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The Future of Electronics Assembly

Report of the Panel on Strategic Electronics Manufacturing Technologies

Manufacturing Studies Board
Commission on Engineering and
Technical Systems
National Research Council (U.S.). Panel on Strategic
" Electronics Manufacturing Technologies.

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William Howard
Chairman

CONTENTS

EXECUTIVE SUMMARY

State-of-the-art electronic products are essential to the nation's security. Increasingly, production of these electronic assemblies will require the use of automated manufacturing to make affordable, high quality, functionally superior electronic assemblies or subassemblies quickly and in small volumes, and to change quickly from product to product. To help U.S. industry gain the technical capabilities necessary to provide this, the Department of Defense (DOD) asked the National Research Council's Manufacturing Studies Board to identify new assembly manufacturing technologies that are essential for the U.S. defense supply.

The Panel on Strategic Electronics Manufacturing Technologies, formed by the Board to conduct this project, selected three indicators that a technology should be given special attention by the U.S. defense community. These are:

- Essentiality--technologies absolutely essential to producing affordable, functionally superior electronic assemblies, by definition, deserve attention.
- Barriers--technologies facing major barriers to their development are likely to be beyond the capabilities of a single company and therefore to require outside support.
- World leadership--technologies in which the United States most seriously lags foreign developments are most likely to threaten our ability to compete in world-class electronics assembly manufacturing.

The Panel developed a list of candidate technologies and considered their application to seven factory functions:

- requirements and specifications,
- design,
- acquisition and use of externally acquired components,
- fabrication,
- assembly,
- test of product and process, and
- field support.

On the basis of its own experience and questionnaire responses received from electronics experts, the Panel rated the 30 technological applications that seemed most likely to be important to the U.S. defense community on essentiality, technical and nontechnical barriers, and U.S. position. The Panel then defined a Criticality Index as the product of the three numerical factors. Any technology that rates high on all three factors is, by this calculation, critical to the U.S. defense community.

CRITICAL TECHNOLOGIES

Six technologies emerged as being most critical. They are:

- automated statistical process control,
- automation equipment technologies,
- factory system integration,
- modeling and simulation,
- design automation tools, and
- electronic packaging and interconnect technology,

in that order. The three most critical technologies and their implications for the Department of Defense are described below.

1. Automated Statistical Process Control

Control of each process step, and in particular automatic process control in real time, is essential to automating manufacturing processes. The rate of production of automated factories is too high to allow waiting for product test and evaluation to be completed before making in-line process adjustments. The amount of scrap produced between the time the process goes out of its limits and corrective action is taken is simply uneconomical. In addition, close control of individual steps in complex product fabrication sequences is crucial to achieving acceptable overall product yields.

Leading U.S. companies are as good as other world leaders at process control, but they provide only a small part of defense production. The vast majority of U.S. electronics companies are four to five years behind their foreign competitors, particularly Japanese companies, in the practice of manufacturing process control.

More technical work is needed to achieve automated statistical process control, but the greatest barrier to its widespread use in this country is that many managers believe it is not necessary. Most managers believe that they already exert good control over production processes, but they rarely do. To many, control means the ability to find and correct faulty products rather than faulty processes. Further, the number of U.S. technical personnel competent in manufacturing process control falls well short of current needs.

Control of a process requires thorough understanding of all factors affecting process results, and a solution to the problem in one environment rarely can be transferred to another. Each process requires the investment of time and attention to master the level of detail needed to control it. The costs of achieving this mastery are high--but so are the potential benefits.

Although some technical barriers hinder automated control of processes in electronics assembly factories (sensor technology is particularly lacking), they are minor compared to the gap between technical knowledge and manufacturing practice. The challenge for the U.S. electronics manufacturing community is to tackle the management concerns that are preventing process control from being more widely used.

The Department of Defense has already taken an important step in that direction by highlighting the use of statistical process control (SPC) in its manufacturing requirements, but that is still a relatively weak incentive. Japanese firms that are SPC leaders will soon be competitors of U.S. defense contractors; that alone should be a strong incentive to speed U.S. utilization of these methods.

2. Automation Equipment Technologies

Automation equipment technologies--automated tools, robots, and flexible manufacturing equipment--are essential to factory automation for (1) fabrication, (2) assembly, and (3) testing of products and processes. Proficiency in these technologies allows manufacturers to achieve generally higher quality at lower cost. Higher reliability and reduced downtime of the production line also depend on these technologies. In addition, design for manufacturability requires expertise in automation equipment technologies.

U.S. companies generally lag their foreign competitors in the use of these technologies, by up to 5 years. Despite a strong position in the software and computer hardware components of these tools, the United States lags in the mechatronics (i.e., the technology of computer-controlled mechanical devices) aspect of the technologies, especially in precision engineering. The U.S. academic position in this field is relatively weak, as evidenced by the lack of academic recognition of precision engineering as a university department and by the generally low academic standing of researchers in this field.

Automation equipment technologies are available to U.S. companies, but primarily from Japan. Widespread use of these technologies in the United States is hampered by a shortage of knowledgeable personnel, the high cost of experimenting with the technologies, and the lack of common interfaces.

Cost is a barrier that cannot easily be overcome. The formation of cooperative research and development arrangements would benefit all participants while bringing the cost to an acceptable cost-effectiveness level for each company. While such consortia are not easily established in this country, the creation of Engineering Research Centers, Sematech, the Microelectronics and Computer Technology Corporation, and the National Center for Manufacturing Sciences suggest that the best of U.S. industry is becoming better at forming cooperative arrangements.

The United States already depends on foreign sources for developing key automation equipment technologies; this dependence can only be expected to increase. We have, nonetheless, a unique opportunity to support R&D in these technologies, which are critical in many aspects of weapon development as well as for automated manufacturing tools. Precision engineering and mechatronics, if properly supported, could accelerate not only manufacturing technology but also the development of new products for the national defense. A strong emphasis on these areas, coupled with the U.S. strength in computer tools for design, could change us from laggards to leaders.

3. Integration of the Total Factory System

Total factory integration includes integration of the product design, fabrication, factory management, and test operations necessary to establish a complete manufacturing entity. It requires the skills needed to combine all the pieces into a consistent, interoperating whole. Production of affordable, functionally superior electronic assemblies cannot be achieved without total system integration.

The United States and Japan appear to share world leadership in process integration, but it is a changing field in which either country could gain the lead. The current state of factory system integration extends to islands of automation with limited control linking. Ability to fully configure individual processes remotely, a necessity for fully flexible electronics assembly automation, has not yet been satisfactorily demonstrated.

While many of the technical problems of factory integration remain to be solved, they are not as difficult as the problems of time, cost, and management commitment. In fact, as a result of competing approaches now being taken, the probability of technical success is high. Whether senior company management is able and willing to invest in the lengthy, expensive process of total factory integration during times of financial stress, however, remains to be seen.

The competing approaches are a problem as well as an advantage. Because each of the various vendors (of factory integration systems, hardware, and software) has a different systems approach, the factory integrator cannot invest in a single system with the assurance that it will prevail. Makers of individual manufacturing machines have adopted differing control and data architectures, and existing interface and data base standards are inadequate to enable companies to integrate diverse systems.

The Department of Defense could help overcome the identified technical barriers by:

- requiring its contractors to use standards that are gaining broad-based acceptance in industry;
- helping to bring equipment vendors and factory operators together, by routinely involving lower-tier contractors in such programs as manufacturing technology and mobilization planning;
- encouraging training of technical experts in this cross-disciplinary area through funding of integrative university-based centers; and

- encouraging meaningful demonstrations of the benefits of total factory integration, such as was done by the U.S. Air Force Materials Laboratory on a smaller scale with the integrated sheet metal center.

The current U.S./Japanese parity provides an opportunity for the United States to benefit from a major effort in this area. One possibility is to construct a large, experimental, government-supported facility to demonstrate the state of the art of electronics assembly factory automation, to establish its benefits, and to speed development in those areas impeding progress. Such an operation would make available, to the defense and other domestic electronics manufacturing communities, real-world experience in integrating factory operations, provide leverage from a single, large investment, and provide focus for small suppliers of equipment and materials.

1 INTRODUCTION

The Department of Defense (DOD), as part of its mission to protect national security, asked the National Research Council's Manufacturing Studies Board to identify the new assembly manufacturing technologies that are essential for producing state-of-the-art electronic products. Specifically, the DOD asked the Board to:

