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HEALTH AND ENVIRONMENTAL EFFECTS DOCUMENT FOR PHOTOVOLTAIC ENERGY SYSTEMS — 1983

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ABSTRACT

Health risks arising from the fabrication, installation, operation, and decommissioning of photovoltaic energy systems have been studied. Occupational risks from accidental injuries were quantified, and illness-related effects were examined. Although significant illness-related effects are not expected, potential chemical (e.g., phosphine) and physical (e.g., radio-frequency radiation) hazards found in the workplace merit careful consideration. Public health risks from pollutants (e.g., cadmium) emitted throughout the energy cycle and from physical hazards (i.e., electric shock and fire) associated with rooftop decentralized applications were reviewed. The risks from pollutants seem to be larger than the physical hazards considered, but they are highly uncertain. Risks to exposed individuals from electric shock and fire may be significant, but societal risks are probably small. Research needed to reduce uncertainties in these risk assessments includes examination of new materials and fabrication processes, measurements of public and occupational exposures to hazardous chemical and physical environments, and identification of mechanisms and probabilities of fire and electric shock due to photovoltaics applications.

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SUMMARY

This report summarizes the present state-of-knowledge about potential health and environmental effects of photovoltaic energy systems. Demand for photovoltaic energy systems is expected to grow rapidly in the next two decades. By 2000, these systems could supply (0.1 to 8.4) x 10^{18} J to the U.S. energy economy. Commercial production of these energy systems will impose certain social costs, including public and occupational health effects, which may influence their potential acceptance and widespread application. *A priori* identification and analysis of these issues can reduce design engineering costs and potential health risks, and consequently support the growth of these energy systems.

In this report, the following issues are addressed:

(i) Technological readiness of material and manufacturing options;
(ii) Production rates for effluents and wastes from the industry;
(iii) Potential occupational and public exposures to toxicants and hazards;
(iv) Resultant damage to human health; and
(v) Uncertainty and research needs.

Technological Readiness

Different photovoltaic materials and cell concepts are being developed to produce reliable and economically competitive energy systems. Single-crystal silicon cells, fabricated by an ingot growing process, are now produced commercially and serve as the standard of comparison for new materials and processes. Unfortunately, production costs are high, so alternate processes and materials are being investigated. Presently, silicon cell production alternatives (e.g., cast ingot, ribbon growth, and amorphous)

are the most prominent competitors; they account for ~40% of the total market. Potential production costs, reliability, and longevity of these systems are still not known precisely. Consequently, thin films made from alternate materials (e.g., copper indium diselenide), and use of concentrators are being examined to determine their potential to further decrease system costs.

In light of the dynamic state of this technology, a range of manufacturing and materials options for reference 10 MWp fabrication plants producing devices for use in residential applications are examined: (i) single-crystal silicon cells by ingot growing; (ii) semicrystalline silicon cells by ribbon growing; (iii) semicrystalline silicon cells by dendritic web growing; (iv) semicrystalline silicon cells by ingot casting, and (v) thin-film cadmium sulfide/copper backwall cells by spray deposition. Also, some aspects of producing gallium arsenide cells by ingot growing for control-station applications are examined.

Emissions Production

Measurements of emissions from operating photovoltaic plants are not available. Thus, emissions for the reference 10 MWp plants examined are estimated from design engineering studies which assume use of prudent engineering practices, especially for toxic and hazardous pollutants. A sample output for one fabrication alternative is shown in Table S-1.

Results from these studies suggest that several processes (e.g., etching) have potential to emit large quantities of pollutants, but these can be controlled with available technology (e.g., neutralization and flocculation). Other processes may emit small quantities of more exotic pollutants (e.g., boron trichloride, phosphine), which will probably not be

Table S-1. Estimated pollutant emission rates from the production of silicon Czochralski ingot photovoltaic cells. From Moskowitz, et al. (1981b). Plant Capacity 10 MWp/yr, and 350 working days/yr. Emission rates for the process steps examined are generally reported in units of kg/day plant. For refining processes, it is assumed that each refinery would produce 1000 metric tons/yr of silicon or cadmium. All statistics for the fabrication facilities assume annual production capacities of 10 MWp, about what is projected for a photovoltaic fabrication facility in the late 1980s; the largest production line now in existence is ~1 MWp. Fabrication emission rates are also reported in units of (metric tons/yr) per GWp. Annual production of 1 GWp, projected for around 1990, would thus require 100 facilities, each with a production output of 10 MWp. (NA = not available.)

Activity	Process step	Pollutant	Medium	Quantity/day per plant	Quantity/year per GWp
Silicon production	Carbothermic reduction of silica	SiO as SiO_2	Vapor	1,377 kg	48,180 MT
		Ash	Vapor	33 kg	1,140 MT
		CO	Vapor	5,895 kg	206,340 MT
	Silicon purification	Silicon dust loss from size reduction	Vapor	0.51-1.06 kg	18-37 MT
		Distillation bottoms ($SiCl_4$)	Liquid	1,160-2,000 kg	40,600-70,000 MT
		Noncondensibles (hydrogen)	Vapor	283 kg	9,900 MT
		Vapor dep. by-product (63% $SiCl_4$)	Liquid	8,753 kg	306,370 MT
	Silicon purification by Union Carbide process	Silicon dust loss from size reduction	Vapor	3.5 kg	124 MT
		Waste settler discharge (79% $SiCl_4$)	Liquid	369 kg	12,921 MT
		Filter waste stream (43% H_2, balance chlorosilanes)	Vapor	38.6 kg	1,351 MT
		Stripper overhead (73% chlorosilanes)	Vapor	27.6 kg	965 MT
		Product melter loss (silane and hydrogen; argon not incl.)	Vapor	2.3 kg	81 MT

Cell manufacture	Ingot forming and doping	Dust loss from crushing	Vapor	1.7 kg	60 MT
		BCl_3	Vapor	0.9 g	
	Wafer cutting and etching	Silicon chips and dust	Solid	197 kg	6,890 MT
		slurry (oil, clay, and SiC)	Liquid	30.6 kg	1,070 MT
		Etching liquor (12% SiF_4 88% mixed acids)	Liquid	1,647 kg	57,640 MT
		Etching vapors (hydrogen rate given, but also some fraction of liquor vaporized)	Vapor	7.7 kg	270 MT
	Junction formation	$POCl_3$ dopant	Vapor	0.9 g	30 kg
	Wafer edge grinding and etching	Silicon dust (under water spray)	Liquid	1.7 kg	61 MT
		Etching liquor (mixed acids)	Liquid	NA	NA
		Etching vapors (SiF_4 and H_2)	Vapor	42.3 kg	1480 MT
	Electroless plating and soldering	Spent Ni plating solution	Liquid	85 kg	2,990 MT
		Acetone	Liquid	61 kg	2,140 MT
		Photoresist (urethane varnish and titanium dioxide)	Liquid	21 l	740 m^3
		Rinse water	Liquid	28 kg	1000 MT
	Applicn. of antireflective coating	Exhaust (60% HCl, 33% SiH_2Cl_2)	Vapor	150 g	5.2 MT
		Si_3N_4 deposit on reactor walls	Solid	13 g	450 kg
	Testing, interconn., and encap.				

directly controlled, but controls implemented to reduce major pollutant waste streams may reduce these discharges as well. There is large uncertainty about the type and magnitude of these emissions because many processes described are new and proprietary, and estimates have not been verified by direct measurement.

Public Health

Public health can be adversely affected by pollutants emitted throughout the photovoltaic energy cycle and by physical hazards associated with installation and operation of these systems. In this report, a number of different chemical and physical hazards are examined.

Risk estimates for arsenic, cadmium, and sulfate exposure are summarized in Table S-2. Sulfate health damage, which appears to be the largest source of risk to health from photovoltaic systems arise from materials production (e.g., aluminum, glass, silicon) activities. These are not new risks, but rather a reassignment of existing risks to the photovoltaics industry. Estimates for cadmium induced prostate cancer deaths are based on atmospheric and food chain exposure routes; the food chain route dominates. Estimates for arsenic induced lung cancer are based on only the inhalation route and are unique to gallium arsenide systems. All of these estimates are uncertain because of potential imprecision and inaccuracy in the transport and dose-response models used.

Although large amounts of silicon compounds may be released during the production of solar grade silicon and during silicon cell processing, no adverse public health risks are projected. Chronic exposure to fluorine released from silicon fabrication or waste disposal facilities may produce dental and skeletal fluorosis. Public exposures to these compounds will,

Table S-2. Total estimated public health costs for reference photovoltaic energy systems (per 10 MWp).

Category/ effect	Reference system					
	Si-Czochralski	Si-ribbon	Si-dendritic	Si-cast	CdS	GaAs
Sulfate exposure (deaths/yr)[a]						
Mean	0.086	0.086	0.086	0.086	0.23	N.A.
Range	0-0.85	0-0.85	0-0.85	0-0.85	0-2.0	N.A.
Cadmium exposure (deaths/yr)[b]						
Mean	N.A.	N.A.	N.A.	N.A.	0.09	N.A.
Range	N.A.	N.A.	N.A.	N.A.	0-0.4[c]	N.A.
Arsenic exposure (deaths/year)[d]						
Mean	N.A.	N.A.	N.A.	N.A.	N.A.	0.001
Range	N.A.	N.A.	N.A.	N.A.	N.A.	0-0.01
Electric shocks[e]						
Mean	N.E.	N.E.	N.E.	N.E.	N.E.	N.E.
Range	N.E.	N.E.	N.E.	N.E.	N.E.	N.E.
Fires (deaths/yr)[f]						
Mean	N.E.	N.E.	N.E.	N.E.	N.E.	N.A.
Range	<0.01	<0.01	<0.01	<0.01	<0.01	N.A.

N.A. = Not applicable.
N.E. = Not estimated.

a. Based on near- and far-field atmospheric exposures and a dose-response function developed by Morgan et al. (1978). Sulfur dioxide emissions arise, principally, from materials production.

b. Based on near- and far-field atmospheric and food chain exposures, and a dose-response function for prostate cancer developed by the Carcinogen Assessment Group (1978). Emission estimates based on hypothetical design engineering studies.

c. Upper bound estimate needs to be examined in greater detail.

d. Based on near- and far-field atmospheric exposures and a dose-response function for lung cancer developed by Mushak et al. (1980). Emmission estimates based on hypothetical design engineering-studies for a 7.9 MW production output.

e. Mode and frequency for such an occurrence has not been identified. Exposed individuals are, however, at significant risk to ventricular fibrillation.

f. Event occurrence and risk estimates based on data for electrical fires from all sources. Event probability and risk estimates for photovoltaic applications alone are not available.

however, be strictly controlled by the Resource Conservation and Recovery Act, Clean Water Act, and Safe Drinking Water Act. Acute hazards from accidents may still exist. Risks from other emitted materials have not yet been examined.

Homeowners or contractors installing, maintaining, or removing rooftop photovoltaic systems may be at risk of electrical shock. Although the probability of such shocks and how they will occur are not known, potential health consequences are examined by comparing health data (e.g., release thresholds) with the electrical engineering characteristics of a residential demonstration application. Results from this analysis suggest that the voltage generated by six modules connected in series is sufficient to cause ventricular fibrillation in 0.5% of the population at normal temperatures.

Owners of photovoltaic arrays may also be subject to fire hazards caused by electrical shorts or spontaneous combustion from heat buildup in a dead air space. Again, the probability of either in a photovoltaic application is unknown. Crude upper-bound estimates of risk from fire related to rooftop applications are made by assuming that risk from photovoltaic systems are equivalent to risk from other electrical systems now found in the home. This suggests that there would be <1 reportable fire/10 MW_p/year and $<10^{-2}$ deaths/10 MW_p/year installed capacity.

Occupational Health

Occupational health can be adversely effected by workplace accidents resulting in acute or chronic injury/illness or death. Occupational health statistics for photovoltaic fabrication facilities are not available because of the relative immaturity of this industry. To gain perspective on potential health issues, occupational health statistics collected by the

U.S. Bureau of Labor Statistics and the California Department of Industrial Relations for the semiconductor industry are used as a surrogate. Risks associated with other steps in the energy cycle (i.e., installation, operation, and decommissioning) are examined using similar statistics for related industries (e.g., construction).

Energy cycle analysis (i.e., from materials production activities through to decommission) using these data suggests that there would be ~0.01 - 0.03 deaths and 70 - 130 worker days lost per unit (10 MWp) activity (Table S-3). Fabrication appears to be the largest source of risk. Among the manufacturing alternatives, differences in health cost are small.

Table S-3. Total estimated labor and occupational health costs for reference photovoltaic energy systems (per 10 MWp).[a] Range indicates 90% confidence limits.

Category/ estimate	Reference system				
	Si-Czochralski	Si-ribbon	Si-dendritic	Si-cast	CdS
Labor (10^2 MY)[b]					
Mean	1.34	1.12	1.29	1.18	1.51
Range	1.25 - 1.43	1.05 - 1.20	1.21 - 1.38	1.11 - 1.26	1.43 - 1.60
Morbidity (WDL)[c]					
Mean	83	71	78	77	124
Range	78 - 88	67 - 75	74 - 83	70 - 79	117 - 132
Mortality (10^{-2} deaths)[c]					
Mean	1.2	1.2	1.2	1.2	2.4
Range	1.1 - 1.3	1.1 - 1.2	1.1 - 1.2	1.1 - 1.2	2.2 - 2.6

a. No estimates are presented for the GaAs potovoltaic devices because these systems will only be used in central-station applications.

b. Labor estimates for fabrication are based on design engineering studies prepared by Owens et al. (1981) and Ungers et al. (1983). Estimates for other activities are principally from an input-output model described by Rowe and Groncki (1980).

c. Estimates for fabrication risks are based on data from the semiconductor industry developed by Owens et al. (1980) and Ungers et al. (1983). Estimates for remaining steps in the energy-cycle are based on data collected from related industries by the U.S. Bureau of Labor Statistics (1980).

Analysis of illness/disease data from the semiconductor industry shows that workers in this industry do not have elevated incidence rates compared with those in other manufacturing sectors. Available actuarial statistics, however, do not adequately describe potential health hazards related to toxic chemical exposures because of a variety of factors: difficulty in establishing causation, time lag, etc. In-plant surveys of the semiconductor and electronic industries conducted by federal and state agencies have observed a number of different effects including respiratory and dermal sensitization, nausea, headaches, dizziness, and liver and kidney problems. The etiology and long-term health consequences of these reported effects are unclear.

Uncertainty and Research Needs

The risk assessments presented in this report are based on a compilation of data from design engineering studies, exposure/response models, and information from surrogate industries (e.g., semiconductor) and situations (e.g., electrical shock). Use of these data introduce uncertainty of differing types (i.e., systematic vs random) and magnitudes (i.e., small vs large) into the analysis. Principal sources of important uncertainty to the decision making process include "Large Random" and "Large Systematic".

Large Systematic errors are inaccuracies arising from model or objective function misspecification. In this analysis, principal sources of this type of error are the pollutants chosen for analysis, the transport media examined (e.g., atmospheric vs hydrospheric), the toxicologic endpoints (e.g., carcinogenic vs toxic), and the surrogate data used (e.g., semiconductor). The numeric consequences of these inaccuracies cannot be easily examined.

Large Random errors arise from model imprecision. Potentially imporant sources of imprecision include: emission estimates for the reference industries, food chain exposures for cadmium, probabilities of fires and electric shocks, labor requirements for alternate fabrication sequences, and chronic health risks to photovoltaic plant workers.

In Table S-4, health and environmental research needs for the photovoltaic technology development program are identified. This list is subjectively ranked by level of importance. Objective methods for screening these identified research items (e.g., the DEMOS model) and for determining their relative criticallity and effect on the quantitative risk estimates presented are now being developed. These analyses, when implemented, will permit decision-makers to determine research priorities.

Table S-4. Health and environmental research needs (ranked by level of importance).

HIGH

1. Health and environmental risk assessment of alternative materials, processes, and effects.
2. Materials sampling and characterization: Measure types and quantities of pollutants present in the workplace and emitted by pilot- and commercial-scale photovoltaic fabrication facilities.
   - 2.1 Dopants: arsenic, phosphine, silane, phosphorus oxychloride, phosphorus pentoxide, arsenic tetrafluoride, boron trifluoride.
   - 2.2 Physical agents: ultraviolet, microwave, and radio-frequency radiation.
   - 2.3 Reaction by-products: formaldehyde from solder and flux, hydrogen chloride from phosphorus oxychloride deposition, fluoride from plasma etching, phosgene from cleaning.
   - 2.4 Solvents and etchants: trichloroethylene, trichloroethane, methylene chloride, methanol, boric acid, hydrofluoric acid.
   - 2.5 Carcinogens: beryllium, selenium, cadmium, arsenic.
3. Process information: Collect engineering and environmental data for alternative materials and fabrication processes nearing commercial viability.
   - 3.1 Material alternatives: amorphous silicon, copper indium selenide.
   - 3.2 Process alternatives: E-beam and x-ray photolithography, dry chemical and physical etching, ion implantation, plasma enhanced chemical vapor deposition, automatic masking systems, automatic diffusion systems.
4. Operational data: Prepare analyses examining source and frequency of occurrence of electric shocks and fires.
   - 4.1 Electric shocks: Prepare fault-tree analysis identifying type and origin of electric shock hazards associated with alternative applications. Combine with health-related data to determine consequences.
   - 4.2 Fires: Examine potential fire hazard in greater detail. Identify likely origins and risks and combine with health-related data to determine potential consequences.

MEDIUM

5. Toxicology and epidemiology: Conduct animal studies and initiate human epidemiological and clinical investigations to determine toxic, mutagenic, teratogenic, and carcinogenic hazards posed by specific materials.
   - 5.1 Animal Studies
     - 5.1.1 Toxicology: arsenic pentafluoride, arsine, diborane, phosphorous and its elemental compounds, fused and amorphous silicon, silane, and chlorosilanes.
   - 5.2 Human epidemiological and clinical studies
     - 5.2.1 Irritant and allergenic potential of epoxy resins.
     - 5.2.2 Biomedical causes and risks of hypersensitivity.
     - 5.2.3 Risks related to continuing exposures to glass fibers used as a filler in pottants.
     - 5.2.4 Existence of a threshold response to renal dysfunction from chronic cadmium exposure. Identify relationship between B_2 microglobulin in urine and human morbidity and mortality. Reexamine potential food-chain effects.
     - 5.2.5 Morbidity and mortality studies by occupational category for semiconductor and photovoltaic fabrication facilities.
     - 5.2.6 Morbidity and mortality studies for electric arc-furnace workers where semiconductor grade silicon is produced.
6. Industrial hygiene and control technology: Conduct in-plant surveys of pilot and commercial-scale photovoltaic fabrication facilities, characterize health and safety risks to production workers, and evaluate potential control technology requirements.
   - 6.1 Evaluate exhaust ventilation required at different work stations to maintain adequate workplace air quality, and subsequently identify controls required to minimize public health risk.
   - 6.2 Develop systematic control strategies to handle a variety of different gases, including arsine, phosphine, diborane, silane, chlorosilanes, and diphosphine which have unusual properties and concerns associated with their use, handling, containment, storage and disposal.
   - 6.3 Design equipment, personal protective devices, and strategies for the safe handling and disposal of corrosive and toxic materials likely to be used in large-scale fabrication facilities.

LOW

7. Micro- and meso-scale biological and climatic effects: Evaluate magnitude of risk associated with large central station applications.
   - 7.1 Examine effects of large central-station operation on shading, wind flow, soil moisture, etc.
   - 7.2 Examine magnitude of potential biological risk (e.g., change in species diversity).
   - 7.3 Examine magnitude of potential micro- and meso-scale climatic response (e.g., increased thunderstorm incidence).

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PREFACE

This document was prepared for the Health and Environmental Risk Analysis Program (HERAP), Office of Energy Research, U.S. Department of Energy. The major objective of HERAP is to provide an improved basis for identifying, managing, and defining an environmental research program focused on obtaining information necessary to reduce critical uncertainties regarding potential health and environmental impacts of emerging energy technologies. HERAP provides funding for universities, national laboratories, and others to perform risk analyses and to develop improved risk analysis methods. The principal product of a HERAP effort is the Health and Environmental Effects Document (HEED). A HEED is a "snapshot in time" of current knowledge and uncertainties regarding potential health and environmental effects that may be associated with the fabrication, installation, operation, and decommissioning of an energy industry.

This HEED summarizes knowledge and uncertainty regarding potential health consequences of the emerging photovoltaics industry. Related reports completed to date which were drawn upon in the preparation of this report include the following:

A comparison of Input-Output and Process analysis, P.D. Moskowitz and M.D. Rowe (BNL 30751). Presented at Workshop on Assessing Health Impacts of Energy Technologies at the National or Regional Level, Upton, NY, Dec. 1981.

A prospective method for estimating occupational health risks in new energy technologies, P.D. Moskowitz, T. Briggs, L. Ungers, and L.D. Hamilton (BNL 30748). Presented at 109th Annu. Mtg., Am. Public Health Assoc., Los Angeles, CA, Nov. 1981.

A Reference Material System for Estimating Health and Environmental Risks of Selected Material Cycles and Energy Systems, M.A. Crowther and P.D. Moskowitz, BNL Report 51563, July 1981.

A reference system for estimating health risks of selected energy material cycles, P.D. Moskowitz. Presented at 110th Annu. Mtg., Am. Public Health Assoc., Montreal, Canada, Nov. 1982.

Assessing systemwide occupational health and safety risks of energy technologies, M.D. Rowe (BNL 30732). In WHO-UNEP-IAEA Int. Symp. on Health Impacts of Different Sources of Energy, Nashville, TN, June 1981.

