Determining occupational health and safety risks posed by emerging technologies is difficult because of limited statistics. Nevertheless, estimates of such risks must be constructed to permit comparison of various technologies to identify the most attractive processes. One way to estimate risks is to use statistics on related industries. Based on process labor requirements and associated occupational health data, risks to workers and to society posed by an emerging technology can be calculated. Using data from the California semiconductor industry, this study applies a five-step occupational risk assessment procedure to four processes for the fabrication of photovoltaic cells. The validity of the occupational risk assessment method is discussed.

Methodology for an occupational risk assessment: an evaluation of four processes for the fabrication of photovoltaic cells

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introduction

The emergence of new technologies inevitably fosters the development of industries with novel and potentially dangerous environments for the work force. Recent interest in alternative energy systems has spurred the development of new and sophisticated technologies. Solar alternatives have attracted considerable interest, in part because of widespread public concern over health and environmental risks associated with competing energy technologies.

The photovoltaic industry is currently in its infancy. Full-scale production of photovoltaic cells will probably begin within the decade and use technology that is now only partially defined. The U.S. Department of Energy projects that photovoltaic systems will provide 0.1 to 1.0 quad (10^{15} Btu) of generating capacity by the year 2000.(1) This is expected to represent approximately 2 percent of U.S. energy needs, the equivalent of approximately 200 million barrels of oil per year. Although the exact technology that will provide the generating capacity is unknown, two processes for the fabrication of silicon cells and processes for the fabrication of cadmium sulfide and gallium arsenide cells have been identified as offering reasonable promise.(2)

Despite the public reputation of photovoltaic technology as a clean, hazard-free alternative to more traditional means of power generation, the industry poses some risks. Table I presents chemical and physical hazards that workers have confronted at research or pilot-plant facilities and may face at full-scale facilities.(3) A quantitative characterization of these hazards is difficult because no full-scale facilities have been built.

Determining occupational health and safety risks for emerging technologies is difficult because statistics on new industries are unavailable. Estimates of risk must nevertheless be constructed to permit comparison of alternative technologies. PEDCo Environmental, Inc., and the Biomedical and Environmental Assessment Division of Brookhaven National Laboratory have developed an occupational risk assessment (ORA) procedure to determine the disability and mortality rates associated with new technologies. This paper explains the ORA procedure and applies it to four photovoltaic production alternatives: silicon I, silicon II, cadmium sulfide, and gallium arsenide processes. The risks each process poses to workers and society are compared, and the validity of the ORA procedure is discussed.

methodology

The ORA procedure is based on the assumption that characteristic risks can be associated with specific occupations or occupational categories. Workers in a given occupation (*e.g.*, welders) are expected to confront similar hazards and to experience risks to their health and safety distinctly different from the risks experienced by workers in other occupations.

An industrial process requiring only one type of worker is assumed to pose hazards different in type and magnitude from those posed by a process requiring only another type of worker. An extreme example might be a process requiring only welders versus one requiring only engineers. A process requiring both welders and engineers would pose a collective risk somewhere between the higher risk to welders and the lower risk to engineers. According to the ORA procedure, the risk associated with this occupational mix depends on the ratio of welders to engineers.

The ORA procedure consists of the following steps:

1. Identification of process operations within a process
2. Identification of occupations involved with each process operation

TABLE I
Potential Chemical and Physical Hazards to Workers From Full-scale Production of Photovoltaic Cells[3]

