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# Exposure Assessment for Retrospective Follow-Up Studies of Semiconductor- and Storage Device-Manufacturing Workers

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## Learning Objectives

- Describe how exposure assessments were used to assign each employee to one of 34 work groups in a large population of workers at facilities manufacturing semiconductors and storage devices, both elements of the microelectronics industry.
- Explain how distinguishing between manufacturing eras can aid analyses of cancer incidence and mortality.
- Outline the role of agent matrices in detecting differences in potential exposures between different work groups.

## Abstract

***Objective:*** *This exposure assessment was conducted in the first large study of mortality and cancer incidence in semiconductor and storage device manufacturing.* ***Methods:*** *Unique combinations of division, department and job codes and names (DDJ) from work history records were assigned to work groups and exposure categories. Agent exposure matrices assessed differences in potential exposures between groups. Changes in exposure over time were tracked by dividing the production history into manufacturing eras.* ***Results:*** *Nineteen work groups were developed to capture 310,351 unique DDJs from 1965–1999. Agent exposure matrices contrasted exposure potential to solvents, metals, and work in cleanrooms between groups, and three manufacturing eras were identified for each site.* ***Conclusions:*** *The work groups, manufacturing eras and agent matrices have been used to classify workers in the study of cancer incidence and mortality.* (J Occup Environ Med. *2005;47:983–995*)

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This exposure assessment was conducted as part of the first large study of mortality and cancer incidence in the semiconductor- and storage device-manufacturing sectors in the microelectronics industry. The study evaluated mortality among 126,836 employees in International Business Machine's (IBM) semiconductor-manufacturing facilities in East Fishkill, New York (NY), and Burlington, Vermont (VT), and storage product device-manufacturing facility in San Jose, California (CA).[1] The study also evaluated cancer incidence among 89,054 employees at the East Fishkill and the San Jose facilities. These two semiconductor-manufacturing facilities and the storage device-manufacturing facility essentially comprise the entire US manufacturing capacity of IBM. The purpose was to determine whether mortality or cancer incidence was related to employment in any of the three facilities or in groups with particular work activities.

In most retrospective studies of occupational populations, actual exposure measurements of individual employees are rare before the mid-1970s. When they are available, they often are limited to specific subjects or specific groups of subjects. In addition, measurements may have been made intermittently and may not be representative of the entire time period covered by the study. Consequently, qualitative and categorical exposure classifications frequently are undertaken, based upon knowledge of factors that were determinants of po-

tential exposure, including production processes, job titles and relation to locations and job tasks, exposure controls, factors such as ventilation (ie, HVAC) systems, and information on changes in these factors over the time period of interest.

The exposure assessment for this study involved classifying the workers employed during the period from 1965 through 1999. The goal of the exposure assessment was to assign each subject to a workgroup in such a way that differences in exposure within the workgroup are minimized, and to maximize the contrast of exposures between workgroups. Because production processes change, sometimes rapidly, a supporting goal was to identify "manufacturing eras," which were periods of time during which factors, such as production processes, exposures, exposure controls and employee work practices, were relatively constant.

## Description of Facilities

### East Fishkill, NY

The East Fishkill facility has been in operation since 1963 on a 450-acre site in the Hudson River valley approximately 70 miles from New York City. Products manufactured included solid logic technology (SLT) devices and metallized ceramic packaging. SLT manufacturing produced 1.3-inch wafers and had begun developing 1.5-inch wafers by 1967. Over the period of this study, waste disposal and wafer and chemical handling became more automated, enclosure of process units and gas supply lines increased substantially, and there were significant improvements in both the type and quantity of personal protective equipment worn by the workers. A chronology of changes is presented in Table 1.

The East Fishkill facility has always had dual roles as a production and as a development facility. Technology developed at East Fishkill migrated to other manufacturing locations, including the Burlington and San Jose facilities.

### Burlington, VT

The Burlington facility opened in February 1957 in Essex Junction, Chittenden County, VT. The Burlington operation began by developing wire

**TABLE 1**
Manufacturing Eras and Associated Characteristics for East Fishkill

| Identifying Factors | 1963–1973 | 1974–1983 | 1984–1999 |
|---|---|---|---|
| Manual application of chemicals, eg., photoresist | All | Some | R&D only |
| Manual dipping of wafers in chemical baths | All | Some | None |
| Manual refilling of chemicals in tools | All | Some | None to rare |
| Manual delivery of chemicals to the Fab | All | Some | None |
| Manual pushing and pulling of wafers | All | Some | None |
| Manual collection and removal of wastes from the Fab | All | Some | None or very little |
| Manual cleaning of metal deposition equipment | All | Some | Curtains used |
| Enclosures of piping systems at rear of furnaces | None | Some | All |
| Enclosures of toxic gas lines | None | Some | Selected gases |
| Toxic gas monitoring | None | Some | Selected gases |
| Excess flow control valves on toxic gases | None | None | Selected gases |
| Type of smock used in clean rooms | Lab coat/hair net | Full length/hood/boots | Single, double suits most common |
| PPE: gloves 100% inspected for pin holes by manufacturer | None | Some | Full implementation |
| Most common types of hoods | Dexon + CEPS | CEPS | CEPS + SCP + FSI + IAS + CFM + Steag |
| Plenum ventilation of Fab (through core area) | All plenum | Floor & plenum | Floor & plenum |
| Ethyl or methyl series glycol ethers (or acetates) | Yes | Yes | Phased out (~1992) |
| Known Carcinogens used | Yes | Yes | Yes |
| Building or fire codes for semiconductor plants | No | Codes under development | Yes |
| Junction formation | Diffusion | Diffusion & some ion implant | Ion implant very limited diffusion |
| Type of photoresist | Negative | Negative and positive | Negative & positive, predominantly positive |
| Etching and photoresist removal | Wet | Wet and Dry | Dry (very limited wet) |
| Wafer size | <3.25" | 3.25"–5" | 5"–12" |
| Device geometry | >5 μm | 1–5 μm | <1 μm |
| Clean room class | 10k–100k | 100–10k | 1–100 |

contact relays. The first product manufactured at the facility was a wire contact relay switch. In 1962, bipolar or SLT developed one-transistor chips for read-only storage capabilities. Semiconductor manufacturing has been the primary activity at the Burlington facility since its opening.

Similar to East Fishkill, wafer size increased during the study period, the process became more automated and the class of cleanroom necessary to produce the products became lower and lower (fewer and fewer airborne particles). The same general pattern of process enclosure, containment of chemical delivery systems, and personal protective equipment observed at East Fishkill occurred at Burlington. The chronology of changes at Burlington is summarized in Table 2. At the time of this study, there were three components of semiconductor manufacturing at Burlington: a mask house (opened in 1965), two semiconductor fabricators (in Burlington 970 and 973), and back-end-of-line operations, which are manufacturing activities associated with packaging. The Burlington facility is 3.2 million square-feet and is located on a 725-acre site.

