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A PROSPECTIVE METHOD FOR ESTIMATING OCCUPATIONAL HEALTH RISKS IN NEW ENERGY TECHNOLOGIES

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Abstract

In design, development, and acceptance of new energy technologies, concern for health and safety is increasingly important. Determining risks for emerging technologies is difficult because health statistics associated with these new alternatives are unavailable. Nevertheless boundaries on such risks must be determined to identify potentially significant hazards and to permit technology comparisons to be made. An approach to determining occupational health costs is to disaggregate labor requirements of an emerging industry by different worker classifications. Risks to workers can then be determined for these classifications from occupational health statistics of related industries. By summing risks for each worker classification, prospective estimates of individual and societal risk from an emerging technology can be developed. Although this approach identifies accident-related effects, it cannot be used to quantitate occupationally induced disease. An example of this method analyzing different photovoltaic fabrication alternatives is given. Individual vs. societal risk is considered in these analyses.

1.0 Introduction

In the design, development, and commercialization of new energy technologies, concern for health and safety is increasingly important. Prospectively defining types and levels of health problems that will confront a labor force in the production of energy can permit system-designers to minimize chemical, physical, and ergonomic stresses, and permit decision-makers to formulate wise and workable policies.

Estimation of risks from existing technologies is complex but somewhat amenable to analysis because of the ability to observe and measure actual working conditions. Determining risks for emerging technologies is more difficult because production facilities may not exist; only engineering estimates may be available. Nevertheless, commercial success may well be influenced by the perceived health risks likely to be imposed by new energy systems.

Health risks of these new energy systems must therefore be determined. Qualitative review, for example, of the types of chemicals used may permit some perspective, but quantitative estimates are needed. To develop quantitative estimates, one must use health experiences from other industries. This paper describes a method used to estimate quantitatively occupational risks of several photovoltaic fabrication alternatives. Although analyses are for a specific set of photovoltaic energy systems, the approach can be used to estimate some occupational health costs of other energy technologies.

2.0 Approach

Health statistics for new energy technologies may not be accurate or available because of the limited or unique modes of operation of pilot and demonstration facilities. In lieu of obtaining reliable statistics from these facilities, health risks may be estimated by dissaggregating the labor requirements of an emerging industry into different worker classifications. Risks for these classifications can than be defined from occupational health statistics from related industries. By summing risks among all worker classifications, prospective estimates of occupational risk for new technologies can be made.

Estimation of risk by this method requires: (1) identification of process operations in production of the energy form; (ii) identification of occupational categories in each process operation; (iii) estimates of labor requirements for each process; and (iv) estimates of mortality and morbidity rates by occupational category. Specification of a network structure and items (i) to (iv) suffice to generate quantitative estimates of some occupational health and safety risks in commercialization of a new energy technology. Other risks, such as those from occupational exposure to toxic chemicals must be evaluated using dosimetry and dose-response models.

2.1 Process Identification

In the early stages of development of any energy system, engineering studies are prepared defining the discrete production steps in a particular technology. Process information, developed by system-designers, generally requires supplementation from the literature for health assessment. Processes should preferably be disaggregated to their lowest common denominator. Figure 1 is an example for production of a photovoltaic energy system. As noted, process descriptions may begin with production of the active portion of the solar cell and end with testing and shipping of the completed device.[5,6] Although all these steps will likely be within the confines of a single facility, the approach need not be constrained by this physical boundary.

2.2 Occupational Categories

After all process steps are defined, work-station labor requirements must be identified through contact with manufacturers of production machinery and simultaneous discussion with system-designers. More than one occupational skill may be required at any single work-station (e.g. operators and maintenance personnel). The level of disaggregation must ultimately correspond with labor demand and occupational health coefficients. Confusion can be avoided by aggregating specific occupations into occupational categories based on their physical interaction with the production process. Freight handlers, material handlers, and shipping and receiving clerks, for example, can all be included in the materials handling category. Other suggested aggregations are described elsewhere.[6] Table 1 shows the occupational categories used to estimate risks from photovoltaic fabrication facilities.[5,6]