Electric Shocks: Health Hazards Associated with a Residential Photovoltaic Energy System, S. Rabinowitz, BNL Report 51659, Aug. 1982.

Estimates of Occupational Safety and Health Effects Resulting from Large-Scale Production of Major Photovoltaic Technologies, (P. Moskowitz, Project Officer), T. Owens, L. Ungers, and T. Briggs, BNL Report 51324, Aug. 1980.

Examining Public and Occupational Health Risks of Photovoltaic Energy Technologies, P.D. Moskowitz, E.A. Coveney, M.A. Crowther, L.D. Hamilton, S.C. Morris, K.M. Novak, P. Perry, W.A. Sevian, J.E. Smith, and P.J. Walker, BNL Report 51467, Aug. 1981.

Health and Environmental Effects Document for Photovoltaic Energy System Systems - 1982, P.D. Moskowitz, J.I. Barancik, E.A. Coveney, L.D. Hamilton, P.E. Perry, S. Rabinowitz, M.D. Rowe, and I. Wilenitz, BNL Report 51599, Sept. 1982.

Health risk assessment of energy technologies, S.C. Morris, P.D. Moskowitz, M.D. Rowe, and L.D. Hamilton (BNL 30746). Presented at 109th Annu. Mtg., Am. Public Health Assoc., Los Angeles, CA, Nov. 1981.

Health risks of photovoltaic energy technologies, P.D. Moskowitz, L.D. Hamilton, S.C. Morris, K.M. Novak, C.V. Robinson, and M.D. Rowe (BNL 30745). In WHO-UNEP-IAEA Int. Symp. on Health Impacts of Different Sources of Energy, Nashville, TN, June 1981.

Health risks of photovoltaic energy technologies, P.D. Moskowitz (BNL 31472). In Environmental and Economic Considerations in Energy Utilization (Proc. 7th Nat. Conf. on Energy and the Environment, Phoenix, AZ, Nov. 1980), J.P. Reynolds et al., eds., pp. 520-32.

Methodology for an occupational risk assessment: An evaluation of four processes for the fabrication of photovoltaic cells, L.J. Ungers, P.D. Moskowitz, T.W. Owens, A.D. Harmon, and T.M. Briggs (BNL 30129). Am. Ind. Hyg. Assoc. J. 43:73-9 (Feb. 1982).

Occupational Health and Safety Impacts of Renewable Energy Sources, M.D. Rowe and P.J. Groncki, BNL Report 51307, Sept. 1980.

Occupational Safety and Health Risks of Producing Selected Materials for Solar Energy Technologies: A Preliminary Report, M.A. Crowther, H.C. Thode, Jr., P.D. Moskowitz, and S.C. Morris, BNL Report 51407, May 1981.

Photovoltaic Energy Systems: Environmental Concerns and Control Technology Needs, P.D. Moskowitz, P. Perry, and I. Wilenitz (BNL 31478, Nov. 1981). EPA-600/57-82-066, March 1983.

Photovoltaic energy technologies: Examining public and occupational health risks, P.D. Moskowitz, L.D. Hamilton, S.C. Morris, and K.M. Novak, (BNL 29565). Solar Cells 5:1-18 (1981-82).

Photovoltaic Energy Technologies: Health and Environmental Effects Document, P.D. Moskowitz, L.D. Hamilton, S.C. Morris, K.M. Novak, and M.D. Rowe, BNL Report 51284, Sept. 1980.

Programs and Subroutines for Calculating Cadmium Body Burdens Based on a One-Compartment Model, C.V. Robinson and K.M. Novak, BNL Report 51306, Aug. 1980.

Rooftop photovoltaic arrays: Electric shock and fire health hazards, P.D. Moskowitz, E.A. Coveney, S. Rabinowitz, and J.I. Barancik. Solar Cells 9:1-10 (1983).

Toxicity of Arsenic and Its Compounds, P.G. Green, BNL Report 51510, July 1981.

Toxicity of Silicon Compounds, K.M. Novak, BNL Report 51509, March 1980.

Toxicity of Cadmium and Its Compounds: A Review of the Literature Aimed at Identifying Dose-Response Relationships, K.M. Novak, BNL Report 51511, March 1980.

1 INTRODUCTION

Photovoltaic solar cells are solid-state devices that convert sunlight directly into electricity. Commercial production of photovoltaic cells and modules has been technically feasible for many years; however, present manufacturing costs make it more expensive to produce electricity this way than by conventional alternatives. Recent recognition of the finiteness of conventional fuels, and of the social costs associated with their use, has generated great interest in the role of photovoltaic systems in the future U.S. energy economy. Consequently, the U.S. Congress has passed several laws to provide research funds and economic incentives to the private sector to accelerate development of reliable and economically viable photovoltaic systems (U.S. Congress 1974, 1978a-c, 1982). Large research investments have also been made by the private sector.

Although it is generally thought that health and environmental risks from photovoltaic systems are not large, it is known that no energy system operates without risk (Hamilton 1980; Holdren et al. 1980; Morris et al. 1981; Morgan 1981). In recognition of these risks, Congress has also required the U.S. Department of Energy (DOE) to resolve social, technical, environmental, institutional, and legal issues relating to the widespread adoption of photovoltaic systems. Identification and analysis of such issues, before the technology becomes fully commercialized, can limit potential investment costs while simultaneously minimizing health and environmental risks. Also, such analysis can help administrators make wise and useful decisions about allocating limited resources and directing future research.

In this report the technological readiness to produce and operate photovoltaic systems on a commercial scale and the associated health concerns are examined. (i) Detailed engineering descriptions of five different manufacturing options covering a spectrum of materials and processes likely to be commercialized are given. (ii) Public health risks associated with exposure to compounds important to the photovoltaics production process which have generated great interest, as well as the risks from electric shocks and fires associated with rooftop installations, are examined. (iii) Occupational accident- and illness-related risks arising from exposure to hazardous working conditions are evaluated. (iv) Priorities for research needs are suggested.

2 BACKGROUND

2.1 Historical Overview

Photovoltaic systems are based on solar energy conversion technologies -- i.e., technologies for the conversion of light energy (photons) directly into electricity. This phenomenon, known as the photovoltaic effect, begins with the excitation of electrons in a solid by absorption of light. This excitation creates a population of negative and positive charges that are free to move through a semiconductor material if it contains appreciable numbers of impurity centers. A semiconductor that is specially treated (doped) with certain impurities can convert incident sunlight into electrical energy.

Although the photovoltaic effect had been observed in 1839, development of a reasonably efficient silicon solar cell did not occur until 1954 -- along with the development of a process for purifying silicon monocrystals

(Palz 1978). Single-crystal silicon cells are currently produced commercially and serve as the standard of comparison for new materials and concepts, but their production is costly, and several alternative forms of silicon are being investigated. Processes nearing commercial use include ingot casting and ribbon growing (Kelly 1978; Costello and Rappaport 1980; Smith 1981) and production of amorphous devices.

Inexpensive production of thin film photovoltaic cells represents an alternative to existing fabrication technologies. Thin films of specialized materials such as cadmium sulfide/copper sulfide, polycrystalline gallium arsenide, and amorphous silicon have the potential to yield photovoltaic cells at comparatively low production costs. The major disadvantages of thin films are their low efficiencies and short lifetimes (Smith 1981).

Existing photovoltaic technologies are expensive, in part, because of the diffuse nature of sunlight. Concentrators offer one alternative for overcoming this problem, but use of concentrators instead of flat-plate collectors increases engineering complexity (e.g., additional support and tracking may be required) and consequently, the capital costs of photovoltaic systems. Some analysts have concluded that cell efficiencies of ~30% (twice that of single-crystal silicon ingot cells) are required for concentrators to be cost effective (Costello and Posner 1979).

2.2 Past, Present, and Future Markets

After development of the silicon cell in 1954, commercial production began. Early sales in 1955-1959 of single-crystal silicon cells were for terrestrial applications. Following the launch of the first satellite in 1958, silicon cells became the principal power source for all satellites and most sales were made for this use. Photovoltaic cells enjoyed great commercial success in this market because they were lighter than any other power source in terms of weights of fuels and conversion devices versus rated power.

In 1975, world production of silicon solar cells was ~100 kWp/yr, a rate that had remained constant for ~15 years, but more solar cells were sold for use on the ground than in space. Since the terrestrial market was insignificant in 1973, this represented a tremendous growth in demand (Palz 1978). In 1976, the free-world market for photovoltaic cells was about 308 kWp, of which ~208 kWp were sold by U.S. manufacturers (Kelly 1978; Costello and Posner 1980). Table 1 lists estimated photovoltaic module shipments for 1975-1982. During this period, annual shipments increased at a rate of ~100%/yr.

Future growth in the photovoltaic industry is expected to be large. The most widely held view is that the technology will penetrate, stepwise, three different markets. The near-term market generally includes small remote-sited applications, e.g., mountaintop radio-repeaters, for which commercial sales are currently being made and annual sales of 3 to 7 MWp are expected. An intermediate market, e.g., water pumping and general power supplies for remote villages, could ultimately range from 50 to 500 MWp

Table 1. Estimated photovoltaic module shipments (MWp). From Kelly (1978); Costello and Posner (1980); Krantz (1983).

Geographic background	Year							
	1975	1976	1977	1978	1979	1980	1981	1982
World	0.10	0.31	~0.62	0.8	>1.0	3.3	5.5	8.4 - 9.0
U.S.	N.A.	0.21	N.A.	N.A.	N.A.	2.5	3.5	4.9 - 5.5
U.S. market share	N.A.	67%	N.A.	N.A.	N.A.	76%	64%	58% - 60%

annually, but photovoltaic systems are not yet cost competitive for this market. The ultimate market for photovoltaic energy systems will be the large electric power sectors, comprising small (<3 to 10 kWp), intermediate (<500 kWp), and large (~100 MWp) installations serving single residences, commercial and industrial settings, and central-station generators, respectively. Estimates of the potential size of this last market vary according to projected costs of photovoltaic and conventionally generated electricity (Costello 1980; Smith 1981; Costello and Posner 1979). The percentages of present sales going to these markets are shown in Table 2.

Table 3 gives some estimates for the potential role of photovoltaic energy systems in the U.S. energy economy. To meet these goals, massive sustained growth in manufacturing capabilities is needed. Moskowitz et al. (1981b) have estimated, for example, that an annual sustained growth rate of 63%/yr between 1981 and 2000 would be needed to meet the minimum DOE supply estimate of 0.1×10^{18} J by the year 2000 (1980). The accuracy of these estimates and the ability of the industry to grow at this rate have been questioned, for example, the value of shipments from the semiconductor industry increased only by a factor of ~10 over 17 years (1960 to 1977) (Noyce 1977). Reductions in federal research and development funds for photovoltaics research may increase the difficulty of meeting these goals.

Table 2. Estimated world photovoltaics market share by end-use category (%). From Krantz (1983).

End use	Year 1981	Year 1982
Stand alone	76	52
Central station	0	24
Intermediate	6	6
Residential	1	1
Specialty	17	15

Table 3. Photovoltaic energy supply projections.

Reference	Year	Projected supply (10^{18} J)
Council on Environmental Quality (1978)	2000	2.1 - 8.4
Council on Environmental Quality (1978)	2020	11 - 32
U.S. Department of Energy (1979)	2000	0.11 - 1.1
U.S. Department of Energy (1980)	2000	0.11 - 1.1
National Audubon Society (1981)	2000	0.74

2.3 Material and Manufacturing Options

In 1979, at least eight U.S. companies were producing terrestrial photovoltaic modules in commercial quantities, and all produced single-crystal silicon flat-plate modules. Polycrystalline and concentrating modules, using single-crystal silicon, are now being sold commercially (see Table 4); amorphorus silicon solar cells are being produced commercially in Japan and U.S. production is imminent. At least ten additional U.S. companies and a large number of European and Japanese consortiums are investing significant amounts of capital in photovoltaics research and development. Plans for commercial production of concentrating gallium arsenide modules are being formulated. Other technologies, such as those using indium phosphide, polycrystalline gallium arsenide, and advanced concentrator materials, require research before commercial production can begin (Palz 1978; Costello and Posner 1979; Costello and Rappaport 1980; Smith 1981).

3 RISK ASSESSMENT METHODS

The basic elements examined in this risk assessment are shown in Figure 1. The assessment begins by defining basic attributes of the reference industries, including detailed analyses of manufacturing and

Table 4. Photovoltaics market share by technology (%). From Krantz (1983).

Technology/material	1981	1982
Czochralski/silicon	69	62
Semi-XTL/silicon	11	18
Amorphous silicon/silicon	3	9
Ribbon/silicon	0	1
Concentration/silicon	17	11

material options, operator requirements and occupational hazards, control technology needs and potential pollution releases. Next, transport routes of pollutants through air, water, and terrestrial food chains are examined. The estimated exposures are then used in combination with dose-response models to determine effects of released pollutants on public health. Physical hazards from the energy system are studied by using data developed for the specific issues. Similarly, occupational hazards are quantitatively examined by using actuarial data from related industries, and exposure and dose-response models for specific chemical hazards. System-wide (e.g., material supply activities) occupational health risks are studied by using an Input-Output model. Specific details on models and data used in these analyses are presented below.

4 REFERENCE INDUSTRIES

The photovoltaic energy cycle includes (i) extraction, processing, and refining of raw materials, (ii) fabrication, installation, and operation and maintenance of devices, and (iii) decommissioning of spent devices. In this analysis, considerable effort was devoted to potential risks related to fabrication, installation, operation and maintenance, and decommissioning. These steps were examined intensively because they are specific to the

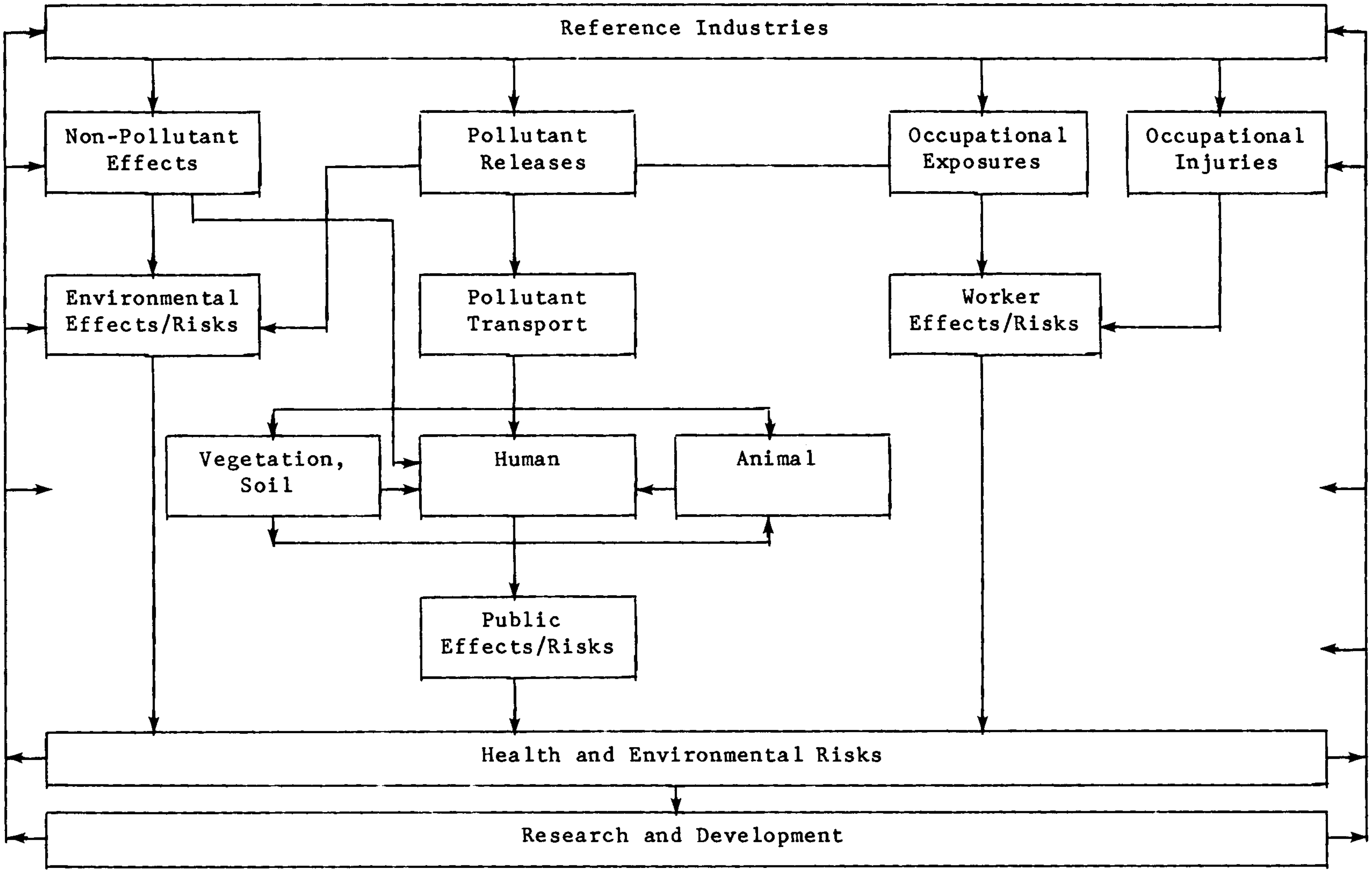

Figure 1. Conceptual diagram of the approach for performing a health and environmental risk assessment. Modified from Layton et al. (1981).

photovoltaic energy cycle and/or represent major steps for which chemical and physical hazards may exist.

In photovoltaic cell fabrication, six different processes (Figure 2) were considered, those producing (i) single-crystal silicon cells by ingot growing, (ii) semicrystalline silicon cells by ribbon growing, (iii) semicrystalline silicon cells by dendritic web growth, (iv) semicrystalline silicon cells by ingot casting, (v) thin-film cadmium sulfide/copper sulfide backwall cells by spray deposition, and (vi) gallium arsenide heterojunction cells by ingot growing. These alternatives cover a range of manufacturing options and materials likely in near-term commercialization activities. Risks from other processes nearing commercial viability (e.g., those producing silicon amorphous cells) may differ from those examined.

In describing these reference industries, production processing and labor requirements are identified, material inputs and outputs are stated, occupational risks are quantified, and control technology availability is reviewed. Emission estimates are based on the use of prudent engineering practices, especially for toxic and hazardous pollutants. Since environmental hazards due to installation and to operation and maintenance are generally common to all photovoltaic systems, they are discussed without regard to specific photovoltaic cell type. Effects related to extraction of all materials and refining of materials commonly used throughout industry are not discussed here, although they have been examined (Crowther and Moskowitz 1981; Moskowitz et al. 1980, 1981a).

Table 5 summarizes pollution controls likely to be used in this emerging industry (Moskowitz et al. 1981b). Because of the wide variety of materials used, control experience and technologies from other industries

Silicon Czochralski Ingot Process	Silicon Ribbon Process	Silicon Dendritic Web Process	Silicon Cast Ingot Process	Cadmium Sulfide Process	Gallium Arsenide Process
Single-Crystal Growth	Ribbon Growth	Sheet Growth	Ingot Casting	Process Glass Substrates	Single-Crystal Growth
Ingot Processing		Cleaning and Prediffusion Etch	Ingot Processing	CdS Application	Ingot Processing
Junction Formation	Aluminum (p^+) Application	Back Junction Formation	Surface Preparation Preparation		Liquid Phase Epitaxial Deposition
Perimeter Grinding	Plasma Etching	Front Junction Formation	Junction Formation		
Wafer Etching	Ion Implantation	Antireflective Coating	Antireflective Coating	Grid Forming	CVD Deposition
Metallization	Metallization	Print and Etch Grind Pattern	Print and Etch Grind Pattern	Cu Ion Implant	Wafer Etching
Antireflective Coating	Antireflective Coating	Metallization	Solder Applicn. Wafer Etching	Metallization	Metallization
Cell Testing		Cu Plate Cell Separation	Cell Testing		Antireflective Coating
Cell Interconnection	Cell Interconnection	Cell Interconnection	Cell Interconnection	Cell Interconnection	Cell Interconnection
Encapsulation	Encapsulation	Encapsulation	Encapsulation	Encapsulation	Encapsulation
Module Testing	Module Testing	Module Testing	Module Testing	Module Testing	Module Testing

Figure 2. Process operations associated with reference photovoltaic fabrication industries.

Table 5. Review of control technology requirements. From Moskowitz et al. (1981b).

