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MISSION ANALYSIS OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION
VOLUME 4

Supplementary Studies

By
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MASTER

December 1977
(TIC Issuance Date)

Work Performed Under Contract No. EY-76-C-03-1101

The Aerospace Corporation
Energy and Transportation Division
El Segundo, California

U.S. Department of Energy

Solar Energy

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MISSION ANALYSIS OF PHOTOVOLTAIC
SOLAR ENERGY CONVERSION

Volume IV

Supplementary Studies

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El Segundo, California

Date Published - March 1977

PREPARED FOR THE UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT
ADMINISTRATION
DIVISION OF SOLAR ENERGY
UNDER CONTRACT NO. EY76-C-03-1101
PROJECT AGREEMENT 8

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FOREWORD

This document constitutes the fourth volume of a four-volume final report on a study carried out under Contract No. EY76-C-03-1101, Project Agreement 8, "Mission Analysis of Photovoltaic Solar Energy Systems," for the Division of Solar Energy of the U. S. Energy Research and Development Administration. This volume covers the work on Task 3, Review and Updating of the ERDA Technology Implementation Plan; Task 4, Critical External Issues; Task 5, The Impact of Incentives; and Task 6, The Societal Costs of Conventional Power Generation. The other volumes in the report are: Volume I, Executive Summary; Volume II, Survey of Near-Term (1976-1985) Civilian Applications in the United States; and Volume III, Major Missions for the Mid-Term (1986-2000).

The study was conducted by the Energy Systems Group of the Energy and Transportation Division of The Aerospace Corporation. Dr. Leonard Magid, Acting Chief of the Silicon Technology Programs Branch, was the ERDA Program Manager for this contract, and Dr. A. B. Greenberg, General Manager of the Energy and Transportation Division, was the Principal Investigator. Dr. M. B. Watson is the Director of the Energy Systems Group, and Dr. S. L. Leonard, Director, Photovoltaic Projects, provided the program management.

This volume was prepared by Dr. S. L. Leonard, Dr. P. Breisacher, Dr. P. K. Munjal, and J. A. Neiss. The authors wish to express appreciation to J. R. Hallett for overseeing the production of the report.

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SECTION 1

OCCUPATIONAL AND ENVIRONMENTAL HAZARDS OF PHOTOVOLTAIC ARRAY PRODUCTION

1.1 INTRODUCTION

One of the dominant concerns of the American people and their government over the past several years has been the need to guarantee adequate supplies of energy to power the U.S. economy, both now and in the future. This concern, however, has arisen at a time when there is also widespread public awareness of (a) the need to prevent further deterioration of the environment in which we all must live and (b) the need to provide adequate protection of workers from the avoidable hazards of their jobs. It is therefore necessary, when any alternative source of energy is evaluated, to include in the assessment the possible environmental and occupational hazards that may be associated with its exploitation. The photovoltaic conversion of solar energy should not be an exception to this general requirement.

It was for this reason that a preliminary evaluation was made, as part of the Photovoltaic Mission Analysis study discussed in this report, of the environmental and occupational dangers that might result from the widespread use of photovoltaic systems. Although such systems are currently produced and used in a number of different applications, the total production volume is so small that little attention has yet been given to any hazards. If photovoltaic solar energy conversion is to make a significant contribution to the U.S. energy economy, however, array production will have to be increased enormously. The current ERDA goal is to achieve a production volume of 500 MW_{pk} of arrays per year by 1986 and to increase this to 50 GW_{pk}/year by the year 2000. At such production rates, any associated hazards could no longer be ignored.

The normal operation of a photovoltaic system should be quite benign, completely free of the problems associated with the emission of the

products of combustion of any fuel. The only occupational hazards resulting from plant operation would be those common to any electric power generation plant. However, since many of the chemicals required in the manufacture of photovoltaic arrays are hazardous and toxic, array production may well present more problems, and it is upon these problems that the main emphasis has been placed in the investigation reported here. Some attention has also been given to the somewhat related hazards that would be produced by combustion of an array in a residential or industrial fire. In these assessments, three different types of solar cells have been considered: silicon cells, cadmium sulfide cells (actually CdS/Cu₂S heterojunction cells), and gallium arsenide cells (GaAlAs/GaAs structures).

The following pages contain a discussion of the most significant problems associated with the production and deployment of photovoltaic arrays. The principal chemical compounds to be used in the manufacture of silicon, gallium arsenide, and cadmium sulfide photovoltaic arrays are discussed with respect to physical and chemical properties, sources of the raw materials required to extract or synthesize these materials, the methods of manufacture, storage and handling in large quantities, transportation restrictions, spills, leaks, ignition and explosion. A discussion of safety hazards associated with the finished products is followed by an analysis of the toxicological properties of all raw, refined, and finished chemical species involved.

1.2 SOLAR CELL FABRICATION DATA

1.2.1 Silicon Cells

The manufacture of silicon solar cells requires the availability of high purity silicon. Several processes are now being studied for the purpose of lowering the cost of making this metal. All of these methods involve the use of some highly sensitive and toxic materials. Although these materials have been safely handled by the industry for some time, occupational health regulations in the future may require further control of the work environment in order to preclude any long-term chronic exposures of employees.

Waste products from some of the processes are minimal and therefore should not inflict any damage to the surrounding air or water supplies. The little waste sludge that will be a by-product of some of the processes can be easily contained by standard scrubbing techniques. Catastrophic destruction of reactor vessels by rupture, fire or explosion could have a serious effect upon the worker and surrounding community. Adequate preparation must be made by each manufacturing complex to contain such releases by implementing proper emergency procedures.

The principal reagents used for silicon solar cell manufacture are silicon dioxide (SiO_2), silicon tetrachloride (SiCl_4), silicon tetrafluoride (SiF_4), and silane (SiH_4). On-site synthesis of these compounds may involve use of the halogens (Cl_2 , F_2 , I_2), the halogenated acids (HCl , HI , HF), hydrogen (H_2), magnesium silicide (Mg_2Si) and some other less reactive reagents. Some of the proposed purification systems may require the handling of reactive intermediates such as the silicon fluoride polymers $(\text{SiF}_2)_x$ and the chlorosilanes (SiH_xCl_y).

1.2.2 Gallium Arsenide Cells

Gallium arsenide (GaAs) solar cells are made by a variety of processes involving the reactions of arsenic and gallium compounds. Some of these synthesis techniques require the use of compounds of both elements, which are susceptible to rapid ignition and hydrolysis. Included among these compounds are the gallium alkyls, arsine, arsenic trichloride, and the elements themselves at elevated temperatures.

Gallium is a rare element principally found in bauxite and certain zinc bearing ores. It is a by-product of the aluminum and zinc refining industry. The chief sources of arsenic originate from copper and lead bearing bores. Demand for arsenic has not increased greatly during the past 25 years. The use of many arsenicals in the agricultural industry has declined because of potential hazards in application and removal of residuals from plant life.

The toxicity of Ga or its compounds is low. All arsenic compounds are well known poisons. GaAs itself has been reported to demonstrate little toxicity although insufficient work has been done to confirm this completely. GaAs is stable to hydrolysis and oxidation at room temperature; it only begins to oxidize when heated above 600°C.

1.2.3 Cadmium Sulfide Cells

The principal toxic material involved in the manufacture of cadmium sulfide solar arrays is the metal cadmium itself. The separation, processing, and purification of cadmium from zinc ores is the major source of cadmium emissions into the air and water. Because of the high toxicity of cadmium compounds, stricter control regulations are constantly being enacted by both federal and state agencies. The CdS solar cell manufacturing industry is likely to be faced with similar controls, especially with respect to occupational health regulations. In particular, special precautions will have to be taken to prevent release of any cadmium compounds into the work space. The high temperature vacuum deposition of cadmium or cadmium sulfide onto suitable substrates is likely to represent the single most hazardous step in the manufacture of these cells.

1.3 RAW MATERIALS - PROPERTIES, SOURCES, MANUFACTURING

A large-scale expansion of the manufacture of solar cells will involve the use of increased amounts of the primary reagents required to formulate these materials. Many of these have been handled or used routinely by the chemical industry for decades. Only the application is new. Despite this, it is necessary to determine whether a concentration of raw material manufacturing facilities will create a potential future hazard either within the industrial plant or, in case of accident, to the surrounding area. The basic raw materials needed to make the three types of solar cells are Cd, CdS, Si, Ga, As, and GaAs. If the projected 50 GW_{pk}/year in solar array production in the year 2000 is in the form of flat-plate silicon arrays,

roughly 120,000 tons/year of silicon would be required. If, instead, GaAs arrays are produced, and if (because of the higher cost of this material) these arrays are used with sunlight concentration systems with a concentration ratio of 1000:1, about 65 tons/year of GaAs would be needed. If flat-plate CdS arrays are produced, 9000 tons/year of cadmium would be needed. In making these estimates, material thicknesses of 100 μ (silicon), 50 μ (GaAs), and <5 μ (CdS) were assumed.

1.3.1 Production

Present U.S. production schedules for these basic substances are difficult to obtain. Limited data appearing below are extracted from the U.S. Statistical Abstracts and several editions of the Minerals Yearbook, formerly published by the Department of Interior.

Silicon. About 133,000 tons of silicon metal (not semiconductor grade) was made in 1973. Over 105,000 tons were consumed, leaving about 13,000 tons in stock at year end. Over 7600 tons of Si were imported in 1973, principally from Holland, Britain, and France. The estimated 120,000 tons needed for solar cell manufacture will, therefore, require a substantial increase in U.S. silicon production. Since silicon is one of the earth's most abundant elements, however, there is no fundamental obstacle to meeting the increased demand.

Cadmium. Practically all cadmium is currently obtained as a by-product of zinc recovery. The latest figures (1973) showed that U.S. production is gradually declining due to a reduction in zinc refining. A total of 3714 tons of cadmium was produced and 6228 tons consumed in this year. Imports accounted for 1946 tons and 385 tons were sold from government stocks. Production of cadmium sulfide was 1412 tons. The average price of Cd was \$4/lb, and the U.S. stockpile of Cd at the end of the year was 4242 tons. Canada was the principal source of imported Cd; others in declining order include Mexico, Australia, Belgium, and Peru. World production was 18,800 tons, the U.S. being the largest manufacturer (20% of the world) while consuming 33% of the world production. The projected requirement for

9000 tons/year in 2000 would greatly strain U.S. and world supplies. Major increases in refining capacity would have to be created.

Gallium. Production figures for 1973 are not available. However, consumption was ~9 tons and imports totaled ~12 tons. Domestic production is, therefore, not nearly sufficient to meet demand. 98% of the metal is utilized in the electronics industry. Year-end stock of Ga metal was about 2.2 tons. The total production of GaAs was 10 tons in 1973. The price for Ga was \$0.75/gram in large quantities. Principal foreign sources are Canada, Holland, and Switzerland.

Arsenic. In 1968 the world production of arsenic was 56,000 tons. U.S. production figures are unavailable but are believed to be very low today. The small amount of As required for GaAs cells should be available from domestic sources.

1.3.2 Sources, Properties, Synthesis

1.3.2.1 Silicon Solar Cells

The principal compounds or elements presently being considered as basic building block chemicals for solar cell manufacture will be briefly surveyed with regard to those physical and chemical properties which may be pertinent in their present application. The primary ingredients presently being considered for silicon solar cell manufacture include silicon metal, silica, silicon tetrachloride, silicon tetrafluoride, silane, carbon black, iodine, chlorine, hydrogen fluoride, zinc metal, and zinc chloride.

Silicon (Si) is the second most abundant terrestrial element (27.7%). It is not found in the free state. The usual source is either in the form of silica (SiO_2) or silicates (M_2SiO_3) or (M_4SiO_4), M representing an alkali metal. Some of the principal uses include the manufacture of ferro-silicon alloys for deoxidizing steel for casting, for inclusion in cast iron, and for making corrosion-resistant alloys. Another major use is for silicon steel laminations in electric motors and transformers. Silicon for these applications is usually made from silica (quartzite or quartz) and coke by

heating in an electric arc furnace. This material is not of the highest purity. To obtain ultrapure Si several other processes have been used. One involves the direct reaction of scrap silicon with chlorine to form silicon tetrachloride (SiCl_4) which is subsequently reduced to Si by zinc or magnesium, both of which have been purified prior to use. The ZnCl_2 and MgCl_2 are evaporated from the product mixture to leave a spongy mass of very pure Si.

Silicon is a hard, brittle metal which does not react with any of the halogen acids (HF , HCl , HBr , HI) at room temperature. Concentrated sulfuric acid (H_2SO_4) will slowly oxidize Si at room temperature. If finely divided Si is contacted with hot concentrated nitric acid (HNO_3), then a rapid oxidation will occur. The halogens (Cl_2 , F_2 , Br_2) have varying reactivities toward Si. Liquid Br_2 , Cl_2 and F_2 will not react with Si. Gaseous F_2 will vigorously attack Si at room temperature to form SiF_4 . Both Br_2 and Cl_2 gas will react with Si at elevated temperatures to form SiCl_4 and SiBr_4 , respectively. Hydrogen will not react with Si at even moderate (up to 500°C) temperatures. Si will react with alkali metal hydroxides to form silicates (M_4SiO_4) with the release of H_2 . Chlorosilanes (SiH_xCl_y) are formed when Si reacts with H_2 and HCl at moderate ($300\text{--}400^\circ\text{C}$) temperatures. Reaction of Si with SiCl_4 at high (1000°C) temperatures results in the formation of higher silicon halides (Si_2Cl_6 , Si_3Cl_8 , $\text{Si}_4\text{Cl}_{10}$). Silicon will react with most alkali or alkaline earth metals to form silicides (M_2Si).

Silica (SiO_2) is the most abundant form of combined silicon on earth. The principal minerals (quartz, tridymite, cristobalite) have high melting and boiling points. No reaction occurs with the halogen acids or halogens except fluorine. With 40% HF , SiO_2 dissolves and reacts to form SiF_4 and H_2SiF_6 (fluorosilicic acid). Fluorine will react with well dried glass after an induction period. The only reactions of significance are those with melted alkali metal hydroxides or carbonates to form the alkaline metal silicates (M_2SiO_3). Metal oxides, in general, will react with SiO_2 at elevated temperatures to form different glasses.

Silicon tetrafluoride (SiF_4) is a non-flammable gas (b.p., -85°C) with a pungent odor. It is hydrolyzed slowly to form fluorosilicic acid (H_2SiF_6). It is stable to an electric spark and will not react with hydrogen or oxygen at ordinary temperatures. It will react with silicon tetrachloride at elevated temperatures to form mixed halide derivatives (SiF_xCl_y). Thermal decomposition does not occur at temperatures below 2000°C . It is prepared industrially by a variety of methods. In one process SiF_4 is a by-product in the treatment of phosphate rock [apatite, $\text{Ca}_5(\text{PO}_4)_3\text{OH}$] with sulfuric acid during the manufacture of phosphate fertilizer. Another common process involves the reaction of SiO_2 and concentrated H_2SO_4 with a reactive fluoride such as calcium fluoride (CaF_2). More direct methods involve the reaction of elemental Si with anhydrous HF at moderate temperatures and the reaction of SiO_2 with concentrated aqueous HF.

Silicon tetrachloride (SiCl_4) is a non-flammable liquid (b.p., 57°C) with a similar odor to SiF_4 . It will hydrolyze very quickly in liquid H_2O to form fluorosilicic acid. It is unreactive to H_2 or O_2 at room temperature. The principal industrial process for manufacturing SiCl_4 involves the high temperature (1250°C) reaction of silicon carbide (SiC) and chlorine. Other methods include the direct chlorination of the silicide (M_2Si) or silicon metal with chlorine. One of the principal uses of SiCl_4 is the synthesis of silane (SiH_4). In this reaction SiCl_4 is reacted with lithium aluminum hydride (LiAlH_4) in a solvent (ether). By-products include lithium chloride (LiCl) and aluminum chloride (AlCl_3). Another common industrial process involves the reaction of SiO_2 with Mg to form the silicide Mg_2Si which is easily hydrolyzed to SiH_4 .

Silane (SiH_4) is a colorless gas (b.p., -111.8°C) which is spontaneously flammable in air or oxygen. It will hydrolyze rapidly to form silicic acid. It is far less stable than the corresponding hydrocarbons. It will decompose slowly at 300° when heated in the absence of O_2 or air. Decomposition to higher silanes and H_2 occurs on silica gel between 300 and 500°C . Above 500°C pure silicon is formed. SiH_4 can even be oxidized by

weak oxidizing agents such as methanol. It is a powerful reducing agent capable of reducing potassium permanganate (KMnO_4) to manganese dioxide (MnO_2) and mercury and silver salts to the elements. SiH_4 is readily chlorinated by HCl with the evolution of H_2 . The slightest trace of alkali in the presence of water decomposes SiH_4 to H_2 and hydrated silica.

The halogens and halogenated acids are either reactants or reaction products in many of the processes proposed. The halogens are the most reactive of all non-metallic elements. They will combine with a great number of substances and are used by the chemical industry in large quantities to make many thousands of compounds. Hydrocarbons can be halogenated and serve as insecticides (DDT), cleaning fluids (perchloroethylene), refrigerants (Freons), fumigants (methyl bromide) and fire extinguishing agents (Halon). All of the halogens are corrosive and have strong irritating odors. None of them will burn, but fluorine is such a powerful oxidizer that it will cause the spontaneous ignition of combustible materials, especially organic compounds. Fluorine is a pale yellow gas which can vigorously attack glass and most metals. Reaction with H_2O yields O_2 and HF . Hydrogen will combine with F_2 violently. It will also react rapidly with other interhalogen compounds such as IF_5 or BrF_3 .

Chlorine is by far the most widely used halogen. It is produced by the electrolysis of sodium chloride (NaCl). It is used to manufacture a vast array of chemical compounds. Chlorine has a pungent, irritating odor. It liquifies under a moderate pressure, or when cooled to -30°F to a greenish yellow corrosive liquid. It can form explosive mixtures with many flammable gases, ether, hydrocarbons and metal powders. In sunlight it will combine explosively with acetylene. It will react with H_2O but not as fast as F_2 .

Bromine (Br_2) is a liquid at room temperature. The reddish-brown fuming liquid has a harsh suffocating odor. Br_2 is a strong oxidizer, capable of causing ignition of organic matter upon contact. It will attack metals, alkali bases, arsenates and mercury salts. It will react with water and ammonia; the latter can sometimes be used to neutralize escaped Br_2 .

Iodine (I_2) is less violent than the other halogens in its chemical activity. It can react with certain hydrocarbons and ammonia. In the presence of moisture it will attack metals. The vapor is extremely irritating and toxic.

The halogenated acids (HF, HCl, HBr, HI) are all non-flammable and do not cause significant heating and ignition of combustible materials. They do react with many metals with the release of hydrogen. All four acids are clear, colorless to yellowish liquids which fume strongly, especially in moist air. They all have pungent, irritating odors. All are quite soluble in H_2O . Hydrofluoric acid (HF) is used extensively to pickle copper, brass, and stainless steel. It is also used for polishing, etching, and frosting glass. HF is made from the reaction of calcium fluoride with sulfuric acid. Production in the U.S. is over 300,000 tons annually. Hydrochloric acid (HCl) is produced by the reaction of NaCl and H_2SO_4 at high temperature. A more popular process involves the chlorination of organic compounds with Cl_2 . HCl is used to activate oil wells and to manufacture vast quantities of inorganic and organic chlorine containing compounds. Other uses include the refining of metal ores, the preparation of starches and proteins in the food industry, and the removal of scale from metals.

Zinc (Zn) and zinc chloride ($ZnCl_2$) are both highly stable innocuous chemicals commonly used without any outstanding reactivity of note.

Many of the reagent compounds to be used in the manufacture of silicon solar cells have physical and chemical properties which make them quite sensitive or reactive to temperature or exposure to air or moisture. Adequate knowledge of the characteristics of each of these materials should be made available to workers using these substances. All of the chemicals have been utilized in large quantities for a long time by other industries with no significant problems.

1.3.2.2 Cadmium Solar Cells

Cadmium chemicals required are cadmium metal (Cd), cadmium sulfide (CdS) and cadmium oxide (CdO). Cadmium is a rare element in the earth's crust, and the metal is made as a by-product of zinc manufacture. Cadmium is soluble in most acids and bases and oxidizes slowly in moist air. Rapid oxidation occurs in steam when the metal is at red heat. Cadmium will also ignite in air, if moderately heated, to form CdO.

Cadmium sulfide occurs in the mineral greenockite. When heated, the pure CdS begins to sublime at 1000°C and melts at 1750°C. It is only slightly soluble in water.

None of the Cd compounds are sensitive to air or moisture. Reactivity with most common acids or bases is not great. The overall problem associated with the Cd compounds is with their toxicity, which will be discussed later.

1.3.2.3 Gallium Arsenide Solar Cells

The principal chemicals required to produce gallium arsenide solar cells include arsenic, arsine, arsenic trichloride, gallium, gallium alkyls $[\text{Ga}(\text{CH}_3)_3]$, $\text{Ga}(\text{C}_2\text{H}_5)_3$, phosphine, germanium, and tantalum oxide.

Arsenic (As) is found in the form of the sulfide, oxide, or intermetallic sulfide. The most common mineral is a mixed sulfide, FeAsS (mispickel). It is industrially produced by heating this sulfide, the As being separated by sublimation from the FeS. Arsenic occurs in several forms. Yellow arsenic is the least stable; grey arsenic is the common, most stable form. The vapor consists of As_4 molecules which are stable to 800°C when they begin to break up to As_2 . Arsenic will oxidize only at elevated temperatures and is stable to water. At high temperatures in a vacuum As will react with most metals and some non-metals. It will also dissolve in molten alkali to form arsenates. The latter compounds represent one of the principal uses of As - the manufacture of pesticides and defoliants.

Arsine (AsH_3) is a colorless gas (b.p., -62.5°C) that decomposes slowly at room temperature. In the presence of As metal decomposition

is much more rapid. It is slightly soluble in water and some organic solvents. It is a strong reducing agent that is capable of precipitating metals from salts in solution. A common industrial process for manufacture is the reaction of arsenic trioxide (As_2O_3) with NaOH and potassium borohydride (KBH_4).