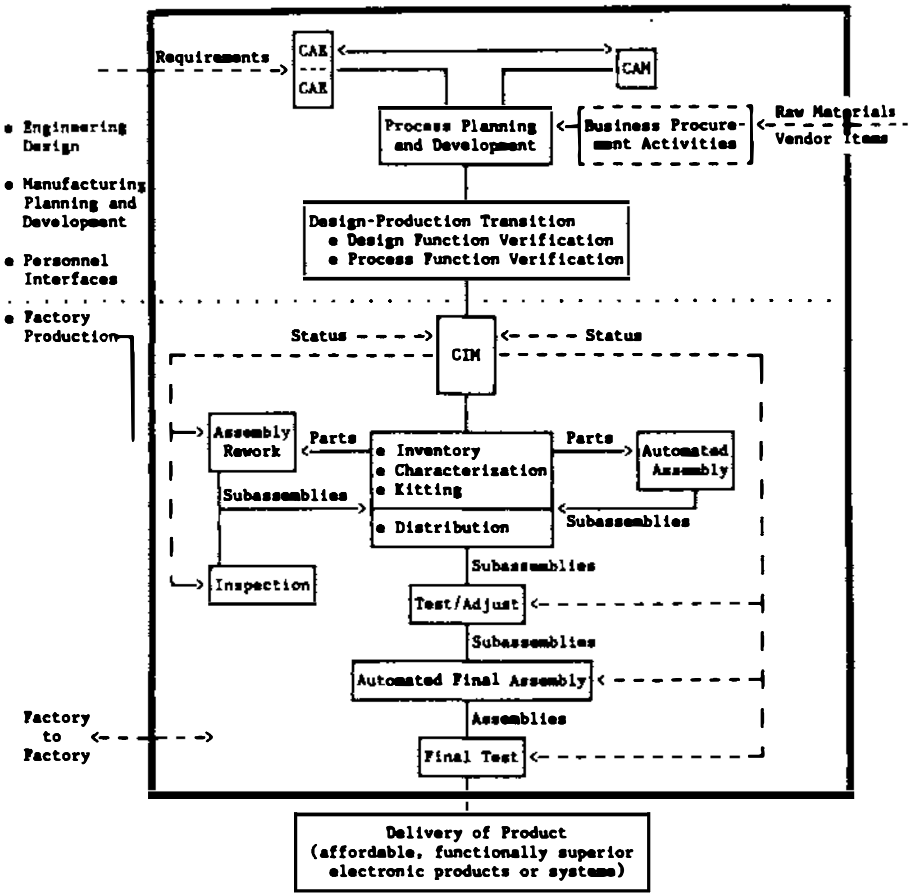
- identify current key technologies and anticipated developments during the next 5 to 10 years,
- appraise the net position of the U.S. compared to international competitors for each of those technologies,
- identify major technological barriers inhibiting progress, and
- recommend those technologies on which the U.S. defense community (the DOD and its civilian contractors) could best concentrate resources to maintain or gain a lead in the automated manufacture of complex electronic assemblies.

To conduct that project, the Board formed the Panel on Strategic Electronics Manufacturing Technologies, a part of the existing Committee on Electronics Automation. From 1985 to 1987, that committee looked into the procedural and technical changes that would maximize the benefits to the Department of Defense from the automated manufacture of complex electronic equipment such as communications security systems.

FRAMEWORK FOR CONSIDERING ELECTRONICS MANUFACTURING TECHNOLOGIES

The Department of Defense used the diagram of a factory shown in Figure 1-1 to describe the location where

Figure 1-1. FACTORY FOR AUTOMATED PRODUCTION OF ELECTRONIC ASSEMBLIES



automated manufacturing will be applied. The products of this factory are electronic assemblies at the device or system level, with high-variety, low-volume production. The Panel focused on the technologies that are essential to enable the factory to produce affordable, functionally superior electronic products.

The Panel defined manufacturing broadly, to include not just production processes, but all the steps from requirements definition through support of the product in the field. These manufacturing functions can be divided as follows:

- requirements and specifications,
- design,
- acquisition and use of externally acquired components,
- fabrication,
- assembly,
- test of product and process, and
- field support.

The trend toward computer-integrated manufacturing means that companies are moving toward greater real-time interaction among these functions. The Panel addressed these functions separately, but also addressed the integration of functions.

The Panel compiled an initial list of 32 candidate technologies, shown in Figure 1-2, that are likely to be important for automated electronic assembly. The Panel then reduced the list to 11 technologies that were considered absolutely essential to produce affordable, functionally superior electronic products or systems. These 11 technologies were addressed in detail.

The 11 key technologies and the 7 factory functions listed above formed a matrix of potential Key Technological Applications, shown in Figure 1-3. The Panel then applied the "absolutely essential" criterion a second time to select the key technological applications--that is, technologies that are essential to achieving automation for particular manufacturing functions. The 30 applications that resulted from this two-step selection process are identified in Figure 1-3 by boxed numbers. The first one, for example, reflects the Panel's judgment that design automation tools applied to the requirements and specifications function will be essential to the production of affordable, functionally superior electronic products.

Figure 1-2. INITIAL LIST OF IMPORTANT TECHNOLOGIES FOR AUTOMATED ELECTRONIC ASSEMBLY

Information Handling and Processing

Design automation tools (computer-aided engineering, design for manufacture, mechanical, electronic, test, design, design rules, etc.)
Computer capability (software and hardware; mainframe to microprocessor)
Artificial intelligence (various forms)
Data base technologies (organization, size, integrity, consistency, security)
Modeling/simulation/prototyping (including software prototyping)
Management Systems (manufacturing requirements planning, configuration)

Process Technologies

Automated statistical process control (real time)
Component mounting and connection
Patterning (transfer of design to product)
Metal plating and deposition
Materials shaping and forming (including near net shape)
Nondestructive assembly and repair (as components become more sensitive)

Equipment Technologies

Robotics, flexible equipment, and data-driven automated tools
Controllers
Vision systems, especially three-dimensional
Tactile sensing
Fault-tolerant systems
Material handling
Label sensors (e.g., bar code)
Lasers (multiple functions--measurement, cutting, etc.)
Diagnostic/maintenance technology--factory

Factory System Technologies

Data networking (Manufacturing Automation Protocol, local area networks, etc.) and security
Total system integration
Factory system architecture

Materials and Components

Materials selection and substitution
Polymer and adhesive chemistry
Printed wiring board interconnections
Mechanical connectors and fasteners

Facilities

Facility engineering and construction
Contamination control

Human Factors

Training technologies/process instruction
Man/machine interfaces (including voice recognition)

Figure 1-3. MATRIX OF KEY TECHNOLOGICAL APPLICATIONS

Key Production Technologies	Manufacturing Functions						
	requirements & specifications	design	externally acquired components	fabrication	assembly	test product process	field support
Information Handling/Processing							
• Design Automation Tools (computer-aided engineering, design for manufacture, mechanical, electronic, test, design, design rules, etc.)	1	2			2	4	
• Computer Capability (software & hardware mainframe to microprocessor)		5				6	
• Artificial Intelligence Tools (various forms)	7	6				9	10
• Database Technologies (organization, size, integrity, consistency, security)		11				12	13
• Modeling/Simulation/Prototyping (including software prototyping)	14	13		10	17		
Process Technologies							
• Automated Statistical Process Control (real time)				18	19	20	
• Component Mounting and Connection					21		
Equipment Technologies							
• Robotics, Flexible Equipment, & Data-Driven Automated Tools				23	23	24	
Factory System Technology							
• Data Networking (MAP, LAN, etc.) and Security		25		26	27	28	
• Total System Integration (including system adaptability)	29	29	29	29	29	29	
Human Factors							
• Training Technologies/Process Instruction				30	30	30	

These 30 key technological applications are described in detail in Appendix A. For each application, the appendix lists the current status and anticipated developments within the next 5 and within the next 10 years.

COMMITTEE PROCEDURE

The Panel used the 30 key technological applications as the basis for a questionnaire that was sent to experts in automated manufacturing technologies in the electronics industry. A sample page from the questionnaire is shown in Figure 1-4. The questionnaire devoted a page to each of the 30 applications, and respondents were asked to fill out the pages in areas about which they had knowledge.

While most of the respondents were from the electronics industry, responses were also received from federal agencies and from universities. Sixty questionnaires were sent, and 26 responses received. Most of the responses reflected the work of more than one person. The Panel members used the responses to supplement their own knowledge in developing the findings presented in the remainder of this report.

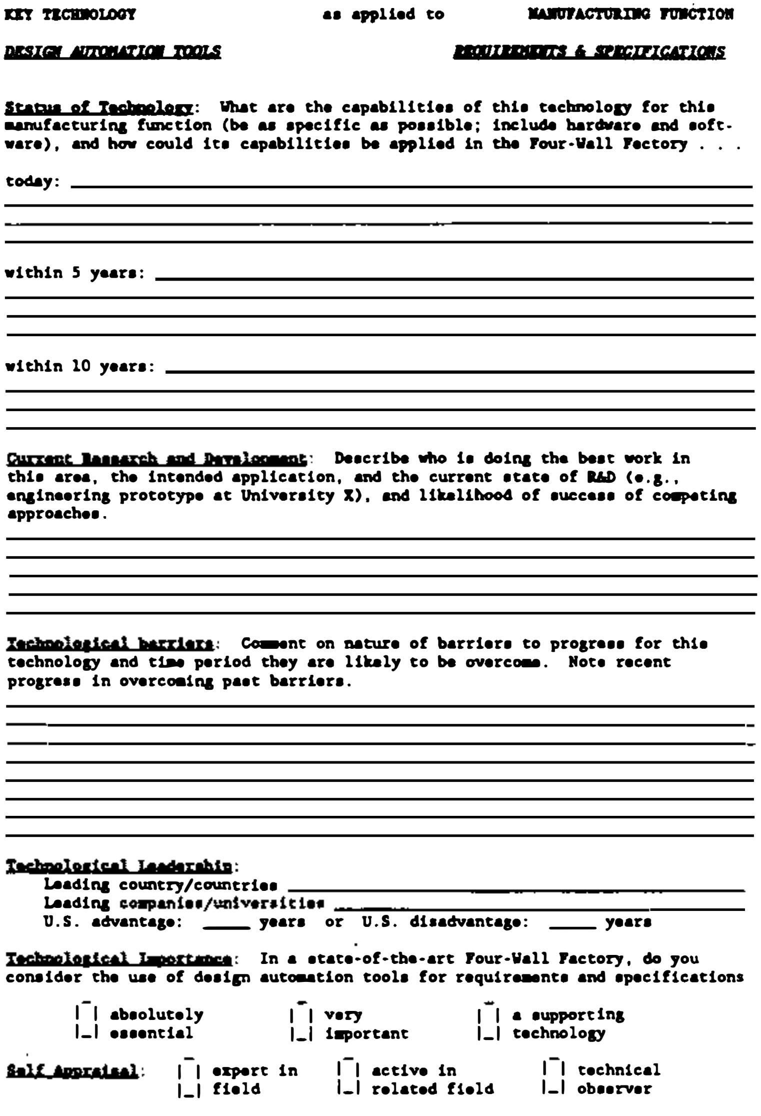
ORGANIZATION OF THE REPORT

The Panel has organized its findings to present different levels of aggregation. Chapter 2 rates the importance, net U.S. position, and technical and nontechnical barriers of the 30 technological applications; these ratings are used to identify the technological applications that are most critical to the defense community. The chapter provides the Panel's basic findings about where the DOD should place its emphasis.