## San Jose, CA

The San Jose operation began in 1956 in San Jose, Santa Clara County, California. The primary activities of the facility have been the development, manufacture, and packaging of storage product devices such as hard disk drives, network servers, magnetic tape drives and, more recently, microdrives. This site develops, manufactures and markets storage components (thin film magnetic recording heads and thin film storage disks) and systems (disk drives).

The original facilities on the site were devoted to the production of 14-inch and 10-inch disk drives. A new type of recording/reading head called a "thin film head" began to be produced in 1979. In the 1990s a variety of disk materials and disk

**TABLE 2**
Manufacturing Eras and Associated Characteristics for Burlington

| Identifying Factors | 1962–1973 | 1974–1988 | 1989–1999 |
|---|---|---|---|
| Manual application of chemicals, e.g., photoresist | Yes | Some | None |
| Manual dipping of wafers in chemical baths | All | Some | Some, but limited |
| Manual refilling of chemicals in tools | All | Some | None to rare |
| Manual delivery of chemicals to the Fab | All | Some | Bulk from mid-1980s |
| Manual pushing and pulling of wafers | All | Some | None |
| Manual collection and removal of wastes from the Fab | All | Most till mid 1980s | None to rare |
| Manual cleaning of metal deposition equipment | All | Until 1983 | Outsourced to vendor |
| Enclosures of piping systems at rear of furnaces | None | Some, All from early 1980s on | All |
| Enclosures of toxic gas lines | None | Some | Selected gases |
| Toxic gas monitoring | None | Some | Selected gases |
| Excess flow control valves on toxic gases | None | Some | Selected gases |
| Type of smock used in clean room | Lab coat | Full length/hood/boots | Full enclosure (double suits) |
| PPE: gloves 100% inspected for pinholes by manufacturer | None | Yes, from mid-1980s on | Yes |
| Most common type of hood | Dexon | Dexon and CEPS | Dexon and CEPS |
| Plenum ventilation of Fab (through core area) | All plenum | Floor & plenum | Floor and plenum |
| Ethyl or methyl series glycol ethers (or acetates) | Yes | Yes | Phased out 1992 |
| Known carcinogens used | Yes | Yes | Yes |
| Building or fire codes for semiconductor plants | None | Mid 80's on | Yes |
| Junction formation | Diffusion | Diffusion and ion implant | Ion implant |
| Type of photoresist | Positive and negative | Positive and negative | Negative, positive, mostly positive |
| Etching and photoresist removal | Wet | Wet and dry | Wet and dry, mostly dry |
| Wafer size | 1.3–2.25 inch | 2.25–5 inch | 5–8 inch |
| Device geometry | $>4\ \mu$ | $1–4\ \mu$ | $<1\ \mu$ |
| Clean room class | 100k, 10k | 10k, 1k, 100 | 10k, majority 1k, 100 (one area Class 10) |

coatings were being used to manufacture storage devices. During the period of 1960 to 1990, San Jose also was a large research and development site with many small laboratories working on different projects with different potential exposures.

The manufacturing processes that were used in San Jose differ significantly from those of the other two studied sites. In particular, the processes for producing semiconductor devices, storage devices such as disks or ferrite cores have different substrates, mechanical processes, and process chemicals. Production of disks, disk drives, and box assembly also are different from the semiconductor, packaging, or masking operations performed at Burlington and East Fishkill. As with the other two sites along with changes in engineering controls, over these years there were significant improvements made in both the type and quantity of personal protective equipment worn by the workers (Table 3).

San Jose had many groups on-site, a number of which were nonmanufacturing. For example, there were large numbers of programmers, networking specialists, and customer support personnel. The San Jose site occupies 429 acres of land and consists of 34 buildings. The buildings comprise approximately 3.8 million square-feet of space, of which 1.2 million square-feet is manufacturing space.

## Materials and Methods

### Information Sources

Information sources used to classify subjects' work activities were IBM's year-end files (YEFs) and the Corporate Employee Resource Information System (CERIS) file. YEFs, available for each year from 1965 to 1999, contained data on IBM employees' work assignment (facility, division, department, position) as of the end of the year. CERIS records identified all jobs, regardless of length of assignment, beginning in 1984.

We compiled a work history for each subject from YEF and CERIS records. From the work histories, we extracted a list of unique combinations of division code and name, department code, and name and job code and name (DDJ) used at each study facility. We used the list of DDJs to identify workgroups at each facility, and we assigned each DDJ on the list to a workgroup and to an exposure category.

Historical industrial hygiene records including personal exposure monitoring were retained at all three plants, dating back to the period of 1971 to 1974. A company-wide air contaminant-monitoring program was instituted in 1979, providing more systematic sampling strategies, data collection, and record retention practices than were in use before that time. A revised sampling strategy for measuring airborne contaminants was adopted in 1989, and a new system of qualitative exposure assessments was implemented in 1997. We examined the historical industrial hygiene data for possible use in future research but did not directly use the data in the exposure classification process because it was beyond the scope of this investigation.

### Development of Work Group Descriptions

We developed workgroup descriptions for each site to capture all the DDJs from each of the facilities. The groups were formed based upon similarity in working conditions, activities, and potential exposures within each group while maximizing the contrast in working conditions and potential exposures between the groups. Members of a particular workgroup are assumed to have similar exposures.[2,3] The workgroup definitions were developed from a consensus of the investigators, and the initial workgroup list and associated definitions were sent to the

**TABLE 3**
Manufacturing Eras and Associated Characteristics for San Jose

| Identifying Factors | 1956–1972 | 1973–1989 | 1990–1999 |
|---|---|---|---|
| Manual application of chemicals | Yes | Some | No (very limited) |
| Manual refilling of chemicals in tools | Yes | Some | No (very limited) |
| Manual delivery of chemicals to the Fab | Yes | Yes | No (limited) |
| On-site bulk storage of chemicals | No | Yes | No |
| Manual collection and removal of wastes | Yes | Yes | No (very limited) |
| Type of smock used in clean rooms | Lab coat | Full suit | Full suit |
| PPE: gloves 100% inspected for pinholes by manufacturer | None | Some | Full implementation |
| Ventilation | Local | Plenum, Local, CEPS | Plenum, Local, CEP |
| Ethyl or methyl series glycol ethers (or acetates) | Yes | Yes | Phased out (~1992) |
| Known Carcinogens used | Yes | Yes | Yes |
| Building, fire, environmental regulations | Least | Moderate | Most comprehensive |
| Manufacture | | | |
| Ferrite | Yes | Yes (until 1979) | No |
| Thin film sputtered disks | No | No | Yes |
| Lapping of disks | Yes | No | No |
| Clean room class | 10k–100k | 100–10k | 100 |

company for review and comment. Written comments were received and, if appropriate, the workgroup definitions were modified by the investigators. The overall classification process is illustrated in Fig. 1.