Arsenic trichloride (AsCl_3) is a colorless liquid (m.p., -13°C) that is reasonably stable in the presence of moisture and O_2 . It is principally prepared industrially by the reaction of As with Cl_2 in an inert atmosphere or by the reaction of As_2O_3 with HCl at elevated temperature. AsCl_3 will react with other arsenic halides (e.g., AsF_3) to form mixed halides.

The largest source of gallium (Ga) is the mineral germanite. This is a complex metallic sulfide which contains 0.1 → 0.8% Ga. It is also found in the aluminum-bearing ore bauxite. Germanite is one of the main zinc ores and is used for extracting and refining this metal. Therefore, Ga is produced as a by-product in the aluminum and zinc refining industries.

Gallium is a peculiar metal with a very large liquid temperature range. It has a very low melting point (29.6°C) and very high boiling point (2270°C). Cold air will not affect Ga, no oxide film will form, but it will burn to Ga_2O in air at high temperatures ($>1000^\circ\text{C}$). It is attacked by hot nitric and concentrated HF and perchloric (HClO_4) acids. The halogens (except I_2) will react with Ga at room temperature. An interesting series of compounds is formed when Ga is heated with sulfur, selenium, tellurium, phosphorus, arsenic and antimony. Ga is quite corrosive at high temperatures since reaction with most other metals occurs under these conditions. Gallium trimethyl $\text{Ga}(\text{CH}_3)_3$ is a colorless liquid (m.p., -16°C) that is very unstable in the presence of moisture or oxygen. Spontaneous ignition occurs in air at temperatures well below zero. Hydrolysis results in the formation of complexes such as $\text{CH}_3\text{Ga}(\text{OH})_2$. The compound is industrially manufactured by the reaction of Ga with dimethyl mercury $(\text{CH}_3)_2\text{Hg}$ or gallium chloride (GaCl_3) with the Grignard reagent (CH_3MgBr).

Gallium triethyl $\text{Ga}(\text{C}_2\text{H}_5)_3$ is a liquid quite similar to the methyl derivative. Properties are identical especially with respect to moisture and oxygen sensitivity. It is prepared industrially by reacting GaCl_3 with triethyl-aluminum $[(\text{C}_2\text{H}_5)_3\text{Al}]$ and potassium chloride (KCl).

Phosphine (PH_3) is a gas (m. p., -133°C) that is not particularly sensitive to oxygen or moisture at room temperature. Despite this, precaution must be observed when PH_3 and O_2 are present at reduced pressures to prevent explosion of the mixture. Phosphine is only slightly soluble in water. The gas is usually made by heating phosphorus in a strong alkaline solution or by heating phosphorus acid in the absence of water.

Germanium (Ge) is, like gallium, a by-product of zinc refining. Small quantities (0.17%) are found in the mineral germanite. It is prepared by acid leaching the germanium from the mineral, converting the precipitated germanium oxide (GeO_2) to germanium tetrachloride (GeCl_4) followed by reduction of the latter to Ge metal with H_2 . Germanium absorbs gases strongly, especially H_2 , CO , and H_2O . Organic halides attack the metal to form alkyl-germanium halides. Dry HCl at high temperatures reacts with Ge to form GeCl_4 and hydrohalides GeH_xCl_y . Hydrogen sulfide will attack Ge at elevated temperatures ($>400^\circ\text{C}$) to form germanium sulfide (GeS_2). Concentrated sulfuric acid only slightly attacks Ge.

Most of the arsenic-containing compounds employed as reagent chemicals in the manufacture of GaAs solar cells are relatively stable to air and moisture. Reactivity to strong acids or bases is minimal. The alkyl derivatives of Ga are typical hypergolic compounds that will also react with moisture. Minimal problems should occur during the use of these chemicals although a careful accounting of all arsenic should be made to avoid unplanned dispersal in the workplace.

1.4 RAW MATERIALS - STORAGE, HANDLING, TRANSPORT

1.4.1 Storage

Many potential hazards are associated with the storage of the compounds to be used for manufacturing solar cells. A thorough knowledge

of the properties of each chemical can assist in planning a safe method of stockpiling these materials. Consideration must be given to the long-term stability of each compound in order to establish the allowable chemical storage time limits. Chemicals should be separated according to flammability, explosive nature, oxidizing power, corrosiveness, and water sensitivity. SiCl_4 , SiF_4 , SiI_4 , HCl , HF , AsCl_3 , GaCl_3 should be stored in cool, dry, well ventilated areas. Provision for neutralizing escaping vapors (nominally HCl) should be provided within the storage area. Safety showers, eye wash fountains, and other required protective equipment should always be operable for personnel handling these substances. Solid, toxic irritants, often present in a finely divided form include As_2O_3 , CdO , CdS , and the elements As and Ge . Dust control is a necessary precaution in their safe handling. This requires proper exhaust ventilation and proper protective clothing for workers handling these materials. When absorption through the skin is possible, protective creams are sometimes applied. Careful instructions as to their removal should be transmitted to all personnel. Spontaneously flammable chemicals such as $\text{Ga}(\text{CH}_3)_3$, $\text{Ga}(\text{C}_2\text{H}_5)_3$, or SiH_4 should be very carefully stored in cool areas away from heat or electrical sparks. A fire hazard exists when any compound has sufficient volatility to mix rapidly with air in ignitable proportions. The degree of hazard depends upon its ease of ignition and whether an explosive mixture can be formed. Decomposition products from these three flammable liquids are not especially toxic although protective masks may be necessary precautions in handling these materials to prevent inhalation of finely divided particles.

All of the halogenated acids should be stored away from oxidizers and highly flammable materials. Acids can be oxidizing agents, increasing the likelihood of ignition and the intensity of a subsequent fire when they contact combustible materials. The release and ignition of hydrogen gas upon contact of a halogenated acid with certain metals is an example of a secondary ignition caused by the products of a reaction. HF presents special problems in storage and handling due to its high reactivity with glass,

wood, most metals, and concrete. Special containers are specified for HF at various concentration levels. For example, when liquid HF of over 70% concentration is present the inside container must be of natural rubber, polyethylene, lead, or any other material resistant to the acid.

The halogens are an extremely reactive group of chemical compounds. Storage of these materials must be carefully planned. Fluorine, the most powerful oxidizer, should be stored in an area where there is no possibility of physical damage, no sources of heat, and no other chemical stored. It is best kept by itself in an isolated, locked, well ventilated, concrete room. Bromine should be stored in a cool, dry, isolated area separated from combustibles. Since bromine has a narrow liquid range (20-138°F) the storage temperature should be controlled to stay above freezing, yet well below temperatures that would increase the vapor pressure. Chlorine should be stored in an out-of-doors, open-ended metal building away from traffic areas with no combustibles or reactants in the vicinity.

Storage of significant quantities of reagent chemicals required for the manufacture of solar cells presents some serious hazards if not properly performed. Many industries (among them the electrochemical and semiconductor companies) have had long experience in storing these materials. No defined problems should occur if proper procedures adopted from previous experience are used.

1.4.2 Handling

The use of large amounts of the halogenated acids requires common sense precautions which are usually observed in any industrial environment. Protective clothing such as rubber or plastic aprons, gloves, and gas-tight chemical safety goggles plus acid-resistant clothing should be worn by personnel transferring these materials to reactors or process streams. Gas cylinders should always be protected from foreign material suck-back by a check valve, vacuum break, or trap since this might cause the development of excessively high pressures in the cylinder. When handling HF

transfers, workers should be protected by full coverage clothing at all times. Special emphasis should be made to make sure all protective equipment is not subject to HF attack in case of leakage. Discharge of HF into an open vessel should never be attempted. Direct application of heat to a cylinder for the purpose of accelerating discharge rates is not advised.

The halogens should all be handled with full protective clothing if large quantities are to be transferred to a reaction vessel. A gas mask suitable for the particular halogen being handled should be provided for use in case of emergency. Fluorine transfers should be handled with remote-valves, preferably those that can be actuated by extension handles passing through a suitable barricade. Regulators or double valving should be employed near the source of high pressure fluorine in order to reduce pressure safely. The latter precaution is especially important when large quantities of F_2 are to be used. All equipment with which F_2 is to come in contact should be thoroughly cleaned, degreased and dried, then treated with increasing concentrations of fluorine gas so that any impurities may be burned out without the simultaneous ignition of the equipment. Neoprene is an excellent protective material for gloves or clothing since it is also resistant to films of HF which would be formed as escaping F_2 is hydrolyzed by water. Any apparatus which contains fluorine must be thoroughly purged with an inert gas and pumped out prior to transferring F_2 . Large transfers of F_2 require the installation of purge towers, which might include a fluorine-hydrocarbon-air burner, scrubber and stack. A soda-lime stack followed by a drier should be included in the vacuum line to remove traces of fluorine that might enter the vacuum pump. Special study of the literature and consultation with the producer of F_2 should be done prior to designing any F_2 handling facility. The other halogens are all somewhat less hazardous with respect to explosiveness and toxicity but, as mentioned earlier, should be handled with adequate precautions.

The hypergolic compounds SiH_4 , $Ga(CH_3)_3$, and $Ga(C_2H_5)_3$ must all be handled with great care to keep away from air or water. Transfer

lines must be continuously checked for leaks in order to prevent ignition or explosion within the apparatus. All should be stored at positive pressure. SiH_4 should never be condensed. Liquid and solid SiH_4 have caused serious accidents. Transfers must be made with caution to apparatus that previously contained any halogen or halogenated compound. Traces of halogen will explode violently with SiH_4 . All equipment used to handle SiH_4 should be grounded to protect from electric sparks. The halides AsCl_3 , SiCl_4 , and SiF_4 should be handled using protective clothing. They are quite corrosive and generally can form halogenated acids or fluorosilicic acids upon hydrolysis. It is best to handle SiF_4 in the same way as HF . Special precautions must be observed to make sure all lines are free of moisture prior to use. The oxidation products (As_2O_3 , Ga_2O_3 , SiO_2) are probably quite finely divided; therefore, precautions should be exercised to prevent touching surfaces that have been dusted by these materials or to protect all workers with readily available face masks designed to capture these substances prior to inhalation. The solid reagents As , As_2O_3 , CdO , Ta_2O_5 , and CdS should be handled in clean environments, especially the highly toxic CdO and As_2O_3 . Adequate precautions should be exercised to prevent As_2O_3 from contacting strong acids or heat since some of the products of reaction can be absorbed through the skin.

The safe handling of most of the reagent chemicals to be used for the manufacture of photovoltaic cells requires establishment of strict rules designed to protect the worker from injury. Many of the chemicals have been safely used by industry in large quantities for decades. Some, such as GaAs or the Ga alkyls, are not so well tested in use and must be carefully utilized initially. No major overall problems should occur if proper precautions are taken in handling these chemicals.

1.4.3 Transportation

Many of the raw materials for solar cell production are clearly restricted as to how they may be packaged or transported. The restrictions are in most cases not new and have been in effect for a considerable number

of years. Recently, the Department of Transportation* has more formally outlined the exact procedures to be adopted for a large number of potentially hazardous compounds. Some of the chemicals to be used in the solar cell industry come under these regulations. Compounds are classified according to hazard class, required labeling, any exceptions, packaging requirements, and maximum allowable quantities in single air and water shipments. As_2O_3 , for example, is classified as a poison which must be packaged in such a way that the actual container is adequately cushioned to prevent breakage. The size or amount of As_2O_3 in a single package is limited depending on what mode of transport is chosen. In large shipments it might be shipped in collapsible rubber containers not over a certain total volume. Commercial aircraft shipments are restricted in size depending on whether a passenger or all-cargo flight is used. Arsine (AsH_3), for example, is forbidden on passenger aircraft as are all poisonous and flammable compounds. This distinguishes As_2O_3 from AsH_3 in that the former is a poison that is not subject to spontaneous ignition. AsCl_3 and As are subject to the same restrictions as As_2O_3 . SiF_4 is classified as a non-flammable gas that is forbidden on passenger aircraft and must be kept removed from foodstuffs. SiCl_4 is labeled as a corrosive material and cannot be carried in glass containers on certain public carriers. All of the halogenated acids are also labeled as corrosive materials. None of the halogens can be carried on commercial passenger aircraft. Although not specifically mentioned, it is doubtful that free access to public carriers would be allowed for gallium alkyls or cadmium compounds.

1.5 RAW MATERIALS - SPILLS, LEAKS

The substances to be used within the solar cell manufacturing industry generally are a group of compounds which if suddenly released within a working area would present moderate to severe occupational

*Department of Transportation, Materials Transportation Bureau, Hazardous Materials Regulations Federal Register, Thursday, April 15, 1976.

health hazards to the employees. Extensive venting into the surrounding area in the majority of cases is not allowed for the protection of the lives and property of the citizens in the surrounding community. Therefore, it is important that proper attention be paid to applicable air and water pollution rules when accidental release of these compounds occurs within an industrial plant.

The Safety and Fire Protection Committee of the Manufacturing Chemists Association has outlined specific procedural methods for the safe disposal of hazardous chemicals which are spilled or are leaked into the atmosphere. Over 1200 chemicals have been listed. Additional compounds are continually being added. Categorization of disposal procedures by chemical classes offers a means by which information can be obtained on the disposal of chemicals not specifically listed. In addition to the normal fire and explosion hazards of flammable liquids and their vapors and the expected hazards of toxic materials, certain other hazards must be anticipated in waste or spill disposal. Some materials are corrosive to piping or exhaust ducting when drained or vented. Disposal by these routes would often be in violation of air and water pollution standards. Pretreatment procedures for the cleanup of hazardous, toxic materials are designed to convert them to less toxic, or lower vapor pressure, substances.

Many of the chemicals to be used in this industry would probably present major problems if spilled in large quantities. For example, the silicon halides if released in large quantities would present a basic problem in control of the hydrolysis products HF and HCl. A SiCl_4 spill can be rapidly neutralized by covering with sodium carbonate (Na_2CO_3) followed by addition of ammonium hydroxide (NH_4OH). The whole area should be covered with crushed ice until evidence for the formation of ammonium chloride (NH_4Cl) has ceased. A SiF_4 leak should be shunted if possible into a neutralizing mixture of potassium hydroxide (KOH) and calcium oxide (CaO). A leaking tank valve should be immersed in a mixture of vermiculite and Na_2CO_3 followed by mist spraying with water. SiH_4 presents significant problems when

leakage develops. Since it is flammable the first thing to do is to remove any ignition sources. Attempts should be made to flush the leaking area with an inert gas if ignition has not occurred. Removal to a vented area for repair or disposal is recommended but not always possible. To prevent ignition it is necessary to have available some rather well-dried sand which could be used to smother the leak followed by spraying with a mixture of butyl alcohol, H_2O and dilute HCl to rapidly hydrolyze the SiH_4 without ignition. Widespread dispersal of fine dusts of toxic materials such as As , Cd , CdO , or As_2O_3 present significant hazards to all persons within the affected area until cleanup has occurred. The danger of inadvertent physical or foodstuff contact with contaminated surfaces must be avoided. Specific decontamination procedures for each compound must be carefully prepared if large quantities of these substances are to be used.

The OSHA regulations presently being enforced in all industrial plants will closely control the manner in which many of the reagent chemicals must be used to prevent escape into the plant or surrounding area. Special procedures must be planned in advance to suppress major leaks or spills of most of the compounds to be used and continual air and water monitoring of the workplace may be required for specific chemicals for the protection of the employee. The toxic nature of many of these chemicals will probably require tightening of safety procedures within the industrial plant in the future. Specific requirements for particular compounds (especially As - or Cd -containing substances) will no doubt be changed as experience is gained in allied or other industries also using such materials. Potentially the CdS solar cell industry will be most significantly affected by these safety measures.

1.6

RAW MATERIALS - FIRE, EXPLOSIONS

Combustion of the basic starting materials for solar cell manufacture creates some additional problems which may not be present during spills. Attention must be paid to the physical and chemical nature of the reaction products: are they more or less hazardous than the original compounds

and can these materials be properly disposed of without danger to employee or firefighter? Although many compounds are described as non-flammable, it is usually necessary to attempt to evaluate their behavior under general conflagration conditions in order to prepare adequate emergency procedures. The thermal stabilities of most compounds are usually such that under the hostile environment of a general fire some decomposition will occur even if reaction with air or water is ordinarily minimal. The possibility of explosion of reagent containment vessels, tanks, or lines is probably the most serious hazard, creating the additional problem of limiting the dispersal of large amounts of unreacted compound. One partial solution to major releases of a compound due to fire-related explosions is to disperse the storage vessels and to keep individual sizes to a minimum. This is not always possible in many industrial processes. The principal reagents dealt with here present a complex problem with respect to fire safety. The hypergolic compounds AsH_3 , $\text{Ga}(\text{CH}_3)_3$, and $\text{Ga}(\text{C}_2\text{H}_5)_3$ have well defined combustion products (As_2O_3 and Ga_2O) which can be adequately protected against by use of gas masks while fighting the fire and cleaning up afterwards.

It must be kept in mind that combustion characteristics and reaction products can be vastly different if several compounds are in contact with each other during a fire. Careful consideration of storage compatibility with respect to behavior in case of fire should be determined, as well as the usual criteria of direct interaction with each other. For example, As_2O_3 should never be stored near any halogenated acid or a compound which might, when thermally decomposed, release a halogenated acid. The reaction of As_2O_3 with HCl is a standard manufacturing procedure for AsCl_3 . The silicon halides will probably not burn to completion in an actual fire, instead forming a series of oxyhalosilanes whose properties are not well defined with respect to safety and stability. The elements As, Si, Ge, Ga, and Cd will oxidize to a certain extent under fire conditions resulting in the dispersal of large quantities of probably quite finely divided oxides. The release of halogens or halogen-containing compounds at elevated temperatures could result

in the formation of the highly toxic carbonyl halides such as COCl_2 (phosgene). Many gases such as Cl_2 are stored in tanks which have pressure relief valves designed to open up at elevated temperatures to prevent explosion. This does not eliminate the problem of release of large quantities of gas into the plant area and surrounding community. Chlorine is 2.5 times as heavy as air and will tend to settle down in low-lying areas. This makes an especially hazardous situation and constitutes an emergency of the first magnitude. Fluorine releases can usually initiate a fire since this most powerful oxidizer will ignite almost any organic material. It can even oxidize oxygen to the fluorine oxide. Massive water quenching of fluorine releases and fires is necessary to reduce the hazard to that of HF .

Most of the chemicals to be used in this industry are quite dangerous to health if subjected to exposure to fire or explosion. Indirect spillage or gaseous release caused by explosion can present a severe decontamination problem if the facilities are to be restored for use. Combustion of certain compounds (especially arsenic and cadmium compounds) can release toxic quantities of finely divided, respirable particles of the respective oxides, which not only threaten the fireman and worker, but possibly the surrounding community and agricultural growing crops. The CdS faces the most strict enforcement procedures for the prevention of accidental fires and explosions.

1.7 FINISHED PRODUCTS - GENERAL HAZARDS

1.7.1 Silicon Cells

The silicon solar cell is the simplest of the devices being considered for photovoltaic power generation. The active doped Si is usually covered with an antireflective coating [e.g., silicon monoxide (SiO) and titanium oxide (TiO_x) and tantalum oxide (Ta_2O_5)] and the contact system is made from various metal alloy materials. These substances are basically non-toxic although the final composition of the covering substances and the antireflective coatings may alter this picture. Upon heating, it is remotely

possible that some metal oxide vapors may be released. Catastrophic destruction of a large panel of silicon cells could generate respirable concentrations of the silicon oxides and other metal oxides.

1.7.2 Cadmium Sulfide Cells

The principal constituents of the cadmium sulfide solar cell consist of an outer protective layer which may be made from such materials as mylar, aclar, or teflon, copper sulfide (Cu_2S) and cadmium sulfide (CdS) as the p- and n- semiconducting layers followed by a metallic contact layer (silver, molybdenum, etc.) and a substrate such as alumina or in place of these two layers, a metallized plastic support structure such as Kapton or a metal-coated glass. Collector electrodes are commonly made from copper and zinc. The uncertainty in the identification of the component parts of the CdS solar cells makes it difficult to predict the possible harmful effects of ingesting a portion of a complete cell. Cadmium sulfide itself is naturally toxic and as was noted earlier has a strong emetic effect. Therefore, under ordinary circumstances the occurrence of such an accident should result in rapid regurgitation of this material. Failure for this to occur may be very dangerous to an individual. The other components do not appear to be especially hazardous although the variety of proposed compositions must be carefully studied before a clean bill of health can be rendered. Upon heating, the CdS is even more hazardous since it may oxidize to CdO and be inhaled as well as ingested. The thermal decomposition of protective or substrate plastic layers such as teflon, aclar or Kapton may create hazardous gaseous species. Also, little is known about the possible irritative or toxic effects of various metal oxide fumes (other than Cd) such as might be present if the cells were accidentally exposed to high temperatures.

1.7.3 Gallium Arsenide Cells

The complete solar cell will contain other materials besides the small amount of GaAs . These may include tantalum oxide (Ta_2O_5) as the antireflection coating, a semitransparent metal and interfacial oxide layer

such as gold (Au) and the oxide (Au_2O), a substrate such as germanium metal (Ge), and a backing electrode (steel, metal-coated glass). None of these materials are toxic in their stable unheated, unreacted form. Accidental ingestion of any or all materials contained in these cells should not result in anything more than mild, temporary gastrointestinal disorders. If GaAs is heated, inhalation of the oxidation product (As_2O_3) is very hazardous. Also, it is not known what effects will be observed if any other oxides are inhaled in large quantities although none are thought to be highly irritating to the respiratory system.

Accidental ingestion of portions of any of the three types of solar cells should not present a major medical emergency except possibly in the case of CdS, although the latter is a relatively benign poison when compared with CdO. Proper emergency procedures should include stomach emptying or inducement of regurgitation.