Media/category	Pollutants	Control technology	Comments
1. Atmospheric			
1.1 Vapor: nonorganic, combustible	CO, H_2, chlorosilanes.	CO combustion, air dilution, combustion of chlorosilanes to form muriatic acid.	Technologies commonly employed, limits must be identified.
1.2 Vapor: organic	Isopropanol, with or without breakdown products of dopants. Solvent mixtures, including acetates, alcohols and xylene. Pure organics, including methanol, terpineol and trichlorethane.	Dilute with air, combust in fume incinerators, adsorb on activated carbon. If quantities make it worthwhile, use as auxiliary fuel in boiler, or recover from activated carbon during steam regeneration.	Technologies commonly employed, limits must be identified.
1.3 Vapor: other	HF, HCl, HBr, NH_3, Br_2, F_2, BBr_3, BCl_3, $POCl_3$, PH_3, P_2O_5, HCN(?), SiF_4, CF^4, Si oxyfluorides.	Air dilution; treat in water, lime, or caustic scrubber; discharge liquor to lagoon and neutralize if necessary.	Design studies required in order to achieve limits.
1.4 Dust	Metals, Si, SiO_2, Cd, lead oxide.	Bag filters or cyclones.	97 to 99% removal.
2. Liquid			
2.1 Acids	HF, HCl, acetic, HNO_3, H_2SO_4.	Neutralization and discharge to lagoon.	Impervious lagoon, overflow liquid may be hazardous, sludge will be hazardous.
2.2 Alkalies	NaOH and other alkaline solutions.	Neutralize, or use to neutralize acidic streams.	Same as above.
2.3 Metal solutions	Cd, Cu, As, Ni, Si, Ti, Al.	Flocculation (lime, alum, ferric salts, polyelectrolytes).	Flocculation technique must be identified. Effective standards must be met, and sludge will require control.
2.4 Rinse waters waters	Dilute streams containing HF, NaOH, HCl, Ti, Ni.	Deionized water: recycle to deionizers. Other: use for diluting discharges.	Ensure that deionizers can handle the concentrations involved.
2.5 Solvents	Methanol, acetone, and proprietary mixtures.	Collect in drums or tanks and sell for recovery.	
2.6 Other	Chlorosilanes, slurry, solvents, cutting oils, proprietary solutions.	Process revisions, distillation. Collect and return to vendors.	Chlorosilanes could be feedstock.
3. Solid			
3.1 Hazardous	As, Cd, F, and other compounds, rejected cells, spent filter media.	Resale or recycle, where possible. Otherwise, disposal in controlled landfill.	Metals and F noted under RCRA guidelines.
3.2 Non-hazardous	Si and its compounds, metals, glass, and plastics.	Resale or disposal in sanitary landfill.	

may ultimately be applied to the photovoltaics industry. The final degree of control is likely to be determined more precisely by specific design engineering studies seeking compliance with specific standards.

Table 6 lists emission estimates for a single technology, for illustrative purposes; emission estimates for the other systems examined are given in the Appendix. Because many of the processes described are new and, more importantly, because many of them are proprietary, it has seldom been possible to quantify emission streams by direct measurement. Therefore, these data, being based not on actual measurements of waste streams from existing plants but rather on extrapolations from pilot facilities and design engineering studies, should be used with care.

Analysis suggests that several processes (e.g., etching) could emit potentially large quantities of pollutants, but these can be controlled with available technology (e.g., neutralization and flocculation). Other processes may emit small quantities of more exotic pollutants (e.g., boron trichloride, phosphorus oxychloride, phosphine) which will probably not be directly controlled unless significant health hazards are identified. To the degree that processes are integrated within plants and automated, any controls implemented to reduce the major pollutant waste streams may also reduce the discharges of these more exotic pollutants (Moskowitz et al. 1981b).

5 OCCUPATIONAL HEALTH

Occupational health costs of photovoltaic systems may arise from workplace accidents resulting in acute or chronic injury or illness or in death. To examine these risks, quantitative and qualitative approaches were

Table 6. Estimated pollutant emission rates from the production of silicon Czochralski ingot photovoltaic cells. From Moskowitz, et al. (1981b). Plant Capacity 10 MWp/yr, and 350 working days/yr. Emission rates for the process steps examined are generally reported in units of kg/day plant. For refining processes, it is assumed that each refinery would produce 1000 metric tons/yr of silicon or cadmium. All statistics for the fabrication facilities assume annual production capacities of 10 MWp, about what is projected for a photovoltaic fabrication facility in the late 1980s; the largest production line now in existence is ~1 MWp. Fabrication emission rates are also reported in units of (metric tons/yr) per GWp. Annual production of 1 GWp, projected for around 1990, would thus require 100 facilities, each with a production output of 10 MWp. (NA = not available.)

Activity	Process step	Pollutant	Medium	Quantity/day per plant	Quantity/year per GWp
Silicon production	Carbothermic reduction of silica	SiO as SiO_2	Vapor	1,377 kg	48,180 MT
		Ash	Vapor	33 kg	1,140 MT
		CO	Vapor	5,895 kg	206,340 MT
	Silicon purification	Silicon dust loss from size reduction	Vapor	0.51-1.06 kg	18-37 MT
		Distillation bottoms ($SiCl_4$)	Liquid	1,160-2,000 kg	40,600-70,000 MT
		Noncondensibles (hydrogen)	Vapor	283 kg	9,900 MT
		Vapor dep. by-product (63% $SiCl_4$)	Liquid	8,753 kg	306,370 MT
	Silicon purification by Union Carbide process	Silicon dust loss from size reduction	Vapor	3.5 kg	124 MT
		Waste settler discharge (79% $SiCl_4$)	Liquid	369 kg	12,921 MT
		Filter waste stream (43% H_2, balance chlorosilanes)	Vapor	38.6 kg	1,351 MT
		Stripper overhead (73% chlorosilanes)	Vapor	27.6 kg	965 MT
		Product melter loss (silane and hydrogen; argon not incl.)	Vapor	2.3 kg	81 MT
Cell manufacture	Ingot forming and doping	Dust loss from crushing	Vapor	1.7 kg	60 MT
		BCl_3	Vapor	0.9 g	
	Wafer cutting and etching	Silicon chips and dust	Solid	197 kg	6,890 MT
		slurry (oil, clay, and SiC)	Liquid	30.6 kg	1,070 MT
		Etching liquor (12% SiF_4 88% mixed acids)	Liquid	1,647 kg	57,640 MT
		Etching vapors (hydrogen rate given, but also some fraction of liquor vaporized)	Vapor	7.7 kg	270 MT
	Junction formation	$POCl_3$ dopant	Vapor	0.9 g	30 kg
	Wafer edge grinding and etching	Silicon dust (under water spray)	Liquid	1.7 kg	61 MT
		Etching liquor (mixed acids)	Liquid	NA	NA
		Etching vapors (SiF_4 and H_2)	Vapor	42.3 kg	1480 MT
	Electroless plating and soldering	Spent Ni plating solution	Liquid	85 kg	2,990 MT
		Acetone	Liquid	61 kg	2,140 MT
		Photoresist (urethane varnish and titanium dioxide)	Liquid	21 l	740 m^3
		Rinse water	Liquid	28 kg	1000 MT
	Applicn. of antireflective coating	Exhaust (60% HCl, 33% SiH_2Cl_2)	Vapor	150 g	5.2 MT
		Si_3N_4 deposit on reactor walls	Solid	13 g	450 kg
	Testing, interconn., and encap.				

used. Accident risks were quantitatively examined by combining accident data with engineering estimates of labor required for unique steps in the photovoltaic energy cycle: fabrication, installation, operation and maintenance, and decommissioning. Systemwide (i.e., material supply activities) estimates of labor and occupational accidents for steps common to the U.S. economy were examined by using an Input-Output model and occupational health statistics. To supplement these accident-related statistics, hazards posed by specific production processes and/or materials were examined by using available dose-response models and health data from the semiconductor industry.

5.1 Accident-Related

Determination of occupational health and safety risks for emerging technologies is difficult because statistics are insufficient or unavailable. Risk must nevertheless be estimated for decision-making purposes.

In lieu of obtaining actuarial statistics, estimates of risk from a new industry must be extrapolated from data for related industries. Extrapolation requires specification of (i) types of occupations or categories associated with production of a particular energy form; (ii) labor required per unit activity; and (iii) risk per unit activity.

Estimated occupational risks for the reference manufacturing facilities have been prepared and are summarized elsewhere (Moskowitz et al. 1980, 1981a, 1982; Owens et al. 1980; Ungers et al. 1982). Table 7 presents results from a sample analysis. These estimates were based on detailed design engineering studies of labor required, by process, to fabricate each

Table 7. Estimated lost workdays and fatalities for a 10-MWp/yr photovoltaics plant (silicon Czochralski ingot process). Modified from Owens et al. (1980). Linearly scaled from 25 MWp to 10 MWp annual production output.

Process operation (P.O.)	Occupational category (O.C.)	Labor, emp-hrs per yr	Lost Workdays per O.C.	Fatalities per O.C.	Lost workdays per P.O.	Fatalities per P.O.
Single-crystal growth	Technical	40,248	8.5	4.0×10^{-4}	11.7	5.5×10^{-4}
	Inspection	5,616	1.4	7.9×10^{-5}		
	Maintenance	5,250	1.7	6.8×10^{-5}		
Silicon ingot process	Material abrading and polishing	24,150	4.8	Neg.	10.2	2.4×10^{-4}
	Inspection	5,616	1.4	7.9×10^{-5}		
	Metal plating	600	0.2	1.4×10^{-5}		
	Maintenance	11,685	3.8	1.5×10^{-4}		
Junction formation	Technical	1,725	0.4	1.7×10^{-5}	0.7	2.8×10^{-5}
	Inspection	210	0.1	2.9×10^{-6}		
	Maintenance	630	0.2	8.2×10^{-6}		
Perimeter grinding	Material abrading and polishing	1,380	0.3	Neg.	0.4	3.8×10^{-5}
	Technical	36	Neg.	3.6×10^{-7}		
	Inspection	180	0.1	2.5×10^{-6}		
	Maintenance	72	Neg.	9.4×10^{-7}		
Wafer etching	Metal plating	1,200	0.4	2.9×10^{-5}	0.5	3.4×10^{-5}
	Inspection	90	Neg.	1.3×10^{-6}		
	Maintenance	270	0.1	3.5×10^{-6}		
Metallization	Metal plating	2,400	0.8	5.8×10^{-5}	0.9	6.0×10^{-5}
	Inspection	24	Neg.	3.4×10^{-7}		
	Maintenance	144	0.1	1.9×10^{-6}		
Antireflective coating	Technical	4,200	0.9	4.2×10^{-5}	1.0	4.6×10^{-5}
	Inspection	42	Neg.	5.9×10^{-7}		
	Maintenance	252	0.1	3.3×10^{-6}		
Cell testing	Assembling	11,400	2.6	1.4×10^{-4}	2.8	1.5×10^{-4}
	Inspection	114	Neg.	1.6×10^{-6}		
	Maintenance	684	0.2	8.9×10^{-6}		
Cell interconnection	Assembling	5,202	1.2	6.2×10^{-5}	1.8	8.9×10^{-5}
	Inspection	720	0.2	1.0×10^{-5}		
	Maintenance	1,320	0.4	1.7×10^{-5}		
Encapsulation	Assembling	10,200	2.3	1.2×10^{-4}	2.4	1.3×10^{-4}
	Inspection	120	Neg.	1.7×10^{-6}		
	Maintenance	300	0.1	3.9×10^{-6}		
Module testing	Inspection	606	0.2	7.0×10^{-6}	0.2	8.0×10^{-6}
	Maintenance	36	Neg.	4.7×10^{-6}		
Total		136,722			32.6	1.3×10^{-3}

of the cell alternatives. Complementary estimates of occupational risk by job category were derived from data collected by the California Department of Industrial Relations (1980a, b).

Table 8 presents estimates of risk associated with installation, operation and maintenance, and decommissioning of these reference systems. These estimates were extrapolated from data from the installation and operation of an integral rooftop shingle by using related labor estimates (e.g., Moskowitz et al. 1981a) and occupational health statistics (U.S. Department of Labor 1980). Estimates for intermediate and central station applications will be different and are not examined.

As shown, labor and risk within any single reference energy cycle generally increase in the following order: decommissioning, operation and maintenance, installation, inverter fabrication, and photovoltaic cell fabrication. Among the reference systems, variations are not large, but health costs increase in the following order: silicon ribbon, silicon cast ingot, silicon dendritic web, silicon Czochralski, and cadmium sulfide. Although manufacturing health costs for the cadmium sulfide system are low, system-wide health costs are much higher because of the relatively low efficiency assumed for this system (5%) compared with the others (15%).

Estimated direct (e.g., photovoltaic cell manufacture) and indirect (i.e., supply of raw materials) labor and occupational health costs have recently been examined by using outputs from both Input-Output (Rowe 1981b) and Process-Level analyses (Crowther and Moskowitz 1981; Moskowitz and Rowe 1981). In this assessment, risk estimates for all material supply activities and inverter fabrication are derived from the BNL Input-Output model. Estimates for all other activities (i.e., photovoltaic cell

Table 8. Estimated labor requirements and occupational health costs for the reference photovoltaic energy cycle (per 10 MWp). From Moskowitz et al. (1981a), Owens et al. (1980), Ungers et al. (1982), and Moskowitz et al. (1982). Assumes 15% conversion efficiency for all silicon alternatives and 5% efficiency for the CdS system. Similar estimates for the GaAs system have not been prepared because the cell will be used principally in a central station concentrator application. Range indicates 90% confidence limit, calculated by using DEMOS model developed by Henrion (1982). This analysis assumes that all labor and risk estimates are normally distributed with one standard deviation equal to 10% of the median estimate. For simplicity, the estimated ranges are shown only for the totals. Estimates for GaAs are not presented because this system will only be used in a central-station application.

	Reference system				
Sector/category	Si Czochralski	Si Ribbon	Si Dendritic	Si Cast	CdS
Fabrication, PV cell					
Labor (10^{2} MY)	6.84x10^{-1}	4.70x10^{-1}	6.35x10^{-1}	5.29x10^{-1}	3.10x10^{-1}
Morbidity (WDL)	3.26x10^{1}	2.08x10^{1}	2.78x10^{1}	2.41x10^{1}	1.42x10^{1}
Mortality (deaths)	1.3 x10^{-3}	1.0 x10^{-3}	1.3 x10^{-3}	1.04x10^{-3}	6.4 x10^{-4}
Fabrication, inverter					
Labor (10^{2} MY)	3.77x10^{-1}	3.77x10^{-1}	3.77x10^{-3}	3.77x10^{-1}	3.77x10^{-1}
Morbidity (WDL)	2.02x10^{1}	2.02x10^{1}	2.02x10^{1}	2.02x10^{1}	2.02x10^{1}
Mortality (deaths)	2.23x10^{-3}	2.23x10^{-3}	2.23x10^{-3}	2.23x10^{-3}	2.23x10^{-3}
Installation					
Labor (10^{2} MY)	1.54x10^{-1}	1.54x10^{-1}	1.54x10^{-1}	1.54x10^{-1}	4.62x10^{-1}
Morbidity (WDL)	1.63x10^{1}	1.63x10^{1}	1.63x10^{1}	1.63x10^{1}	4.87x10^{1}
Mortality (deaths)	4.46x10^{-3}	4.46x10^{-3}	4.46x10^{-3}	4.46x10^{-3}	1.33x10^{-2}
Operation and maintenance					
Labor (10^{2} MY)	7.11x10^{-2}	7.11x10^{-2}	7.11x10^{-2}	7.11x10^{-2}	2.13x10^{-1}
Morbidity (WDL)	7.97x10^{0}	7.97x10^{0}	7.97x10^{0}	7.97x10^{0}	2.39x10^{1}
Mortality (deaths)	2.40x10^{-3}	2.40x10^{-3}	2.40x10^{-3}	2.40x10^{-3}	3.18x10^{-3}
Decommissioning					
Labor (10^{2} MY)	4.97x10^{-2}	4.97x10^{-2}	4.94x10^{-2}	4.97x10^{-2}	1.49x10^{-1}
Morbidity (WDL)	5.57x10^{0}	5.57x10^{0}	5.57x10^{0}	5.57x10^{0}	1.67x10^{1}
Mortality (deaths)	1.54x10^{-3}	1.54x10^{-3}	1.54x10^{-3}	1.54x10^{-3}	4.62x10^{-3}
Total					
Labor (10^{2} MY)					
Mean	1.34	1.12	1.29	1.18	1.51
Range	1.25-1.43	1.05-1.20	1.21-1.38	1.11-1.26	1.43-1.60
Morbidity (WDL)					
Mean	83	71	78	74	124
Range	78-88	67-75	74-83	70-79	117-132
Mortality (10^{-2} deaths)					
Mean	1.2	1.2	1.2	1.2	2.4
Range	1.1-1.3	1.1-1.2	1.1-1.3	1.1-1.2	2.2-2.6

fabrication, installation, operation and maintenance, and decommissioning) come from detailed process analyses. This combined approach was used to overcome problems arising with the system boundaries chosen for risk analysis purposes. This analysis suggests that ~60 to 70% of the labor demand and occupational risk arises from indirect activities required for implementation of this energy system.

In reviewing these analyses, it should be noted that the estimates implicity recognize that work imposes some risk; there are also health costs related to being unemployed. Analysis of "net risk" provides some measure of the marginal costs or benefits to the existing workforce imposed by a particular energy system.

Net risk can be determined by various approaches. Simple calculations of net risk can be made by comparing "estimated" with "expected" health costs of workers already employed within industry. More complex calculations of net risk can be made by comparing "estimated" and "expected" health costs from competing or base-line energy systems. Analysis of the latter type, however, requires detailed examination of different energy systems with use of common boundaries and assumptions.

Moskowitz et al. (1981a) have examined net risk imposed by photovoltaic energy systems using the first approach. The "expected" number of WDL and fatalities were based on occupational statistics from three different economic sectors: mining, manufacturing, and construction. In developing estimates of expected health cost, they assumed (i) that labor structure was unaffected by the large-scale commercialization of the energy system being studied, i.e., labor demand was not satisfied by workers drawn from the unemployed, and (ii) that individual workers within any of the three different economic sectors remained employed within the same sector.

On the basis of these assumptions, they calculated the "expected" mortality and morbidity rates for selected reference applications. Results from their analyses suggested that no significant changes in risk were to be expected in the workforce from the commercialization of photovoltaic energy systems, but rather a reapportionment of risk present in industry today. Comparison of estimates produced in this study with expected risks of competing energy cycles have not yet been made because of inconsistencies in system boundaries and assumptions.

5.2 Illness-Related

Actuarial data can be used for reasonable examination of acute risks of physical injury in industry, but such data cannot provide an accurate description of potential chronic hazards. Because of this limitation, this problem has been dealt with in three ways: (i) simple highlighting of potential chemical and physical hazards faced by workers in photovoltaic fabrication facilities, (ii) use of deterministic approaches to bound potential hazards to workers from examination of specific chemicals, and (iii) examination of illness-related experience in the closely related semiconductor industry, where processes and materials are similar to those likely to be used in photovoltaics fabrication plants. *A priori* identification of any hazard can enable engineers to develop control strategies to mitigate its effects, and risks discussed below must be viewed in this context.

5.2.1 Potential Chemical and Physical Hazards

Fabrication of photovoltaic devices may involve use of chemicals and of physical processes, some of acute concern. Table 9 lists identified chemical and physical hazards presenting acute or chronic toxicological risks which might be encountered in photovoltaic fabrication facilities. Quantitative risk estimation based on this information is not possible. Prudent design engineering, however, should be incorporated into the planning of all new processes to ensure that exposures to many of these

Table 9. Potential chemical and physical hazards to workers from full-scale production of photovoltaic cells.

POTENTIAL CHEMICAL HAZARDS

Acetic acid
Acetone
Aluminum (powder)
Ammonia
Ammonium hydroxide
Beryllium
Boron hydride
Boron tribromide
Boron trichloride
Boron trifluoride
Cadmium
Cadmium chloride
Cadmium sulfide
Carbon monoxide
Carbon tetrafluoride
Chlorosilanes
Chromium
Copper
Copper chloride
Ethanol
Hydrogen
Hydrogen bromide
Hydrogen chloride
Hydrogen fluoride
Isopropanol
Lead
Methanol
Nickel
Nickel chloride
Nitric acid
Nitrogen
Nitrogen dioxide
Nitrogen monoxide
Ozone
Phosphine
Phosphorus oxychloride
Polyethylene
Silicon
Silicon carbide
Silicon dioxide
Silicon hydride
Silicon nitride
Silicon oxyfluorides
Silicon tetrachloride
Silicon tetrafluoride
Silver
Sodium hydroxide
Sodium hypophosphite
Sulfuric acid
Terpineol
Thiourea
Tin
Tin chloride
Tin oxide
Titanium dioxide
Trichloroethanes
Urethane
Vinyl acetate and other organic acetates
Xylene
Zinc chloride

POTENTIAL PHYSICAL HAZARDS

Heat
Electrical energy
Laser
Noise
Ultraviolet light
Mechanical energy
X-rays
RF radiation

hazards do not exceed existing standards and consequently threaten occupational health.

5.2.2 Deterministic Modeling

Since in-plant measurements of occupational exposures in the phtovoltaics industry are not available, quantitative analysis of illness-related health risks must be done by deterministic or hypothetical approaches, that is, by estimating the response magnitude if a worker is chronically exposed to a chemical at a specific concentration.

In operating facilities, it is unlikely that chronic exposures will exceed levels equal to the Threshold Limit Values (TLVs) (American Conference of Governmental and Industrial Hygienists 1971). Therefore, we used TLV's in combination with available dose-response models to develop upper-bound occupational risk estimates. Results of an analysis combining estimated TLVs for cadmium, silicon, and arsenic with available dose-response models (see Sections 6.1.2 to 6.1.4) are summarized in Table 10. As indicated, chronic occupational exposure to air concentrations equal to the respective TLVs could produce significant health responses. Lung and prostatic cancer rates from arsenic and cadmium exposures, for example, might well exceed the background cancer incidence rates. Alternatively, chronic exposure to 40 $\mu g/m^3$ cadmium could cause kidney burden levels to exceed identified health damage thresholds by a factor of 2. Inhalation of silicon at exposures equal to the TLV could produce an 8% reduction in forced vital capacity (FVC). Likely exposures, of course, will be much lower than those modeled, but design engineers should nevertheless take note of these potential concerns.

Table 10. Potential occupational health risks of inhalation exposure to arsenic, cadmium, and silicon compounds.