## Development of Manufacturing Eras

On the basis of changes in production processes, chemical usage, and regulatory environments, a series of questions was developed for each study site. The goal was to identify periods of time in which potential exposures, controls, and agents used in production were relatively constant. The company assembled teams of "experts" (ie, long-term employees and retirees who had the institutional memory necessary to answer questions across the study period). It was well known from the start of this study that significant changes in manufacturing technology and processes occurred during the study period, and it also was clear that potential exposures to workers would be expected to change.[4–6] The "manufacturing eras" developed as part of this exposure assessment correspond to time periods during which manufacturing processes, chemical/physical agent usage, work tasks, ventilation, and other exposure controls remained relatively constant and the resulting exposures were expected to be relatively constant within each era.[7,8] The information was reviewed, and preliminary manufacturing eras were developed. After company review and comment final manufacturing eras were developed. In all cases, the investigators made final decisions about the classifications.

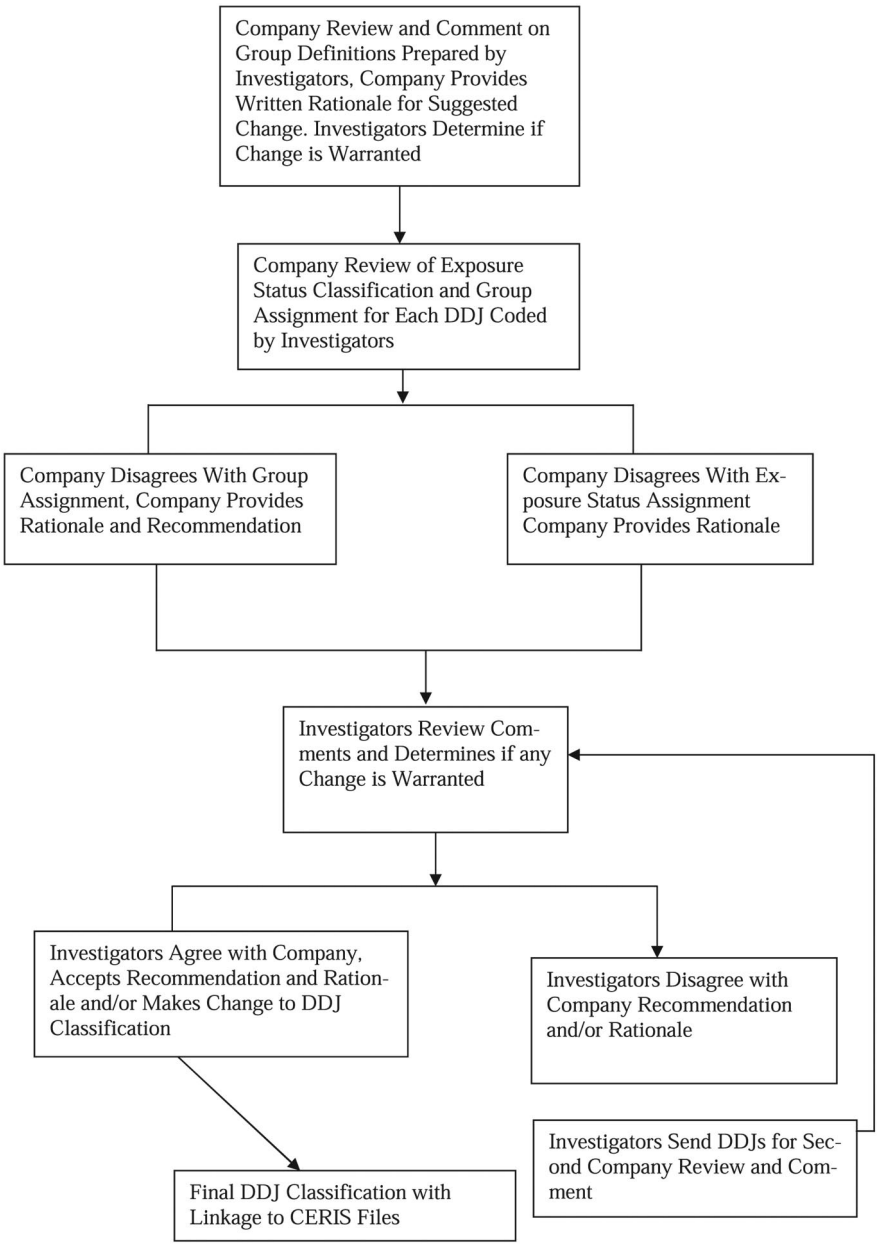


**Fig. 1.** Work group and exposure classification process.

## Assignment of DDJs to Work Groups and Exposure Categories

For each employee the company maintained a record of the division, the department and the jobs (DDJ) that they had while employed. If the worker changed jobs or departments or if the division changed, a new DDJ was created. Therefore, by classifying each unique DDJ into workgroups and exposure categories, each portion of an employee's work history was assigned to that workgroup and exposure category until the DDJ changed. The goal of this part of the exposure assessment was to assign each unique DDJ (Division/Department/Job code) to the most appropriate workgroup and exposure category. During this process the investigators were blind to the identity and vital status of the workers holding each DDJ.

Exposure categorization was performed on a qualitative basis. There were two exposure categories. One category coded "1" meant the DDJ reflected a potential exposure to nonoffice working environments. DDJs coded as "0" meant that the DDJ reflected no reasonably anticipated exposure to nonoffice environments and had exposure to only office-type environments. The information used

to classify the DDJs into workgroups was obtained from documents, pictures, site visits and interviews with long-term employees. Two site visits were conducted at each of the study facilities. Figure 1 shows a flowchart that describes the classification process. In all cases, final decisions about the classifications were made by the investigators.

### Development of Agent Groups for Each Work Group

The assumption that members of a particular workgroup have similar exposures led to the development of a matrix for each facility that indicates how similar or different each group was from the other with respect to potential exposures. Using the workgroup descriptions, the information gained from the site visits, the review of historical records, and interviews with long-term employees, it was possible to extract and summarize characteristics of the work environments for each workgroup with respect to their relative potential for exposure to solvents, metals/acids/bases, non-ionizing radiation, ionizing radiation and work in a cleanroom. Although work in a cleanroom is not directly equivalent to exposure to a particular agent, this classification was used to identify any workers exposed to the cleanroom environment. The workplace characteristics were used in the matrices to estimate each workgroup's relative potential for exposure. The ranking scheme was "0" if the agent was absent or present in very small amounts or few locations in environment or if activities did not require work in cleanrooms; "1" if the agent was extensively used in work environment or if activities were frequently/always conducted in cleanrooms; and "2" if the agent was present in environment but in fewer locations, smaller amounts or lower concentration than in workgroups classified as 1 or if activities were occasionally carried out in cleanrooms. In all cases, the investigators made final decisions about the classifications.

