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BIOMEDICAL AND ENVIRONMENTAL
ASSESSMENT DIVISION
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OF ENERGY SYSTEMS

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Health and Environmental Risk Analysis Program

Research Supported by the Division of Photovoltaic Energy Technology, Conservation and Renewable Energy and the Health and Environmental Risk Analysis Program, Human Health and Assessment Division, Office of Energy Research, U.S. Department of Energy

BNL--51467

DE82 014260

BNL 51467
UC-63
(Photovoltaic Conversion — TIC-4500)

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Under Contract No. DE-AC02-76CH00016 with the
UNITED STATES DEPARTMENT OF ENERGY

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Summary

This report examines potential public and occupational health and safety risks associated with different photovoltaic cell types (silicon n/p, silicon metal/insulator/semiconductor [MIS] and cadmium sulfide/copper sulfide) and their use in small rooftop shingle, rooftop panel, and ground-based units. Potential development of this technology has aroused concern about public health risks from use, and release of specific pollutants (e.g. silicon and cadmium) from photovoltaic cell fabrication, and conventional pollutants from preparation of structural materials (e.g. sulfur oxides), hazards of electrical shock, and about occupational health risks of accident- and illness-related hazards. Also, questions exist about potential uncertainties in these estimates, and differences in risk among different fabrication alternatives.

This report does not resolve all these concerns but provides some perspective:

(i) What photovoltaic fabrication alternatives and uses will be commercialized in the near-term?

(ii) What types and quantities of materials will be used and what wastes will be produced?

(iii) What effects will these pollutants have on environmental quality?

(iv) What risks will these pollutants pose to public health?

(v) What are the principal occupational health risks?

Commercial Status

A variety of materials and cell concepts are presently being examined for use in different markets; small-remote (<$10kW_{pk}$) for non-grid connected applications, and small ($10kW_{pk}$) to large ($100MW_{pk}$) systems for use in

residences, commercial and industrial settings, and central-station generation. Those showing greatest promise include silicon technologies and thin films.

Materials Consumed and Released

Material consumption is a function of cell type, application, and related engineering characteristics. Of the engineering characteristics, risk estimation is most influenced by differences in photovoltaic cell efficiencies and expected operating lifetimes. Other variables including inverter efficiency, and cell failure rate are less important (Table 1). In general, material demands for the ground-based uses are greater than for rooftop alternatives (Table 2). Because of existing concerns, about public health noted in the literature or expressed by reviewers of our previous efforts, only silicon, cadmium and sulfur dioxide emission estimates are given (Tables 3 and 4), although data for many pollutants are available. Silicon-refining and cadmium sulfide-photovoltaic cell fabrication probably represent the largest sources of these respective materials from throughout the individual energy cycles. Sulfur dioxide emissions are produced principally during preparation of structural materials. Emission estimates for material supply activities are probably accurate because they are based upon actual measurements. Emission coefficients for fabrication and disposal activities are estimated hypothetically because measurements are not available; they are therefore highly uncertain.

Air Quality

The inhalation route is generally thought to pose the greatest risk. Thus, local-exposures from airborne pollutants were estimated for comparison with threshold-based health effects. These estimates for simple terrain are thought to be fairly accurate (±2). Accuracy of the long-range transport model used to examine non-threshold related health effects has not yet been defined, although locational uncertainty modifies the estimated exposures by a factor of ±6. Estimated local maximum exposures were 34 x 10^{-4} ug/m^3 (±6) and 0.76 x 10^{-4} ug/m^3 (±6) for silicon and cadmium, respectively (Tables 5 and 6). Measured background levels exceeded these estimates by factors of 10^6 for silicon (measured as total particulates) and 10^2 for cadmium. Local-exposure to sulfur dioxide was not examined. Estimated systemwide exposures due to long-range transport were 4.7 x 10^0 person-ug/m^3 and 2.14 x 10^3 person-ug/m^3 for cadmium and sulfates, respectively (Table 7). No estimates of background exposures for cadmium are available, but estimated sulfate exposures were 10^6 times greater than those expected from photovoltaic material supply activities. Since low-level exposures to silicon compounds do not appear to pose any risk, long-range exposures were not calculated.

Public Health

Estimating public health risk is complex and subject to great uncertainty because of the many assumptions and models used. Although uncertainty is large, estimating the size of health risk related to inhalation of cadmium, silicon and sulfur dioxide is possible. Although no epidemiological evidence suggests that release of silicon dioxide dust produces silicosis or reduces pulmonary function in non-occupationally exposed settings, we nevertheless used an occupationally derived dose-response function to estimate the magnitude of the public risk from these emissions. Using a pulmonary function dose-response model we estimated that the maximum cumulative life-time exposure to silicon dioxide in the general population was 10^{-3} dust-years/10^{12} Btu; 3 x 10^2 dust-years is required to reduce pulmonary lung functions in exposed individuals by 50% (Figure 2).

Chronic cadmium exposure produces a variety of effects including chronic kidney dysfunction and possibly prostate cancer. Using a simulation model, potential contributions of cadmium to the kidney from different sources were examined. Results suggested that potential contribution from the photovoltaic energy cycle was small (1 ug/g) when compared with background contributions from food (43 ug/g) and smoking (11 ug/g). Also, total cumulative burden from all sources was well below any theshold where chronic kidney damage would be expected - 50 ug/g total vs. a threshold of 200 ug/g. Although low-level exposure to cadmium did not impose risks to renal dysfunction, there may be risk of prostate cancer because of the non-threshold response assumed for many carcinogens. Using a dose-response function developed by the Environmental Protection Agency-Carcinogen Assessment Group prostate cancer risk was examined. We estimated that the cadmium released would result in 12×10^{-5} prostate cancer fatalities/10^{12} Btu, with a range of 0 to 240×10^{-5} fatalities/10^{12} Btu (Table 8).

The largest public health risk is probably due to release of air pollutants from fuel combustion and process emissions in material supply cycles. These risks are not new, but instead allocated to materials used in photovoltaic energy system fabrication. Using the sulfate damage function, with all the caveats in its use, we estimated there would be 0.6 fatalities/10^{12} Btu (90% confidence range of 0-13 fatalities/10^{12} Btu) (Table 9).

The potential consequences of electrical shock hazards were also examined. Analysis suggested that risk would be minimized if collector outputs did not exceed 50 volts.

Occupational Health

Development of all energy technologies requires labor to extract and process fuels and materials, and to fabricate, install, operate and decommission devices used to convert alternative forms of energy into more useable states. This resultant labor force is inherently exposed to a mix of chemical and physical working environments affecting worker health and safety. Using a modified and updated version of the Reference Material System network model, process specific and systemwide labor demands, and occupational mortality and morbidity were estimated. From actuarial statistics, we estimated that production of 10^{12} Btu of energy by photovoltaic systems would result in 100 worker-days lost (range 39-560 worker-days lost 10^{12} Btu) and 0.02 fatalities (range 0.005-0.08 fatilities/10^{12} Btu) (Tables 11 and 12). Among the alternatives, use of the silicon MIS cell imposed the least health cost, and among the applications, rooftop shingles were the least costly.

Net estimates of occupational risk were calculated by comparing "estimated" with "expected" health costs of workers in related industries. This analysis suggested that large-scale commercialization of photovoltaic energy systems would not produce large changes in the levels of risk presently experienced (Tables 14 and 15).

To examine more adequately illness-related risks, health related experience in the semiconductor industry was reviewed and deterministic dose-response simulations prepared. In the semiconductor industry, the reported illness rate is almost 4 times greater than for private industry (Table 17). These statistics have heightened concern about occupational health risks in this and related industries (i.e. photovoltaic). Some of these differences may relate to methods of aggregating the data and subsequent reporting. These industries use large quantities of toxic and hazardous materials; the health effects still remain largely uncertain.

Because in-plant measurements of occupational exposure in the photovoltaic industry were unavailable, potential magnitude of chemical risk was explored using the simulation models previously discussed (Table 18). Exposure estimates for these simulations were based upon Threshold Limiting Values (TLV). Admittedly, these may not adequately describe actual occupational exposures within photovoltaic fabrication facilities, but were instead used to bound the size of the problem. From this analysis, chronic exposure to silicon dioxide at the TLV would be expected to produce a decrease in pulmonary lung function in 8% of the exposed population. Chronic exposure to cadmium at concentrations equal to the TLV (500 ug/m^3) would result in a prostate cancer fatality rate of 1235 fatalities/10^5 persons; the background occurrence rate is 17.6 fatalities/10^5 persons. Results from the cadmium-kidney burden model suggested that chronic exposure to cadmium at a concentration of 40 ug/m^3, or 10% of the TLV, could cause kidney burden levels to exceed expected thresholds for damage by a factor of 2.

Conclusion

Principal public health risks are from release of conventional air pollutants emitted during preparation of structural materials. Although the size of these risks are greater than those expected in the occupational setting, they are highly uncertain. Accident-related incidents probably are the largest source of occupational risk, although no large changes in the existing level of risk in industry can be expected. Risk from toxic chemicals is highly uncertain, but likely to be important. Risk estimation is hampered by lack of information on process alternatives and technologies likely to be commercialized, control technologies to be employed, material demands and by-products, measurements of occupational and public exposure to toxic chemicals, and dose-response relationships.

1.0 Introduction

In 1973, the Organization of Petroleum Exporting Countries (OPEC) announced the first of several sharp increases in oil prices. The sudden, widespread recognition of the finiteness of available fossil fuel resources generated interest in possible contributions from other energy sources. Subsequently, the Department of Energy provided substantial support to develop and demonstrate the technical readiness of new and renewable forms of energy.

While developing and demonstrating the technical readinesss of these new energy technologies, the Department of Energy is also obligated to ensure that health and environmental quality are not adversely affected. The Department of Energy Organization Act[1] specifically states that national environmental protection goals should be incorporated into the formulation and implementation of energy programs to advance the goals of restoring, protecting and enhancing environmental quality and assuring public health and safety. The Non-nuclear Energy Research and Development Act[2], also states that environmental and social consequences of a proposed program shall be analyzed and considered in evaluating its potential.

In complying with these obligations, the Health and Environmental Risk Analysis Program, Human Health and Assessment Division, Office of Energy Research, Department of Energy, is examining health and envionmental risks associated with many emerging energy technologies. This report on potential health consequences associated with the large-scale commercialization of photovoltaic energy technologies gives a documented quantitative analysis of knowledge and uncertainty of health effects associated with development of these energy systems.

Potential health risks were identified by examining systematically all steps in representative energy cycles including material extraction, preparation and processing, and device fabrication, installation, operation, and disposal. Specific attention was given to occupational risks from accidents and chronic exposure to toxic pollutants. Similarly, public health risks from emissons released throughout the photovoltaic energy cycle were examined. Sources of uncertainty for each estimate were reviewed and quantitated.

2.0 Analysis Philosophy

Analyzing public and occupational health risks of any energy technology requires detailed understanding and specification of the technology and reference industry responsible for commercialization of the energy system. Subsequently, estimates of health risk can be derived from accident-and illness-related effects of the energy system.

Examination and estimation of these effects depend upon assembling and coupling information from various disciplines, e.g. engineering, law, medicine. Figure 1 diagrams the generic approaches and models used to evaluate potential types and magnitudes of occupational accidents and public and occupational related illness.