1.8 FINISHED PRODUCTS - SPECIFIC FIRE AND EXPLOSION HAZARDS

1.8.1 Silicon Cells

Principal combustion products generated by the large-scale deflagration of silicon solar cell arrays include silicon monoxide (SiO) and dioxide (SiO_2), possibly silicic acids, titanium oxide (TiO_2), and tantalum oxide (Ta_2O_5). Finely divided silicon dioxide is the only major hazard created. Deposition of all of these compounds on plants or water supplies creates no problems. Only inhalation of finely divided ($< 10 \mu$) SiO_2 is dangerous to man. Proper protective respiratory masks should be worn by emergency personnel. An explosion not accompanied by fire should present no toxicological hazards. Little hazard is anticipated if silicon cells are accidentally burned or exploded.

1.8.2 Cadmium Sulfide Cells

Combustion of a large CdS solar cell array can result in the release of considerable quantities of CdO. The latter if inhaled presents a

major hazard to man. CdS is not nearly as toxic and may only create minor gastrointestinal disturbances if ingested. Thermal decomposition of protective or backing materials such as teflon, aclar, or Kapton may create some hazardous combustion products (e.g., HF, COF₂). Any area affected by a major CdS conflagration should be isolated until CdO or Cd metal contamination has been removed. An explosion without combustion of a large array will scatter considerable quantities of CdS over the affected area. Ingestion of CdS is not considered life-threatening to man.

Emergency personnel present during fire suppression procedures should be adequately protected against CdO fume inhalation.

1.8.3 Gallium Arsenide Cells

Combustion of a large array of GaAs cells can result in the formation of considerable quantities of finely divided arsenic trioxide (As₂O₃) and mists of arsenic acids (H₃AsO₃, H₃AsO₄, HAsO₃) plus gallium oxide dust (GaO). Small quantities of Ta₂O₅, Au₂O, and GeO₂ will also be released. Only the arsenic group of compounds is known to be highly toxic. The release of arsenic compounds into the air, deposition upon growing crops, and dissolution into water supplies presents a major hazard to worker populations, firefighters, and the surrounding community. Quarantine of contaminated water supplies and crops should be initiated immediately after an accident. Careful monitoring of arsenic concentrations in the affected area would have to be made for a period subsequent to the incident in order to permit resumption of water or crop use for human or animal consumption. Dispersal of GaAs after an explosion with no fire should present much less of a hazard. At present GaAs is not considered toxic.

1.9 PROCESSES - SPECIFIC HAZARDS

1.9.1 High Volume SiH₄ Production

This process involves the synthesis and handling of some quite hazardous chemical compounds: SiH₄, SiCl₄, H₂SiCl₂, HSiCl₃. HSiCl₃ has a low flash point but can be handled safely in dry air. The trichlorosilane

has a tendency to disproportionate to SiH_4 and H_2SiCl_2 . This process is slow at room temperature if the compound is pure. Silane is spontaneously flammable in air. It can be heated in an inert atmosphere to 400°C before decomposition to hydrogen and silicon begins. The sudden rupture of the hot reactor could create a problem of HCl release and the combustion of the product (SiH_4) or any of the intermediates (H_2SiCl_2 , HSiCl_3). One manufacturer has been making the chlorosilanes for over 20 years without mishap. Some of the impurities in the metallurgical grade Si will wind up as a sludge which will have to be properly disposed of. These include aluminum, magnesium, and iron chlorides. The presence of H_2 in any hot flowing atmospheric system (especially glass) is always somewhat hazardous although normal precautionary measures will preclude any explosion problems. The trapping of large quantities of potentially combustible chlorosilanes must always be carefully monitored to prevent blockage or breakage of the containment vessel. The venting operation (combustion and water scrubber) appears to be adequate to control emissions. The final pyrolysis step ($\text{SiH}_4 \rightarrow \text{Si} + \text{H}_2$) must be adequately protected from leakage or breakage.

None of the potential hazards mentioned appear to be beyond the capability of normal preparative procedures to handle unscheduled ruptures or reactor breakage by external causes.

1.9.2 SiF_2 Polymer Purification Process for Si

In this process the high temperature reaction of SiF_4 with Si is followed by polymerization to $(\text{SiF}_2)_x$ and finally decomposition of the latter to pure Si , SiF_4 , and higher silicon fluorides. The handling of SiF_4 and Si at high temperature will require normal precautions, especially in reactor vessels made of quartz. The $(\text{SiF}_2)_x$ condensation trap must be properly designed to prevent rupture or blockage since the polymer is somewhat unstable in air. A large SiF_4 release will result in the formation of fluorosilicic acid mists, HF and hydrated silica, which must be controlled as quickly as possible. Si metal will not react with air at room temperature

but will react above 950°C to oxidize rapidly. This process is probably one of the less hazardous methods of manufacturing pure silicon. The total amount of SiF_4 required is quite small since a large fraction is recovered for reuse in the final polymer decomposition step.

1.9.3 SiO_2 -C Plasma Torch Process

This process involves the direct reduction of SiO_2 in an argon plasma flame using finely divided mixtures of SiO_2 and carbon black. Preparation of the reagents involves grinding, which does not present any hazards to the operator. The high temperature process is protected from catastrophic rupture since the plasma will quench rapidly upon exposure to air. The by-product CO can be easily removed by absorption or combustion. There is little danger of the release of significant quantities of respirable SiO_2 if explosion or fire should expose the reactor. If H_2 were used as the arc gas, then problems of safety would become more significant.

1.9.4 Reduction of SiCl_4 Using Zinc

The in-plant production of SiCl_4 from the chlorination of SiO_2 -carbon mixtures is probably one of the more hazardous reactions to be considered in the silicon purification process. Handling of large quantities of Cl_2 at high temperature could be a problem if an accidental discharge or break occurred. SiCl_4 itself is quite reactive if released into the air, hydrolyzing rapidly with the release of HCl and finely divided SiO_2 . Adequate precautions must be adopted in this process to choose materials of construction that will be compatible with the potentially corrosive chemicals used. An experienced manufacturer should have no problems with this reaction system. This process is silicon halide intensive in that economic considerations preclude the recycling of SiCl_4 . Special care must be exercised to prevent discharge of process sludge into the environment, especially public water supplies. The impurities recovered will include other metal chlorides besides silicon.

Of the four silicon purification processes only the reaction of silicon halides with zinc presents significantly greater potential hazards

than the other procedures. This is principally due to the silicon halide intensive nature of the synthesis. The use of normal precautionary measures used by the chemical industry should permit the use of this reaction in a safe manner. Proper precautions must also be taken to prevent the release of the chlorosilanes in the SiH_4 synthesis.

1.10 TOXICOLOGY, PHYSIOLOGY - RAW MATERIALS,
FINISHED PRODUCTS

Many of the raw materials required for the manufacture of solar cells are considered hazardous to human health. In some cases a hazard is present only when particular reactions or decomposition of a compound occurs. Toxicological data and physiological response to different levels and lengths of exposures to some of the substances are available, whereas some compounds have not been studied. Reliability of these data is often in question, especially when translation from animal to human exposure studies is to be made. The chemicals identified as the chief ingredients for solar cell manufacture probably do not include every material that will be used. They do, however, focus on those substances that will be synthesized, handled, and reacted in large quantities by supplier industries and the manufacturers of solar cells as planned at this time.

None of the chemicals or finished products present a new problem to the chemical industry. All or most of them have been made or used for long periods of time. Most of the health-related literature has been concerned with occupational exposures within the manufacturing or mining industries. Data from these studies should be useful in an evaluation of possible environmental hazards that could develop if a large-scale expansion of the solar cell manufacturing industry were to occur.

The most straightforward manner of summarizing the extensive data is to refer to past literature whenever applicable and only to the most clearly defined results available. The question of what happens to a toxicological agent once released must be answered. How does it enter the environment and in what form? How is it assimilated by man or plant?

Does it accumulate within living organisms, and when does it constitute a hazard? This brief survey will limit itself to those chemicals already discussed with special reference to their oxidation or hydrolysis products whenever stability in air indicates that these materials would not exist in their original form for very long. For example, the halides of Si, Ga, and As will be regarded as problems of halogenated or oxyhalo acids and metal oxide hazards. The halogens will be toxic in themselves, and could constitute a problem of carbonyl halide formation under fire conditions. The metals Si, Ge, As, and Cd must also be thought of as metal oxides hazards. The Ga alkyls will always constitute a metal oxide hazard. Any other hypergolic compounds are best regarded as metal oxide fume hazards (AsH_3 , SiH_4 , PH_3). The finished products GaAs, CdS, or Si cells can be studied as formulated or, in the event of combustion, as the metal oxides.

A substance has an adverse environmental effect if evidence can be obtained that the presence of this material can injure man, animal, plants, or building structures and equipment. Throughout history pollutants generated by human activity rather than natural processes have eventually been implicated as injurious to the environment in one manner or another. Recent examples might include asbestos fibers, carbon tetrachloride, vinyl chloride, and the haloethane anesthetics. Unless every existing chemical in use today were to be exhaustively tested for toxicity or general environmental interaction and dispersal, then we will probably continue to discover materials that have been used for a long time that are actually quite harmful to society. A further observation is that in many cases detailed toxicological and physiological tests often fail to result in definitive conclusions. The variability of human or animal response to a particular material can frequently mask the more subtle physiological effects.

Despite these limitations, government agencies for the past 40 years have made some efforts to protect society from harmful materials. The earliest work was performed by the U.S. Public Health Service in attempts to modify some of the more dangerous practices occurring in the

industrial environment. Criteria for the maximum allowable concentrations (MAC) of many substances in the plant air environment were established. The premise on which these MAC levels were based was that all chemical substances will produce a response at some concentration if exposure occurs for a long enough period of time while at the same time a concentration exists for any substance from which no response of any kind is shown no matter how long the exposure, assuming an 8-hour workday and a 40-hour workweek. These concentration limits were first published in 1946 and were regarded as quite reasonable at the time.

Recently two factors have raised considerable doubt about the validity of these MACs. One concern was that some substances are quite toxic at any measurable concentration and that exposure to these agents can be injurious even if the exposure period is quite short. Secondly, advances in response measuring techniques have been able to determine increasingly sensitive indicators of stress. As a result of these developments, the standards based on MACs were modified to include a factor incorporating a margin of safety for those individuals considered most susceptible. These allowable concentrations were termed threshold limit values (TLV). The magnitude of the safety factor varies according to the substance. For example, the safety factor for cyanides or arsenic compounds would be much greater than for sulfur dioxide or trichloroethylene since the latter demonstrate initial responses which are far from lethal while the former have lethal potential, even after short exposure.

It was not until the middle 60's that any effort was made to protect the general public from toxic substances that may enter the air, water or soil from industrial or citizen generated sources. The passage of major legislation to establish standards of air and water quality has initiated enormous efforts to reduce the emission of existing effluents and to establish standards of allowable concentrations for many chemical compounds. The responsibility for establishing and monitoring the air and water quality standards is with the Environmental Protection Agency (EPA), whereas the

industrial standards are set by the National Institute of Occupational Safety and Health (NIOSH). Monitoring of industrial safety and health standards is assigned to the Occupational Safety and Health Administration (OSHA), a part of the Department of Labor.

1.10.1 Silicon Cells

1.10.1.1 Silicon Compounds

Silicon dioxide will be one of the basic raw materials used to produce pure silicon. It is anticipated that considerable quantities will be required for the synthesis of some of the silicon halides and the SiO_2 reduction process with carbon. The critical physiological factor to consider when handling SiO_2 is the average particle size. Respirable particles, that is, those that can penetrate to the alveolar spaces and small bronchi must be quite small. Particles smaller than $10\ \mu$ are believed to be capable of passage to the lower portions of the lung. Pneumoconioses are occupational diseases of the lungs caused by retention of dusts.

Silicosis is one of the most malignant forms of pneumoconiosis caused by retention of SiO_2 dust. It is characterized by fibrosis of the lung. Two distinct forms of the disease are produced by silica. Very small (up to $0.5\ \mu$) particles produce typical fibrotic nodules in the lung, while larger particles cause classical nodular silicosis. These conditions can develop rather rapidly within some occupational groups. For example, sandblasters have developed silicosis after only a few months on the job (Refs. 1,2). The average tenure on the job of a sandblaster in Britain is only 10 years (Ref. 3). An evaluation of protective hoods used in this industry (Ref. 4) indicated that these devices were quite inadequate in most cases. The TLV of $0.1\ \text{mg}/\text{m}^3$ of respirable silica was exceeded by a factor of 20 when the employee was not actually sandblasting and had removed his protective hood.

There are many conflicting theories for explaining the extraordinary fibrogenic properties of crystalline free SiO_2 : wherever retained particles are present, they become foci for local inflammatory reactions,

followed by proliferation of fibrous tissue and the development of the characteristic silicotic nodules. These nodules gradually coalesce as additional silica dust is inhaled.

Conceivably an accidental burning of a large quantity of SiH_4 could release a fine dust of SiO_2 . Such an intense exposure may produce what has been called acute silicosis, which is characterized by the onset of widespread interstitial pneumonitis, quite dissimilar to normal silicosis. Another disease, Shaver's disease, is caused by intense exposures to amorphous silica. It is characterized by diffuse interstitial fibrosis, leading to rapid disability or death. Both of these afflictions have become rare today, ever since even minimal protective safety measures were adopted by industry.

It is anticipated that both the supplier and cell manufacturing industries are well aware of the problems of handling SiO_2 or accidental release or production of SiO_2 and are presently taking adequate safety precautions. The SiO_2 used in the high temperature plasma reactor process appears to be of large enough particle size to preclude any occupational health problems.

The silicon halides (SiCl_4 , SiF_4) are capable of producing acute inflammatory reactions in the nasal and bronchial passages. Hydrolysis of these compounds occurs rather rapidly as soon as contact is made with the mucous membranes. The problem is therefore generally regarded as a HCl or HF problem. The toxicity of the halosilanes (SiH_xCl_x or SiH_xF_y) is believed to be equivalent to that of the silicon halides. Some of these compounds may be present in the hydrolysis products of the silicon halides.

Silicon is not a nutritionally essential trace element. It is a minor constituent (0.02%) of plant or animal tissue in the form of hydrous silica or silicic acid. In plants such as wheat-straw it can reach 2-4% silica. Silicon has no influence on metabolic function, sensory perception, or motor function. Excretion of silicon is extremely rapid due to its high solubility in blood plasma. Silica or silicates appear to be beneficial to plant nutrition in that silicon causes an increase in phosphorus uptake from phosphate fertilizers.

1.10.1.2 Carbon Dusts

Carbon deposition in the lungs has been suspected as causing simple coal workers pneumoconiosis (Ref. 5), graphite pneumoconiosis (Ref. 6), and carbon pneumoconiosis amongst rubber workers exposed to carbon black (Ref. 7). Another study investigated the effects of inhaling activated carbon dust (Ref. 8). Prolonged inhalation of these dusts appeared to have no detrimental effect upon respiratory symptoms or pulmonary function parameters despite the fact that x-rays showed evidence of deposition of dust and signs of pneumoconiosis around these deposits. The inhalation of carbon dust has been shown to increase mucociliary transport velocities (Ref. 9). The dust therefore temporarily increases the ability to clear foreign particles from the trachea and bronchi. The effect of carbon dust upon human respiratory function appears to demonstrate no permanent detriment although an interpretation of some of the contradictory radiographic data requires some further explanation. Carbon black as used in the $\text{SiO}_2 + \text{C}$ reduction process should not present a hazard to the worker or, if accidentally released, poses no threat to the surrounding community.

1.10.1.3 The Halogens (Cl_2 , F_2)

All of the halogens are to varying degrees powerful vesicants and respiratory irritants. Acute exposures to high doses of Cl_2 causes dyspnea, cough, intercostal pain, and death by asphyxiation. Low level exposures result in cough with sputum production, higher frequency of colds, dyspnea, palpitation, and chest pain. Some studies have demonstrated x-ray evidence for increased fibrosis of the lung and evidence for emphysema after chronic exposures to low levels of Cl_2 (Ref. 10). Other evidence does not confirm these findings in a study of a large number of cases of acute Cl_2 exposures (Ref. 11). Another study indicated that long-term exposures to low levels of Cl_2 did not have any effect upon hematology, chest x-rays, or the electrocardiogram (Ref. 12). Acute exposures showed no irreversible damage based on x-ray data and pulmonary function tests. The TLV for Cl_2 is presently at 1 ppm.

Fluorine is a highly toxic compound, and its present TLV is 0.1 ppm. Very low concentrations of F_2 can cause severe eye injury or skin burns or lethal damage to the lung. Upon contact with the skin or mucous membranes, F_2 reacts rapidly with moisture and acts very similarly to HF. However, in most cases F_2 exposures result in more severe injuries. If F_2 were to be used to any extent by the solar cell industry, then the usual strict usage rules for F_2 would have to be closely followed.

1.10.1.4 Halogenated Acids (HCl, HF, HBr, HI)

All of these compounds are extremely toxic, attacking the upper respiratory tract, eyes, skin, and mucous membranes. HCl acid mist in air will cause throat irritation at concentrations of 35 ppm. At levels of 50-100 ppm, breathing difficulties develop after a short while. Concentrations above 3500 ppm can be fatal within a few minutes. The release of low concentrations of HF can be quickly detected by the characteristic prickling and burning sensation it causes in the nose, throat, eyes, and mouth. This is due to the immediate formation of the highly caustic hydrofluoric acid when it comes in contact with moisture in the mucous membranes. At higher concentrations (>100 ppm) many tissues are destroyed with marked ulceration. Chronic low level exposures have produced weight loss, anorexia, unusual fluoride storage in the bone, eosinophilia, lymphocytosis, and asthmatic disorders in man. Acute exposures to HF gas constitutes a major medical emergency. The development of edema of the lungs should be prevented by administering oxygen immediately for an extended period. Exposed skin and eye areas should be adequately flushed with water followed by application of some neutralizing paste. Hydrogen bromide is similar in properties to HCl. The TLV (1968) for HCl is 5 ppm, and 3 ppm for HBr and HF. Large amounts of these acids will be utilized by the raw material suppliers and by the cell manufacturers. In some cases use will be restricted to actual synthesis of starting materials and in some the acids will be by-products of reactions. Normal precautions presently observed by the user industry should present no difficulties to the solar cell manufacturing industry.

1.10.1.5 Phosphine

Acute exposures to phosphine (PH_3) can result in congestion of all internal organs with edema of the lungs. Exposures to concentrations as high as 0.2% for 30 minutes can be fatal. Chronic exposure to low (<10 ppm) concentrations is marked by kidney problems, faintness, lassitude, and an increase in pulse rate.

1.10.1.6 Phosgene

Phosgene (COCl_2) exposures are primarily irritants to the lungs. Hydrolysis of the gas to HCl and CO_2 occurs in the alveoli where the HCl causes massive pulmonary inflammation and edema. Deterioration of the alveolar walls is evident after acute exposures. If not treated promptly cardiovascular collapse will occur.

1.10.2 Cadmium Sulfide Cells

1.10.2.1 Cadmium Compounds

Cadmium compounds are widespread environmental pollutants that have frequently been implicated as systemic cumulative poisons to man, principally affecting the lungs and kidneys. Excellent overall reviews of the sources of cadmium pollutants, their mode of entry into the ecology, and their subsequent interaction with man, animals, and plants are available (Refs. 13,14). Cadmium is classified as a non-essential element. It is not required for the maintenance of growth and for the regulation of normal physiological functions (Ref. 15). Chronic lifelong exposure results in accumulation of this element with age (Ref. 16). Preferential sites for deposition occur in the liver and kidneys (Refs. 17,18), causing renal lesions in the tubules and glomeruli (Refs. 19-21). The metal also causes bone abnormalities (Ref. 22), and has been implicated in the development of hypertension (Refs. 23,24) and anemia (Ref. 25). Acute exposure to large doses of cadmium results initially in lung irritation marked by difficulty in breathing followed by violent gastrointestinal disturbances, emesis and intense

cyanosis, and death (Refs. 26, 27). It is fair to state that cadmium in any form can cause severe injury to man and for this reason the threshold limit for Cd dusts has been set at $100 \mu\text{g}/\text{m}^3$. Other workers have suggested even lower limits (to $20 \mu\text{g}/\text{m}^3$) (Refs. 28, 29). Cadmium enters the food environment, resulting in an estimated daily intake of about $50 \mu\text{g}$ in western adults. Sewage sludge used to serve as a plant nutrient source can transfer considerable concentrations of Cd to a growing crop (Ref. 30). For this reason, all operations with Cd should take special care to avoid discharge into waterways and water supplies. The major problem to be expected in the solar cell industry is occupational exposures to Cd salts or other compounds. The welding, brazing, and smelting industries have had problems maintaining exposure levels to within the established TLV, which at present may still not be low enough to fully protect human health. Combustion of large arrays of CdS cells will result in the release of high concentrations of CdO fumes, which will represent an acute hazard to any exposed individual. Ingested CdS itself is not nearly as hazardous as CdO because of its low solubility in gastric juice.

The overall impact of the solar cell manufacturing and fabricating industry should not have any measurable effect upon the total release of Cd compounds into the air or water environment. However, the actual workplace and the immediate surrounding community must be protected from low or catastrophic releases of any form of Cd compounds.

1.10.3 Gallium Arsenide Cells

1.10.3.1 Elemental Arsenic and Arsenic Compounds

Arsenic is a widespread environmental contaminant present in U.S. industry. It is estimated that 1.5 million workers are exposed to inorganic arsenic (Ref. 31). Many of these people are employed in the pesticide and copper or lead smelting industries. Until recently the insecticides, calcium and lead arsenate, were extensively used in the tobacco and grape growing industries. These compounds were usually made by reacting the metal oxides (CaO or PbO) with arsenic acid (H_3AsO_4), which in turn is

made from As_2O_3 . Evidence has been gathered that exposure to arsenicals (Refs. 32-34) and As_2O_3 (Ref. 35) itself can increase lung cancer incidence. A more recent study showed that a marked increase in respiratory cancer death was experienced by a pesticide industry worker population (Ref. 36). Those persons engaged in product packaging were the most severely affected. Careless methods and lack of use of available protective equipment were noted. As_2O_3 can absorb through the skin to a slight extent, but most of the intake is usually through ingestion or inhalation. Arsenic in acute dosages is usually fatal. Heart and kidney functions are both severely affected. Arsine (AsH_3) if inhaled can be fatal with rapid onset of symptoms if concentrations as high as 400 ppm are present. At lower concentrations (<6 ppm) some delay in effects occurs. Usually the general major physiological response is difficulty in breathing, gastric disturbances, and severe anemia and jaundice. A TLV of 0.05 ppm has been established for this compound. The toxicity of GaAs has not been studied. In the event of combustion some As_2O_3 may be formed. Gallium oxide does not appear to be toxic.