Chapter 3 addresses some broad issues affecting the ability of the U.S. defense community to use automated manufacturing technologies for electronics assembly. It describes where world leadership in the technologies is located and suggests some nontechnical barriers that, if addressed, offer opportunities to achieve or maintain world leadership in the manufacturing technology used for defense products.

Chapter 4 provides additional detail on six groups of technological applications that the Panel found to be

Figure 1-4. SAMPLE QUESTIONNAIRE PAGE



KEY TECHNOLOGY as applied to MANUFACTURING FUNCTION

DESIGN AUTOMATION TOOLS *REQUIREMENTS & SPECIFICATIONS*

Status of Technology: What are the capabilities of this technology for this manufacturing function (be as specific as possible; include hardware and software), and how could its capabilities be applied in the Four-Wall Factory . . .

today: ____________________

within 5 years: ____________________

within 10 years: ____________________

Current Research and Development: Describe who is doing the best work in this area, the intended application, and the current state of R&D (e.g., engineering prototype at University X), and likelihood of success of competing approaches.

Technological barriers: Comment on nature of barriers to progress for this technology and time period they are likely to be overcome. Note recent progress in overcoming past barriers.

Technological Leadership:
Leading country/countries ____________________
Leading companies/universities ____________________
U.S. advantage: _____ years or U.S. disadvantage: _____ years

Technological Importance: In a state-of-the-art Four-Wall Factory, do you consider the use of design automation tools for requirements and specifications

☐ absolutely essential ☐ very important ☐ a supporting technology

Self Appraisal: ☐ expert in field ☐ active in related field ☐ technical observer

1

critical. Chapter 5 summarizes the Panel's findings and recommendations to the Department of Defense.

In addition, three appendices provide greater detail on the subjects of the earlier chapters. Appendix A describes the current and future status of technologies. The questionnaire data that were used in the calculations are in Appendix B. Names of leading companies and universities in the relevant fields are in Appendix C.

2 SELECTION OF CRITICAL TECHNOLOGIES

The 30 key technological applications around which the questionnaire was organized were the Panel's first iteration in narrowing the design and production technologies on which the U.S. defense community should concentrate its resources. To reduce the list further, the Panel developed a criticality index based on the questionnaires.

This single measure, criticality, used three factors that the Panel considered fundamental to decisions by the Department of Defense about which technologies to emphasize. These factors are:

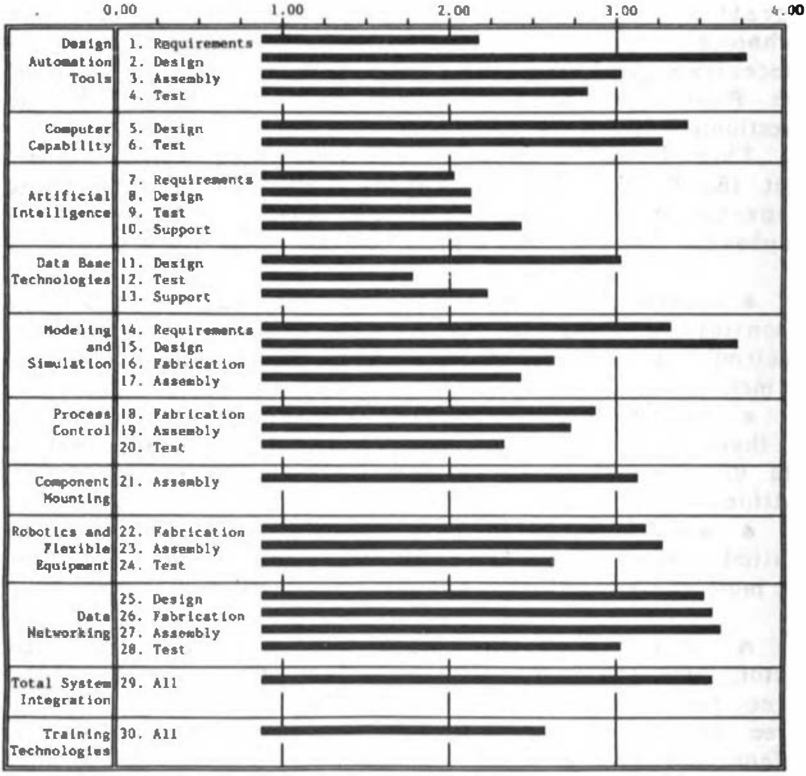
- *essentiality*--technologies that are absolutely essential to producing affordable, functionally superior electronic assemblies; without them DOD's needs will not be met;
- *barriers*--technologies facing major barriers to their development are likely to be beyond the capabilities of a single company and therefore likely to require outside support; and
- *world leadership*--technologies in which the United States most seriously lags foreign developments are most likely to threaten our ability to compete.

A numerical rating scale was developed for each factor, and criticality was defined as the product of the three factors. Any technology that rates high on all three factors is, by our definition, critical to the U.S. defense community. The remainder of this chapter defines the factors and presents the ratings of the technological applications by factor, followed by their ratings on the criticality index.

ESSENTIALITY

Questionnaire respondents were asked to rate the essentiality of the technological applications using three categories: absolutely essential to achieving affordable functional superiority, very important, or a supporting technology. The essentiality rating for a technological application is the weighted average of the responses given by those who described themselves as experts in that application, with the following weights:

Figure 2-1. ESSENTIALITY INDEX



3 WORLD COMPETITION IN ELECTRONICS MANUFACTURING AUTOMATION

THE CHANGING BASIS FOR WORLD LEADERSHIP

World competition in electronics assembly has changed dramatically during the past 15 years. Global leadership in the manufacture of low-cost, high-performance, high-reliability hardware has passed from U.S. companies that virtually invented both the component and assembly technologies to Far Eastern companies (primarily in Japan) that came to electronics manufacturing from a very different perspective.

The United States, traditionally the leader in nearly all facets of the electronics business, built its competence on developing, manufacturing, and supporting complex electronic systems to meet defense, industrial, and general computational demands. Until a decade ago, success in the world market was associated with low-volume, high-performance systems, which depended on skills in product development, product performance, software, and systems integration. Manufacturing processes were a secondary consideration at best, and the benefits of volume learning processes in a disciplined manufacturing environment eluded many electronics hardware assemblers.

The high-volume part of the electronics industry, consumer products, was regarded in the United States as a subordinate business. Manufacturing technology for electronics assembly advanced slowly in this part of the industry. Instead, emphasis was placed on product appearance and low manufacturing cost, often at the expense of manufacturing capital investment and product quality and reliability.

The Japanese and a number of other Asian-based consumer electronics manufacturers have developed, over the past 35 years, a strong electronics assembly industry based on consumer electronics products. Beginning with transistor radio developments shortly after the introduction of the transistor itself, these manufacturers used experience in manufacturing high volumes of product to establish a national niche in the world electronics market.

Although they were aided by low-cost labor and a number of other cost advantages, these volume leaders captured the bulk of the world's consumer electronics business by emphasizing careful attention to the details of electronics hardware manufacturing. They overcame a national image of cheap, throwaway, low-technology products to assume leadership in product quality, reliability, and design and yet retained low manufacturing costs.

From their experience with transistor radios, the Japanese moved on to dominate the black and white television set business, then color TV, and finally branched out into new video, audio, and appliance products, often based on developments elsewhere. At the same time, faced with determined competition from abroad, many U.S. consumer electronics manufacturers either moved to Asia themselves or quit the business, often selling out to their Japanese competitors.

In recent years, the technology embodied in consumer products has advanced substantially as products such as videotape recorders, compact disks, and cam-corders have reached the market. In many respects, the technological demands of some of these new products rival those of high-performance computational and defense hardware. As a result, the technological base of Far Eastern electronics hardware manufacturers has become competitive with that of some of the more performance-oriented electronics companies in the United States and Europe.

The difference between the Japanese and Western perspectives on electronics is in the emphasis on manufacturing. This difference may be increasingly important as technologies become still more complex, requiring that long sequences of closely controlled fabrication processes be carefully managed to get even a minimal yield of reliable, high-performance subsystems.

During the past several years, a few leaders in the U.S. electronics industry have sought to develop competence in high-volume manufacturing. They have done so through major efforts to institute manufacturing management techniques, improve product quality and reliability, and achieve competitive costs. These leading companies appear to be closing the electronics assembly leadership gap with the Japanese; however, the remainder of the U.S. electronics assembly industry remains in a poor competitive position.

While U.S. manufacturers have been concentrating mainly on Japanese competitors, companies elsewhere in the Far East have developed aggressive native electronics assembly industries. Korea, Taiwan, Hong Kong, and Singapore have based their industrial programs on the Japanese model and have captured the low end of the consumer electronic products spectrum.

The development of the Japanese and other Far Eastern electronics industries teaches a clear lesson: a strong civil electronics manufacturing base is a good way to develop world leadership in electronics assembly capability--and it may be the best way.

Questionnaire Findings

The responses to the Panel's questionnaire support the scenario described above. The chart in Figure 3-1 reflects the respondents' comments on foreign competition. The left side of the chart shows areas in which the United States lags the competition, and the right side shows areas in which the U.S. leads. The scale is the average of the experts' judgments of the number of years by which the United States leads or lags.