As shown, occupational accidents were examined within the context of the Reference Material System[3] displayed in Appendix A and described in greater detail elsewhere[4-6]. The Reference Material System provides a framework for tracing flows of materials from extraction through to device fabrication and ultimate disposal. The system also permits labor demands, occupational accidents and emissions to be traced and quantified. Use of this system requires: (i) end-use material demands; (ii) efficiency coefficients for all processes, e.g. ratio of material output : material input; (iii) standardized labor productivity estimates for all processes, e.g. amount of labor required to mine 1 ton of copper ore; (iv) occupational health and safety coefficients

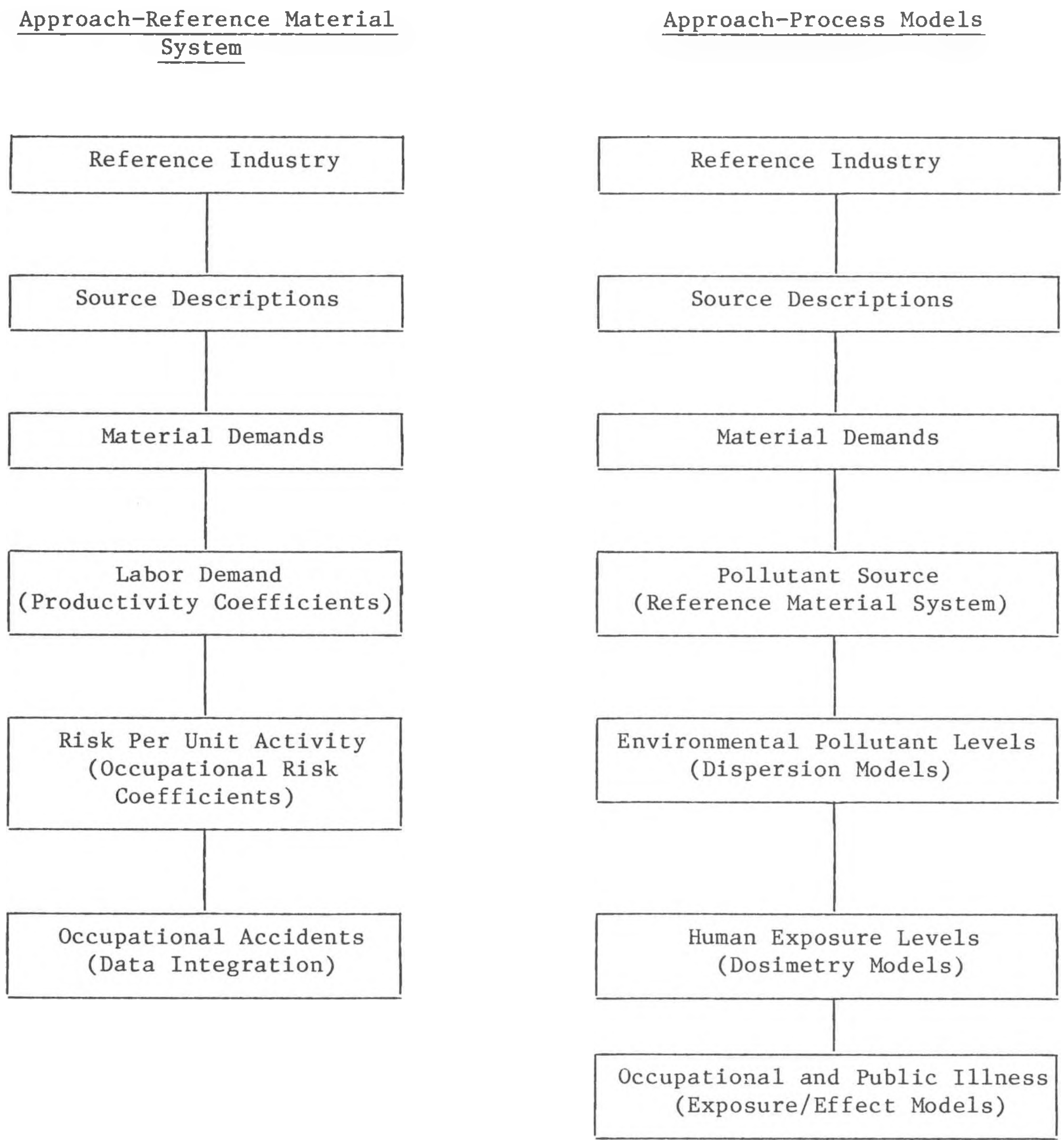

Figure 1. Approaches used in estimating occupational and public health risk from photovoltaic energy technologies.

by process, e.g. worker days lost (WDL)/man-year (MY); and (v) environmental emission coefficients by process. Specification of a network structure and quantities (i) to (v) suffice to generate estimates of some of the occupational health and safety risks and environmental residuals produced in commercializing a technology.

Other risks, such as those from occupational and public exposure to toxic chemicals must be evaluated by pollutant dispersion, dosimetry and response. As shown in Figure 1, estimation of illness-related effects is necessarily complex, based upon many models and assumptions.

In estimating accident- and illness-related effects it must be recognized that each data set and model introduces uncertainty into the final estimates. In this analysis we have tried to describe the uncertainty introduced by each of these components. Because the statistical distributions of these variables are not always known, confidence intervals for each estimate were not based upon the root-mean-squares determination of the geometric standard deviation for all variables but were instead developed from bounding analyses, i.e. estimates of extremes for each variable were multiplied by extremes of interacting variables to determine lower and upper confidence limits. This overestimates the statistically likely range of the estimate, but this approach is necessary because of the lack of data. When there are more precise estimates of the distributions of each of these variables, more detailed estimates of uncertainty will be possible.

3.0 Perspective on the Photovoltaics Industry[7-12]

The technological capability to produce a commercial photovoltaic cell was first demonstrated in 1953. Since then, a small but highly competitive U.S. industry has developed to supply photovoltaic systems for domestic and international markets. Present U.S. production capacity is ~ 1 MW_{pk} per year. Future demand and growth is expected to be large.

The most widely-held view of photovoltaic development is that the technology will penetrate stepwise 3 different markets. The near-term market generally includes small remote sited applications, e.g. mountain-top radio-repeaters. Commercial sales are currently being made in this market; annual sales of 3 to 7 MW_{pk} are expected. An intermediate market, such as water pumping and general power supplies for remote villages could ultimately range in size from 50 to 500 MW_{pk} of annual sales. Photovoltaic systems are not yet cost competitive for this market. The ultimate market for photovoltaic energy systems will be the large electrical using sectors. This market includes small (3-10 kW_{pk}), intermediate ($<$ 500 kW_{pk}) and large ($\sim$ 100 MW_{pk}) applications for single residences, commercial and industrial settings, and central station generation, respectively. Potential size of this overall market varies according to projected costs of photovoltaic and conventionally generated electricity.

A variety of material and cell concepts are presently being examined for these different applications. Those showing greatest promise include silicon technologies, thin films and concentrators.

Single-crystal silicon cells are currently produced commercially and serve as the standard of comparison for new materials and concepts being developed. Production of these cell types is costly; several alternatives are being investigated currently. Processes near commerical application include both ingot casting and ribbon growing.

Inexpensively produced thin films represent an alternative to existing fabrication technologies. Thin film cells include a large group of materials and processes produced in a similar way. Thin films of specialized materials such as cadmium sulfide/copper sulfide, polycrystalline gallium arsenide, polycrystalline silicon and amorphous silicon have the potential to yield photovoltaic cells at comparatively low production costs. The major disadvantages of thin film cells are their low efficiencies and shortened lifetimes.

Photovoltaic technologies are currently expensive because of the diffuse nature of sunlight. Concentrators offer an alternative to reduce photovoltaic system costs. Use of concentrators instead of flat plate collectors increases engineering complexity and capital costs of the photovoltaic systems. Many analysts have concluded that cell efficiencies of ~ 30% (~ 2X higher than single crystal silicon ingot) are required for concentrators to be cost effective.

4.0 Photovoltaic Reference Systems

In this analysis 3 different photovoltaic systems were examined for use in 2 different applications. The photovoltaic cell types examined include: (i) silicon n/p cells produced by ingot growing; (ii) silicon metal/insulator/semiconductor [MIS] cells produced by ribbon growing; (iii) cadmium sulfide/copper sulfide backwall cells produced by spray disposition. These alternatives cover a range of manufacturing options and materials likely to be used in near-term commercialization activities. Applications examined include ground-based and rooftop installations. For the rooftop installations, a standoff panel and integral shingle were explored.

The generic designs for the ground-based and standoff roof mounted panel were based upon an existing 25 kW_{pk} decentralized photovoltaic system built by the Massachusetts Institute of Technology-Lincoln Laboratory and described by Watts et al.[13]. The system produces power to pump irrigation water at the university of Nebraska Field Laboratory near Mead. The solar array is composed of a total 28 flat plate panels, each 8 ft. by 25 ft. The array output is fed into a building housing system control equipment and inverters to convert the direct current produced by the photovoltaic cells into alternating current at 220 volts. The unit's peak power output of 25 kW makes it one of the largest operating systems in the U.S.

The concept of the photovoltaic rooftop shingle was initially conceived by the General Electric Corporation and further developed under contract to the Jet Propulsion Laboratory[14]. The General Electric shingle is composed of an active solar cell enclosed within various plastics, adhesives and other minor components. The shingle concept differs significantly from either the ground-based or standoff panel in that the shingle acts as both an electricity generating unit plus a rooftop shingle. Because of the latter function served, credit is ultimately provided for these services (e.g. installation labor costs are reduced).

The design engineering characteristics for each of the different photovoltaic systems are shown in Table 1. A median or best guess value is shown for each variable identified along with reasonable expectations of the range of that value. These data were derived from many references[15-25].

Total electrical output produced by any individual system is determined using the equation shown below:

$$E = Q_e \cdot \eta_{pv} \cdot A_c \cdot \frac{1}{T}\sum_{t=1}^{T} (1-f_{pv})^{12t} \cdot \eta_i \cdot \frac{1}{T}\sum_{t=1}^{T} (1-f_i)^{12t} \cdot C_r \cdot T \cdot K$$

where

E = Energy output (Btu),

Q_e = Annual insolation (kWh/m^2-yr),

η_{pv}= Efficiency of photovoltaic cell,

A_c = Cell Area (m^2),

T = Operating lifetime (yrs),

Table 1
Photovoltaic Engineering Characteristics

Technical Characteristics	Systems		
	Si - n/p	Si - MIS	CdS
Photovoltaic Cell Efficiency	0.13 0.10-0.19	0.12 0.10-0.19	0.08 0.06-0.13
Annual Insolation (kWh/m^2-yr)	1696 1265-2161	1696 1265-2161	1696 1265-2161
Operating Lifetime (yr)	25 20-30	25 20-30	25 20-30
Photovoltaic Cell Failure Rate (/month)	0.0005 $0.25\text{-}1.04 \times 10^{-3}$	0.0005 $0.25\text{-}1.04 \times 10^{-3}$	0.0005 $0.25\text{-}1.04 \times 10^{-3}$
Inverter Efficiency	0.88 0.85-0.90	0.88 0.85-0.90	0.88 0.85-0.90
Inverter Failure Rate (/month)	0.0005 $0.25\text{-}1.04 \times 10^{-3}$	0.0005 $0.25\text{-}1.04 \times 10^{-3}$	0.0005 $0.25\text{-}1.04 \times 10^{-3}$
Lifetime Energy Output (Btu)	10^{12}	10^{12}	10^{12}
Cell Area ($10^4 m^2$)	7.05 2.90-17.4	7.64 2.90-17.4	11.4 3.67-31.2

f_{pv} = Monthly failure rate of the photovoltaic cell (/month),

η_i = Efficiency of the inverter,

f_i = Monthly failure rate of the inverter (/month),

C_r = Concentration ratio,

K = Constant for converting kWh to Btu (3413 Btu/kWh).