Arsenic is found in the atmosphere and waters of the U.S. at concentrations as high as $50 \mu\text{g}/\text{m}^3$. Most of these emissions can be attributed to the coal and petroleum industry. Any slight releases by the solar cell manufacturing industry should have no detectable effects upon the ambient levels of arsenic already present in the environment. It will, of course, be necessary to adopt normal hygienic procedures in handling the various arsenic compounds to be employed in making GaAs cells.

1.10.3.2 Gallium

Gallium (Ga) and the oxides (Ga_2O_3 , GaO) are not toxic although mild reactions such as tooth decay and minor nervous or gastrointestinal disorders have occurred after acute exposures. Meager Soviet data indicate that GaAs is not toxic when ingested in small quantities. Further research is necessary to fully explore the toxicology of this compound. The gallium alkyls are not believed to be toxic because they rapidly oxidize to the innocuous oxides.

1.10.3.3 Germanium

Animal experimentation and observations with humans indicate that germanium (Ge) constitutes no toxicological hazard. Neither inhalation nor ingestion of the metal dust or vapor causes lesions on the lungs or other illnesses. The oxide dust is rapidly cleared from the lung.

1.10.3.4 Tantalum

Tantalum oxide (Ta_2O_5) has demonstrated no occupational hazards to man. No data are available on lung clearance rates or on the possible accumulation of this element in body tissues.

1.11 RESULTS AND CONCLUSIONS

1.11.1 Summary

A large-scale expansion of the photovoltaic solar cell manufacturing industry will probably not (except for some reservations with respect to cadmium sulfide cells) impose a significant national environmental impact. Compared with most other chemical or fabricating industries, the solar cell manufacturing facilities as projected will be relatively small in size. It is believed that of the three candidate types of solar cells investigated, silicon and gallium arsenide will be producible without any significant impact on the ecology. The severe toxicity of cadmium coupled with its limited availability, however, may significantly restrict the use of cadmium sulfide as a candidate material for solar cells.

1.11.2 Silicon Cells

Silicon metal purification is already well established within the semiconductor market. An analysis of silicon's general properties, storage, transport, behavior in event of spill, fire, explosion, and toxicology indicates that this manufacturing industry should be able to operate safely within the constraints of normal environmental protection. It is believed that no new control technology will have to be developed to meet the state and federal occupational health and safety laws. Establishment of new manufacturing

facilities should not face any significant obstacles despite the anticipated requirement that approvals must be gained for detailed environmental and occupational safety guidelines in each case.

Adequate precautions should be taken by manufacturers against the extremely remote possibility of catastrophic destruction of a large panel of silicon cells. Such an occurrence could generate respirable concentrations of silicon oxides and other metal oxides, which are harmful to man.

The estimated tonnage of silicon needed for solar cell manufacture would require a substantial increase in U.S. production. However, since silicon is one of the most abundant elements, it appears this increased demand could be met.

1.11.3 Gallium Arsenide Cells

The gallium arsenide cell industry will involve such small amounts of material that even if concentrated at one location it would not present any serious hazards. Gallium and its compounds appear to be quite innocuous. Only the small amount of arsenic used must be adequately controlled. When swallowed or inhaled in acute dosages, arsenic compounds can produce severe cardiovascular or renal reactions, whereas chronic sub-acute exposures have been implicated in an increase in the incidence of respiratory cancer. Caution must therefore be observed in the handling of all arsenic compounds. This is especially true if arsine (AsH_3) is to be used, as it is one of the most toxic gases known. Exposure to concentrations of 50-100 ppm for even a short while can be fatal.

The discharge of waste products or the scrapping of spent cells must be strictly controlled. The entry of arsenic compounds into the water systems of the surrounding area must be avoided.

It is not believed that any significant expansion of the arsenic refining industry will be required to meet the demand of cell manufacturers.

1.11.4 Cadmium Sulfide Cells

Special problems could arise with the manufacture of cadmium sulfide cells. The amount of cadmium required represents a significant

multiple (200% of 1973 production) of the total used in this country. This will mean a major step-up of domestic production or an increase in imports. The latter is questionable since worldwide resources of this metal are also quite limited. A major increase in domestic production will require the establishment of several large zinc refining plants (cadmium is a very minor constituent of zinc ores). Many of the existing zinc producing plants are already beset by severe environmental restrictions, principally because of the persistence of slight Cd emissions. It is anticipated that private industry might be quite reluctant to establish a series of new smelting facilities if environmental clearances are increasingly difficult to obtain.

The severe toxicity of Cd and its compounds will probably further tighten environmental controls. Low-level chronic exposures to Cd compounds can result in accumulation within the body leading to detrimental physiological effects in the respiratory, renal, gastrointestinal, and cardiovascular system. It is estimated that the half-life for Cd elimination is of the order of 10 to 25 years. Long-term non-acute exposures are quite subtle, eventually affecting all organs and systems of the body. Acute exposures to respirable Cd result in severe pulmonary irritation and difficulty in breathing followed by the development of chemical pneumonitis. Unless promptly treated, it can lead to death. Ingestion of Cd compounds can lead to similar physiological distress but is somewhat less hazardous than inhalation due to the strong emetic effects of Cd compounds.

The installation of fabricated CdS cell modules will present no environmental hazard as long as the devices are untouched by fire or explosion. However, CdS will oxidize to cadmium oxide when burning in adequate supplies of oxygen. Under some circumstances the CdS may also be converted to CdSO₄. Both CdO and CdSO₄ are highly toxic and would present a hazard to the worker or disaster control personnel. Scattering of any cadmium compounds over an agricultural or residential area might permit the metal to enter the food or water cycle of the surrounding community. Proper notifications and decontamination procedures must be adopted

subsequent to such incidents for the safety of the citizen and worker. All firefighters should be physically checked for cadmium intoxication after suppression of a fire involving any cadmium compounds. All cleanup and reconstruction should be performed only under the guidance of an industrial toxicologist fully familiarized with the problems of cadmium hazards.

Proper disposition of failed CdS arrays should be required to prevent their entry into waste disposal sites such as landfills or incinerators. It is anticipated that Cd should be recovered quantitatively from spent cell modules.

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SECTION 2

A PRELIMINARY INVESTIGATION OF THE IMPACT OF SEVERAL FINANCIAL INCENTIVE STRATEGIES ON THE ECONOMICS OF PHOTOVOLTAIC POWER PLANT OPERATION

2.1 INTRODUCTION

Until quite recently, most utility companies were able to maintain good earnings and financial ratios, which enabled them to secure adequate financing for the construction of new power plants. Within the last few years, however, the impacts of inflation on construction and fuel costs, of environmental requirements, of regulatory rate approval delays, and of consumer resistance to the high cost of energy have caused erosion both in earnings and in the relevant financial ratios. The combined effect of this erosion, the current tight capital market, and rapid changes in tax structures and accounting procedures has forced many utilities to make large-scale cutbacks in their power plant construction projects. A number of cutbacks have also been due to the complexities of the technical problems involved and the costs of solving them. Until utilities can improve their financial position, the financing of high technology, high risk, and high cost power plant projects will continue to be difficult.

Since photovoltaic power plants, at least at the outset, will possess all three of these characteristics (high technology, high risk, and high capital cost), it is likely that some form of government financial incentive will be necessary in order to stimulate their timely construction. This will probably be true even when it has been demonstrated that such plants can be competitive with alternative generation methods in terms of life-cycle cost of energy production. It was for this reason that a preliminary examination of alternative incentive strategies was included as part of the mission analysis project. The remainder of this section of the report is devoted to a discussion of this investigation.

The principal tool used in the evaluation of incentive strategies was a new Public Utility Financial Analysis and Planning Model that had been developed for just such purposes by The Aerospace Corporation, using internal corporate funds. This model is described in some detail in Section 2.2 below. After adaptation to match the characteristics of photovoltaic plants, it was used in the comparative evaluation of six different incentive strategies. The candidate strategies, the rationale for their selection, and the results of the comparative evaluation are presented in Section 2.3.

2.2 PUBLIC UTILITY FINANCIAL ANALYSIS AND PLANNING MODEL

2.2.1 Introduction

Many aspects of the economics of electric power generation can be handled quite adequately by the relatively simple and straightforward levelized fixed charge approach. That approach was used, for example, under Task 1 (as reported in Vol. 2) and Task 2 (as reported in Vol. 3) of this study, in computing the cost of energy production by various means. However, when subtler or more complex problems are involved, such as the impact of incentives on power plant economics, a much more detailed analytical methodology is needed. The required procedure must permit determination not only of the cost of service (expressed both as an annual cost and as a uniform, or levelized, cost) but also of the sensitivity of this cost to variations in the costs of construction, operating costs, financing costs, income and other taxes, the rate of inflation, and system performance. It must also make possible the computation of the effects of variations in these quantities on cash flow, dividend payout, and stockholder equity over the economic life of the plant. The Aerospace Corporation Public Utility Financial Analysis and Planning Model was designed to satisfy these requirements.

2.2.2 General Description

The structure of the Public Utility Financial Analysis and Planning Model is illustrated in block diagram form in Figure 1. It treats

Figure 1
UTILITY FINANCIAL PLANNING MODEL

cash flows, taxes, depreciation, working capital allocations, and allowed revenues in a manner that is consistent with the way that power plant economics are viewed by such regulatory agencies as the Federal Power Commission (FPC). The central element of the model is the determination of the revenue stream that will be just sufficient to cover all costs and provide an adequate return on the equity funds employed. This revenue determination is based on separate calculations of (a) total plant investment costs, (b) the rate base, the utility's net investment at a given time as determined in accordance with regulatory practice, (c) the allowable rate of return on rate base, (d) currently payable and deferred income taxes, and (e) all other expenses, including plant operation and maintenance costs, depreciation, interest on debt, and taxes. A provision is also made for including the cost of periodic replacement of major plant subsystems that have a service life of less than that of the plant itself (typically 30 years).

The total construction cost of the plant (including spares, contingencies, indirect costs), evaluated as of a selected base year, is one of the principal inputs to the model. The first step in the program is the escalation of these base year construction costs to current dollars and the computation of the allowance for funds used during construction (AFUDC). Other taxes payable and working capital are also computed to determine the total investment and depreciable cost at the first year of commercial operation (YR_{co}).

Annual amounts for depreciation are computed for each major construction facility item according to its forecast economic lifetime. Interest is computed semiannually and debt is retired uniformly in accordance with the debt retirement financial assumption. The cost of financing is also amortized uniformly. When replacement facilities are required, the program computes the new cost for each replacement facility item every 5 or 10 years. Financing of replacement facilities is accomplished through an addition to long term debt. Interest, debt retirement, financing cost, and amortization of financing costs associated with such replacement facilities are computed by the same procedures as were used in connection with the initial facilities.

An annual rate of return on rate base is computed on the basis of the average capitalization and the cost of capital. The rate base is composed of the investment cost of the average utility plant in service minus average accumulated depreciation and deferred income taxes plus an allowance for working capital.

Federal and state income taxes are computed on the basis of the return on rate base. The tax adjustments resulting from differences between book and tax depreciation and tax losses from prior years are considered in computing the amounts of payable and deferred income taxes.

Annual operating and maintenance costs are computed from inputs to the program. The sum of the total operating expenses and return on rate base provides the annual operating revenue. Other income from the investment tax credit is added to the net operating income while interest charges are deducted in order to arrive at net income.

The cash flow program computes both annual dividend requirements and cash available from net income and working capital, taking into account debt retirement and allowances for working capital and for materials and supplies. Dividends accumulated during the construction period are paid as soon as possible once the plant enters service. Retained earnings are a function of net income and dividend payout policy.

2.2.3 Operational Features

2.2.3.1 Input and Output Data

The required inputs to the model and the outputs that it generates are listed in Figure 2. The computer program utilizes the Plan Analysis and Modeling System (PAMS) of the Getty Oil Company and is run on an IBM 370 computer. Input data furnished to the program include unescalated power plant construction costs by year, by major cost category, generally following the Uniform Systems of Accounts prescribed by the FPC. Unescalated annual operating costs covering fuel, operation and maintenance, and insurance are also inputs.

Figure 2
 INPUT-OUTPUT DATA -- AEROSPACE PUBLIC UTILITY
 FINANCIAL ANALYSIS AND PLANNING MODEL

2.2.3.2 Financial and System Performance Assumptions

Included among the required inputs to the program are the assumed values for the financial and performance parameters listed in Section 2.3, Table 2. The financial parameters that are to be specified include debt/equity proportions, interest and dividend rates, financing cost, and tax rates. The only system performance inputs are rated plant capacity (in MW_e) and plant capacity factor. Any of these inputs can be varied from year to year, so that the model can reflect, for example, changes in inflation rates or variations in plant performance (as indicated by changes in the plant capacity factor).

2.2.3.3 Construction Cost Program

For each year of construction, the construction cost program escalates construction costs to current dollars and computes the funds required to cover plant construction, taxes, working capital, and interest. At the same time, the program maintains the selected ratios of debt to preferred and common equity. While the program assumes that construction costs are incurred uniformly over the year, they may be entered semiannually to account for seasonal variations in construction schedules. Financing and interest costs are also computed semiannually. The construction program also computes the equity portion of AFUDC, including or excluding, as desired, the interest on accumulated dividends. A complete breakdown of cash sources, cash uses, and depreciable costs during construction, along with the equity portion of AFUDC, is provided as an output by the program.

2.2.3.4 Depreciation

Depreciation routines in the model take into account depreciation life, depreciation timing (beginning, middle, or end of year), and salvage value and are applied to each major facility construction item. If a facility item has an economic life of less than 30 years, the program depreciates it according to its economic life and then calculates a new replacement facility cost in current dollars. The depreciated facility value is then deducted from

the utility plant-in-service total. At the same time, the new replacement facility item is added to the construction costs and depreciated in following years. The program contains both a 5- and 10-year replacement program and can be modified to include other periods. Over 30 years, a facility item with a 5-year economic life will be replaced five times. A statement of depreciation is provided as a program output.

Book and tax depreciation may be computed via any of the following five methods:

Straight line

Double declining balance

Double declining balance/straight line

Double declining balance/sum of years digits

Sum of years digits

2.2.3.5 Rate of Return on Rate Base

To compute the rate of return on rate base, the program calculates average capitalization amounts for outstanding debt and preferred and common stock. Average annual costs are obtained by averaging the expense figures for the current year with those for the prior year.

The weighted average debt cost (percent) is calculated by dividing the total interest charges by the average outstanding debt. Interest charges include amortization of debt expense.

The rate of return on rate base (percent) is computed by summing the separate products of the cost of capital (percent) and the average capitalization components for long term debt, preferred shares, and common equity, respectively. As outstanding debt is retired, the proportion of debt to equity decreases. This results in a decreasing contribution to the rate of return from the long term debt component and an increasing contribution from the preferred and common equity components. The computed rate of return is also provided as a program output.

2.2.3.6 Return on Rate Base

The determination of the return on rate base is one of the most important computations in the program, since this is the largest element of the cost of service. The rate base is determined by adding an allowance for working capital to the total investment cost of the plant or plants in service and then subtracting the values of the accumulated depreciation and deferred income taxes. The return on rate base is then computed simply by multiplying the rate base by the allowed rate of return (as discussed in Section 2.2.3.5). The financial data associated with this calculation are also provided as a program output.

2.2.3.7 Federal and State Income Taxes

Federal and state income taxes, deferred income taxes, and income taxes currently payable are calculated after the return on rate base has been computed.

The equity portion of the return is the return on rate base minus interest expense. The book depreciation on the equity earnings capitalized during construction is added to this amount. (This latter amount is the net income earned during construction on invested equity funds. These earnings are capitalized over the plant economic life.)

The program distinguishes between income taxes (state and federal) that are currently payable and those that are deferred, taking proper account of such factors as the difference between book depreciation and tax depreciation, tax losses from prior years, and tax loss carryovers (to future years).

2.2.3.8 Investment Tax Credit

The total investment tax credit earned is computed by applying the investment tax credit rate to the total plant cost or to that portion of the plant cost to which the investment tax credit applies. Investment tax credit earned on replacement facilities is computed in a similar manner.

The program does not allow for the inclusion of the tax credit in the income statement until there is a federal income tax payable and then only up to half the amount of the taxes payable. Under high debt/equity ratios, full utilization of the investment tax credit will take place over a long period. In fact, if the investment tax credit rate is higher than 10%, there will likely be an unused investment tax credit. The investment tax credit is assumed to be an incentive for plant investment and is not used to reduce the cost of service.

2.2.3.9 Dividends

Dividends paid to stockholders are a function of earnings and of management policy. A utility company may choose to maintain a constant dividend flow, utilizing working capital when necessary, or it may set the dividend payout equal to a fixed percentage of net income.

The model is presently programmed in accordance with the former policy, i. e., it maintains a constant dividend flow as long as earnings and working capital permit. Common dividends are not payable until the amount due preferred shareholders is first paid. Dividends earned during construction are paid to stockholders as soon as possible once the plant enters service. Allowances for working capital and materials and supplies are excluded from dividends available. Under this dividend payout method, stockholder equity is reduced in the later years of plant service life.

The model can also set dividends equal to a fixed percentage of net income. Funds transferred to working capital in this case would be reinvested and accrue interest. The interest income would be taxable and the net would be added to net income. Under this dividend payout method, working capital would not generally be utilized for dividends and would be adequate at the end of the plant's economic life to repay stockholders their original investment.

2.2.3.10 Income and Retained Earnings

In order to evaluate the financial condition of the utility plant over its economic lifetime, the model provides statements of income and retained earnings, a balance sheet, and a cash flow statement.

The income and retained earnings statement provides the financial results of each year's operation. Operating revenues are the sum of operating expenses and the return on rate base. Separate financial schedules are provided for operating and maintenance costs, depreciation, and income taxes. Retained earnings at the beginning and end of the year are also shown.

2.2.3.11 Cash Flow

The cash flow schedule identifies the actual cash sources and cash uses from the beginning of construction to the end of the economic life of the utility plant. During the construction period there is no cash flow from operations since net income is offset by the equity component of AFUDC. The funds from investors represent the cash required in order to pay for initial and replacement facilities.

During operation of the plant, the cash flow from operations is the net income plus the non-cash adjustments for depreciation, deferred income taxes, and amortization of debt expense. In later years as deferred income taxes become payable, deferred income taxes become a credit. Since net income continually decreases, the deferred income taxes payable reduce the annual cash funds available for dividends. In order to meet preferred dividends, funds from working capital must generally be utilized. The cash flow schedule also records the change in net current assets, the cash addition or deduction from working capital.

2.2.3.12 Balance Sheet

The balance sheet schedule shows what the utility plant owns (its assets), what it owes (its liabilities), and its net worth. During construction the utility plant assets are the value of its construction work in

progress and the working capital. Its liabilities and net worth are its proprietary capital and long term debt.

Once the plant enters service, the investment value of the construction work in progress is replaced by the value of the utility plant in service, which, for any given year, reflects the accumulated depreciation at year's end. Additional current assets include materials and supplies and other working capital (i. e., the cash represented by the positive or negative change in net current assets as listed in the cash flow schedule.)

2.2.3.13 Annual Cost of Service

An annual cost of service, in mills per kWh, is computed for each of the cost-of-service components. This is accomplished simply by dividing each of the operating expense elements and the return on rate base by the net annual energy production. The model permits plant capacity factor to be changed in any year to produce a varying annual net generation. An average cost of service over the plant's economic life is also computed.

2.2.3.14 Discounted Cash Flow Analysis and Financial Ratios

In addition to the annual financial balance-sheet computations that are outlined above, the model carries out a comprehensive discounted cash flow analysis of plant economics over the entire service life of the plant. It determines the effective after-tax discount rate and the associated capital recovery factor for each year of operation. It then uses these values in computations of the total present values over plant service life of: (a) the cost of service (busbar energy cost), (b) dividends on common and preferred stock, and (c) operation and maintenance expense. On the basis of these present value totals, it then computes the levelized busbar energy cost (the constant, or levelized, figure for the annual cost of service that would lead to the same total present value as was computed in the discounted cash flow analysis) and the associated levelized fixed charge rate.

The program also computes the values for a number of useful financial parameters, such as the cumulative dividend payout rates for

preferred and common stock, the effective tax rate, the tangible net worth, and the interest coverage ratio. Standard definitions for these parameters are given in Table 1.

Table 1
DEFINITIONS OF FINANCIAL PARAMETERS

<u>Parameter</u>	<u>Definition</u>
Discount Rate	Weighted average cost of capital over 30-year plant life with weighting proportional to discount factor in that year.
Annualized Fixed Charge Rate	Factor by which the present value of capital investment must be multiplied to obtain the contribution of capital investment to the annualized cost.
Levelized Busbar Energy Cost	Price per unit of energy (mills per kWh) which, if held constant throughout the life of the plant, would provide the required revenue, assuming that all cash flow interim requirements or excesses are borrowed or invested at the utility's internal rate of return.
Present Value	The present value of a cash flow is its real value adjusted for the interest that could be earned, or must be paid, between the time of the actual cash flow and the specified "present" time. The "present" in present value calculations is January 1, the first year of commercial operations.
Capital Recovery Factor	The uniform periodic payment, as a fraction of original principal, that will fully repay a loan including all interest.
Cumulative Dividend Rate	Total dividends earned from start of construction divided by dividends paid.
Interest Coverage	Ratio of earnings, excluding AFUDC, to interest on debt plus amortization of debt expense.
Tangible Net Worth	The sum of preferred and common stockholder's equity, including retained earnings.

2.3

PRELIMINARY FINANCIAL INCENTIVES ANALYSIS

The model described in the preceding section has been used in a preliminary evaluation of the impact of six different financial incentive strategies on the economics of photovoltaic power plant operation. Each candidate strategy was treated as a perturbation of a baseline case in which a photovoltaic power plant (basic plant cost: \$1743/kW, in 1990 dollars) is assumed to go on line in 1990. The basic financial and plant performance parameters of the baseline case are those summarized in Table 2.