2.3 Labor Demands

Estimates of annual labor demand by process and occupational category are needed to determine the size of the workforce at risk. Similar to the process descriptions, these data are generally developed during the design engineering stage. Levels of disaggregation of these data must correspond with constraints imposed by health statistics and occupational category assignments. Table 2 gives labor requirements for the processes described in Figure 1.[5,6]

2.4 Health Coefficients

The final information required is estimates of occupational mortality (fatalities/man-year) and morbidity (worker-days lost/man-year) by occupational category. Although Federal and state agencies publish actuarial statistics by 2, 3, and 4 digit standard industrial classification (SIC) codes,[1-3] disaggregations by industry/occupational category are not generally available. In California, however, health data collected by the California Department of Industrial Relations can be combined with employment data collected by the California Employment Development Department to produce health incidence statistics specific to different occupations.[6]

The data developed for estimating risks from photovoltaic energy systems are given in Table 3. These data were derived from statistics collected for the semiconductor industry. They serve as a particularly good surrogate for assessment of photovoltaic energy systems because of the similarities in production requirements. Efforts are currently underway at the Biomedical and Environmental Assessment Division, Brookhaven National Laboratory to prepare similar estimates for a larger number of occupational categories and industries.

2.5 Risk Estimation

Estimates of health risk in production of an energy system are ultimately developed by summing the product of labor demand times risk per unit of labor for all occupational categories and processes. This can be expressed by the equation:

$$R_t = \sum_{i=1}^{n} (l_n r_n)$$

where

R_t = Total risk measured by fatalities or worker-days lost,

l_n = Labor required for occupational category n,

r_n = Risk (e.g. worker-days lost/man-year) for occupational category n.

3.0 Discussion

Table 4 gives results of quantifying a network with the data from Tables 1-3. Figures 2 and 3 summarize of results for other photovoltaic alternatives examined and described elsewhere.[5] Examination of risks to individuals, to society and among competing alternatives gives useful insights.[4]

Risk to individuals (e.g. worker-days lost/man-year) estimates the frequency and severity of a worker being injured on the job. Estimates of individual risk vary both by occupational category and by industry. Results from this analysis suggest that risks to workers in photovoltaic fabrication facilities equals ~50 worker-days lost/100 man-year and ~0.002 fatalities/100 man-year. By comparison individual morbidity risk in the semiconductor (SIC 3674), electronics (SIC 36) and private manufacturing sectors, are 39, 49, and 96, respectively.[1,3,5,6] The mortality rate for all manufacturing is 0.006 fatalities/100 man-year.[1] Disaggregations by 4 digit SIC codes are not generally listed. Estimated risk in photovoltaic fabrication facilities thus appears to be somewhat larger than in related industries, but below that for manufacturing as a whole. Differences between photovoltaic fabrication and semiconductor risk estimates, may relate to expected mix of occupational skills required for photovoltaic cell manufacture or to uncertainties in input assumptions. Figure 4 compares projected morbidity risks to individuals in the photovoltaics industry with risks in other energy industries.[1,3,5,6]

Societal risk measures the health burden related to the production of any technology. This risk is calculated simply by multiplying risk per individual by the size of the workforce.[4] This approach may not adequately measure net occupational risk. As shown in Figures 2 and 3, societal risks related to the production of different photovoltaic devices vary by a factor of ~2. Although each technology may produce equivalent quantities of energy, societal costs may nevertheless vary. Results are most sensitive to differences in total labor demand since individual risk is relatively constant.

Risks within the photovoltaic industry must be compared with competing alternatives to determine the relative or net costs and benefits for inter-technology comparisons.[4] Table 5 shows individual and societal risks for coal mining and fabrication of photovoltaic energy systems. Individual risks for underground coal mining are much greater than those expected in the photovoltaics industry - 352 vs. 50 WDL/100 man-year. Risks to society are somewhat different. Societal health costs are about equal for surface mining and photovoltaics, and about an order of magnitude greater for underground coal mining than for photovoltaic cell manufacturing.

Similarities and differences in societal health costs relate to the labor intensity of the process as well as to individual risk. As shown, it is feasible to develop alternatives that have lower individual risk but greater societal cost.