By inverting this equation and setting E equal to a constant unit of energy output (10^{12} Btu), the active area of photovoltaic cells to be constructed (A_c) to produce this quantity of energy can be calculated.

Application of this equation with the data shown in Table 1 produced the results in the last row in Table 1. Presented are best guess estimates of the amount of active photovoltaic cell area to be constructed using median values for each variable and estimates of the engineering uncertainty based upon sole use of low and high coefficients, respectively. As shown, the engineering uncertainty is large. This uncertainty systematically affects all estimates subsequently produced (e.g. material demands and emissions). Among the variables affecting the engineering uncertainty, importance generally decreases as follows: photovoltaic cell efficiency, annual insolation, lifetime, inverter efficiency, photovoltaic cell failure rate, and inverter failure rate. In this analysis the concentration ratio was always equal to 1.

In addition to these engineering characteristics, material demands associated with each of the different applications and cell types must also be identified. Material demand estimates used in this study are shown in Table 2. As noted, these estimates were based upon studies by the General Electric Corporation[14] and the Massachusetts Institute of Technology[13].

Each of these studies provides only single estimates of materials required for the respective systems. Since the studies were based upon detailed engineering estimates, we assumed that they were accurate for the systems described. We estimated the uncertainty of the material demands to be within +10%. Obviously, these estimates may not adequately describe material requirements for similar applications with radically different designs.

Using these engineering estimates and data from the Reference Material System, emissions, labor demands, and occupational risks were estimated for each stage in the photovoltaic energy cycle ranging from material extraction to device fabrication and ultimate disposal. Emission estimates were ultimately combined with dispersion and health effect models to assess public health risks.

Table 2
Material Requirements (kg/25kW$_{pk}$)[1]

Technology/ Application/ Estimate	Material							
	Cd	Si	Al	Concrete	Cu	Glass	Fe and Steel	Plastic
Si n/p - Shingle								
Median		69	8.8		140	0.88	500	2200
W/O Engineering		62–76	3.4–4.2		120–150	0.79–0.97	450–550	2000–2500
W Engineering		25–190	1.4–10		50–370	0.32–2.4	180–1400	830–6100
Si n/p - Panel								
Median		83	560		520	1.0	3200	160
W/O Engineering		75–92	500–610		470–570	0.92–1.1	2900–3600	140–170
W Engineering		31–230	210–1500		190–1400	0.37–2.8	1200–8800	58–430
Si n/p - Ground								
Median		83	6500	44000	490	0.68	5200	120
W/O Engineering		75–92	5900–7200	39000–48000	440–540	0.61–0.75	4600–5600	108–132
W Engineering		31–230	2400–18000	$10000–12x10^4$	180–1300	0.25–1.8	1900–14000	44–330
Si MIS - Shingle								
Median		29	3.8		140	0.88	500	2200
W/O Engineering		26–32	3.4–4.2		120–150	0.79–0.97	450–550	2000–2500
W Engineering		9.9–73	1.3–9.6		46–340	0.30–2.2	170–1300	770–5700
Si MIS - Panel								
Median		29	720		660	1.0	3700	210
W/O Engineering		26–32	650–800		540–720	0.92–1.1	3300–4100	190–230
W Engineering		9.9–73	250–1800		220–1600	0.35–2.6	1300–9300	71–520
Si MIS - Ground								
Median		29	9400	61000	654	0.70	5800	170
W/O Engineering		26–32	8500–10000	55000–67000	590–720	0.63–0.77	5200–6300	152–190
W Engineering		9.9–73	3200–24000	$21000–15x10^4$	220–1600	0.24–1.8	2000–15000	58–420
CdS - Shingle								
Median	1.4		3.8		140	0.88	500	2200
W/O Engineering	1.3–1.6		3.4–4.2		120–150	0.79–0.97	450–550	2000–2400
W Engineering	0.42–4.3		1.1–11		39–400	0.25–2.6	140–1500	650–6700
CdS - Panel								
Median	1.4		720		660	2400	3700	210
W/O Engineering	1.3–1.6		650–790		590–720	2200–2700	3300–4100	190–230
W Engineering	0.42–4.3		210–2200		190–2000	700–7300	1100–12000	60–620
CdS - Ground								
Median	1.4		10000	61000	660	2400	4300	19
W/O Engineering	1.3–1.6		9100–11000	55000–67000	590–720	2200–2700	3900–4700	17–21
W Engineering	0.42–4.3		2900–31000	$21000–15x10^4$	190–2000	700–7300	1200–13000	5.5–57

[1]See text for a description of engineering uncertainty.

5.0 Emission Estimates

Production of electricity by photovoltaic energy systems, in contrast with many other energy alternatives, does not result in direct generation of emissions. Materials, however, are used and pollutants generated by material and device production activities must be estimated to examine potential public health risks associated with the entire energy system. These estimates can then be compared to competing alternatives.

In contrast with our previous efforts[4], we only give systemwide emission estimates for the following air pollutants: silicon, cadmium, and sulfur compounds. Although estimates for other pollutants are available upon request (e.g. nitrogen oxides, particulates), only these materials were used for health assessment. All estimates were derived by quantifying the Reference Material System[5,6].

Systemwide emission estimates are shown in Tables 3 and 4. Median, low and high estimates for each technology and application are presented. Uncertainties within each estimate relate to differing assumptions concerning control technology capability, processes employed, and ultimate form of disposal. Also, the chemical form of the final pollutant is not known with great certainty.[5]

Several points should be noted: (i) within each application, low to high estimates can vary by an order of magnitude; (ii) for the silicon technologies, most silicon is emitted during processing; (iii) for the cadmium sulfide system, most cadmium is emitted during cell fabrication; (iv) if we assume that 10% of the primary material contained in each of the photovoltaic devices is emitted during disposal, then emissions from incineration of spent cells dominate all other estimates; (v) engineering uncertainty if added to these estimates would increase the ranges shown by a factor of approximately

Table 3
Estimates of Systemwide Primary Emissions[1]
(lbs/10^{12} Btu)

Technology/Application Estimate	Probable Pollutant	Emission Estimate[2]
Si n/p - Shingle		
Median	SiO_2	6800
W/O Decommissioning		2300 - 17000
W Decommissioning		6400 - 22000
Si n/p - Panel		
Median	SiO_2	8800
W/O Decommissioning		3000 - 23000
W Decommissioning		8200 - 29000
Si n/p - Ground		
Median	SiO_2	8800
W/O Decommissioning		3000 - 23000
W Decommissioning		8200 - 29000
Si MIS - Shingle		
Median	SiO_2	1900
W/O Decommissioning		640 - 4700
W Decommissioning		2400 - 6800
Si MIS - Panel		
Median	SiO_2	1900
W/O Decommissioning		640 - 4700
W Decommissioning		2400 - 6800
Si MIS - Ground		
Median	SiO_2	1900
W/O Decommissioning		640 - 4700
W Decommissioning		2400 - 6800
CdS - Shingle		
Median	CdO, $CdCl_2$, CdS	66
W/O Decommissioning		18 - 120
W Decommissioning		150 - 290
CdS - Panel		
Median	CdO, $CdCl_2$, CdS	66
W/O Decommissioning		18 - 120
W Decommissioning		150 - 290
CdS - Ground		
Median	CdO, $CdCl_2$, CdS	66
W/O Decommissioning		18 - 120
W Decommissioning		150 - 290

[1]W/O Decommissioning asumes no release of the identified pollutant.
W Decommissioning assumes a 10% release from incineration.

[2]Expressed as lbs of the elemental substance (i.e. Si and Cd) and not the specific compound. Does not include engineering uncertainty.

Table 4
Estimates of Systemwide Sulfur Dioxide Emissions (10^5 lbs/10^{12} Btu)[1]

Technology	Estimate	Application: Shingle	Panel	Ground
Si n/p				
	Median	1.1	3.8	4.1
	W/O Engineering	0.85-1.5	2.8-5.0	3.1-5.3
	W Engineering	0.32-3.7	1.1-12	1.3-13
Si MIS				
	Median	1.0	4.5	4.8
	W/O Engineering	0.72-1.3	3.3-5.8	3.6-6.2
	W Engineering	0.27-3.0	1.3-13	1.4-14
CdS				
	Median	1.5	6.7	7.2
	W/O Engineering	1.1-1.9	4.9-8.8	5.3-9.3
	W Engineering	0.35-9.5	1.6-24	1.7-25

[1]See text for a description of engineering uncertainty.

+3; (vi) sulfur oxide emission estimates generally increase in the following order: shingle, panel, and ground; (vii) among each of the different fabrication alternatives there appears to be little difference in expected sulfur oxide emission levels; (viii) major sources of sulfur oxides include processing of the structural materials and silicon preparation.

6.0 Dispersion Estimates

Emitted pollutants may affect man directly through inhalation and ingestion, or indirectly through food chain interactions. Only the inhalation route for the selected air pollutants was examined here. This route is generally thought to impose the greatest health risks.[26-28]

Estimates of local and long-range exposures from transport of these materials were prepared. Estimation of local transport is needed to examine acute and threshold related health effects (e.g. kidney dysfunction).

Alternatively long-range exposure must be estimated to examine non-threshold health effects (e.g. prostate cancer).

Local exposures were only estimated for the major source of each primary pollutant in each of the different energy cycles: i.e. silicon-refining, and cadmium sulfide-fabrication. Except for possible incineration of photovoltaic devices, emissions from other sources are significantly smaller.

Local exposures were calculated using a Gaussion dispersion model to estimate annual average pollutant concentration at ground-level receptors within 50 miles of the point of release. The input parameters to this model include: (i) joint frequency distributions of wind speed, wind direction and stability; (ii) average annual emission rates; (iii) receptor-grid configuration; (iv) deposition rate; (v) other climatological data.[29] It has been estimated that the uncertainty of results produced by this model is $\pm$ 2 for annual average concentrations when applied to flat terrain. In complex terrains, uncertainty significantly increases. Inputs employed in this modeling effort are described elsewhere.[4]

Long-range exposures were calculated using matrix models developed at Pacific Northwest Laboratory and Brookhaven National Laboratory.[30,31] These models estimate Air Quality Control Region (AQCR) and national-level exposures from hypothetical facilities emitting unit quantities of pollutants. In developing these matrix estimates, data from four different months were run and averaged to calculate the annual averages used in this study. The accuracy of the estimates produced by these models is not yet defined. Estimates of uncertainty related to variations in possible facility locations were examined. Locational uncertainty causes different integrated exposures for releases from different AQCR's. Since the precise locations of the future industry are not known, best guess integrated exposure was based upon a median value for all AQCR's. The range of this estimate was based upon the 90% confidence limits surrounding the median.

Results of this modeling are shown in Tables 5, 6 and 7. Included are estimates of emission and model uncertainty. Engineering uncertainty is not specifically included, but would increase the existing range shown by a factor of $\sim \pm 3$. In Table 5, only maximum estimated exposures at each distance are shown. Maximum to minimum exposures at equivalent distances vary by a factor of 10.

As shown, incremental exposures associated with these activities are small, e.g., the National Ambient Air Quality Standard for particulates is $\sim 10^6$ times larger than any value estimated.[32] Measured background levels for cadmium range from 10^{-2} to 10^{-3} $\mu g/m^3$ or $\sim 10^2$ times greater than the maximum shown in Table 5.[33]

Tables 6 and 7 give estimates of integrated exposures (population x concentration). Measured background sulfate exposures are $\sim 10^9$ person-$\mu g/m^3$ or $\sim 10^6$ greater than those expected from photovoltaic material processing activities.[34] Since low-level exposure to silicon does not appear to pose any health threat (see Section 7), long-range exposures were not calculated. Both local and long-range exposure estimates were used in different health effects models discussed below.