2.3.1

Incentive Strategies

The primary criteria used in selecting the six candidate incentive strategies were that the incentives must have a reasonable chance of implementation and they must have one or more of the following direct effects: (a) reduce the cost of debt financing, (b) reduce the financial risk to investors (thereby reducing the cost of equity financing, (c) improve utility and stockholder earnings, or (d) reduce the overall cost of electric service (so that photovoltaic plant operation will not adversely impact the overall financial stability, growth, or rate structure of the utility company). Financial incentive strategies that would impact plant construction costs before financing were not considered, nor were direct operating subsidies.

The strategies selected for investigation are listed below:

1. Expensing of Interest During Construction

Under this incentive a utility would be allowed to treat the interest during construction as a current expense (rather than as an addition to the investment cost) for rate making and tax purposes. This would reduce the amount of construction cost capitalized and eliminate most of the tax loss carry-over. It would also allow a utility to include the cost of construction work in progress in its current rate base.

Table 2
FINANCIAL AND PERFORMANCE ASSUMPTIONS FOR
100 MW PHOTOVOLTAIC POWER PLANT

Financial Assumptions

Debt Equity Ratios, %	
Long term debt	55.0
Preferred stock	18.0
Common stock	27.0
Equity Ratio, %	45.0
Interest Rates, %	
Long term debt	9.0
Short term debt	
Financing Cost, %	
Long term debt	1.0
Short term debt	
Bond Retirement, years	
Initial facilities	30.0
Replacement facilities, 10 yr	0.0
Replacement facilities, 5 yr	0.0
Amortization of Financing Cost, yr	
Initial facilities	20.0
Replacement facilities, Group B	0.0
Replacement facilities, Group C	0.0
Dividend Rates, %	
Preferred	9.0
Common	15.0
Income Tax Rates, %	
Federal	48.0
State	9.0
Other Taxes, %	
During construction	1.0
Plant operations	2.0
Investment Tax Credit, %	10.0

Table 2

FINANCIAL AND PERFORMANCE ASSUMPTIONS FOR
100 MW PHOTOVOLTAIC POWER PLANT (Continued)

Investment Tax Credit Liability Rate, %	50.0
Book Depreciation, years	
Group A	30.0
Group B	0.0
Group C	0.0
Book Depreciation Method, Straight Line	
Tax Depreciation, years	
Group A	24.0
Group B	0.0
Group C	0.0
Tax Depreciation Method, Declining Balance/ Sum of Years Digits	
Materials and Supplies, %	1.0
Working Capital Allowance, %	1.0
Inflation Rate, %	
Plant construction	5.0
Replacement facilities	5.0
Operating and maintenance	5.0
Performance Assumptions	
Plant Size, megawatts	100.0
Plant Capacity Factor, %	40.7

2. 20% Investment Tax Credit, 80% Investment Tax Credit Liability Rate

The current 10% investment tax credit is effective in increasing a utility's cash flow. Because of low earnings and the limitation on the amount of investment tax credit that can be applied to taxes currently payable, however, many utilities are unable to take maximum advantage of the investment tax credit. In some instances, the investment tax credit is likely to expire before it can be utilized. This combination of an increase in the investment tax credit from 10% to 20% plus an increase from 50% to 80% in the proportion of taxes currently payable to which the credit can be applied would, however, increase a utility's earnings significantly. In evaluating this incentive, it is assumed that the investment tax credit is to be used to encourage plant investment and is not to be used to reduce the cost of service. With this incentive, a utility's dividend flow and interest coverage would be improved, thereby increasing its ability to secure financing at favorable terms.

3. Reduction in Federal and State Income Tax Rates

A reduction in both the federal and state income tax rates applicable to new photovoltaic power plants (to 40% and 7.5%, respectively) would reduce the cost of service, making the plant more attractive to a utility. It would also increase the dividend flow to stockholders and assist the utility in obtaining favorable financing terms.

4. 75/25 Debt Equity Financing, 8% Interest and Preferred Dividend Rate, 14% Common Dividend Rate

The structure of this financial incentive is based on the assumption that a federal loan guarantee has enabled a utility to obtain a 75% loan at an 8% interest rate. Since the loan guarantee reduces stockholder risk, the cost of equity funds is also reduced.

5. 100% Debt, 8% Interest, No Income and Other Taxes
This choice of financial parameters would be appropriate in the case of a government-owned, privately operated utility plant or a municipally owned utility plant. Financing is assumed to be from long term government bonds.
6. Combination of Financial Incentives 1, 2, and 4
This financial incentive combines the expensing of interest during construction, 20% investment tax credit, the 75/25 debt equity ratio, and reduced cost-of-capital rates.

2.3.2 Results of Preliminary Financial Incentives Analysis

The results of the financial incentives analysis are presented in Tables 3 and 4. Shown in Table 3 are the impact of each of the financial incentives on total construction costs, the discounted cash flow analysis, financial ratios, and the annual cost of service for the 1st, 15th, and 30th year of service. Table 4 contains a breakdown of the levelized cost of service (levelized busbar energy cost) into its constituent elements. The figures for the baseline case are displayed, for comparison, in the left-hand column of each table. The overall impact in each case can be summarized as follows:

1. Expensing of Interest During Construction
The expensing of interest during construction decreases the total construction cost 7.2% and the levelized busbar energy cost 6.0%. With the elimination of the tax loss carryover of the interest during construction, the effective tax rate increases from 47.1 to 49.2%. In addition, because of the higher taxes, there is a decreased dividend flow to stockholders.
2. 20% Investment Tax Credit, 80% Investment Tax Credit Liability Rate
The additional 10% investment tax credit increases the dividend flow to the common stockholders. The cumulative common

Table 3

**COMPARISON OF FINANCIAL INCENTIVES FOR
100 MW PHOTOVOLTAIC POWER PLANT**

		Financial Incentive Alternatives					
	Base Case	1. Expensing of Interest During Construction	2. 20% Investment Tax Credit	3. 40% Federal, 7.5% State Income Tax Rate	4. 75/25 Debt/Equity 8/8/14 Int. Div. Rate	5. 100% Debt 8% Interest No Income and Other Taxes	6. Alternatives 1, 2 and 4
<u>Construction Costs (Current dollars, \$/kW)</u>							
Initial Plant Costs	1,743	1,743	1,743	1,743	1,743	1,743	1,743
Allow for Funds Used During Construction	342	188	342	342	287	254	97
Other Taxes and Working Capital	50	50	50	50	50	17	50
Total Construction Costs	2,135	1,981	2,135	2,135	2,080	2,014	1,890
<u>Discounted Cash Flow Analysis</u>							
Levelized Busbar Energy Cost (mills/kWh)							
1990 dollars	100.1	94.1	100.1	95.6	75.6	57.7	68.4
1976 dollars	50.6	47.5	50.6	48.3	38.2	29.1	34.5
Annualized Fixed Charge Rate (%)	15.7	15.8	15.7	14.9	11.9	9.0	11.7
Capital Recovery Factor (%)	11.6	11.6	11.6	11.6	10.1	9.0	10.1
Discount Rate (%)	11.1	11.1	11.1	11.1	9.4	8.2	9.4
<u>Financial Ratios (30 years, %)</u>							
Cumulative Dividend Payout Rate							
Preferred Stock	7.3	6.9	7.4	8.1	5.6	0	5.3
Common Stock	9.8	8.4	10.8	10.2	8.7	0	5.7
Effective Tax Rate	47.1	49.2	41.5	38.5	36.7	0	23.6
Interest Coverage	3.3	3.0	3.4	3.2	1.7	1.0	1.7
<u>Annual Cost of Service (Current dollars, mills/kWh)</u>							
1st Year	137.5	127.9	137.5	127.3	106.9	68.6	94.3
15th Year	71.1	66.5	71.1	70.9	55.6	51.6	50.4
30th Year	42.3	40.5	42.3	41.5	40.1	37.9	37.9

Table 4
LEVELIZED COST OF SERVICE FOR 100 MW PHOTOVOLTAIC POWER PLANT
 (mills/kWh in 1990 Dollars)

Service Element	Base Case	Financial Incentive Alternatives					
		1. Expensing of Interest During Construction	2. Investment Tax Credit 20%	3. 40% Federal 7.5% State Income Tax Rate	4. 75/25 Debt/Equity 8.14 Div. Rate	5. 100% Debt 8% Interest No Income and Other Taxes	6. Alternatives 1, 2 and 4
Operations and Maintenance Expense							
Fuel	0	0	0	0	0	0	0
Other	5.9	5.9	5.9	5.9	6.1	6.4	6.2
Insurance	1.5	1.4	1.5	1.5	1.4	1.4	1.3
Total	7.4	7.3	7.4	7.4	7.5	7.8	7.5
Depreciation Expense	19.6	18.2	19.6	19.6	19.1	18.5	17.3
Taxes, Other Than Income	8.5	7.9	8.5	8.5	8.0	0	7.2
Provision for Income Taxes							
Federal	20.2	18.5	20.2	15.5	7.8	0	5.8
State	4.2	3.8	4.2	3.1	1.6	0	1.2
Total	24.4	22.3	24.4	18.6	9.4	0	7.0
Return On Rate Base	40.2	38.4	40.2	41.5	31.6	31.4	29.4
Levelized Busbar Energy Cost	100.1	94.1	100.1	95.6	75.6	57.7	68.4

stock dividend rate increases from 9.8 to 10.8%. The additional investment tax credit also lowers the effective tax rate 11.9%, and increases the interest coverage slightly.

3. Reduction in Federal and State Income Tax Rates

While the reduction in federal and state income tax rates decreases the effective tax rate 20.4%, it only decreases the levelized busbar energy cost 4.5%. The income tax rate reduction also increases the dividend flow to stockholders. The cumulative dividend payout rate for preferred stock increases from 7.3 to 8.1%, whereas the common stock payout rate increases from 9.8 to 10.2%.

4. 75/25 Debt Equity Financing, 8% Interest and Preferred Dividend Rate, 14% Common Dividend Rate

The impact of this incentive is to reduce income taxes and the cost of capital, thereby decreasing the levelized busbar energy cost by 25%. The lower cost of capital is reflected in the decrease in the discount rate from 11.1 to 9.3%. The higher interest costs resulting from the 75% debt rate decrease the effective tax rate 21.7%. The dividend flow to stockholders is decreased because of the lower dividend rates and lower net income.

5. 100% Debt, 8% Interest, No Income and Other Taxes

This incentive provides the lowest levelized busbar energy cost, fixed charge rate, capital recovery factor, and discount rate. The 100% debt financing provides the lowest cost of capital. With no income taxes and dividends to pay, the levelized cost of service is reduced 42.4%. Although this incentive basically applies to a municipal or federally owned utility, it could also apply to a situation where the utility is government owned but privately operated.

6. Alternatives 1, 2 and 4

This incentive combines the expensing of interest during construction, 20% investment tax credit, and the 75/25 debt/equity financing ratio. It is assumed that such financing is achieved as a result of a federal loan guarantee that enables the utility to secure an 8% loan and obtain equity financing at lower rates.

While the total construction cost is decreased 11.5%, the levelized busbar energy cost is decreased 21.7% to 68.3 mills per kWh. With the 20% investment tax credit, the effective tax rate is reduced 50.4%. Without the increase (from 50% to 80%) in the proportion of the taxes payable to which the credit can be applied, however, the effective tax rate would only have been reduced 12.7%; most of the additional 10% investment tax credit could not have been utilized.

2.3.3 Implications of Results

Of the six incentives that were considered, only those that increased the debt/equity ratio resulted in significant decreases in busbar energy cost. This result implies that federal loan guarantees might be the most effective way of improving the competitive position of photovoltaic power plants. It must be recognized, however, that investor-owned utilities may not be in a position to utilize such financing, because (a) existing bond covenants may place a maximum ceiling on bonded indebtedness, (b) stockholder approval may be required, or (c) a federally guaranteed loan may restrict future financing.

The other incentives considered primarily impact the overall utility system's cash flow and earnings, without significantly changing the busbar cost of energy. If photovoltaic plants were already economically competitive, however, such incentives might be the strategies of choice in persuading a utility to choose a photovoltaic plant in preference to an alternative that would otherwise be economically equivalent.

SECTION 3

SOCIETAL COSTS OF COAL-FIRED ELECTRIC POWER GENERATION

3.1 INTRODUCTION

Traditionally, the market price of the energy produced from a given source has determined the degree of societal acceptance and the share of the energy market that is gained by that source. It is widely believed, however, that the market prices of electric energy from conventional fossil-fuel or nuclear generation plants do not adequately reflect the total societal costs or external diseconomies of generation. Since photovoltaic solar power generation is inherently free of many of the sources of such diseconomies, the projected price of the energy produced may not reliably indicate the relative merit of this new source of energy. The non-internalized societal costs (i. e., costs to society that are not included in the price of electricity) associated with conventional generation constitute a hidden subsidy that may put photovoltaic generation at an unfair disadvantage. It is therefore appropriate to investigate the nature and magnitudes of these non-internalized costs.

In this report, an account is given of an attempt to assess the full non-internalized costs of coal-fired power generation. These societal costs are viewed as external diseconomies or indirect forced subsidies whose price has to be ultimately paid by society at large. In this analysis, no attempt has been made to include the societal benefits (societal economies) that are associated with coal-fired power production, since these are, in general, common to all electric generation methods. The purpose of this report is rather to provide a quantitative estimate of the societal diseconomies that are associated with conventional coal-fired power plants in order to assist in the determination of the appropriate size of federal incentives or subsidies that may be justifiable for photovoltaic solar power plants.

The major thrust of the present study has been to incorporate, wherever applicable, a quantitative, systematic approach for compiling these societal costs. Extensive and varied literature on these different types of societal damage was reviewed with the objective of identifying the types of damage that contribute significantly to the total. A critical assessment was then made of the data found on these significant damage elements, and their total economic impact (in mills/kWh) was computed on the basis of the data judged to be most reliable. In these computations, it was assumed that the coal-fired power generation systems were in compliance with current federal law (in particular, the Coal Health and Safety Act and the New Source Performance Standards of the Clean Air Act). The resulting numbers, of course, are subject to appreciable uncertainty, largely because of their dependence on (a) long chains of assumptions linking original cause to resulting damage cost and (b) the particular set of social priorities that are reflected in the unit cost assigned to each type of ultimate damage.

The computation methodology is based on the implicit assumption that the effective inflation and discount rates associated with these societal costs are approximately the same. This simplified assumption was made out of necessity, as a result of the relative uncertainty of the assigned unit damage costs, the associated different life cycles of various types of damage and their recovery periods, the uncertainty of the inflation rates for costs resulting from various damages (e.g., property values, health costs, etc.), the uncertainty of future societal discount rates (which are different from the discount rates of industry and business), and the lack of ability to account for the unrecoverable and intangible costs associated with certain damages (e.g., damage of being ill, individual pain and suffering from injuries, environmental changes that can never be full restored, etc.).

Assessment of the full non-internalized costs of coal-fired power generation must take into account the entire production cycle, including fuel production (mining), fuel transportation, and power generation (Refs. 37, 38). In Figure 3 are listed the principal sources of societal damage that are associated with each of these three elements of the coal-fired power generation

FUEL PRODUCTION		FUEL TRANSPORTATION		POWER GENERATION	
DAMAGE SOURCE	SOCIETAL DAMAGE TO:	DAMAGE SOURCE	SOCIETAL DAMAGE TO:	DAMAGE SOURCE	SOCIETAL DAMAGE TO:
COAL DUST	PROPERTY VALUES	ACCIDENT	PEOPLE: INJURIES AND DEATHS	EMISSION OF: SO _x (sulfates)	PHYSICAL HEALTH
MINE WASTES	ROAD AND HIGHWAYS	OVERLOADING OF ROAD BEDS	INCREASED ROADBED MAINTENANCE	NO _x	MATERIALS
COAL DEBRIS	AGRICULTURE: ENVIRONMENT		PROPERTY DAMAGE	PARTICULATES	AESTHETICS
LAND DISTURBANCE	ANIMAL LIFE			METALLIC TRACE ELEMENTS	MENTAL HEALTH
UNDERGROUND DISTURBANCE	HUMAN LIFE			CO	CLIMATE
EXPOSURE TO POTENTIAL ACCIDENTS	HEALTH OF MINERS			POLYCYCLIC HC	DOMESTIC ANIMALS
	MINE-SITE COMMUNITIES				WILDLIFE, VEGETATION
	LAND (subsidence)				
	WATER SYSTEMS				

Figure 3
SOCIETAL COSTS OF COAL-FIRED ELECTRIC
POWER GENERATION SYSTEM

system. Also shown are the main types of damage that occur. In preparing this figure, no attempt was made to relate (by juxtaposition) a damage source with the resultant damage. Many societal damages result from the synergistic effect of several damage sources, and several types of damages may be produced by a single damage source. Some of the listed damages (e.g., to property values and to health) can, in principle, be quantified in economic terms, although there is considerable disagreement about the computed magnitudes. Other damages (e.g., to mental health or to climate) are so uncertain, at least at present, that no economic quantification is possible.

In the following sections, a more detailed description of the various damage elements and their associated societal costs are given for coal production, coal transportation, and coal-fired power generation. The associated societal costs do not include the current backlog of previous unsupported societal costs left over from earlier coal-fired electric power production. However, in many instances estimates of the magnitude of specific societal costs are based upon modifications or adjustments of the corresponding figures for these costs as determined before the recent federal acts were instituted to curb future societal damages. For those societal cost estimates that required specification of power plant characteristics, a 1000 MW_e coal-fired power plant operating at 0.8 capacity factor was assumed. The estimates of societal costs that are given in the following sections are intended to represent coal-fired electric power generation in the mid-1980's and are given in 1976 dollars.

3.2 SOCIETAL COSTS OF COAL PRODUCTION FOR POWER GENERATION

Coal production causes a variety of societal damages which can be divided into the two groups: (a) health and welfare damage and (b) environment-related damage. The health and welfare damage is primarily borne by the coal miners and mine-site communities. The environment-related damage is wider in scope and generally covers regions extending several hundred miles from the mine site. These damages are different, of course, for underground and surface mining of coal. In the U.S.A., the proportionate

amount of coal produced from surface mining has increased from approximately 10% in 1940 to almost 50% by 1975. At present, it is very difficult to predict the exact percentage of coal that will come from surface mining in the future, although it is generally agreed that it could be up to 60% of the total coal production. In this analysis it is assumed that future coal production will be evenly divided between the production modes of underground and surface mining.

Before analyzing the future societal costs of coal production, a brief description of health and safety standards in coal mining, as affected by the Federal Coal Mine Health and Safety Act of 1969, is given in Section 3.2.1. This is followed by discussions of the societal health and welfare costs (Section 3.2.2) and environment-related societal costs (Section 3.2.3) of coal production.

3.2.1 Health and Safety Standards for Coal Mining

Traditionally, occupational health and safety problems of coal mining have been the most damaging aspects of coal production. Coal miners' pneumoconiosis or "black-lung" disease is the most serious occupational health hazard associated with underground coal mining. However, under the Federal Coal Mine Health and Safety Act of 1969 (83 stat. 742; 30 U.S.C. 801; Public Law 91-173), all existing and all future coal mines in the U.S.A. must be operated in accordance with the mandatory health and safety standards of this act. The law should have the long-term effect of significantly reducing pneumoconiosis as a major occupational health problem.

Incidence of pneumoconiosis is highly correlated with levels of coal dust exposure. The Coal Mine Health and Safety Act of 1969 called for limiting the coal dust level to 3 mg/m^3 , and after December 31, 1972 this limit was dropped to 2 mg/m^3 . Under this law, approved respirators that meet specific criteria must be provided for use by workers exposed to dust deleterious to health. Standards for mine ventilation quality, quantity, and velocity are set, as well as standards for ventilation control devices to assure uninterrupted coursing of air in underground workings. Noise standards setting the maximum sound levels to which mine workers can be

exposed without use of devices are included. Standards of qualification are set for persons certified to test air quality and quantity, perform electrical work, and operate mine hoists. Approval by the Bureau of Mines of the roof control program is required, and procedures are specified for installation, maintenance, and inspection of roof support systems. Standards for storage, transportation, handling, and use of explosives, as well as for transportation of men, equipment, supplies, and coal, are specified. Automatic detection and suppression standards for fire protection are enumerated for specific areas and equipment.

For surface mining, the Act specifies recommended methods of disposing of coal refuse to prevent spontaneous ignition, slides, and impoundments of surface water. Standards have also been enumerated for inspections of active working areas and surface installations on a daily basis by certified persons. In order to assure compliance with this Act, periodic regular and spot inspections of surface facilities at all coal mines and work areas at surface coal mines are made by Bureau of Mines inspectors, who are duly authorized representatives acting on behalf of the U.S. Secretary of the Interior. Further details of the Federal Coal Mine Health and Safety Act and its anticipated effects on the health and safety of coal-mine workers are given elsewhere (Ref. 39).

3.2.2 Health and Welfare Costs of Coal Production

It is very difficult to devise a completely acceptable procedure for assigning dollar values to the societal health and welfare costs of coal production. Converting coal miners' death, disability, or health degradation figures into costs in terms of dollars is generally accomplished simply by adding together the direct costs of injury treatment and the individual costs of foregone earnings. Essentially this procedure was used in our study, although it is recognized that some potentially significant costs are ignored. For example, the procedure does not allow for the additional amount that society or an individual would pay in order to reduce mortality and to maintain good individual health, free from the suffering and pain that result from sickness or injury. Nor does it include the additional societal costs resulting

from the loss of the services to family and community that would otherwise be performed by a dead or incapacitated head of household.

For the purposes of this study, the damages to societal health and welfare from coal production were divided into the following four categories:

1. Black lung disease of miners
2. Mine accidents
3. General health degradation of miners
4. Rehabilitation of mine-site communities

In the following sections, the details of the methods used to estimate the costs resulting from each of these damages are discussed and the results are summarized.