4.0 Conclusion

This approach is a useful method for estimating risks in new and emerging energy technologies quantitatively. The accuracy of the estimates depends upon the quality of the input assumptions and availability of health statistics from related industries and occupational settings. While this method cannot describe illness-related health problems adequately, it provides a reasonable way to estimate accident-related health and safety risks quantitatively.

5.0 Acknowledgement

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Table 1
Occupational Descriptions for the California Semiconductor Industry[5,6]

Occupational Category	Source: California Department of Industrial Relations — Occupational Classes (code)	Source: California Employment Development Department — Occupational Descriptions
Material handling	Shipping and receiving clerks (374) Freight and material handlers (753)	Shipping and receiving clerks Shipping packers Production packers Order fillers
Metal plating	Metal platers (635)	Dip platers Electroplaters
Material abrading and polishing	Filters, polishers, sanders and buffers (621) Grinding machine operatives (651)	Filers, grinders, buffers Grinding and abrading machine operators Gear cutting and grinding machine operators
Assembling	Assemblers (602)	Electrical and electronic assemblers – Class A – Class B Electro-mechanical assemblers – Class A – Class B Encapsulators Instrument makers – Class A – Class B All other assemblers – Class B – Class C
Inspecting	Checkers, examiners, and inspectors (610)	Inspectors Supervisors Testers
Maintenance	Electricians and electrician apprentices (430, 431) Sheet metal workers, tinsmiths and apprentices (535, 536) Plumbers, pipefitters and apprentices (522, 523) Air conditioning, heating and refrigeration mechanics, and repairmen (470) Miscellaneous mechanics and repairmen (492) Mechanics and repairmen not specified elsewhere (495)	Electricians Helpers Instrument mechanics Maintenance repairmen and general utility Mechanic, maintenance Sheet metal workers Millwrights All other mechanics and repairmen
Technical	Electrical and electronic technicians (153) Mechanical engineering technicians (155) Engineering and scientific technicians (162) Chemical technicians (151) Technicians not specified elsewhere (173)	Electrical and electronic technicians Mechanical engineering technicians Scientific technicians All other engineering technicians All other technicians
Occupations not specified	–	–
All occupations	All workers	All occupations

Table 2
Labor Requirements by Process and Occupational Category (Per 100 MW Plant)[6]

Process Operation	Occupational Category	Labor Requirement (man-hours/yr)
Single-crystal growth	Technical	402,480
	Inspecting	56,160
	Maintenance	52,500
Silicon ingot processing	Material abrading and polishing	241,500
	Inspecting	56,160
	Metal plating	6,000
	Maintenance	116,850
Junction formation	Technical	17,250
	Inspecting	2,100
	Maintenance	6,300
Perimeter grinding	Material abrading and polishing	13,800
	Technical	360
	Inspecting	1,800
	Maintenace	720
Wafer etching	Metal plating	12,000
	Inspecting	900
	Maintenance	2,700
Metallization	Metal plating	24,000
	Inspecting	240
	Maintenance	1,440
Antireflective coating	Technical	42,000
	Inspecting	420
	Maintenance	2,520
Cell testing	Assembling	114,000
	Inspecting	1,140
	Maintenance	6,840
Cell interconnection	Assembling	52,020
	Inspecting	7,200
	Maintenance	13,200
Encapsulation	Assembling	102,000
	Inspecting	1,200
	Maintenance	3,000
Module testing	Inspecting	6,060
	Maintenance	360
Total		1,367,220

Table 3
Estimated Disability and Mortality
Rates for the Photovoltaic Industry by Occupational Category[6]

Occupational Category	Disability Rate[a]	Mortality Rate[b]
Material handling	169.6	9.4×10^{-3}
Metal plating	69.6	4.8×10^{-3}
Material abrading and polishing	39.6	–
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}

a = Worker-days lost/100 man-year.
b = Fatalities/100 man-year.