7.0 Public Health

Public health risks may arise from routine or accidental release of toxic materials from different stages of the photovoltaic energy cycle and from physical accidents (e.g. electric shock) asociated with materials handling and/or device operation. In this analysis potential acute and chronic health risks from exposure to silicon, cadmium and sulfur compounds are examined. Electrical shock hazards are also discussed.

Table 5
Estimated Maximum Annual Average
Exposures to Primary Pollutants[1]
(10^{-4} μg/m^3)

Technology/ Activity/ Estimate	Pollutant	Distance (Miles) 0-10	10-20	20-30	30-40	40-50
Si n/p - Refining	Si					
Median		34	9.0	7.3	5.4	4.1
W/O Dispersion		12-91	3-18	2.7-13	2.0 -9.2	1.5 -7.0
W Dispersion		6.2-180	1.6-36	1.3-25	0.99-18	0.75-14
Si MIS - Refining	Si					
Median		7.2	1.9	1.5	1.1	0.86
W/O Dispersion		3.3-19	0.88-3.8	0.72-2.7	0.53-1.9	0.40-1.5
W Dispersion		1.7-38	0.44-7.7	0.36-5.3	0.27-3.9	0.20-3.0
CdS - Fabrication	Cd					
Median		0.76	0.16	0.082	0.050	0.034
W/O Dispersion		0.23-1.4	0.049-0.30	0.025-0.15	0.015-0.092	0.0090-0.063
W Dispersion		0.12-2.8	0.025-0.60	0.12-0.30	0.008-0.18	0.0052-0.13

[1]Expressed as μg/m^3 of the elemental substance. "W/O Dispersion" means that dispersion model uncertainty not explicitly incorporated into the estimates. "W Dispersion" means that uncertainty is included.

Table 6
Estimated Systemwide Cadmium Exposures Due to Long-Range Transport[1]
(person-μg/m^3)

Technology/Application/Estimate	Exposure
CdS - Rooftop Shingle	
Median	4.7
W/O Decommissioning	0.14 - 39
W Decommissioning	1.2 - 90
CdS - Rooftop Panel	
Median	4.7
W/O Decommissioning	0.14 - 39
W Decommissioning	1.2 - 90
CdS - Ground-Based	
Median	4.7
W/O Decommissioning	0.14 - 39
W Decommissioning	1.2 - 90

[1]Median estimates assumes an exposure of 143 person-μg/m^3/ton of emissions. The range is based upon estimates of 16-631 person-μg/m^3/ton on emissions. Median estimate based upon median emissions multiplied by median dispersion coefficient. Low and high estimates are similarly calculated.

Table 7
Estimated Systemwide Sulfate Exposures Due to Long-Range Transport[1]
(10^3 person-μg/m^3)

Technology	Estimate	Application		
		Shingle	Panel	Ground
Si n/p				
	Median	2.1	7.4	7.9
	W/O Engineering	0.37-7.0	1.2-23	1.3-25
	W Engineering	0.14-17	0.47-56	0.56-60
Si MIS				
	Median	1.9	8.7	9.3
	W/O Engineering	0.31-6.0	1.4-27	1.6-29
	W Engineering	0.12-14	0.56-60	0.60-65
CdS				
	Median	2.9	13	14
	W/O Engineering	0.47-8.8	2.1-41	2.3-43
	W Engineering	0.15-44	0.69-110	0.73-120

[1]Median estimates assume an exposure of 38.7 person-μg/m^3/ton of emissions. The range is based upon estimates of 8.6-93 person-μg/m^3/ton of emissions. Range calculated in a manner similar to that discussed in Table 6.

In identifying potential health risks from exposures to toxic materials it is important to remember that use of animal, epidemiologic and toxicologic data ultimately depend upon the identification of the precise chemical substance, particle size, mode and length of exposure. These are difficult to estimate for technologies and processes still under development.

7.1 Silicon[35]

Use of silicon n/p and silicon MIS photovoltaic cells will ultimately result in some public and occupational exposure to fine particulates composed principally of silicon dioxide (SiO_2) or silica. The hazardous effects of silica to man have been documented as far back as 1556 when Agricola described the dangers of mining on workers' health. 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). Silicosis is a fibrotic lung disease caused by inhalation of silicon dioxide particles, while silicatoses refers to pneumoconeoses caused by dust containing silicates but no free silica. The hazardous effects of pure silicon are unknown.[36]

Although public exposure to silica and any consequent effects on health to the general public are not documented, the Occupational Safety and Health Administration (OSHA) standard for crystalline silica is 10^{-4}g/m^3 assuming an 8 hr shift. There are no National Ambient Air Quality Standards for respirable silicon, but, if developed would likely be two orders of magnitude below the OSHA standard, or 10^{-6}g/m^3.[37] Although such a standard can be used to determine qualitatively the potential for damage, dose-response functions must ultimately be developed to determine quantitatively their potential size.

As previously noted, no data suggest that public health risks from exposure to silicon dioxide exist. Some occupational studies are, however, available and were used to develop a dose-response model for this analysis. In 1969, a joint study between Harvard University and the Vermont Division of Industrial Hygiene was begun to assess the relationship between granite dust exposure, quartz content and lung disease in 792 active granite shed workers in Vermont. Results of pulmonary function tests showed that granite dust and quartz dust caused decreased forced vital capacity, forced expiratory volume and total lung capacity, but not residual volume. A significant decrease of 2 ml/dust-year was defined, where a dust-year equalled an exposure for 40 hr/wk for 1 year to an average dust concentration of 523μg/m^3 for all occupations. Of 784 workers chosen for chest roentgenograms, 551 had normal and 233 had abnormal readings. Workers with abnormal readings were exposed to an average of 2.3 times more dust than workers with normal readings. A dose-response curve (see Figure 2) relating the effects of granite dust exposure on ventilatary function (forced vital capacity) and chest roentgenograms was subsequently prepared. The damage function suggests a lag time of 13.5 dust-years for the appearance of abnormal roentgenograms. A total of 32.5 dust-years of exposure was necessary to affect the ventilatary function of half of the workers.[38-40]

7.2 Cadmium

Chronic exposure to cadmium may result in chronic kidney dysfunction and possibly prostate cancer. The first clinical manifestation of kidney dysfunction and subsequent tubular damage is characterized by the urinary excretion of a high-molecular weight protein. The level at 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); although some believe the range of individual variability to be between 150 and 300 μg/g. Proteinuria, specifically B_2-microglobulin in urine, begins at this level. While protenuria has been associated with renal damage from chronic cadmium exposure, a causal relationship betwen this clinical condition, cadmium toxicity, and resulting mortality has not been established. Nevertheless, cadmium buildup in the kidney can be modeled and subsequent concentrations compared with stated thresholds.[41-45]

To analyze such effects, a single compartmental model can be used to estimate the cadmium in the kidney. The rationale for using this model was based on two considerations: (i) multicompartment modeling was overly complex for making gross estimates of aggregate health risks; and (ii) this particular approach was sophisticated enough to incorporate the important effects of age on the various parameters.

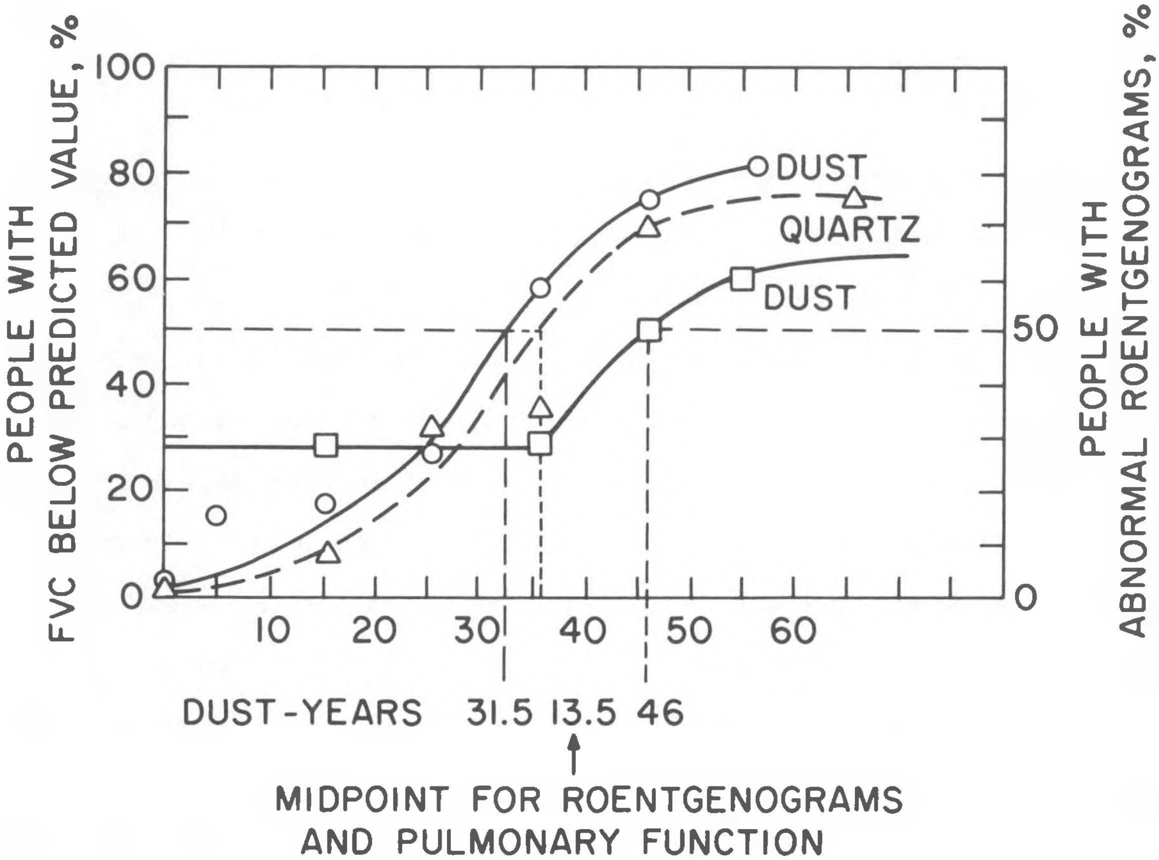

Figure 2. Dose-Response Curve of Dust on Roentgenograms and Forced Vital Capacity.