3.2.2.1 Black Lung Disease of Miners

Black lung disease, or pneumoconiosis, is caused by long-continued inhalation of coal dust, resulting in disruption of cleaning mechanisms in the lung and in eventual cell damage. Complicated pneumoconiosis causes disability and seriously shortens life expectancy. It has been estimated (Ref. 40) that the number of U.S. coal miners suffering from the disease is as large as 125,000. It is also estimated (Ref. 41) that total payments from all sources to coal-miners and their widows as a result of black lung disease had amounted to \$1 billion by 1973. The total is expected to reach \$8 billion by 1980, indicating that the current annual cost is in the neighborhood of \$1 billion per year. Most of these costs are non-internalized, since only a small fraction of the total are compensated by disability payments from the coal industry (Ref. 37).

It has been argued that future societal costs from black lung disease will drop sharply when the new limits on respirable coal dust in mines (imposed by the Mine Safety Act of 1969) have had a chance to take effect. Since modern coal mining equipment and continuous mining techniques tend to create more dust than did earlier methods, however, it may prove difficult to maintain the new coal dust standards. Since black lung disease is

a result of years of exposure and takes a long time to become evident, there are as yet no data on the actual effect of the changed air quality standards. For the purposes of this study, therefore, it was assumed as a rough approximation that the future non-internalized annual cost to society as a result of miners' black lung disease will be 20% of the current annual cost, the reduction being a result either of improved air quality in mines or of the inclusion of some of the black lung cost in the price of coal.

The details of the calculation of the projected societal cost of miners' black lung disease, expressed in mills per kWh of coal-fired electricity generation, are presented in Table 5.

3.2.2.2 Mine Accidents

Mine accidents are another hazard of the coal mining industry. Comparative injury data indicate that the number of man-hours lost as a result of accidents is higher in the coal industry (Refs. 42, 43) than in any other. There is, of course, great variation in the accident records of different coal mines. The explanation of the differences seems to be in the attitude towards safety, the safest mines being those owned by the big steel companies (Ref. 44). Thus, the accident rate associated with coal production for electric power plants is probably higher than the national average. Coal production companies pay some of these costs through workman's compensation programs and insurance premiums, and they in turn pass them on to electric utilities in the price of coal. However, the income-replacement benefits paid to coal miners are significantly below their normal income. For example, in eight of the coal-producing states, the maximum benefits are below the poverty level (\$82.69 a week for a family of four) set by the U.S. Department of Labor in 1973 (Ref. 41). The more generous states like Alaska and Arizona pay an injured miner only \$175 and \$150 a week, respectively - far short of his otherwise earned income of \$300/week (Ref. 41). Table 5 gives details of the procedure used to estimate the non-internalized portion of the societal costs that are associated with mine accidents, i.e., the costs in excess of the internalized costs associated with the disability benefits.

The estimates presented in Table 5 are based on a number of underlying assumptions. For example, it has been assumed that coal production for use in power plants is derived half from underground mines and half from surface mines. On the basis of data presented in Reference 41, the expected future fatal injury rate in the course of coal production for power plants is then 0.33 per million tons, and the future non-fatal injury rate is expected to be 21 per million tons. Since the annual coal tonnage requirement for a 1000 MW power plant (6×10^9 kWh/year) is $3.5 (10^6)$ tons, one can project 1.2 fatal injuries and 74 non-fatal injuries per year in connection with the production of coal for such a plant. The total societal cost of a fatal injury has been assumed to be \$300,000, on the basis that such an injury represents 6000 days (30 years) of lost wages at \$50/day (Ref. 45). Of this total, it has been assumed that 50% will be internalized (i.e., included in the price of coal, and thus in the price of electricity), so that the non-internalized portion is \$150,000/death.

In the case of non-fatal injuries, it has been assumed that the period of disability is 1 year, or 200 days, so that the total wage loss per injury (at \$50/day) is \$10,000. If, again, 50% of this cost is internalized, the non-internalized portion is \$5000 per injury.

3.2.2.3 General Health Degradation of Miners

Besides pneumoconiosis, coal miners also suffer from chronic bronchitis, emphysema, pneumonia, heart disease, pleurisy, etc. (Ref. 37). If it is assumed that continued exposure to these diseases reduces the life expectancy by five productive years, or 1000 days, the total societal cost per miner (at \$50/day) is \$5000, none of which is internalized. The calculation of the associated societal cost of coal mining for power production is shown in Table 5.

Table 5
SOCIETAL HEALTH AND WELFARE COSTS OF COAL
PRODUCTION FOR POWER GENERATION

Societal Damage	Societal Cost Calculation	Estimated Societal Costs, mills/kWh
Black Lung Disease Miners	$\frac{0.2 \times 10^9 \text{ (a)} \times 0.53 \text{ (b)} \times 1.3 \text{ (c)}}{2 \times 10^{12} \text{ (d)} \times 0.46 \text{ (e)}}$	0.15
Mine Accidents	$\frac{1.2 \text{ (f)} \times 150,000 \text{ (g)} + 74.0 \text{ (h)} \times 5000 \text{ (i)}}{6000 \times 10^6 \text{ (j)}}$	0.09
General Health Degradation of Miners	$\frac{136,300 \text{ (k)} \times 0.00652 \text{ (l)} \times 50,000 \text{ (m)}}{30 \text{ (n)} \times 6000 \times 10^6 \text{ (j)}}$	0.25
Rehabilitation of Mine Site Communities	$\frac{2000 \text{ (o)} \times 0.1 \text{ (p)} \times 0.1 \text{ (q)} \times 3600 \text{ (r)} \times 5 \text{ (s)}}{6000 \times 10^6 \text{ (j)}}$	0.06
Total Health & Welfare Societal Costs of Coal Production for Power Generation		0.55

Notes:

- (a) Total annual cost resulting from black lung disease (20% of 1973 cost) in future years. Compliance with the Federal Coal Health and Safety Act of 1969 is assumed.
- (b) Fraction of total U.S. coal consumed by electric power generation.
- (c) Consumer Price Index increase between 1973-1976.
- (d) Annual total electric power generated in U.S.

Table 5

SOCIETAL HEALTH AND WELFARE COSTS OF COAL PRODUCTION
FOR POWER GENERATION (Continued)

- (e) Fraction of national electric power generated in coal-fired plants.
- (f) Estimated number of fatal injuries/year in coal production to support 1000 MW_e coal-fired plant.
- (g) Estimated societal cost of one fatal injury (to the extent not reflected in the price of coal).
- (h) Estimated number of non-fatal injuries/year in coal production to support a 1000 MW_e coal-fired plant.
- (i) Estimated societal cost of one non-fatal injury (to the extent not reflected in the price of coal).
- (j) Estimated annual kWh of electric energy generated by 1000 MW_e coal-fired power plant.
- (k) Number of working miners in coal industry.
- (l) Fraction of total miners required to support a 1000 MW_e coal-fired plant.
- (m) Estimated societal costs due to a reduction in the productive life expectancy of an average coal miner by 5 years.
- (n) Average number of productive working years of a coal miner.
- (o) Average number of direct and indirect numbers of labor-force required for coal production to support a 1000 MW_e coal-fired plant.
- (p) Estimated average fraction of coal production labor force requiring rehabilitation and other welfare support at any time during their working careers.
- (q) Estimated average fraction of those discussed in footnote (p) who begin requiring assistance in a given year.
- (r) Estimated annual costs required for the rehabilitation and welfare of a coal production worker's household.
- (s) Estimated average number of years required for the rehabilitation of a family to self-supporting status.

3.2.2.4 Rehabilitation of Mine-Site Communities

Rehabilitation of mine-site communities towards the end of the coal production phase is another societal cost element that is not included in the price of coal. Coal mining creates a disruptive economic impact on the mine-site communities. Many times, the local governments go bankrupt after the end of the coal mining, when the community's business and population declines (Ref. 46). The coal miners and other young and able-bodied workers often move to another new mine-site community, leaving behind a deserted community of largely unemployed people. State and federal governments then have to provide welfare and rehabilitation assistance to families who were previously supported by the mines or by business from the coal mining labor force. Estimates of the societal cost of rehabilitation of mine-site communities, and the details of the estimation procedure, are given in Table 5.

3.2.3 Environment-Related Societal Costs of Coal Production

Environment-related damages due to coal production are numerous and complex, and estimates of the resulting societal costs are necessarily both vague and controversial. This situation is further complicated by the fact that environment-related societal costs are very dependent on the characteristics of a given mine-site location and on numerous other regional environmental factors.

For the purposes of this study, the environment-related societal damages resulting from coal production were divided into the following categories:

- a. Lowered Property Values
- b. Land Subsidence
- c. Diminished Recreational Values
- d. Acid Mine Drainage
- e. Damages from Disposal of Mine Wastes
- f. Need for Land Reclamation

In the following sections, these types of damage and the procedures used in estimating the associated societal costs are discussed, and the resulting cost estimates are reported.

3.2.3.1 Lowered Property Values Near Mine Site

Coal production generally lowers the assessed value of land and buildings near the mine site, primarily as a result of increased noise, dust, and general unsightliness. There is also significant damage to the roads and highways that is caused by the moving of heavy equipment and coal trucks. This drop in the assessed property values is heavily dependent on the socioeconomic conditions near a specific mine site, the type of coal extraction mode (viz, underground or strip mining), and the time scale.

Albright (Ref. 47) gives some data on the average assessed value of coal-producing lands in Ohio. His data indicate that the average value of land decreased by 15-30% and that of buildings by approximately 25%. Grossniklaus (Ref. 48) has also reported similar changes in land values near mine-site regions. Partly on the basis of these data, estimates were made of the societal costs of lowered property values due to coal production for electricity generation. The calculation procedure and the results are presented in Table 6.

3.2.3.2 Diminished Recreational Values of Land

Strip mining of coal diminishes the recreational value of land, because land disfiguration and water pollution reduce the influx of people interested in pursuing recreational activities. One study gives an estimate of \$24 per acre per year as the annual cost resulting from diminished recreational value (Ref. 46). The author further estimates that an additional 1.25 acres are diminished in value for each acre of mined surface. Estimates of the societal costs associated with such reductions in the recreational values of land as a result of surface coal mining are also presented in Table 6.

3.2.3.3 Land Subsidence Costs

In the underground coal mining regions of Appalachia, land subsidence above the coal mines has caused extensive property damage.

Table 6
ENVIRONMENT-RELATED SOCIETAL COSTS OF COAL
PRODUCTION FOR POWER GENERATION

Societal Damage/ Requirement of Environment Restoration	Societal Costs Calculation and Assumption	Estimated Societal Costs, mills/kWh
Lowered Property Values	$\frac{8000^{(a)} \times 6^{(b)} \times 5000^{(c)} \times 0.25^{(d)}}{30^{(e)} \times 6000 \times 10^6^{(f)}}$	0.33
Diminished Recreational Values (Surface Mines)	$\frac{8000^{(a)} \times 2.25^{(g)} \times 0.5^{(h)} \times 15^{(i)} \times 24^{(j)} \times 1.75^{(k)}}{30^{(c)} \times 6000 \times 10^6^{(f)}}$	0.02
Land Subsidence (Underground Mines)	$\frac{8000^{(a)} \times 0.5^{(h)} \times 0.5^{(l)} \times 10,000^{(m)} \times 1.75^{(k)}}{30^{(c)} \times 6000 \times 10^6^{(f)}}$	0.19
Acid Mine Drainage (Surface Mines)	$\frac{1.73 \times 10^9^{(n)} \times 1.45^{(o)} \times 0.5^{(h)} \times 10,000^{(p)}}{4.4 \times 10^9^{(q)} \times 20 \times 10^6^{(r)}}$	0.14
(Underground Mines)	$\frac{0.2^{(s)} \times 1.45^{(o)} \times 0.5^{(h)} \times 10,000^{(p)}}{20 \times 10^6^{(r)}}$	0.07
Disposal of Mine Wastes (Surface Mines)	$\frac{0.28^{(t)} \times 0.5^{(h)} \times 1.45^{(o)} \times 10,000^{(p)}}{4^{(u)} \times 20 \times 10^6^{(r)}}$	0.03
Land Reclamation (Surface Mines)	$\frac{0.5^{(v)} \times 1.45^{(o)} \times 10,000^{(p)} \times 0.5^{(h)}}{20 \times 10^6^{(r)}}$	0.18
Total Environment-Related Societal Costs of Coal Production for Power Generation		0.96

Notes

- (a) Estimated average direct land requirement for coal production to support a 1000 MW_e coal-fired plant for 30 years.
- (b) Multiplying factor to estimate the total amount of land directly and indirectly affected by coal production.
- (c) Estimated average property value per acre (land plus buildings).
- (d) Estimated decline in property value (as fraction of original value).
- (e) Average number of operating years for a coal-fired power plant.
- (f) Estimated annual average kWh electric power generated by 1000 MW_e coal-fired plant.
- (g) Ratio of area in which recreational values are damaged to area actually surface-mined.
- (h) Assumed fraction of coal utilized in power generation that comes from surface mining.
- (i) Average years of reduced recreational activities.
- (j) Reduced yearly recreational value per acre in 1968 dollars.
- (k) Consumer price index increase for 1967-1976 period.
- (l) Assumed fraction of abandoned underground coal mines that would require backfilling.
- (m) Cost estimate per acre for backfilling abandoned mines.
- (n) 1970 cost estimate of controlling acid mine drainage due to surface mines.
- (o) Consumer price index increase for 1970-1976.
- (p) Average heat rate of power plant turbine, Btu/kWh.
- (q) Total coal production up to year 1970 by surface mining.
- (r) Average heat content of one ton of coal, Btu.
- (s) 1970 cost estimate (\$/ton of coal) for abating acid mine drainage due to underground coal mines.
- (t) Estimated cost to dispose of each ton of mine wastes.
- (u) Average unit quantity of coal production for each unit of resulting mine wastes.
- (v) Estimated societal cost for reclaiming land for each ton of surface-mined coal.

Approximately one third of the underground mine area had subsided by 1969. Quarries (Ref. 49) estimated in 1971 that there was a threat of additional subsidence in more than 250 communities in 28 states. Cost of backfilling abandoned mines had ranged from \$10,000 to \$15,000 per acre during the 1965-1970 time period in Pennsylvania coal regions (Ref. 50).

The manner in which these data were used in this study to derive estimates of the societal cost of land subsidence caused by underground coal mining is shown in Table 6; the result is also given there.

3.2.3.4 Costs of Acid Mine Drainage

Acid mine water, which drains from both surface and underground coal mines, kills the aquatic life in streams and makes the water unfit for human consumption. It was estimated in 1966 that mining operations in the Appalachian region alone had damaged 6000 miles of streams and 15,000 acres of land impoundments (Ref. 44).

Because of the very complex nature of aquatic ecosystems and the difficulty in assigning economic value to ecosystem damage, however, it is very hard to develop a fully acceptable method for estimating the societal cost of mine drainage. The estimates used in this study are therefore based on the estimated costs of controlling the drainage or of processing the water to render it harmless. In 1969 the U.S. Department of the Interior estimated that to achieve 95% control of all acid mine drainage would require a capital investment of $\$6.6 \times 10^9$, of which about $\$1.73 \times 10^9$ is due to surface mining (Ref. 51). In another study it was estimated, on the basis of experience in treating acid mine water at four deep bituminous coal mines in Pennsylvania, that the cost of treatment amounted to about \$0.20 per ton of coal produced (Ref. 41).

The procedures used in estimating the societal costs resulting from acid mine waters, and the results, are presented in Table 6. The cost estimate in the surface mining case is based on the Interior Department estimate of the cost of controlling drainage, while the estimate of costs resulting from underground mining is based on the treatment cost indicated by the Pennsylvania study.

3.2.3.5 Disposal of Mine Wastes

Mine wastes resulting from underground coal mining are often discarded into huge piles. These large amounts of debris are very unsightly and create a real environmental problem. Bureau of Mines studies of mining operations in Kentucky and Alabama (Ref. 52) showed that each ton of coal produced from underground coal mining resulted in creating 1/4 ton of mine waste materials and that it would cost the taxpayers an average of \$0.28 to dispose of each ton of mine wastes. The estimates made in this study of the societal cost of the disposal of mine wastes, as shown in Table 6, are based on this figure.

3.2.3.6 Land Reclamation Costs

Land reclamation of surface mines means the elimination of off-site environmental damage and the return of the mined land to productivity--biologic, economic, recreational, etc. It does not mean that the land has to be restored to its previous state of ecology and topography. Reclamation efforts in the U.S. have ranged from a mere aerial reseeding of spoil banks all the way to nourishment of lush growth in the original topsoil, and the corresponding costs are estimated by one source to range from \$500 to \$1500 per acre (Ref. 50). Another cost estimate was developed in a Bureau of Mines study of land reclamation projects in the Appalachian states, which concluded that it would cost \$1100 per acre to return surface-mined land to productive use. Yet another cost figure can be found in a report of the Council on Environmental Quality (Ref. 53) where \$2000 per acre is given as the estimated cost of reclaiming land disturbed by surface mining. It should be noted, however, that these estimates are based in general on experience in the Appalachian region where most of the surface-mined land is flat or rolling and there is adequate rainfall. Somewhat similar topography and rainfall are characteristic of the regions in Germany where perhaps the best land reclamation program in the world has been in progress for some years (Ref. 54). There, over 33,000 acres of surface-mined land have been reclaimed for forestry, agriculture, and recreational use at a cost ranging

from \$3000 to \$4500 per acre. On the basis of this German experience, it has been estimated that similar results could be achieved in the U.S. at a comparable cost, or ~\$4000/acre (\$0.50/ton of coal).

For the purposes of this study it has been assumed that the last of the above cost estimates, \$4000/acre or \$0.50/ton of coal, represents the average cost of reclaiming surface-mined land in the U.S. The details of the calculation of the corresponding contribution to the societal cost of coal-fired power generation are given in Table 6.

It is recognized that these figures are likely to be underestimates. Many surface-mined lands may never be fully restored, no matter how much money is spent. This is particularly probable in the arid western coal regions of the U.S., from which an increasing proportion of the nation's coal supply is expected to come in future years. Since there is, however, no generally acceptable way to define the residual societal cost incurred when such lands are left in an only partially restored state, these latter somewhat intangible costs have had to be left out of the quantitative totals.

3.3 SOCIETAL COSTS OF TRANSPORTING COAL FOR POWER GENERATION

The principal societal costs of coal transportation are those resulting from deaths and injuries in accidents - mainly railroad accidents, since most U.S. coal is transported by rail. The majority of rail accidents involving death or injury occur at grade crossings under circumstances where railroad liability is small or zero. As a result, most of these costs are not paid by the railroad and therefore are not reflected in the cost of shipping, or in the ultimate cost of the delivered product.

The total societal cost of the accidental deaths and injuries that are associated with the transport of coal from mine to power plant has been estimated in this study via two slightly different chains of reasoning (details are presented in Table 7). The first chain, Method 1, is based on the assumption that since about 10% of all U.S. railroad cars are used in transporting coal to power plants (Ref. 56), about 10% of the 2300 deaths and 20,000 injuries that occur each year in accidents involving trains or railroad

An alternative chain of reasoning begins with the assumption that the fraction of accidental deaths and injuries resulting from transportation of coal to power plants is proportional to the number of railcar-miles involved. It is again assumed that the rate of accidental death and injury is the same, per ton of coal, for other modes of transportation as it is for rail transport. The chain of reasoning in this case is outlined in the lower half of Table 7, as Method 2, and the resulting societal cost figure is 0.13 mills/kWh. In this case the corresponding average numbers of fatal and non-fatal injuries associated with transporting coal for a 1000 MW power plant generating 6000×10^6 kWh/year are 2.4 and 20.8, respectively. Estimates in a recent report by the Council on Environmental Quality (Ref. 57) lead to almost identical figures, namely, 2.3 deaths and 23.4 non-fatal injuries annually as a result of transporting coal for such a power plant.

As indicated in the notes to Table 7, it has been assumed in both chains of computation that the average societal cost of an accidental death is \$300,000 and that of a non-fatal injury is \$2600. These numbers are based on a procedure suggested by the American National Standards Institute (Ref. 45) in which a fatal injury is treated as equivalent to the loss of 6000 work days and a non-fatal injury as equivalent to the loss of 52 work days. If the average "value" of a lost work day (lost income) is taken to be \$50 (Ref. 50), then the \$300,000/death and \$2600/injury numbers are obtained.

3.4 SOCIETAL COSTS OF COAL COMBUSTION IN ELECTRIC POWER PLANTS

The dominant sources of societal damage that result directly from the operation of coal-fired power plants are the combustion products that are emitted from the flue stacks. These pollutants are probably, in fact, the largest sources of damage in the entire coal-fired power generation cycle.

The amount of pollutant material that is emitted by a coal-fired power plant varies significantly from one plant to another, depending strongly on the type and quantity of coal that is burned and on the type of pollution control equipment used in the plant. In Table 8 are shown the hourly

Table 7
SOCIETAL COST OF TRANSPORTING COAL
FOR POWER PRODUCTION

Method 1

Number of fatal injuries per year accreditable to transport of coal for power generation

$$= \frac{2300^{(a)} \times 0.1^{(b)}}{0.73^{(c)}} = 315$$

Number of non-fatal injuries per year accreditable to transport of coal for power generation

$$= \frac{20000^{(d)} \times 0.1^{(b)}}{0.73^{(c)}} = 2740$$

$$\text{Societal Cost} = \left[\frac{315 \times 300,000^{(e)} + 2740 \times 2600^{(f)}}{2 \times 10^{12(g)} \times 0.46^{(h)}} \right] \times 1000^{(i)} = 0.11 \text{ mills/kWh}$$

Method 2

Ratio of railcar-miles (equivalent) used in coal transportation for power production to total U.S. railcar-miles

$$= \frac{1200^{(j)} \times 6 \times 10^8^{(k)} \times 0.53^{(l)}}{800^{(m)} \times 3 \times 10^{10(n)}} = .159$$

Number of fatal injuries per year accreditable to transport of coal for power generation

$$= 2300^{(a)} \times .159 = 366$$

Number of non-fatal injuries per year accreditable to transport of coal for power generation

$$= 20000^{(d)} \times .159 = 3180$$

$$\text{Societal Cost} = \left[\frac{366 \times 300,000^{(e)} + 3180 \times 2600^{(f)}}{2 \times 10^{12(g)} \times 0.46^{(h)}} \right] \times 1000^{(i)} = 0.13 \text{ mills/kWh}$$

Table 7
SOCIETAL COST OF TRANSPORTING COAL
FOR POWER PRODUCTION (Continued)

Notes

- (a) Total annual deaths in railroad accidents.
- (b) Fraction of total number of U.S. railcars that are used for transporting coal to power plants.
- (c) Fraction of the U.S. coal tonnage that is transported by rail.
- (d) Total annual non-fatal injuries in rail accidents.
- (e) Societal cost of one fatal injury, dollars.
- (f) Societal cost of one non-fatal injury, dollars.
- (g) Total annual electric energy generated in U.S., kWh.
- (h) Fraction of U.S. electric power generated in coal-fired plants.
- (i) Number of mills per dollar.
- (j) Average round trip mileage from coal mine to power plant.
- (k) Total annual coal production in U.S., tons/year.
- (l) Fraction of total U.S. coal consumed in power generation.
- (m) Average load of railroad coal car, tons.
- (n) Annual railcar-miles of rail traffic in U.S.

equipment (Ref. 56) should be assigned to coal-fired power generation. It is also assumed that (a) the proportion of coal for power plants that is shipped by rail is the same as the proportion, 73% (Ref. 55), of all coal that is shipped by rail and (b) the numbers of accidental deaths and injuries incurred by shipping coal to power plants by other means (barge, truck) are the same, per ton of coal, as for rail shipment. The elements of this first chain of reasoning are spelled out in the upper half of Table 7 and lead to a figure of 0.11 mills/kWh for the total societal cost resulting from the transport of coal to power plants. From another point of view, this chain of reasoning would lead to the conclusion that, on the average, 2.1 deaths and 17.9 non-fatal injuries take place annually in transporting coal for a typical 1000 MW power plant generating 6000×10^6 kWh/year.