## Results

### Work Group Assignments and Manufacturing Eras

Table 4 shows the distribution of employees by workgroup and manufacturing era for the three sites. Fifteen workgroups were established for East Fishkill and Burlington, and 19 groups were developed for San Jose. The workgroup descriptions are included in the Appendix. (Detailed work group specifications are available in online appendix.) The distribution of study subjects by workgroup and manufacturing era are presented in Table 1. Groups 10 (office workers), 14 (cafeteria), and 15 (not classified) are not presented. The factors that were considered in forming the manufacturing eras are presented in Tables 1 to 3.

In Burlington 17.2% of the employees came from the earliest manufacturing era whereas East Fishkill had 23.7% of employees from its earliest manufacturing era. San Jose had only 14% of its employees in the earliest manufacturing era. Manufacturing era two was characterized by rapid population growth at San Jose and Burlington (44.7% and 43.8%, respectively, of employees classified as exposed, had their first employment in era two) compared with East Fishkill (28.4%). At Burlington, 83.0% of the increase of 10,911 employees was in groups 1 (Semiconductor), 5 (Masking), 9 (Process Equipment Maintenance), and 13 (Test/probe/dicing/slicing/die removal/wire bonding). At East Fishkill, from manufacturing era one to two, there was an increase of 2721 employees. Groups 1 (Semiconductor) and 13 (Test/probe/dicing/slicing/die removal/wire bonding) declined by a total of 11.2%, whereas groups 2 (Packaging), 6 (Research and Development), 9 (Process and Equipment Maintenance), and 11 (Other Manufacturing) increased by a total of 52.1%. San Jose experienced an increase of 18,963 employees from manufacturing era one to two. Groups 1 (Disk Manufacture), 2 (Head wafer/tape head manufacturing), 5 (Head Fabrication), 8 (Head suspension/head disk assembly/box), and 9 (Process and Equipment Maintenance) each grew by 300% to 500%.

In manufacturing era three, employee counts declined at Burlington and San Jose (2645 and 1015, respectively) whereas at East Fishkill employee counts increased by 11,126. The decline at Burlington was occurred mainly in groups 1 (Semiconductor), 2 (Facilities/Lab), and 13 (Test/probe/dicing/slicing/die removal/wire bonding). These groups experienced a decline of 3211 employees whereas groups 8 (Backlap/CMP) and 9 (Process and Equipment Maintenance) grew by 1084. The large increases at East Fishkill were attributable to expansion of semiconductor operations in the "West Complex" and in building B323. As for San Jose, there was an overall decline of 1015 employees, but there were groups with large net increases whereas others had large decreases. For example, groups 3 (Facilities/Lab), 6 (Research and Development), 11 (Other Manufacturing), 16 (Assembly), and 18 (VLSI) experienced a total decline of 5892 employees. Groups 1 (Disk Manufacture), 2 (Head wafer/tape head manufacturing), and 5 (Head Fabrication) experienced a net gain of 5738 employees.

### Distribution of Subjects and Person-Years (PY)

A total 310,351 DDJs were classified into 34 different workgroups and two exposure categories across the three sites. The distribution of DDJs was as follows: East Fishkill had 125,503; Burlington had 80,341; and San Jose had 104,507. At East Fishkill, the 45,492 employees had an average of 6.0 and a median of 3.0 unique DDJs over their time at the company. At Burlington (29,962 em-

**TABLE 4**
Number of Employees by Manufacturing Era of First Potential Exposure in Each Work Group, by Plant

| Plant and Work Group | Manufacturing Era 1 | 2 | 3 | Total |
|---|---|---|---|---|
| East Fishkill | 1965–1973 | 1974–1983 | 1984–1999 | |
| 1. Semiconductor fabrication | 5093 | 4574 | 9317 | 18,984 |
| 2. Packaging | 1864 | 2893 | 7159 | 11,916 |
| 3. Facilities/labs | 1362 | 1441 | 1865 | 4668 |
| 4. Chem mix | 121 | 402 | 419 | 942 |
| 5. Masking | 207 | 636 | 365 | 1208 |
| 6. Research and development | 1259 | 1465 | 1244 | 3968 |
| 7. Field service | 1 | 43 | 42 | 86 |
| 8. Chemical mechanical planarization/backlap | 99 | 87 | 809 | 995 |
| 9. Process equipment maintenance | 815 | 1446 | 1330 | 3591 |
| 11. Other manufacturing | 879 | 1383 | 1311 | 3573 |
| 12. Plating | 3 | 319 | 874 | 1196 |
| 13. Test/probe/dicing/slicing/die removal/wire bonding | 1874 | 1609 | 2689 | 6172 |
| Burlington | 1965–1973 | 1974–1988 | 1989–1999 | |
| 1. Semiconductor fabrication | 2463 | 8669 | 7007 | 18,139 |
| 2. Packaging | 49 | 560 | 223 | 832 |
| 3. Facilities/labs | 751 | 1310 | 624 | 2685 |
| 4. Chem mix | 20 | 267 | 329 | 616 |
| 5. Masking | 491 | 868 | 632 | 1991 |
| 6. Research and development | 82 | 209 | 61 | 352 |
| 7. Field service | 15 | 169 | 196 | 380 |
| 8. Chemical mechanical planarization/backlap | 0 | 9 | 718 | 727 |
| 9. Process equipment maintenance | 925 | 1680 | 2055 | 4660 |
| 11. Other manufacturing | 817 | 497 | 269 | 1583 |
| 12. Plating | 39 | 0 | 5 | 44 |
| 13. Test/probe/dicing/slicing/die removal/wire bonding | 1189 | 3514 | 2988 | 7691 |
| San Jose | 1965–1972 | 1973–1989 | 1990–1999 | |
| 1. Semiconductor fabrication | 434 | 2547 | 3710 | 6691 |
| 2. Packaging | 308 | 1849 | 3529 | 5686 |
| 3. Facilities/labs | 827 | 2054 | 336 | 3217 |
| 4. Chem mix | 4 | 105 | 82 | 191 |
| 5. Masking | 513 | 2828 | 5723 | 9064 |
| 6. Research and development | 679 | 1873 | 641 | 3193 |
| 7. Field service | 101 | 256 | 148 | 505 |
| 8. Chemical mechanical planarization/backlap | 1404 | 5805 | 6229 | 13,438 |
| 9. Process equipment maintenance | 201 | 978 | 372 | 1551 |
| 11. Other manufacturing | 1710 | 2513 | 1462 | 5685 |
| 12. Plating | 22 | 244 | 177 | 443 |
| 13. Test/probe/dicing/slicing/die removal/wire bonding | 872 | 2367 | 1915 | 5154 |
| 1. Semiconductor fabrication | 1668 | 4030 | 2458 | 8156 |
| 2. Packaging | 16 | 40 | 9 | 65 |
| 3. Facilities/labs | 191 | 399 | 80 | 670 |
| 4. Chem mix | 32 | 57 | 59 | 148 |

ployees) the average was 6.6 and a median of 3.0 unique DDJs, whereas at San Jose (54,455 employees), the average was 5.0 and a median of 3.0 unique DDJs.