The basic form of this model is represented by the following differential equation:

$$\frac{dX(T)}{dT} = g(T) - \lambda(T)\cdot X(T),$$

where

$X(T)$ = cadmium in 1 gram of renal cortex,

$g(T)$ = fraction of absorbed cadmium which goes into 1 gram of kidney cortex,

$\lambda(T)$ = excretion rate,

T = age,

and under the condition that $X(0) = 0$ or that there is no cadmium in the renal cortex at birth. Using this model and appropriate data, individuals at risk can be identified.[46,47]

Some animal and epidemiological studies also suggest that cadmium may be a carcinogen. Injection of cadmium in experimental animals results in the development of malignant tumors (sarcomas) at the injection site. Also, subcutaneous injection significantly increases tumors at distant sites. Orally administered cadmium has not significantly increased tumors in experimental animals. Epidemiological studies examining cadmium and public health are available but present only minimal evidence suggesting that cadmium is a potential carcinogen. Occupational epidemiological studies, however, have reported associations between cadmium exposure and excess prostate cancer. At an alkaline battery plant, a proportionate mortality study reported a high frequency of prostatic cancer in workers exposed to cadmium for at least 10 years. Another study at the same plant involving a follow up of the population of workers who were exposed at least one year to cadmium showed a statistically significant increase in the incidence of prostatic cancer. At a cadmium smelter, a retrospective cohort study of workers exposed to cadmium for at least two years reported a significant increase in cancer deaths, mainly due to respiratory cancer. A statistically significant excess in prostate cancer was found only in workers exposed for more than 20 years. In a survey of four rubber producing plants, workers dying of prostate cancer were associated with exposure to cadmium and other metal oxides.[48]

Based on these studies, the U.S. Environmental Protection Agency-Carcinogen Assessment Group (CAG) has developed a dose-response function to estimate risks of prostate cancer due to cadmium in the ambient air.[48] CAG concludes that the annual probability of contracting prostate cancer from cadmium exposure can be calculated according to the following equation:

$$N = R/70.9 \cdot A \cdot P,$$

where

N = number of cancer fatalities,

R = median estimate of 1.75×10^{-3}, high estimate of 1.88×10^{-3},

A = annual average ambient exposure to cadmium ($\mu g/m^3$),

P = size of population exposed.

We assumed that the lower level of risk was equal to 0.

7.3 Other Air Pollutants

Fuel combustion and process emissions from the material supply activities produce a wide range of air pollutants including particulates, sulfur dioxide, nitrogen oxides, carbon monoxide, polycyclic aromatic hydrocarbons, and trace metals such as iron, mercury, and arsenic. These primary pollutants contribute to atmospheric chemical reactions producing secondary pollutants such as ozone, sulfates, and nitrates. Current knowledge is inadequate to describe the individual health effects of these pollutants in detail.[49] Considerable evidence, however, links sulfur-particulate air pollution with health effects. It has been hypothesized that sulfate compounds produced directly by coal and oil combustion and by oxidation of sulfur dioxide in the atmosphere are good indicators of this effect.

Based on this hypothesis, Morgan et al. developed a sulfate damage function.[50] The sulfate health-damage function links annual average sulfate exposure with an increased annual mortality rate. It does not represent the acute effects of episodes, but the long-term impact on the population of continuing environmental exposure. Although the sequence of events leading to this impact in the population is unknown, long-term exposure to air pollution, particularly in childhood, presumably increases susceptibility to respiratory infection. A history of repeated respiratory infection, possibly coupled with continued air pollution exposure, increases the prevalence of chronic respiratory disease. This leads to early deaths from a broad range of cardiopulmonary diseases. Thus, an increase in air pollution exposure results in degradation of the health of the population, which is eventually reflected in the mortality rate.

Under steady-state conditions, the number of deaths occurring over future years attributable to a pollution exposure of any single year equals the number of deaths occurring that year due to the summated pollution exposure of all previous years. Based partly on this, Morgan et al. developed a linear health-damage function from cross-sectional studies as a simplified way to estimate effects of alternative energy strategies. In this model, incremental sulfate exposure inevitably leads to an increment of health damage and a given number of premature deaths. The incremental health damage is proportional to the incremental sulfate exposure and is independent of the total sulfate exposure. The fraction of premature deaths might be taken as a rough estimate of the eventual contribution to mortality of a continuing air-pollution exposure of the given level; it is not the fraction of total deaths attributable to this level of exposure occurring in the same year.

It seems doubtful that the damage function is truly linear and has no threshold over the entire exposure range. More likely, at low total levels of exposure, the health impact of a unit increase in sulfate is reduced. Crude estimates indicate that imposition of a threshold in the model may reduce the estimated effect by as much as an order of magnitude. There may be a threshold below which there is no detectable health impact. The data on which the dose-response function is based are from urban areas with generally high background sulfate levels but, significantly, the linear function is consistent with data from urban and rural areas with high and low pollution levels. Use of a linear function to estimate effects of small changes in sulfate levels in areas with high background levels seems reasonable. Estimates of the effects of substantial changes in background levels, or of small changes in areas with low initial background levels, are subject to increased uncertainty. In this regard, contributions of sulfate attributable to photovoltaics are expected to include only small increments to total background exposures.

The health-damage function described by Morgan et al. gives a range of 0 to 12 deaths per 10^5 persons per $\mu g/m^3$ sulfate, with a median vlaue of 3.7, 95% confidence interval 0 to 11.5. These estimates were derived by a subjective analysis of data principally from correlation studies of the type conducted by Lave and Seskin. Such studies are subject to methodological and data problems discussed in detail elsewhere; standing alone, they are not an adequate basis for ascribing the observed effects to sulfate air pollution. Together with toxicological and epidemiological studies, however, they provide a useful means of estimating the magnitude of the damage.[34] A study is currently underway to revise and update this damage function in light of new information on the chemical form of sulfates and animal toxicology.

7.4 Quantitative Assessment

7.4.1 Cadmium-Kidney Dysfunction

Using the single compartment model, potential levels of cadmium in the kidney were previously studied in great detail.[5] Results from the modeling exercise suggested that potential contributions from airborne cadmium emitted by photovoltaic facilities are quite small; potential background contributions from food and smoking are significantly larger. Also, total buildup from all three sources is well below any threshold where chronic kidney damage is expected. Thus, direct risks related to airborne inhalation of cadmium appeared to be unimportant. Because exposure levels in both studies are similar, the model was not rerun.

Potential indirect health effects arising from food chain contamination were not examined, but may be more important because cadmium is rapidly absorbed and passed from soils into plants and their consumers. Also, soils represent the ultimate repository for this material.

7.4.2 Cadmium-Prostate Cancer

Although low-level exposure to airborne cadmium does not appear to impose risks to renal dysfunction because of the kidney's threshold response; there may be a risk of prostate cancer. This relates to the validity of assuming a linear non-threshold response for potential carcinogens, i.e., release of a small quantity of a potential carcinogen may produce a small number of excess cancers.

The size of this potential risk can be examined by combining estimates from national-level exposure models with the CAG developed dose-response function. Estimated annual excess cancer fatalities from the photovoltaic energy cycle are given in Table 8; the expected number of excess cancer fatalities is exceedingly small. If upper value estimates incorporating decommissioning and engineering uncertainty are included, the number of excess fatalities is still not large. Thus, it must again be concluded that this risk is of no consequence for photovoltaic development and does not require additional analysis.

7.4.3 Silicon - Lung Damage

There is no epidemiological evidence to suggest that the release of silicon dioxide produces silicosis or reduces pulmonary efficiency in the general population. Furthermore, the physical characteristics of the particulates from silicon refining facilities are significantly different, from mining activities. We nevertheless, used an occupationally derived dose-response function to estimate size of risk expected from estimated exposures. Use of the occupationally derived dose-response function first requires that public exposure be converted to the dust-year measurement used in the silicon response model (see Section 7.2). If one assumes that public exposures occur over the entire day, rather than the 8 hrs per day of measured occupational exposures, then a public dust-year is equivalent to an average exposure of 124μg/m^3:

$$\text{Public dust-year} = \frac{8 \text{ hrs/day} \cdot 5 \text{ days/week}}{24 \text{ hrs/day} \cdot 7 \text{ days week}} \cdot 523\ \mu\text{g/m} = 124\ \mu\text{g/m}$$

Using maximum estimated exposures shown in Table 5, annual public dust-year exposure was estimated to equal 10^{-5} dust-year per year (34×10^{-4} μg/m^3/124 μg/m^3). Assuming an average exposure of 70 years, we calculated a total lifetime exposure of 10^{-3} dust-years. Cross-tabulating this estimate with the dose-response function in Figure 2 suggests that no significant public health effects would be expected.

Table 8
Estimates of Systemwide Cadmium Emissions, Exposures and Response
(Per 10^{12} Btu)

	Emissions (lbs)[1]	Exposure (Person-ug/m^3)[2]	Response (10^{-5} Deaths/yr)[3]
CdS - Rooftop Shingle			
Median	66	4.7	11.7
W/O Decommissioning	18 - 120	0.14- 39	0 - 100
W Decommissioning	150 - 290	1.2 - 90	0 - 240
CdS - Rooftop Panel			
Median	66	4.7	11.7
W/O Decommissioning	18 - 120	0.14- 39	0 - 100
W Decommissioning	150 - 290	1.2 - 90	0 - 240
CdS - Ground-Based			
Median	66	4.7	11.7
W/O Decommissioning	18 - 120	0.14- 39	0 - 100
W Decommissioning	150 - 290	1.2 - 90	0 - 240

[1]See section 5.
[2]See section 6.
[3]Assumes entire population to be males. If actual ratio of males/females is assumed, then estimates would be reduced by ~ 50%.

7.4.4 Sulfur Oxides - Excess Mortality

Table 9 presents estimates of premature fatalities from the sulfate air pollutant model. The estimates do not represent a large health risk but are much greater than potential health costs attributable to cadmium and silicon Further, the sulfate effects in general do not represent new effects, but a reallocation of effects of current exposure. In this analysis, risk is simply related to quantity of emitted sulfur oxides. As a result, there is significant uncertainty with use of this surrogate.

7.5 Electrical Shock[51]

The potential for accidental exposure to electrical shock from operating photovoltaic cells has aroused some concern. Such shocks could arise from accidental short circuiting of a photovoltaic module, panel or

Table 9
Estimated Premature Fatalities Due to Sulfate Exposure
(Fatalities/10^{12} Btu-Year)

Technology	Estimate	Rooftop Shingle	Rooftop Panel	Ground-Based
Si n/p				
	Median	0.079	0.27	0.29
	W/O Engineering	0-0.77	0-2.6	0-2.7
	W Engineering	0-1.9	0-6.1	0-6.6
Si MIS				
	Median	0.072	0.32	0.34
	W/O Engineering	0-0.66	0-3.0	0-3.2
	W Engineering	0-1.5	0-6.6	0-7.2
CdS				
	Median	0.11	0.48	0.52
	W/O Engineering	0-0.97	0-4.5	0-4.8
	W Engineering	0-4.9	0-12	0-13

array by a homeowner maintaining his small rooftop or ground-based system. Although, a range of engineering alternatives to eliminate this hazard are envisioned, we nevertheless felt it was important to examine this issue.

Array subsystems present electrical hazards inherent in use of any electrical equipment. Assuming exposure to sunlight, the array subsystem will be generating electricity and a shock hazard may exist if there is contact with the exposed parts.

Voltage levels considered for use in photovoltaic systems are not likely to exceed 600v direct current (dc). A 10 kW rated array under investigation by Jet Propulsion Laboratory (JPL) may carry a rated dc input voltage of 150-300v depending on the circuitry. The dc output voltage of a 10kW rated array is generally 150v, but it may vary with the site requirements.[52] The Solar Energy Research Institute (SERI) reports input voltage specifications of 100-300v dc for up to 50 kW rated arrays and 160-240v dc for up to 10 kW rated arrays.[53-59]

Exposure to live parts at these voltage levels creates working conditions which could result in minor, recurring, or permanent injury and possibly death. The maximum "safe" voltage when contacting a circuit of maintained voltage largely depends upon the dryness and dielectric strength of the epidermis at points of contact. Dalziel states that, for wet contact conditions, the range of reasonably safe dc let-go voltage for man, is 51-104v for 99.5% of the population.[55] The corresponding voltage for alternating current (ac) is 10-21v for 99.5% of the population.[55,56] A safe contact range under dry conditions is not identified in the literature, but will be higher than the wet conditions.