Potential Chemical Hazards		Potential Physical Hazards
Acetic acid	Nickel[B]	Laser
Acetone	Nitric acid	Noise
Aluminum (powder)	Nitrogen dioxide	Ultraviolet light
Ammonia	Nitrogen	X-rays
Ammonium hydroxide	Nitrogen monoxide	RF radiation
Arsenic trioxide[A]	Ozone	
Beryllium[B]	Phosphorous oxychloride	
Boron hydride	Phosphine	
Boron trichloride	Polyethylene[E]	
Boron trifluoride	Silicon	
Cadmium[B,C]	Silicon carbide	
Cadmium chloride[B,C]	Silicon dioxide	
Cadmium sulfide	(amorphorous)	
Carbon monoxide	Silicon dioxide	
Carbon tetrafluoride	(crystalline)	
Chromium	Silicon hydride	
Copper	Silicon nitride	
Copper (II) chloride	Silicon tetrachloride	
Ethyl alcohol[C,D]	Silicon tetrafluoride	
Gallium arsenide	Silver[D]	
Gold[D]	Sodium hydroxide	
Hydrogen	Sodium hypophosphite	
Hydrogen bromide (anhydrous vapor and aqueous aerosol)	Sulfuric acid (anhydrous vapor and aqueous aerosol)	
Hydrogen cyanide	Thiourea[B]	
Hydrogen fluoride	Tin[D]	
(anhydrous vapor and	Tin (II) chloride	
aqueous aerosol)	Tin (II) oxide	
Hydrogen peroxide	Titanium dioxide[D]	
Isopropanol	Trichloroethylene[B]	
Lead	Urethane	
Magnesium	Vinyl acetate	
Methanol	Zinc chloride	

[A]Suspect human carcinogen.
[B]Positive animal carcinogen.
[C]Teratogenic in one or more animal species.
[D]Carcinogenic in one or more animal species.
[E]Neoplastic in one or more animal species.

3. Calculation of the labor requirement for each occupation to complete a given process operation
4. Calculation of disability and mortality rates and application of them to labor requirements
5. Summation of all occupational disability and mortality values by individual operation and by fabrication process

Steps 1 and 2 define the components of each process and establish the limits of the assessment effort. Steps 3, 4, and 5 quantify the risk associated with each occupation, each process operation, and each process.

The ORA procedure requires the separation of a process into components, or process operations. A process operation is defined as any activity that changes the product in some fundamental way, either by the addition or subtraction of material or by the physical transformation of the material

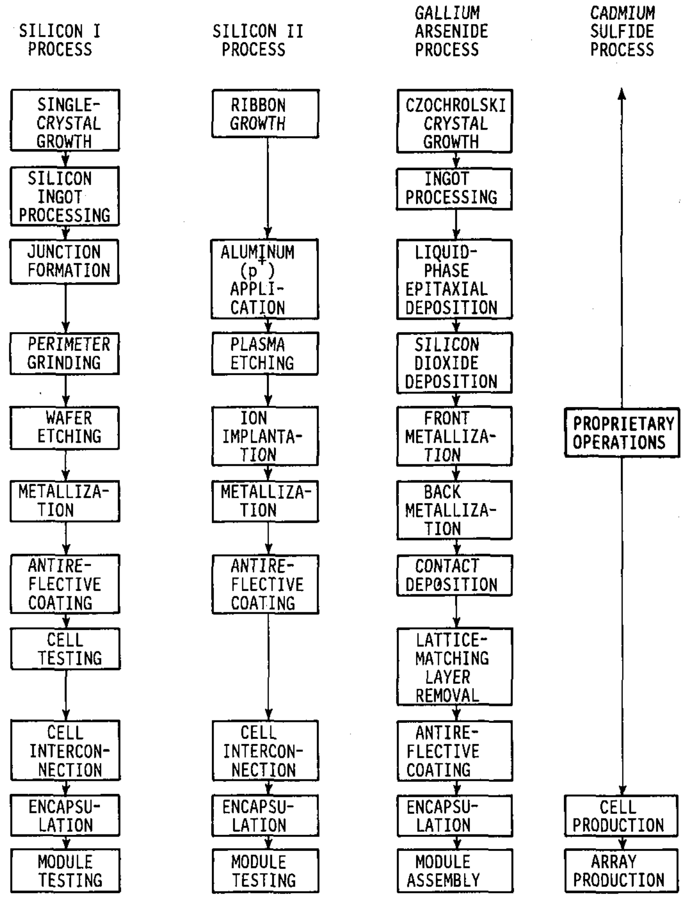

Figure 1 — Process operations associated with photovoltaic processes.