Table 4
Estimated Worker-days Lost and Fatalities (Per 100 MW Plant)[6]

Process Operation	Occupational Category	No. of Worker-days Lost per Occupational Category	No. of Worker-days Lost per Process Operations	No. of Fatalities per Occupational Category	No. of Fatalities per Process Operation
Single-crystal growth	Technical	85.3	116.6	4.0×10^{-3}	5.5×10^{-3}
	Inspecting	14.3		7.9×10^{-4}	
	Maintenance	17.0		6.8×10^{-4}	
Silicon ingot processing	Material abrading and polishing	47.8	101.9	–	2.43×10^{-3}
	Inspecting	14.3		7.9×10^{-4}	
	Metal plating	2.1		1.4×10^{-4}	
	Maintenance	37.7		1.5×10^{-3}	
Junction formation	Technical	3.6	6.1	1.7×10^{-4}	2.8×10^{-4}
	Inspecting	0.5		2.9×10^{-5}	
	Maintenance	2.0		8.2×10^{-5}	
Perimeter grinding	Material abrading and polishing	2.7	3.5	–	3.8×10^{-5}
	Technical	0.1		3.6×10^{-6}	
	Inspecting	0.5		2.5×10^{-5}	
	Maintenance	0.2		9.4×10^{-6}	
Wafer etching	Metal plating	4.2	5.3	2.9×10^{-4}	3.4×10^{-4}
	Inspecting	0.2		1.3×10^{-5}	
	Maintenance	0.9		3.5×10^{-5}	
Metallization	Metal plating	8.4	9.0	5.8×10^{-4}	6.0×10^{-4}
	Inspecting	0.1		3.4×10^{-6}	
	Maintenance	0.5		1.9×10^{-5}	
Antireflective coating	Technical	8.9	9.8	4.2×10^{-4}	4.6×10^{-4}
	Inspecting	0.1		5.9×10^{-6}	
	Maintenance	0.8		3.3×10^{-5}	
Cell testing	Assembling	26.0	28.5	1.4×10^{-3}	1.5×10^{-3}
	Inspecting	0.3		1.6×10^{-5}	
	Maintenance	2.2		8.9×10^{-5}	
Cell interconnection	Assembling	11.9	18.0	6.2×10^{-4}	8.9×10^{-4}
	Inspecting	1.8		1.0×10^{-4}	
	Maintenance	4.3		1.7×10^{-4}	
Encapsulation	Assembling	23.2	24.5	1.2×10^{-3}	1.3×10^{-3}
	Inspecting	0.3		1.7×10^{-5}	
	Maintenance	1.0		3.9×10^{-5}	
Module testing	Inspecting	1.5	1.6	7.0×10^{-5}	8.0×10^{-5}
	Maintenance	0.1		4.7×10^{-6}	
Total		324.8	324.8	1.3×10^{-2}	1.3×10^{-2}

Table 5
Comparative Occupational Health and Safety Risks[4]

Technology/ Activity	Total Labor (10^2MY)	Health and Safety Incidence Rates: Accidents (WDL/10^2MY)[a]	Health and Safety Incidence Rates: Fatalities (Deaths/10^2MY)	Health and Safety Impacts: Accidents (WDL/10^{12}Btu)	Health and Safety Impacts: Fatalities (Deaths/10^{12} Btu)
Photovoltaic - silicon n/p cell mfg.	3.6×10^{-1}	47.5	0.002	1.8×10^{1}	7.4×10^{-4}
Photovoltaic - silicon MIS cell mfg.	2.7×10^{-1}	44.9	0.002	1.2×10^{1}	5.7×10^{-4}
Photovoltaic - cadmium sulfide backwall cell mfg.	1.7×10^{-1}	45.8	0.002	9.1×10^{0}	3.4×10^{-4}
Photovoltaic - gallium arsenide cell mfg.	5.7×10^{-1}	49.2	0.002	2.9×10^{1}	1.6×10^{-3}
Coal mining - surface	1.8×10^{-1}	117	0.02	2.1×10^{1}	3.6×10^{-3}
Coal mining - underground	6.3×10^{-1}	352	0.08	2.2×10^{2}	5.0×10^{-2}

[a]WDL/10^2 MY = Worker-days Lost/100 man-year.