In keeping with Dalziel's suggestions, Nearhoof et al. proposed that live parts of the electrical equipment operating at 50v or more be guarded against accidental contact.[57] The authors go on to say that voltages less than 50v dc may be safe if your feet are on the ground, but these voltages may be more hazardous when put in the context of a typical rooftop installation; i.e., voltage less than 50v dc may not be lethal but the fall off a roof may. The Jet Propulsion Laboratory Low Cost Solar Array Project has recommended that residential system voltage not exceed 30v dc, therefore minimizing the dangers of electric shock.[57]

Because of biological variability, no absolute safe voltage level can be determined.[55] Wide variations in human skin resistance are cited as the restrictive factor in predicting "safe" let-go voltages.[54-56] Since the current magnitude through the body determines the physiological responses, a voltage may be considered safe only when the total resistance is maintained by natural or artifical barriers at a sufficiently high level to limit the current below the recommended threshold.

8.0 Occupational Health and Safety

The development of all energy technologies requires labor to extract and process materials and to fabricate, install, operate and decommission devices used to convert alternative forms of energy into more usable states. This resultant labor demand is distributed among many occupational activities (e.g. mining, manufacturing, construction). Each occupation inherently possesses different physical and chemical working environments which can affect worker health and safety. By examining all occupations needed to produce energy from a specific technology, type and degree of occupational risk to individuals and to society can be estimated.

In this analysis, occupational risks from physical and chemical hazards were examined. Types and sizes of physical risks were estimated within the framework of the Reference Material System. Estimates of occupational mortality (fatalities) and morbidity [worker-days lost (WDL)] were based upon actuarial data for most occupational activities of interest. Similar data to measure occupational illness are not available generally. Therefore potential illnesses were examined quantitatively using dose-response models previously discussed and through descriptive examination of specific problems.

8.1 Physical Risks

Estimation of the physical risks associated with deployment of any energy technology requires specification of several data sets: (i) process efficiency; (ii) occupations needed to produce a specific energy system; (iii) labor per activity; (iv) risk per activity. Specification of a network structure and quantities (i) through (iv) suffice to generate estimates of occupational risk associated with development of a specific energy system.

The Reference Material System described elsewhere [4-6] provides such a specification and includes detailed data bases[5] for each element. Using this

Reference Material System, we estimated the systemwide labor required to produce each of the reference photovoltaic energy systems described previously. Subsequently, the number of WDL and fatalities for each of these systems were estimated. These results are in Tables 10-12. Each table, gives median, lower and upper confidence estimates. The uncertainty included within these confidence estimates include systematic errors introduced by Reference Material System data sets and what was previously described as "engineering" uncertainty. Detailed disaggregations by activity are available upon request, but not given here.

Review of these data suggest the following: (i) within each application, the rooftop is least costly for each measurement and the ground-based is the most costly; these differences relate principally to variations in material and installation demands; (ii) among all applications the silicon MIS alternative appears to impose the least costs and the cadmium sulfide alternative the most; silicon n/p is in between. These differences are principally due to assumed fabrication labor demand and expected cell efficiencies; (iii) among all different photovoltaic cell types and applications, the confidence limits for each estimate overlap; (iv) engineering uncertainty appears to be much larger than Reference Material System uncertainty.

Although not obvious in the aggregated estimates presented, there are significant differences in the types of labor required to produce each of the different applications. Shown in Table 13 are percentage labor demands by activity grouping. As noted, the rooftop applications require proportionally greater quantities of construction labor than the ground-based alternative. Conversely, labor demand in the ground-based application is more dependent on

Table 10
Systemwide Labor Demand (10^5 Man-hours/10^{12} Btu)

Technology	Estimate	Application: Rooftop Shingle	Rooftop Panel	Ground-Based
Si n/p				
	Median	2.9	3.0	3.2
	W/O Engineering	2.6-3.2	2.7-3.3	2.8-3.6
	W Engineering	1.7-7.8	1.3-8.2	1.2-8.9
Si MIS				
	Median	2.5	2.3	2.8
	W/O Engineering	2.2-2.7	2.0-2.5	2.5-3.2
	W Engineering	0.84-6.2	0.77-5.8	0.94-7.2
CdS				
	Median	3.7	3.0	3.8
	W/O Engineering	3.3-4.1	2.7-3.3	3.4-4.3
	W Engineering	1.4-10	0.87-9.1	1.1-12

Table 11
Systemwide Occupational Morbidity (10^2 Worker Days Lost/10^{12} Btu)

Technology	Estimate	Application: Rooftop Shingle	Rooftop Panel	Ground-Based
Si n/p				
	Median	1.1	1.3	1.3
	W/O Engineering	0.96-1.3	1.1-1.5	1.1-1.6
	W Engineering	0.39-3.2	0.45-3.7	0.46-4.0
Si MIS				
	Median	0.87	0.96	1.19
	W/O Engineering	0.76-1.0	0.82-1.2	0.97-1.4
	W Engineering	0.29-2.3	0.31-2.6	0.37-3.2
CdS				
	Median	1.3	1.3	1.6
	W/O Engineering	1.1-1.5	1.1-1.6	1.4-2.0
	W Engineering	0.46-3.7	0.37-4.5	0.44-5.6

Table 12
Systemwide Occupational Mortality (10^{-2} Deaths/10^{12} Btu)

Technology	Estimate	Application: Rooftop Shingle	Rooftop Panel	Ground-Based
Si n/p				
	Median	2.0	2.2	1.8
	W/O Engineering	1.6-2.4	1.8-2.7	1.6-2.3
	W Engineering	0.65-5.8	0.74-6.7	0.64-5.6
Si MIS				
	Median	1.6	1.8	1.6
	W/O Engineering	1.2-2.0	1.4-2.3	1.3-2.1
	W Engineering	0.46-4.6	0.52-5.2	0.51-4.7
CdS				
	Median	2.4	2.7	2.4
	W/O Engineering	1.9-2.9	2.1-3.3	2.0-3.0
	W Engineering	0.78-7.3	0.68-9.1	0.64-8.2

Table 13
Application/Sector Labor Demands[1] (% of Total)

Application/Sector	Technology: Si n/p	Si MIS	CdS	Average
Rooftop Shingle				
Mining	1.9	1.4	1.2	1.5
Manufacturing	63	59	59	60
Construction	35	40	40	38
Rooftop Panel				
Mining	4.8	6.0	6.6	5.8
Manufacturing	61	50	45	52
Construction	34	43	49	42
Ground-Based				
Mining	6.5	8.0	8.5	7.7
Manufacturing	80	77	75	77
Construction	13	15	16	15

[1]Median estimates only.

the mining and manufacturing sectors. These labor-demand shifts influence the type and size of total risk.

Differences between the ground-based and rooftop applications are not as large as intuitively expected. Detailed review of the data suggests that differences are minimized because of countervailing properties. The ground-based application demands greater material for fabrication but less labor for installation. Alternatively, the rooftop applications require less labor from material production but greater labor from installation and decommissioning. The sum total of the activities thus minimizes the net differences between the different applications.

8.2 Net Risk From Accidents

Although public health effects represent external societal costs related to the development of any energy technology, simple estimates of the number WDL or fatalities do not describe adequately the net occupational cost related to that same energy system.[60] Occupational health risk estimates are made from actuarial data of risk in industry. These estimates implicitly recognize that work imposes some risk; there are also health costs related to unemployment. Net risk analysis must therefore determine if the energy system being examined, increases or decreases the overall risk to the existing work force.

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

In this study, we estimate net risk by the first approach. The "expected" number of WDL and fatalities are based upon occupational statistics from 3 different economic sectors; mining, manufacturing, and construction. In developing estimates of expected health cost, we assume that labor structure is unaffected by the large-scale commercialization of the energy system being studied, i.e. labor demand is not satisfied by workers drawn from the unemployed, and that individual workers within any of the 3 different economic sectors remain employed within that same sector. Stated differently, if an individual was not working in the photovoltaics industry, they would be still working somewhere in the mining, manufacturing, or construction industry and subject to their average risk level there.

Based on these assumptions, we calculated the "expected" mortality and morbidity rates for each of the different applications (see Appendix A). These rates are based upon the proportionate demand for labor by sector combined with published occupational health coefficients.

In Tables 14 and 15, "expected," "estimated" and net WDL and fatalities are presented for the 3 different technologies and 3 different applications examined. These results suggest that no significant changes in risk are to be expected in the workforce from the commercialization of photovoltaics 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.

8.3 Chemical Risk

Risks of physical accidents normal in industry can be examined adequately through use of actuarial data.[61-66] This data base, however, cannot accurately describe potential acute and chronic hazards related to exposure

Table 14
Net Occupational Morbidity (10^2 WDL/10^{12} Btu)[1]

Technology/ Application/ Estimate	Labor Demand (10^5 Man-hours)	Estimated (WDL)	Expected (WDL)	Net Risk[2] (WDL)
Si n/p - Rooftop Shingle				
Median	2.9	1.1	1.3	
W/O Engineering	2.6-3.2	0.96-1.3	1.1-14	-0.14
W Engineering	1.1-7.8	0.39-3.2	0.46-3.3	
Si n/p - Rooftop Panel				
Median	3.0	1.3	1.4	
W/O Engineering	2.7-3.3	1.1-1.5	1.2-1.5	-0.11
W Engineering	1.3-8.2	0.45-3.7	0.60-3.8	
Si n/p - Ground-Based				
Median	3.2	1.3	1.4	
W/O Engineering	2.8-3.6	1.1-1.6	1.2-1.6	-0.08
W Engineering	1.2-8.9	0.46-4.0	0.51-3.9	
Si MIS - Rooftop Shingle				
Median	2.5	0.87	1.1	
W/O Engineering	2.2- 2.7	0.76-1.0	0.95-1.2	-0.19
W Engineering	0.84-6.2	0.29-2.3	0.36-2.7	
Si MIS - Rooftop Panel				
Median	2.3	0.96	1.0	
W/O Engineering	2.0-2.5	0.82-1.2	0.93-1.2	-0.09
W Engineering	0.77-5.8	0.31-2.6	0.35-2.7	
Si MIS - Ground-Based				
Median	2.8	1.1	1.2	
W/O Engineering	2.5-3.1	0.97-1.4	1.1-1.4	-0.07
W Engineering	0.94-7.2	0.37-3.2	0.41-3.1	
CdS - Rooftop Shingle				
Median	3.7	1.3	1.6	
W/O Engineering	3.3-4.1	1.1-1.5	1.4-1.8	-0.30
W Engineering	1.4-10	0.46-3.7	0.59-4.3	
CdS - Rooftop Panel				
Median	3.0	1.3	1.4	
W/O Engineering	2.7-3.3	1.1-1.6	1.2-1.5	-0.04
W Engineering	0.87-9.1	0.37-4.5	0.40-4.2	
CdS - Ground-Based				
Median	3.8	1.6	1.7	
W/O Engineering	3.4-4.3	1.4-2.0	1.5-1.9	-0.04
W Engineering	1.1-12	0.44-5.6	0.48-5.2	

[1]WDL = Worker Days Lost. Based upon accident statistics only, excludes illness-related health effects.
[2]Median estimates only.