The classification of study subjects based upon the number of years since first employment (YSF) and number of years worked (YRS) at each facility, as well as the distribution of the study population by gender, exposure category, cleanroom category, and workgroup (exposed workers only) are presented in Tables 5 to 7.

## Agent Matrices

The agent matrix for East Fishkill and Burlington is shown in Table 8. Among the manufacturing jobs, the greatest contrast was seen between group 1 (Semiconductor) and group 12 (Plating). Semiconductor workers (group 1) work extensively in cleanrooms where solvents and a variety of potential exposures are possible, while plating workers do not commonly work in a cleanroom, have little or no potential exposure to solvents, nonionizing, or ionizing radiation but do have potential for exposure to metals/acids/bases. Similar contrasts in exposure are also seen in the San Jose agent matrix (Table 9).

**TABLE 5**
Number of Subjects and Person-Yr (PY) by Years Since First Employment (YSF)* and Number of Years Worked (YRS)* for East Fishkill

| | Men | | Women | | All Subjects | | Percent |
|---|---|---|---|---|---|---|---|
| | Subjects | PY | Subjects | PY | Subjects | PY | Total PY |
| Total | 30,290 | 574,385 | 15,202 | 239,575 | 45,492 | 813,961 | 100 |
| YSF & YRS at facility | | | | | | | |
| <15 YSF, <5 YRS | 30,290 | 252,301 | 15,202 | 143,093 | 45,492 | 395,395 | 48.6 |
| <15 YSF, 5+ YRS | 13,569 | 123,015 | 4235 | 37,878 | 17,804 | 160,893 | 19.8 |
| 15+ YSF, <5 YRS | 7469 | 65,007 | 4544 | 27,549 | 12,013 | 92,555 | 11.4 |
| 15+ YSF, 5+ YRS | 11,398 | 134,062 | 3501 | 31,056 | 14,899 | 165,118 | 20.3 |
| Exposure category | | | | | | | |
| Unexposed | 8276 | 118,667 | 5790 | 93,361 | 14,066 | 212,028 | 26 |
| Exposed, ever | 23,656 | 442,649 | 9859 | 143,005 | 33,515 | 585,654 | 72 |
| 15+ YSF, 5+ YRS | 8218 | 92,257 | 2056 | 16,508 | 10,274 | 108,765 | 13.4 |
| Unknown | 784 | 13,069 | 222 | 3210 | 1006 | 16,279 | 2.0 |
| Cleanroom category (exposed employees only)† | | | | | | | |
| Frequently/always | 13,646 | 250,319 | 5846 | 88,179 | 19,492 | 338,497 | 41.6 |
| Sometime/occasional | 17,518 | 320,759 | 6127 | 80,905 | 23,645 | 401,664 | 49.4 |
| Rarely/never | 2717 | 52,474 | 1320 | 22,228 | 4037 | 74,702 | 9.2 |
| Work group (exposed employees only)† | | | | | | | |
| Semiconductor fab. | 13,362 | 243,637 | 5622 | 84,117 | 18,984 | 327,754 | 40.3 |
| Masking | 770 | 15,796 | 438 | 7426 | 1208 | 23,222 | 2.85 |
| Packaging | 7975 | 124,597 | 3941 | 49,233 | 11,916 | 173,830 | 21.4 |
| Facilities/labs | 3988 | 77,878 | 680 | 9734 | 4668 | 87,613 | 10.8 |
| Res. and dev. | 3642 | 73,866 | 326 | 4675 | 3968 | 78,541 | 9.65 |
| Proc. equip. maint. | 3365 | 61,160 | 226 | 2937 | 3591 | 64,096 | 7.9 |
| Test/dice/probe‡ | 4617 | 89,061 | 1555 | 22,807 | 6172 | 111,868 | 13.7 |
| Other manufacturing | 2536 | 49,246 | 1037 | 16,207 | 3573 | 65,453 | 8.04 |

*YSF, years since first record of employment at facility; YRS, yr of recorded work at facility.
†Work groups and cleanroom categories are not mutually exclusive.
‡Test/probe/dicing/slicing/die removal/wire bonding.

## DDJ Classification Overview

The approach we used to classify the DDJs was first to develop a series of workgroup definitions that would cover all the DDJs (jobs) performed at each site. For Burlington and East Fishkill the classification process resulted in 15 groups, whereas for San Jose there were 19 groups. Each DDJ listing from the work histories was then assigned to the most suitable group based upon our understanding of the work activities conducted by workers with that DDJ. Each DDJ was also assigned to an exposure category (unexposed, or potentially exposed). DDJs were classified as unexposed if that DDJ had no reasonable potential for exposure to manufacturing processes and/or nonoffice types of exposures. An example of a job that would have been classified as unexposed would be a secretary, lawyer or human resource professional. Examples of jobs that would be classified as potentially exposed would be technicians, production specialists and production operators. Because of limitations on quantitative and descriptive exposure information further refinement of the exposure status of the DDJs was not possible.

Within each workgroup, there were potentially exposed and unexposed DDJs. For example, if a secretary worked in semiconductor manufacturing the DDJ would be classified as nonexposed and placed in the semiconductor workgroup (group 1). If an engineer worked in semiconductor manufacturing, the DDJ would be classified as potentially exposed and also placed in group 1. The DDJs that were classified as potentially exposed in a group other than 10 (Office and Other Support) or DDJs classified as nonexposed in group 10 can be thought of as concordant pairs. Most of these would be potentially exposed jobs that occurred in departments with potential to expose workers to manufacturing conditions. Many of the unexposed DDJs show up in group 10 because the department the DDJ is in, eg, personnel, does not present the potential for exposure to manufacturing conditions.

Discordant pairs can occur in which a DDJ is classified as potentially exposed and the department is classified as Office (unexposed, group 10). This occurrence is relatively common in the DDJ data, eg, a DDJ with a job title of "engineer" in a marketing department. Here, the job would indicate potential for exposure but the department is not one where workers spend time in the manufacturing environment. It is also possible to have an exposure