The preponderance of experts' references were to U.S. or Japanese leadership in the field; few references were made to European work. In fact, Europe was viewed as more formidable than Japan for only one application--data networking applied to design. Furthermore, references to both U.S. and Japanese competence in electronics assembly technology were mostly to broad areas of strength, whereas those to European accomplishments were generally to isolated areas of competence.

Figure 3-1 clearly shows Japanese leadership in the process and manufacturing equipment technologies, with the United States stronger in systems and computer-based technologies. This reflects the antecedents of the electronics assembly industries in those countries as described above.

A critical question is how the United States could build on its leadership in computer and systems

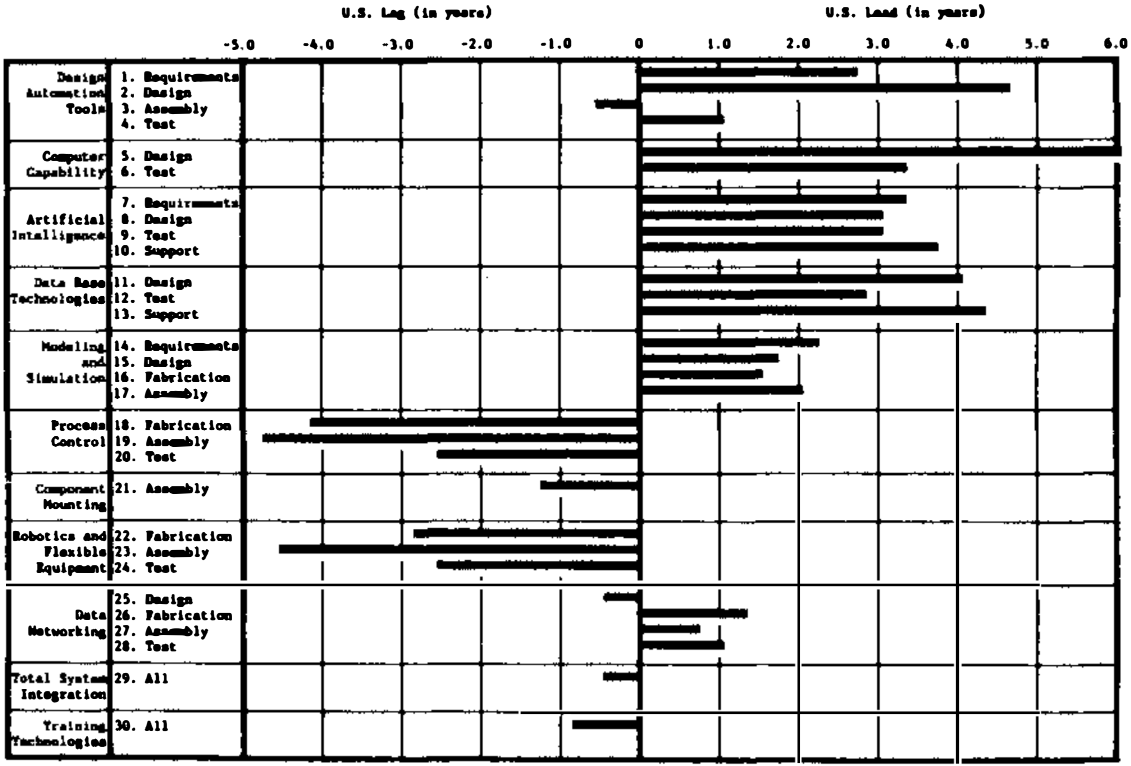


Figure 3-1. THE U.S. POSITION IN ELECTRONICS AUTOMATION TECHNOLOGY

technologies to compensate for relative weakness in process and equipment technologies.

INTERNATIONAL DIFFERENCES

U.S. companies must change some of their practices to regain or retain world leadership in electronics. While they will not want to slavishly copy their competitors' specific practices, they can learn from the successes and failures of firms in other countries. In addition, an understanding of what underlies international differences should help U.S. companies to capitalize on their strengths.

Manufacturing excellence has become critical to competing successfully in many facets of the business. The Panel has identified several nontechnical considerations that can limit success with automated manufacturing in electronics--but can be overcome. They are:

- the status of manufacturing within companies is low;
- most U.S. managers do not yet emphasize manufacturing as a means of achieving world leadership in electronics;
- DOD, too, pays little attention to manufacturing but emphasizes engineering in electronics procurement;
- defense manufacturing technology is now driven by commercial manufacturing technology, which the United States has been losing to Asian countries;
- competitive success depends on mastering not only the hard manufacturing technologies (facilities and equipment) but also the soft technologies (operating procedures) involved in their use, and Asian countries seem to lead in the latter;
- the Japanese have a structural advantage because the U.S. electronics industry lacks vertical integration;
- U.S. companies have little experience or skill in managing strategic partnerships, yet the lack of vertical integration creates a greater need for all types of alliances;
- the strength of the United States is in the fundamentals of science and technology, not their application; and
- furthermore, the United States is weak in the language skills that will become increasingly necessary as

more of the technical literature originates in other countries.

These interrelated issues suggest strategies that should be pursued to improve U.S. use of electronics automation.

Status of Manufacturing Within Companies

The U.S. electronics industry has traditionally been driven by research and development and marketing functions. The manufacturing function and managers in charge of manufacturing activities have tended to be less influential than their R&D and marketing counterparts. This second-class citizenship is reflected in the career paths of many manufacturing managers.

The impact of this informal class distinction within U.S. companies can best be understood by considering company cultures in other countries. Some traditional industrial organizations of Britain and France, for example, display a clear schism between an elite (senior management and research staff) and the rest of the staff (including manufacturing personnel). One's place in the hierarchy is determined more by educational background than by company performance, with less qualified workers being assigned to routine production assignments. Movement between the two classes is rare.

Policy makers in such countries have indicated serious concerns about their ability to transfer new product and process technologies from the research and development laboratory to manufacturing status. Further, technology transfer is clearly impeded by communications and perception problems between the two classes of industrial managers and engineers. The overall poor manufacturing performance of companies with such rigid class distinctions has materially affected their competitive position in the world.

Many large Japanese companies, in contrast, have concentrated on manufacturing as their core competence. These companies also hire new university graduates on the basis of educational background, but regardless of background often expect them to serve an extended tour of duty in manufacturing operations before moving to more specialized functions. As a result, managers and engineers share a common perspective of the importance of manufacturing considerations in every aspect of company activities, facilitating the transfer of products from engineering and design into production and emphasizing manufacturing requirements in every phase of product life.

In addition, several Japanese companies have formed manufacturing research laboratories. Their function is to develop manufacturing technology the same way that product and process research develops technology for future businesses. These laboratories have attracted some of the most productive of the company's technical contributors.

The informal structures of U.S. manufacturing companies tend to lie between the European rigid specialization and the Japanese common culture models. Some leading U.S. firms have recognized the need to improve the role of manufacturing in their businesses if they are to compete with world-class rivals, and several firms have created manufacturing research laboratories. Manufacturing must be seen as an attractive career for some of the brightest, most aggressive managers and engineers, on a par with other vocations within the company. Failure to achieve this change may lead to our suffering the symptoms of the European class distinction problem.

Management Attitude

Leading U.S. firms have now realized the need to make fundamental changes in manufacturing status, investment, technology, and quality; however, many corporate managers are not yet aware of the scope or urgency of needed changes. Failure to understand the need for change is particularly strong in the defense electronics manufacturing industry, where the threat of foreign competition has been missing. Pressure for short-term financial results, inertia, and preoccupation with other facets of the business all divert attention from the need for continuous improvement in manufacturing performance.

The increasing strength of foreign firms in defense markets must not be underestimated, however. Countries that have achieved leadership by designing and manufacturing other electronic products will soon turn to military hardware in an effort to expand available market opportunities. Even Japan has begun slowly to change its historical disregard of military products to plan for long-term growth of its armaments supply capability, to meet both internal and export market needs.

Contrary to common perception, the level of technology now employed in consumer electronics products such as videotape recorders, cam-corders, personal computers, and digital audio systems compares favorably with the general level of electronics technology seen in military equipment. In fact, long system-development cycles and lengthy component qualification procedures have meant that the technology available in deployed U.S. military electronics systems lags well behind that available in commercial systems and consumer products. The point was documented in the earlier report of the Committee on Electronics Automation.

DOD must take the lead in encouraging the management of its electronics hardware suppliers to understand the need for world-class flexible manufacturing and to invest in and change their company operations accordingly. Within the United States are companies that have successfully used techniques for changing traditional electronics assembly manufacturing. Among these techniques are just-in-time manufacturing, statistical process control, simulation, and well-thought-out approaches to factory setup and design, scheduling, and the flexible factory. Use of these techniques should be a criterion in the award of production contracts.

Nature of the Department of Defense Business

The depressed status of manufacturing in U.S. companies is currently mirrored by the low emphasis given to manufacturing process development by the Department of Defense. Requirements for U.S. defense electronic systems tend to emphasize high performance, high reliability, and high-technology product content.

With few exceptions (such as artillery and mortar, proximity, and electronic time fuzes), the volume requirements for defense electronics are modest by the standards of commodity electronics manufacturing. As a result, DOD procurement practices emphasize good development engineering practice, but are not well suited to developing strong manufacturing competence. Cost accounting, unique technology, and special reliability procedures have forced much of this country's defense electronics manufacturing activity into isolated job shops. Lessons learned from commercial activities under way in the same company are slow to be applied to military product production.

Development of truly efficient, flexible electronics manufacturing automation for defense products will proceed slowly until defense production can be efficiently combined with manufacturing of similar, high-volume commercial hardware to create a critical mass for development of efficient manufacturing technology and effective use of lessons learned from marketplace competition in other products. Further, military production contracts should provide incentives for good manufacturing practices, in addition to the traditional focus on engineering practice. By requiring the use of statistical process control in some contracts, DOD has begun to provide such incentives.

