultimate fates, pathways to man and other receptors, dose, and dose effects, associated with each radionuclide should be described mathematically in order to make valid comparisons. Also, improvements in radwaste system technology are expected to have a dramatic effect on radionuclide release rates.

Table 5.24 shows that cooling water use is negligible in the other steps of each fuel cycle compared to the requirement at the power plant. This fact can also be deduced from the energy efficiency description, Tables 5.8 and 5.9, which indicates that process heat and electricity consumption are small compared to the output of energy for each cycle. Since cooling requirements are proportioned to energy use, barring exothermic and endothermic processes in the fuel cycle, it follows that the most significant cooling water requirement would occur in that part of the cycle where the greatest energy consumption takes place, i.e., at the power plant.

Looking across the cycles, the fossil fuel plants all have similar water requirements that are roughly half the nuclear requirements. The similarity among fossil fuels arises because waste heat rejection and thus cooling water needs are determined by the design of the turbines, boilers, and steam system, which are practically identical for coal, oil, and gas. The systematic difference between LWR and fossil power plants is due in part to lower temperatures and thus lower thermal efficiencies

TABLE 5.26A

RADIOACTIVITY RELEASES TO WATER

(Curies per Year)

	Fossil			Nuclear		
	Coal	Oil	Gas	PWR	BWR	
Mining/Pumping	0	0	0			Mining
Fuel Processing	0	0	0	0.1	0.1	Milling - Fabrication
				400	400	Reprocessing & Transportation
Power Plant Operation	0	0	0	500	100	Power Plant Operation
Totals	0	0	0	~1,000	~500	Totals

Basis: 1000 MWe Power Plant
75% Capacity Factor

in LWRs. The fossil fuel plants also have an advantage in waste heat dissipation due to the fact that exhaust gases carry off heat up the stack.

5.7 ABATEMENT COSTS

Section 5.2 presented estimates of 1980 conventional energy costs for the alternative energy systems. Effort was made to exclude abatement costs, although it is frequently difficult to delineate clearly abatement measures or devices from the fundamental process or machine in question.

The purposes of this section are to present estimates of certain abatement costs, to compare these additional costs to the base conventional costs, and to compare the abatement costs of the competing energy systems (1980 dollars).

Abatement measures and devices may occur in a supporting fuel cycle as well as at the power plant. The abatement measures and devices considered here are those for which technical and economic data was available: cooling towers to dispose of waste heat at a power plant, SO_2 removal from coal-fired power plant stack gases, near-zero radwaste treatment systems for light water reactors, desulfurization of residual fuel oil, and reclamation of surface-mined land.

Tables 5.27 and 5.28 summarize the estimates of 1980 abatement costs in millinos of dollars per year and in mills/kWhe, respectively. In each of the energy systems, an increase in heat rate (decrease in net thermal efficiency) results from the installation of a cooling tower. Thus, more fuel is required to produce the same quantity of electrical energy. The economic effect of this penalty becomes more severe as fuel prices increase.

SO_2 removal from coal-fired plant stack gases incurs the dominant abatement cost in the coal energy system. Oil desulfurization is the major source of abatement cost in the RFO energy system. Sulfur is removed from natural gas at the processing plant, and thus sulfur abatement is already an internalized cost. Near-zero radwaste systems add little to the LWR system energy costs.

Tables 5.27 and 5.28 show that the coal energy system suffers the largest abatement cost, followed by the RFO energy system and the natural gas system. The light water reactor systems suffer the lowest abatement costs.

TABLE 5.27

ANNUALIZED ABATEMENT COSTS FOR 1000-MWe PLANTS

(10^6/year)

Abatement Measure	Type of Plant				
	Coal	RFO	Gas	PWR	BWR
.Cooling Towers					
Additional capital[a]	1.95	1.95	1.95	1.20	1.20
Additional O&M	0.36	0.36	0.36	0.45	0.45
Additional fuel[b]	1.28	3.60	4.74	0.78	0.78
Rounded Total	3.6	5.9	7.1	2.4	2.4
.SO_2 Removal					
Additional capital[a]	11.25	-	-	-	-
Additional O&M	13.04	-	-	-	-
Additional fuel[c]	1.60	-	-	-	-
Rounded Total	25.9	-	-	-	-
.Near-zero Radwaste					
Additional capital[a]	-	-	-	1.2	1.8
.RFO Desulfurization					
Additional fuel cost[d]	-	4.6-9.2	-	-	-
.Surface Mine Reclamation					
Additional fuel cost[e]	0.1-1.0	-	-	-	-
TOTALS	29.6-30.5	10.5-15.1	7.1	3.6	4.2

[a] 15% fixed charge rate and 75% plant capacity factor.

[b] Heat rate increase of 2%.

[c] Heat rate increase of 2.5%.

[d] 6.3×10^6 BTU/barrel @ 50¢/barrel and $1/barrel.

[e] 0.3 acres/1000 tons coal and 50% production from strip mines @ $300/acre and $3000/acre.

TABLE 5.28

ABATEMENT COSTS

(mills/kWhe)

Abatement Measure	Type of Plant				
	Coal	RFO	Gas	PWR	BWR
Cooling Towers	0.55	0.90	1.07	0.37	0.37
SO_2 Removal	3.94	-	-	-	-
Near-Zero Radwaste	-	-	-	0.18	0.27
RFO Desulfurization	-	0.7-1.4	-	-	-
Surface Mine Reclamation	0.04-0.4	-	-	-	-
TOTALS	4.53-4.89	1.60-2.30	1.07	0.55	0.64
Conventional Cost	18.4	35.2	43.0	18.5	18.5
Conventional + Abatement	23.1	37.2	44.1	19.1	19.1
Abatement Fraction	0.2	0.05	0.02	0.03	0.03