Pollutant	Estimate exposure	Model	Type of response	Model results	Comments
As	10 μg/m^3	CAG	Lung cancer	2.0×10^{-2} Excess cancers/ person	Background lung cancer incidence rate = 3.3×10^{-2} per person
	OSHA TWA std. = 10 μg/m^3			Range = $0\text{-}3.4\times10^{-2}$	
Cd	50 μg/m^3	CAG	Prostate cancer	1.23×10^{-3} Excess cancers/ person	Existing fatality rate for prostate cancer = 1.76×10^{-4} per person
	TLV = 50 μg/m^3			Range = $0\text{-}1.32\times10^{-2}$	
Cd	1 μg/m^3 10 μg/m^3 20 μg/m^3	BNL	Cadmium concentration in kidney	130 μg/g 200 μg/g 600 μg/g	Threshold for damage ranges from 150 to 300 μg/m^3
	TLV = 50 μg/m^3				
Si	100 μg/m^3	Harvard	Reduction in FVC	Cumulative lifetime exposure = 6.3 dust-years producing an 8% decrease in FVC	Relationship between a reduction in FVC and mortality and morbidity is not available
	TLV = 100 μg/m^3				

5.2.3 Illness-Related Hazards in the Semiconductor Industry

Several groups have studied health-related experiences in the semiconductor industry (Pasquini and Laird 1981; Wade and Williams 1981; Lassiter 1981). Efforts to identify illness- as opposed to accident-related data are hampered by several problems commonly encountered in similar studies: (i) direct causation is more difficult to establish because illness often has many interacting causes, some of which may not be obvious and/or may not be directly related to the workplace; (ii) illness usually takes longer to develop, and there is often a time lag between exposure to causative agent(s) and recognizable symptoms; and (iii) workers experiencing occupationally related illness may not identify the problem as work related and are thus less likely to report it as such.

California statistical data on illness alone (California Department of Industrial Relations 1980a, b) reveal an illness incidence rate for the semiconductor industry (SIC 3674) four times as great as that for all private industry; occupational disease incidence rates are also higher. These differences may be explained by the inclusion of acid burns in the illness data bases: most worker complaints are related to skin conditions, eye conditions, and chemical burns, all attributable largely to the use of acids. The California data also show higher disease rates for women than for men, for two reasons: women are employed in fabrication and production activities where acid spills are more frequent, and women generally report health problems more readily than men.

The most definitive quantitative analysis of illness-related problems in the semiconductor industry was conducted by the Semiconductor Safety Division (SSD) of the Semiconductor Industry Association (SIA) (Lassiter 1981). Lassiter examined recorded injury and illness statistics from 16 semiconductor facilities in California. Compiled illness statistics were then compared with illness statistics from other manufacturing sectors; analysis suggested that workers in the semiconductor industry faced less overall injury and illness risk (measured in lost workdays per unit effort) than workers in other industries.

A few studies of worker complaints at electronics plants were examined by the National Institute for Occupational Safety and Health (NIOSH) (Center for Disease Control 1980). Worker complaints fell into two categories: irritant and narcotic. The medical investigators hypothesized that airborne chemical agents in the workplace were responsible. Inadequate or cross-contaminated ventilation systems were at least partially at fault.

Similarly, the California Occupational Safety and Health Administration conducted a study of injury and illness incidence rates for workers in the semiconductor industry in Santa Clara and San Mateo Counties ("Silicon Valley") from October 1978 to March 1980 (Wade and Williams 1981). Thirteen facilities using five major processes were surveyed, and in-depth industrial hygiene samplings were performed. Problems identified included potential exposure to large numbers of compounds (including some potential human carcinogens), and respiratory and dermal sensitization. Little is known about the long-term health consequences of sensitization or of chronic low-level exposure to some of the identified pollutants.

NIOSH surveyed 15 U.S. facilities to identify health hazards associated with fabrication and production in four segments of the electronics components manufacturing industry (Pasquini and Laird 1981). They found that problems might arise from the use of several specific agents. Silane gases, used in epitaxial growth and passivation processes, are irritating to respiratory mucosa. Soldering, brazing, and welding processes may expose workers to hazardous fumes. Some fumes (for example, colophony) may act as sensitizers and prompt the development of allergic reactions in the exposed worker. Also, workers may be simultaneously exposed to several different compounds; hazards from such combined exposures have not been adequately researched. NIOSH also noted several potential physical hazards in the industry: electromagnetic and particulate radiation (x-ray, ultraviolet, infrared, microwave, and radio-frequency), noise, vibration, temperature, and pressure. Identified worker complaints included nausea, headaches, dizziness, respiratory problems, and liver and kidney problems. Again, the long-term health consequences are not known.

A recent NIOSH bulletin discusses possible adverse health effects of non-ionizing radiation, thermal and nonthermal (U.S. Department of Health, Education and Welfare 1979). Monitoring surveys showed that most workers using radio-frequency sealers and heaters, similar to those used in the semiconductor industry, were exposed to levels exceeding standards set by the U.S. Occupational Safety and Health Administration, some by a factor of 10. Though not much is known about radio-frequency effects on humans, results from animal studies indicate the possibility of changes in eyes, central nervous system, reflex behavior, heart rate, composition of blood, immunological response, and reproductive system (teratogeneity).

6 PUBLIC HEALTH

Public health risks from photovoltaic energy systems may arise from exposure to pollutants (e.g., sulfur dioxide and particulates) emitted during processing of materials (e.g., glass) or fabrication of photovoltaic devices (e.g., silicon), and from physical hazards associated with their operation (e.g., fire and electric shock).

6.1 Chemical Hazards

Public health may be adversely affected by release of pollutants (e.g., sulfur dioxide) during the processing of materials used throughout industry (e.g., aluminum) and others more specifically related to photovoltaic energy systems (e.g., silicon, and cadmium compounds). Risks from selected pollutants likely to be emitted during the photovoltaics energy cycle are examined below.

6.1.1 Sulfur Oxides and Particulates

Fuel combustion and process emissions from material supply activities produce a wide range of air pollutants including sulfur dioxide and particulates. Exposures to sulfur oxides have been associated with acute and chronic respiratory disease. Epidemiological studies have shown that mortality rates are correlated with sulfur oxide and total suspended particulate levels.

A health damage function described by Morgan et al. (1978) gives a range of 0 to 12 deaths per 10^5 persons per $\mu g/m^3$ sulfate, with a median value of 3.7 (95% confidence interval of 0 to 11.5). Use of this damage function, combined with estimates of emissions from material supply activities described by Moskowitz et al. (1981a) and Crowther and Moskowitz (1981) and exposure estimates from a long-range transport model described by Rowe (1981b) produces the results shown in Table 11.

These estimates do not represent large health risks, but they are much greater than potential health costs attributable to other materials (see Section 6.1.3). Furthermore, the sulfate effects do not represent new effects, but rather, a reallocation of effects from current exposures. In this analysis, risk is simply related to the quantity of sulfur dioxide emitted throughout the material supply cycle, and use of this surrogate gives rise to significant uncertainty.

Table 11. Estimated premature fatalities due to sulfate exposure from material supply activities (fatalities/10 MWp). Modified from Moskowitz et al. (1981a). Original estimates displayed in Table 9 of scaled by the following: 10^4 kW/7875 kW x 13%/15% for all silicon alternatives, and 10^4 kW/7875 kW x 8%/5% for the CdS alternative. Because efficiencies are equal for all silicon alternatives examined, material demands are also assumed to be equal.

Technology	Median estimate	Range
Silicon Czochralski	0.086	0 - 0.85
Silicon ribbon	0.086	0 - 0.85
Silicon dendritic web	0.086	0 - 0.85
Silicon cast ingot	0.086	0 - 0.85
Cadmium sulfide/copper sulfide	0.23	0 - 2.0

6.1.2 Silicon

Use of silicon photovoltaic cells will ultimately result in some public and occupational exposure to fine particulates composed principally of silicon dioxide (SiO_2) or silica from electric arc furnaces, silicon purification plants, and possible fabrication facilities. The hazardous effects of silica on humans have been documented as far back as 1556 when Agricola described the dangers of mining to workers' health (Novak 1981). Since then there have been numerous reports of lung disease associated with particular occupations (e.g., coal workers' pneumoconiosis, foundry workers' pneumoconiosis) and in particular with exposure to silica (e.g., silicosis, silicotuberculosis). The hazardous effects of pure silicon (Si), however are unknown (Sax 1975).

Although public exposure to silica and any consequent effects on health to the general public are not documented, the Occupational Safety and Health Administration has set a standard for crystalline silica of 100 $\mu g/m^3$. There are no National Ambient Air Quality Standards for respirable silicon, but, if developed, they would likely be two orders of magnitude below this standard, or 1 μg/m^3 (Neff 1981).

As previously noted, there are no data suggesting that public health risks exist from exposure to silicon dioxide. Some occupational studies are, however, available (Theriault et al. 1974a,b,c), and these were used to develop a dose-response model (Figure 3) relating granite dust exposure to ventilary function (forced vital capacity) and chest roentgenograms. Use of this model and an assumed maximum lifetime exposure estimate of 10^{-3} dust years (see Moskowitz et al. 1981a) suggests that no significant public health effects would be expected.

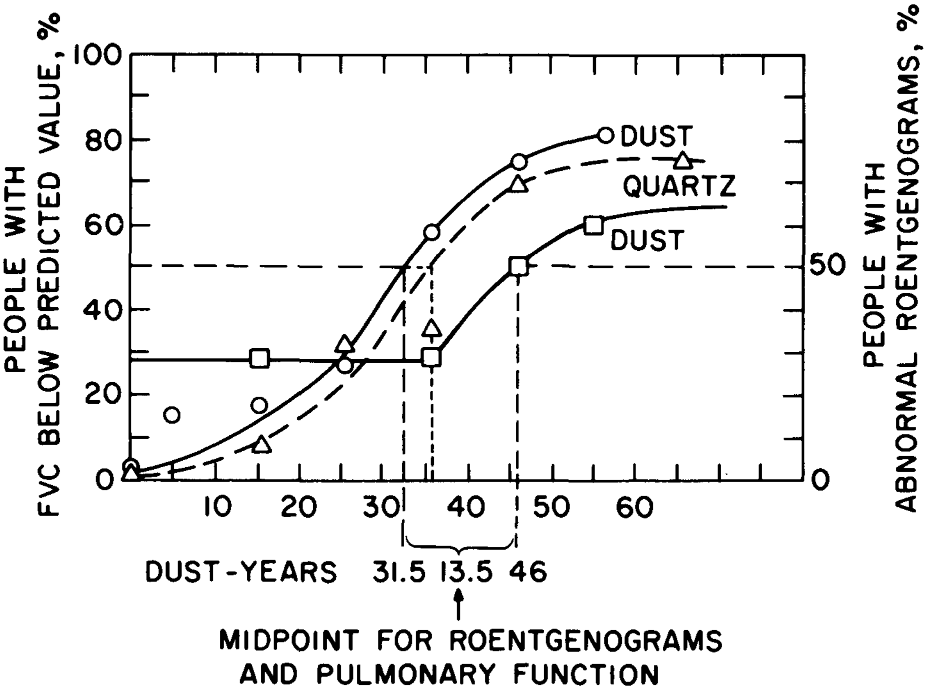

Figure 3. Dose-response curve for the effect of dust on roentgenograms and forced vital capacity.

6.1.3 Cadmium

Cadmium may be emitted during refining of raw materials and during fabrication and disposal of cadmium sulfide photovoltaic devices. Chronic exposure to cadmium may result in chronic kidney dysfunction and possibly prostate cancer.

To analyze the potential for the occurrence of kidney dysfunction, a simple single-compartment model (Robinson and Novak 1980) was used in combination with estimated levels of chronic exposure to cadmium emited throughout the cadmium sulfide energy cycle to determine the peak concentration in the kidney. In these analyses, cadmium concentration in the renal cortex serves as an indicator for potential damage. The level up to which clinical effects are not seen is estimated to correspond to a concentration in the renal cortex of ~200 μg/g (wet weight of cadmium); some investigators think the range of individual susceptibility varies between 150 and 300 μg/g. Although proteinuria has been associated with renal damage from chronic cadmium exposure, a relationship between this clinical condition, cadmium toxicity, and resulting mortality has not been established. Results of this analysis are shown in Table 12. This modeling exercise suggested that potential contributions from airborne cadmium emitted by phtotovoltaics-related facilities are quite small; potential background contributions from food and smoking are significantly larger.

Although low-level exposure to airborne cadmium does not appear to impose risk of renal dysfunction because of the kidney's threshold response, there may be risk of prostate cancer. This relates to the validity of assuming the cadmium is a carcinogen, and that a linear non-threshold response exists. The size of this potential risk was examined by combining

Table 12. Estimated cadmium concentration in the renal cortex (μg/g), in the general public associated with the photovoltaics energy cycle. Estimates based on production of 7875 kWp of CdS photovoltaics cells.

Activity	Age of peak concentration	Source of cadmium burden at peak size			
		Food	Ambient* air	Smoking	Total
Mine and mill	48	43.36	0.85	10.82	55
Refinery	47	43.36	0.04	10.82	54
Fabrication	47	43.36	0	10.82	54
Disposal	47	43.36	0.01	10.82	54

*Based on ambient air exposure in the worst sector around each facility.

estimates from national-level exposure models (air, water, and food) described elsewhere (Moskowitz et al. 1982) with a dose-response function developed by the U.S. Environmental Protection Agency - (Carcinogen Assessment Group 1978). Results from this analysis are given in Table 13. Overall risks from ingestion dominate these estimates. The upper bound estimates, although highly uncertain because of the large number of assumptions used in generating them, are large enough to warrant further investigation.

6.1.4 Arsenic

Although specific photovoltaic cells will contain gallium arsenide, little toxicity information is available for either gallium or gallium arsenide (Sax 1975). Therefore, examination of health effects related to these materials was based on toxicologic information for arsenic.

Arsenic, a toxic agent that can adversely affect metabolic processes, tissues, and organs, also appears to produce cancer in man, although not in animals. Arsenic may exist in a variety of chemical states (e.g.,

Table 13. Estimates of system-wide cadmium emissions, exposure, and cancer response for production and use of CdS photovoltaic systems (per 10 MWp).

Technology/estimate	Exposure (person-$\mu g/m^3$)	Response (10^{-3} deaths/yr)		
		Inhalation	Ingestion	Total
CdS rooftop shingle				
Median[a]	4.8	0.12	90	90
Range[b]	1.3 - 21	0 - 0.53	0-420	0-420

a. Assumes energy cycle emission release of 134 lb/10 MWp production, an exposure of 72 person-$\mu g/m^3$/ton of emission, an inhalation to ingestion ratio of 1 to 800, and a dose-response of $2.5x10^{-5}$ excess prostate cancers per person-$\mu g/m^3$ exposure. Data from Moskowitz et al. (1980, 981b).
b. Assumes energy cycle emission releases of 37 to 590 lb/10 MWp production. Lower risk estimate based on the assumption that cadmium is not a carcinogen. All other values are kept constant.

trivalent, pentavalent inorganic, and methylated organic arsenic), each having different toxicological potentials.

The acute lethal dose to humans for trivalent arsenic is reported as 70 to 80 mg; however, it should be noted that individual susceptibility, particularly with respect to age, may be found at much lower doses. Chronic and subacute effects of arsenic are organ specific and are determined primarily by chemical form, mode, and extent of exposure. Typically, these effects involve the cardiovascular, integumentary, nervous, respiratory, and gastrointestinal systems as well as the reproductive and developmental systems.

Carcinogenic effects of arsenic have been seen among occupationally exposed individuals. The strongest links between arsenic and carcinogenesis exist for skin and lung cancers. Associations with other forms of cancer (i.e., liver, hemangiosarcoma, lymphomas, leukemia, renal adenocarcomas, and nasophrangeal carcinoma) have also been suggested.

At the exposure levels of interest, the principal suspected effect of arsenic is cancer (Lee and Fraumeni 1969; Ott et al. 1974; Pinto et al.

1977; Mushak et al. 1980). In the examination of potential risks posed by this material a dose-response relationship developed by the U.S. Environmental Protection Agency - Carcinogen Assessment Group (Mushak et al. 1980) was used. The resulting equation for the standard mortality ratio (SMR), i.e., the ratio of actual deaths to "expected deaths," is given by

$$SMR = 1 + \frac{\beta}{\alpha} x$$

where β is the change in the respiratory cancer rate for each (μg As/m^3), α is the base respiratory cancer rate in the absence of atmospheric arsenic, and x is the average lifetime exposure to atmospheric arsenic. The two extreme values of 3.3% (Lee and Fraumeni 1969) and 17.0% (Ott et al. 1974) were used to estimate a reasonable range for β.

Results of the arsenic modeling exercise are shown in Table 14. The analysis suggests that arsenic released during the photovoltaic energy cycle could induce a lung cancer risk of 10^{-8} to 10^{-5} deaths per 100,000 individuals per year within 80 km of photovoltaics-related facilities. If, because of the non-threshold carcinogenic effect assumed for arsenic, exposures beyond 80 km are considered, the maximum calculated effect would still be only 10^{-3} to 10^{-2} deaths per year over the entire U.S. population ($\sim 200 \times 10^6$ persons) per 10^{12} Btu (7875 KWp) installed capacity produced. Effects arising from alternative media (e.g., food chain) have not been examined, but are also expected to be quite small.

6.1.5 Fluorine

Fluorine releases from silicon photovoltaic cell fabrication or waste disposal facilities (see Section 5.2) may present risks not yet examined quantitatively. At this time, estimates of acute and chronic exposure

Table 14. Estimated effects on lung cancer incidence, in the general public within 80 km ($7.8x10^5$ persons), of arsenic released during the GaAs photovoltaic energy cycle (per 10^2 Btu output or per 7875 kWp production).

	Arsenic concentration for the following activities				
	Mine and mill	Refinery	Fabrication	Disposal	Total[a]
Max. conc. ($\mu g/m^3$)	$4.9x10^{-4}$	$3.3x10^{-5}$	$6.0x10^{-6}$	$1.2x10^{-7}$	-
Total pop. exposure (person-$\mu g/m^3$)	$9.9x10^0$	$2.8x10^0$	$2.8x10^{-1}$	$6.3x10^{-3}$	$1.3x10^1$
Pop.-weighted av. conc. ($\mu g/m^3$)	$1.3x10^{-5}$	$3.6x10^{-6}$	$3.5x10^{-7}$	$8.0x10^{-9}$	-
Estimated cancer deaths (per year)	(1.4-7.2) $x10^{-4}$	(0.40-2.1) $x10^{-4}$	(0.39-2.1) $x10^{-5}$	(0.90-4.6) $x10^{-7}$	(1.8-9.5) $x10^{-4}$
Cancer death rate (deaths/ 100,000/yr)	(1.8-9) $x10^{-5}$	(0.51-2.7) $x10^{-5}$	(0.50-2.6) $x10^{-5}$	(1.2-5.9) $x10^{-8}$	(0.28-1.4) $x10^{-4}$

a. Totals based on additions of lower and upper bound estimates.

levels have not been prepared. Chronic exposure to these compounds, however, will be strictly controlled by the Environmental Protection Agency as specifically required by the Resource Conservation and Recovery, Clean Water and Safe Drinking Water Acts. Thus, potential risk from chronic exposure will be minimized. Acute hazards arising from accidental situations may still exist.

Literature on health risks associated with fluorine exposure is extensive, including detailed reviews of risk from ingestion of fluorides in drinking water (National Academy of Sciences 1977). Small amounts of fluoride, 1 mg/liter, have the beneficial effect of preventing dental caries, but chronic exposure to excessive intake can cause mottling of tooth enamel or dental fluorosis, and skeletal fluorosis. Because of the large quantities of fluorine waste products which could be produced by the silicon photovoltaic industry, exposure and response information need to be more closely examined.

6.2 Physical Hazards

6.2.1 Electric Shock

Home owners or contractors installing, maintaining, or removing rooftop photovoltaic systems may be at risk to electrical shock. Photovoltaic systems, unlike conventional alternatives, begin to generate electricity immediately upon exposure to sunlight. Although engineering safeguards are being developed to limit the potential for grounding or contact occurrences, it is unlikely that these systems will be completely fault free or that safeguards will not ever be circumvented. Should a grounding or contact occur, it is important to determine the possible health consequences.

Physiologic and anatomic effects of electric shocks, important in examining health and safety risks, include perception of electric current flow and release thresholds (Rabinowitz 1983). Exposure to electric currents produces a spectrum of responses -- from subclinical disturbances, to clinical injuries such as burns, up to death from cardiac or pulmonary arrest. The main factors affecting electric shock severity are (i) type of circuit (alternating current or direct current); (ii) circuit voltage; (iii) impedence of the human body; (iv) size of current flows through tissues; (v) current pathway through the body; and (vi) contact duration. In general, low-voltage direct current is not considered as harmful as the corresponding alternating current because it does not produce strong tetanic contraction of muscle.

Perception of electric current is not normally considered hazardous (e.g., feeling of slight warmth or tingling in the hand). The median direct current perception threshold is ~5.2 mA for men and 3.5 mA for women. These values are between four and five times the values obtained for median 60-Hz alternating current perception threshold. Contact with currents near or above a perception threshold may, however, induce a sudden reaction which could produce a hazardous response (e.g., release of one's grip on a ladder, resulting in a fall and fractures) (Rabinowitz 1983). Exposures in excess of these perception thresholds may produce more significant health responses including ventricular fibrillation and possible death.

Median direct current release thresholds or let-go currents are estimated as ~76 mA for men and 51 mA for women (Dalziel 1956). Although prolonged exposure to alternating current slightly above the let-go threshold might "freeze" the victim and ultimately result in death, the release response threshold for direct current is not analogous because it is based on a psychological limit derived from laboratory studies on humans, not an actual physical limitation (let-go ability) (Dalziel 1956). Since release threshold is only a psychological limit, its use in health risk analysis is limited (Rabinowitz 1983).