Table 8
HOURLY AMOUNT OF EMISSIONS PRODUCED BY A TYPICAL
1000 MW_e FOSSIL-FUEL FIRED POWER PLANT

Fuel Used	Emissions per Hour* (lb)		
	SO ₂	NO _x	Particulates
Coal (10% ash and 2% sulfur)	32,000	8,430	67,400
Oil (2% ash)	21,000	6,930	670
Gas	4	3,730	140

* Heat Rate: 10⁴ Btu/kWh

amounts of the three major classes of pollutant (viz, SO₂, NO_x, and particulates) that are emitted by a typical 1000 MW_e coal-fired plant operating without any pollution control equipment. For comparison purposes, the corresponding emissions from typical 1000 MW_e oil and gas-fired plants, operating without pollution control equipment, are also shown.

In order to reduce these pollution levels, the Environmental Protection Agency in 1970 set primary and secondary ambient air quality standards for six common pollutants, including SO₂ (considered to be the most damaging to the population). Primary standards were to be met by the middle of 1975, with a 1977 deadline for a few areas. Secondary standards were to be met within a "reasonable time." In addition, New Source Performance Standards (NSPS) were promulgated as part of the Clean Air Act (covering all pollutants) to restrict emissions for five classes of stationary sources: fossil-fuel steam generators, incinerators, cement plants, sulfuric acid plants, and nitric acid plants. Table 9 gives the NSPS for fossil-fuel power plants. Besides these national standards, states are also required under the Act to develop State Implementation Plans.

These EPA standards (Table 9) are expressed in terms of pounds of pollutant per million Btu of fuel burned. These same standards,

Table 9
NEW SOURCE PERFORMANCE STANDARDS FOR FOSSIL
FUEL-FIRED STEAM GENERATORS

Pollutant Type	Standards
Sulfur dioxide	0.80 lb per million Btu heat input, maximum two-hour average when liquid fossil fuel is burned 1.2 lb per million Btu heat input, maximum two-hour average when solid fuel is burned
Nitrogen oxides	0.20 lb per million Btu heat input, maximum two-hour average, expressed as NO ₂ , when gaseous fossil fuel is burned 0.30 lb per million Btu heat input, maximum two-hour average, expressed as NO ₂ , when liquid fossil fuel is burned 0.70 lb per million Btu heat input, maximum two-hour average, expressed as NO ₂ , when solid fossil fuel (except lignite) is burned
Particulate matter	0.10 lb per million Btu heat input, maximum two-hour average 20% opacity (except that 40% opacity is permissible for not more than two minutes in any hour)

Source: EPA Regulations 40 CFR 60.42 to 40 CFR 60.44

expressed in terms of pounds of pollutant permitted per hour of operation for a 1000 MW_e power plant are presented in Table 10. These figures are compared with the average uncontrolled emissions, which vary somewhat with the fuel grade and sulfur and ash content.

In Sections 3.4.1 through 3.4.3, an account is given of the methods used in this study to estimate the societal damage caused by the three classes of pollutant considered above and the societal costs that result. Following that, in Section 3.4.4, the damages associated with a number of other materials that are also present in trace quantities in stack gases from coal-fired generation plants are considered.

Table 10
POLLUTANT EMISSIONS (POUNDS/HOUR) FROM 1000 MW_e
FOSSIL FUEL-FIRED POWER PLANT

	EPA Standards		
	SO ₂	NO _x	Particulates
Coal	12,000	7,000	1,000
Oil	8,000	3,000	1,000
Gas	8,000	2,000	1,000
	Average Uncontrolled Emissions		
	SO ₂	NO _x	Particulates
Coal	16,000 × S	8,430	6740 × A
Oil	10,500 × S	6,930	670
Gas	4	3,730	140

Where A = Ash content (%); S = Sulfur content (%)

3.4.1 Societal Costs Resulting from SO₂ Emissions

The single most damaging pollutant resulting from coal-fired electric power generation appears to be SO₂. Its damage to human health is generally considered to be the most serious of all of the societal costs of coal-fired power generation. Much of the damage resulting from SO₂ emissions, particularly to human health, is not produced directly by SO₂ but rather by suspended particulate sulfates that result when SO₂ is oxidized in the atmosphere. This conclusion is based, in part, on epidemiological studies that have indicated association between ambient sulfate levels and various human health effects. The CHES (Community Health and Environmental Surveillance System) study (Ref. 58) also indicated that deleterious health effects seem to be more closely associated with suspended atmospheric sulfate rather than due to exposure to other pollutants. However, the vast

amount of published information on this subject also indicates that there are considerable uncertainties concerning the extent of the harmful effects of SO_2 emissions and the specific relationships between power plant point source emissions of sulfur dioxide and regional patterns of sulfate formation, dispersion, and deposition.

The societal costs resulting from SO_2 emissions by coal-fired power plants are heavily dependent on power plant location, sulfur content of the coal, and deployment of SO_2 control systems. For example, an uncontrolled power plant burning 3% sulfur coal will cause four times more damage than will a controlled plant that marginally meets the new EPA source standards.

For the societal cost calculations reported in this section, it has been assumed that future emissions from coal-fired power plants will satisfy the requirements of the current EPA New Source Standards of the Clean Air Act, as given in Table 10. This assumption is equivalent to adoption of either one of two possible scenarios: (a) the plant burns coal with a 0.75% sulfur content and does not use flue gas desulfurization, or (b) the plant burns coal with 3% sulfur but uses desulfurization equipment capable of reducing SO_2 concentration in the flue gas by 75%.

Another characteristic of the societal damage caused by emissions from coal-fired power plants is that it is non-uniformly distributed over the country, with a relatively larger percentage of the northeastern section of the U.S. being affected than other sections. This non-uniformity is due to the different oxidation rates of SO_2 to sulfate, varying from 0.1 to 0.2% per hour in clean rural areas to as much as 5% per hour in urban smog areas. Thus, a given quantity of SO_2 emissions will have different polluting effects on urban and rural areas. Additionally, differences in population density, materials at risk, and prevailing winds will result in significantly different societal costs.

Since most of the coal-fired power plants are actually located in the northeastern section of the U.S., the representative power plants considered in this analysis are also assumed to be located in that area. Also, since societal costs are expected to be significantly different for rural and

urban plants, the costs have been estimated for both cases. The various topics addressed in the analysis (and discussed in subsequent sections) are:

- a. Dispersion and oxidation phenomena relating coal-fired power plant SO_2 emissions to ambient concentrations of SO_2 and sulfate.
- b. Physical damage caused by excess sulfate and SO_2 dosage to populations, vegetation, ecological systems, and materials.
- c. The relation between physical damage resulting from unit dosage and the societal damage to the total population at risk as a result of the total dosage experienced.
- d. The total societal costs resulting from the various types of physical damage.

3.4.1.1 Dispersion and Oxidation of SO_2 Emissions

The oxidation rate of SO_2 to sulfate presents the biggest uncertainty in the relationship between power plant SO_2 emissions and resulting ambient sulfate concentration levels. Oxidation rates range from 0.1 to 0.2% per hour in clean air to as much as 5-10% per hour in the presence of other urban smog impurities such as photo-induced radicals, soot, organics, and oxidants. Some of the SO_2 , however, may leave the atmosphere by dry or wet deposition and may be absorbed by vegetation, soil, or water before it is oxidized. Its rate of removal from a volume of air to a surface area is generally expressed as a deposition velocity. The oxidized sulfate can also leave the atmosphere by wet or dry deposition.

The National Academy of Sciences (NAS) has developed a detailed model to relate SO_2 emissions with ambient air quality (Ref. 59). Results obtained from use of this model were scaled for two typical 1000 MW_e power plants that marginally meet the SO_2 emission limits of the New Source Performance Standards of the Clean Air Act and are assumed located, respectively, in urban and rural parts of the northeastern U.S. The resulting increases in average annual ambient concentrations of SO_2 and SO_4 near population centers are given in Table 11 for both the urban and the rural plants. The calculated values for these increases of SO_2 and SO_4 concentrations near population centers are based on several factors: power plant location, SO_2

Table 11
 EXPECTED INCREASE IN SO₂ AND SO₄ CONCENTRATION
 FROM 1000 MW_e URBAN AND RURAL
 COAL-FIRED POWER PLANTS

Increase in Average Annual Ambient Concentrations*	Urban Plant	Rural Plant
Sulfur Dioxide Concentrations	0.75 µg/m ³	0.0585 µg/m ³
Sulfate Concentrations	3.024 µg/m ³	0.141 µg/m ³
* Based on the following assumptions: <u>Site Specific Assumptions</u>		
1. Power plant location	New Jersey - Connecticut area	Western Pennsylvania - Ohio - West Virginia area
2. Distance from urban population	60 km from New York	500 km from Northeast corridor
3. SO ₂ - sulfate oxidation rate	5.0%/hr	0.5%/hr for the first 24 hr, when plume is traveling through rural air; then 5%/hr for 2 hr in the urban air
4. Percent wet deposition of emissions before reaching urban population	10%	25%
<u>Common Assumptions</u>		
1. Power plant capacity factor	0.8	
2. Heat rate of power plant	10 ⁴ Btu/kWh of electric power	
3. Hourly SO _x emission	12,000 lb	
4. Wind speed	20 km/hr	
5. Height of the mixing layer	1000 meters above ground	
6. SO ₂ removal rate	2.88%/hr or deposition velocity of 0.8 cm/sec	
7. SO ₄ removal rate	1.44%/hr or deposition velocity of 0.4 cm/sec	
8. Angle subtended by traversed plume	45°	

to SO_4 oxidation rates, percent of SO_2 and SO_4 dry and wet deposition, wind speed, angle subtended by traversed plume, and height of mixing layer. The assumed values used for these factors are also given in Table 11.

In the following subsection, the expected health damages due to a given increase of sulfate concentration are discussed.

3.4.1.2 Physical Health Damage Caused by Suspended Sulfates

There have been a number of attempts to quantify the expected health damage from various degrees of air pollution. Epidemiological studies have indicated an association between ambient sulfur dioxide levels and adverse effects on human health. The CHES study (Ref. 58) also indicates that health effects seem more closely associated with suspended atmospheric sulfate than with exposure to other pollutants. However, the precise reaction and oxidation mechanisms of sulfur dioxide and suspended particulate matter are not fully understood. It is believed that the broncho-constricting potency of particulate sulfates is related both to the physical properties of the particles (e.g., size) as well as such chemical properties as pH (acidity)(Ref. 59). The biological reactivity of the sulfate particles also appears to depend on ambient humidity, temperature, and synergistic effects of the presence of other pollutants. The main types of measurable health damage from increased atmospheric sulfate concentrations are:

- a. Excess mortality (Refs. 60, 61, and 62)
- b. Aggravation of heart-lung disease symptoms (Refs. 63 and 64)
- c. Asthmatic attacks (Refs. 65, 66, and 67)
- d. Lower respiratory disease in children (Refs. 68 and 69)
- e. Chronic respiratory disease (Refs. 70 and 71)

An attempt to compute the total amount of health damage resulting from suspended particulate sulfate is, however, complicated by the fact that there is no general agreement about the relationship between the dose (the quantity of sulfate inhaled or ingested) received by individual or population and the response in the form of measurable damage to health. This

uncertainty is due to lack of accurate dose information as well as uncertainty about the definitions of illness and incremental illness. In most observed situations, for example, there was uncertainty about the dose received by the exposed population. Also, different studies have used quite different measures of illness response. In many cases, other factors influencing the results have been present and it has not been possible to correct for their effect. For example, it has been shown that the dose-response relationship varies significantly with the characteristics (age, race, smoking habits, etc.) of the population involved. And finally, the basic mechanisms of biological reaction with suspended sulfate particles are not yet fully understood.

As a result of these uncertainties, the NAS (Ref. 59) has supported the use of a relatively simple dose-response relationship that should be approximately correct for a "typical" population. This relationship is given in Table 12, expressed in terms of the percentage increase in illness cases, over the base rate, for a $1 \mu\text{g}/\text{m}^3$ change in suspended sulfate concentration at different ambient sulfate levels. In addition to the five types of health damage given in this table, there appear to be other possible health damaging effects (e.g., cancer, emphysema, mental health, etc.), caused by sulfate concentration. However, these additional health damaging effects have not yet been proven and therefore were not included in the social cost estimates given in subsequent sections.

3.4.1.3 Societal Health-Damage Cost Factors

Societal health-damage costs represent what society should be willing to pay in order to prevent various types of health damage. Such costs vary with the degree of suffering and life term reduction involved, the absolute dollar costs to the individual, and financial circumstances of the individual. Medical and lost-productivity costs represent only the minimum monetary value of societal cost. These minimum societal costs for the types of health damage to be considered in subsequent calculations are given in Table 13 and are representative of the values used by the NAS. These societal costs are the direct dollar costs of the health damage and do not include the incremental price that each person would be willing to pay to avoid being ill. Most health

Table 12
SIMPLE DOSE-RESPONSE RELATIONSHIP
FOR SUSPENDED SULFATES

Health Effect	Annual Average Ambient Sulfate Concentration $\mu\text{g}/\text{m}^3$	Dose-Response Relationship (Percentage of Additional Cases Resulting from an Increase of $1 \mu\text{g}/\text{m}^3$ in the Avg. Sulfate Concentration)
Mortality Rate	12.5	0.0094
	16.0	0.0192
	20.0	0.0431
Aggravated Heart-Lung Disease Symptoms	12.5	1.073
	16.0	1.662
	20.0	1.766
Asthmatic Attacks	12.5	3.21
	16.0	3.21
	20.0	3.21
Lower Respiratory Disease in Children	12.5	3.82
	16.0	7.69
	20.0	7.69
Chronic Respiratory Disease	12.5	11.10
	16.0	11.10
	20.0	11.10

Table 13
SOCIETAL HEALTH DAMAGE COSTS DUE TO
INCREASED SULFATE CONCENTRATION

Damage Item	Monetary Cost
One Premature Death	\$30,000
One Day Aggravation of Heart and Lung Disease Symptoms	\$ 20
One Asthma Attack	\$ 10
One Case of Child's Lower Respiratory Disease	\$ 75
One Case of Chronic Respiratory Disease	\$ 250

damage by airborne sulfate is primarily incurred by children, elderly, and physically weak persons who do not have strong resistance against disease. The resulting minimum monetary cost given in Table 13 reflects the fact that suspended sulfate concentrations tend to merely intensify the disease symptoms of elderly, weak, and ill persons who already have generally lower earning capacity because of their condition. Thus, the societal cost of one premature death of an elderly person due to increased sulfate concentration is lower than the average societal cost of one death resulting from a coal transportation accident.

The societal health damage costs (Table 13) and the dose-response relationship for suspended sulfates (Table 12) were then used in computing the examples of societal health costs given in Table 14. The second column in this table lists the baseline statistics for the indicated types of health damage to a sample northeastern U.S. urban population of 10 million people exposed to an average atmospheric sulfate concentration of $16 \mu\text{g}/\text{m}^3$. The third column gives the annual number of additional damage cases that would be expected if the sulfate concentrations were increased by $1 \mu\text{g}/\text{m}^3$. These incremental damage figures were translated into the cost values in the fourth column on the basis of the unit costs of Table 13.

Table 14
ESTIMATES OF PHYSICAL HEALTH DAMAGE AND ASSOCIATED
SOCIAL COSTS ATTRIBUTABLE TO INCREASE
IN AVERAGE SUSPENDED SULFATES
(Northeastern U.S. Metropolitan Area of 10 Million Population)

Health Damage	Baseline Statistics*		
	Total Number of Cases*	Additional Expected Cases at Average Concentration** Increase of $+1 \mu\text{g}/\text{m}^3$	Additional Social Health Costs at Average Concentration** Increase of $+1 \mu\text{g}/\text{m}^3$ (million \$)
Mortality Rate (deaths per year)	102.6×10^3	20	0.60
Aggravated Heart-Lung Disease Symptoms (person-days of sickness per year)	21.2×10^6	350×10^3	7.04
Asthmatic Attacks (cases per year)	2.18×10^6	70×10^3	0.70
Lower Respiratory Disease in Children (cases per year)	110×10^3	8.5×10^3	0.64
Chronic Respiratory Disease (cases per year)	318×10^3	35×10^3	8.83
Total Social Health Costs			17.80

* Data from the Statistical Abstracts of the U.S., 1970

** Assumes average annual concentration of $16 \mu\text{g}/\text{m}^3$

3.4.1.4

Total Societal Health Damage Costs

In order to estimate the total health damage resulting from SO_2 emissions produced by coal combustion in electric power plants, it is necessary to first determine the size of the population at risk and the increase in the ambient concentration of sulfate particles as a result of plant operation. The calculation of these two parameters involves several assumptions about (a) power plant location and the dispersion behavior that governs the distribution of the emitted SO_2 plumes downwind from the plant, (b) the rates at which SO_2 is oxidized to sulfate in rural and urban air, (c) the deposition rates (wet and dry) for both SO_2 and sulfate particles, and (d) the size and distribution of the population exposed to the resulting increase of suspended sulfate concentration. A comparison of the locations of the various coal-fired power plants with the population density distribution in the continental U.S. made it evident that the bulk of the population to be exposed to increased suspended sulfate concentration is in the Northeast. However, since these power plants are sited in both urban and rural locations, significant differences can be expected in the resulting health damage. The present analysis computes societal health damage and associated costs for "typical" urban and rural 1000 MW_e coal-fired power plants. The urban plant is assumed to be located 60 km from a population center like New York City; the rural plant is assumed to be located 500 km from a region like the northeast corridor of the U.S. Both plants are assumed to be meeting the emission standards set by the New Source Performance Standards of the Clean Air Act, which limit hourly emissions of SO_2 to 12,000 pounds. Table 15 reports the results of the calculation of total annual societal health damage and the associated societal costs resulting from SO_2 emissions from the above typical urban and rural 1000 MW_e coal-fired plants. The expected increases in SO_2 and SO_4 concentrations caused by the construction of such plants were shown in Table 11. A much larger population is put at risk by the rural plant because the dispersed plume covers a much larger populated area before blowing out to sea, but the ambient sulfate concentration is much smaller. The values of SO_2 concentration shown in Table 15 have no direct

Table 15

YEARLY HEALTH DAMAGE RESULTING FROM SO₂ EMISSIONS FROM
1000 MW_e URBAN AND RURAL COAL FIRED POWER PLANTS

Population at Risk	Urban Plant		Rural Plant	
	11.5 million		50 million	
Increase in Average Annual Concentration of Sulfate	0.75 $\mu\text{g}/\text{m}^3$		0.0585 $\mu\text{g}/\text{m}^3$	
Increase in Average Annual Concentration of SO ₂	3.024 $\mu\text{g}/\text{m}^3$		0.141 $\mu\text{g}/\text{m}^3$	
	Health Damage Per Year	Damage Cost (\$10 ⁶)	Health Damage Per Year	Damage Cost (\$10 ⁶)
Excess Premature Deaths	17	0.51	6	0.18
Aggravation of Heart-Lung Disease Symptoms (person-days)	300,000	6.08	100,000	2.06
Asthmatic Attacks (cases)	60,000	0.60	21,000	0.21
Lower Respiratory Disease in Children (cases)	7,300	0.55	2,500	0.19
Chronic Respiratory Disease (cases)	30,000	7.61	10,000	2.58
Total Damage		15.35		5.22
Health Damage Cost per Pound of Sulfur Emitted	\$0.37/lb		\$0.12/lb	
Health Damage Cost per kWh	2.19 mills/kWh		0.75 mills/kWh	

bearing on health damage but are important in the computation of non-health damage costs discussed in later sections.

The data on annual health damage and associated costs in Table 15 are based on the expected increase in sulfate concentrations (Table 11), the dose-response relationships (Table 12), calculated societal health damage costs (Table 13), and the resulting health damage to a given sample exposed population (Table 14). The health damage and associated societal costs for urban and rural coal-fired power plants reflect differences in the size of exposed population and in the ambient suspended sulfate concentration. (It was assumed that health damage increases linearly with sulfate concentrations over the narrow range of concentration change involved in these examples). The translation of total societal damage cost into a cost per kWh was based on the assumption that the 1000 MW_e power plants operated with an annual capacity factor of 0.8. The computation of the health-damage societal costs per pound of sulfur emitted was based on the assumption that the plant is meeting the SO₂ emission standards of the Clean Air Act. This assumption translates into a power plant sulfur release of 42 million pounds annually.

Besides the societal health damage costs resulting from SO₂ emission, there are additional costs resulting from damage to materials, damage to aesthetic values, and damage caused by acid rain. These societal costs are discussed in the following sections.