already in process. Discrete process operations can be identified by a thorough examination of a given process. A comprehensive review of the available literature on even the most recent industrial technologies will yield much process-related information. Data can also be obtained through contacts with process engineers. Figure 1 presents the dis-

TABLE II
Estimated Disability and Mortality Rates for the Photovoltaic Industry by Occupational Category[4]

Occupational Category	Disability Rate (lost workdays per 100 employee-years)	Mortality Rate (fatalities per 100 employee-years)
Material handling	169.6	9.4×10^{-3}
Metal plating	69.6	4.8×10^{-3}
Material abrading and polishing	39.6	Negligible
Assembling	45.6	2.4×10^{-3}
Inspecting	51.0	2.8×10^{-3}
Maintenance	64.6	2.6×10^{-3}
Technical	42.4	2.0×10^{-3}
Work not otherwise specified	47.0	2.6×10^{-3}

TABLE III
Detailed Results of Applying the ORA Procedure to the Silicon I Process

Process Operation	Occupational Category	Labor Requirement (employee-hours/yr)	No. of Lost Workdays per Occupational Category	No. of Fatalities per Occupational Category	No. of Lost Workdays per Process Operation	No. of Fatalities per Process Operation
Single-crystal growth	Technical	402 480	85.3	4.0×10^{-3}	116.6	5.47×10^{-3}
	Inspecting	56 160	14.3	7.9×10^{-4}		
	Maintenance	52 500	17.0	6.8×10^{-4}		
Silicon ingot processing	Material abrading and polishing	241 500	47.8	Negligible	101.9	2.43×10^{-3}
	Inspecting	56 160	14.3	7.9×10^{-4}		
	Metal plating	6000	2.1	1.4×10^{-4}		
	Maintenance	116 850	37.7	1.5×10^{-3}		
Junction formation	Technical	17 250	3.6	1.7×10^{-4}	6.1	2.8×10^{-4}
	Inspecting	2100	0.5	2.9×10^{-5}		
	Maintenance	6300	2.0	8.2×10^{-5}		
Perimeter grinding	Material abrading and polishing	13 800	2.7	Negligible	3.5	3.8×10^{-5}
	Technical	360	0.1	3.6×10^{-6}		
	Inspecting	1800	0.5	2.5×10^{-5}		
	Maintenance	720	0.2	9.4×10^{-6}		
Wafer etching	Metal plating	12 000	4.2	2.9×10^{-4}	5.3	3.4×10^{-4}
	Inspecting	900	0.2	1.3×10^{-5}		
	Maintenance	2700	0.9	3.5×10^{-5}		
Metallization	Metal plating	24 000	8.4	5.8×10^{-4}	9.0	6.0×10^{-4}
	Inspecting	240	0.1	3.4×10^{-6}		
	Maintenance	1440	0.5	1.9×10^{-5}		
Antireflective coating	Technical	42 000	8.9	4.2×10^{-4}	9.8	4.6×10^{-4}
	Inspecting	420	0.1	5.9×10^{-6}		
	Maintenance	2520	0.8	3.3×10^{-5}		
Cell testing	Assembling	114 000	26.0	1.4×10^{-3}	28.5	1.5×10^{-3}
	Inspecting	1140	0.3	1.6×10^{-5}		
	Maintenance	6840	2.2	8.9×10^{-5}		
Cell interconnection	Assembling	52 020	11.9	6.2×10^{-4}	18.0	8.9×10^{-4}
	Inspecting	7200	1.8	1.0×10^{-4}		
	Maintenance	13 200	4.3	1.7×10^{-4}		
Encapsulation	Assembling	102 000	23.2	1.2×10^{-3}	24.5	1.3×10^{-3}
	Inspecting	1200	0.3	1.7×10^{-5}		
	Maintenance	3000	1.0	3.9×10^{-5}		
Module testing	Inspecting	6060	1.5	7.0×10^{-5}	1.6	8.0×10^{-5}
	Maintenance	360	0.1	4.7×10^{-6}		
Total					324.8	1.3×10^{-2}

crete process operations associated with the four processes examined in this analysis.[4]