Larger direct current exposure may produce ventricular fibrillation. Rabinowitz (1983) suuggested, by extrapolating data from animal studies (Knickerbocker 1973), that ventricular fibrillation can be estimated from the following equations:

$$I = 320/t^{0.5} \text{ for a 50-kg person,} \tag{1}$$

$$I = 455/t^{0.5} \text{ for a 70-kg person,} \tag{2}$$

where $t \geq 8.3$ milliseconds and ≤ 5 seconds, I is in mA, and t is in seconds.

Table 15 sumarizes selected risks imposed by direct and alternating current shocks (Rabinowitz 1983). Because of the ways in which test results from limited human experiments are presented, threshold variability may be greater than suggested. A recent report by Underwriters Laboratories, Inc. (1981) on photovoltaic module safety requirements, for example, suggests maximum proposed current value limits of 0.5 mA alternating current and 1.0 mA direct current because of reaction or startle levels.

To place risks of a direct current shock in perspective, the electrical engineering characteristics (Nichols 1981) of a U.S. Department of Energy residential application demonstration project were examined and compared with health-related information (Rabinowitz 1983). In preparing this analysis several assumptions were made. (i) Risks to the most sensitive portion of the population (0.5%) were needed. (ii) Direct contact with the energized part of the array was made with a bare hand. The current pathway was assumed to be from hand to foot. This is not the only shock pathway

Table 15. Selected effects of electric current on humans. From Dalziel (1972a) as modified by Rabinowitz (1983). All effects are based on human data except ventricular fibrillation, which is based on animal studies.

	Milliamperes (mA)			
	Direct current		60-Hz alternating current	
Effect[b]	Men	Women	Men	Women
Slight sensation	1	0.6	0.4	0.3
Perception threshold, median	5.2	3.5	1.1	0.7
Perception threshold, 0.5 percentile	-	-	0.4	0.3
Let-go threshold, median	-	-	16	10
Let-go threshold, 0.5 percentile	-	-	9	6
Release threshold, median	76	51	-	-
Release threshold, 0.5 percentile	62	41	-	-
Ventricular fibrillation, (70-kg man) 0.5 percentile	$455/t^{0.5}$	$455/t^{0.5}$	$165/t^{0.5}$	$165/t^{0.5}$

possible; for example, two direct contacts could be made with both bare hands allowing current to flow through the body between the hands. (iii) Each module added in series had the effect of increasing the shock hazard upon contact.

In calculating shock hazards, the voltage of the circuit was divided by an assumed total body impedance (500 ohms) (Dalziel 1972b) to give the total current flow through the body. Temperature changes affect the open circuit voltage, but varying insolation levels affect it only a little. The change in circuit voltage due to a change in temperature will in turn alter the current flow through the body (via Ohm's law) during electrical contact. Insolation levels affect the system's short circuit current value, which represents the maximum current that can flow through the body because of internal impedance of the source. This value is not significant in this analysis because of the assumed total body impedance and the low modular voltages associated with the photovoltaic array. The calculated current flow through the body is one or two orders of magnitude less than the short circuit current.

Table 16 gives risk analysis calculations for the reference system at a nominal ambient temperature. The analysis suggests that the voltage generated by 6 modules connected in series is sufficient to cause ventricular fibrillation (for 50 and 70-kg persons) and possibly death under the nominal temperature conditions. In colder weather the same effect may be produced by fewer modules.

6.2.2 Fire

Photovoltaic rooftop arrays may present fire hazards from two causes: (i) electrical fires due to short circuits and (ii) spontaneous combustion

Table 16. Physiological effects of a photovoltaic energy system direct current shock at a nominal temperature (82° F).

Number of modules in series	Total OCV relative to ground (V)	Total body impedance (ohms)	Current passing through body (mA)	Physiological effect	
1	17.6	500	35.2	Men: A	Women: A
2	35.2	500	70.4	Men: B	Women: B
3	52.8	500	105.6	Men: B	Women: B
4	70.4	500	140.8	Men: B	Women: B
5	88.0	500	176.0	Men: C	Women: C
6	105.6	500	211.2	Men: C,D	Women: C,D
7	123.2	500	246.4	Men: C,D	Women: C,D

Key to Physiological Effects

A. Between median perception threshold and 0.5% release threshold. Shock is painful, but not fatal. Secondary injuries and minor contact burns are possible for all members of the population.

B. Between 0.5% release threshold and 0.5% fibrillating threshold (for a 50-kg person). Shock is painful and could produce temporary respiratory arrest or cause unconsciousness. Death is possible, but highly unlikely. Secondary injuries and more severe contact burns are also possible for all members of the population.

C. At or above the 0.5% fibrillating threshold for a 50-kg person. Death probably will occur for members of this 0.5% group. Cardiac arrest, unconsciousness, secondary injuries, and contact burns can also occur in all members of the population.

D. At or above the 0.5% fibrillating threshold for a 70-kg person. Death probably will occur for members of this 0.5% group. Cardiac arrest, unconsciousness, secondary injuries, and contact burns can also occur in all members of the population.

due to heat buildup in a dead air space. The probability of either in the photovoltaic complex has not yet been studied, but the consequences of such fires have been analyzed by Moskowitz et al. (in preparation) from data collected by the Federal Emergency Management Agency (1982b).

In the U.S. in 1980 there were nearly 6 deaths per 1000 reported fires. Electrical fires were the fifth leading type of fire and the fourth leading cause of fire deaths. Risk of death per 1000 electrical fires was 6.6, ~14% higher than that from all fires combined.

Fire hazards may differ not only by cause but also by place of origin (living space vs. roof). Most fires originate within the living space of the home. Analysis shows that only 3.5% begin on or within a roof. Risk from rooftop fires was examined in detail because of the proposed location of the arrays. The limited number of recorded deaths in this data set, however, precluded definitive conclusions about relative risk with respect to place of origin of fire.

A crude upper-bound estimate of the marginal risk from photovoltaics-related fires was made from actuarial data with use of two basic assumptions: (i) the probability of a photovoltaic system causing a fire is equivalent to that for all other electrical fires in the residential sector, and (ii) risk from such fire is equivalent to that now found for electrical fires. If these assumptions are valid, health risk from all causes of fire to an individual living in a home with a rooftop array would increase by ~7%, and risk from electrical fires would double.

The marginal annual number of reported fires (RF) for one- and two-family dwelling units per 10 MWp installed capacity was estimated by using the following assumptions:

$$\text{RF}/10\ \text{MWp} = 4000\ \text{fires}/10^6\ \text{persons} \times 3\ \text{persons/dwelling unit}$$

$$\times\ 7\ \text{electrical fires}/100\ \text{fires} \times 1000\ \text{dwelling units}/10\ \text{MWp}$$

$$\simeq 1\ \text{electrical fire}/10\ \text{MWp}$$

Marginal annual risk of fire-related death was estimated similarly.

$$\text{deaths}/10\ \text{MWp} = \text{RF}/10\ \text{MWp} \times 6.59 \times 10^{-3}\ \text{deaths/fire}$$

$$\simeq 10^{-2}\ \text{deaths}/10\ \text{MWp}$$

$$\sim 10^{-2}\ \text{deaths}/(1000\ \text{dwelling units} \times 3\ \text{persons/dwelling unit})$$

$$\simeq 10^{-6}\ \text{deaths/person.}$$

These estimates, although crude, suggest that this problem is unlikely to cause undue societal risk (i.e., risk per individual x number of events). Similarly the estimated annual risk of 10^{-6} deaths per person is equivalent to other risks of ordinary life such as dying in a plane crash when flying from New York to California, or having a fatal reaction to a single smallpox vaccination (Wilson 1980). Fire is nevertheless of significant concern to exposed dwelling occupants and should not be ignored.

7 RESEARCH NEEDS

Table 17 identifies health and environmental research needed in support of the photovoltaic technology development program. This list is subjectively ranked by level of importance. Of highest priority are activities that will provide detailed data and risk estimates for new materials and processes, and activities that will accurately identify exposure conditions in operating photovoltaic fabrication facilities. Although information about biological response to specific chemicals is also needed, assignment of specific priorities must await collection of actual monitoring information. Effects on climate are now being debated, but are probably not critical.

Objective methods for screening these identified research items and for determining their relative criticality and effect on the quantitative risk estimates presented are now being developed. A promising approach uses the DEMOS model (Henrion 1982) to examine effects of parameter uncertainty (arising from our inability to accurately specify model parameters and distributors) on the uncertainty surrounding the total model.

Table 17. Health and environmental research needs (ranked by level of importance).

HIGH

1. Health and environmental risk assessment of alternative materials, processes, and effects.
2. Materials sampling and characterization: Measure types and quantities of pollutants present in the workplace and emitted by pilot- and commercial-scale photovoltaic fabrication facilities.
   - 2.1 Dopants: arsenic, phosphine, silane, phosphorus oxychloride, phosphorus pentoxide, arsenic tetrafluoride, boron trifluoride.
   - 2.2 Physical agents: ultraviolet, microwave, and radiofrequency radiation.
   - 2.3 Reaction by-products: formaldehyde from solder and flux, hydrogen chloride from phosphorus oxychloride deposition, fluoride from plasma etching, phosgene from cleaning.
   - 2.4 Solvents and etchants: trichloroethylene, trichloroethane, methylene chloride, methanol, boric acid, hydrofluoric acid.
   - 2.5 Carcinogens: beryllium, selenium, cadmium, arsenic.
3. Process information: Collect engineering and environmental data for alternative materials and fabrication processes nearing commercial viability.
   - 3.1 Material alternatives: amorphous silicon, copper indium selenide.
   - 3.2 Process alternatives: E-beam and x-ray photolithography, dry chemical and physical etching, ion implantation, plasma enhanced chemical vapor deposition, automatic masking systems, automatic diffusion systems.
4. Operational data: Prepare analyses examining source and frequency of occurrence of electric shocks and fires.
   - 4.1 Electric shocks: Prepare fault-tree analysis identifying type and origin of electric shock hazards associated with alternative applications. Combine with health-related data to determine consequences.
   - 4.2 Fires: Examine potential fire hazard in greater detail. Identify likely origins and risks and combine with health-related data to determine potential consequences.

MEDIUM

5. Toxicology and epidemiology: Conduct animal studies and initiate human epidemiological and clinical investigations to determine toxic, mutagenic, teratogenic, and carcinogenic hazards posed by specific materials.
   - 5.1 Animal Studies
     - 5.1.1 Toxicology: arsenic pentafluoride, arsine, diborane, phosphorous and its elemental compounds, fused and amorphous silicon, silane, and chlorosilanes.
   - 5.2 Human epidemiological and clinical studies
     - 5.2.1 Irritant and allergenic potential of epoxy resins.
     - 5.2.2 Biomedical causes and risks of hypersensitivity.
     - 5.2.3 Risks related to continuing exposures to glass fibers used as a filler in pottants.
     - 5.2.4 Existence of a threshold response to renal dysfunction from chronic cadmium exposure. Identify relationship between B_2 microglobulin in urine and human morbidity and mortality. Reexamine potential food-chain effects.
     - 5.2.5 Morbidity and mortality studies by occupational category for semiconductor and photovoltaic fabrication facilities.
     - 5.2.6 Morbidity and mortality studies for electric arc-furnace workers where semiconductor grade silicon is produced.
6. Industrial hygiene and control technology: Conduct in-plant surveys of pilot and commercial-scale photovoltaic fabrication facilities, characterize health and safety risks to production workers, and evaluate potential control technology requirements.
   - 6.1 Evaluate exhaust ventilation required at different work stations to maintain adequate workplace air quality, and subsequently identify controls required to minimize public health risk.
   - 6.2 Develop systematic control strategies to handle a variety of different gases, including arsine, phosphine, diborane, silane, chlorosilanes, and diphosphine which have unusual properties and concerns associated with their use, handling, containment, storage and disposal.
   - 6.3 Design equipment, personal protective devices, and strategies for the safe handling and disposal of corrosive and toxic materials likely to be used in large-scale fabrication facilities.

LOW

7. Micro- and meso-scale biological and climatic effects: Evaluate magnitude of risk associated with large central station applications.
   - 7.1 Examine effects of large central-station operation on shading, wind flow, soil moisture, etc.
   - 7.2 Examine magnitude of potential biological risk (e.g., change in species diversity).
   - 7.3 Examine magnitude of potential micro- and meso-scale climatic response (e.g., increased thunderstorm incidence).

A first attempt to examine error propogation throughout a model and the consequent need for research was based upon our simple algorithm for estimating prostate cancer risks due to cadmium:

$$C = E \times L \times A \times F \times D$$

where

C = prostate cancer risk (excess prostate cancers),

E = annual cadmium pollutant emission rate (tons/yr),

L = locational factor (unitless),

A = atmospheric dispersion of exposure (person-$\mu g/m^3$/ton),

F = Food chain dispersion and exposure (ratio of food chain to atmospheric exposure), and

D = dose-response model (excess prostate cancers/person-$\mu g/m^3$).

Values and distributions for these different parameters, found in the literature, are shown in Figure 4. In this first examination, uncertainty

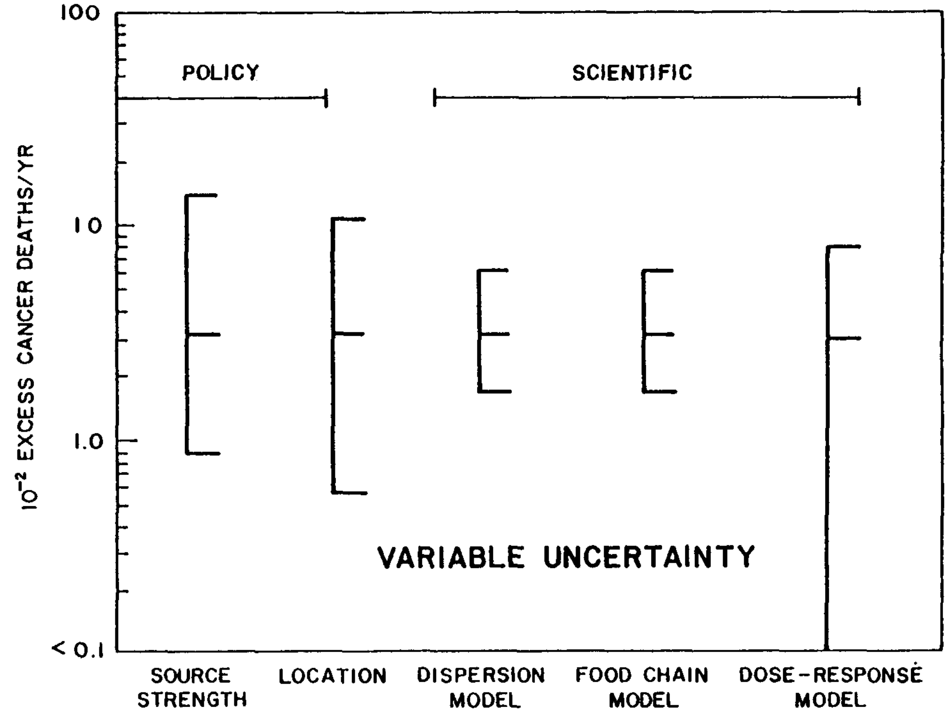

Figure 4. Model parameters and distributions used to assess excess postate cancer risks from cadmium exposures.

among parameters is not propagated to estimate model uncertainty. Ranges merely represent the influence of any single parameter on the model estimate.

In Figure 5A, uncertainties among all parameters are propagated throughout the entire equation with the DEMOS model, to estimate model uncertainty. In this analysis, the dose-response function is based on a combined distribution: quantal (40% probability that cadmium is not a carcinogen and 60% probability that cadmium is carcinogenic) and log-normal based on the data described in Section 6.1.3. This first analysis suggests that uncertainty surrounding the dose-response function is the controlling variable and thus is the area most in need of research.

If it is assumed that the dose-response function is simply log-normally distributed (rather then log-normal and quantal), then the relative importance of the model parameter changes (Figure 5B). In this case, no single parameter can be identified as being more critical.

Ultimately, analyses similar to this will need to be prepared for each issue examined quantitatively. In this way, critical research needs for each estimate presented can be examined. In attempting to identify the most important research needs, subjective weighting factors (e.g., relative importance of a worker-day lost vs. a public fatality) will need to be developed. Combining these weighting factors with the risk estimates should optimize the decision-making process for the allocation of research support. Issues not yet quantitatively examined (e.g., new materials) will, however, still need to be subjectively ranked.

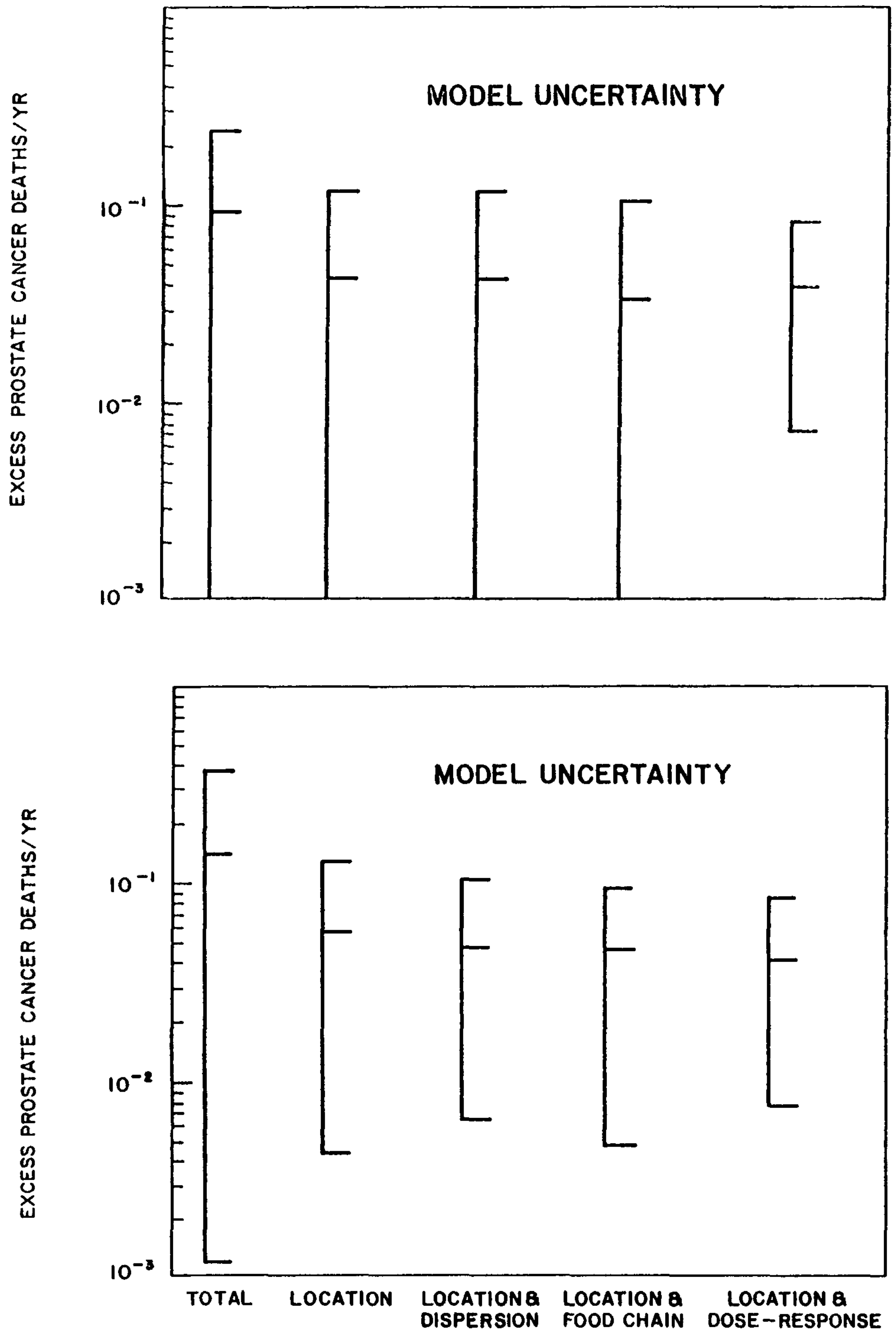

Figure 5. Sources of uncertainty in the estimated excess prostate cancer risks. In the top Figure, 5A, the dose-response function used assumes a 40% probability that cadmium does not produce cancer, and a 60% probability that cadmium is carcinogenic. In the bottom Figure, 5B, the analysis assumes that cadmium is a carcinogen, i.e., 0% probability that no effect would result from exposure to this material. The dose-response function used in this analysis is described in the text.

8 DISCUSSION

Large growth in the photovoltaics industry is expected in the next decade. By 2000, these systems could supply (0.1 to 8.4) x 10^{18} J of electrical energy. To meet this projected demand, various material and cell concepts for producing reliable and economically competitive photovoltaic systems are being examined by the public and private sectors. At present, single-crystal, poly-crystal, and amorphous silicon photovoltaic cells are being commercially produced. Plans for commercial production of single-crystal and concentrating gallium arsenide models are being formulated, and alternative material and cell concepts are being investigated.

Commercialization of photovoltaic cells using the materials and concepts examined, like any other technology or energy system, will impose certain social costs, including both public and occupational injuries, illnesses, and deaths. Health damage will arise from physical and chemical agents. The significance of these social costs depends on (i) the most probable level of damage, (ii) the maximum conceivable damage, (iii) the uncertainties surrounding these estimates, (iv) the real or perceived ability to control these risks, (v) the voluntary versus involuntary nature of these hazards, and (vi) comparisons with competing alternatives. Effects examined must take cognizance of these issues.