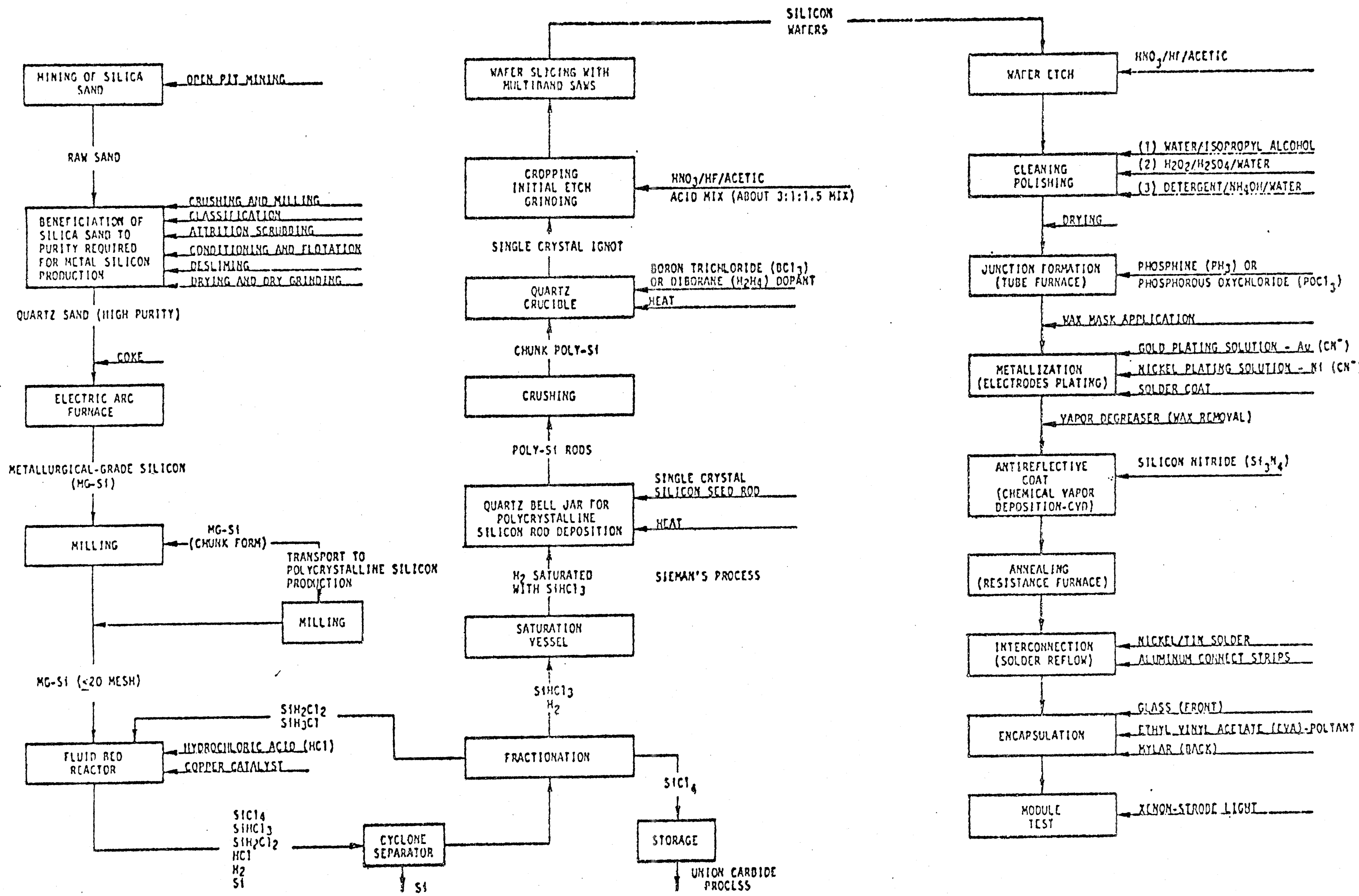

Figure 1. Process descriptions.