Civil Technology Focus

In the past 25 years, many--if not most--of the world's electronics technology developments have been commercially driven; the competitive requirements of the consumer, computer, industrial, and instrumentation markets have provided incentive and direction. Leadership in the industries that support electronics assembly--suppliers of materials, fabrication equipment, components, and piece parts--has tended to go to countries whose manufacturers are volume leaders. The U.S. capabilities in both volume electronics hardware manufacturing and its supporting industries have lost ground to manufacturing competence abroad, especially Japanese companies.

In many electronics manufacturing areas, it is becoming difficult to find competitive U.S. sources of supply for commodity components, semiconductors, materials such as ceramics, and high-volume manufacturing equipment such as pick-and-place machines for printed circuit board assembly. The U.S. infrastructure of the 1950s and 1960s has been replaced by a worldwide supply base.

Offshore supply for some common, multiple-source commodity materials is not likely to be a strategic problem. Reliance on foreign producers of manufacturing equipment, however, could place U.S. military electronics manufacturers seeking to automate at a disadvantage compared to nonnative commercial electronics assemblers working closely with their counterparts in manufacturing equipment.

Soft Versus Hard Technology

U.S. observers of Japanese electronics manufacturing technology frequently comment that Japanese factories seem less modern than their U.S. counterparts, use similar manufacturing processes, and yet produce products that exceed U.S. equivalents in many respects: lower cost, higher quality, and higher reliability are often mentioned. Furthermore, discussions with Japanese line engineers reveal levels of knowledge of manufacturing process detail uncommon in U.S. plants.

If electronics factories have comparable hard manufacturing technology (plant facilities, processes, and equipment), yet one substantially outperforms the other, the difference must lie in soft technology--the manner in which the equipment, facility, and process are managed. Much of the concern about U.S. manufacturing performance comes from our inability to master the relevant analytical, engineering, and management procedures. Soft technology is not covered in formal engineering curricula in colleges and universities, nor is it well treated in the literature. It appears to come out of a strong drive to master all aspects of manufacturing using all the tools at hand, and to push continually for incremental improvement in performance.

Leading U.S. companies have begun training manufacturing personnel to use analytical and statistical tools in mastering the level of detail required for competitive soft technology. However, the average competence in soft manufacturing technology in this country still substantially lags the Japanese competition.

Thorough understanding and optimization of manufacturing line operations is just as important in factory automation as the selection and installation of the equipment. Electronics factory automation must begin with manufacturing simplification and then proceed to selection of automated process technology and, finally, to integration of overall factory operations. This Panel is aware of numerous examples where the first step in the process--simplification--was overlooked in the rush to automate. The result is the proverbial factory that makes the same production errors as it did with manual methods, but at a much higher rate--and substantially higher capital cost.

Electronics manufacturing automation, to succeed, must begin with complete understanding of the nonautomated process and its optimization (the soft technology); only then should sophisticated, hard technology be applied.

U.S. Vertical Disintegration

Unlike the case in Japan, the U.S. electronics industry is not based on large, vertically organized enterprises. It is common in Japan to find elements of the same large company group supplying materials and fabrication equipment to internal users who manufacture electronic assemblies for use in systems made and sold by still other group members. The U.S. industry, in contrast, consists of a multitude of unrelated firms acting independently. Many of these firms, even in critical supply areas, can be quite small and are frequently new ventures.

Smallness has advantages: small companies may be fast at getting products to the marketplace and tend to attract highly motivated personnel. However, small firms frequently lack the resources needed to see major equipment or process developments to completion. They also may have difficulty developing the close relationships with customers necessary to understand user needs completely.

The weakest link in the industrial chain that supports the U.S. capability in electronics assembly manufacturing involves suppliers of automated manufacturing equipment. This weakness includes both the inability of critical small suppliers to sustain their competitive positions over the long haul and communications difficulties between manufacturers and equipment suppliers.

The Department of Defense can help alleviate these weaknesses by encouraging team arrangements in the production phase of DOD electronics hardware, to provide the vertical structure missing from the U.S. industry. The objective of such teaming arrangements would be both to improve vertical communications and to sustain smaller firms in completing costly development efforts.

Strategic Partnerships

Partnerships formed by electronics manufacturing companies to achieve common strategic goals are a comparatively new aspect of corporate strategies. Many firms, particularly smaller ones, have discovered that the competence or investment required to develop or expand their electronics businesses exceeds their resources. As electronics technology continues to grow more complex, even large corporations are realizing that important aspects of their business operations require outside help, generally in the form of strategic partnerships with companies such as suppliers, customers, or, increasingly, competitors. The form of these relationships ranges from simple purchasing and marketing agreements to elaborate industry consortia such as the Microelectronics and Computer Technology Corporation (MCC) and the National Center for Manufacturing Sciences.

Within the generally adversarial tradition of U.S. business practice, management of such strategic partnerships to the long-term benefit of all parties requires unusual skill. Inexperience at partnership management has led to the failure of many otherwise well-conceived alliances to advance electronics manufacturing.

The Department of Defense, by encouraging team approaches to large systems and technology development contracts, has helped establish the partnership ethic among systems suppliers. Similar encouragement in electronics manufacturing procurement may help further develop partnership skills among electronics manufacturing companies.

Experience with successful partnerships might bridge some of the gaps in the vertically disintegrated U.S. electronics industry. Such an outcome would make up for some of the advantages available to countries having highly integrated electronics industries. The recent establishment of Engineering Research Centers, the National Center for Manufacturing Sciences, and Sematech are hopeful signs that U.S. industry, universities, and government are becoming progressively more able to form partnerships and consortia.

Technical Skills

The United States continues to be preeminent in many fields of science and technology. Our basic research continues to lead the world in many areas, and our university educational system, particularly at the graduate level, ranks as the world's best. The number and quality of foreign students seeking admission to U.S. science and engineering curricula is but one indicator of the regard with which the rest of the world holds our general competence in science and technology. In addition, U.S. corporations are highly regarded for their continuing technical leadership in many fields, including electronics.

U.S. engineering education is especially strong in electrical and computer engineering, particularly in fields relating to computer technology: computer applications, software, and systems engineering skills are areas of strength in depth.

Translation of this overall leadership in science and technology into industrial leadership in automated electronics manufacturing is a different kind of problem. Our ability to educate research and development engineers exceeds our ability to train manufacturing engineers and support technicians in a number of critical fields. This is a problem both in the educational system and in company indoctrination and continuing education programs.

Substantial improvement is needed in training professional managers for manufacturing assignments and in attracting some of the best university students to manufacturing careers. Raising the status of manufacturing professionals within firms would help solve this problem. Both engineering and business school curricula must also be examined, however, to determine how best to meet occupational needs in manufacturing.

One specific problem lies in the weakness of U.S. engineering and technician education in the mechanical skills needed for precision mechanics and manufacturing automation engineering. Recent U.S. concern has focused on the relative imbalance in numbers of electrical engineers and technicians produced by this country and Japan. Although little attention has been paid to relative numbers of graduates in mechanical engineering, the problem is of a similar magnitude, as shown in the 1985 data below.

Table 3-1. ENGINEERING DEGREES GRANTED AS A PERCENTAGE OF TOTAL FIRST DEGREES GRANTED BY COLLEGES AND UNIVERSITIES

	Japan	United States
All engineering	19.13%	7.85%
Electrical engineering	5.58%	2.20%
Mechanical engineering	4.11%	1.70%

SOURCE: National Science Foundation

One consequence of U.S. weakness in mechanics is a related weakness in mechatronics, or computer-controlled mechanisms. This field requires simultaneous understanding of computer science and mechanics. The United States is strong in the former but not the latter. An almost systematic neglect of mechanical design has hurt the country's ability to develop and use mechatronics.

Despite emphasis in this new discipline in countries that compete with the United States, no U.S. engineering schools have established curricula leading to degrees in mechatronics. In Japan, for example, 20 to 25 universities grant degrees (including Ph.D.s) in precision engineering or related fields, which are essentially mechatronics. As a result, a number of U.S. electronics companies now rely on offshore engineering skills to make up for the inability to hire U.S. engineers in these areas. Other traditionally low-technology facets of the electronics industry, such as packaging, generally do not receive emphasis either.

The shortage of educated manufacturing personnel in the United States extends to the factory floor. Not only is manufacturing engineering talent more readily available in Japan, but so are low-cost factory workers who are able to do increasingly complex production jobs reliably and well. To compete with low-cost, high-quality labor, the U.S. manufacturing sector will need a major education effort at all levels.

Language Skills

Other countries, as they were rising to challenge U.S. leadership in electronics, relied heavily on the open technical literature available from U.S. sources in the English language. Most educated electronics professionals abroad are trained in English, if only at the reading level, so as to be able to read the international literature.

As non-English speaking countries, particularly those in Asia, become leaders in electronics, however, we will be unable to reciprocate in our awareness of their technical publications since our technical staffs lack the necessary language skills. Yet the emphasis placed by U.S. schools on study of languages having sizable technical literatures has been steadily decreasing.

Reliance on document translation is a poor substitute for staff language competence, since the delays inherent in obtaining a good translation and the loss of context significantly lessen overall understanding.

CONCLUSION

An effective U.S. response to the rapidly changing world competitive situation in electronics assembly automation requires more than a strictly technical approach to the problem. Issues addressed in this chapter are matters of policy and management of our national manufacturing capability, not isolated technological developments. Many of these issues form part of the culture of the enterprises that make up the electronics manufacturing base in this country. Success at adopting modern electronics automation technology will depend in part on the ability to change our industrial manufacturing culture.