As noted, public health may be adversely affected by pollutants emitted throughout the photovoltaic energy cycle, and by physical hazards associated with the operation of these systems. Risks from chemical hazards examined are summarized in Table 18. The values given are based on measured and estimated emission levels, atmospheric transport, and dose-response models.

Table 18. Total estimated public health costs for reference photovoltaic energy systems (per 10 MWp).

Category/ effect	Reference system					
	Si-Czochralski	Si-ribbon	Si-dendritic	Si-cast	CdS	GaAs
Sulfate exposure (deaths/yr)[a]						
Mean	0.086	0.086	0.086	0.086	0.23	N.A.
Range	0-0.85	0-0.85	0-0.85	0-0.85	0-2.0	N.A.
Cadmium exposure (deaths/yr)[b]						
Mean	N.A.	N.A.	N.A.	N.A.	0.09	N.A.
Range	N.A.	N.A.	N.A.	N.A.	0-0.4[c]	N.A.
Arsenic exposure (deaths/year)[d]						
Mean	N.A.	N.A.	N.A.	N.A.	N.A.	0.001
Range	N.A.	N.A.	N.A.	N.A.	N.A.	0-0.01
Electric shocks[e]						
Mean	N.E.	N.E.	N.E.	N.E.	N.E.	N.A.
Range	N.E.	N.E.	N.E.	N.E.	N.E.	N.A.
Fires (deaths/yr)[f]						
Mean	N.E.	N.E.	N.E.	N.E.	N.E.	N.A.
Range	<0.01	<0.01	<0.01	<0.01	<0.01	N.A.

N.A. = Not applicable.
N.E. = Not estimated.

a. Based on near- and far-field atmospheric exposures and a dose-response function developed by Morgan et al. (1978). Sulfur dioxide emissions arise, principally, from materials production.

b. Based on near- and far-field atmospheric and food chain exposures, and a dose-response function for prostate cancer developed by the Carcinogen Assessment Group (1978). Emission estimates based on hypothetical design engineering studies.

c. Upper bound estimate needs to be examined in greater detail.

d. Based on near- and far-field atmospheric exposures and a dose-response function for lung cancer developed by Mushak et al. (1980). Emmission estimated based on hypothertical design engineering-studies for a 7.9 MW production output.

e. Mode and frequency for such an occurrence has not been identified. Exposed individuals are, however, at significant risk to ventricular fibrillation.

f. Event occurrence and risk estimates based on data for electrical fires from all sources. Event probability and risk estimates for photovoltaic applications alone are not available.

Because of the large number of assumptions used, the speculative nature of selected data sets (e.g., estimates of emissions from photovoltaic fabrication facilities), and the general lack of scientific knowledge for other data points (e.g., cadmium-induced prostate cancer), it is clear that these risk estimates are highly uncertain. On the basis of the analysis, however, it appears that the incremental risk to public health associated with the estimated exposure levels is likely to be extremely small, if not insignificant.

Nevertheless, several items require monitoring or additional analysis to ensure that public health is not endangered. Sampling and chemical analysis of waste streams from photovoltaic fabrication facilities are needed to supplement or supplant existing assessments, which are based largely on hypothetical analyses of process streams and control technology capabilities. Toxicologic information is required for gallium arsenide to evaluate its range of potential health effects. Potential toxicity of arsenic and cadmium compounds requires that use and disposal of these materials must be carefully controlled to limit public exposures to levels as low as reasonably achievable. Risk from cadmium food-chain exposures appears to be large enough, though uncertain, to warrant further investigation. Similarly, effects of acute release of fluoride by-products need to be quantitatively explored.

Physical hazards from electric shock and fire may exist for individuals using these devices. Home owners or contractors installing, maintaining, or removing rooftop photovoltic systems may risk electrical shock; however, the probability of such shocks and how they will occur cannot now be clearly defined. Owners of photovoltaic arrays may also be subject to fire hazards caused by electrical shorts or spontaneous combustion from heat buildup in a dead air space. Again, the probability of either in a photovoltaic application is unknown.

With respect to these physical hazards, studies are needed to define possible failure modes and to measure incidence rates and consequent damage. Application of fault-tree analysis and related techniques to various designs representing state-of-the-art module and rooftop applications should permit system designers to identify various failure modes. Further analyses of epidemiological and clinical data are needed to reduce the uncertainties in human health and safety estimates. Establishment of an event occurrence and injury registry should be considered to assist system designers in developing optimal prevention strategies. Continued validation of safeguard effectiveness merits further consideration.

Exposure to chemical and physical hazards in the workplace can result in acute or chronic injury or illness or death. Table 19 presents estimates of the occupational health costs arising from accidents for the reference energy cycle. These estimates suggest that, within a single reference cycle, risk generally increases in the following order: decommissioning, operation and maintenance, installation, fabrication (inverter), and fabrication (photovoltaic cell). Among the reference manufacturing processes, differences in health cost are not large, but they increase as follows: silicon ribbon, silicon cast ingot, silicon dendritic web, silicon Czochralski, and cadmium sulfide. Although the cadmium sulfide system has low manufacturing costs, its total health costs are higher than those of the alternatives because of its relatively low efficiency (~5%).

Table 19. Total estimated labor and occupational health costs for the reference photovoltaic energy cycle (per 10 MWp). Range indicates 90% confidence limits.

Category/ estimate	Reference system				
	Si-Czochralski	Si-ribbon	Si-dendritic	Si-cast	CdS
Labor (10^2 MY)[a]					
Mean	1.34	1.12	1.29	1.18	1.51
Range	1.25 - 1.43	1.05 - 1.20	1.21 - 1.38	1.11 - 1.26	1.43 - 1.60
Morbidity (WDL)[b]					
Mean	83	71	78	77	124
Range	78 - 88	67 - 75	74 - 83	70 - 79	117 - 132
Mortality (10^{-2} deaths)[b]					
Mean	1.2	1.2	1.2	1.2	2.4
Range	1.1 - 1.3	1.1 - 1.2	1.1 - 1.2	1.1 - 1.2	2.2 - 2.6

a. Labor estimates for fabrication facilities are based on design engineering studies prepared by Owens et al. (1981) and Ungers et al. (1983). Estimates for other activities are principally from an input-output model described by Rowe and Groncki (1980).
b. Estimates for fabrication risks from data on the semiconductor industry developed by Owens et al. (1980) and Ungers et al. (1983). Estimates for remaining steps in the energy-cycle based on data collected from related industries by the U.S. Bureau of Labor Statistics (1980).

Comparison of direct and indirect health effects by using both Input-Ouput and Process model results shows that the indirect effects account for ~60% of the accident-related health costs associated with this energy system. These results by themselves are not necessarily useful. Analysis by this approach, however, could permit administrators to make rational judgments concerning the relative costs and benefits of conventional versus alternative energy systems. Incomplete comparative analyses now found in the literature can merely confuse decision makers and the public and may result in incorrect or suboptimal choices.

Available actuarial statistics do not adequately describe potential acute or chronic hazards related to toxic chemical exposures. Analysis of data from the semiconductor industry shows that workers in this industry do not appear to have elevated illness or disease incidence rates compared with the rates in other manufacturing sectors. Available illness data, however, may not capture the actual incidence rate because (i) direct causation is more difficult to establish than the accidents since illness often has many interacting causes, some of which may not be obvious and/or may not be directly related to the workplace; (ii) illness often develops slowly, so that there is a time lag between exposure to causative agent(s) and recognizable symptoms; and (iii) workers experiencing occupationally related illness may not identify the problem as work related and are thus less likely to report it as such.

In-plant surveys of the semiconductor and electronic industries, conducted by federal and state agencies, have shown effects due to acid burns, respiratory and dermal sensitization, nausea, headaches, dizziness, and liver and kidney problems. The long-term health consequences of these reported effects are unclear.

With respect to chronic exposure to arsenic, cadmium and silicon compounds, deterministic modeling exercises suggest that exposures should be kept below existing TLVs. In the case of cadmium, modeling exercises suggest that chronic exposure to cadmium levels above 50 $\mu g/m^3$ in the workplace is likely to produce cadmium kidney body burdens exceeding a threshold (~200 $\mu g/g$) above which kidney damage could be expected; such exposure would also give rise to a large prostate cancer risk. For arsenic, the modeling studies suggest that chronic exposure at levels equivalent to the TLV (50 $\mu g/m^3$) could produce a significant number of lung cancers in excess of the background for all lung cancers. Inhalation of silicon dust at exposures equal to the TLV could produce a significant reduction in forced vital capacity, but the significance of this reduction in terms of mortality and morbidity is unknown.

Although it now appears that development of photovoltaics technology will not impose large occupational health costs, continued surveillance and analysis of potential chemical and physical hazards is needed for preventative purposes. Failure to include such analyses in process development and commercialization could result in significant health consequences because of the types of materials and processes involved.

REFERENCES

American Conference of Governmental and Industrial Hygienists, Documentation of Threshold Limit Values for Substances in Workroom Air, 3rd ed., Cincinnati, OH, 1971.

California Department of Industrial Relations, Employer's First Reports of Occupational Injury or Illness, California Semiconductor Industry, 1978, San Francisco, 1980a.

California Department of Industrial Relations, Occupational Injuries and Illness Survey, California, 1978, San Francisco, 1980b.

Carcinogen Assessment Group, Assessment of Carcinogenic Risks to Cadmium, U.S. Environmental Protection Agency, Washington, DC, 1978.

Center for Disease Control, National Institute for Occupational Safety and Health, Health Hazard Evaluation Project No. HHE 79-66, Interim Report 2, U.S. Department of Health, Education, and Welfare, Jan. 31, 1980.

Costello, D. and D. Posner, An overview of photovoltaic market research, Sol. Cells 1:37-53, 1979.

Costello, D. and P. Rappaport, The technical and economic development of photovoltaics, Annu. Rev. Energy 5:335-56, 1980.

Council on Environmental Quality, Solar Energy Progress and Promise, Executive Office of the President, Washington, DC, 1978.

Crowther, M.A. and P.D. Moskowitz, A Reference Material System for Estimating Health and Environmental Risks of Selected Material Cycles and Energy Systems, BNL 51563, Brookhaven National Laboratory, Upton, NY, July 1981.

Dalziel, C.F., Deleterious effects of electric shock, in Handbook of Laboratory Safety, 2nd ed., CRC Press, Cleveland, OH, 1972a.

Dalziel, C.F., Electric shock hazard, IEEE Spectrum 9:41-50, 1972b.

Dalziel, C.F., Let-go currents and voltage, AIEE Trans. 75:49-56, 1956.

Federal Emergency Management Agency, Fire in the United States, 2nd ed., FEMA-22, Washington, DC, 1982a.

Federal Emergency Management Agency, NFIRS 1980 Data Base, 8 computer data tapes obtained from R.G. Katz, Office of Fire Protection Engineering and Technology, Washington, DC, April 1982b.

Hamilton, L.D., Comparative risk assessment in the energy industry, Presented at the 3rd Annu. ORNL Life Sci. Symp., Symp. on Health Risk Analysis, Gatlinburg, TN, Oct. 1980.

Henrion, M., DEMOS User Manual, Draft version III, Carnegie-Mellon University, Pittsburgh, PA, 1982.

Holdren, J.P., G. Morris, and I. Mintzer, Environmental aspects of renewable energy sources, Annu. Rev. Energy 5:241-91, 1980.

Kelly, H., Photovoltaic power systems: A tour through the alternatives, Science 199(4329):634-43, 1978.

Knickerbocker, G.C., Fibrillation parameters of direct and alternating (20-Hz) currents separately and in combination, an experimental study, IEEE Trans. and Commun., COM 21, 1015-27, 1973.

Krantz, A., Industry trends, Presented at Photovoltaics Program Annual Review, Crystal City, VA, Feb. 1983.

Lassiter, D.V., Occupational Safety and Health in the Semiconductor Industry, Semiconductor Safety Division, Semiconductor Industry Association, Cupertino, CA, 1981.

Layton, D.W., L.R. Anspaugh, and K.D. O'Brien, Health and Environmental Effects Document on Geothermal Energy, 1981, UCRL-53232, Lawrence Livermore Laboratory, Livermore, CA, 1981.

Lee, A.M. and J.F. Fraumeni, Arsenic and respiratory cancer in man: An occupational study, J. Natl. Cancer Inst. 42(6):1045-52, 1969.

Morgan, M.G., Probing the question of technology induced risk, IEEE Spectrum, 18:58-64, Nov. 1981.

Morgan, M.G., S.C. Morris, A.K. Meier, and D.L. Shenk, A probabilistic methodology for estimating air pollution health effects from coal-fired power plants, Energy Systems and Policy 2:287-310, 1978.

Morris, S.C., P.D. Moskowitz, M.D. Rowe, and L.D. Hamilton, Health risk assessment of energy technologies, Presented at the Annu. Meet. Am. Pub. Health Assos., Los Angeles, CA, Nov. 2-5, 1981.

Moskowitz, P.D., J.I. Barancik, E.A. Coveney, L.D. Hamilton, P.E. Perry, S. Rabinowitz, M.D. Rowe, and I. Wilenitz, Health and Environmental Effects Document for Photovoltaic Energy Systems, 1982, BNL 51599, Brookhaven National Laboratory, Upton, NY, Sept. 1982.

Moskowitz, P.D., E.A. Coveney, and J.I. Barancik, Residential energy use: Fire risks, Ms. in preparation.

Moskowitz, P.D., E.A. Coveney, M.A. Crowther, L.D. Hamilton, S.C. Morris, K.M. Novak, P. Perry, W.A. Sevian, J.E. Smith, and P.J. Walker, Examining Public and Occupational Health Risks of Photovoltaic Energy Technologies, BNL 51467, Brookhaven National Laboratory, Upton, NY, 1981a.

Moskowitz, P.D., L.D. Hamilton, S.C. Morris, K.M. Novak, and M.D. Rowe, *Photovoltaic energy technologies: Health and environmental effects document*, BNL 51284, Brookhaven National Laboratory, Upton, NY, 1980.

Moskowitz, P.D., P. Perry, and I. Wilenitz, *Photovoltaic Energy Systems: Environmental Concerns and Control Technology Needs*, EPA-600/57-82-066, U.S. Environmental Protection Agency, Cincinnati, OH, 1981b.

Moskowitz, P.D. and M.D. Rowe, A comparison of input-output and process analysis, Presented at *Workshop on Assessing Health Impacts of Energy Technologies at the Regional or National Level*, Brookhaven National Laboratory, Upton, NY, Dec. 1981.

Mushak, P., W. Galke, U. Hasselbald, and L. Grant, *Health Assessment Document for Arsenic*, Environmental Criteria and Assessment Office, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1980.

National Academy of Sciences, *Drinking Water and Health*, Washington, DC, 1977.

National Audubon Society, *The Audubon Energy Plan: Technical Report*, New York, NY, 1981.

Neff, T.L., *The Social Costs of Solar Energy: A Study of Photovoltaic Energy Systems*, Pergamon Press, New York, NY, 1981.

Nichols, B.E., *The Carlisle House, An all Solar Electric Residence*, Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, MA, 1981.

Novak, K.M., *Toxicity of Silicon Compounds*, BNL 51509, Brookhaven National Laboratory, Upton, NY, June 1981.

Noyce, R.N., Microelectronics, *Sci. Am.* *237*(3):63-6, Sept. 1977.

Ott, M.G., B.J. Holder, and L.H. Gordon, Respiratory cancer and occupational exposure to arsenicals, Arch. Environ. Health 29:250-5, 1974.

Owens, T., L. Ungers, and T. Briggs, Estimates of Occupational Safety and Health Impacts Resulting from Large-Scale Production of Major Photovoltaic Technologies, BNL 51324, Brookhaven National Laboratory, Upton, NY, 1980.

Palz, W., Solar Electricity, An Economic Approach to Solar Energy, Butterworth, Boston, MA, 1978.

Pasquini, D. and L. Laird, Hazard Assessment of the Electronic Component Manufacturing Industry, Draft Report RTI/43U-2076/F1, (for National Institute of Occupational Safety and Health), Research Triangle Institute, July 1981.

Pinto, S.S., P.E. Enterline, V. Henderson, and M.O. Varner, Mortality experiences in relation to a measured arsenic trioxide exposure, Environ. Health Perspectives 19:127-30, 1977.

Rabinowitz, S., Electric Shocks: Health Hazards Associated With a Residential Photovoltaic Energy System, BNL 51659, Brookhaven National Laboratory, Upton, NY, 1983.

Robinson, C.V. and K.M. Novak, Programs and Subroutines for Calculating Cadmium Body Burdens Based on a One-Compartment Model, BNL 51306, Brookhaven National Laboratory, Upton, NY, Aug. 1980.

Rowe, M.D., Assessing occupational health and safety risks of renewable energy technologies at the national level, Presented at Workshop on Assessing Health Impacts of Energy Technologies at the Regional or National Level, Brookhaven National Laboratory, Upton, NY, Dec. 1981a.

Rowe, M.D., Human Exposure to Particulate Emissions from Power Plants, BNL 51305, Brookhaven National Laboratory, Upton, NY, May 1981b.

Sax, N.I., Dangerous Properities of Industrial Materials, 4th ed., Van Nostrand Reinhold, New York, 1975.

Smith, J.L., Photovoltaics, Science 212:1472-78 (1981).

Theriault, G.P., W.A. Burgess, L.J. DiBerardinis, and J.M. Peters, Dust exposure in the Vermont granite sheds, Arch. Environ. Health 28:12-17, 1974a.

Theriault, G.P., J.M. Peters, and L.J. Fine, Pulmonary function in Granite shed workers of Vermont, Arch. Environ. Health 28:18-22, 1974b.

Theriault, G.P., J.M. Peters, and W.M. Johnson, Pulmonary function and roentgenographic changes in granite dust exposure, Arch. Environ. Health 28:23-27, 1974c.

Underwriters Laboratories, Inc., Development of Photovoltaic Arrays Module Safety Requirements, DOE/JPL 955392-1, Jet Propulsion Laboratory, Pasadena, CA, 1981.

U.S. Congress, Solar Energy Research and Development Act, P.L. 93-473, Oct. 24, 1974.

U.S. Congress, Department of Energy Act, P.L. 95-238, February 25, 1978a.

U.S. Congress, Solar Photovoltaic Energy Research, Development and Demonstration Act, P.L. 95-590, Nov. 4, 1978b.

U.S. Congress, National Energy Conservation Policy Act, P.L. 95-619, Nov. 9, 1978c.

U.S. Congress, Public Utility Regulatory Policies Act, P.L. 95-617, Nov. 9, 1982.

U.S. Department of Energy, National Energy Plan II, Washington, DC, 1979.

U.S. Department of Energy, National Photovoltaics Program: Multi-Year Program Plan, Photovoltaic Energy Systems Division, Washington, DC, 1980.

U.S. Department of Health, Education, and Welfare, Radiofrequency sealers and heaters: Potential health hazards and their prevention, Current Intelligence Bulletin 33, National Institute of Occupational Safety and Health, and U.S. Department of Labor, Occupational Safety and Health Administration, Dec. 4, 1979.

U.S. Department of Labor, Occupational Injuries and Illnesses in the United States by Industry, 1978, Bull. 2078, Bureau of Labor Statistics, Washington, DC, Aug. 1980.

Ungers, L., T. Owens, and T. Briggs, Estimates of occupational safety and health impacts resulting from large-scale production of two near-term photovoltaic technologies, Ms. in preparation, Brookhaven National Laboratory, Upton, NY, 1982.

Wade, R. and M. Williams (Semiconductor Industry Study, California Occupational Safety and Health Administration), Personal communication, 1981.

Wilson, R., Risk/benefit analysis from toxic chemicals, Ecotoxicology and Environmental Safety 4:370-83, 1980.

APPENDIX

Supplemental Tables

Table 1. Pollutant emission rates from the production of silicon ribbon photovoltaic cells.[a]

Activity	Process step	Pollutant	Medium	Quantity per day per plant*	Quantity per year per GWp
Silicon production	Carbothermic reduction of silica	SiO as SiO_2	Vapor	524 kg	18,344 MT
		Ash	Vapor	12.4 kg	434 MT
		CO	Vapor	2,245 kg	78,560 MT
	Silicon purification by Siemens process	Silicon dust loss from size reduction	Vapor	200 - 400 g	7 - 14 MT
		Distillation bottoms ($SiCl_4$)	Liquid	442 - 761 kg	15,460 - 26,650 MT
		Noncondensibles (hydrogen)	Vapor	108 kg	3,770 MT
		Vapor dep. by-product (63% $SiCl_4$)	Liquid	3,333 kg	116,650 MT
	Silicon purification by Union Carbide process	Silicon dust loss from size reduction	Vapor	1.3 kg	47 MT
		Waste settler discharge (79% $SiCl_4$)	Liquid	141 kg	4,920 MT
		Filter waste stream (43% H_2, balance chlorosilanes)	Vapor	14.7 kg	514 MT
		Stripper overhead (73% chlorosilanes)	Vapor	10.5 kg	367 MT
		Product melter loss (silane and hydrogen; argon not incl.)	Vapor	900 g	31 MT
Cell manufacture	Melting, ribbon forming and cutting	NEGLIGIBLE			

Back-contact application	Al-ethanol slurry (5% Al by weight)	Liquid	230 kg	8,063 MT
	Ethanol vapor (diluted with air)	Vapor	94 kg	3,290 MT
Plasma etch	Exhaust via vacuum pump (SiF_4 and oxyfluorides)	Vapor	SMALL	
Ion implant	Exhaust (phosphine and hydrogen. Dilution air rate not given)			
Metallization	Ag ink (vehicle not known)	Liquid	51.2 kg	1,793 MT
	Vaporized vehicle	Vapor	NA	NA
	Cleaning solvent	Liquid	NA	NA
Antireflective coating	TiO_2 spray (vehicle not known)	Liquid	1.5 l	53.6 m^3
	Vaporized vehicle	Vapor	NA	NA
	Cleaning solvent	Liquid	NA	NA
Testing, interconn., and encap.	NEGLIGIBLE			

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*Plant capacity 10 MWp/yr, and 350 working days/yr.
NA = not available
[a]From Moskowitz et al. (1981b).