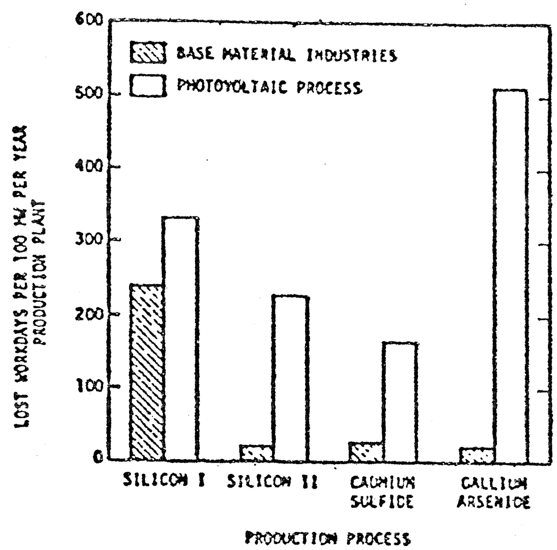

Figure 2a. Total number of workdays lost for four 100-MW per year photovoltaic cell production processes - societal lost workday risks.

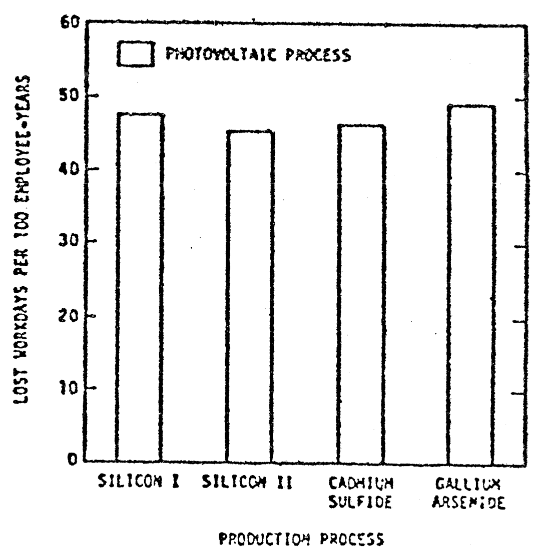

Figure 2b. Workdays lost per 100 employee-years for the photovoltaic cell production processes - worker lost workday risks.

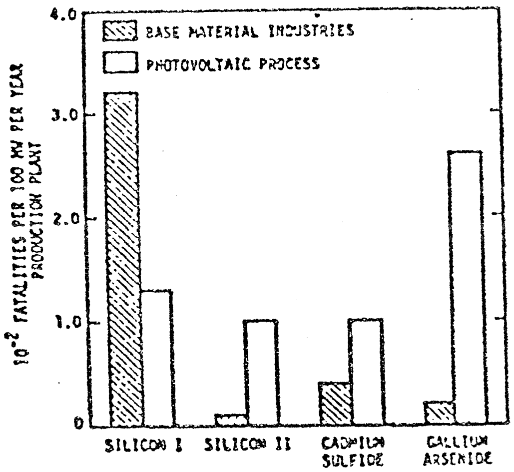

Figure 3a. Total number of fatalities for four 100 MW per year photovoltaic cell production processes - societal fatality risks.

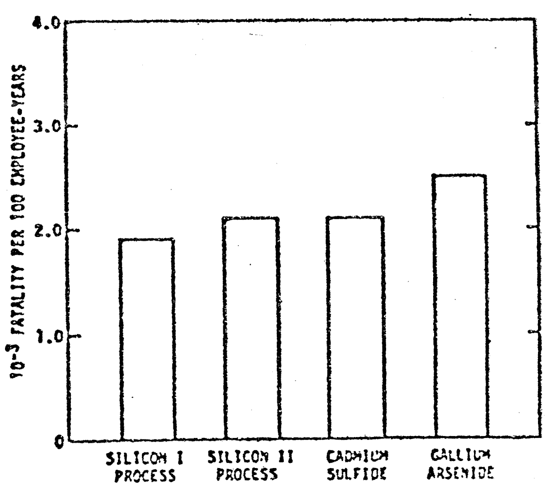

Figure 3b. Fatalities per 100 employee-years for the photovoltaic cell production processes - worker fatality risks.