With the development of strong international competition in consumer electronics, manufacturing technology has become an important factor in establishing world electronics dominance. U.S. consumer electronics manufacturers have been notably unsuccessful at meeting Asian challenges, partly because of their inability to master the manufacturing aspects of their businesses. Companies' inability to adapt their cultures to meet new competitive manufacturing standards has caused the loss of much of the U.S. consumer electronics industry to offshore suppliers.

The Department of Defense's action plan for enhancing the U.S. electronics manufacturing base must include steps to encourage development of a competitive manufacturing climate, as well as addressing the specific technical issues identified in subsequent chapters of this report.

4 SIX KEY TECHNOLOGIES

As the Panel looked further into the 30 key technological applications identified in Figure 1-3, six groups emerged as focal points as the defense community works toward the factory for automated production of electronics assemblies shown in Figure 1-1. These six technologies account for 20 of the 30 applications, as follows (in numerical order):

Design Automation Tools (1, 2, 3, 4)
Modeling and Simulation (14, 15, 16, 17)
Process Control (18, 19, 20)
Electronic Packaging and Interconnection (21)
Automation Equipment Technologies (22, 23, 24)
Factory System Integration (25, 26, 27, 28, 29)

The six technologies account for all of the 30 applications that had a criticality index of 8 or greater, plus some related technological applications that scored lower. The 10 applications not included fall into two categories. The first, applications 5 through 13, is information handling and processing technologies in which the United States has both a comfortable lead and more technology available than has been applied; further, these technologies are not as important to the production of state-of-the-art electronic assemblies as some of the other technologies. The second, application 30, is human factors. Human factors are fundamental to overcoming the barriers to technological applications, as described in Chapter 3, but they are not a technology as such.

The Panel analyzed the six key technologies in detail. That analysis forms the remainder of this chapter. The technologies are presented in order of relative importance, as indicated by the criticality index and the Panel's judgment. The order is:

- Process Control
- Automation Equipment Technologies
- Factory System Integration
- Modeling and Simulation
- Design Automation Tools
- Electronic Packaging and Interconnect Technology

Placement near the bottom of this list does not mean that the technology is not important. All of these technologies were found to be critical to the defense community, outranking many technologies that are not listed here. For each of the six technologies, we give:

- Definition
- Importance
- U.S. Position
- Barriers
- Opportunities
- Implications for the Defense Community

PROCESS CONTROL

Definition

Process control in a manufacturing environment consists of the management of individual fabrication steps to assure consistent, controllable results within process specifications and tolerances. Process control includes both the monitoring of process results and the process adjustment to bring out-of-tolerance processes back under control. In many process control activities statistical methods play an important role in simplifying complex control problems.

Process control procedures regulate measurable process parameters according to established criteria, often including (1) process average, (2) upper and lower control limits, and (3) upper and lower process stop limits.

Importance of Process Control

Control of each process step, and in particular automatic process control in real time, is essential to automating manufacturing processes. The rate of production of automated factories is too high to allow waiting for product test and evaluation to be completed before making in-line process adjustments. The amount of scrap produced between the time the process goes out of its limits and corrective action is taken is simply uneconomical. In addition, close control of individual steps in complex product fabrication sequences is crucial to achieving acceptable overall product yields.

Rigorous process control discipline carries with it numerous collateral benefits:

- assurance that each manufacturing process step achieves desired results, consistent with design parameters;
- assurance of quality and consistency in both design and production of the product;
- application to both high- and low-volume production;
- speedy diagnosis of line problems with minimum production disruption;
- effective manufacturing cost control;
- process history for future field failure analysis;
- minimization of product rework;
- lead indicator for new process and equipment needs; and
- facilitation of communication between engineering and manufacturing.

U.S. Position in Process Control

Questionnaire respondents said, and the Panel agreed, that U.S. electronics assembly manufacturers lagged their Japanese counterparts by approximately three years. This statistic conceals wide variation. While leading U.S. companies are as good as other world leaders at process control, there are very few of them. The vast majority of U.S. electronics companies are four to five years behind in the practice of manufacturing process control.

The status of process control technology in specific work centers in the U.S. electronics industry is shown in Table 4-1.

Barriers to Use of Process Control

Questionnaire respondents gave automated statistical process control a technical barrier rating of 2.6 and a nontechnical barrier rating of 3.0, on a scale of 4.0

Table 4-1. AVAILABILITY OF PROCESS CONTROL

Work Center	Availability of Automated Process Control
Fabrication/Machine Shop	available
Printed Circuit Fabrication	available
Printed Circuit Assembly	limited
Subassembly	none
Wire Wrap	none
Cabling	none
Final Assembly	none
Test	limited
Microelectronics	limited

(4.0 = most difficult). The major barriers to effective manufacturing process control are cultural, though more technical work is also needed. The barriers follow:

- Most managers believe that they already exert good control over production processes, but they rarely do. To many, control means the ability to find and correct faulty products rather than faulty processes. Failure to understand the full payoff possible has limited the management commitment and motivation to see installation of a rigorous process control discipline.
- While the number of U.S. technical personnel competent in manufacturing process control falls well short of current needs, the technical training needed for existing factory staffs to exert good process control is not difficult to provide. Courses and consulting help are widely available and not time-consuming in relation to benefits to be realized.
- The number and variety of process steps incorporated in an electronics assembly factory demand that a variety of process control methods and data collection tasks be mastered. The exact nature of these tasks varies with the particular fabrication sequence.
- Sensors are the greatest technical barrier to automated process control. For many electronics assembly steps, devices capable of automatically sensing in-line process results have not been developed. Although specific computer applications hardware and software are not currently available for real-time statistical process control of interacting processes, U.S. computer and

control expertise is more than sufficient to handle such data, once sensed. Development of in-line monitoring instrumentation and of control algorithms for optimizing specific processes will reduce the technical barriers.

- Control of a process requires thorough understanding of all factors affecting process results. Each process requires the investment of time and attention to master the level of detail needed to control it. The costs of doing this are high.

Opportunities to Benefit from Process Control

The potential benefits of good factory process control, which have been proven in practice, really are manifestations of good management practice. The benefits are:

- improved product quality and reliability at lower cost,
- shortened manufacturing cycle times,
- products that function as they are designed to function,
- lower total life-cycle costs,
- minimum field failure rates, and
- scrap minimization.

Implications for the Defense Community

The technical barriers to automated control of processes in electronics assembly factories are minor compared to the gap between technical knowledge and manufacturing practice. The challenge for the U.S. electronics manufacturing community is to tackle the management concerns that are preventing process control from being more widely used.

The Department of Defense has already taken an important step in that direction by highlighting the use of statistical process control (SPC) in its manufacturing requirements, but that is still a relatively weak incentive. Japanese firms that lead in the use of SPC will soon be competitors of U.S. defense contractors; that alone should be a strong incentive to speed U.S. utilization of these methods.

AUTOMATION EQUIPMENT TECHNOLOGIES

Definition

Automation equipment technologies comprise the group of technologies necessary to produce the equipment used in the manufacturing process. They include automated tools, robots, and flexible manufacturing equipment (e.g., automated warehouses, automated guided vehicles).

Importance of Automation Equipment Technologies

Automation equipment technologies are essential to factory automation for (1) fabrication, (2) assembly, and (3) testing of products and processes. Of the five basic components of the automated factory--machining centers, robots, automated guided vehicles, automated warehouse, and main computer center--these technologies affect the first four.

Proficiency in automation equipment technologies allows manufacturers to achieve generally higher quality at lower cost. Higher reliability and reduced downtime of the production line also depend on these technologies. In addition, design for manufacturability requires expertise in automation equipment technologies.

U.S. Position in Automation Equipment Technologies

The consensus of questionnaire respondents and the Panel is that the United States generally lags in automation equipment technologies by 2.5 to 5 years. The country has a strong position in the software and computer hardware components of these tools; the lag is primarily in the mechatronics (i.e., the technology of computer-controlled mechanical devices) aspect of the technologies and precision engineering.

While the fields of mechatronics and precision engineering overlap to a large degree, the computer-controlled mechanism of mechatronics might be high precision (as in cam-corders or high-speed printers) or it might not be (as in automotive applications). Precision engineering, while it often involves computer controls, might not (as in precision optics or metrology).

In the areas where these fields overlap, which are so important to automation, the United States has cause for concern. The U.S. academic position in mechanical engineering is relatively weak, as described in the previous chapter. Further, although a number of Japanese universities grant advanced degrees in precision engineering, the U.S. academic community has yet to recognize precision engineering as a university department, and researchers in this field generally have a low academic standing.

Barriers to Automation Equipment Technologies

The questionnaire respondents rated the barriers to automation equipment technologies as insignificant (technical difficulty = 1.2; nontechnical difficulty = 1.5) because the technologies are available: U.S. companies are buying Japan's technology. Yet the barriers to widespread use of automation equipment technologies in the United States are significant, especially in the lack of available know-how, the cost of experimenting with the technologies, and the lack of common interfaces.

The development of know-how is hampered by the relatively unstable work force of a typical U.S. company compared with its Japanese counterpart. In Japan, lifetime employment guarantees that training manufacturing engineers in advanced proprietary automation technologies is not only a good investment but a safe one. This has allowed Japan to form manufacturing research centers that all major companies support; these centers coexist with the more traditional general research centers, which are also well established in the United States as components of all major high-technology companies.

The lack of know-how (technical and managerial) is exacerbated by the lack of trained manpower and by the increasing tendency to use overseas facilities and manufacturing plants. This trend, in turn, contributes to increased know-how in these countries and not in the United States; as a consequence, the introduction of new products is delayed. Lack of cost-effective robotics hardware is a problem, especially for low-volume production.

The cost of experimentation with the technologies is a barrier that cannot easily be overcome. Consortia of companies, or of companies and government, could help support the effort required, but they are not easily established in this country. As noted in Chapter 3, the isolation of U.S. companies from each other (no vertical integration between machine builders and machine users) is a serious barrier, and small machine tool builders are risking the company each time they plan to introduce a new product. Furthermore, the inability of companies to form strategic partnerships that benefit both sides is inhibiting the use of consortia to overcome the lack of vertical integration.