Table 2. Pollutant emission rates from the production of silicon dendritic web photovoltaic cells.[a]

Activity	Process step	Pollutant	Medium	Quantity per day per plant*	Quantity per year per GWp
Silicon production	Carbothermic reduction of silica	SiO as SiO_2	Vapor	348 kg	12,167 MT
		Ash	Vapor	8.3 kg	288 MT
		CO	Vapor	1,489 kg	52,106 MT
	Silicon purification by Siemens process	Silicon dust loss from size reduction	Vapor	129 - 268 kg	4.5 - 9.3 MT
		Distillation bottoms ($SiCl_4$)	Liquid	293 - 505 kg	10,253 - 17,700 MT
		Noncondensibles (hydrogen)	Vapor	71.5 kg	2,500 MT
		Vapor dep. by-product (63% $SiCl_4$)	Liquid	2,210 kg	77,370 MT
	Silicon purification by Union Carbide process	Silicon dust loss from size reduction	Vapor	860 kg	31.2 MT
		Waste settler discharge (79% $SiCl_4$)	Liquid	93.5 kg	3,260 MT
		Filter waste stream (43% H_2, balance chlorosilanes)	Vapor	9.8 kg	341 MT
		Stripper overhead (73% chlorosilanes)	Vapor	7.0 kg	243 MT
		Product melter loss (Silane and hydrogen; argon not incl.)	Vapor	600 g	21 MT
Sheet growth	Susceptor cleaning	Impure silicon (10% loss assumed)	Solid	9.4 kg	330 MT
Cleaning and prediffusion etch	Methanol wash	Methanol	Liquid (some vapor)	25.6 l	895 m^3

	HF etch	HF, conc $\leq$ 48.9%	Liquid	51.1 l	1,790 m^3
		SiF_4	Vapor	700 g	24.8 MT
	Deionized water	Water containing some HF	Liquid	1,644 l	58,000 m^3
	Plasma etch	$CF_4, O_2, SiF_4, SiOF_2$ Si_2OF_6, CO, CO_2, F_2	Vapor	480 g	16.8 MT
	Web inspection	Rejected Si web	Solid	57 g	2 MT
Silox application and back junction formation	Deposition of SiO_2 on front of strip	Isopropanol and breakdown products of "hydroxylated silica"	Vapor	1.07 kg	37.3 MT
	Removal of traces of SiO_2 from back of strip	Silica	Solid	NA	NA
	Boron tribromide diffusion	BBr_3, Br_2, HBr	Vapor	111 g	3.9 MT
	HF etch	HF, conc. unknown containing SiF_4 and	Liquid	15.4 l	537 m^3
		B SiF_4	Vapor	NA	NA
	Deionized water wash	Water containing some HF	Liquid	955 l	33,400 m^3
Silox application and front junction formation	Deposition of SiO_2 on back of strip	Isopropanol and breakdown products of "hydroxylated silica"	Vapor	1.07 kg	37.3 MT

Table 2. (continued)

Activity	Process step	Pollutant	Medium	Quantity per day per plant*	Quantity per year per GWp
	Removal of traces of SiO_2 from front of strip	Silica	Solid	NA	NA
	Phosphorus oxychloride diffusion	$POCl_3$,HCl,PH_3,P_2O_5,Cl_2	Vapor	115 g	4 MT
		Glass and plastic fixtures	Solid	15 g	500 kg
	HF etch	HF, conc. unknown,	Liquid	1.59 l	556 m^3
		SiF_4	Vapor	NA	NA
	Deionized water wash	Water containing some HF	Liquid	955 l	33,400 m^3
Silox application and front junction formation	Deposition of SiO_2 on back of strip	Isopropanol and breakdown products of "hydroxylated silica"	Vapor	1.07 kg	37.3 MT
	Removal of traces of SiO_2 from front of strip	Silica	Solid	NA	NA
	Phosphorus oxychloride diffusion	$POCl_3$,HCl,PH_3,P_2O_5,Cl_2	Vapor	115 g	4 MT
		Glass and plastic fixtures	Solid	15 g	500 kg
	HF etch	HF, conc. unknown,	Liquid	1.59 l	556 m^3
		SiF_4	Vapor	NA	NA
	Deionized water wash	Water containing some HF	Liquid	955 l	33,400 m^3

Antireflection coat and photoresist deposit	Dip in AR coating tank	Isopropanol	Vapor	3.06 kg	107 MT
	Photoresist deposit	Cellosolve acetate	Vapor	1626 g	57.3 MT
		n-butyl acetate	Vapor	310 g	12.4 MT
		xylene	Vapor	314 g	12.6 MT
	Methanol rinse	Methanol	Liquid (some vapor)	107 l	3,744 m^3
Exposure and develop photoresist and Etch Grind	Developing	Proprietary solution (treat as NaOH)	Liquid	22 l	76.3 m^3
	Acetone wash	Acetone	Liquid (some vapor)	NA	NA
	HF etch	Fuming HF, 70% conc.	Liquid	2.27 l	79.4 m^3
		SiF_4 and HF	Vapor	NA	NA
	Deionized water wash	Water containing some HF	Liquid	2,913 l	101,940 m^3
Metallization	Vacuum deposition	Ti metal	Solid	280 g	9.8 MT
		Ni metal	Solid	141 g	4.9 MT
		Cu metal	Solid	233 g	8.2 MT
		Vacuum pump oil	Liquid	48 ml	1,680 l
Photoresist removal and copper plating	Ultrasonic cleaning	Acetone	Liquid	242 l	8,464 m^3
	Methanol wash (metals removed in both acetone and methanol baths)	Methanol	Liquid	107 l	3,744 m^3
		Ti metal	Solid	251 g	8.8 MT
		Ni metal	Solid	127 g	4.4 MT
		Cu metal	Solid	210 g	7.4 MT
	H_2SO_4 wash	H_2SO_4, conc. unknown	Liquid	206 ml	7.2 m^3
	Copper plating		NO ROUTINE DISCHARGE		

Table 2. (continued)

Activity	Process step	Pollutant	Medium	Quantity per day per plant*	Quantity per year per GWp
	Deionized water wash.	Water containing $CuSO_4$, H_2SO_4, and other compounds	Liquid	5,359 l	187,570 m^3
Cell separation and Test	Cutting Si strips into cells by laser	Silicon dust	Solid	NEGLIGIBLE	
Inter-connection	Seam bonding of of cells to Al interconnections to form modules	Damaged Al strips	Solid	590 g	20 MT
Module lamination	Encapsulation of cell modules	Defective glass	Solid	104 g	3.6 MT
		Other rejected materials	Solid	985 g	34.4 MT
		Hydrocarbons from heated EVA plastic	Vapor	NA	NA
		Organic silane and methanol	Vapor	NEGLIGIBLE	

*Plant capacity 10 MWp/yr, and 350 working days/yr.
NA = not available.
[a] Modified from Ungers et al. (1982). Linearly scaled from 25 MWp to 10 MWp annual production output.

Table 3. Pollutant emission rates from the production of silicon cast ingot photovoltaic cells.[a]

Activity	Process step	Pollutant	Medium	Quantity per day per plant*	Quantity per year per GWp
Silicon production	Carbothermic reduction of silica	SiO as SiO_2	Vapor	114 kg	3,970 MT
		Ash	Vapor	2.7 kg	94 MT
		CO	Vapor	486 kg	17,010 MT
Ingot casting and cutting	Ingot casting	Slag (as Si)	Solid	21.1 kg	740 MT
	Band saw sectioning	Si dust	Solid	3.8 kg	132 MT
	Wafer slicing	Si dust	Solid	18.6 kg	652 MT
Surface preparation	NaOH etch	NaOH, 31% conc., containing Na silicates	Liquid	472 l	15,520 m^3
		Hydrogen [assumes 1% of Si removed in etch]	Gas	**3.4 m^3	**118,400 m^3
	Filtered tap water rinse	Water, containing NaOH	Liquid	3.2 m^3	113,200 m^3
	HCl neutralization	HCl, conc. unknown	Liquid	47.2 l	1,650 m^3
	Deionized water rinse	Water, containing HCl	Liquid	3.2 m^3	113,200 m^3
Front junction formation	Spray with water-based proprietary solution containing phosphorosilica	Dopant solution, unknown composition	Vapor and Liquid	1.9 l	65.5 m^3
Back junction formation	Application of Al paste	Terpineol	Vapor	4 kg	140 MT
	Wash with HCl to dissolve excess Al	Acidic solution of $AlCl_3$. Assumed nearly saturated at 15°C	Liquid	109 kg	3,800 MT
		Hydrogen	Gas	1.04 kg	36.3 MT
	Deionized water wash	Water containing HCl and $AlCl_3$	Liquid	57 l	2000 m^3
	HF etch	Spent acid, 4.8% conc., containing oxides of P and Al	Liquid	20 l	702 m^3
	Deionized water wash	Water, containing some HF	Liquid	57 l	2,000 m^3
Antireflection coating	Spray with titanium isopropoxide	Spray mixture composition:	Liquid	1.4 l	48.7 m^3
		Ti isopropoxide		111 g	3.9 MT
		Butylacetate		303 g	10.6 MT
		2 ethyl 1 hexanol		396 g	13.9 MT
		Isopropanol		364 g	12.7 MT
	Drying and sintering	Solvents:	Vapor		
		Butyl acetate		163 g	5.7 MT
		2 ethyl 1 hexanol		213 g	7.5 MT
		Isopropanol		196 g	6.9 MT
		Organic fraction of isopropoxide	Vapor	49 g	1.7 MT
Screen print grid pattern	Application of photoresist and cure	Solvents:	Vapor		
		Butyl cellosolve acetate		940 g	32.1 MT
		Solvent 103-A		410 g	14.4 MT
		Carbitol acetate		570 g	20.0 MT

Table 3. (continued)

Activity	Process step	Pollutant	Medium	Quantity per day per plant*	Quantity per year per GWp
Etching of grid pattern and metal-lization	Etching of grid pattern	Air with HF vapor	Vapor	NA	NA
	Deionized water wash	Water containing Ti fluorides	Liquid	152 l	5,315 m^3
	Electroless plating	Air with NH_3 vapor (spent solution returned to manufacturer)	Vapor	600 m^3	$2x10^7$ m^3
	Tap water rinse	Water containing trace Ni	Liquid	152 l	5,315 m^3
Resist removal	"Vapor degreasing" with 1,1,1-trichlorethane (TCE)	TCE carried off in air Spent TCE filter medium	Vapor Solid	6.2 kg NA	216 MT NA
Solder application	Flux bath and solder bath	Isopropanol and breakdown products of the flux Lead oxide	Vapor Vapor	140 kg NA	4,940 MT NA
	Filtered tap water rinse	Water (said not to be contaminated with heavy metals)	Liquid	2.8 m^3	92,280 m^3
Perimeter edging	Removal of cell edges by laser	Si dust Rejected cells	Solid Solid	NEGLIGIBL NA	 NA
Cell finishing	Inspection and testing	Rejected cells	Solid	NA	NA

Tab and string cells (acid flux employed)	Air containing HCl vapor	Vapor	NA	NA
	Rejected cells	Solid	NA	NA
Tap water spray, alkali neutralizer spray and water rinse	Streams of water and alkali solution	Liquid	NA	NA
Priming of glass superstrate by silane chemical spray and drying	Air stream to carry away methanol vapor	Vapor	78,000 m^3 of air per kg methanol	
Lamination and curing	Defective glass	Solid	104 g	3.6 MT
	Other rejected materials	Solid	985 g	34.4 MT
	Hydrocarbons from heated EVA plastic	Vapor	NA	NA
	Organic silane and methanol	Vapor	NEGLIGIBLE	

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*Plant capacity 10 MWp/yr, and 350 working days/yr.
NA = not available.
[a] Modified from Ungers et al. (1982). Linearly scaled from 25 MWp to 10 MWp annual production output.

Table 4. Pollutant emission rates from the production of cadmium sulfide/copper sulfide photovoltaic cells.[a]

Activity	Process step	Pollutant	Medium	Quantity per day per plant*	Quantity per year per GWp
Production of CdS-Coated substrates	Electrowinning	Heavy metal precipitate (as FeO)	Solid	110 g	3.90 MT
		Spent electrolyte Conc. unknown but containing the following quantities of	Liquid		
		$CdSO_4$		420 g	14.65 MT
		$Mn(SO_4)_2$		390 g	13.63 MT
	$CdCl_2$ production	Hydrogen	Vapor	300 g	10 MT
	Processing of glass substrates	Exhaust (mostly methanol vapor, containing some formic acid HCl, µ $SnCl_2$. Dilutant air rate not given)	Vapor	16.1 g	562.4 MT
	CdS applicn	Exhaust (60% thiourea, 35% breakdown products. Rest is $CdCl_2$. Dilutant air rate not given)	Vapor	9.6 g	336 MT
Cell manufacture	Grid forming	CdS dust	Solid	60 g	2 MT
		SnO vapor (dilutant air rate not given)	Vapor	20 g	600 kg
	Cu ion implant	Plating solution containing 20 mg/l Cu and 18 mg/l Cd	Liquid	128 l	4,473 m^3
		Deionized water rinse	Liquid	NA	NA

Metallization	Metals deposited on vacuum chamber walls:	Solid		
	Copper		5.9 kg	207 MT
	Lead		21.5 kg	753 MT
	Unknown metal		NA	NA
Testing, Interconn. and Encap.			NEGLIGIBLE	

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*Plant capacity 10 MWp/yr, and 350 working days/yr.

NA = not available.

[a] From Moskowitz et al. (1981b).

Table 5. Lost workdays and fatalities for a 10-MWp/yr photovoltaics plant (silicon Czochralski ingot process).[a]

Process operation (P.O.)	Occupational category (O.C.)	Labor emp. hrs per yr	Lost workdays per O.C.	Fatalities per O.C.	Lost workdays per P.O.	Fatalities per P.O.
Single-crystal growth	Technical	40,248	8.5	$4.0x10^{-4}$	11.7	$5.5x10^{-4}$
	Inspection	5,616	1.4	$7.9x10^{-5}$		
	Maintenance	5,250	1.7	$6.8x10^{-5}$		
Silicon ingot process	Material abrading and polishing	24,150	4.8	Neg.	10.2	$2.4x10^{-4}$
	Inspection	5,616	1.4	$7.9x10^{-5}$		
	Metal plating	600	0.2	$1.4x10^{-5}$		
	Maintenance	11,685	3.8	$1.5x10^{-4}$		
Junction formation	Technical	1,725	0.4	$1.7x10^{-5}$	0.7	$2.8x10^{-5}$
	Inspection	210	0.1	$2.9x10^{-6}$		
	Maintenance	630	0.2	$8.2x10^{-6}$		
Perimeter grinding	Material abrading and polishing	1,380	0.3	Neg.	0.4	$3.8x10^{-5}$
	Technical	36	Neg.	$3.6x10^{-7}$		
	Inspection	180	0.1	$2.5x10^{-6}$		
	Maintenance	72	Neg.	$9.4x10^{-7}$		
Wafer etching	Metal plating	1,200	0.4	$2.9x10^{-5}$	0.5	$3.4x10^{-5}$
	Inspection	90	Neg.	$1.3x10^{-6}$		
	Maintenance	270	0.1	$3.5x10^{-6}$		
Metallization	Metal plating	2,400	0.8	$5.8x10^{-5}$	0.9	$6.0x10^{-5}$
	Inspection	24	Neg.	$3.4x10^{-7}$		
	Maintenance	144	0.1	$1.9x10^{-6}$		
Antireflective coating	Technical	4,200	0.9	$4.2x10^{-5}$	1.0	$4.6x10^{-5}$
	Inspection	42	Neg.	$5.9x10^{-7}$		
	Maintenance	252	0.1	$3.3x10^{-6}$		
Cell testing	Assembling	11,400	2.6	$1.4x10^{-4}$	2.8	$1.5x10^{-4}$
	Inspection	114	Neg.	$1.6x10^{-6}$		
	Maintenance	684	0.2	$8.9x10^{-6}$		
Cell interconnection	Assembling	5,202	1.2	$6.2x10^{-5}$	1.8	$8.9x10^{-5}$
	Inspection	720	0.2	$1.0x10^{-5}$		
	Maintenance	1,320	0.4	$1.7x10^{-5}$		
Encapsulation	Assembling	10,200	2.3	$1.2x10^{-4}$	2.4	$1.3x10^{-4}$
	Inspection	120	Neg	$1.7x10^{-6}$		
	Maintenance	300	0.1	$3.9x10^{-6}$		
Module testing	Inspection	606	0.2	$7.0x10^{-6}$	0.2	$8.0x10^{-6}$
	Maintenance	36	Neg.	$4.7x10^{-6}$		
Total		136,722			32.6	$1.3x10^{-3}$

[a] Modified from Owens et al. (1980). Linearly scaled from 25 MWp to 10 MWp annual production output.

Table 6. Lost workdays and fatalities for a 10-MWp/yr photovoltaics plant (silicon ribbon process).[a]

Process operation (P.O.)	Occupational category (O.C.)	Labor emp. hrs per yr	Lost workdays per O.C.	Fatalities per O.C.	Lost workdays per P.O.	Fatalities Per P.O.
Ribbon growth	Technical	55,400	11.7	$5.5\mathrm{x}10^{-4}$	12.7	$5.9\mathrm{x}10^{-4}$
	Maintenance	3,120	1.0	$4.1\mathrm{x}10^{-5}$		
Aluminum (p^+) application	Technical	1,950	0.4	$2.0\mathrm{x}10^{-5}$	0.5	$2.5\mathrm{x}10^{-5}$
	Maintenance	390	0.1	$5.1\mathrm{x}10^{-6}$		
Plasma etching	Technical	3,240	0 7	$3.2\mathrm{x}10^{-5}$	0.8	$3.6\mathrm{x}10^{-5}$
	Maintenance	320	0.1	$4.2\mathrm{x}10^{-6}$		
Ion implantation	Technical	3,028	0.6	$3.0\mathrm{x}10^{-5}$	0.7	$3.3\mathrm{x}10^{-5}$
	Inspection	30	Neg.	$4.2\mathrm{x}10^{-7}$		
	Maintenance	182	0.1	$2.4\mathrm{x}10^{-6}$		
Metallization	Technical	1,378	0.3	$1.4\mathrm{x}10^{-5}$	0.5	$2.7\mathrm{x}10^{-5}$
	Inspection	192	Neg.	$2.7\mathrm{x}10^{-6}$		
	Maintenance	770	0.2	$1.0\mathrm{x}10^{-5}$		
Antireflective coating	Technical	2,858	0.6	$2.9\mathrm{x}10^{-5}$	0.7	$3.4\mathrm{x}10^{-5}$
	Maintenance	382	0.1	$5.0\mathrm{x}10^{-6}$		
Cell interconnection	Assembling	7,511	1.7	$9.0\mathrm{x}10^{-5}$	2.3	$11.7\mathrm{x}10^{-5}$
	Inspection	505	0.1	$7.1\mathrm{x}10^{-6}$		
	Maintenance	1,504	0.5	$2.0\mathrm{x}10^{-5}$		
Encapsulation	Assembling	10,489	2.4	$1.3\mathrm{x}10^{-4}$	2.5	$13.2\mathrm{x}10^{-5}$
	Inspection	121	Neg.	$1.7\mathrm{x}10^{-6}$		
	Maintenance	351	0.1	$4.6\mathrm{x}10^{-6}$		
Module testing	Inspection	339	0.1	$4.7\mathrm{x}10^{-6}$	0.1	$5.0\mathrm{x}10^{-6}$
	Maintenance	20	Neg.	$2.6\mathrm{x}10^{-7}$		
Total		94,080			20.8	$1.0\mathrm{x}10^{-3}$

[a] Modified from Owens et al. (1980). Linearly scaled from 25 MWp to 10 MWp annual production output.

Table 7. Lost workdays and fatalities for a 10-MWp/yr photovoltaics plant (silicon dendritic web process).[a]

Process operation (P.O.)	Occupational category (O.C.)	Labor emp. hrs per yr	Lost workdays per O.C.	Fatalities per O.C.	Lost workdays per P.O.	Fatalities Per P.O.
Sheet growth	Technical	59,760	12.7	$6.0x10^{-4}$	12.7	$6.0x10^{-4}$
Cleaning and pre-diff. etch	Technical	6,600	1.4	$6.6x10^{-5}$	1.7	$7.6x10^{-5}$
	Maintenance	792	0.3	$1.0x10^{-5}$		
Back junction formation	Technical	6,000	1.3	$6.0x10^{-5}$	1.5	$6.9x10^{-5}$
	Inspection	180	Neg.	Neg.		
	Maintenance	720	0.2	$0.9x10^{-5}$		
Front junction formation	Technical	6,000	1.3	$6.0x10^{-5}$	1.5	$6.9x10^{-5}$
	Inspection	180	Neg.	Neg.		
	Maintenance	720	0.2	$0.9x10^{-5}$		
Antireflective coating	Technical	2,400	0.5	$2.4x10^{-5}$	0.7	$3.1x10^{-5}$
	Inspection	144	Neg.	Neg.		
	Maintenance	576	0.2	$0.7x10^{-5}$		
Print and etch grid pattern	Technical	6,000	1.3	$6.0x10^{-5}$	1.5	$6.9x10^{-5}$
	Inspection	180	Neg.	Neg.		
	Maintenance	720	0.2	$0.9x10^{-5}$		
Metallization	Technical	2,400	0.5	$2.4x10^{-5}$	0.8	$3.5x10^{-5}$
	Inspection	288	0.1	$0.4x10^{-5}$		
	Maintenance	576	0.2	$0.7x10^{-5}$		
Photoresist removal, copper plating, cell separation	Technical	14,400	3.1	$1.4x10^{-4}$	3.5	$1.6x10^{-4}$
	Inspection	192	Neg.	Neg.		
	Maintenance	1,344	0.4	$1.7x10^{-5}$		
Cell inter-connection	Assembling	4,800	1.1	$5.8x10^{-5}$	1.3	$6.7x10^{-5}$
	Inspection	144	Neg.	Neg.		
	Maintenance	576	0.2	$0.9x10^{-5}$		
Encapsulation	Assembling	10,200	2.3	$1.2x10^{-4}$	2.4	$1.3x10^{-4}$
	Inspection	120	Neg.	Neg.		
	Maintenance	300	0.1	$0.4x10^{-5}$		
Module testing	Inspection	606	0.2	$0.7x10^{-5}$	0.2	$0.7x10^{-5}$
	Maintenance	36	Neg.	Neg.		
Total		126,954			27.8	$1.3x10^{-3}$

[a] Modified from Ungers et al. (1982). Linearly scaled from 25 MWp to 10 MWp annual production output.

Table 8. Lost workdays and fatalities for a 10-MWp/yr photovoltaics plant (silicon cast ingot process).[a]

Process operation (P.O.)	Occupational category (O.C.)	Labor emp. hrs per yr	Lost workdays per O.C.	Fatalities per O.C.	Lost workdays per P.O.	Fatalities Per P.O.
Ingot casting and processing	Material abarding and polishing	15,115	3.0	Neg.	4.1	5.0 x10^{-5}
	Technical	3,474	0.7	3.5x10^{-5}		
	Maintenance	1,186	0.4	1.5x10^{-5}		
Surface preparation	Technical	1,032	0.2	1.0x10^{-5}	0.2	1.0 x10^{-5}
	Maintenance	48	Neg.	4.8x10^{-7}		
Junction formation	Technical	6,048	1.3	6.0x10^{-5}	1.6	7.2 x10^{-5}
	Inspection	288	0.1	4.0x10^{-6}		
	Maintenance	576	0.2	7.5x10^{-6}		
Antireflective coating	Technical	4,800	1.0	4.8x10^{-5}	1.2	5.4 x10^{-5}
	Maintenance	480	0.2	6.2x10^{-6}		
Print and etch grid pattern, and metallization	Technical	12,480	2.6	1.2x10^{-4}	1.0	4.4 x10^{-5}
	Inspection	182	Neg.	2.5x10^{-6}		
	Maintenance	446	0.1	5.8x10^{-5}		
Solder application and wafer edging	Technical	3,720	0.8	3.7x10^{-5}	1.0	4.4 x10^{-5}
	Maintenance	552	0.2	7.2x20^{-6}		
Cell testing	Inspection	4,752	1.2	6.7x10^{-5}	1.2	6.7 x10^{-5}
Cell interconnection	Assembling	9,600	2.2	11.5x10^{-5}	2.2	11.5 x10^{-5}
Encapsulation	Technical	25,200	5.3	2.5x10^{-4}	9.7	4.4 x10^{-4}
	Assembling	5,040	1.1	6.0x10^{-5}		
	Maintenance	10,080	3.3	1.3x10^{-4}		
Module testing	Inspection	606	0.2	7.0x10^{-6}	0.2	8.0 x10^{-6}
	Maintenance	36	Neg.	4.7x10^{-6}		
Testing		105,741		24.1		1.04x10^{-3}

[a] Modified from Ungers et al. (1982). Linearly scaled from 26 MWp to 10 MWp annual production output.

Table 9. Lost workdays and fatalities for a 10-MWp/yr photovoltaics plant (cadmium sulfide/copper sulfide process).[a]

Process operation (P.O.)	Occupational category (O.C.)	Labor emp. hrs per yr	Lost workdays per O.C.	Fatalities per O.C.	Lost workdays per P.O.	Fatalities per P.O.
Substrate						
CdS application						
Grid forming						
Copper ion	PROPRIETARY INFORMATION					
Metallization						
Cell interconnection						
Encapsulation						
Module testing						
Total		61,945			14.2	$6.4\text{x}10^{-4}$

[a] Modified from Owens et al. (1980). Linearly scaled from 25 MWp to 10 MWp annual production output.

Table 10. Occupational hazards in the production of silicon Czochralski ingot photovoltaic cells.

Activity	Process step	Feed materials	Main product	By-products	Occupational hazards
Silicon production	Carbothermic reduction of silica	Coke Quartz	MG-Si	SiO (SiO_2) dust Ash dust CO gas	Burns and electric shock from furnaces. Eye injuries from coke and quartz dust during furnace loading. Inhalation of SiO_2 dust (cryst., fused, amorphous) and CO from leaks.
	Siemens process for purification	MG-Si HCl Cu catalyst Solvents for cleaning reactors	SeG-Si	Si dust H_2 gas Chlorosilanes liq. and vapor Polysiloxanes Amorphous Si	Inhalation of Si dust. Burns and eye injuries from exposure to chemicals from leaks and drains. Physical injuries when handling feed and product materials. (Chlorosilanes and atmos. moisture yield HCl).
	Union Carbide process for silicon purification	MG-Si Make-up H_2	SeG-Si	Si dust H_2 gas HCl Chlorosilanes liq. and vapor Fumed SiO_2	Inhalation of Si and SiO_2 dust. Burns and eye injuries from exposure to chemicals from leaks and drains. (Chlorosilanes - see previous.)
Cell manufacture	Ingot forming and doping	SeG-Si BCl_3 dopant Solvents for cleaning	Single-crystal ingot	Si dust Unreacted BCl_3 Crucible scrap	Inhalation of Si dust. Inhalation of and skin contact with solvent used in equipment cleaning.
	Wafer cutting and etching	Slurry Mixed acids	Etched wafers	Si dust Slurry with Si kerf Waste acids	Physical injuries and inhalation of Si dust during ingot handling and machining. Inhalation of vapors and burns from acids from leaks and drains.
	Junction formation	$POCl_3$ dopant	Doped and etched wafers	$POCl_3$ and its breakdown products	Chronic or acute exposure to $POCl_3$ and its products. Burns from hot furnace and wafers. Physical injuries in materials handling.
	Wafer edge grinding and etching	Spray water Mixed acids	Clean wafers	Si dust in water Waste acids	Minor injuries from materials handling. Inhalation of vapors and burns from acid from leaks and drains.
	Electroless plating and soldering	Plating solution Photoresist Acetone Rinse water Flux Solder	Metallized wafers	Spent plating solution Acetone Photoresist Rinse water Flux fumes Solder fumes	Exposure to nickel and its compounds. Inhalation of organic solvents. Inhalation of acid fumes from flux. Inhalation of lead oxide fumes from solder.
	Application of anti-reflective coating	SiH_2Cl_2 NH_3	Finished wafers	Si_3N_4 SiH_2Cl_2 NH_3	System operates under vacuum, but potential inhalation of vapors from leaks. Possible skin contact with Si_3H_4, when cleaning reactor walls.
	Testing, interconnection and encapsulation	Cu interconnects Solder Glass sheets Ethylene vinyl acetate sheets Mylar sheets Al frames	Modules	Solder fumes Hydrocarbon fumes Glass, plastic, and metal scrap	Inhalation of lead oxide fumes from solder. Cuts and burns from glass and heat application. Inhalation of fumes from heated EVA.

Table 11. Occupational hazards in the production of silicon ribbon photovoltaic cells.

Activity	Process step	Feed materials	Main product	By-products	Occupational hazards
Silicon production	Carbothermic reduction of silica	Coke Quartz	MG-Si	SiO (SiO_2) dust Ash dust CO gas	Burns and electric shock from furnaces. Eye injuries from coke and quartz dust during furnace loading. Inhalation of SiO_2 dust (cryst., fused, amorphous) and CO from leaks.
	Siemens process for purification	MG-Si HCl Cu catalyst Solvents for cleaning reactors	SeG-Si	Si dust H_2 gas Chlorosilanes liq. and vapor Polysiloxanes Amorphous Si	Inhalation of Si dust. Burns and eye injuries from exposure to chemicals from leaks and drains. Physical injuries when handling feed and product materials. (Chlorosilanes and atmos. moisture yield HCl).
	Union Carbide process for silicon purification	MG-Si Make-up H_2	SeG-Si	Si dust H_2 gas HCl Chlorosilanes liq. and vapor Fumed SiO_2	Inhalation of Si and SiO_2 dust. Burns and eye injuries from exposure to chemicals from leaks and drains. (Chlorosilanes - see previous.)
Cell manufacture	Melting, ribbon forming and cutting	SeG-Si	Wafers	Si dust	Inhalation of very small amounts of Si dust. Hazards from use of laser cutting device.
	Back-contact application	Al-ethanol slurry	Aluminized wafers	Waste slurry Ethanol vapor	Emissions removed by filter exhaust air system. Inhalation of small amount of alcohol vapor a possibility.

Plasma etching	Etchant gas, mixture of CF_4 and O_2	Etched wafers	Waste etchant gas and reaction products (SiF_4, Si oxyfluorides, O_2, F_2, CO_2)	Process performed under vacuum. Hazards few and quantities small. Potential exposure to the radiofrequency field that generates the plasma. However, frequency low compared to OSHA standards.
Ion implantation	Implant gas, mixture of PH_3 and O_2	Doped wafers	Waste implant gas	Process performed under vacuum. Hazards few, and quantities small. Potential exposure to electrical shock and laser radiation. Electrical interlocks and radiation shields provided.
Metallization	Ag ink (vehicle not known)	Metallized wafers	Waste ink Vehicle vapors Solvent vapors	Ink contains significant levels of other toxic metals besides silver. Dermal absorption possible. Inhalation of solvent and vehicle vapors. Possible concentrations of silver in atmosphere greater than TLV.
Anti-reflective coating	TiO_2 spray (vehicle not known)	Finished wafers	Waste spray Vehicle vapors Solvent vapors	Minor potential hazards from exposure to fumes (inhalation) and handling of coating materials (skin contact). Infrared ovens used, but system enclosed and exposure to radiation minimal.
Testing, interconnection and encapsulation	Cu interconnects Solder Glass sheets Ethylene vinyl acetate sheets Mylar sheets Al frames	Modules	Solder fumes Hydrocarbon fumes Glass, plastic, and metal scrap	Inhalation of lead oxide fumes from solder. Cuts and burns from glass and heat application. Inhalation of fumes from heated EVA.

Table 12. Occupational hazards in the production of silicon dendritic web photovoltaic cells.

Activity	Process step	Feed materials	Main product	By-products	Occupational hazards
Silicon production	Carbothermic reduction of silica	Coke Quartz	MG-Si	SiO (SiO_2) dust Ash dust CO gas	Burns and electric shock from furnaces. Eye injuries from coke and quartz dust during furnace loading. Inhalation of SiO_2 dust (cryst., fused, amorphous) and CO from leaks.
	Siemens process for purification	MG-Si HCl Cu catalyst Solvents for cleaning reactors	SeG-Si	Si dust H_2 gas Chlorosilanes liq. and vapor Polysiloxanes Amorphous Si	Inhalation of Si dust. Burns and eye injuries from exposure to chemicals from leaks and drains. Physical injuries when handling feed and product materials. (Chlorosilanes and atmos. moisture yield HCl).
	Union Carbide process for silicon purification	MG-Si Makeup H_2	SeG-Si	Si dust H_2 gas HCl Chlorosilanes liq. and vapor Fumed SiO_2	Inhalation of Si and SiO_2 dust. Burns and eye injuries from exposure to chemicals from leaks and drains. (Chlorosilanes - see previous.)
Cell manufacture	Sheet growth	SeG-Si	Si ribbon	Crucible scrap	Possible eye exposure to laser of melt-level sensors.
	Cleaning and Prediffusion Etch	Methanol Hydrofluoric acid Etchant gas mixture (CF_4 and O_2) Deionized water	Etched strips	Methanol liq. and vapor HF Liquid SiF_4 vapor Etchant gas and reaction products Low pH water	Possible eye exposure to strip-cutting laser. Major hazard is inhalation of fluoridic fumes and dermal contact. Also inhalation of, and skin contact with, methanol. Possible corrosion of exhaust system by SiF_4. Etching done under vacuum. Hazard minimal.

Silox applic. and back junction formation	Hydroxylated silica in isopropanol Boron dopant gas Hydrofluoric acid Deionized water	Strips with back junction	Vapors of isopropanol and breakdown products of hydrox. silica Silica dust Vapors of BBr_3 and reaction products HF liquid SiF_4 vapor Low pH water	Major hazards are inhalation of fluoridic fumes and dermal contact. Possible inhalation of isopropanol vapor. Serious hazard from inhalation of bromide fumes. Possible corrosion of exhaust system by SiF_4.
Silox applic. and front junction formation	Hydroxylated silica in isopropanol Boron dopant gas Hydrofluoric acid Deionized water	Strips with back and front junctions	Vapors of isopropanol and breakdown products of hydro. silica Silica dust Vapors of $PoCl_3$ and reaction products HF liquid SiF_4 vapor Low pH water	Major hazards in inhalation of fluoridic fumes and dermal contact, and exposure to $POCl_3$ and its reaction products. Possible inhalation of isopropanol vapor. Possible corrosion of exhaust system by SiF_4.
Application of anti-reflective coating and photoresist	TiO_2 and SiO_2 in isopropanol Photoresist Thinner Methanol	Coated strips	Isopropanol vapor Acetate vapors Xylene vapor Methanol liquid and vapor	Major hazards are inhalation of, and skin contact with, isopropanol, acetates, xylene, and methanol.

Table 12. (continued)

Activity	Process step	Feed materials	Main product	By-products	Occupational hazards
	Expose and develop photoresist, and etch grid	Proprietary developer (containing NaOH) Acetone Hydrofluoric acid Deionized water	Coated strips with grid exposed	NaOH solution Acetone liquid and vapor HF liquid SiF_4 and HF vapors Low pH water	Major hazard is inhalation of fluoridic fumes and dermal contact. Also contact with developer. Possible corrosion of exhaust system by SiF_4.
	Metallization	Ti, Ni, and Cu metals	Metallized strips	Waste metals	Potential inhalation of nickel fumes and dust. Ti and Cu are not a hazard in this method.
	Photoresist removal and copper plating	Acetone Methanol Sulfuric acid Plating solution Deionized water	Plated strips	Acetone and methanol liquids containing photoresist and metal dust Waste H_2SO_4 Contaminated water	Inhalation of acetone and methanol vapors. Also skin contact with liquids. Possible acid burns and inhalation of acid vapors. Copper sulfate in skin irritant and possible allergen.
	Cell separation		Finished cells	Si dust	Minor hazard from dust inhalation. Possible eye exposure to laser cutting device.
	Testing, interconnection and encapsulation	Al interconnects Solder Glass sheets Ethylene vinyl acetate sheets Mylar sheets Al frames	Modules	Solder fumes Hydrocarbon fumes Glass, plastic, and metal scrap	Inhalation of lead oxide fumes from solder. Cuts and burns from glass and heat application. Inhalation of fumes from heated EVA.

Table 13. Occupational hazards in the production of silicon cast ingot photovoltaic cells.

Activity	Process step	Feed materials	Main product	By-products	Occupational hazards
Silicon production	Carbothermic reduction of silica	Coke Quartz	MG-Si	SiO (SiO_2) dust Ash dust CO gas	Burns and electric shock from furnaces. Eye injuries from coke and quartz dust during furnace loading. Inhalation of SiO_2 dust (cryst., fused, amorphous) and CO from leaks.
Cell manufacture	Ingot casting and cutting	MG-Si	Wafers	Slag Si dust	Possible inhalation of Si dust.
	Surface preparation	NaOH solution Filtered tap water Hydrochloric acid Deionized water	Cleaned wafers	Contaminated NaOH solution Hydrogen gas High and low pH waters HCl	Inhalation of caustic and acid fumes and skin contact with the liquids. H_2 is an explosion hazard.
	Junction formation	Proprietary dopant solution (containing phosphorus) Oxygen	Doped wafers	Dopant solution, vapor and liquid	Toxicological properties of dopant solution not entirely known, but possibly hazards due to inhalation and skin contact.
	Back junction formation	Paste of Al powder in terpineol Hydrochloric acid Deionized water Hydrofluoric acid Deionized water	Wafers doped on both sides	Terpineol vapor Spent HCl liquid Spent HF liquid Low pH waters	Skin contact with hydrochloric and hydrofluoric acids. Inhalation of terpineol vapor.
	Applic. of anti-reflective coating	Ti isopropoxide solution in mixture of organic solvents	Coated wafers	Antireflectant solution liquid Mixed solvent vapors	Inhalation and ingestion of antireflectant liquid and solvent vapors. These are possible irritants to eyes and mucous membranes. Skin contact is a minor hazard.
	Screen-print grid pattern	Photoresist	Patterned wafers	Solvent vapors from photoresist (acetates and others)	Hazard from inhalation of solvent vapors.
	Etch grid pattern and metallize	HF vapor Deionized water Electroless plating solution ($NiCl_2$, NH_4OH, and others) Tap water	Metallized wafers	HF vapor Spent plating solution High and low pH waters	Potential problems from handling acid and plating solution. Acid burns and ammonium hydroxide burns are potential hazards. $NiCl_2$ skin contact and inhalation of vapors also potentially hazardous. Inhalation of Ni fumes unlikely.
	Photoresist removal	1,1,1-trichloroethane	Cleaned metallized wafers	TCE vapor Spent TCE filters.	Inhalation of, and dermal contact with, TCE is hazardous.
	Solder application and perimeter edging	Flux (isopropanol, resin and organic acids) Tin-lead solder Filtered tap water	Finished cells	Isopropanol vapor and flux breakdown products Metal oxide fumes Contaminated water Silicon dust	Potential exposure to isopropanol and aldehyde vapors, and to lead oxide fume. Inhalation of Si dust.
	Testing, interconnection and encapsulation	Cu interconnects Solder Glass sheets Ethylene vinyl acetate sheets Mylar sheets Silane Al fumes	Modules	Solder fumes Hydrocarbon fumes Glass, plastic, and metal scrap	Inhalation of lead oxide fumes from solder. Cuts and burns from glass and heat application. Inhalation of fumes from heated EVA. Possible hazard of methanol inhalation due to use of silane.

Table 14. Occupational hazards in the production of cadmium sulfide/copper sulfide photovoltaic cells.

Activity	Process step	Feed materials	Main product	By-products	Occupational hazards
Production of CdS-coated substrates	Electro-winning	Cadmium sponge (99.5% pure) Steam Sulfuric acid Manganese dioxide Animal glue	Cadmium metal (99.995% pure)	Heavy metal oxides Spent electrolyte containing $CdSO_4$ and $Mn(SO_4)_2$	Exposure to cadmium. Possible hazard of acid burns and inhalation of acid fumes.
	Cadmium chloride production	Hydrochloric acid (aqueous)	$CdCl_2$ solution	Hydrogen gas	Exposure to cadmium metal and chloride Possible hazard of acid burns and inhalation of acid fumes. Hydrogen is explosion hazard.
	Processing of glass substrates	Wash water Tin chloride solution in methanol	Substrates coated with tin oxide	Methanol vapor, containing some formic acid, HCl, and $SnCl_2$	Possible exposure to fumes of tin compounds and to methanol vapors. Also possible cuts from glass handling.
	Cadmium sulfide application	Aqueous solutions of $CdCl_2$ and thiourea	Coated substrates	Vapors containing thiourea, $CdCl_2$, and breakdown products	Exposure to cadmium compounds.
Cell manufacture	Grid forming	Permanent resist Temporary resist	Patterned wafers	CdS dust SnO vapor	Inhalation of CdS dust. Possible eye exposure to laser beam used to vaporize SnO layer.
	Copper ion implant	Proprietary copper chloride solution Deionized water	Implanted wafers	Spent solution Contaminated water	Possible inhalation of copper compounds. Skin contact with $CdCl_2$ is hazardous. Possible burns from hot solution.
	Metallization	Copper Lead Unknown metal	Metallized wafers	Metals deposited on walls and fittings of vacuum chamber	If metal pellets produced elsewhere, hazard potential is low. Production of lead pellets is hazardous.
	Testing, interconnection and encapsulation	Metal interconnects Solder Encapsulation materials (not known)	Modules	Negligible	Negligible hazard.

Table 15. Photovoltaic array information for the Carlisle house.*

	Nominal	Hot	Cold
Module V_{ppp}	13.6 V	13.4 V	15.5 V
I_{ppp}	4.25 A	4.15 A	4.45 A
OCV	17.6 V	16.8 V	20.8 V
SCC	4.8 A	4.8 A	4.8 A
P_p	58 W	56 W	69 W
String V_{ppp} (14 modules)	190 V	188 V	217 V
I_{ppp}	4.25 A	4.15 A	4.45 A
OCV	246 V	235 V	291 V
SCC	4.8 A	4.8 A	4.8 A
P_p	812 W	784 W	966 W
Array V_{ppp} (9 strings)	190 V	188 V	217 V
I_{ppp}	38 A	37.3 A	40.0 A
OCV	246 V	235 V	291 V
SCCC	43.2 A	43.2 A	43.2 A
P_p	7.3 kW	7.1 kW	8.7 kW
Cell temperature	46°C	56°C	6°C
Ambient temperature	82°F	100°F	10°F

*From Nichols (1981) as modified by Rabinowitz (1983).