Table 15
Net Occupational Mortality (10^{-2} Deaths/10^{12} Btu)

Technology/ Application/ Estimate	Labor Demand (10^5 Man-hours)	Estimated (Deaths)	Expected (Deaths)	Net Risk[1] (Deaths)
Si n/p - Rooftop Shingle				
Median	2.9	2.0	3.4	
W/O Engineering	2.6-3.2	1.6-2.4	3.1-3.8	-1.5
W Engineering	1.1-7.8	0.65-5.8	1.3-9.3	
Si n/p - Rooftop Panel				
Median	3.0	2.2	2.8	
W/O Engineering	2.7-3.3	1.8-2.7	2.5-3.1	-0.59
W Engineering	1.3-8.2	0.74-6.7	1.2-7.8	
Si n/p - Ground-Based				
Median	3.2	1.8	2.2	
W/O Engineering	2.8-3.6	1.6-2.3	2.0-2.5	-0.39
W Engineering	1.2-8.9	0.6-5.6	0.82-6.2	
Si MIS - Rooftop Shingle				
Median	2.5	1.6	2.9	
W/O Engineering	2.2-2.7	1.2-2.0	2.6-3.2	-1.3
W Engineering	0.84-6.2	0.46-4.6	1.0-7.4	
Si MIS - Rooftop Panel				
Median	2.3	1.8	2.2	
W/O Engineering	2.0-2.5	1.4-2.3	1.9-2.4	-0.31
W Engineering	0.77-5.8	0.52-5.2	0.73-5.5	
Si MIS - Ground-Based				
Median	2.8	1.6	2.0	
W/O Engineering	2.5-3.1	1.3-2.1	1.7-2.2	-0.31
W Engineering	0.94-7.2	0.51-4.7	0.65-5.0	
CdS - Rooftop Shingle				
Median	3.7	2.4	4.4	
W/O Engineering	3.3-4.1	1.9-2.9	4.0-4.9	-2.0
W Engineering	1.4-10	0.79-7.3	1.6-12	
CdS - Rooftop Panel				
Median	3.0	2.7	2.9	
W/O Engineering	2.7-3.3	2.1-3.3	2.6-3.2	-0.19
W Engineering	0.87-9.1	0.7-9.1	0.82-8.7	
CdS - Ground-Based				
Median	3.8	2.4	2.7	
W/O Engineering	3.4-4.3	2.0-3.0	2.4-3.0	-0.31
W Engineering	1.1-12	0.64-8.2	0.73-8.3	

[1]Median estimates only.

to toxic chemicals. Acute hazards can of course be qualitatively examined by comparing estimated exposure to Occupational Safety and Health Administration (OSHA) standards.[67] Chronic illness, where cause and response are not clearly linked and response may take more than 10 years, is not adequately described by the same statistics. Therefore, examination of occupational risk from exposure to toxic chemicals must be done using toxicologic and epidemiological data from related industries. There are difficulties in using such data because of differences in chemical environments. Use of data generated by these studies, however, permits order of magnitude estimates to be prepared.

8.4 Acute Hazards

As noted in our previous efforts, fabrication of photovoltaic devices involves use of large quantities of chemicals, some of acute concern. In Table 16, we list identified chemicals, and physical hazards of concern. Quantitative risk estimation based on this information is not possible. Prudent engineering design, however, should be incorporated into the planning of all new processes to insure that exposures to many of these materials do not exceed existing standards and subsequently threaten occupational health.

8.5 Chronic Hazards

Estimation of hazards arising from chronic exposure to different pollutants depends upon measurement of type and size of exposure and availability of suitable information to develop dose-response functions. Since the photovoltaic technologies described in this report are new or still undergoing engineering review, such data are not available. Therefore, analysis of chronic hazards must be approached qualitatively from review of heath experience in related industries or by using deterministic models. Data from both are given below.

Table 16

Potential Chemical and Physical Hazards in Photovoltaic Cell Fabrication[69]

Hazards

I. Chemicals

a. Solvents
Acetone, Amines (Epoxy), n-Butyl Acetate, Chlorobenzene, Ethanol, Ethylene Glycol, Freons, Hexamethyldisilazane (HMDS), Isopropanol, Methanol, Methylene Chloride, Methyl Ethyl Ketone, Morpholine, Petroleum Distillates, Phenol, Trichloroethylene, Triethanolamine, 1,1,1-Trichloroethane, Xylene

b. Acids
Acetic, Ammonium Fluoride, Chromic, Hydrochloric, Hydrofluoric, Nitric, Phosphoric, Sulfonic, Sulfuric, Aqua Regia ($HCl + HNO_3$), Buffered Oxide Etch - "BOE" ($HF + NH_4F$)

c. Caustics
Ammonia, Ammonium Hydroxide, Potassium Hydroxide, Sodium Hydroxide

d. Other Chemicals

i. Corrosives
Catechol, Dichlorosilane, Ethanol Amine, Ethylenediamine, Hydrogen Chloride, Hydrogen Fluoride, Silicon Tetrachloride, Silicone Tetrafluoride, Trichlorosilane

ii. Flammables
Hydrogen

iii. Inerts
Argon, Carbon Dioxide, Freons, Helium, Nitrogen

iv. Oxidizers
Ammonium Persulfate, Hydrogen Peroxide, Nitrous Oxide, Oxygen, Ozone

e. Metals
Aluminum, Antimony, Arsenic, Beryllium, Boron, Chromium, Gold, Lead, Mercury, Nickel, Phosphorus, Silver, Tantalum, Tin, Titanium, Tungsten, Vanadium

f. Dusts
Aluminum Oxide, Antimony, Asbestos, Polycrystalline Silicon, Silicon, Carbide, Single Crystal Silicon.

II. Dopants

a. Gas, Arsenic Pentafluoride, Arsenide, Boron Trichloride, Boron Trifluoride, Diborane, Phosphine, Phosphorous Pentafluoride

Table 16 (Cont)

b. Liquid Antimony Trichloride, Arsenic Trioxide + Solvent, Boron Tribromide, Boron Trioxide + Solvent, Silicon Tetrabromide, Phosphorus Oxychloride, Phosphorus Tribromide, Phosphorus Trichloride, Phosphorus Trioxide + Solvent, Triethyl Borate + Solvent

c. Solid Antimony Trioxide, Arsenic Trioxide, Boron Nitride, Boron Trioxide Phosphorus Pentoxide

d. Other Chemicals

   i. Pyrophorics, Diborane, Diphosphine, Silane

   ii. Toxics
   Ammonia, Antimony Trioxide, Arsenic Pentafluoride, Arsenic Trioxide, Arsine, Carbon Monoxide, Chlorine, Diborane, Phosgene, Phosphine, Phosphorus Pentoxide, Phosphorus Pentafluoride

Physical

a. Ionizing Radiation
Beta Scopes, E-Beam Evaporators, Ion Implanters, Krypton 85, Scanning Electron Microscope (SEM), Static Eliminators, Video Displays (CRT), X-ray Diffraction, X-ray Units

b. Non-ionizing Radiation
Cryogenic, Infrared, Laser, Radio Frequency (RF), Ultraviolet

c. Noise

IV. Ergonics and Psychological

Age, Biscopes and CRTs, Controlled Environment, Cultural, Intangibles, Language, Repetitive Tasks

V. Major Hazards

Emergency Response, Flammables, Gas Systems, Materials Handling, Protective Equipment, Training, Ventilation System, Waste Handling

8.5.1 Illness in the Semiconductor Industry[68]

To identify potential illnesses in the photovoltaics industry, health related experiences of the semiconductor industry were reviewed. An extensive search of the available literature revealed little information on occupational illness in the semiconductor industry but a few articles on the electronic industry were found.[70-72] Specifically a series of articles by Burge et al. on occupational asthma in a British electronics factory. In these articles, the authors surveyed workers by questionnaire, examined the records of employees leaving the industry, and finally investigated workers with occupational asthma to document some connection between the respiratory problems and the nature of the workplace environment. They found a significantly high level of respiratory disease. All workers investigated were sensitive to colophony fumes, a component of solder flux. A significantly greater proportion of shop-floor workers left the factory because of ill-health than store and office area employees, and the authors cite work-related respiratory disease as the main reason for the difference.

Another report explored the increased incidence of spontaneous abortions among women. A particularly high frequency of spontaneous abortion for women in the electronics industry was noted. These authors also indicated a possible connection to solder fumes, in particular resin (colophony) flux.[73]

While soldering is used to some extent in the semiconductor and photovoltaics industry and its hazards should be known, there are many other potentially dangerous processes, and the effects of long-term exposure to various chemicals need to be explored. There is a lack of literature in these areas.

Acute accidental exposure to hazardous chemicals and the unknown effects of long-term exposure probably pose the greatest health threat to workers in semiconductor manufacturing. The industry itself, however, believes that long-term exposure is not a problem; accidental exposure is the main threat but accidents are kept under control. This view is supported by the fact that the industry's record for safety is better than most. Another view is that, in general, no specific health problem exists for the industry. Little is known about chemical hazards, but traditional occupational health concerns (inhalation and accidents, for example) may not be as important as some of the less obvious problems, such as the tediousness of the work, the pressure to produce quality products, the relatively low-level of training of most workers, and the sometimes poorly designed machinery. All of these may lead to chronic health problems.[74-81]

As indicated in Table 17, California statistical data reveals an illness rate for SIC 3674 (semiconductor and related devices) more than four times higher than for all private industry. These figures have heightened concern for health in the industry. Much of the difference between these rates is, however, explained by the inclusion of acid burns in the illness data. The breakdown on reports of disease supports this; the bulk of worker's complaints consist of skin conditions, eye conditions, and chemical burns (all largely attributable to acids.) Similar problems are expected in photovoltaic fabrication facilities.

Other chemically caused problems often reported include; nausea, headaches, dizziness, respiratory problems, and liver and kidney problems. Another complaint includes eye strain from microscope work.[83-85]

Chemical hazards can exist at each basic step in production. The following are believed to be some of the most dangerous chemicals used: cadmium, arsenic, arsine, phosphine, tricloroethylene and boron.[74,76,81] Documented hazardous chemicals include solvents, acids, caustics, metals, gases, dusts and dopants in gas, liquid and solid form (see Table 16).

One important physical hazard is radiation, ionizing and non-ionizing. A National Institute for Occupational Safety and Health (NIOSH) Current Intelligence Bulletin, "Radiofrequency (RF) Sealers and Heaters: Potential Health Hazards and Their Prevention", identifies possible adverse health

Table 17
Illness Statistics for the Semiconductor Industry[82]

Measurement	SIC	Year 1978	Year 1979		
Occupational Injury and Illness Rates					
	3674[1]	9.1	8.0		
	367[2]	9.5	9.0		
	36[3]	8.3	8.0		
	Private Industry	10.5	10.6		
Occupational Illness Rates	3674	1.3	0.8		
	367	1.0	0.8		
	36	0.6	0.5		
	Private Industry	0.3	0.3		
		1976 Total	1976 Men	1976 Women	
Occupational Diseases[4]	36	15.1	12.0	20.7	
	Manufacturing	11.4	11.7	10.7	
		Total	Skin Conds.	Chem Burns	Eye Conds.
Type of Illness	36	3,686	1,063	843	1,047
	367	2,079	497	709	564

[1]3674-Semiconductors and related devices.
[2]367-Electronic components and accessories.
[3]36-Electrical and electronic machinery, equipment and supplies.
[4]Per 1,000 workers.

effects of non-ionizing radiation both thermal and non-thermal. Thermal effects result from deep heating of body tissue which may alter cells; nonthermal effects usually occur at lower exposure levels and with no measurable increase in body temperature. A "false sense of safety" may thus exist if workers do not notice a temperature rise in their body tissue.[86]

Though not much is known about RF effects on humans, results from animal studies indicate the possibility of changes in eyes, the central nervous system, reflex behavior, heart rate, the composition of blood, immunological response, and possibly reproductive hazards (teratogenicity). In recent monitoring surveys, NIOSH found most workers using RF sealers and heaters were exposed to levels greater than the units set by OSHA, sometimes up to ten times the OSHA standard.