Research is needed in the areas of three-dimensional modeling, design-manufacturing interface standards development, robot-hand development, reel-to-reel flexible circuit assembly and test, specific automotive testing, flexible material handling systems, and data-driven inspection.

Opportunities to Benefit from Automation Equipment Technologies

Progress in automation equipment technologies would permit direct dynamic reconfiguration of the manufacturing line by the design tools themselves in real time.

The formation of cooperative research and development arrangements would benefit all participants while making these technologies cost effective for each company.

Implications for the Defense Community

The United States already depends on foreign sources for developing key automation equipment technologies; this dependence can only be expected to increase. There is, nonetheless, an opportunity to support R&D in these technologies, which are critical in many aspects of weapon development as well as for automated manufacturing tools. Precision engineering and mechatronics, if properly supported, could accelerate not only manufacturing technology but also the development of new products for the national defense. Strong emphasis in these areas, coupled with U.S. strength in computer tools for design, could change us from laggards to leaders. A historical parallel is the U.S. work on missile hardware in the 1960s; although behind the Soviets, the United States achieved the know-how which, coupled with existing strength in computers, led to leadership in the space race.

The country's vanishing infrastructure in precision engineering and mechanics makes automated equipment technologies an important area in which to act quickly.

INTEGRATION OF THE TOTAL FACTORY SYSTEM

Definition

Total factory integration is the technology of bringing together all elements of the automated electronics factory. Integration requires all system design and consolidation skills necessary to incorporate the product design, fabrication, factory management, and test operations necessary to establish a complete manufacturing entity.

Elements of total system integration include:

- closed-loop automation of manufacturing processes, including fabrication, in-line test, and process control;
- communications capability to link and control individual process centers within the overall factory system;
- incorporation of a central data base/library/control capability, with distributed control as appropriate;
- in-process evaluation and built-in product test, together with statistical process control methods, which eliminate the need for 100 percent inspection yet assure zero defects;
- the ability to accommodate a heterogeneous array of hardware and software; and
- establishment of the overall control strategies for management of the complete factory.

Importance of Total System Integration

Whereas the other key technologies discussed in this section relate to particular phases of product design, manufacturing, or factory management, total system integration refers to the skills needed to bring all the pieces into a consistent, interoperating whole. Automated production of affordable, functionally superior electronic assemblies requires total system integration.

Factory automation has been proceeding through several phases in sequence, beginning with manual methods, moving to development of individual pieces of automated equipment, next to isolated islands of automation, and finally achieving a fully linked system. The benefits of the final goal--the fully linked, seamless production system--include true factory flexibility, improved consistency and quality, shorter manufacturing cycle times, and, ultimately, lower cost.

Questionnaire respondents rated total factory integration third of the technologies most critical for automated electronics assembly manufacturing. They further indicated that data networking is a key ingredient in successful integration.

U.S. Position in Total System Integration

The United States and Japan appear to share world leadership in total system integration. The questionnaire respondents' average estimation of U.S. leadership at 0.4 year is so short as to be meaningless. Large Japanese manufacturers of automobiles and semiconductors were cited as leaders in total system integration.

The current state of factory system integration extends to islands of automation with limited control linking. Ability to fully configure individual processes remotely, a necessity for fully flexible electronics assembly automation, has not yet been demonstrated.

Several leaders in computer systems (e.g., IBM and DEC) are currently competing to determine industry standards for factory system interconnection and control. In addition, efforts to establish factory data communication standards, led by a number of large manufacturers, are under way. Japan is already moving toward complementary vendor standards on a national scale.

Barriers to Total System Integration

While many of the technical problems of factory integration remain to be solved, both questionnaire respondents and the Panel felt these are not as difficult as the problems of time, cost, and management commitment. In fact, as a result of competing approaches now being taken, the probability of technical success is high. Whether senior company management is willing and able to commit to the lengthy, expensive process of total factory integration during times of financial stress, however, remains to be seen.

The competing approaches are a problem as well as an advantage. Each of the various vendors (of factory integration systems, hardware, and software) has adopted a different systems approach, and this proliferation makes it difficult for the factory integrator to commit to a single system with the assurance that it will prevail. Individual manufacturing machines have differing control and data architectures, and existing interface and data base standards are inadequate to enable companies to integrate diverse systems.

Total factory automation cannot be addressed on a small scale. It is a complex, expensive, cross-disciplinary process that involves the entire factory entity. The technology does not lend itself to prototyping, as scaling problems can be substantial. Furthermore, even experimental use of such a costly technology must be justified on a return-on-investment basis. The costs of setting up and keeping data networks current are high. Furthermore, there remains realistic skepticism that the predicted benefits of total factory integration can be realized. Management, therefore, has difficulty addressing the issue.

The field is not without technical barriers. Although the science of distributed process integration is only beginning, Japanese companies have the advantage because of just-in-time and preferred vendor programs. Research is needed in total network simulation, network performance measurement, communication systems for central data bases, high-speed interfaces, vision detection systems, token passing systems, switched network systems, and data base communication interfaces.

Opportunities to Benefit from Total System Integration

Further development of total factory system integration within the U.S. defense electronics manufacturing community can provide a number of important advantages:

- the ability to design, develop, and produce variations of electronic equipment hardware quickly to respond to new threats or sources of competition;
- the ability to produce DOD systems with a variety of different operating characteristics, thereby complicating the enemy's countermeasures problems;
- reduction of production costs for the low-volume products characteristic of many military hardware products while achieving higher quality and field reliability;

- increased demand for domestic supplies of factory automation equipment, stimulating the U.S. equipment industry's support for non-DOD needs and reducing dependence on foreign suppliers;
- motivation of the U.S. defense community to stretch toward automated production; and
- the possibility of building on existing U.S. strengths in systems, systems integration, computers, and software, as well as military systems.

Implications for the Defense Community

The Department of Defense could help overcome the identified technical barriers to total system integration by:

- encouraging the establishment of factory integration interface standards,
- helping to bring equipment vendors and factory operators together,
- encouraging training of technical experts in this cross-disciplinary area, and
- encouraging meaningful demonstrations of the benefits of total factory integration.

The current U.S./Japanese parity provides an opportunity to benefit from efforts in this area. One such possibility is to construct, in a DOD-controlled environment, a large experimental facility to demonstrate the state of the art of electronics assembly factory automation, to establish its benefits, and to speed development in areas impeding progress. Such an operation would make available, to the defense and other domestic electronics manufacturing communities, real-world experience in integrating factory operations, provide leverage from a single, large investment, and provide focus for small suppliers of equipment and materials.

MODELING AND SIMULATION

Definitions

Modeling: Technology of constructing computational representations (models) of electronic product and manufacturing process performance.

Simulation: Use of models in design automation tools to couple the designer's work to expected product performance, manufacturing process results, and product test and verification.

Factory modeling: Use of models representing work flow, throughput, line balance, control of process variables, statistical control estimation, tolerance estimates.

Product modeling: Use of models representing performance, yield, cost, design verification, validation of software.

Importance of Modeling and Simulation

The twin technologies of modeling and simulation are the essential links between product and process design activities and real world factory results. Realistic and accurate modeling and simulation capability drastically shortens design cycle times and reduces designer errors by allowing prediction of product characteristics, in turn reducing the need for long prototyping and characterization experiments. Such capability is essential to integrating design and manufacturing activities in electronics factories. Modeling and simulation techniques facilitate engineering changes in existing products and processes, thus reducing line disruption.

U.S. Position in Modeling and Simulation

The United States currently enjoys a modest lead (estimated to be approximately two years) in modeling and simulation. However, Japanese electronics manufacturers are emphasizing modeling and simulation methods as important elements of their future manufacturing strategy. Germany and France are also starting to close the technology gap in this field. Since the technology--modeling and simulation of electronics products and manufacturing processes--is still in its infancy, the slight U.S. lead is not decisive.

Barriers to Use of Modeling and Simulation

Both technical and nontechnical barriers to use of modeling and simulation need to be overcome;

questionnaire respondents rated them at 2.8 and 3.3 respectively. Specific barriers include:

- Modeling and simulation require attention to detail and extensive on-line data; this area is frequently misunderstood or ignored by management. Continual attention and process characterization is essential. Technological advances are needed to improve knowledge representation and to permit interactive modeling and simulation.
- There is no standard solution to modeling and simulation problems; models must be customized for each factory situation. Useful models of specific tools and processes are often not available and must be determined in each case. Progress in modeling and simulation will be limited by the availability of talent, the high costs, and the long time needed to establish models.
- Several practical solutions are required for parallel processing algorithms for modeling and simulation and for the development of data base methodologies for design applications. Areas of needed research cited in the questionnaires were: models of components developed to standards by component vendors; simulation programs with animated front ends and what-if capabilities; real-time simulation and object-oriented environments; mixed simulation products (analog and digital); expert systems for time-critical functions to generate optimized designs for performance; feature-based technology; vision systems and three-dimensional modeling; time simulation for fabrication; total factory simulation to improve efficiency; artificial intelligence scheduling, simulation of parts flow through plant; and simulation of tolerance stack-ups from processes.

Opportunities to Benefit from Modeling and Simulation

Better models and more widespread use of modeling and simulation technology can reduce trial-and-error delays in factory and product design and can speed overall product engineering activities.

Implications for the Defense Community

Modeling and simulation are crucial in flexible manufacturing, where cycle time determines success, a wide variety of products is the rule, and the volume of each product is so small as to preclude dedicated facilities and processes.