3.4.1.5 Societal Costs Resulting from Damage to Materials

Sulfur dioxide accelerates the degradation of materials and exterior paints and the corrosion of metal structures. According to one study (Ref. 72), SO₂ accounts for more than 90% of the national economic cost of air-pollution-caused corrosion. Waddell (Ref. 73) has assessed the national SO₂-related materials damage cost in 1970 to be between \$0.4 to \$0.8 billion. There is uncertainty about the dose-response relationship for damage to materials (e.g., concrete, metal building materials, paints, fibers, etc.). If the \$600 million national average value suggested by Waddell is used and it is assumed that 50% of the damage occurred in the New England

states and New York, Pennsylvania, Maryland, New Jersey, Delaware, and Greater Washington, the calculated cost resulting from damage to materials in this area amounts to \$300 million per year. If it is further assumed that the total materials damage is caused equally by SO₂ and sulfate pollution, and that the damage is proportional to the size of the population (~50 million), the societal materials damage costs for this region due to SO₂ emission would be given by the relation

$$\frac{300(10^6)(0.5)}{50(10^6)} \left(\frac{\Delta a_1}{a_1} + \frac{\Delta a_2}{a_2} \right) P = 3 \left(\frac{\Delta a_1}{a_1} + \frac{\Delta a_2}{a_2} \right) P$$

where

a_1, a_2 = prevailing ambient concentrations of SO₂ and SO₄

$\Delta a_1, \Delta a_2$ = incremental increases in SO₂ and SO₄ concentrations

P = exposed population.

This relationship was used to calculate the total societal cost resulting from damage to materials by SO₂ emission from the "typical" urban and rural power plants discussed earlier. The values for Δa_1 , Δa_2 , and P used in the computation were those shown in Table 15 and the prevailing ambient SO₂ and SO₄ concentrations were taken to be 45 µg/m³ and 16 µg/m³, respectively. The results of this computation are displayed in the upper two lines of Table 16. It should also be pointed out that a review of materials damage costs by Nisbet (Ref. 59) suggests that Waddell's estimate of \$0.4 to \$0.8 billion is among the lowest of a range that could be obtained from the same data source and suggests that a factor of 4 or 5 times higher may be more appropriate. However, because of the uncertainty concerning any one of these estimates, the more conservative lower costs of Waddell were used in the present analysis.

Table 16

YEARLY NON-HEALTH DAMAGE RESULTING FROM SO₂ EMISSIONS FROM
1000 MW_e URBAN AND RURAL COAL FIRED POWER PLANTS

	Urban Plant		Rural Plant	
	Concentration/ Amount of Damaging Substance	Damage ₆ Cost (\$10 ⁶)	Concentration/ Amount of Damaging Substance	Damage ₆ Cost (\$10 ⁶)
Materials Damage				
Sulfate Damage	0.75 µg/m ³	1.62	0.0585 µg/m ³	0.55
Sulfur Dioxide Damage	3.024 µg/m ³	2.32	0.141 µg/m ³	0.47
Aesthetics	42 × 10 ⁶ lb of sulfur	1.47	42 × 10 ⁶ lb of sulfur	1.47
Acid Rain	42 × 10 ⁶ lb of sulfur	0.63	42 × 10 ⁶ lb of sulfur	0.63
Total Societal Non-Health Damages		6.04		3.12
Societal Costs per Pound of Sulfur Emissions		14.4¢/lb		7.4¢/lb
Societal Costs per kWh		0.86 mills/kWh		0.45 mills/kWh

3.4.1.6 Societal Aesthetic Costs

The general public and various environmental groups believe that aesthetic societal costs resulting from SO_2 emission are quite substantial. Aesthetic costs include visibility reduction, soiling, noxious odors, and damage to objects of historic and artistic importance. In one study (Ref. 74) the cost of aesthetic damage by the Four Corners power plant was estimated to be roughly \$25 million per year in 1970 (626 MW_e capacity). Waddell (Ref. 73) estimated \$5.8 billion as the total social costs of aesthetic and soiling effects, and evenly divided it between SO_2 and particulates. An NAS study (Ref. 59) assumed 20% of Waddell's figure (~\$1.16 billion) for aesthetic damages by sulfates and arrived at a value of 3.5¢/lb of sulfur emissions based on the national total of 33.2×10^6 tons of sulfur dioxide. This value was used to estimate the aesthetic social costs resulting from SO_2 emission by urban and rural plants, as given in Table 16. Unlike societal health costs, the aesthetic costs may be quite significant in rural areas containing national parks and other areas with high recreational value.

3.4.1.7 Societal Costs Resulting from Acid Rain

The sulfur cycle has been extensively studied by Kellog, et al. (Ref. 75), Rodhe (Ref. 76), Robinson and Robbins (Ref. 77), and Eriksson (Ref. 78). Sulfur is introduced into the atmosphere via three principal routes:

- a. Spray from ocean waves (neutral sulfates)
- b. Decomposition of biological materials (H_2S)
- c. Combustion of fossil fuels (SO_2)

After becoming airborne, transported and oxidized, it is returned to earth by four principal mechanisms:

- a. Absorption of SO_2 by soil and vegetation
- b. Deposition of SO_2 in rain or snow
- c. Deposition of sulfates in rain or snow
- d. Dry deposition of particles containing sulfates

Acid rain causes acidification of soils, retardation of forest growth, and death of fish from low pH in lakes and streams. Social costs due to acid rain damage are estimated to be \$500 million annually (Ref. 59) which is equivalent to approximately 1.5¢/lb of sulfur emissions. This value was used to estimate the societal acid rain damage cost of urban and rural plants, as shown in Table 16.

3.4.1.8 Total Non-Health-Related Societal Costs Resulting
from SO₂ Emission by Typical Urban and Rural
Power Plants

The total societal costs resulting from damage to materials and to aesthetic values and from acid rain, as a result of SO₂ emission by the typical urban and rural power plants discussed previously, are also shown in Table 16. These costs are given in terms of cost per pound of sulfur emissions and cost per kWh of generated electric power. These are based upon the assumption that both urban and rural 1000 MW_e coal-fired power plants are meeting SO₂ emission standards of the Clean Air Act, operate with an annual capacity factor of 0.8, and are located in the Northeast.

3.4.1.9 Societal Costs Due to SO₂ Emissions: National
Average Case

In the previous section, societal damage costs due to SO₂ emissions were calculated for "typical" 1000 MW_e urban and rural coal-fired power plants located in the northeastern U.S. An alternate approach is to calculate these SO₂-emission-related societal costs for a "national average" case, on the basis of data generated by the Environmental Protection Agency for total costs of air pollution and for amounts of emitted pollutants. Table 17 gives the basic data on the societal costs of air pollution damage from different pollutants in 1968, along with estimates of emissions for different pollutants for the same year, both representing U.S. totals (Ref. 79).

The societal damage costs were obtained for the "national average" case by deriving costs per pound of emitted pollutant from the data given in Table 17. The amount of each pollutant emitted on a per kWh basis by coal-fired plants that meet the New Source Performance

Table 17
ESTIMATED SOCIETAL COSTS OF AIR POLLUTION
AND AMOUNTS OF EMITTED POLLUTANTS

A. Estimates of Nationwide Emissions, 1968
(10⁶ tons/year)

Source \ Pollutant	CO	Part. *	SO ₂	HC	NO _x
Transportation	63.8	1.2	0.8	16.6	8.1
Fuel Combustion in Stationary Sources	1.9	8.9	24.4	0.7	10.0
Industrial Processes	9.7	7.5	7.3	4.6	0.2
Solid Waste Disposal	7.8	1.1	0.1	1.6	0.6
Miscellaneous	16.9	9.6	0.6	8.5	1.7
Total	100.1	28.3	33.2	32.0	20.6

B. Societal Costs of Air Pollution Damage, 1968
(\$ billion/year)

Damage Category \ Pollutant	SO ₂	Part. *	Oxidants	NO _x	Total
Health	3.272	2.788	-	-	6.060
Residential Property	2.808	2.392	-	-	5.200
Materials	2.202	0.691	1.127	0.732	4.752
Vegetation	0.013	0.007	0.606	0.040	0.120
Total	8.295	5.878	1.187	0.772	16.132

*Particulates

Standards of the Clean Air Act has been given earlier. For each pollutant type, the product of the social cost (in dollars per pound) and the emission rate (in pounds per kWh) represents a national average societal cost (in dollars per kWh) resulting from emissions of the pollutant in question.

Table 18 gives the computed societal costs due to SO₂ emissions for this "national average" case. These costs are based on the assumption that the SO₂ emissions are limited to 12,000 lb per hour for a 1000 MW_e coal-fired power plant. This is equivalent to 0.012 lb of SO₂ emissions per kWh of generated electric power.

3.4.2 Societal Costs Resulting from NO_x Emissions

NO_x (viz., NO, NO₂, N₂O) emissions in the United States have grown at an average rate of over 4% per year for the last three decades, and it is estimated that electric power plants have been responsible for roughly one-fourth of this growth. Although relatively little is known with any degree of certainty about the deleterious effects caused by these emissions, it is believed that the major damage is to materials and, to a lesser extent, to human health and to vegetation. One set of estimates of the societal cost resulting from the damaging effects of NO_x (from Ref. 79) is presented in Table 17, where the total estimated national cost is shown as \$772 million per year in 1968. Also presented in the table are estimates of the amounts of the various pollutants that were emitted, nationwide, in that year. On the basis of these numbers, figures for the societal costs per pound of pollutant are readily calculated. It was these ratios that were used in this study to estimate the societal costs resulting from damage to materials and vegetation by NO_x emitted from coal-fired power plants. It was only necessary to multiply by the amount of NO_x emission that is permitted, under the EPA New Source Standards, for a 1000 MW power plant: 7000 lb per hour, or 0.007 lb per kWh of generated electric power. The results of this calculation are presented in Table 19.

The study that was the source of the damage estimates in Table 17 did not provide any data on damage to health, and no other source of such information could be located. Estimates were available, however, of

Table 18
 SOCIETAL DAMAGE COSTS RESULTING FROM SO₂ EMISSIONS
 FROM COAL-FIRED POWER PLANTS MEETING
 EPA STANDARDS
 (Estimates Based on National Average Data)

Damage Items	Total National SO ₂ Societal Costs in 1968 (\$ billion)	SO ₂ Societal Damage Cost* (mills/kWh)
Health Damage	3.27	1.01
Non-Health Damage		
Residential Property	2.81	0.86
Materials	2.20	0.68
Vegetation	0.01	--
Subtotal Non-Health Damage	5.02	1.54
Total Societal Damage	8.29	2.55

$$\frac{* (\text{Total national SO}_2 \text{ societal costs}) (0.012 \text{ lb of SO}_2 \text{ per kWh}) (1.7)^{**}}{(66.4 \times 10^9 \text{ lb of national SO}_2 \text{ emissions})^{\dagger}}$$

** Increase in consumer price index (1968-1976)

[†] Estimates of nationwide SO₂ emissions, 1968
 (million tons/year)

<u>Emissions Source</u>	<u>SO₂ Emissions</u>
Transportation	0.8
Fuel combustion in stationary sources	24.4
Industrial processes	7.3
Solid waste disposal	0.1
Miscellaneous	0.6
Total	33.2

Table 19
 SOCIETAL DAMAGE COSTS RESULTING FROM NO_x EMISSIONS
 FROM COAL-FIRED POWER PLANTS MEETING
 EPA STANDARDS
 (Estimates Based on National Averages)

Societal Damage Items	Societal Costs, mills/kWh
Health	0.01 [*]
Materials and Vegetation	0.22 ^{**}
Total Damage	0.23

$$\frac{* (2650 \text{ avg. no. of total deaths}) \times (0.007 \text{ lb of NO}_x \text{ per kWh}) \times (\$30,000 \text{ per life})}{(41.2 \times 10^9 \text{ lb of national NO}_x \text{ emissions})^\dagger}$$

$$\frac{** (\text{Total national NO}_x \text{ societal costs}) (0.007 \text{ lb of NO}_x \text{ per kWh}) \times 1.7^{\dagger\dagger}}{(41.2 \times 10^9 \text{ lb of national NO}_x \text{ emissions})^\dagger}$$

[†] Estimates of nationwide NO_x emissions, 1968
 (million tons/year)

<u>Emissions Source</u>	<u>NO_x Emissions</u>
Transportation	8.1
Fuel combustion in stationary sources	10.0
Industrial processes	0.2
Solid waste disposal	0.6
Miscellaneous	1.7
Total	20.6

^{††} Increase in consumer price index (1968-1976)

the number of premature deaths caused annually by ambient nitrogen oxide, namely, 800 to 4500 (Ref. 74). For the purposes of this study, the average of these two extremes, or 2650 deaths per year, was taken as the measure of health damage resulting from NO_x emissions. This figure was then used in computing the societal cost arising from health damage caused by NO_x emissions by coal-fired power plants. The computational procedure and the results are shown in Table 19.

3.4.3 Societal Damage Costs from Particulate Emission

Uncontrolled particulate emission from coal-fired power plants is next in importance after SO_2 in causing societal damage. As seen in Table 17, the total societal damage by particulates from all sources was estimated to have cost $\$5.878 \times 10^9$ for 1968. This cost represented damage to residential property, materials, health, and vegetation, and was based upon a national annual particulates emission of 28.3×10^6 tons. According to the EPA New Source Standards, particulates emission from coal-fired power plants must be limited to 1000 lb per hour for a 1000 MW_e power plant. This is equivalent to 0.001 lb of particulates emissions per kWh of generated electric power. On the basis of these values, the total societal costs resulting from emission of particulates by a coal-fired power plant meeting EPA standards were estimated. The computational procedure and the results are presented in Table 20.

3.4.4 Societal Damage from Metallic Trace Pollutants

Coal contains a number of metallic trace pollutants in concentrations that vary significantly from region to region. A typical eastern coal contains mercury, cadmium, selenium, arsenic, fluorine, iodine, beryllium, uranium, thorium, and radon. These elements are released during coal combustion and significant portions of them escape capture by stack gas cleaning systems. For example, it has been reported (Ref. 80) that only 4% of the mercury from coal-fired power plants is retained by stack gas cleaning processes and that as much as 23% of the environmental mercury is produced by burning coal (Ref. 81). Table 21 gives the annual amounts of metallic

Table 20
 SOCIETAL DAMAGE COSTS FOR PARTICULATES EMISSIONS FOR
 COAL-FIRED POWER PLANT MEETING EPA STANDARDS
 (Based on Averaged U.S. Data)

Societal Damage Items	Total National Particulates Societal Costs in 1968, \$ billions	Particulates Societal Damage Cost, * mills/kWh
Health Damage	2.79	0.08
Non-Health Damage		
Residential Property	2.39	0.07
Materials	0.69	0.02
Vegetation	0.01	--
Subtotal Non-Health Damage	3.09	0.09
Total Societal Damage	5.88	0.17

* $\frac{(\text{Total national societal costs})(0.001 \text{ lb of particulates per kWh})(1.7)**}{(56.6 \times 10^9 \text{ lb of national particulates emissions})***}$

** Increase in consumer price index (1968-1976)

*** Estimates of nationwide particulates emissions, 1968
 (million tons/year)

<u>Emissions Source</u>	<u>Particulates Emissions</u>
Transportation	1.2
Fuel combustion in stationary sources	3.9
Industrial processes	7.5
Solid waste disposal	1.1
Miscellaneous	9.6
Total	28.3

Table 21
ANNUAL AMOUNTS OF METALLIC TRACE
POLLUTANTS FROM A TYPICAL
1000 MW_e COAL-FIRED POWER PLANT*

Metallic Trace Element	Annual Emissions, lb/year
Mercury	4000
Arsenic	4000
Selenium	6000
Lead	400
Nickel	1000
Beryllium	80

* Capacity factor = 0.8

trace pollutants emitted by a typical 1000 MW_e coal-fired power plant operating at a capacity factor of 0.8 (Ref. 55).

It has not been possible to make quantitative societal cost estimates for these metallic trace pollutants, primarily because population and material exposure estimates, as well as the corresponding dose-response relationships, have not been developed for these elements. However, there is little disagreement that emission of these elements is potentially damaging to society and to the environment and that the damage could be quite significant. Among the trace metallic pollutants, mercury is considered to be the most damaging element. Mercury can be concentrated and methylated in biological chains and has been detected in swordfish at several locations. Although the EPA has formulated chemical plant mercury emission standards, there are no existing standards for power plant mercury emission. The average mercury emission for a 1000 MW_e coal-fired plant is about twice the amount allowed by EPA standards for chemical plants.

Coal-fired power plants also release radioactive substances in the stack gases and fly ash produced from burning coal. A 1000 MW_e coal-fired plant releases annually ~0.012 curies of radium and thorium through

stack emission and 1.55 curies in the resulting fly ash (Ref. 82). By contrast, a nuclear boiling water reactor (BWR) of 1000 MW_e capacity releases 10 curies of tritium, 0.3 curies of iodine 131, and 50,000 curies of radioactive krypton and xenon as stack gases (Ref. 82). In another study (Ref. 83), it has been reported that the emissions from a 1000 MW_e coal-fired power plant, burning 9% ash coal and having 97.5% stack gas cleaning efficiency, produce local radiation exposure levels about 400 times greater than those for a modern pressurized water reactor (PWR) and 180 times less than those for a modern boiling water reactor (BWR) of equivalent stack height. However, a direct comparison of the radiological health damage produced by coal-fired and nuclear power plants is not possible because emissions of the nuclear power plant are mostly noble gases that produce wholebody exposure, while long-lived coal-fired fly ash affects mainly bones and lungs. The highest exposure rate found by coal-fired power plants has been only 1-3% of the exposure rate limit recommended by the Federal Radiation Council (FRC) for an individual in the population. At present, workers in radiation biology are somewhat divided as to whether or not these exposure rates constitute a serious health hazard. Therefore, it is not possible to assign societal costs to this possibly damaging component of power plant emission.

Other potentially damaging emissions from coal-fired power plants include a wide variety of organic compounds, mainly polycyclic hydrocarbons, that are suspected of being carcinogenic. According to one recent study, emissions of benzopyrene (considered as an indicator of carcinogenic polycyclic organic matter) by a 1000 MW_e coal-fired power plant without stack gas cleanup equipment is 0.24 to 2.4 g/hr (Ref. 84). Stack gas cleaning equipment is believed to be capable of significantly reducing this amount. According to an NAS study, it is suspected that polycyclic organic matter (POM) may contribute to increased incidence of lung cancer (Ref. 59). However, neither the dose-response relationships nor the percent contribution of POM by coal-fired power plants has been estimated. Because of this it is not possible to assign societal costs to these emissions.

SUMMARY AND CONCLUSIONS – TOTAL
SOCIETAL COSTS

Table 22 summarizes the values obtained in this preliminary study for the total societal costs to be ascribed to coal-fired power generation systems. The societal fuel production costs include both health and welfare costs in addition to environment-related costs. The societal health and welfare costs of fuel production were given in Table 5, and include costs associated with black lung disease, mine accidents, general health degradation, and rehabilitation of mine-site communities. Environment-related societal costs of coal production were given in Table 6 and include various costs due to lowered property values, diminished recreational values, land subsidence, acid mine drainage, disposal of mine wastes, and land reclamation.

The societal costs of coal transportation were shown in Table 7 and include costs due to both fatal and non-fatal injuries. It can be seen from Table 22 that the societal damages due to coal transportation are much lower than those due to coal production and power generation.

Societal damages due to coal combustion for electric power generation are the largest sources of societal costs in the entire coal-fired power generation cycle. These costs range from under 50% of the total societal costs for rural power plants to as much as 70% for urban plants. In the "national average" case the estimated costs of coal combustion are approximately 65% of the total societal damage cost. Total societal costs due to power generation include damage resulting from the emission of SO_2 , NO_x , and particulates. Societal health costs due to SO_2 emissions were given in Table 15 for both urban and rural plants and include damage due to excess premature deaths, aggravation of heart-lung disease, asthmatic attacks, lower respiratory disease in children, and chronic respiratory disease. Non-health-related societal costs due to SO_2 emissions were given in Table 16 for both urban and rural plants and include damage to materials and aesthetic values and damages resulting from acid rain.

It should be emphasized that the total societal costs shown in Table 22 represent merely the "out-of-pocket" costs resulting from damage

Table 22
 EXPECTED SOCIETAL COSTS FOR TOTAL COAL-FIRED
 POWER GENERATION CYCLE

Power Generation Fuel Cycle Element	Societal Costs (mills/kWh)		
	National Average	Typical Rural Plant	Typical Urban Plant
Fuel Production			
Health and Welfare	0.55	0.55	0.55
Environment	0.96	0.96	0.96
Subtotal	1.51	1.51	1.51
Fuel Transportation	0.13	0.13	0.13
Power Generation			
SO ₂ Emissions	2.55	1.20	3.05
NO _x Emissions	0.23	0.13	0.33
Particulates	0.17	0.10	0.25
Subtotal	2.95	1.43	3.63
Total Costs	4.59	3.07	5.27

- Societal damages are unevenly divided; especially affected are:
 - Personnel and families working in the power plant fuel cycle
 - Families who choose or are obliged to live in the pollution area
 - Children and the elderly and physically weak who do not have strong resistance against disease
- Before compliance with the Federal Coal Health and Safety Act and New Source Performance Standards of the Clean Air Act, societal costs were 2 to 3 times the present and expected future costs.

to health and property. They do not include, for example, the incremental amount a person would be willing to pay to avoid illness, injury, or death, and they do not include costs associated with damage that cannot be quantified in economic terms. Furthermore, it should be recognized that the costs are unevenly distributed over the population; the burden is mainly borne by the three groups identified in the footnote to Table 22.

Finally, the costs are based on the assumption that there is, or will be, essentially total compliance with existing federal law with respect to air pollution and health and safety hazards. It is estimated that before these acts were in force the total societal costs of coal-fired power production were from two to three times greater than the totals shown in Table 22.

These societal costs equal between 5-10% of current (1976) prices for delivered electrical energy and, if eliminated by use of non-polluting energy sources such as photovoltaic power generating systems, represent a legitimate credit against the cost of power from such systems.

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