The second step in the procedure requires that an association be established between certain occupations and each process operation. These occupations can be identified through contact with manufacturers of production machinery. Information can be obtained on the education and training required of an individual to operate a given piece of equipment. Sales representatives can also indicate the level of supervisory or maintenance personnel required to ensure proper operation of the equipment.

The ORA procedure further analyzes each operation according to the labor requirement needed to effect the desired change in the product. This requirement is defined as the number of employee-years needed for a category of workers to achieve a specific level of throughput. In this analysis, we are concerned with the annual labor required to fabricate cells providing 100 MW of peak output. Machinery throughput and labor requirement are used to estimate the amount of equipment and number of workers required to obtain the desired annual rate of fabrication. The labor requirement in number of employee-hours per year is obtained by multiplying the number of workers by an annual work effort of 2000 hours. The total number of employee-

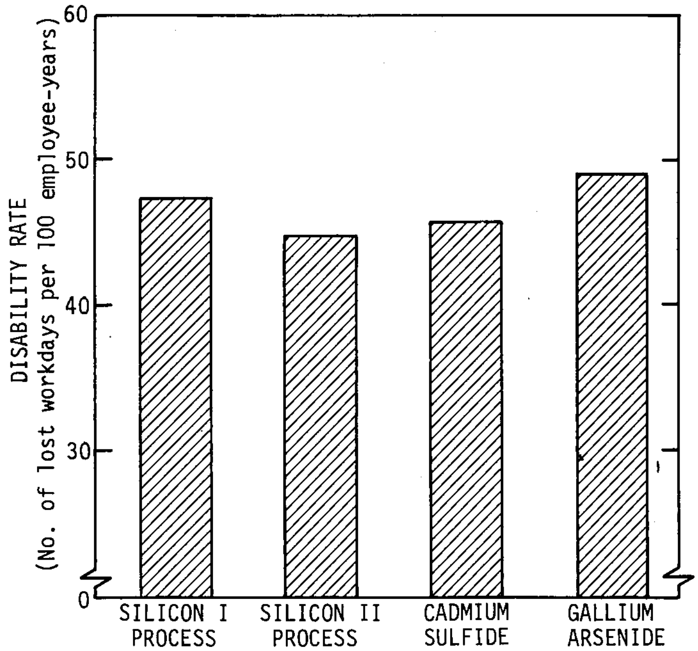

Figure 2 — Disability rates for photovoltaic workers.

hours worked is converted to 100 employee-years by dividing by 2.0×10^5.

After the identification of specific occupations and the calculation of labor requirements, representative health and safety statistics must be determined for each occupation. This step can present a major hurdle to the investigator. The governmental sources of statistical information and the representatives of various manufacturers may identify occupations by different names. Confusion can be avoided by aggregating specific occupations into broad occupational categories based upon their physical interaction with the fabrication process. For example, freight handlers, material handlers, and shipping and receiving clerks are all included in the material handling category, whereas dip platers and electroplaters are included in the metal plating category.

In the photovoltaic industry, eight occupational categories were identified: material handling, metal plating, material abrading and polishing, assembling, inspecting, maintenance, technical work, and work not otherwise specified. Each occupational category can include individuals with a wide range of education or training. It is their common interaction with the fabrication process that justifies their aggregation into a single category.

Disability and mortality rates characterizing occupations within specific industries are not available from the pool of published labor statistics. These rates, however, can be estimated from lost workday incidence data and from occupational employment figures.