Japanese manufacturers are catching up; it is important that the United States maintain its lead in this technology. DOD can help strengthen the U.S. position by:

- encouraging or requiring the use of modeling and simulation techniques in its purchasing procedures; and
- supporting modeling and simulation research in academe, government, and industry--particularly in the mechanical area and for those processes where statistical variations affect product yields.

DESIGN AUTOMATION TOOLS

Definition

Design automation tools are the computer-aided design and manufacturing tools, both hardware and software, applied to the design and improvement of products to be produced. Examples include workstations, communication, and mainframe hardware and software used in computer-aided engineering for both analysis and design, often incorporating design for manufacture and process design rules.

Importance of Design Automation Tools

Questionnaire respondents and the Panel rated the effective application of design automation tools to product and manufacturing engineering as the single highest technology on the essentiality scale. These tools are essential because of their fundamental role in creating and documenting products, in communicating product information throughout the factory, and in serving as the designer's window into the factory. Design automation tools are essential to successfully handling increasingly complex electronic assemblies in a short product life cycle/engineering change environment.

U.S. Position in Design Automation Tools

The United States currently leads the world in the development and use of design automation tool technology, especially as applied to requirements, specifications, and design. Nonetheless, the United States must extend application of this technology to incorporate design for manufacturability, test, and assembly engineering if it is to maintain its lead. Questionnaire respondents rated the U.S. lead as one to four years, except in assembly, in which Japan now has--and is likely to maintain--the lead. While large mainframe computer companies are one source of U.S. strength in design automation tools, most of the country's competence derives from small workstation companies who depend on U.S. leadership in microprocessors and software.

Barriers to Use of Design Automation Tools

The major technical barrier to use of design automation tools is uncertainty about which methods are best for integrating design automation tools into an automated electronics assembly factory. In particular, the lack of software for integrated simulation and analysis is a significant barrier to the achievement of automated electronics manufacturing and test; this is true for both production and product design. The technical difficulty was rated 2.25 out of 4.0. The tremendous efforts being applied, however, suggest that technical success is likely.

Two cultural barriers (difficulty = 3.1) limit the effectiveness with which engineers and factory technicians use design automation tools and design for manufacturability. The barriers are: (1) otherwise experienced design and manufacturing engineers are not trained in use of design automation tools, and newly graduated engineers and technicians, while competent with the tools themselves, have not learned the value of design for manufacturability; (2) the need to link product design with manufacturing operations using design automation systems is not yet widely accepted.

Although individual workstations are not expensive, design automation technology requires a large commitment across whole projects--or even companies. It is not helpful to invest in small amounts of integrated design automation tools and manufacturing.

Opportunities to Benefit from Design Automation Tools

U.S. leadership in design automation tools provides a tremendous opportunity to offset high engineering labor costs by increasing engineering productivity and compensating for shortcomings in other technological areas by reducing design and manufacturing cycle times.

If U.S. electronics assemblers can effectively integrate design automation tools into an overall product development and manufacturing system, they will have capabilities unmatched in the world. Both cost (of development and of capital investment) and potential payoff are high.

Implications for the Defense Community

Design automation tools is the only one of the identified key technologies in which the United States has a commanding lead. Because it is such an important area, maintaining design automation leadership should enable the United States to offset some of its other technological disadvantages. It is worthwhile, therefore, for the U.S. defense community to work to maintain the competence of suppliers of design automation equipment and software and to encourage sensible deployment of these systems in electronics assembly manufacturing and design operations. Possible strategies for accomplishing some of this include judicious development of standards and increased training for managers and technical staff.

ELECTRONIC PACKAGING AND INTERCONNECT TECHNOLOGY

Definition

Electronic packaging and interconnect technology encompasses the tools, techniques, and materials for fabricating the second and third levels of interconnect (the connections between devices on the chip itself being the first level). This includes the fabrication of the wiring substrate, the chip attachment techniques, chip encapsulation techniques, and connector technology. (It includes #21 from the matrix of Figure 1-3, but for fabrication as well as assembly.)

Examples of substrates include printed circuit boards, advanced ceramic and silicon substrates, and copper/polyimide systems. Attachment techniques are surface mount, flip-chip, and tape automated bonding, using solder reflow, thermocompression bonding, laser bonding, and amalgams. Advanced encapsulation techniques promise to allow reliable chip-on-board systems.

Importance of Packaging and Interconnect

It is the packaging and interconnect technology, rather than the chip technology, that limits the performance of modern high-speed digital systems. In the fastest computers today, about half of the cycle time is the time of flight of pulses between logic circuits. To go faster, systems must be smaller, which requires higher-density wiring and higher-capacity heat removal techniques. In such systems, the fraction of cost allocated to the packaging and interconnect technology will become a larger part of the system cost.

Similarly, further improvements in system reliability can be expected to come primarily from fewer and more reliable interconnections rather than from reductions in failures of the devices themselves.

U.S. Position in Packaging and Interconnect

The United States is generally a year or more behind Japan in the development and use of surface mount equipment. The Japanese also lead in tape-automated bonding technology (TAB); both the NEC SX-2 supercomputer and the Sony Watchman miniature television, for example, use this technology. In fact, the Watchman actually uses TAB that is more demanding than the SX-2.

While IBM enjoys a clear lead in flip-chip attachment to multilevel ceramic substrates, this technology is not generally available to others.

In the area of materials, the Japanese enjoy a clear lead in ceramics.

Barriers to Use of Packaging and Interconnect

The major barrier to use of packaging and interconnect technology (difficulty = 1.0 out of 4.0) is the lack of accepted standards in the industry. These are needed to give decision makers in this fragmented industry the confidence that the product of an investment will remain in the mainstream, and to justify the effort and investment needed for the additional research and development to work out the process details and verify reliability issues.

Research is needed on reel-to-reel flexible circuit assembly and test, development of manufacturing rating systems for component mounting, improvements in solder and solder joint reliability, and integration of surface mount technology into workstation design rules leading to total computer-integrated manufacturing.

Opportunities to Benefit from Electronic Packaging and Interconnect

Advanced packaging and interconnect technology will enable (and is necessary for) higher-performance, lighter, smaller, and more reliable electronics systems to be produced. The technology also offers the opportunity to reduce manufacturing costs at the same time, as individual operations such as wire bonding are replaced by operations that attach a whole chip in one step, such as TAB or flip-chip. Direct attachment of chips to substrate will eliminate both manufacturing steps and failure points.

As the integrated circuits become more dense and complex, requiring ever more input/output connections, the dimensions of the attachments must shrink accordingly; at some point the dimensions will preclude manual operation, leaving no alternative to automated attachment.

Implications for the Defense Community

The defense community has the opportunity to influence the directions taken by these technologies for embedding and interconnecting advanced integrated circuits into systems. In doing so, it could ensure that these techniques are developed in ways that are suited to defense needs. At the same time, such support and guidance would benefit the industry as a whole, strengthening it as a supplier of defense equipment. On the other hand, if DOD fails to involve itself in the directions these

technologies take, it will risk not only incompatibilities with defense needs but also dependence on foreign sources for high-performance system technology.

5 CONCLUSION

The United States, once preeminent in the development and application of electronics assembly technology, no longer leads in all sectors of the industry. The basis for competitive success has shifted from low-volume, high-performance systems to low-cost, high-quality systems and the U.S. electronics industry has been losing the competition. In effect, the technology for consumer electronic products is no longer subordinate to that used for defense. One result of this shift is that manufacturing technology, rather than product development, is becoming much more important to determining leadership in the electronics industry. While a few U.S. firms have retained a lead in manufacturing technology, there is a wide disparity between them and the smaller companies that are more typical of the DOD supplier base.

The sponsor of the report asked the Panel to identify the technologies that will be important to the defense community over the next 5 to 10 years but to stop short of recommending specific DOD actions. DOD, armed with that knowledge, will be in a better position than the Panel to select the appropriate response. In that spirit, we offer the following observations on the implications of the changing technology for the U.S. defense community:

- A strong civil manufacturing industry is an excellent base from which to develop world leadership in electronics. The Department of Defense, therefore, should not be unconcerned by a world split in which the Japanese dominate consumer electronics while the United States dominates military electronics.
- The domestic electronics industry should not be complacent in the expectation that it can continue to

dominate the U.S. defense market. Japanese firms, among others, are beginning to consider military electronic systems as a source of continuing growth of market share.

- Despite the shift in technological leadership in electronics, the United States has great technological strengths on which it can build.

Of primary importance to electronics assembly in the United States in the next 10 years will be three technological areas:

- information handling and computer capability,
- process control, and process and equipment technologies, and
- total system integration.

The United States has a comfortable lead in information handling technology and computer capability. These technologies are an important source of U.S. strength in electronics assembly. In order to maintain this strength and build on it, we recommend that it continue to be the focus of major research efforts.

While leading in information handling, the U.S. electronics industry has lost its leadership in process control and in process and equipment technologies. These areas will be crucial to the production of affordable, functionally superior electronics assemblies. The barriers to widespread use of these technologies are managerial, not technical. We therefore recommend a concerted effort to bring practice among defense contractors up to the state of knowledge.

Total system integration is a technology in transition. As companies around the world work toward this goal, the apparent leaders change their relative positions. At present, it is not possible to determine whether Japan or the United States is in the lead. Because of the huge potential benefits of total system integration, and because of the complexity of the technical work needed to achieve it, we recommend that it be the subject of a concerted, cooperative, national effort via consortia.

Appendix A
CURRENT AND FUTURE STATUS OF KEY ELECTRONIC MANUFACTURING TECHNOLOGIES

STATUS TODAY	WITHIN 5 YEARS	WITHIN 10 YEARS
	REQUIREMENTS AND SPECIFICATIONS	
1. Design Automation Tools		
Limited availability of labor-intensive design automation tools. (Data base software with limited capabilities.) