CHAPTER 6

Manufacturing: Quality, Reliability, and Automation

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Manufacturing: Quality, Reliability, and Automation

Overview

Assuming comparable products–and a lack of subsidies or other strong exogenous influences—costs are a primary determinant of international competitiveness, in electronics as in any industry, Comparable products may not be identical, and small differences in performance or specifications can override small differences in costs in the eyes of customers. But even for military systems, manufacturing costs —which depend on both the design of the product and the design of the production system—are almost always a major consideration.

In electronics, costs are much more critical to the successful marketing of some types of products than others. Intense price competition in consumer electronics—televisions, video cassette recorders, stereo equipment—makes low manufacturing costs a vital competitive weapon. Much the same is true for standardized semiconductor products ranging from discrete transistors to random access memory chips; price cutting is the rule, costs highly sensitive to the yields of the production process (ch. 3). For other types of semiconductor devices, low manufacturing costs and low prices are less vital; if only a single firm makes a particular integrated circuit (IC)—perhaps one that meets unusual or demanding performance requirements such as a high-speed, high resolution analog-digital converter—it will probably set prices to maximize profits, given the lack of competition. Leading-edge computer hardware and software falls in much the same category. Even so, electronics firms are seldom able to establish and maintain technological advantages so large that manufacturing costs are of little relevance.

In addition to direct and indirect manufacturing costs, prices charged to purchasers reflect expenses associated with research, design, and development, as well as marketing and distribution. While accounting procedures vary, such costs are generally treated as *indirect* expenses—i.e., a percentage is added to the direct manufacturing cost of each item produced, as for other overhead. Depreciation of plant and equipment is handled the same way. *Direct* manufacturing cost then consists primarily of parts, materials, and labor, Research, design, and development costs are much higher for products such as computers or large-scale ICs than for consumer items where technical change is slow and incremental, major redesigns infrequent. In the production of semiconductor devices and computers, research and development tends to account for a considerably greater percentage of costs; depreciation charges are also likely to be greater because new production equipment must be purchased as the technology advances.

But costs are not the only way in which manufacturing operations affect competitiveness. Beyond production costs—which depend on wage rates, prices of materials, supplies, and components, capital charges, and related factors—lie dimensions such as the quality and the reliability of the goods produced. While more sophisticated purchasers are most interested in the quantifiable dimensions of quality and reliability, in markets for consumer products perceptions—whether or not well founded—influence the decisions of prospective customers. Along with other qualitative aspects, such as appearance, purchasers base their assessments of value for money on perceptions of quality and reliability.

These attributes—both the reality and the perception—depend on factors such as engineering design, how the people in the work force are trained, organized, and managed, and on the capabilities, indeed the quality, of the manufacturing equipment. Automation can improve quality by reducing the probability of human error or simply improving the consistency of the production process. In other instances, there will be no effect. In some cases, quality may be degraded; people are better at some jobs than machines, and vice versa—human skills far exceed those of machines for tasks involving pattern recognition, or where judgments must be made based on partial or imperfect information. Regardless of specifics, *the quality of a firm products will ultimately depend on the stress top management places on quality as a goal of the production process.*

By the end of the 1970's, issues of product quality were in the public eye for industries as disparate as nuclear power, automobiles, and semiconductors. Perceptions were widespread that the quality of American goods had declined compared to those from foreign countries.[1] Some observers speculated that American firms and American labor had slipped, others that consumers had become more demanding and were no longer satisfied by quality standards that had once been acceptable in the U.S. market. Either way, a "quality gap" with respect to imports, extending even to commodity items such as steel, has frequently been advanced as a contributing factor in the declining international competitiveness of American firms and industries. To take an example from electronics, the reputation of RCA's color TVs had slipped badly by the end of the 1960's.[2] Not only did this hurt the company's sales, RCA also lost some of its dealer base. Automated production was at the heart of the company's effort to improve the quality and reliability of its TV line.

Despite the importance of direct costs of production for competitive success in electronics, OTA has not attempted to estimate or compare manufacturing costs. Companies guard cost data closely, More important, the dynamics of shifting cost structures, rather than costs at a given point in time, are central to changing competitive fortunes. To some extent these dynamics can be inferred without the need for proprietary data. This chapter then focuses on aspects of manufacturing such as quality and reliability, plus automated production technologies.

Product quality is treated primarily from a hardware perspective: What *are* the relative levels of quality in the United States and Japan? (The comparison is limited to these two countries.) How do product design and the application of production engineering and quality assurance techniques affect quality? How do products fail?[3] Less tangible but equally important matters of the human element in manufacturing and quality control—including questions of management and organization, as well as the education and training of the work force —are also discussed in chapter 8.

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[1] OTA's contractor on quality and reliability notes that about 80 percent of the attendees at an April 1980 American Management Association seminar on Japanese techniques for quality control and productivity improvement felt that the products of their own firms were surpassed by products from Japan. Those surveyed were at the seminar to learn from the experience of Japanese companies-not a random sample. See J. Mihalasky and A. B. Mundel, "Quality and Reliability y of Semiconductors and CTVs: United States v. Japan, " report No. C972, prepared for OTA by Consultant Services Institute, Inc., under contract No. 033-1170.0, p. 6.

[2] R. A. Joseph, "Automation Helps RCA and Zenith Keep Color-TV Leadership in Face of Import s," Waif *Street Journal,* May 5, 1981, p. 56.

[3] Much of the material on quality and reliability assembled below is drawn from "Quality and Reliability of Semiconductors and CTVs: United States v. Japan, " op. cit. This report is based in part on a series of questionnaires and surveys—20(1 covering both manufacturers and purchasers of ICs, 60 covering independent TV service shops—plus 42 visits to facilities of U.S. and Japanese firms that make ICs or semiconductor manufacturing equipment.

While comparisons between products of American and Japanese firms were of primary interest, some of those surveyed also commented on the West European electronics industry. In general, the feeling was that European firms had been behind both American and Japanese manufacturers in the quality and reliability of their ICs and TV receivers. While European producers may recently have caught up to the United States in the quality and reliability of certain types of semiconductor devices, overall they probably still lag both the United States and Japan.

Quality and Reliability

Meanings and Measurement

Quality, meaning fitness for function–the extent to which a product meets the specifications of its designers and manufacturers, the expectations of users—can be treated subjectively or objectively, Consumers typically make subjective judgments concerning the quality of competing products. Manufacturers attempt to define quality in terms of parameters that can be measured quantitatively–e.g., the ability of a TV set to receive weak signals. In addition, they may adopt rating scales which trained inspectors apply to characteristics that are not inherently quantitative. Often the indices are based on comparisons with samples or standards; an example would be the appearance of the cabinet for a TV set—whether the trim fit properly and colors matched, whether the panels were free of waviness, the number of visible flaws and blemishes.

Through measures like these, manufacturers try to satisfy consumers' perceptions of quality as well as ensure that their products function properly—all at a reasonable cost, For products like ICs or computers, the quality image that a firm establishes is likely to be more nearly consistent with quantitative measures than for consumer goods; indeed, some electronic components are sold to specifications written by the purchaser. Nevertheless, the perceptions and subjective judgments of customers sell many computers, and ICs are inspected to be sure that logotypes and part numbers are properly printed and convey the desired image.

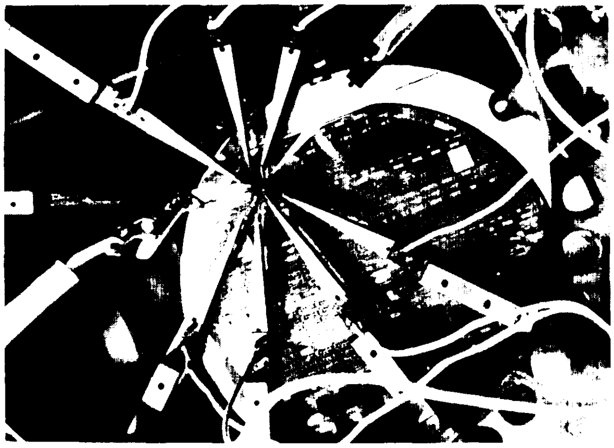


Photo credit Bell Laboratories

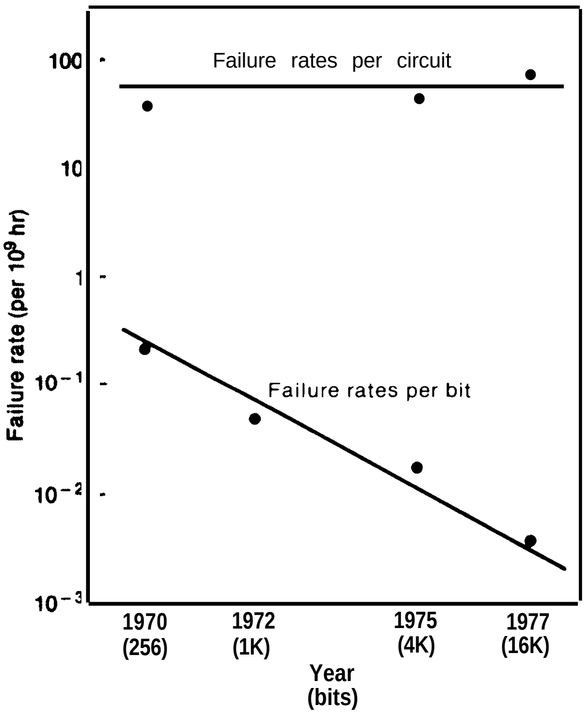
Probes for testing Integrated circuit chips

Reliability is a measure of *continuing* fitness for function once a product is placed in service. While quality is determined at a single point in time—generally the end of the manufacturing process or the beginning of service life—reliability is measured *over* time, as a failure rate or similar parameter.

The most common indicators of reliability are mean time to failure or mean time between failures–the interval between disabling failures averaged over a large number of items, usually in terms of actual hours of operation, Failures that average one per million hours can be expressed as a mean time between failures of 10^6 hours or as a failure rate of 10-~ per hour. The graphical presentation in figure 36 shows the number of ICs (from a much larger group) expected to fail in 10^9 (1 billion] hours of operation. A billion hours is 114 centuries; such plots are constructed from short-term data using statistical techniques. A failure rate of one per billion hours means that the expected or most likely lifetime for a single item chosen at random is 10^9 hours.

Definitions of reliability based only on failures that *prevent* the product from functioning are straightforward, Measurement can nonetheless be time-consuming, as well as presenting difficult statistical problems. Still, a light bulb works until it burns out—testing a large enough sample of nominally identical bulbs will yield a statistically valid mean time to failure. Partial failure, or gradual degradation in performance, is more difficult to quantify. A lo-year-old TV set may still function, but not as well as when new; there are no simple measures of "reliability" that apply to such phenomena.

Figure 36.—Data for MOS RAMs Showing Constant 'Failure Rates per Circuit as Integration Levels Increase, Decreasing Failure Rates per Bit



SOURCE T. Goto and N. Manabe, "How Japanese Manufacturers Achieve High IC Reliability," *Electronics*, Mar 13, 1980, p. 140

The reliability of computer software presents another type of problem. Software does not "fail" or "wear out" from physical causes as does hardware—although the media that store the software may suffer such failures. But software still needs continual maintenance; complex programs are altered and updated periodically—sometimes to correct errors that are caught only after the software has been placed in service, other times to improve performance, The reliability of a piece of software then depends on the frequency of modifications required to correct programing errors that could cause the system to malfunction.[4] As a result, the reliability of an entire computer *system* depends on both hardware reliability and software reliability—failures of the first type having physical causes (although ultimately depending on design and manufacturing practices), failures of the second type depending wholly on the design of the software.

Exhaustive engineering efforts are directed at ensuring the reliability of new and complex systems of all types, particularly where failures can be costly or dangerous—e.g., airplanes or nuclear powerplants. To improve reliability, designers apply techniques such as failure mode analysis—estimating the probabilities of different types of failures and attempting to minimize the more serious. A common practice is to add redundancy to the system, providing functional alternatives so that the failure of one part does not compromise the whole. A wire rope has a great deal of redundancy because one strand, or many strands in a large enough cable, can break without impairing the strength significantly. A chain, in contrast, has no redundancy. Complex computer systems often include redundant processors and other hardware components, as well as fault-tolerant software that can reconfigure the system following hardware failures. In any type of system, degraded performance will normally be preferable to sudden and total failure, For example, electronic control systems for automobile engines are designed so that component failures–perhaps of a sensor or a memory chip —will not cause the engine to suddenly stop running. Instead, the engineers aim for "soft" failure modes, or "limp-home" capability.

While quality and reliability are related, they are by no means synonymous. Reliability depends more heavily on design engineering, quality on control of the manufacturing process. In general, as experience in making a product accumulates, levels of quality and reliability both increase. Note the similarity with yield increases for semiconductors, as discussed in chapter 3. Figure 37 illustrates the reliability improvement over time of the Motorola 6800 microprocessor, a popular 8-bit circuit that has been in production since 1974.

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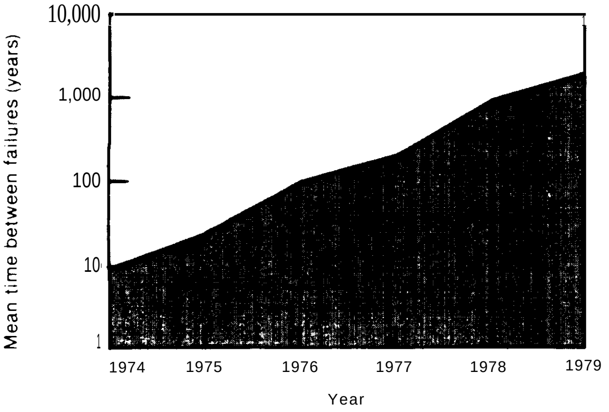
[4] J. D. Musa, "The Measurement and Management of Software Reliability," Proceedings *of the IEEE*, vol. 68, 1980, p. 1131. More generally, see R. Dunn and R. Unman, *Quality Assurance for Computer Software* (New York: McGraw-Hill, 1982). New computer programs tend to have of the order of one mistake per hundred lines; some but not all of these will be found before the program is placed in service—M, Lipow, "Number of Faults per Line of Code," *IEEE Transactions on Software Engineering*, vol. SE-8, July 1982, p. 437.

Figure 37.—Reliability Improvement With Cumulative Production Experience for a Microprocessor (Motorola 6800)



SOURCE D Queyssac, Projecting VSLI s Impact on Microprocessors, ' *IEEE Spectrum* May 1979 p 38

Statistical methods can be applied to quality and reliability problems during both the design and manufacturing stages, but the specialized discipline of statistical quality control is largely a tool of the production process. s As an example, defects in ICs can be monitored over time to give insight into the effects of processing variables. In contrast, reliability analysis techniques are applied, not to process variables but to tests conducted on finished products and to field service experience. Steps taken to improve quality sometimes but not always improve reliability.

Organizing and Managing for Quality

Managing the interface between design engineering and manufacturing engineering presents a classic set of problems that affect production costs, as well as quality and reliability. Designers specify the characteristics of products in great detail, while manufacturing engineers must determine how to make the product so that it will have those characteristics. Sometimes the same people are involved in both functions, but more commonly the responsibilities fall on different parts of an organization,

Separation of responsibility for design, production, and quality control characterize manufacturing enterprises all over the world, but perhaps more so in the United States than elsewhere (e. g., in Japan), One reason for the prevalence here appears to be the heritage of scientific management, an approach to job methods and the organization of production originating in the work of an American engineer, Frederick Taylor, during the early part of the century.[6]

Production engineering includes all the technical aspects of the manufacturing process: plant layout, process design, work methods, selection of equipment, quality assurance. In larger firms some of these functions may not only fall in different departments, but be further subdivided. Still, regardless of organization charts that isolate the design, manufacturing, and quality functions from one another, these activities are closely related functionally.[7] Product design affects the choice of manufacturing technology. The equipment that a firm has on hand, together with the costs of investing in new equipment, can severely constrain the design of its products. Inspection and testing, quality and reliability, depend not only on the choice of manufacturing technologies, but on the overall control of the process. Application of statistical quality control techniques to individual steps in manufacturing may be straightforward, but overall integration and control of a complex production process is much more than the sum of control of the individual steps.

Although design and production are inherently interdependent, in some cases even simple communication is lost. Stories of design and production supervisors who are not on speaking terms—or the commonplace of the design group "tossing the drawings over the

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[5] See, for example, J. M. Juran, F. M. Gryna, Jr., and R. S. Bingham, Jr. (eds.), *Quality Control Handbook*, 3d ed. (New York: McGraw-Hill, 1974), especially sees. 22-27,

‘See, in particular, *Quality Control Handbook*, op. cit., sec. 48 on "Quality Control and the National Culture, " which points out that the sharp divisions of responsibility typical of larger organizations in the United States—e. g., separate departments for quality control or inspection–create reservoirs of specialized expertise, but at the same time may hinder the widespread *application* of this expertise, Scientific management is discussed in more detail in ch. 8.

[7] J. A. Alic, "Manufacturing Management: Effects on Productivity and Quality, " *Efficiency of Manufacturing Systems* (New York: Plenum Publishing Corp., 1983), p. 281.

wall" to the manufacturing department—are rife. There is at least anecdotal evidence that *foreign firms may handle, not only the problems of training design and manufacturing personnel, but of managing the interface between design and production, better than many American companies.* One approach is to make the same individuals or groups responsible for both design and production, or at least extend management responsibility for integrating design and manufacturing farther down into the organizational structure.[8] In Japan, for example, companies often rotate design engineers through production departments early in their careers.[9] Not only do Japanese electronics firms tend to stress integration of product and process design within their organizations, but they frequently involve vendors, distributors, and customers in the work of their manufacturing engineers.

While some American firms have grappled with such problems more successfully than others, companies here begin with a fundamental handicap: low prestige and low pay tend to be associated with white-collar jobs in manufacturing relative to other categories of engineering or management; the best people are seldom attracted to such jobs. Manufacturing carries higher status in European or Japanese corporations. And, on the manufacturing side of an American firm, quality control tends to be at the bottom of the pecking order. Too often it seems that manufacturing managers see quality control only as an obstacle to production.

American management has been criticized for overemphasizing the costs of quality, whereas some quality control professionals argue that a comprehensive program for designing and building quality (and reliability) into a product at all stages can save money. Again, there seems to be a contrast with the typical attitude in Japanese companies—discussed in more detail below—where prevention of defects is emphasized more strongly than detection through inspection.

One reason for the low status of manufacturing in the United States is simply the low priority that industry places on it, as indicated by low pay scales in manufacturing relative to other parts of the firm; engineers employed in manufacturing and quality control get salaries near the bottom of the range for their age and experience groups at all points during their careers; engineers doing administrative work earn 50 percent more than those involved in production.[10]

Another indication of lack of attention to manufacturing is that only 4 percent of graduates of engineering technology programs in the United States specialize in the "manufacturing, quality control, industrial" category .11 Engineering technology is a relatively new field intended to provide practically oriented training meeting the needs of industry (see ch. 8 for further discussion of technology education), thus it is particularly surprising that such a small fraction of graduates are oriented toward careers in manufacturing. In engineering programs, so few U.S. graduates receive degrees in manufacturing that they are not separately tabulated. Although students who have studied mechanical or industrial engineering often find manufacturing jobs, many programs in these fields have dropped the once common required courses in such topics as manufacturing processes and plant layout,

The Importance of Design

Figure 38 contrasts schematically the effects of design and manufacturing on reliability. Reliability tends to improve with production experience, but failures stemming from design weaknesses sometimes show up only after long periods in service, hence may even increase over time. Such behavior is typical of many

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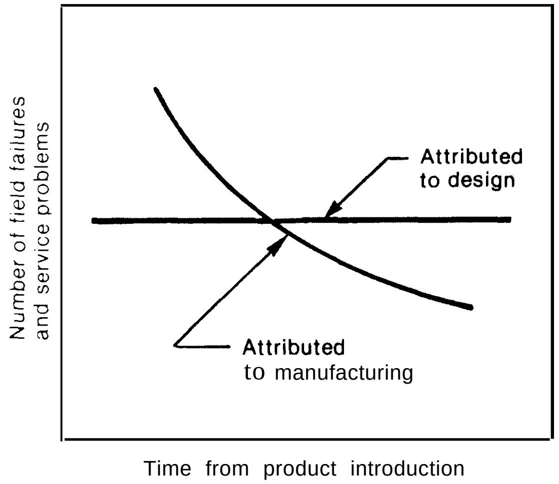
[8] R. E. Cole, "The Japanese Lesson in Quality, " Technology *Review,* July 1981, p. 29. See also "Sources of Japan's International Competitiveness in the Consumer Electronics Industry: An Examination of Selected Issues, " report prepared for OTA by Developing World Industry and Technology, Inc., under contract No. o33-101o.o, pp. 103-104.

[9] J. M. Juran, "Japanese and Western Quality–A Contrast," *Quality Progress,* December 1978, p. 10.

[10] R. Connolly, "Career Outlook," *Electronics,* June 16, 1981, p. 266.

[11] P. J. Sheridan, "Engineering and Technology Degrees, 1982," *Engineering Education,* April 1983, p. 715. The percentage is the total for associate and bachelor levels.

Figure 38.—Typical Trends in Failures Attributed to Design and Production



SOURCE *Quality and Reliability* of Semiconductors *and CTVS United States v Japan* report No C972, prepared for OTA by Consultant Services Institute Inc under contract No 033.11700 p 18

types of manufactured products, not just electronics.

Table 47 indicates the extent to which the reliability of color TVs depends on design as compared to production. According to the table, a greater percentage of service failures have their sources in the design and development process than in assembly. One of the reasons that Japanese TVs achieved better reliability than American-made sets during the 1970's appears to have been more conservative design practice. For example, Japanese sets were designed to draw less power. Picture tubes operated at lower voltages, with some sacrifice to picture quality but lower internal temperatures and less stress on components. In some contrast, the vice president for engineering of an American TV manufacturer, now taken over by a Japanese firm, has been quoted as saying, "At Warwick, much of the design work happened after the product was introduced. We relied on field failure information to tell us where we had a problem."[12]

Table 47.—Causes of Field Service Failures in Color TV Receivers

Attribution	Percentage of field failures
Design (and development) ... ., .	20-400/o
Quality of components	40-65 0/0
Final assembly ., ...	15-20 0/0

SOURCE: J M Juran Japanese and Western Quality—A Contrast, ""Qua/ /(y *Progress* December 1978, p 10

According to the estimates in table 47, about half the failures in TVs are due to defective components. Some of these maybe purchased, others manufactured internally—some components fail because they themselves suffer from design problems. Many of the components in a television receiver are transistors or ICs. As illustrated by figure 36, failure rates per chip tend to remain about the same as circuit density increases. If so, going to higher levels of integration and increasing the number of circuit functions per chip will have two important consequences. First, it will cut assembly costs because the total number of components will decrease. Second, there will be fewer components to fail, hence reliability should improve. The cost and quality/reliability advantages of chassis designs based on fewer but more complex ICs have led to rapid reductions in the numbers of components in TV receivers, In 1977, Zenith's 25-inch color TV contained 685 components. Less than 2 years later, the number had been reduced to 441.[13]

As part of their strategic thrust into the U.S. market, Japanese consumer electronics firms set out to create an image of high-quality, reliable products (ch. 5). They needed trouble-free products in reality as well as appearance in order to exploit the distribution channels available to them. Reductions in parts counts were one of the techniques adopted. Likewise, by the end of the 1970's Japanese semiconductor products had attained enviable reputations for

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[12] '' American Manufacturers St rive for Qual It}-] Japanese Style, " *Business Week*, Mar. 12, 1979, p. 32B.

[13] Ibid. Over roughly the same time period, the] apanese-owned Quasar firm reduced its parts count from 516 to 406, while Toshiba claims a 60-percent decrease in parts count between 1971 and 1979. Other Japanese firms have reported similar reductions, typically coming earlier than for American 'I'\' manufacturers. For example, the number of parts in a particular Panasonic color TV mode] went from 1023 in 1972 to 488 in1976—see "Quality and Reliability of Semiconductors and CTVs: United States v. Japan, " op. cit., p. 47. Japanese T\' manufacturers often pursued simpler chassis designs in parallel with the development of automated production facilities, as discussed later in the chapter,

quality and reliability. But manufacturers in Japan have not relied on design improvements alone; employees of the large, integrated Japanese electronics companies tend to have considerably more training in quality control and production technologies than their counterparts in the United States.

The Japanese Approach

Managements of Japanese electronics firms profess to believe that improvements in quality and reliability will automatically cut costs and increase productivity, as well as aiding their marketing strategies, The rhetoric emanating from top managers in Japan emphasizes quality to a greater extent than statements by American executives. More concretely, Japanese manufacturing companies rely much more heavily on line managers for quality assurance, rather than the staff specialists common in American firms.

Despite this and other organizational differences, most of the methods that Japanese manufacturers use in pursuit of quality and reliability have been borrowed from the United States, just as for product technologies. Japanese industrialists have been noted for their study missions to visit foreign companies and research laboratories. Engineers and managers from Japan have become skilled at picking out useful ideas from such visits—whether related to product technologies or to aspects of manufacturing such as quality control—and improving on them. The theory and practice of quality assurance may have diverged more in the United States than in Japan,

Origins of Quality Consciousness

Stress on quality and reliability within Japanese manufacturing firms goes back at least to the period of postwar reconstruction.[14] Managers realized that Japan's exports were widely viewed as cheap and shoddy. Much of the early effort toward improving Japanese products was orchestrated by the Union of Japanese Scientists and Engineers (JUSE), which helped to locate foreign expertise in quality and reliability, and diffused this knowledge through publications, training courses, and conferences. As many as 10 million workers may now have passed through JUSE training courses.[15]

During the 1950's, well-known Americans such as W. E. Deming and J. M. Juran traveled and lectured extensively in Japan; Juran, in particular, is credited with much of the visibility that quality control now enjoys at upper management levels in Japanese companies, In many respects, the quality control movement in Japan began at the top and spread downward—in considerable contrast to the situation in the United States, where the principal advocates of quality assurance have often been lower level technical specialists. The well-known Deming Prizes–established in 1951, and given to both companies and individuals for achievements in quality control—illustrate the prestige of such activities; they are among the most coveted industrial awards in Japan.[16]

Japanese executives like Hajime Karatsu, Managing Director of Matsushita Communication Industries, have been quality control advocates for years; the Reliability Center for Electronic Components of Japan was formed in the early 1970's at the urging of industry leaders, including Karatsu. Financed privately by more than 200 electronics firms, the center conducts tests on components and systems, establishes procedures for determining reliability, drafts specifications, and diffuses information on quality improvement within the industry.[17]

The Japanese emphasis on line responsibility has led to extensive training programs for assembly workers and foremen. Efforts to reach the latter have included radio and TV

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[14]'' Quality and Reliability of Semiconductors and CTVs: United States v. Japan," op. cit., pp. 38-40. The historical material that follows is drawn largely from this report.

I[5]'' American Manufacturers Strive for Quality—Japanese Style," op. cit.

[16]*Quality Control Handbook*, op. cit., sec. 48, p. 48-9. On the prominence of the Deming Prizes, see U. C. Lehner, "Japanese Firms' Stress on Quality Control Is Reflected in Dogged Vying for Award, " *Wall Street Journal*, Sept. 24, 1980, p. 52. There is even a widely publicized "Quality Month" in Japan.

1[7]'' Guide to REI, " Reliability Center for Electronic Components.

broadcasts; about 100,000 of the accompanying textbooks were sold in the first year (1956) of the radio series alone, A monthly magazine Gemba-to-QC (QC for the Foreman), was established about the same time and evidently served as a breeding ground for quality circles—a technique that has recently received a great deal of attention in the United States (see ch. 8). The first quality circle was registered with JUSE in 1962; within 15 years, memberships in registered quality circles had grown beyond 800,000. JUSE reports that about 100,000 circles are now in operation, with about 80 percent of the nation's blue-collar work force involved.[18]

Standards

In the United States, product standards tend to be voluntary, but Japan's Industrial Standardization Law, passed in 1949, places the responsibility with government. The law deals explicitly with quality and provides that all Japanese exports must carry the approval of the Japanese Institute of Standards (JIS).[19] Consumers in Japan are also said to look for the JIS mark. In 1957, the Japanese Government took a further step aimed at upgrading the quality image of the country's products, passing the Export Inspection Law. This regulation created an additional set of standards aimed mostly at smaller companies, and also provided for the establishment of testing laboratories.

Organizing for Quality

Despite the visibility of quality circles, they are only one tool among the many that Japanese electronics firms have adopted, Because training in quality is widespread, and responsibility for quality assurance diffused within the organization, quality control departments in Japanese firms tend to be small compared to the United States. Companies in Japan have often dispensed with some fraction of in-process inspectors, making each worker responsible for accepting or rejecting the parts passing through his or her station. This is but one example of the diffusion of responsibility through the organization. It is effective in part because—at least in the larger companies—employees are carefully selected even for unskilled, entry-level jobs. Transfers of blue-collar employees within the firm are common—a practice facilitated by unions organized on a companywide rather than craft basis, and newly hired workers, or those transferred to an unfamiliar job, typically pass through training programs that are lengthy compared to those in the United States. At Matsushita, for instance, new assembly line workers are given a month of training—with a week devoted to quality control—before they begin to work on the line.[20] In the United States, new assembly line workers would typically get a few minutes informal instruction by a foreman, who would then monitor their performance as they learned by doing. Both approaches have their advantages.

An apparent paradox has developed in the wake of the 30-year history of quality control activities in Japan outlined above. Many of the original techniques imported from the United States were concerned with statistical quality control—a subject in which Deming and Juran were authorities, Yet there is little evidence that the application of statistical techniques to quality or reliability has advanced any further in Japan than elsewhere. In fact, applications of statistics are seldom mentioned in descriptions of the quality control procedures of Japanese electronics firms, Rather, the *Japanese appear to have focused their efforts on making individual employees aware of—and committed to—the achievement of quality*. Statistical quality control is no more than a small part of the

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[18] "Quality and Reliability of Semiconductors and CTVs: United States v. Japan, " op. cit., p. 60. Circles also enroll clerical and management personnel, It has been claimed that the average quality circle in Japan saves an employer about $100,000 per year.

[19] Ibid., p. 66. A number of other Asian nations have followed the Japanese example in trying to improve the quality image of their exports. In Taiwan, a small tax is levied to cover the cost of inspection; the tax drops as quality levels go up. See "American Manufacturers Strive for Quality—Japanese Style, " op. cit.

[20] "Quality and Reliability of Semiconductors and CTVs: United States v. Japan, " op. cit., p. 52. While three-quarters of the workers in Japanese electronics firms were classed as unskilled at the end of the 1970's, the proportion of skilled as compared to unskilled employees is expected to rise rapidly as automation proceeds. Presumably this is an important motivation for the training programs found in many companies.

quality programs of typical Japanese electronics manufacturers, which the companies themselves often refer to as "companywide quality control. " Intangibles and consciousness-raising are at least as important.

Quality and Reliability of Integrated Circuits

Manufacturing and Testing

Chapter 3 outlined the steps in making ICs. Most of the larger American merchant firms perform some but not all of these in domestic plants, with labor-intensive operations carried out offshore, A typical pattern might be as follows:

- Operations performed in the United States:
  1. Silicon crystals, generally purchased from outside vendors, are sliced into wafers and prepared for lithographic processing,
  2. Wafer fabrication processes such as lithographic patterning, oxidation, etching, diffusion of dopants, metallization, and annealing are carried out; some of these may be highly automated.
  3. Each of the hundreds of ICs (chips) on a wafer is tested; those that fail are marked, typically with an ink drop.
- Operations often performed in offshore facilities:
  4. Individual circuits are separated from the wafer, and the defective chips detected in step 3 discarded.
  5. Each good chip is mounted on a substrate (chip carrier).
  6. Lead wires are bonded to pads on the chip (the lead wires connect to external pins, which plug into sockets installed on circuit boards).
  7. The chip is encapsulated in a metal, plastic, or ceramic package that provides mechanical and environmental protection (metal and ceramic packages are normally hermetically sealed).[21]

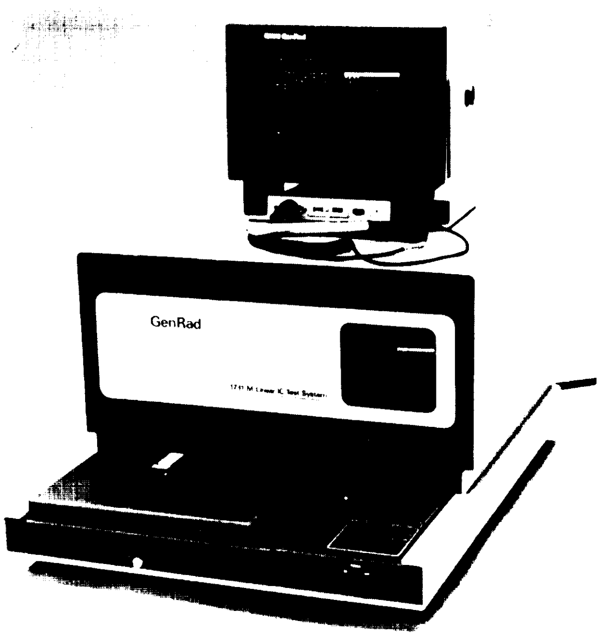

Photo credit GenRad, Inc

Test equipment for integrated circuits

  8. The packaged ICs are subjected to functional tests.

Often the circuits are shipped back to the United States for the final testing in step 8, particularly if destined for American rather than third-country markets. (Economic aspects of offshore assembly are outlined in app. B.)

Outcomes at all these stages in processing—purity of the silicon crystal, wafer flatness, lithographic precision, integrity of wire bonds, hermetic sealing—can affect quality and reliability. Some are more important than others; patterning flaws and poor wire bonds are among the most common causes of failures.[22] During the manufacturing process, inspection

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[21] For a more complete description of packaging and assembly, see A. B. Glaser and C. E. Subak-Sharpe, *Integrated Circuit Engineering: Design, Fabrication, and Applications* (Reading, Mass.: Addison-Wesley, 1977), ch. 10.

[22] For a discussion of failure modes in semiconductor devices, see E A. Doyle, Jr., "How Parts Fail, " *IEEE Spectrum*, October 1981, p. 36. An important technique, particularly for ensuring reliability, is the analysis of failures. ICs that fail during testing or in service can be examined by a variety of methods—e. g., direct observation in a scanning electron microscope—and the causes of failure diagnosed. Corrective action, which might range from a modified circuit design to simple adjustments in process parameters such as temperature, can then be taken. A comprehensive treatment of reliability, emphasizing the importance of the *design* of the circuit, is C. G. Peattie, et al., "Elements of Semiconductor-Device Reliability," *Proceedings of the IEEE*, vol. 62, 1974, p. 149.

and testing are possible at some points but not others; in the absence of good methods for direct testing following a particular processing step, the engineers must rely on control of process parameters based on downstream test results.

Customer Requirements

Differing customer demands lead to a range of standards for the quality and reliability of semiconductor devices. Purchase agreements often specify the testing procedures to be followed. Military circuits must meet especially demanding specifications for resistance to shock, vibration, and severe environments (including radiation); reliability is emphasized for satellite applications. Limited-volume markets for parts intended for military or space applications are often served by small firms specializing in ultrahigh-reliability components. While semiconductors for commercial markets have seldom faced *specifications* as demanding as for military and space applications, the actual functional requirements-particularly for longevity--may be at least as severe. For instance, some computers operate virtually continuously for years, albeit in a service environment that is well controlled and benign; semiconductor devices for automobiles must function reliably--also over many years—in an environment characterized by vibration and extreme temperatures, as well as exposure to gasoline, oil and grease, rain, road salt, and do-it-yourself repair efforts.

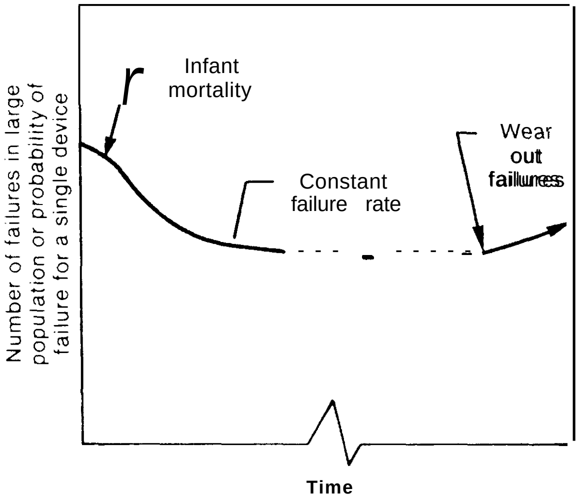
Reliability estimation—e.g., by accelerated life testing—is costly, thus life testing of devices intended for consumer products is minimal, Considerably more reliability testing is carried out on parts destined for computers or communications systems. Because the service record of their products is critical for future sales, and because the costs of locating and replacing faulty parts are high, particularly after the system has gone into service, manufacturers of complex electronic systems demand reliable components. This is one of the reasons firms like IBM or Western Electric chose to build many of their own ICs. Regardless of application, however, the chip manufacturer seeks a production process sufficiently well controlled that testing becomes simply a verification of that control.

Because of these varying customer demands, the electronic components industry has, since well before the semiconductor era, supplied products to a range of quality and reliability specifications; as many as half a dozen levels developed from the initial distinction between military and commercial parts. The lowest level has been for inexpensive consumer products such as toys and games, the highest for applications such as communications satellites, Failure rates for the most reliable devices can be more than a factor of a hundred below those for the least reliable,

Failures in Semiconductors

The time history of failures for a large population of semiconductor devices-as for manufactured products of many kinds—will normally follow a pattern like that in figure 39. Early in life, the failure rate tends to be high, with most of the failures caused by random manufacturing defects. The distinctions between quality and reliability y become rather arbitrary during these early stages, A strict quality standard, for example, might weed out parts that would otherwise fail during the infant

Figure 39.—Typical Failure History for Semiconductor Devices



SOURCE Off Ice of Technology Assessment

mortality period. "Burn-in" tests help detect infant mortality failures; during burn-in, ICs are cycled to high temperatures and exercised by computerized testing equipment.[23]

After the high failure rates early in life, failure frequency usually declines to a nominally constant value—the middle portion of the curve in figure 39. For semiconductor devices, this period typically spans hundreds of thousands, even millions of hours, during which the probability of failure is extremely low, Eventually, the curve may turn up again as devices "wear out" or otherwise deteriorate with age.

While semiconductor products do not wear mechanically, they are susceptible to degradation from environmental exposure, thermal cycling, and a variety of physical processes. Common causes of long-term failures in ICs include: loss of hermetic seal, with consequent damage from moisture or other environmental agents; thermal fatigue of the bond between the chip and its substrate or of the lead wire bonds; gradual thinning and cracking of metallized layers due to electromigration associated with high current densities (even though the currents in ICs are low, the small conducting paths result in high values of current density). Failure probabilities associated with particular mechanisms can be reduced by conservative design at both device and system levels, a common tactic in applications such as satellites or submarine cables,

Testing

Testing costs for ICs increase with levels of integration. Although 100 percent testing is common during the early steps in fabrication, manufacturers normally screen their final output by random sampling; that is, only a small fraction of the outgoing product is subjected to a full battery of tests. Many customers do their own screening of incoming parts. On the other hand, a toy manufacturer may not test incoming chips at all, cutting **costs** by relying on returns and complaints from the field to locate problems. Such an approach is favored where other parts are less likely to fail than the ICs.

Semiconductor products are normally screened and purchased to an *acceptable quality level* (AQL), a procedure much less expensive than 100 percent testing. From the standpoint of the purchaser, the AQL is the permissible fraction of *delivered* parts that can be defective—i.e., that escape detection during inspection and screening. A 1 percent AQL means that no more than one defective circuit out of every 100 is allowed, on the average, in an acceptable lot; statistical sampling methods are tailored to this requirement.

Figure **40** outlines the testing program adopted by a manufacturer of point-of-sale terminals for purchased ICs. Tests are conducted at many points prior to shipment because downstream failures cost much more to find and fix, Costs are even higher for field failures—both the direct expenses of warranty repairs and the possible costs in terms of damage to the firm's reputation. Table **48** illustrates the growth in costs of locating and repairing faulty components at successively later stages. The indirect and intangible costs can be much greater than the direct expenses.

Testing and Screening in Japan

When first qualifying a new vendor, Japanese purchasers normally test all incoming parts, With satisfactory experience, statistical sampling replaces 100 percent testing. If the defect fraction remains below 0.01 percent (100 defects per million parts) and downstream failures are rare, the purchaser may stop screening. Even when purchaser and supplier are unrelated firms, customers prefer to depend on their suppliers to guarantee quality levels. Japanese manufacturers do tend to rely rather extensively on in-process testing, aging, and burn-in—in part to minimize infant mortality failures.

Such practices differ from the arms-length relationships common in the United States. Perhaps because the major Japanese manufacturers of semiconductors are also the major users, they often appear to take the attitude that the objective of quality control is to deliver

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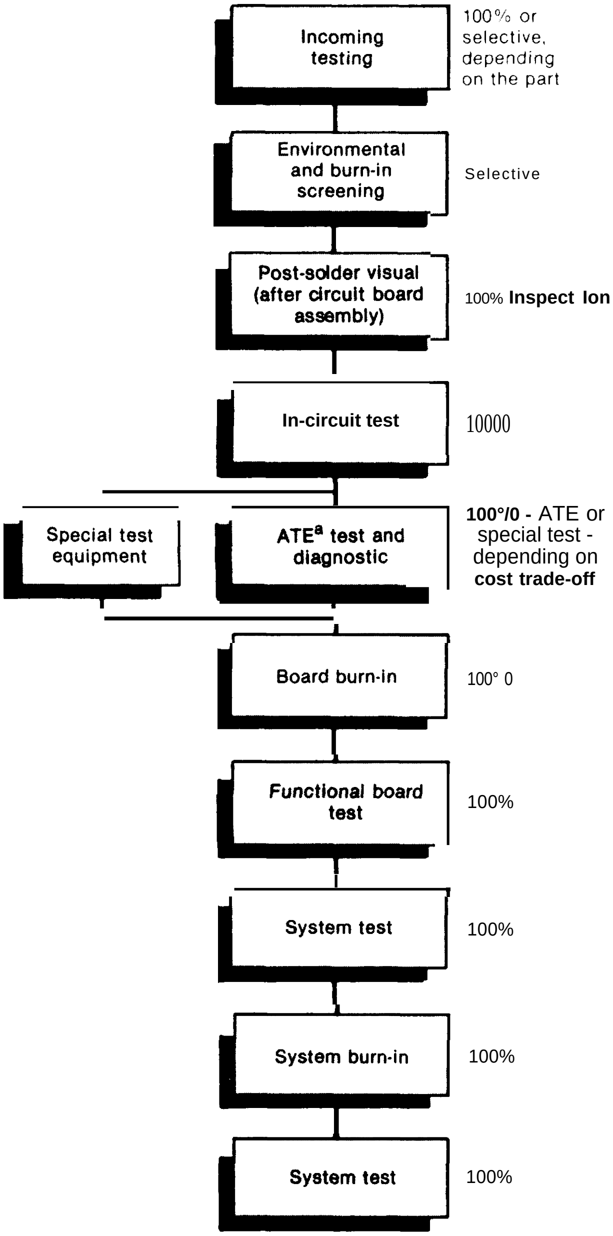
[23] Eleven percent of nearly 20,000 ICs tested for the 1977 Pioneer mission to Venus were rejected, many of these tests involving burn-in periods of 100 to 200 hours. The very high reject rate reflects the severity of the application. See "Quality and Reliability of Semiconductors and CTVs: United States v. Japan, " op. cit., p. 14.

Figure 40.—Testing Sequence for Point-of-Sale Terminals



aATE = Automatic Test Equipment

SOURCE Adapted from R Fleishman. R J Lever and R N Parente, Total Testing *Circuits Manufacturing,* November 1979, p 32

parts that meet their own in-house standards, A more common attitude in the United States has been that parts need only meet the customer's requirements; customers that demand high quality may get it, others receive less attention.

Table 48.—Typical Costs of Detecting and Repairing Faulty Components in an Electronic System

Point of detection	Direct cost	Intangible cost
Device level	Cost of device, if not refunded by manufacturer.	Minimized if more devices than needed are purchased initially.
Circuit board level ...	$5	Manufacturing process dislocated,
System level	$50	Shipment may be delayed, disrupted.
In the field. .,	$500	Customer upset,

SOURCE "Calls Volume Key to Testing Decision," Electronic News, Feb. 18, 1980, supplement p. 20.

Quality and Reliability Comparisons

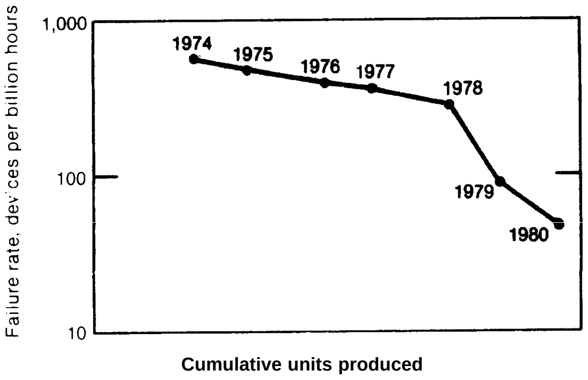
Although respective quality levels of ICs made in the United States and Japan have been debated for several years, there is little concrete data bearing directly on this matter. For a valid comparison, circuits from U.S. and Japanese firms should be tested under the following conditions:

1. The devices should be the same type and of similar designee. g., 4K dynamic RAMs, 8080 microprocessors.
2. Test procedures should be identical, the tests conducted at about the same time. (It is not possible to compare quality or reliability at the present moment. Quality comparisons always refer to some point in the past. And, while the most recent results are always desirable, quality and reliability are dynamic characteristics; they fluctuate with the vagaries of the manufacturing process,)
3. The ICs should be produced to the same purchase specifications in terms of AQL or other quality requirements, ideally for delivery to the same customer.

While it is no surprise that little of this kind of data has been made public, the unfortunate consequence was a series of public relation ploys obscuring the technical questions: Were there real differences in quality? If so, what were the reasons?

By any measure, *semiconductor quality and reliability have improved immensely over the years,* regardless of whether the devices have been produced in the United States, Japan, or Europe. As an example, figure 41 shows de-

Figure 41.— Reliability Trend for Analog Integrated Circuits



SOURCE G Peattie,'Quality Control for ICs *IEEE Spectrum*, October 1981 D 93

creases in failure rates for analog (linear) ICs as used in consumer electronic products. Other types of ICs show similar trends. Nonetheless, sources in the American electronics industry—both manufacturers and purchasers of semiconductors—agree that, during the mid to late 1970's, quality levels delivered by Japanese firms were superior to those delivered by U.S. firms. There is also broad agreement that quality levels delivered by American semiconductor firms have greatly improved since the publicity given the Japanese "quality advantage" during 1980.[24] The available data is summarized in appendix 6A. But at the same time that U.S. semiconductor firms have made rapid strides, Japanese manufacturers have also improved. While the gap has certainly narrowed, Japanese firms *on the average* may remain ahead in quality.

It is also important to recall that discussions and data on IC quality have centered on products sold in the merchant market. No data have been made public on quality levels attained by captive producers such as Western Electric or IBM. Captives account for about 40 percent of all ICs made in the United States (ch. 4); the quality and reliability attained by captive producers would, if available, be a useful indicator of the relative *technological* capability of the American industry.

The ranges in quality level included in appendix 6A, particularly table 6A-2, show a remarkable lack of consistency on the part of all vendors, Even the top 16K RAM suppliers exhibited a factor of five difference between best and worst lots. Much larger spreads were the rule, particularly for the American firms. This illustrates the danger in generalizing from limited samples of IC quality data. It also indicates the importance of a consistent and well-controlled manufacturing process, and the difficulty of maintaining that control.

Spokesmen for the U.S. semiconductor industry have sometimes claimed that Japanese firms create a false image of higher quality by sorting ICs and sending only the best to important customers like Hewlett-Packard—a practice that has been termed "quality targeting" or "quality dumping. " The claim is further made that this is a high-cost strategy, intended to "buy" U.S. market share—and that after their American competitors have been forced out, the Japanese will raise their prices and ship their normal product, which will be found to be poorer in quality .[25] Indeed, manufacturers in many industries and in many countries sometimes attempt such strategies. American semiconductor firms will sort ICs and ship higher quality lots to purchasers who demand them. However, as a widespread and general approach to marketing in the United States, quality dumping by the Japanese seems implausible. In order to ship higher quality lots to the United States, they would have to ship lower quality products to other customers—in either export or domestic markets—thus running the risk of jeopardizing those markets. It is difficult to believe that Japanese IC manufac-

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[24] Much of this publicity stemmed from a seminar entitled "Quality Control: Japan's Key to High Productivity," organized by the Electronic Industries Association of Japan and held in Washington, D. C., on Mar. 25, 1980. Data first released at that seminar appear in appendix table 6A-1, pt. A. A perspective common in much of the American merchant semiconductor industry at that time can be found in T. D. H inkelman, "The Economics of Quality: U.S. vs. Japan, " *An American Response to the Foreign Industrial Challenge in High Technology Industries,* Proceedings of the Semiconductor Industry Association Government Policy Conference, Monterey, Calif., June 18-19, 1980, M. Hodgson (cd.) (Palo Alto, Calif.: Worden Fraser Publisher. 1980), p. 85.

[25] T. D. Hinkelman, op. cit. See also "The Quality Goes On Before the (Japanese) Name Goes On, " *Rosen Electronics Letter,* Mar. 31, 1980, p. 1.

turers would do so in any concerted way, particularly at home.

It is clear from the data in appendix 6A that, at least until the recent past, Japanese large-scale ICs have had, *on the average,* both better quality and better reliability than comparable American parts. This does *not* mean that some products from some U.S. companies were not as good as or better than products from Japan. As the tables in appendix 6A indicate, the range in quality and reliability delivered by any firm is likely to be wide; this is intrinsic to the technology of semiconductor manufacturing, But as a generalization, the United States had fallen behind in both quality and reliability, It is also clear that the performance of American firms on these dimensions has greatly improved—in part because of the competitive pressures generated by the publicity given this issue. According to recent reports, the quality levels of 16K RAMs supplied by a number of American firms are now, on the average, about the same as those of Japanese devices .26

While this is a positive sign for the future, it does appear that Japanese firms devote more resources to analyzing field failures so as to find and eliminate their causes. In Japan, electronics firms have normally maintained captive service organizations which gather and analyze field service results, and feed them back to design and manufacturing departments. One American purchaser of Japanese semiconductor devices was reportedly quite surprised to find a team of engineers dispatched to explore the reasons for a batch of circuits with a defect rate of only **0.25** percent. 27

In the future, *if American managers devote as much attention—and as many resources—to the quality and reliability of their products as do the managers of Japanese firms, there is no reason why U.S. firms should not keep pace with, or surpass, their overseas rivals on these dimensions of IC technology.*

Quality and Reliability of Color TVs

That Japanese TV manufacturers have achieved excellent quality and reliability, and largely succeeded in their marketing strategies, is self-evident. In order to bypass the franchised dealer networks that American manufacturers relied on, they had to forgo extensive service organizations. Failure by Japanese importers to maintain both the image and the reality of a reliable, trouble-free product would risk the largest market in the world. Most surveys continue to show the *reliability* of TVs produced by Japanese firms to be better, though differences in *quality* appear small.

Many of the TVs sold in the United States by Japanese firms are now assembled here. Quality levels achieved in the U.S. operations of both Sony and Quasar—the firm that Matsushita bought from Motorola in 1974—have received a good deal of publicity.[28] Such plants tend to combine features typical of Japanese and American manufacturing operations; see chapter 8 for a discussion of management styles and their effects. At least as important, TVs assembled in the United States by Japanese-owned firms contain large proportions of imported components. Based on the findings for semiconductor devices outlined in the previous section, imported components might be expected to exhibit somewhat higher levels of quality and/or reliability than similar parts from American suppliers.

Most of the information bearing on quality and reliability for TVs comes from sources like *Consumer Reports*. Several years ago this pub-

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[26] E. R. Hnatek, "Semiconductor Memory Update: DRAMs," *Computer Design*, January 1982, p. 109; "Faults Show Up in Japanese RAMs," *Electronics*, Jan. 13, 1982, p. 33; "In Semiconductors, Perfection Is the Goal," *Business Week*, Nov. 1, 1982, p. 72.

[27] "Quality and Reliability of Semiconductors and CTVs: U.S. v. Japan," op. cit., p. 57.

[28] On Sony, see "Statement of Sadami 'Chris' Wada, Assistant Vice president, Sony Corp. of America,' *Quality of Production and Improvement in the Workplace*, hearing, Subcommittee on Trade, Committee on Ways and Means, House of *Representatives*, Oct. 14, 1980, p. 62

At Quasar, quality levels improved rapidly after the Matsushita purchase; however, the baseline is deceptive in that Motorola devoted few resources to its TV operations for a number of years prior to the sale. This case is discussed in more detail in the appendix to ch 8.

lication surveyed nearly 200,000 owners of 19-inch color TVs, the most popular size, sold during the period 1975-79. Nine of the fifteen brands for which the origins are known–all the Japanese makes but no others—were given reliability ratings of “better than average” based on the average cost of repairs during the 1979 calendar year. The remaining six brand names—for practical purposes, all the American brands—were rated “average” (one brand) or “worse than average” (five brands).[29] The *Consumer Reports* survey reflects reliabilities of sets sold during the period 1975-79 only. However, TV designs do not change rapidly; these trends should still be a reasonable indication of comparative reliability levels,

Similar but not identical reliability rankings come from a survey conducted by Trendex in the same year, 1979, but again covering TVs manufactured over a period of years.[30] Of the 12 brands included in this survey, TVs made by Japanese-owned firms filled four of the top five places in terms of reliability, The remaining Japanese brand ranked seventh, with the bottom five positions filled by American firms plus Magnavox.

Table 49 presents data from a survey of TV repair shops that point in a direction rather different from the consumer surveys discussed above. This table covers a smaller number of brands: three American (Zenith, RCA, and Sylvania—the latter at that time U.S.-owned, though since purchased by Philips); three Japanese (Sony, Quasar, and Panasonic—the latter two are Matsushita brand names); plus Magnavox. The repair shops rated the American brands generally superior on all three criteria—performance, reliability, and costs of repair. In particular, the largest-selling U.S. TVs—those made by Zenith and RCA—show up very well, with Zenith top-ranked in each category, In contrast, Zenith and RCA are rated “worse than average” in reliability by *Consumer Reports*. Because the *Consumer Reports* survey covered such large sample sizes—more than 40,000 owners of 19-inch Zenith sets, and 35,000 made by RCA—it must be given considerable weight. However, the data in table 49 are not restricted to any particular screen size, and might be more representative of each manufacturer’s overall product line.

Table 49.— Rankings by Repair Shops of TV Receivers for Quality and Reliability

Rankings in terms of picture quality and other performance features:

1. Zenith
2. RCA
3. Sony
4. Sylvania
5. Quasar
6. Magnavox
7. Panasonic

Rankings in terms of reliability:

1. Zenith
2. Sony
3. RCA
4. Quasar
5. Sylvania
6. Panasonic
7. Magnavox

Rankings in terms of increasing costs of repair:

1. Zenith
2. RCA
3. Sylvania
4. Quasar
5. Magnavox
6. Sony

SOURCE “Quality and Reliability of Semiconductors and CTVs U.S. v. Japan, ” report No, C972, prepared for OTA by Consultant Services Institute, Inc , under contract No 033-1170.0, p. 79, The survey, conducted during 1960, covered 60 repair shops in Chicago, Boston, and Northern New Jersey.

As is true for ICs, American manufacturers of TVs have clearly made considerable strides in improving quality and reliability—spurred by competition among themselves as well as with the Japanese, Consumer electronics firms now screen and burn-in components more thoroughly; they also burn-in complete circuit boards and assembled sets to weed out early failures. Automation has helped quality. Finally, American TV makers are using larger num-

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[29] “19-Inch Color TVs, ” *Consumer Reports,* January 1981, p. 34. The nine brands in the “better than average” reliability category included TVs sold by Sears, most of which are made by Sanyo-some imported, some assembled in the United States. Other private brand merchandisers—e. g., Montgomery Ward, J. C. Penney–tend to purchase from both American and foreign suppliers, Excluding both the Wards and Penney TVs because of their uncertain origins, 15 brands remain. Of the 15, 5 are American, 9 are Japanese, and the other—Magnavox—is owned by Philips. As Magnavox is much more nearly independent of its parent than the American subsidiaries of Japanese firms, it has been considered a U.S. brand for purposes of this comparison.

[30] ’’ Quality and Reliability of Semiconductors and CTVs: U.S. v. Japan, ” op. cit., p. 78.

bers of imported components—mostly from Japan and other Asian countries. Imported components often cost less, but in at least some cases they have been chosen because of superior quality and/or reliability, Even picture tubes—which are bulkier and more difficult to ship than other components—are being imported in increasing numbers; one U.S. manufacturer stated that Japanese picture tubes had one-third the in-process failure rate of American-made tubes .[31]

Consumer perceptions created by and reflected in surveys like those discussed above can be extrapolated with some confidence into at least the near future. Furthermore, because TVs have a design life of **7** to 10 years, the surveys discussed above should do a good job of predicting the reliability of sets presently in use. *The weight of the evidence points toward an advantage in reliability for Japanese TV manufacturers during the* **1970's.** *Even if American manufacturers today are producing TVs as reliable as their Japanese competitors, the image of reliability that the Japanese have gained will persist for a number of years to come,* On the other hand, differences in *quality* among TVs appear to be small.[32]

Automation

Managers make decisions involving the automation of production processes largely on the basis of costs. Automation typically involves tradeoffs between labor cost and capital cost that depend on production volumes; mechanized production facilities also tend to lack flexibility, which raises the costs of adapting them to new product designs. Factors less directly related to costs include the impacts of automation on quality, and the possibility of mechanizing unusually dangerous, dirty, or onerous jobs.

Modern automated production systems usually rely on electronics, although electromechanical control systems were common until recently. Examples of automated processing include:[33]

- automatic machine tools, ranging from lathes and milling machines controlled by mechanical cams, to those that operate under computer control, to machining centers;
- automated gaging, inspection, and testing; examples include inspecting circuit boards by means of video image processing to check for solder runs or other visible defects, measuring the dimensions of machined parts, and determining the chemical composition of steel;
- mechanized systems for materials handling, ranging from computer-controlled conveyors to fully automated warehouses;
- process control systems incorporating sensors and processors that implement control algorithms based on feedback, feedforward, or some combination (see ch. 3, app. 3C, on industrial process control);
- use of computers in management or support functions such as scheduling of job flows, inventory control, or statistical quality control; and
- computer-aided design methods to aid in geometric modeling, in engineering anal-

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[31] Ibid, p. 80. Japanese-owned firms that assemble and sell TVs in the United States still import many components, but are gradually increasing value added here. Mitsubishi—which produces sets in the United States for sale under the MGA brand name—imports about **30** percent of their parts from a subsidiary in Singapore, and another 15 percent from Japan. Sony continues to bring in from Japan about 35 percent of the parts for their American-made sets. In general, the more critical components and subassemblies from a performance and quality standpoint are imported—e.g., circuit boards. Cabinets and nonelectronic parts are the first to be purchased domestically. See *Quality of Production and Improvement in the Workplace,* op. cit., p. 85.

[32] For example, "Small-Screen Color TV's, " *Consumer Reports,* January 1982, p. 17, where the distribution of brand ratings by set performance and quality shows no systematic differences among U .S. and foreign brands.

[33] See, in general, M. P. Groover, *Automation, Production Systems, and Computer-Aided Manufacturing* (Englewood Cliffs, N. J.: Prentice-Hall, *1980).*

ysis, or in preparing design drawings or equivalent design information coded for automated production processes.

The earliest numerically controlled (NC) machine tools operated from instructions on a paper tape or similar storage medium, analogous to the cams and other electromechanical controls used for many years to automate manufacturing. The NC tape, however, could be prepared with the aid of a computer, and easily duplicated or modified, In the next stage, rather than following a sequence of instructions held in a read-only memory such as a paper tape, direct numerically controlled (DNC) and computer numerically controlled (CNC) machines were developed. These respond in real time to commands from the processor of a computer. As a result, control algorithms based on gaging or sensing of machining parameters can, at least in principle, be implemented. In a DNC system, one computer controls several machines; CNC machines operate under the control of a dedicated processor, typically a small minicomputer or a microcomputer.

Sophisticated control systems use information from sensors for regulating the process, typically by adjustments that keep measured parameters within predetermined bounds. For a machining operation, dimensions can be measured; for a wafer fabrication line in a semiconductor plant, possible control parameters include temperatures, pH of reagents, and current flows during ion bombardment, In contrast to such "closed loop" systems, in which information flows from the process back to the controller, systems in which there is no sensing and transmission of information, but which operate purely on preprogrammed instructions, are called "open loop, " A skilled machinist closes the loop just as does an automatic control system on a CNC lathe equipped for automatic gaging. But in fact, most NC machines still run on an open loop basis,

Electronic control systems make possible the automation of many processes that in earlier years were too difficult or too expensive to mechanize.[34] In essence, the flexibility gained through electronic controls makes automation cost effective in applications where production volumes are low. In the past, automation was practical only in continuous process industries such as food preparation and packaging, or in high-volume batch production industries like automobile manufacture. In the automobile industry, simple assembly operations, as well as machining, have been carried out by transfer lines linking a series of machines for many years; human operators have worked along the line performing tasks that were difficult or costly to mechanize.

Fixed and Flexible Automation

Automated production in either continuous process or batch industries can be thought of as spanning a range from "fixed" or "hard" automation to "flexible" or "programmable" automation, Fixed automation is exemplified by an automatic lathe in which the "instructions" are encoded in the profiles of cams. To set up the lathe for a different job, the cams must be changed, Designing and machining a new set of cams is a time-consuming job performed by skilled craftsmen, Conventional transfer lines are examples of fixed automation applied to a sequence of tasks, When an automobile manufacturer designs a new engine or transmission, the entire transfer line might have to be scrapped and replaced. Much the same is true if an electronics firm using such equipment wishes to introduce a new design for a printed circuit board, TV chassis, or computer terminal.

Until recently, automated production equipment with the flexibility to accommodate substantial variation in the design of the product was the exception rather than the rule.[35] Machines seldom adapt very well to perturbations

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[34] J. A. Alic, "Government Attitudes "reward Programmable Automation, " *proceedings of the Twenty-third International Machine Tool Design and Research Conference, 13.* J. Davies (cd,] [London: Macmillan, 1983), p. 521.

[35] Flexibility in the context of manufacturing systems carries a number of possible meanings; see, for example, D. Gerwin, "Do's and Don'ts of Computerized Manufacturing, " *Harvard Business Review,* March-April 1982, p. 107,

in the process—e.g., a part that comes down a conveyor sideways—much less to new product designs. When flexibility has been needed, manufacturing operations have depended on people. Engine lathes, which are operated entirely under manual control, are the flexible counterpart of the automatic lathe. A skilled machinist can make an amazing variety of different parts on an engine lathe, but the cost per part will be high.

One reason for the lack of flexibility characteristic of fixed automation is that new hardware—fixtures, tooling—is needed to accommodate a new design. A second reason is that the controls must be reprogrammed. A hardwired electronic control system—whether analog or digital—requires new circuitry every time the control logic is altered, This is costly and time-consuming, just as for an automatic lathe that requires a new set of cams. In recent years, computer control has become cost effective for replacing many mechanical or electromechanical control systems.

While the performance of a computer-based programmable controller—as a control system—will generally be superior to the alternatives, this is not necessarily the case for *hardware*. Often, flexibility in hardware trades off against performance, and perhaps capital cost as well. For example, a robot can be programed to weld together sections of pipe, but might not be as fast as a specially designed automatic welding machine—which might also produce better quality welds. However, the robot could be programed to do other tasks. In general, then, a flexible facility may be less efficient for making *any one product* than a dedicated, hard-automated manufacturing system.[36]

As flexible automation technologies incorporating computer-based control systems improve, an enormous pool of potential applications will open; the consequences will include, not only cost reductions and productivity improvements, but shifts in the composition of the factory work force. Skill mixes needed in manufacturing industries will change, and the total number of employment opportunities in the manufacturing sector of the U.S. economy may shrink even as total output increases. (Employment levels and work force composition are discussed in chapter 9.)

Automation in Electronics Manufacture

Reasons for Automating

Most applications of automation by U.S. electronics firms have been driven by costs; noncost factors have perhaps weighed more heavily for Japanese manufacturers. The industry in Japan has at times faced labor shortages; in addition, Japanese firms may sometimes have been motivated by potential quality improvements to automate earlier than their American counterparts.[37]

Table 50 presents the results of a 1979 survey in which Japanese electronics manufacturers were asked to list reasons for their decisions to automate. The most common response was to reduce costs, with quality improvements second; in contrast, a 1975 survey found labor shortages ranked at the top. Comparison of 1975 and 1979 results shows a rapid increase in automation by Japanese electronics manufacturers.[38]

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[36] Recent R&D work at Westinghouse illustrates a typical application of flexible manufacturing—here assembly, one of the most challenging tasks for automation. Westinghouse makes more than 450 different models of small electric motors, with an average lot size of 600; model changes average 13 per day. In such cases, labor-intensive manufacturing methods have generally been preferred. Fixed automation using transfer lines has been a real option only for long production runs of similar or identical products. For a description of the flexible assembly system under development, see R. G. Abraham, "ADAS Adaptable Programmable Assembly System," *Computer Vision and Sensor-Based Robots*, G. G. Dodd and L. Rossol (eds.) (New York: Plenum Press, 1979), p. 117.

Another example of flexible automation in assembly—this one already in use—is a machine developed in Japan by Nippondenso that can put together 288 different versions of an automobile dashboard indicator, The average lot size is 40, with 200 changeovers per day. See "British Government Finances Robotics Development," *West Europe Report: Science and Technology*, No. 70, Joint Publications Research Service JPRS 78820, Aug. 25, 1981, p. 14.

[37] K. Ito, E. Taira, S. Yagi, K. Iwamoto, and H. Tsukamoto, "The Progress of Automation and the Improvement of Reliability in Production of Color TV Receivers," *IEEE Transactions on Manufacturing Technology*, vol. MFT-3, December 1974, p. 55.

[38] "Quality and Reliability of Semiconductors and CTVs: United States v. Japan," op. cit., p. 47. Japanese consumer electronics firms reportedly spend about a third of their R&D dollars on man-

Table 50.—Reasons Given by Japanese Electronics Firms for Automating

Percent of firms surveyed[a]	Reasons for automating
840/o	Reduction in manufacturing cost
69	Improvement in quality
43	Increase in production volume
43	Improvement in workplace conditions
32	Labor shortage

[a]Multiple responses were common.

SOURCE: *Nikkan Kogyo Shimbun,* May 1, 1979, and July 11, 1979, cited in "Quality and Reliability of Semiconductors and CTVS United States v. Japan, " report No. C972, prepared for OTA by Consultant Services Institute, Inc , under contract No 033-1170.0, p. 50.

Consumer Electronics

Manual assembly was at one time the rule for electronic products ranging from radios and TVs to computers. Components were first inserted and/or soldered into circuit boards, the boards then installed in a chassis, the assembly finally tested and adjusted. Component insertion was one of the first tasks to be mechanized. This is relatively easy for discrete components with axial leads, more difficult for ICs. Consumer electronics manufacturers first moved to automatic insertion of discrete parts; as ICs were designed into TVs, they were at first still inserted manually. By the end of the 1970's much of this work had been automated as well, using equipment roughly similar to that pictured in figure 42.

The spread of automation in the U.S. consumer electronics industry has been incremental. Firms automated at different times and for different reasons, depending in part on strategic responses to foreign competition. In most cases, the initial reaction, based on Japanese advantages in labor costs, centered on moving labor-intensive operations offshore rather than automating.

When American TV manufacturers did respond to competitive pressures by automating, cost was the driving force, quality and reliability improvements secondary. Meanwhile, the Japanese continued to take the initiative in automation, even though their labor costs remained lower. By 1976-77, 50 to 80 percent of all component insertion in Japanese TV factories had been mechanized.[39] Computer-controlled testing and inspection of components, subsystems such as circuit boards, and complete TVs also spread rapidly. Concurrently, chassis were redesigned to take advantage of the characteristics of automated production equipment. According to one study, labor productivity in the assembly of color TV receivers was a little greater in the United States than in Japan in 1970, but by 1977 productivity in Japan was more than twice that here–figure 43.[40]

Semiconductors

In the earlier years of the semiconductor industry, virtually all production operations—fabrication, assembly, inspection and testing—were labor-intensive. Among U.S. firms, the spread of automation may have been retarded by the widely publicized difficulties of Philco Corp., which invested heavily in automated manufacturing during the late 1950's only to see rapid changes in transistor technology render its equipment obsolete.[41] Philco later dropped out of the semiconductor business.

At present, semiconductor firms in all parts of the world are automating rapidly, not only in manufacturing but in computer-aided circuit design. A few companies—both American and foreign—have installed fully mechanized production lines, from wafer fabrication through inspection, testing, wire bonding, and packaging. The benefits include increased yields as

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ufacturing developments; see *Transfer of Technology in the Consumer Electronic Industry, Sectoral Study No. 2* (Paris: Organization for Economic Cooperation and Development, Sept. 14, 1979), p. 41. This percentage is probably a good deal higher than in the United States or Europe.

s@ For a description of some of the technology used by Mitsubishi, see T. R. Crossley, "Study Tour of Industrial Robots in Japan, " European Office of Aerospace Research and Development report No. EOARD-TR-80-3, London, August 1979, pp. 32-33. At the time of this visit, Mitsubishi was using robots of their own design for assembling printed circuit boards for TVs. The assembly line could be changed over for a different board configuration in 2 hours.

[40] I. C. Magaziner and T. M. Hout, *Japanese Industrial Policy* (London: Policy Studies Institute, 1980), p. 22. The data comes from work performed by the Boston Consulting Group.

[41] J. E. Tilton, *International Diffusion of Technology: The Case of Semiconductors* (Washington, D. C.: The Brookings Institution, 1971), p. 83.

Figure 42.—Automatic Installation of Integrated Circuits Onto Ceramic Substrate

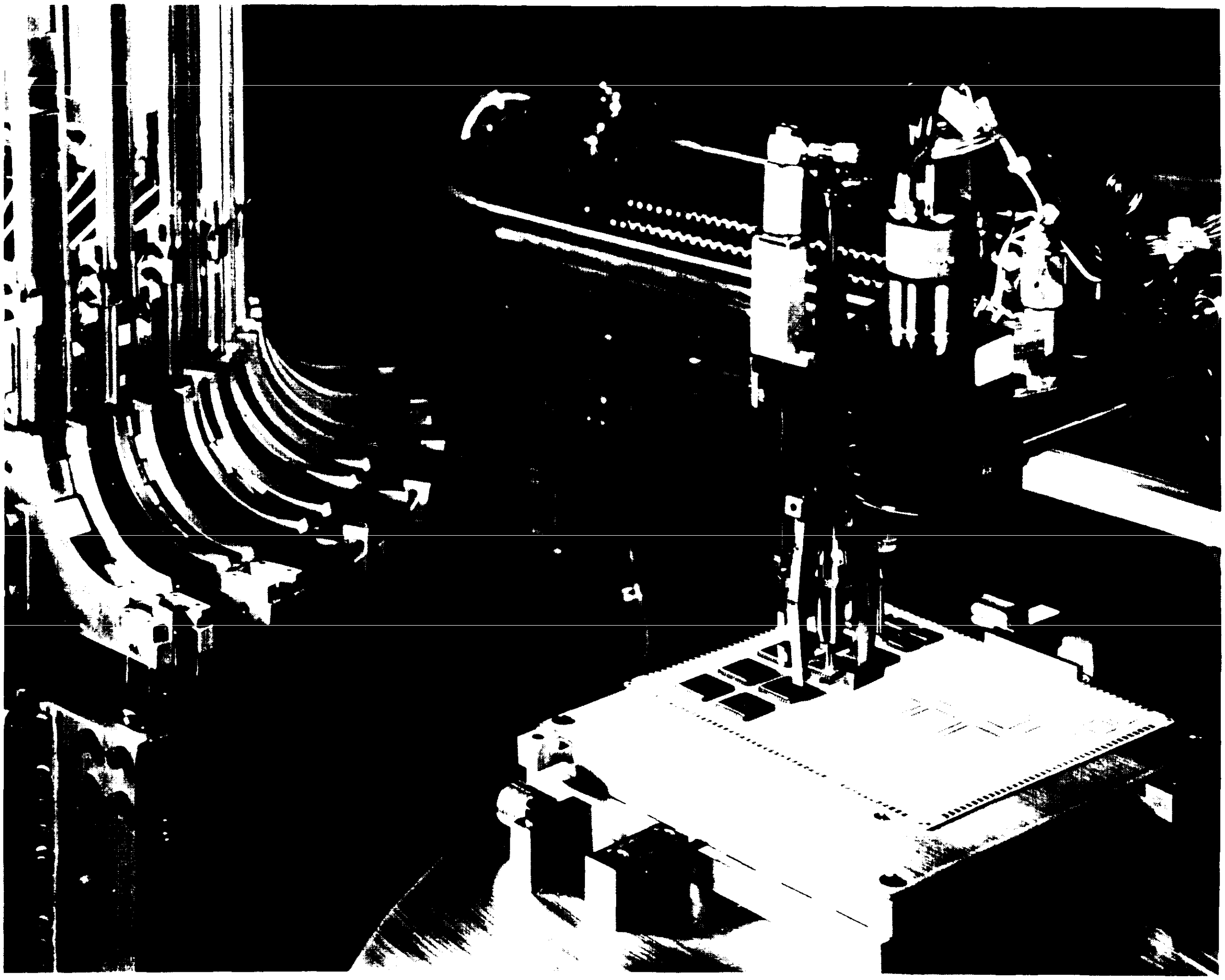

Photo credit Universal /instruments Corp

a result of better process control, Toshiba, for example, claims that its automated wafer fabrication facility has increased yields by 10 to 15 percent, and production rate by 20 to 40 percent; the control system, based on a central mainframe computer, includes 3 minicomputers and 74 microcomputers.[42]

Rates of Automation in the United States and Japan

While much of the evidence for the push toward automation in Japan is anecdotal, and quantitative data on relative extents of automation scarce, many commentators point to attitudes toward automation as an important difference between U.S. and Japanese manufacturers in both consumer electronics and semiconductors.[43] At the same time, it appears that the more integrated American semiconductor manufacturers—e.g., Western Electric, Texas Instruments, IBM—automated at a more rapid pace than smaller merchant firms. Japanese

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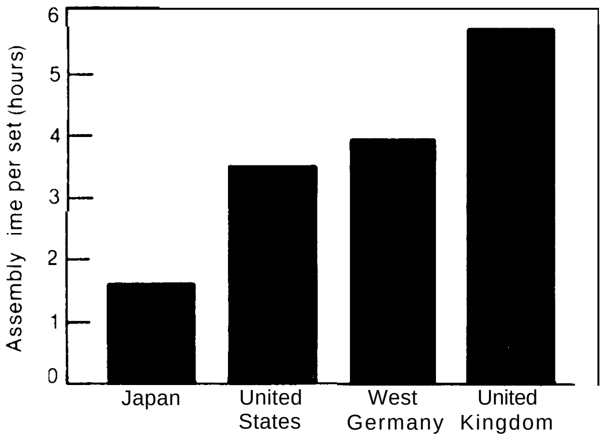
[42] "Toshiba Completes Fully Automated Production of IC's," *Japan Report*, Joint Publications Research Service JPRS 1./10264, Jan. 19, 1982, p. 85.

[43] R. H. Silin, *The Japanese Semicon doctor Industry: An Overview* (Hong Kong: Bank of American Asia Limited, January 1979), p. 124. See "The Drive for Quality and Reliability, Part 1," *Electronics*, May 19, 1981, for a discussion of the use of automation by Japanese IC manufacturers, especially p. 133.

Figure 43.—Average Labor Hours for Assembly of 21-Inch Color TV Receivers (1977)



SOURCE I C Magaziner and T M Hout, *Japanese Industrial Policy* (London. Policy Studies Institute, 1980), p 23. Data are from a client study performed by the Boston Consulting Group.

electronics companies do seem to have adopted robots more quickly than their American counterparts, Two to three times more robots are at work in Japanese factories than in the United States; about 40 percent of these have been installed in the factories of Japanese electronics and electrical equipment firms.[44] But again, a number of the larger American electronic companies are well known both for their R&D in robotics technology and for their applications of robots in manufacturing.

Some American electronics firms may have had difficulty in finding the capital needed for automation. The replacement of labor-intensive production operations by capital-intensive equipment aggravates the problems of financing expansion (ch. 7); a transfer line for inserting components in a circuit board can easily cost half a million dollars. In contrast, to their smaller American competitors, Japan's integrated electronics manufacturers can take advantage of internally generated funds—as well as somewhat lower costs for external capital—to invest in mechanized equipment. Furthermore, the Japanese Government has reportedly given preferential tax treatment for investments in production equipment that will improve the quality and reliability of Japanese goods, particularly those for export.[45] Such actions have probably affected the timing of investments more than the eventual extent of automation.

Although a few American semiconductor firms make some of their own manufacturing equipment—notably the larger, more highly integrated companies—most such equipment is designed and built by independent suppliers, In Japan, it is more common for electronics firms to design and fabricate their own. Matsushita, for example, meets 30 to 40 percent of its equipment needs internally.[46] Internal capability for equipment development can help speed automation.

As integration levels for ICs continue to increase, automation will become a necessity. Fine line widths and other requirements for very large-scale integration (VLSI) demand levels of cleanliness that are much easier to achieve if human intervention is minimized. More complex circuits can only be designed with computer-aided techniques, together with computer-aided drafting and mask generation; once built, such circuits can only be tested with computerized equipment. Better process control models—now limited by gaps in fundamental understanding of the physics of electron devices—will be needed to ensure the quality and reliability of VLSI circuits. Continued automation may reduce pressures for offshore

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[44] R. Ristelhueber, "Robotics-The Applications Gap, " *Electronic News*, Jan. 11, 1982, p. 60,

[45] " Quality and Reliability of Semiconductors and CTVs: United States v. Japan, " op. cit., p. 25.

[46] U. C. Lehner, "Japan Strives To Move From Fine Imitations to Its Own Inventions, " *Wall Street Journal*, *Dec.* 1, 1981, p. 1. Japanese firms continue to purchase a good deal of automated production equipment from American suppliers; as pointed out in ch. 4, about half the equipment used by Japanese semiconductor manufacturers comes from the United States, This percentage has been declining, however, with some observers predicting that Japan will produce 70 percent of its needs by 1985. Japanese firms are reportedly already designing and building fifth-generation automated wire bonders, while U.S. firms are still working with first or second generation machines; see "Pushing for Leadership in the World Market, " *Business Week*, Dec. 14, 1981, p. 61. In some cases—e.g., automated testing equipment—Japanese products have the reputation of being somewhat more reliable than those of American suppliers, largely because they are simpler, However, industry opinion generally holds that U.S. equipment is as good as or better than that made in Japan or in Europe, as well as being less expensive. See "Can Semiconductors Survive Big Business?" *Business Week*, Dec. 3, 1979, p. 81.

manufacturing because labor costs will become a smaller fraction of total manufacturing cost.

Robotics

Industrial robots comprise a subset of programmable automation technologies mimicking some of the attributes of the human work force, They are more flexible-in terms of ability to perform new tasks, or to carry out complex motion sequences-than other types of programmable equipment. Because advances in robotics depend to considerable extent on electronics and computer science they are discussed in some detail below. In the future, robots will be used to automate many of the operations in making electronics products now carried out by hand. In Japan, robots are already being used to produce more robots by a subsidiary of one of the major electronics companies—Fanuc, a part of the Fujitsu organization.[47]

The changing proportion of costs associated with electrical and mechanical components since the first industrial robots were introduced in the 1960's demonstrates the importance of electronics for this technology. A few years ago, about half the direct cost of making a robot was associated with the electronics, the other half with mechanical components. Now only about 15 percent of the costs go into electronics, largely because of the increases in computing power available with cheap ICs. Costs for the mechanical components have not changed greatly, but the total costs of robots have decreased, the mechanical parts now accounting for 85 percent of the total.

Technology

Industrial robots, those used for factory work, are machines that can move a manipulator, or end effecter, at the end of a chain of mechanical links, The end effecter may be a gripping device similar to fingers; alternatively, the end of the robot arm may carry a tool, welding torch, or nozzle for spraying paint. The simplest robots have only two or three degrees of freedom; an illustration of a two-degree-of-freedom system would be an "arm" that could only extend and rotate, as for tightening a bolt. The most sophisticated robots have seven or eight degrees of freedom, which allows them to reach around obstacles. Figure 44 shows a pair of typical robot designs.

While robots trace their descent from more primitive manipulators having little flexibility—e.g., with position and sequencing con-

Figure 44.—Two Approaches to the Design of Industrial Robots

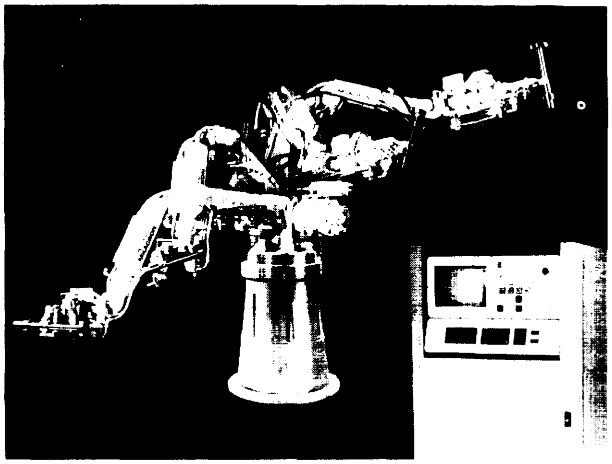

Photo credit Cincinnati Milacron

(a) This robot emulates the human arm

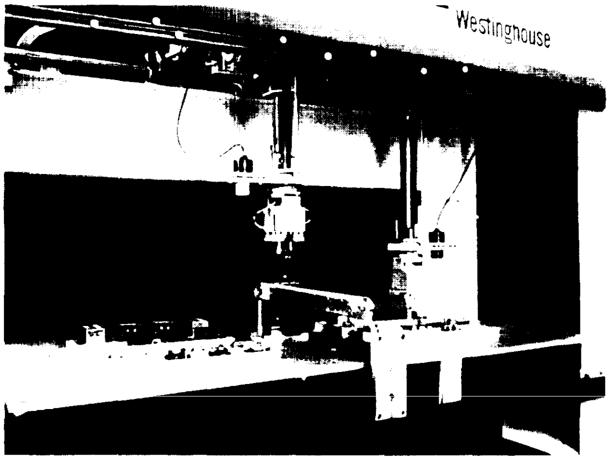

Photo credit Westinghouse

(b) This robot moves rectilinearly

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[47] N. Usui, "Untended Machines Build Machines,' *American Machinist*, June 1981, p. 142,

trolled by limit switches—state-of-the-art designs now operate under computer control, often a microcomputer. In routine production applications, the robot is commonly "taught" a sequence of motions by a human operator, who leads the arm through these motions while they are stored in memory. The machine can then repeat them on command. Although satisfactory for simple applications like spray painting or some forms of welding, off-line programing—in which the instruction sequence is developed independently and loaded into the computer when needed—is a major R&D goal.

Virtually all robots still operate with relatively primitive open loop control systems.[48] This is one of the factors limiting operating speeds, as well as the accuracy with which the end effector can be positioned, Current-generation robots are also burdened by complex and expensive actuators that tend to restrict performance. At some future time, one robot may be able to throw a part across the factory floor to another, but this is far in the future. Making robots "smart' '-i.e., with the ability to gather and process substantial amounts of information, then make decisions based on that information—is a related problem. Few robots can yet make even simple decisions.

As such examples indicate, robotics technology depends on computer technology. While computer firms like IBM, Digital Equipment Corp., and Texas Instruments are expected to enter the market for robots—and Fujitsu and Hitachi are already two of the leading producers in Japan—many of the robots in current production come from machine tool builders. In the United States, for instance, Cincinnati Milacron has a substantial share of the market.

From the perspective of the machine tool industry–whether the portion that builds metal-cutting equipment or the manufacturers of hard-automated assembly equipment such as transfer lines—robots trace their descent mostly from NC machines. In fact, much of the technology in the control systems of current-generation robots is similar to that for DNC and CNC machine tools. Companies that intend to compete in the design and manufacture of future generations of robots will need a broader range of technical capability; those moving into programmable automation from other high-technology fields may have the advantage, particularly firms with experience in automatic controls and the modeling of complex mechanical systems,

Robots in Manufacturing

Robots are usually installed in factories where they can cut costs (compared to human workers) and increase labor productivity—the same motives that drive other capital investments. In many early installations of robots, human workers were replaced on a one-for-one basis, a substitution facilitated by the robot's ability to emulate the human arm. In comparing the costs of robots to those for human workers, one-for-one replacement has often been assumed, This is potentially misleading because a more thorough redesign of the production facility means that some robots may each replace several people, while in other cases several robots might be needed to do the work of one person. A cost analysis comparing robots and people must also take account of the number of shifts planned for the facility, maintenance and repair costs, depreciation, and energy consumption. A robot may use a hundred times as much energy as a human worker. Generally speaking, when production volumes are small, human operators will still be the least cost alternative because of the expenses associated with setting up and programing the robot—figure 45, Moreover, at sufficiently high production volumes, fixed automation will be cheaper because there is no need to trade off performance for flexibility. In general, robots tend to be the low-cost alternative for annual production volumes of roughly 300,000 to 3 million units.[49]

The plot in figure 46 has been well publicized by Unimation, one of the largest robot manufacturers in the United States. It compares the

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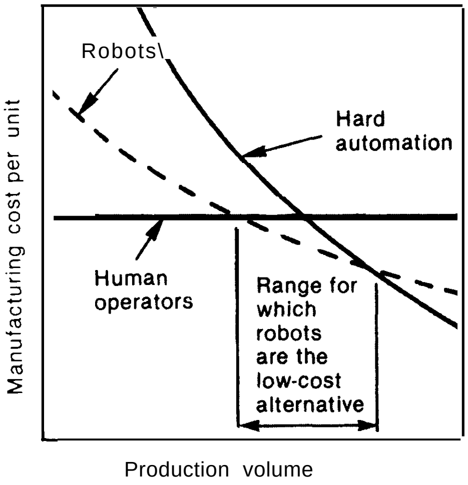
[48] "Government Attitudes Toward Programmable Automation, " op. cit. Much of the material that follows is drawn from this paper.

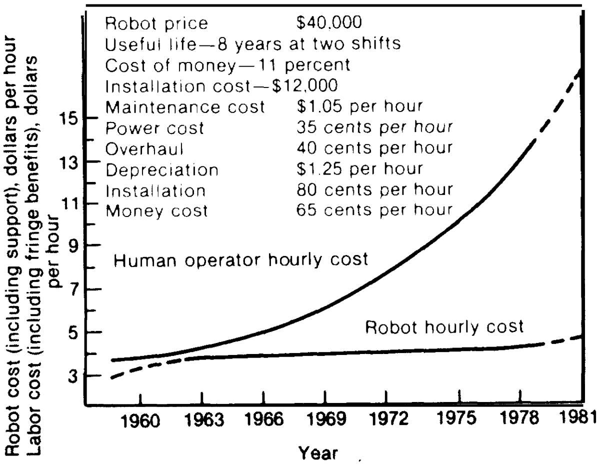
[49] R. Allan, "Busy Robots Spur Productivity, " *IEEE Spectrum*, September 1979, p. 31.

Figure 45.— Manufacturing Costs for Robots, Hard Automation, and Human Operators as a Function of Production Volume



SOURCE Off Ice of Technology Assessment

Figure 46.—Cost Comparison for Human Operator and Robot Assuming One-for-One Replacement and Two-Shift Operation in the Automobile Industry



SOURCE R Allan, "Busy Robots Spur Productivity," *IEEE Spectrum,* September 1979, p 31

costs for one of their robots with the costs of wages plus fringe benefits for an autoworker, assuming the robot to be a direct replacement, According to figure 46, hourly costs for industrial robots have gone up only slightly since their introduction in the 1960's, a period over which wages and fringe benefits for autoworkers increased sharply. Note that installation of the robot is included, but not the engineering costs for the application. For a new installation, development costs, including programing and general debugging, can easily total twice the purchase price of the robot.

In electronics, robots can contribute to quality and reliability by minimizing mechanical damage to delicate parts—which also cuts direct costs—and by helping improve cleanliness. The latter is particularly important for large-scale ICs, where "clean rooms" with levels of dust and other contaminants reduced to very low levels are required. Because people bring contaminants into the production area with them, automation helps raise yields and reduce fabrication costs.

Beyond the now routine applications like spray painting and welding lies a great deal of scope for robots that extend or improve on human capabilities, Some of these robots will be larger than those currently on the market, others smaller. While a few robots now available can handle loads in the range of 500 to 2,000 lb, most are designed with lifting capacities in the range of 50 to 200 lb. Until recently, robots intended for low loads (e. g., under 10 lb) and precision work have been rare. Limitations on precision and repeatability have placed severe constraints on potential applications.[50]

Robots and Jobs

Despite the fact that robots are simply one type of flexible automation, with roots in a number of familiar manufacturing methods—and that automation itself is as old as the industrial revolution—it is as difficult for many people to be dispassionate and objective about robots as it is for them to regard nuclear power as just another means of generating electrici-

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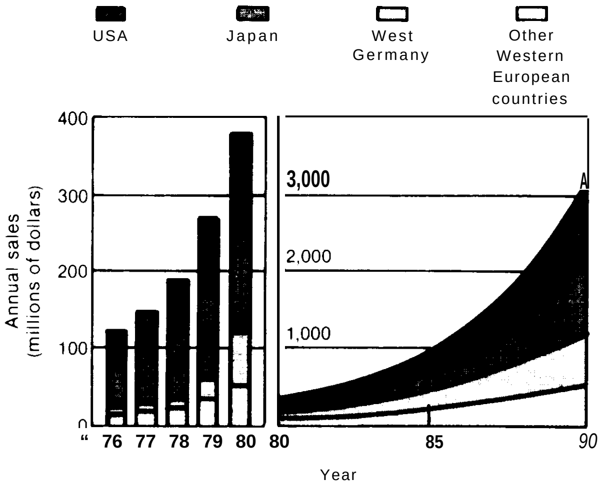
[50] Electronics firms need robots with high accuracy because the small and delicate parts used in electronic equipment are so easily damaged. Nippon Electric Co. [N EC) has recently described a machine with a load capability of about 5 lb and a claimed positioning accuracy of 0.00016 inches, an order of magnitude better than previous high-precision robots. NEC plans to use it in circuit board assembly, as well as wire bonding for ICs. See R. Neff, "Robot Moves by Micrometers, " *Electronics,* Apr. 7, 1981, p. 84.

ty. The entire set of technologies for automating manufacturing and services poses very real threats to the employment opportunities and current job skills of a large segment of the U.S. labor force, as discussed in chapter 9. But it is the whole family that is the proper focus of attention. While it is too early to predict the full range of impacts of computerized manufacturing, it is likely that—as with most instances of major technological change—these will come relatively slowly and in piecemeal fashion. Just as these impacts are likely to be random and incremental, many will be unexpected—and to the extent that they are, people and institutions will be unprepared for them.

Market Growth

If the effects of programmable automation will not become visible overnight, this is in part simply a result of time scales for production and installation; *rates* of increase will be high, but total penetration will mount rather slowly. Figure 47 gives estimates for worldwide robot sales through 1990, According to this projection, the market will exceed $3 billion by the end of the decade, an increase of nearly 10 times over the 1980 level. Other estimates range both higher and lower. To set these figures in perspective, note first that spending for capital equipment in U.S. manufacturing industries is currently $80 billion to $85 billion per year, and second that during the 1980's expenditures on robots are expected to remain well under 10 percent of total expenditures just on automated equipment.[51] Again, from a job displacement viewpoint, all types of automation must be considered.

Figure 47.—Worldwide Annual Sales of Robots, Past and Projected



SOURCE E Heer Robots in Modern Industry *Astronaut/es & Aeronautics,* September 1981 p 52

Figure 48 illustrates the growth in sales by application expected in Japan over the period 1980-90. While many of the robots sold in 1980 were for use in casting, metal forming (i. e., forging and stamping), and painting, the projections in the figure indicate that these applications will be far outstripped by assembly, welding, loading and unloading of machine tools, and inspection, Some observers predict even more rapid market growth in the United States than figure 48 shows for Japan,

When markets grow this rapidly, a good deal of technical and market volatility can be expected, with many opportunities for entrepreneurial firms pursuing innovative technologies. While there are no guarantees that robot manufacturing will follow a path similar to semiconductors, it would not be surprising to see startups in the United Stated challenging established leaders like Unimation and Cincinnati Milacron. The multidisciplinary demands of advanced robots—both hardware (microelectronics, kinematics and mechanical design, instrumentation) and software (artificial intelligence and computer engineering, automatic control theory, the production engineering skills needed to integrate robots into the workplace)—create conditions favoring innovation and fresh thinking. New companies may emerge to lead this industry into the third generation of robotics, just as Unimation—originally a startup and now owned by a larger corporation—led the first and second generations,

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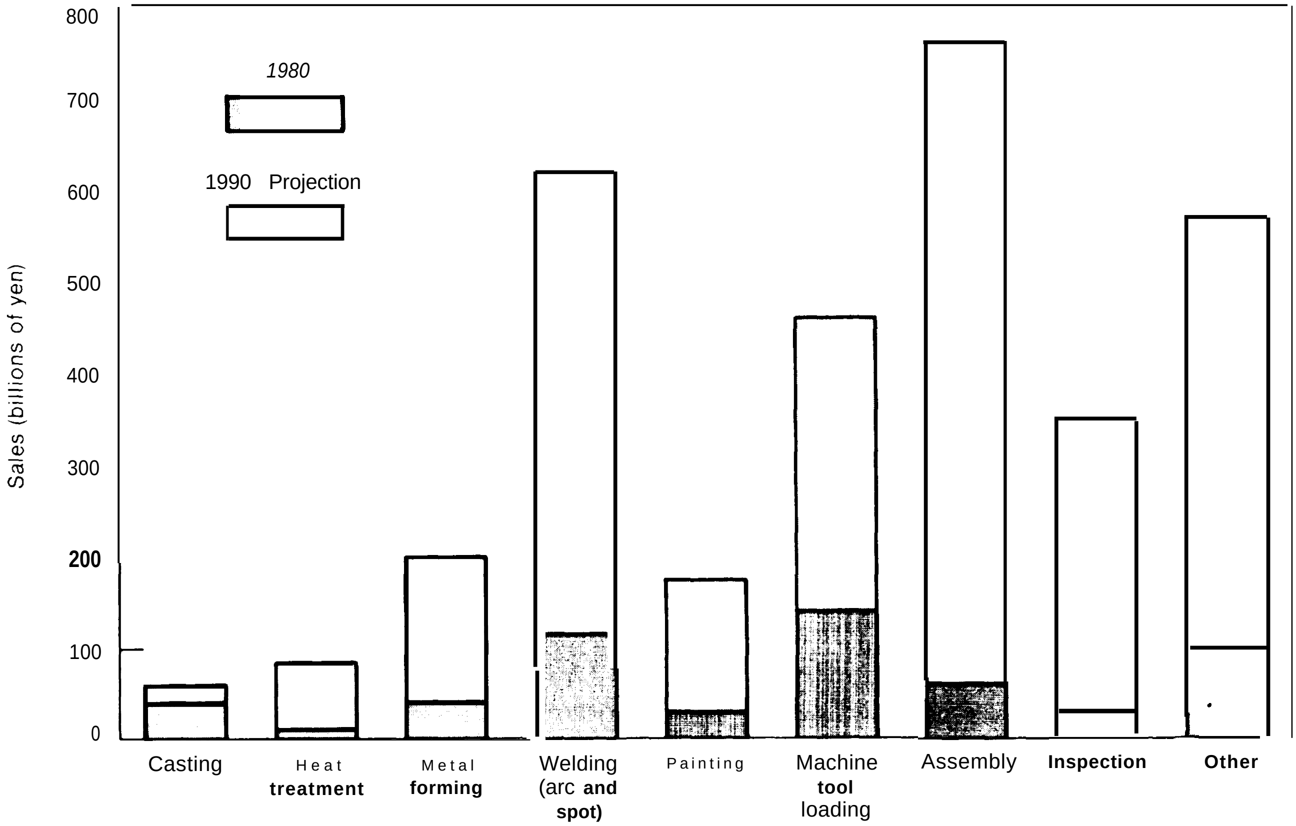
[51] J. T. Woodward, E. P. Seskin, and J. S. Landefeld, "Plant and Equipment Expenditures, the Four Quarters of 1982," Survey *of Current Business,* September 1982, p. 35 (capital equipment spending); "Industrial Robotics, " *Emerging Issues in Science and Technology, 1981* (Washington, D, C.: National Science Foundation, June 1982), p. 28 (robotics as fraction of spending on automation).

Figure 48.—Robot Sales in Japan by Application



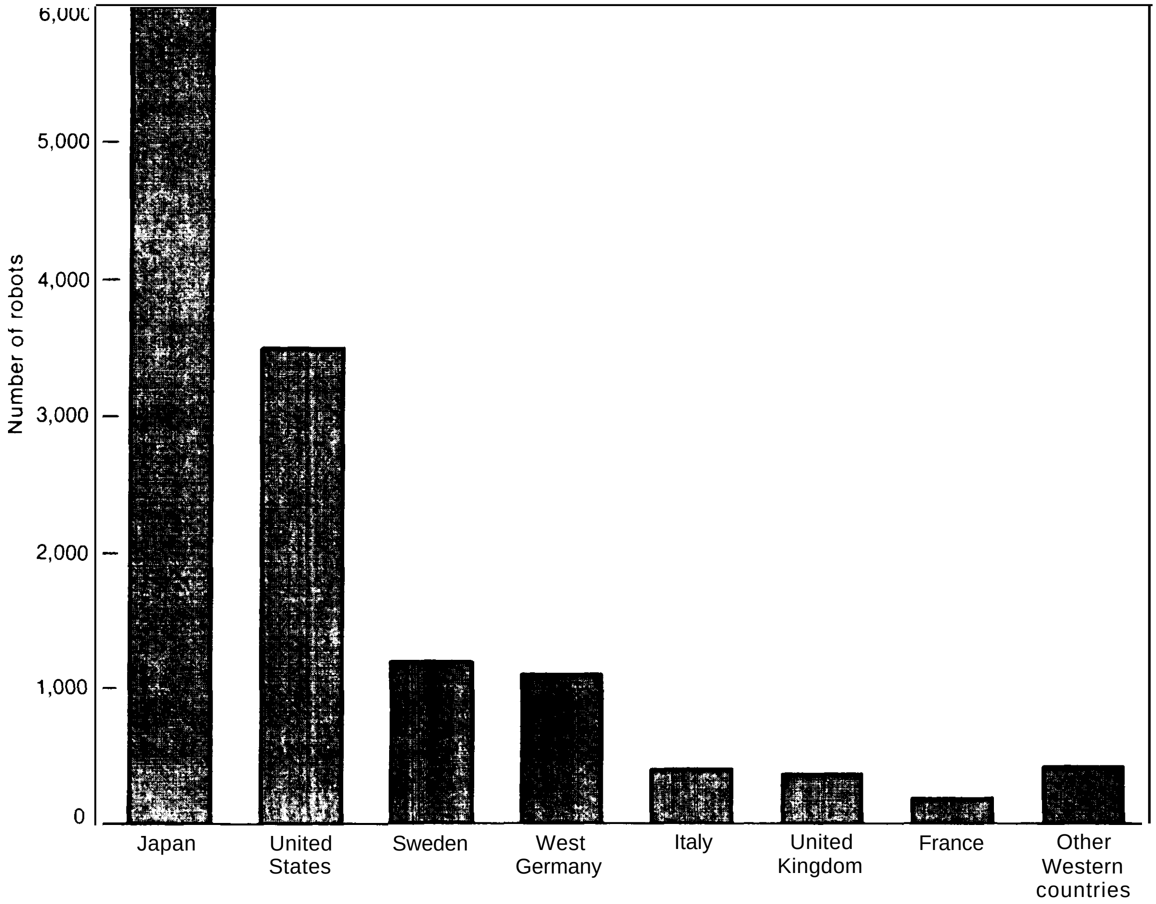
SOURCE Based on data in Robot Industry to Grow Rapidly in 1981 ," *Japan Report*, Joint Publications **Research Service** JPRS L/9744, May 19 1981 p 33

Japanese firms are applying robots in manufacturing more intensively than their competitors in other countries—figure 49. Although most observers feel that the United States still leads in the relevant technologies, there are more firms building robots in Japan—130 to 150, perhaps five times the number here—and, indications that Japan may be ahead in learning to apply robots in typical factory environments. As figure 47 indicated, future robot installations in Japan are expected to at least match those in the United States.

Using Robots

While the critical technical problems in the further development of robots center around modeling and control, the critical implementation problems for even the existing robots center on integrating them into the production process. More than half the costs of typical batch manufacturing operations are associated with scheduling and otherwise managing the flow of production—i.e., with software, broadly speaking. These management and production control costs involve: getting the right parts, materials, and supplies to the right place at the right time; seeing that shop floor personnel have the information (now including computer programs) they need; and ensuring that machinery is available and in good repair when scheduled for use. Tasks involving production planning and machine scheduling, job flows, inventory control, and the related routing and coordinating functions might seem straightforward, but in fact they are extraordinarily complex; experience shows them to be among the most critical factors in controlling manufacturing costs. Computer-aided manufacturing holds a great deal of promise for reducing at

Figure 49.— Estimated Numbers of Robots in Use, 1980



SOURCE: 'CAM An International Comparison, " *American Machinist*, November 1981, p. 214

least some of these costs—e.g., those associated with materials handling, control of the inventory of tools, jigs, and fixtures, routing of parts—but only when appropriately integrated into the production environment. Integration will require a great deal of rethinking at both the design and manufacturing stages—rethinking for which cheap computing power is necessary but hardly sufficient. The potential benefits in terms of productivity are huge, but no one anywhere in the world knows at present how to realize them,

Computer-integrated manufacturing will affect the cost structures of many industries; as labor productivity improves, fixed costs will increase relative to variable costs. Engineering and software development expenses will rise compared to blue collar labor costs. Flexibility will make small-batch production more attractive; product differentiation and product customization will become relatively less expensive. The result will be far-reaching changes in the product and marketing strategies of manufacturing companies throughout the world.

International Trends

As has happened in so many other industries, Japanese firms–which began to manufacture robots by importing technology from the United States and Europe—are now quite capable of advancing the state of the art on their own. Currently, robotics technology is flowing between the United States and Japan in both

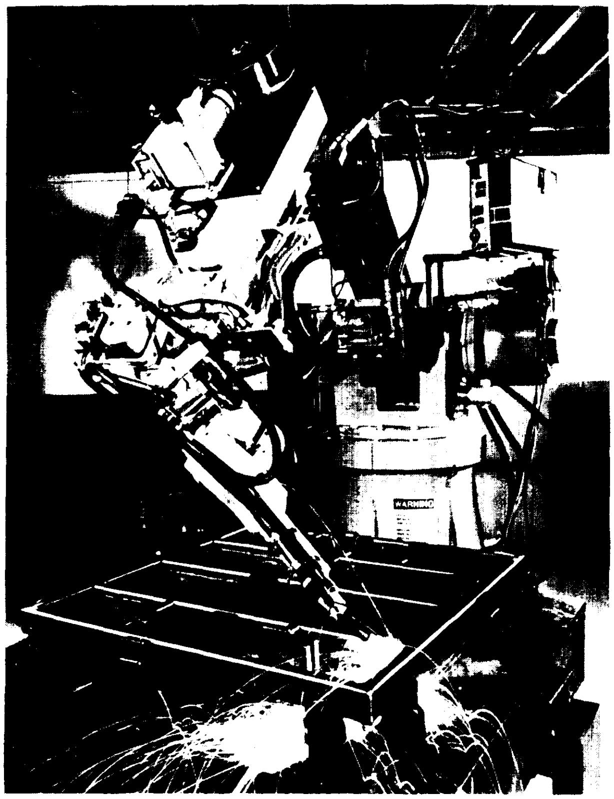


Photo credit Cincinnati Milacron

Robot welding frame assembly for computer

directions; General Electric, for example, has begun to build robots under license from Hitachi. While fewer than 5 percent of the robots produced in Japan during 1980 were exported [imports were comparably small), Japan expects to export 15 to 20 percent of its robot production by 1985.[52]

Again as in other industries, the Japanese Government—via the Ministry of International Trade and Industry (MITI)—has designed programs to encourage and support builders of robots. A number of Western European governments are following suit. MITI sponsored several manufacturing-oriented R&D programs which encompassed robotics during the 1970's. One of the agency's first steps to support the robotics industry itself was the establishment of a leasing program. The Japan Robot Leasing Company, Ltd. (JAROL), incorporated in 1980, is owned 70 percent by 24 robot manufacturers and 30 percent by 10 insurance companies. About 60 percent of JAROL's capital has been borrowed from the Japan Development Bank and from commercial banks. The consortium uses this capital to purchase robots, which are then leased, primarily to smaller firms.[53] While the program is similar to that operated by the Japan Electronic Computer Corp. for financing computers, JAROL does more than just lease equipment; its engineering staff provides assistance in installing and programing robots. Among its other initiatives, the Japanese Government has also granted an extra 13 percent depreciation allowance to purchasers of advanced types of robots, while smaller firms that buy robots for modernization or to automate hazardous jobs can take advantage of low-interest loans.[54]

Much more ambitious is MITI's plan for a joint R&D program aimed at making robots smarter.[55] This effort, with a proposed annual funding level of about 30 billion yen (roughly $135 million), will be organized much like other government-sponsored R&D programs in Japan, About 10 companies are expected to be involved, plus the Electrotechnical Laboratory of the Agency for Industrial Science and Technology, Major thrusts planned over the 7-year schedule beginning in 1982 include:

- improved sensory capabilities—e.g., pattern recognition, force/torque sensors;
- control algorithms incorporating true adaptive or "intelligent" behavior which would allow the robot to operate more-or-less au-

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[52] M. Kanabayashi, " In March of the Robots, Japan's Machines Race Ahead of America' s," *Wall Street Journal,* Nov. 24, 1981, p. 1.

[53] Y. Machida, "Industrial Robot in Japan, I, *TCB* Research, Long-Term Credit Bank of Japan, March/April 1981, p. 4.

[54] The special depreciation provisi apply t robot purchased between 1980 and 1983 that are computer (controlled, have six or more degrees of freedom, and meet specified standards for positioning accuracy, The added 13 percent depreciation in the first year means that a total of 53 percent can be written off (assuming the 5-year, double declining balance depreciation procedure that is normal in Japan). See "Robotics: They Are Smart and Never Need a Tea-B reak, " *Far Eastern Economic Review*, Dec, 4, 1981, p. 70.

[55] "MITI To Launch 7-Year Project To Develop Intelligent Robot," *Japan Report,* Joint Publications Research Service JPRS 1,/10125, Nov. 18, 1981, p. 31.

tonomously, making decisions based on sensory data it receives from the operating environment; and

- improved mechanical design, including manipulators and mobility, the latter very much a controls problem as well.

The program is in part a sequel to previous MITI-sponsored work on remote control devices for maintaining and repairing the radioactive portions of nuclear powerplants. However, the robot program will be much broader.

Summary and Conclusions

In the past, Japanese electronics firms making both TV receivers and ICs—notably memory chips for the merchant market—have emphasized quality and reliability more heavily than their counterparts in the United States. This does not mean that the best performing American firms may not have had quality and reliability as good as the Japanese, or that captive manufacturers in the United States may not have been as good or better than IC makers anywhere, It does mean that specific types of products—color TVs and dynamic RAMs—have, in the past, been produced to higher average levels of quality and reliability in Japan. The picture at present is less certain—indeed, reliability cannot be estimated until products are well along in their service lives. It is plain that American firms have made major efforts to improve quality and reliability—with considerable success. But it is not obvious that they have caught–much less surpassed—the Japanese, who have been improving their own performance at the same time.

Japanese manufacturers may have succeeded in creating *perceptions* of quality and reliability outstripping any actual performance margins, particularly for color TVs; certainly the strategies of Japanese electronics firms have parallels in other industries—e.g., cameras or automobiles—where the emphasis placed on both the image and the reality of quality had an important role in the penetration of U.S. markets. For American firms to match this image demands top management attention,

While the Japanese stress on quality begins with management and appears to permeate organizations from the top down, quality assurance has often been an orphan in the United States. Quality control personnel here have been viewed as obstacles to production; they have had integral roles in neither design nor manufacturing. Japanese firms learned many of the basic techniques of quality control from American engineers, but they have gone a step beyond conventional practice in much of the rest of the world by, for instance, making individual workers responsible for the quality of their own efforts.

Electronics firms in Japan also invest more heavily in employee training. At all levels—assembly workers, engineers and designers, foremen and supervisors, sales and management—employees of American electronics firms tend, on average, to be less knowledgeable concerning quality and reliability than their counterparts in Japan. Although many of the recognized authorities in these fields are Americans, expertise is not spread as widely here as in Japan. Moreover, U.S. electronics manufacturers may still to some extent be paying lip service to quality and reliability, Over time, the depth of their commitments will become more apparent. In particular, it takes time to design quality and reliability into a product line.

In general, Japanese electronics manufacturers also appear to do a better job of managing the interface between design and production. Moreover, the characteristically close working relationships between vendors and purchasers in Japan’s electronics industry evidently yields benefits in quality and reliability. Production equipment made in Japan does not, however, appear superior to that available here; indeed, Japanese electronics firms continue to purchase a good deal of manufacturing equipment from U.S. suppliers.

Japanese companies automated the production of TV receivers and other consumer electronic products earlier than most American firms. Extensive applications of robots—in electronics and other industries—will help the Japanese increase manufacturing productivity still further, and will also improve quality and reliability. At present, robots remain a small subset of automated production equipment with limited impact, but they will be a key part of future manufacturing facilities. And, while robots will spread rather slowly through industry in both the United States and Japan–with unpredictable effects, as for any new technology—the cumulative impacts of these and other types of factory automation will be massive, affecting productivity and competitiveness, the skill mix in the work force, and the total number of job opportunities in the economy, Computer-integrated manufacturing will shift corporate strategies in many industries toward greater product differentiation, Japanese companies can be expected to apply computerized manufacturing technologies at least as fast as American firms, wherever there are benefits in terms of cost, quality, worker safety, or product design and marketing.

Appendix 6A—Quality and Reliability Comparisons for Integrated Circuits

This appendix summarizes the data that have been made public concerning quality and reliability levels of chips supplied by American and Japanese firms to the merchant market. The most widely noted comparisons have come from Hewlett-Packard Corp., a U.S. firm that purchases large numbers of semiconductors on the merchant market, and also manufactures ICs for internal use.

Quality Levels

As indicated in table 6A-1, part A, at the end of 1979 the quality levels of Hewlett-Packard's U.S. suppliers were poor relative to Japanese firms. While Hewlett-Packard had an obvious interest in pressing their suppliers to provide high quality, this data is not just another case of a purchaser playing its vendors off against one another; the semiconductor industry has generally accepted Hewlett-Packard's test results as valid, although offering a variety of explanations for the relatively poor showings by domestic manufacturers.

The data in table 6A-1 are all for 16K RAMs; indeed, most of the public discussion of quality has focused on RAMs, because they are bought in large quantities by many customers and have become a locus of international competition. Part C of the table shows that American suppliers of 16K RAMs dramatically improved their quality and reliability y during 1980, but that they continued to trail Japanese firms. Improvements by Japanese suppliers over the time period covered in the table were negligible. Note that failure rate after burn-in-parts B and C of the table—is essentially an indication of infant mortality failures, and thus more closely associated with quality than with reliability'. Needless to say, conclusions based on such results should be generalized only with care; the table refers solely to circuits purchased by Hewlett-Packard, and differences from shipment to shipment even from a single manufacturer can be large.

Table 6A-2 presents data gathered for OTA on quality levels for RAMs, 4K as well as 16K. As for the first set of the Hewlett-Packard data, the Japanese 16K RAMs were superior by a large margin. The 4K RAM data—though limited to only one Japanese vendor—are quite different, showing the American-made devices to be superior.

Along with quantitative data on RAMS such as that in tables 6A-I and 6A-2, purchasers of ICs surveyed by OTA's contractor sometimes provided more general comments. One purchaser. for instance, included the following comparison:

Origin	*Percent of ICs rejected on incoming inspection*
Japan	0-3.0%
United States	0.5-15.0
Western Europe	1.0-5.0

Table 6A-1.—Hewlett-Packard Data on 16K Random Access Memory (RAM) Circuits

A. ***Reported March 1980.***

Country of manufacture		Percent failing incoming inspection	Field failure rate (o/o per thousand hours)	H-P composite qualitv index[a]
Japan-	1[b]	0	0.010 ”/0	89.9
	2	0	0.019	87.2
	3	0	0.012	87.2
United States-	1	0.190/0	0.090 ”/0	86.1
	2	0.11	0.059	63.3
	3	0.19	0.267	48,1

[a] This index is based on 10 equally weighted factors, of which incoming inspection and field failure rates are two; the others include such things as cost and delivery schedules

[b] Evidently, the three suppliers (not necessarily in order) were Fujitsu, Hitachi, and NEC, **American** suppliers (again not in order) Intel, Mostek, and Texas Instruments. See “The Quality Goes On Before the (Japanese) Names Goes On, ” *Rosen Electronics Letter,* Mar 31, 1980, p 1

SOURCE: R W Anderson, “The Japanese Success Formula Quality Equals the Competitive Edge, ” Verbatim Record, Seminar *on Quality Control Japan Key to High Product/vi(y, Washington, D C,* Mar *25, 1980, p 40*

B. Reported November 1980.

Country of manufacture		Failure rate after burn-in	
Japan-	1	0.05 ”/0	
	2	0.10	
	3	0.12	Average = 0.17°/oa
	4	0.35	
	5	0.25	
United States-	1	0,60	
	2	0.50	
	3	1.20	Average = 0.75%[a]
	4	0.70	

[a] Averages are not weighted by numbers of circuits from each manufacturer.

SOURCE: B LeBoss, “U S Reject Rate Still Trails Japanese,” *Electronics,* Nov 6, 1960

C. Reported April 1981.

		Failure rate after burn-in			
Country of manufacture		First half 1980		Second half 1980	
Japan-	1	0.060/0		0.04	
	2	0.13	Average = 0.25%[a]	0.13	Average = 0.24%[a]
	3	0.40		0.40	
	4	0.40		0.40	
United States-	1	0.60		0.35	
	2	1.20	Average = 0.97%[a]	0.20	Average = 0.35%[a]
	3	1.10		0.50	

[a] Averages are not weighted by numbers of circuits frOm each manufacturer.

SOURCE: R W Anderson, *Seminar on* Management, *Productivity and Reindustrializat /on* East *Meets West*, Washington, D.C , Apr 2, 1981.

Consistent with such patterns, an independent testing firm noted that rejection rates following screening and burn-in were twice as high (about 4 percent) for American-made ICs as for Japanese (1 to 2 percent). End users of ICs generally reported similar results, several noting that they no longer felt it necessary to screen or burn in Japanese circuits.[1]

Reliability Levels

While screening and other tests can locate defective circuits and ‘measure quality, determinations of *reliability* must await field experience; long-term

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[1] See, for example, J. Lyman, “The Drive for Quality and Reliability, Part I,” op. cit., where an executive of the American minicomputer firm Data General is quoted as follows: “The best U.S. devices are about the equivalent of average Japanese products, Good Japanese lots run at a rejection rate of about 0.03 percent, whereas a good U.S. lot shows about 0.3 percent . . That’s why the only RAMs we are not burning in are Japanese ones, ” Other information in this paragraph is based on “Quality and Reliability of Semiconductors and CTVS: U.S. v, Japan, ” op. cit., pp. 74-76.

Table 6A-2.–Quality Levels of Japanese and U.S. Random Access Memory (RAM) Circuits

		Percent rejected on Incoming inspection		
Country of manufacture		Average		Range
A. *16K RAMs*				
Japan-	1	0.30 "/0		0.1-0.5%
	2	0.53	**Average = 0.87°/0** [a]	**0-1.8**
	3	1 77		0.1-5.0
United States-	**1**	0.70 %		0-2.7
	2	0.85	Average 1.7 %	o-4.7
	3	1,07		0-6.2
	4	411		0-12.4
B. 4K RAMs				
Japan-	1	1.07 "/'0		0-5,3
United States-	1	0.32 0/0		0-2.0
	2	**0,41**	Average o 53 "/0	O-24.5
	3	**0.87**		0.1-1.1

[a] Averages are not weighted by numbers of circuits from each manufacturer

SOURCE Quality and Reliability of Semiconductors and CTVs United States v Japan report prepared for OTA by Consultant Services Institute Inc under contract No 033 1170 p 72

Table 6A-3.— Reliability Levels of Japanese and U.S. Random Access Memory (RAM) Circuits

Country of manufacture		**Field failure rate** (% Per thousand hours)	
A. 16K RAMs			
Japan-	1	**0 0062°/0**	
	2	**0.0263**	**Average . 0 027'/oa**
	3	**0.0507**	
United States-	**1**	**00167**	
	2	**0.0687**	
	3	**0.0889**	**Average O.125%** [a]
	4	0.107	
	5	0.1268	
	6	0.3421	
B. 4K RAMs			
Japan-	1	0 "/0	
United States-	1	0.0524	
	2	0.0526	
	3	0.1018	
C. ***1K RAMs***			
Japan-	1	0.07560/o	
United States-	1	0.0667	

[a] Averages are weighted by numbers of chips from each manufacturer

SOURCE "Quality and Reliability of Semiconductors and CTVs United States v Japan report prepared for OTA by Consultant Services Institute Inc , under contract No 03311700, p 72

tests are very expensive, and burn-in failures more properly ascribed to quality problems. Field failure data assembled by Hewlett-Packard for 16K RAMs were included in table 6A-1, part A. Table 6A-3 contains the remainder of the reliability data available to OTA. Consistent with the Hewlett-Packard results, this shows the reliability of Japanese 16K RAMs to have been markedly better than American products.

Soft Errors

Failure modes for ICs can be divided into "hard" and "soft" failures. Hard failures are repeatable and final: the device no longer functions properly. In contrast, soft failures are random and nonrepeatable. Alpha radiation can cause soft errors in RAM circuits, a problem that was not appreciated until densities reached 16K. The radiation—emitted at low levels from ceramics and other materials used in packaging ICs—sometimes causes a bit stored in a memory cell to switch from "0" to "1" or vice versa.[2] The result is a soft error that appears when the contents of that cell are next recalled.

The frequency of soft errors caused by alpha radiation can be reduced by a number of techniques, which Japanese manufacturers evidently implemented more rapidly than American firms—perhaps because Japanese semiconductor firms were more willing to accept the extra costs. One purchaser of 64K RAMS reported soft failure rates of *10-8* per hour for circuits from *two* Japanese manufacturers; the rates for the products of a pair of American firms were 10^{-3} and 10^{-6} failures per hour.[3]

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[2] T. C. May, "Soft Errors in VLSI: Present and Future," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, vol CHMT-2, December 1979, p. 377.

[3] "Quality and Reliability of Semiconductors and CTVs: U.S. v. Japan," op. cit., p. 73. Several years ago, the alpha-induced soft error rate for Fujitsu's 16K RAM was reported to be three orders of magnitude better than that of Mostek's device. The differences were attributed to the designs of the circuits. See J. G. Posa, "Dynamic RAMs: What to Expect Next," *Electronics*, May 22, 1980, p. 119. The resistance of Mostek's 16K RAM to alpha radiation has since been greatly improved, and U.S. firms in general have adopted measures that substantially reduce sensitivity to alpha particles.