**TABLE 6**
Number of Subjects and Person-Years (PY) by Years Since First Employment (YSF)* and Number of Years Worked (YRS)* for Burlington

| | Men | | Women | | All Subjects | | Percent |
|---|---|---|---|---|---|---|---|
| | Subjects | PY | Subjects | PY | Subjects | PY | Total PY |
| Total | 19,676 | 317,120 | 10,286 | 147,271 | 29,962 | 464,390 | 100 |
| YSF and YRS at facility | | | | | | | |
| <15 YSF, <5 YRS | 19,676 | 137,294 | 10,286 | 86,829 | 29,962 | 224,122 | 48.3 |
| <15 YSF, 5+ YRS | 8797 | 75,866 | 2893 | 24,740 | 11,690 | 100,606 | 21.7 |
| 15+ YSF, <5 YRS | 3105 | 25,592 | 2511 | 16,590 | 5616 | 42,182 | 9.08 |
| 15+ YSF, 5+ YRS | 7090 | 78,368 | 2361 | 19,125 | 9451 | 97,493 | 21 |
| Exposure category | | | | | | | |
| Unexposed | 4492 | 53,808 | 2510 | 37,954 | 7002 | 91,762 | 19.8 |
| Exposed, ever | 16,391 | 254,498 | 8067 | 103,701 | 24,458 | 358,199 | 77.1 |
| 15+ YSF, 5+ YRS | 5350 | 55,788 | 1530 | 10,863 | 6880 | 66,652 | 14.4 |
| Unknown | 391 | 8814 | 229 | 5616 | 620 | 14,430 | 3.1 |
| Cleanroom category (exposed employees only)† | | | | | | | |
| Frequently/always | 12,299 | 178,641 | 6345 | 81,290 | 18,644 | 259,931 | 56.0 |
| Sometimes/occasional | 10,062 | 159,747 | 3718 | 42,222 | 13,780 | 201,969 | 43.5 |
| Rarely/never | 1661 | 33,323 | 492 | 9669 | 2153 | 42,992 | 9.3 |
| Work group (exposed employees only)† | | | | | | | |
| Semiconductor fab. | 11,964 | 170,668 | 6175 | 78,193 | 18,139 | 248,862 | 53.6 |
| Masking | 1345 | 24,078 | 646 | 8766 | 1991 | 32,844 | 7.07 |
| Packaging | 665 | 10,108 | 167 | 2123 | 832 | 12,231 | 2.63 |
| Facilities/labs | 2300 | 43,996 | 385 | 5079 | 2685 | 49,075 | 10.6 |
| Res. and dev. | 323 | 6486 | 29 | 420 | 352 | 6906 | 1.49 |
| Proc. equip. maint. | 4011 | 61,647 | 649 | 5806 | 4660 | 67,453 | 14.5 |
| Test/dice/probe‡ | 5172 | 77,747 | 2519 | 29,850 | 7691 | 107,597 | 23.2 |
| Other manufacturing | 1317 | 28,834 | 266 | 5884 | 1583 | 34,718 | 7.48 |

*YSF, years since first record of employment at facility; YRS, years of recorded work at facility.
†Work groups and cleanroom categories are not mutually exclusive.
‡Test/probe/dicing/slicing/die removal/wire bonding.

status of nonexposed (eg, secretaries) and be assigned to a group other than 10.

The percentage of potentially exposed and unexposed subjects varied by site. Only 59.6% of the DDJs for San Jose were classified as potentially exposed. This contrasts with Burlington and East Fishkill, in which the percent potentially exposed was 76.6% and 69.1%, respectively. Of the 54,455 workers at San Jose, 34,880 (64.0%) were classified as ever "exposed," 9778 (18.0%) were classified as having "frequently/always" worked in cleanrooms, and 7528 (13.8%) of the potentially exposed workers had 15+ years since first exposure and 5+ years of employment (Table 7). These numbers are quite different as shown in Tables 5 to 6 for Burlington and East Fishkill, in which 81.6% and 73.4% of workers, respectively, were classified as "exposed" and 62.2% and 42.8%, respectively, were cleanroom workers. The differences in the presence and nature of manufacturing operations, as well as the presence of cleanrooms are consistent with these relative differences between the plants.

The semiconductor fabrication activities (group 1) were essentially confined to Burlington and East Fishkill. The semiconductor manufacturing workgroup comprised 42.9% of the DDJs, 60.5% of the workers and 53.6% of the PY used in the analyses for Burlington. At East Fishkill, the semiconductor fabrication group comprised 28.4% of the DDJs, 41.7% of the workers and 40.3% of the PY used in the analyses for this site. San Jose did have a very minor 0.18% of its DDJs in the VLSI (a semiconductor manufacturing) group. These proportions of group 1 members are consistent with Burlington's primary role as a semiconductor manufacturing site, the multiple roles of East Fishkill as a research and production site, and the non-semiconductor fabrication focus of the San Jose site as a storage device production facility.

Group 3, at East Fishkill and Burlington consists of individuals who perform work related to environmental health and safety, facilities, laboratories, or quality assurance. At San Jose, quality assurance was placed in its own group, but the rest of group 3 remained the same. Burlington and East Fishkill were very similar in the percentage of group 3 DDJs with 5837 (7.27%) and 9106 (7.26%), respectively. San Jose had only 4597 (4.40%) of its DDJs in group 3. As for workers classified as group 3, Burlington, East Fishkill, and San Jose had 9.0%, 10.3%, and 5.9%,

**TABLE 7**
Number of Subjects and Person-Years (PY) by Year Since First Employment (YSF)* and Number of Years Worked (YRS)* for San Jose

| | Men | | Women | | All Subjects | | Percent |
|---|---|---|---|---|---|---|---|
| | Subjects | PY | Subjects | PY | Subjects | PY | Total PY |
| Total | 35,443 | 568,939 | 19,012 | 247,957 | 54,455 | 816,895 | 100 |
| YSF &and YRS at facility | | | | | | | |
| <15 YSF, <5 YRS | 35,443 | 269,659 | 19,012 | 147,477 | 54,455 | 417,135 | 51.1 |
| <15 YSF, 5+ YRS | 11,744 | 107,149 | 4355 | 37,975 | 16,099 | 145,123 | 17.8 |
| 15+ YSF, <5 YRS | 7734 | 68,379 | 4343 | 30,745 | 12,077 | 99,125 | 12.1 |
| 15+ YSF, 5+ YRS | 10,360 | 123,752 | 3632 | 31,760 | 13,992 | 155,512 | 19 |
| Exposure category | | | | | | | |
| Unexposed | 13,896 | 213,621 | 8126 | 122,749 | 22,022 | 336,370 | 41.2 |
| Exposed, ever | 23,670 | 342,419 | 11,210 | 120,209 | 34,880 | 462,628 | 56.6 |
| 15+ YSF, 5+ YRS | 5690 | 63,636 | 1838 | 14,319 | 7528 | 77,954 | 9.54 |
| Unknown | 661 | 12,898 | 255 | 4999 | 916 | 17,897 | 2.2 |
| Cleanroom category (exposed employees only)† | | | | | | | . |
| Frequently/always | 5881 | 61,472 | 3897 | 36,895 | 9778 | 98,367 | 12.0 |
| Sometimes/occasional | 13,718 | 205,968 | 5425 | 51,016 | 19,143 | 256,984 | 31.5 |
| Rarely/never | 14,079 | 218,670 | 6609 | 83,838 | 20,688 | 302,508 | 37.0 |
| Work group (exposed employees only)† | | | | | | | |
| Head fabrication | 5319 | 51,063 | 3745 | 35,144 | 9064 | 86,206 | 10.6 |
| Disk manufacturing | 4701 | 56,432 | 1990 | 14,438 | 6691 | 70,870 | 8.68 |
| Head wafer/tape head | 3483 | 34,385 | 2203 | 18,120 | 5686 | 52,505 | 6.43 |
| Facilities/labs | 2573 | 52,183 | 644 | 8831 | 3217 | 61,013 | 7.47 |
| Res. and dev. | 2753 | 48,708 | 440 | 5334 | 3193 | 54,042 | 6.62 |
| Test/slice/dice | 3950 | 63,182 | 1204 | 12,601 | 5154 | 75,783 | 9.28 |
| Head suspension/head/disk/ assembly/box | 8506 | 106,967 | 4932 | 59,594 | 13,438 | 166,561 | 20.4 |
| Other manufacturing | 4604 | 88,249 | 1081 | 16,497 | 5685 | 104,746 | 12.8 |
| Assembly | 5728 | 98,473 | 2428 | 35,679 | 8156 | 134,152 | 16.4 |

*YSF, years since first record of employment at facility; YRS, years of recorded work at facility.
†Work groups and cleanroom categories are not mutually exclusive.

**TABLE 8**
Agent Matrix for East Fishkill and Burlington*

| Work Group No. | Work Group | Solvents | Metals/ Acids/Bases | Nonionizing Radiation | Ionizing Radiation | Cleanroom |
|---|---|---|---|---|---|---|
| 1 | Semiconductor | 1 | 1 | 1 | 1 | 1 |
| 2 | Packaging | 1 | 1 | 1 | 1 | 2 |
| 3 | Facilities/EH&S | 1 | 1 | 0 | 0 | 2 |
| 4 | ChemMix | 1 | 2 | 0 | 0 | 2 |
| 5 | Masking | 1 | 1 | 2 | 2 | 1 |
| 6 | R&D | 1 | 1 | 1 | 1 | 2 |
| 7 | Field service | 0 | 0 | 0 | 0 | 0 |
| 8 | CMP/backlap | 0 | 2 | 0 | 0 | 2 |
| 9 | Process or equipment maint & engineering | 1 | 1 | 1 | 1 | 2 |
| 10 | Office | 0 | 0 | 0 | 0 | 0 |
| 11 | Other manufacturing | 2 | 2 | 2 | 0 | 0 |
| 12 | Plating | 0 | 1 | 0 | 0 | 2 |
| 13 | Test/dice/probe/die removal/wire bonding | 2 | 0 | 0 | 0 | 2 |
| 14 | Food/cafe | 0 | 0 | 0 | 0 | 0 |

*1 = agent was extensively used or present in work environment; 2 = agent was present in environment but in fewer locations, smaller amounts, or lower concentration than in work groups classified as 1; 0 = agent was absent or present in very small amounts or few locations in environment.

**TABLE 9**
Agent Matrix for San Jose*

| Work Group No. | Work Group | Solvents | Metals/ Acids/Bases | Nonionizing Radiation | Ionizing Radiation | Cleanroom |
|---|---|---|---|---|---|---|
| 1 | Disk manufacturing | 1 | 1 | 2 | 0 | 2 |
| 2 | Head wafer/tape head | 1 | 1 | 2 | 0 | 2 |
| 3 | EH&S and facilities | 1 | 2 | 0 | 0 | 2 |
| 4 | ChemMix | 1 | 2 | 0 | 0 | 2 |
| 5 | Head fabrication | 1 | 2 | 2 | 0 | 1 |
| 6 | R&D | 1 | 1 | 2 | 2 | 2 |
| 7 | Field/customer support | 0 | 0 | 0 | 0 | 0 |
| 8 | Head suspension/HDA/box | 2 | 0 | 0 | 2 | 0 |
| 9 | Process/equipment maint & engineering | 1 | 2 | 2 | 2 | 2 |
| 10 | Office | 0 | 0 | 0 | 0 | 0 |
| 11 | Other manufacturing | 2 | 2 | 2 | 0 | 0 |
| 12 | Plating | 0 | 1 | 0 | 0 | 0 |
| 13 | Test, slice, dice | 0 | 0 | 0 | 0 | 2 |
| 14 | Cafeteria | 0 | 0 | 2 | 0 | 0 |
| 16 | Assembly | 0 | 0 | 0 | 0 | 0 |
| 17 | Quality control/quality assurance | 2 | 2 | 0 | 2 | 2 |
| 18 | VLSI/semiconductor | 1 | 1 | 1 | 1 | 1 |
| 19 | Masking | 1 | 1 | 2 | 2 | 1 |

*1 = agent was extensively used or present in work environment; 2 = agent was present in environment but in fewer locations, smaller amounts or lower concentration than in work groups classified as 1; 0 = agent was absent or present in very small amounts or few locations in environment.

respectively, of the total number of workers in the study for these sites in this group. As for PY contributed by group 3, Burlington, East Fishkill, and San Jose had 10.6%, 10.8%, and 7.5%, respectively, of the total PY used in their analyses for each site come from this group. The reasons for the similarity in percentages for Burlington and East Fishkill could be that manufacturing processes are a major determinant of the types of services provided by the workers in this group. Because San Jose had relatively less manufacturing, it could be that there would be less need for quality assurance (group 17), facilities and environmental health and safety (group 3).

One of the necessary steps in semiconductor manufacture is the production of "Masks." Mask production began in East Fishkill but over time the operation migrated to Burlington. East Fishkill had 1582 (1.26%) DDJs classified as masking whereas Burlington had 2629 (3.37%). San Jose had only 196 (0.14%) DDJs classified as masking. The percentage of workers who were classified as masking at Burlington and East Fishkill was 6.6% and 2.7%, respectively. The number of DDJs and the percentage of workers classified as masking in the three plants is consistent with the significant role of masking operations at the Burlington site and the minimal role at San Jose.

Group 9 is comprises process and equipment maintenance personnel. East Fishkill had 5552 (4.42%) DDJs in group 9 whereas Burlington had 5859 (7.29%) San Jose had only 1769 (0.34%) DDJs in group 9. Another difference in group 9 workers from Burlington and East Fishkill is that the process and equipment maintenance group in East Fishkill would be relatively more involved with processes associated with packaging (group 2) than those in Burlington. At East Fishkill, 26.2% of the workers were in group 2 (packaging), whereas Burlington had only 2.6% classified as group 2. The DDJs, and consequently the workers, in group 9 could not be separated into packaging and semiconductor categories therefore the workers in group 9 are a mixture of process equipment maintenance personnel supporting both packaging and semiconductor manufacturing.

The reason(s) for the low number of workers in group 9 in San Jose is unclear. A consensus existed among the investigators that the job titles and department names used in San Jose were relatively less informative and that may have resulted in misclassification of some of the DDJs in group 9 and other workgroups. Another possibility is that the need for these types of skills is relatively higher in Burlington and East Fishkill than it was in San Jose and the small size of group 9 at San Jose is reflective of the nature of the manufacturing operations performed there.

## Manufacturing Eras

The dramatic changes in manufacturing technology in the semiconductor and storage device production processes changed the working environments, and the exposures to workers in those environments. The concept of dividing the production history of each facility into manufacturing eras was intended to distinguish significant differences in

potential exposures associated with the changing workplace conditions. In the exposure classification, for example, the time spent by a worker in group 1 (semiconductor) in the 1970s could be distinguished from time spent in the same group in the 1990s when conditions, and potential exposures were very different.

Three types of factors were considered in creating the manufacturing eras: those associated with changes in the manufacturing requirements; those associated with environmental and occupational regulations; and those associated with work practices. Examples of changes in manufacturing requirements include cleanroom class, wafer size, and device geometry. At East Fishkill and Burlington, these changes resulted in ever greater levels of containment and isolation of the product from the environment over time. A similar trend was noted for the San Jose facility, but the changes were less apparent in cleanroom class and more likely to be associated with changes in product characteristics (eg, transition from ferrite to thin film sputtered disks in 1979). Occupational and environmental regulations also may have been important factors in changing working conditions at all three plants. For example, enclosures of piping systems at rear of furnaces, enclosures of toxic gas lines, installation of toxic gas monitoring systems and excess flow control valves on toxic gases, and elimination of ethyl or methyl series glycol ethers (or acetates) were identified as significant changes that affected workplace exposures. Arsenic, ionizing radiation, ultraviolet light are examples of known carcinogens used at the sites (ranking of at least 2b from the International Agency for Research on Cancer.[9] Factors associated with work practices included the transition from manual to automated systems for application of chemicals (eg, photoresist, dipping of wafers in chemical baths, refilling of chemicals in tools, delivery of chemicals to the Fab and other work locations, pushing and pulling of wafers in furnaces, collection and removal of wastes, and cleaning of metal deposition equipment).

The compilation of these factors (Tables 1 to 3) revealed that the changes in workplace conditions divided the plants' histories into three eras. They were very similar for East Fishkill and Burlington, as manufacturing technologies were first developed at East Fishkill, then migrated to production operations at Burlington. The three eras identified at East Fishkill were 1963 to 1973; 1974 to 1983; 1984 to 1999. At Burlington, the eras were 1962 to 1973; 1974 to 1988, and 1989 to 1999. The operational history of the San Jose facility also supported the creation of three eras, which were different from the other two facilities. For San Jose, the eras were 1956 to 1972; 1973 to 1989; and 1990 to 1999.

At East Fishkill and Burlington, the changes in employee counts across the three manufacturing eras is supported by the a priori descriptions of transitions of specific operations, eg, migration of semiconductor manufacturing and masking from East Fishkill to Burlington, resulting in a decreasing role of East Fishkill in production, and an enhanced research and development role.

The employee headcounts in the three manufacturing eras in San Jose also reflect the a priori statements by the company concerning product introductions and discontinuance, eg, disk manufacture, head fabrication, VLSI and head suspension/box.

### Agent Matrices

The agent matrix for East Fishkill and Burlington in Table 8 indicates that workers in groups 1 to 6 and 9 would be expected to have frequent exposure to solvents as a class, however the specific solvents comprising the exposure could vary between groups. The other workgroups have less, or no substantial likelihood of solvent exposure. For the agents in the metals/acids/bases class, groups 1–3, 5, 6, 9, and 12 have frequent exposure, exceeding the other workgroups. For non-ionizing and ionizing radiation, groups 1, 2, 6, and 9 are rated as being more highly exposed than the other groups, while for cleanroom use, groups 1 and 5 are most likely to be in that environment on a frequent basis. Across the range of potential exposures, workers in semiconductor (group 1) would be expected to have the greatest contact with the agents we rated, followed by packaging (group 2), research and development,[6] and process equipment maintenance.[4,6]

Rating of potential exposure by workgroup at San Jose demonstrates a wider diversity of exposure between groups than was noted at East Fishkill and Burlington. This difference is probably a result of the differences in manufacturing process between the semiconductor production at East Fishkill and Burlington, and the storage device manufacturing at San Jose. Within the San Jose workgroups, groups 1–6, 9, 18, and 19 would be expected to have frequent solvent exposure; groups 1, 2, 6, 12, 18, and 19 the highest rating for metal/acids/bases exposures; group 18 the highest rated nonionizing and ionizing radiation exposures; and groups 5, 18, and 19 the most frequent exposure to cleanroom environments. Across the range of agents, the very large-scale integration/semiconductor workers (group 18) had the highest overall potential exposure ratings, followed by the masking (group 19) workers.

## Conclusions

The strengths of this study are its size both in numbers of individuals, PYs, and the low number of unclassifiable DDJs (0.77%) representing 2.3% of PY. We were able to classify, for the first time in this type of study on cancer incidence and mortality in this workforce, 126,836 workers with only 34 facility-specific workgroups, with 21 unique descriptions. In addition, we were able to describe through agent matrices the different exposure potentials across workgroups. A meth-

odological strength of this study is the use of multiple levels of review for workgroup identification, workgroup descriptions, manufacturing eras and the agent matrices. The review process accommodated input from the company, with the ultimate classification decisions made by the investigators.

As with other studies of this type potential misclassification is probably the most significant limitation.[7,8] It is possible that department names, job titles, and such were misinterpreted during the reviews and the DDJs and ultimately the employees were placed in an inappropriate workgroup. Another type of misclassification that could have occurred is the assignment of workers to a particular manufacturing era based on the presence or absence of certain factors. The cut-off point for a manufacturing era is absolute when in reality the changes in these facilities took place on a continuum where processes, exposure controls, and worker tasks overlapped from one era to another. Any misclassification resulting from these uncertainties is likely to be random, which would tend to diminish the validity of the classifications by workgroup, manufacturing and agent as surrogates for actual exposures.

The agent matrices were helpful in delineating differences in potential exposures between workgroups. They provided a relatively simple illustration of the exposure potential between groups. The limitation is that the scale for measuring these differences is relatively crude. This classification could be refined by improving the definition of the agents, eg, distinguishing between types of solvents rather than classifying only on the basis of potential exposure to solvents. The historical record of air sampling and chemical use could be used to evaluate the validity of qualitative exposure classifications by work category and group. Another improvement would be the use of more quantitative exposure rankings based upon actual measurements of exposure, which could be accomplished by assembling the historical record of industrial hygiene measurements of airborne contaminants, as well as the archived records of chemical use for the three facilities. As IBM has maintained these records, a quantitative reconstruction of historical exposures to agents known or suspected as carcinogens may be possible. Although this reconstruction was outside the scope of the current project, it could be incorporated in a future investigation.

This is the first time that manufacturing eras, workgroups and agent matrices have been established for these workforces. This methodology may be applicable to other studies in the semiconductor and storage device manufacturing industry.

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