The California Department of Industrial Relations participates in a Federal-State cooperative program that provides the public with occupational injury and illness data derived from State records on workmen's compensation. The program, known as the Supplementary Data System (SDS), is sponsored by the Bureau of Labor Statistics.[5] Data on occupational injury and illnesses from 24 states and the Virgin Islands are currently available through SDS. The State of California has the ability to perform computer-assisted retrieval and arrangement of the occupational statistics data. By use of the California retrieval system, data on the semiconductor industry were arranged according to the eight occupational categories.[6]

The California Employment Development Department provides estimates of employment by occupation for industries in the State.[7] These estimates were used along with figures on the incidence of lost workdays to construct disability and mortality rates for the eight occupational categories.[4]

Disability rates show the number of lost workdays resulting from both injury and illness per 100 employee-years. They were determined for occupational categories by use of Equation 1.

$$r_1 = \frac{C_1 w(2 \times 10^3)}{n} \quad (1)$$

where r_1 = disability rate, lost workdays per 100 employee-years

C_1 = number of total lost workday cases

w = average number of lost workdays per lost workday case

n = hundreds of employees

The total lost workday cases include both fatal and nonfatal incidences of lost workdays reported for each occupation. The results of applying Equation 1 to data on the California semiconductor industry are presented in Table II.

Mortality rates were determined for the eight occupational categories by use of Equation 2.

$$r_2 = \frac{C_2 w(2 \times 10^3)}{n} \quad (2)$$

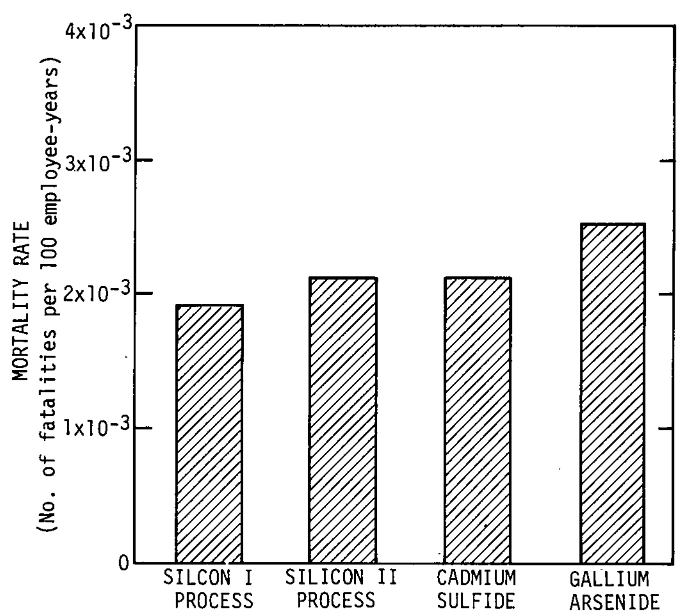

Figure 3 — Mortality rates for photovoltaic workers.

where r_2 = mortality rate, fatalities per 100 employee-years
C_2 = number of fatal lost workday cases
n = hundreds of employees

The cases of fatal lost workdays were determined as a percentage of the total lost workday cases reported for each occupation. The results of applying Equation 2 to data on the semiconductor industry are also presented in Table II.

The mathematical operation performed during the final steps of the procedure is presented in Equation 3.

$$R_a = \sum_{i=1}^{n} (r_n w_n) \quad (3)$$

where R_a = annual occupational risk for process a, lost workdays or fatalities
r_n = disability or mortality rate for occupation n, lost workdays or fatalities per 100 employee-years
w_n = labor requirement for occupation n, number of employee-years

Table III presents detailed results of applying the ORA procedure to the silicon I process. The silicon I process was selected as an example because it is the best defined and developed of the four fabrication technologies. The table shows operations associated with the fabrication process, occupational categories involved in each process operation, labor requirements, and estimated risk associated with each occupational category and process operation.

results

The ORA procedure was used to estimate both the average risk to process workers (lost workdays or fatalities per 100 employee-years) and the total risk to society (lost workdays or fatalities caused by fabrication of cells providing 100 MW of peak output per year) from fabrication of photovoltaic cells.

Figures 2 and 3 show that each process for the fabrication of photovoltaic cells poses roughly the same disability and mortality risks to workers. All the processes demand nearly identical occupational skills. The slight differences in risks are attributable to variations in the occupational mix required by each process.

Worker risk estimates resulting from application of the ORA procedure can be compared with state and national statistics on disability, *i.e.,* lost workdays in the electronics industry. Figure 4 presents disability rates for California and the Nation by each Standard Industrial Classification (SIC) in the U.S. Department of Labor's electronic components and accessories industry group.[8,9] It also presents the mean ORA estimate of the disability rate for a hypothetical

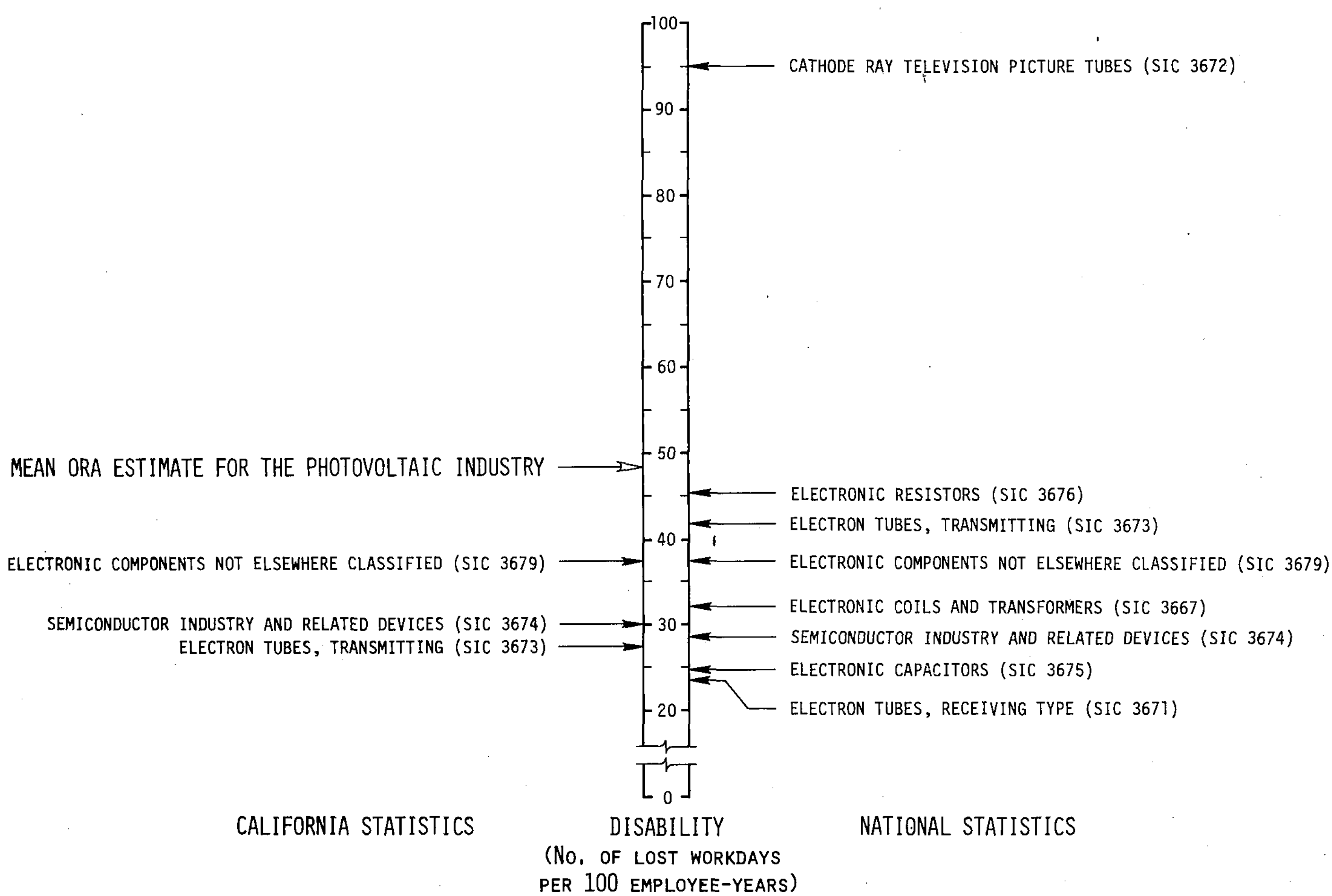

Figure 4 — Disability rates for electronics and photovoltaic workers.

photovoltaic industry based on proportionally equal representation from each of the four technologies. This estimate (48 lost workdays per 100 employee-years) is slightly greater than disability rates for most SIC's in the electronics industry.

Because health statistics are unavailable at the level of detail necessary to characterize the photovoltaic industry, the mean ORA estimate cannot be compared with an "expected" value. The disability rate for the semiconductor industry (SIC 3674), however, can be used as a surrogate "expected" value in assessing the relative validity of the ORA results. The use of this rate as a surrogate is appropriate because the photovoltaic industry constitutes a subset of the larger semiconductor industry and because the occupational health statistics used to calculate the ORA estimate were taken from data on the semiconductor industry.[6]

The mean ORA estimate is approximately 65 percent larger than the disability rate for the national semiconductor industry and 60 percent larger than the rate for the California industry. Given that the ORA procedure yields approximations and that the disability rate for the semiconductor industry is a surrogate "expected" value, the mean ORA estimate seems acceptable.

To assess the validity of the ORA estimates of mortality rates requires statistics on industry-related deaths. The most detailed information available, however, is on the total number of fatalities in the manufacturing sector of the national economy. In 1978, the annual average employment within this sector was 19 759 000, and 1170 deaths occurred.[8] Thus, the mortality rate was 5.9×10^{-3} deaths per 100 employee-years. The mean ORA estimate of the mortality in the hypothetical photovoltaic industry is 2.1×10^{-3} deaths per 100 employee-years, or approximately 36 percent of the overall value for manufacturing.

Societal risk is the burden associated with each technology or process and represents the occupational health and safety costs to society. Figures 5 and 6 present disability and mortality rates for society resulting from the four produc-

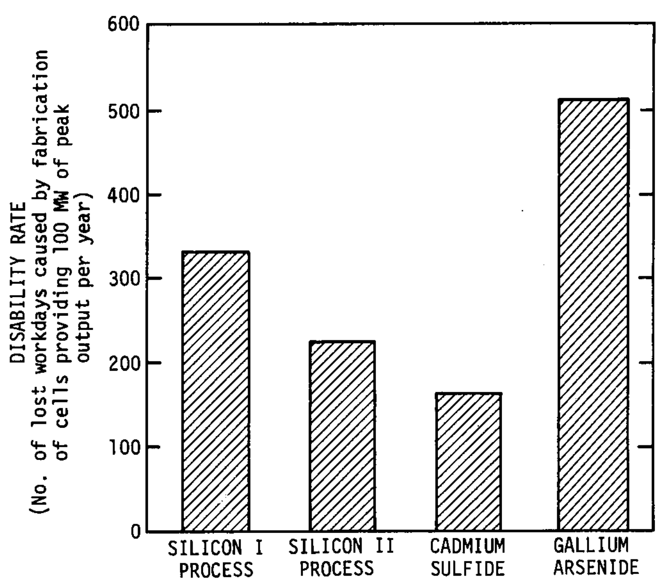

Figure 5 — Disability rates for society resulting from photovoltaic processes.