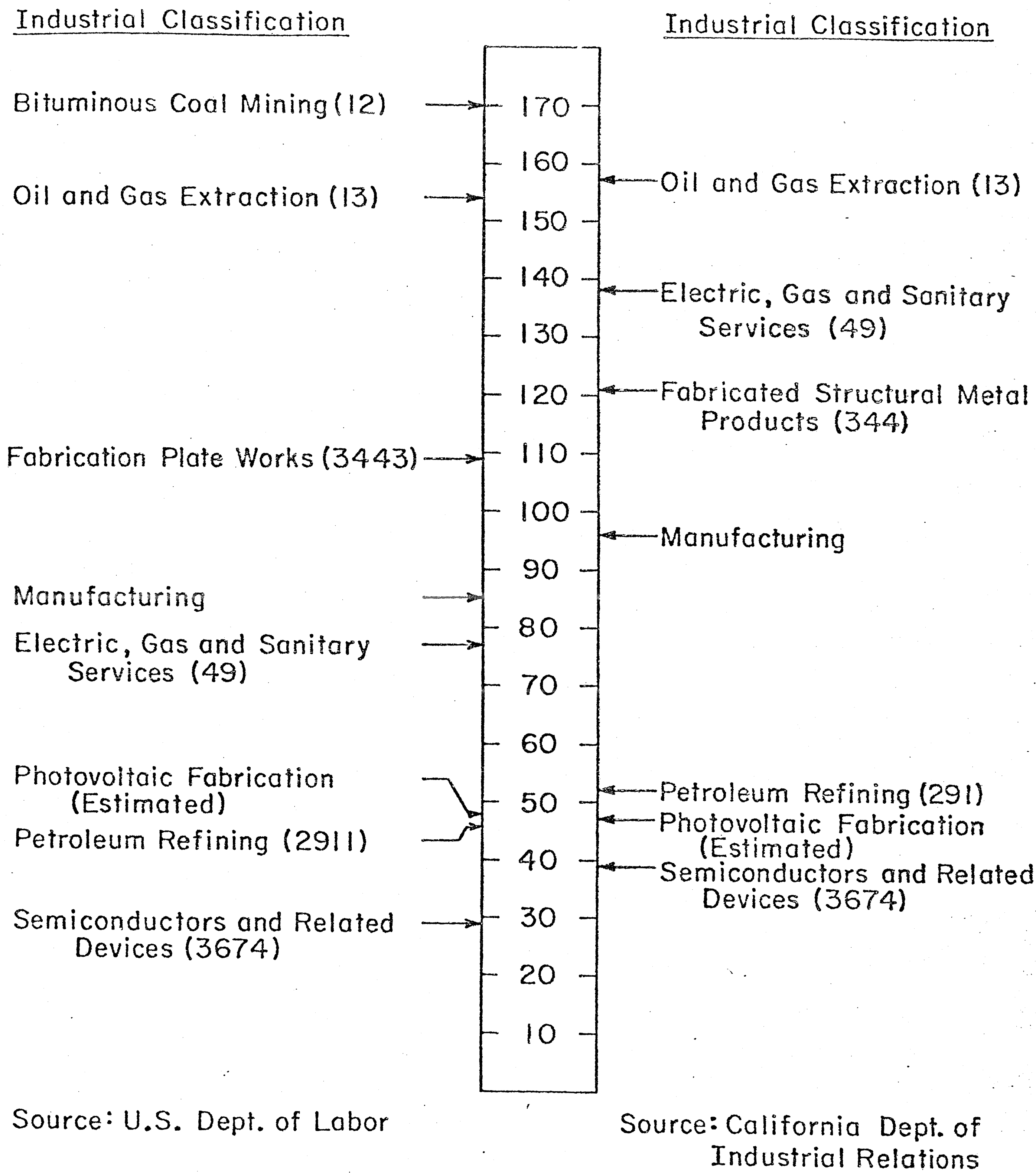

Figure 4. Comparison of disability rates among different data bases and industrial classifications.