New processes and materials are constantly being introduced in the semiconductor industry, and thus a potential exists for worker exposure to hazardous substances that have yet to be used or analyzed. Much more information is needed about possible hazards associated with dry-etching, plasma etching, x-ray lithography, and electron-beam lithography; all of these processes may also be used in photovoltaic cell fabrication.[87] Much information on specific chemicals and their hazards has been borrowed from experience in other industries; the peculiarities of the semiconductor industry and the possible extrapolation to the photovoltaics industry needs exploration in greater detail.

8.4.2 Deterministic Modeling

Since in-plant measurements of occupational exposures in the photovoltaic industry are not known, quantitative analysis of illness-related health risk must be analyzed by deterministic or hypothetical approaches. That is, if a worker is chronically exposed to a chemical at concentration X, the response magnitude is estimated to equal Y. Threshold Limiting Values (TLV)[67] used in combination with the dose-response models prevously described can be used to develop upper boundary estimates of response.

Based on this upper boundary analysis, TLV's for silicon and cadmium were used in combination with the different models described in section 7. Results of model analyses are summarized in Table 18. As indicated, chronic exposure to concentrations equal to the TLV's could produce significant health

Table 18
Occupational Health-Results of Deterministic Modeling

Pollutant	Mode	Estimated Exposure	Model	Type of Response	Model Results	Comments
Cadmium	Inhalation	500μg/m^3 TLV = 500μg/m^3	CAG	Prostate Cancer	1.24×10^{-2} Fatalities/Person Range= $0-1.32 \times 10^{-2}$	Resulting fatality rate = 1235 deaths/ 100,000 individuals Existing fatality rate for prostate cancer = 17.6/100,000[88]
Cadmium	Inhalation	1μg/m^3 10μg/m^3 20μg/m^3 40μg/m^3 TLV = 500μg/m^3	BNL	Cadmium Concentration in the Kidney.	130μg/g 200μg/g 350μg/g 600μg/g	Threshold for damage ranges from 150-300 μg/m^3
Silicon	Inhalation	110μg/m^3 TLV= 110μg/m^3	Harvard	Reduction in FVC	Cumulative lifetime exposure = 6.3 dust-years producing a decrease in FVC in 8% of the population	Relationship between a reduction in FVC and mortality and morbidity is not available

response. Prostatic cancers, for example, might well exceed the existing rate. Alternatively, chronic exposure to 40 μg/m^3 cadmium (~ 20% of the OSHA standard) could cause kidney burden levels to exceed expected thresholds by a factor of 2. Inhalation of silicon at exposures equal to the TLV could produce a reduction in forced vital capacity in 8% of the exposed population. The significance of this reduction in forced vital capacity in terms of mortality and morbidity is unknown. The likely exposures, of course, will be much lower than those modeled, but design engineers should nevertheless take note of these potential hazards. Actual measurements are needed to reduce this uncertainty.

9.0 Conclusion

Estimation of public and occupational health and safety risks for photovoltaic energy systems requires identification of photovoltaic systems and applications likely to be commercialized; processes that will be used to produce these devices; materials used in fabrication and waste by-products (gaseous, liquid and solid); public and occupational exposures to pollutants via different pathways; toxicologic, animal and epidemiologic data; and, model development and assembly. In this effort we have attempted to examine each of these different areas in some detail.

Based on this analysis, the following conclusions can be drawn:

(i) Engineering uncertainty is large. Risk estimation is most influenced by differences in photovoltaic cell efficiencies and expected operating lifetime. Other variables, including inverter efficiency, and cell failure rate, are less important.

(ii) The ability to describe accurately engineering and environmental characteristics of the emerging photovoltaics industry is hampered by the changing state of this industry and the relative scarcity of data for risk assessment.

(iii) Many potential photovoltaic cell types and design alternatives are envisioned. Each has different materials and processing requirements. Differences in these demands can influence the type and size of risk. Nevertheless, estimated differences in health cost are surprisingly small.

(iv) Systematic uncertainty introduced by the Reference Material System is small but presently being examined. Changes in process efficiencies can dramatically influence resulting outputs.

Modification of such outputs will affect estimates of emissions and size of occupational and public health risk.

(v) Emission estimates for material supply activities are very precise and probably accurate because they are largely based upon actual measurements. Emission coefficients for fabrication and disposal activities are hypothetically estimated because measurements are not available and are therefore highly uncertain.

(vi) Local-exposures from airborne pollutants are estimated for comparison with threshold-based health effects. These estimates for simple terrain are fairly accurate (± 2). Accuracy of the long-range transport models used to examine non-threshold related effects has not yet been defined. Locational uncertainty causes the estimated exposure ranges to increase by a factor of $\pm$ 6.

(vii) Estimated maximum annual average exposures to cadmium and silicon emitted throughout the photovoltaic energy cycle are well below existing background levels.

(viii) Estimating public health risk is complex and subject to the greatest uncertainty because of the large number of assumptions and models used.

(ix) Although the uncertainty range of public health risk estimates is large, possible public health effects imposed by the inhalation of cadmium and silicon emitted throughout the photovoltaic energy cycle are small.

(x) The largest public health risk of this energy system appears to be related to the release of air pollutants associated with fuel combustion and process emissions in the material supply cycles. These risks are not new, but instead allocated to the materials used in photovoltaic energy system production. Risks from other materials and processes specific to photovoltaic energy systems were not examined.

(xi) Risk from occupationl accidents are easily examined. Gross estimates of occupational risk, however, do not accurately portray health costs created by the energy system. Net estimates of risk based upon comparison with industry averages or competing energy technologies, provide better indication of the health costs imposed by the technology being studied. Net risks for photovoltaic energy systems when compared with industry averages appear to be small. Comparisons with competing energy sources have not yet been prepared.

(xii) Occupational exposure to toxic chemicals is of significant concern. Adequate acturial and epidemiological data are not available to determine accurately level of risk to the individual employed in this industry, in particular in photovoltaic cell fabrication. Use of deterministic models, however, suggests that limited compliance with existing TLV's will produce measurable health effects.

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Appendix A

Table A-1
Expected Morbidity Rates

Application/ Sector	Labor Demand (% of Total)[1]	Sector Morbidity Rate ($WDL/10^2$ MY)[2]	Expected Morbidity Rate ($WDL/10^2$ MY)[2]
Rooftop Shingle			
Mining	1.5	182	2.7
Manufacturing	60	74.8	45
Construction	38	101	38
Total	100		86
Rooftop Panel			
Mining	5.8	182	11
Manufacturing	52	74.8	39
Construction	42	101	42
Total	100		92
Ground-Based			
Mining	7.7	182	14
Manufacturing	77	74.8	58
Construction	15	101	15
Total	100		87

[1]Refers to labor required throughout the entire photovoltaic energy cycle. Data shown represent average values for median estimates.
[2]WDL = Worker Days Lost; MY = Man Year.

Table A-2 Expected Mortality Rates			
Application/ Sector	Labor Demand (% of Total)[1]	Sector Mortality Rate (Deaths/10^2 MY)[2]	Expected Mortality Rate (Deaths/10^2 MY)[2]
Rooftop Shingle			
Mining	1.5	0.060	0.0090
Manufacturing	60	0.0065	0.0039
Construction	38	0.029	0.011
Total	100		0.024
Rooftop Panel			
Mining	5.8	0.060	0.0035
Manufacturing	52	0.0065	0.0034
Construction	42	0.029	0.012
Total	100		0.019
Ground-Based			
Mining	7.7	0.060	0.0046
Manufacturing	77	0.0065	0.0050
Construction	15	0.029	0.0044
Total	100		0.014

[1]Refers to labor required throughout the entire photovoltaic energy cycle. Data shown represent average values for median estimates.
[2]MY = Man Years.

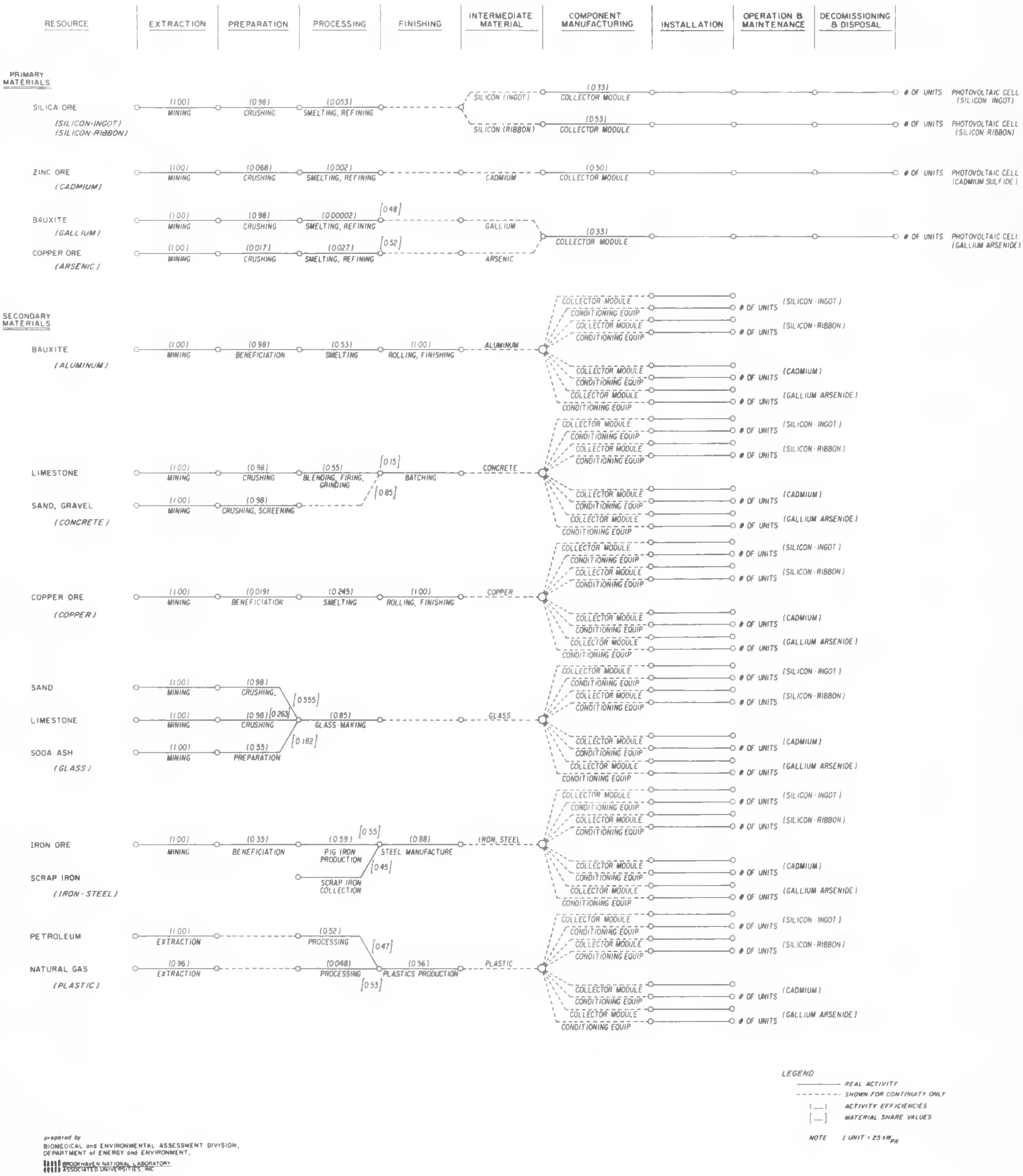

Figure A-1. Reference Material System network diagram.