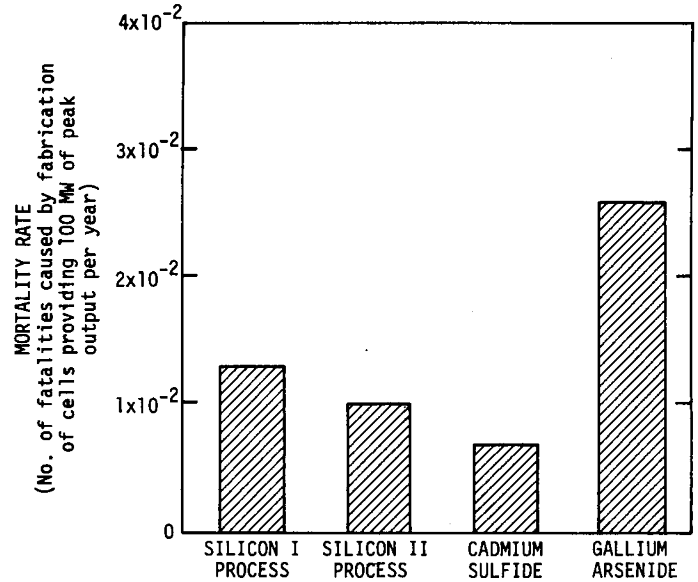

Figure 6 — Mortality rates for society resulting from photovoltaic processes.

tion processes. These figures suggest that the silicon II and cadmium sulfide processes pose less risk to society than the silicon I and gallium arsenide processes. The magnitude of societal risk depends on the mix of occupations required by a process and the labor requirements of a fabrication facility. As indicated by Figures 2 and 3, the risk to the average photovoltaic worker does not vary much among the processes. Significant differences in societal risk must therefore be attributable to the labor requirements of the processes. Indeed, sources indicate that the proposed silicon II and cadmium sulfide processes are more automated than the silicon I and gallium arsenide processes.[3,4]

discussion

As a general method of risk assessment the ORA procedure has both advantages and disadvantages. In specific applications the procedure depends heavily on the availability and quality of occupational health statistics and process labor requirements.

The major advantages of the procedure result from its ability to quantify the occupational risk associated with new production technologies. The assessment discussed in this paper identified the most attractive technology of a number of alternatives and determined occupational health costs to the workers and to society. In a similar fashion, the procedure might be used to assess various production alternatives within a single technology, to provide estimates of health risk to workers, and to assign various health costs to individual production alternatives. The latter application would allow design engineers and industrial hygienists to select production schemes that present the lowest risk to workers and smallest cost to industry.

The major disadvantages associated with the ORA procedure also result from the quantification effort. The procedure cannot account for hazards unique to new technologies because it relies on statistics of occupational exposures in established or related industries. In this assessment, for example, disability and mortality rates were constructed from data on the contemporary semiconductor industry. This industry is based primarily on silicon technology, which is only partially representative of the proposed alternatives.

The availability of health statistics for specific occupations within a given industry presents a major hurdle to the user of the ORA procedure. In this assessment, data from the California semiconductor industry were used to construct a single pair of health statistics for each occupation. In future efforts to characterize specific occupations, an attempt should be made to estimate variation as well as measurements of central tendency.

Good estimates of labor requirements are also required. No specific formula has been proposed to assure adequate estimates of process labor requirements. Instead of any specific methodology, a large, comprehensive effort to develop these figures is believed to be the best hedge against bad estimates.

Within the limitations stated, we believe the ORA procedure can be expected to produce useful estimates of occupational risk when applied to information of similar detail and reliability. We also believe that these estimates can be used to compare the risks that new technologies pose to workers and society.

acknowledgments

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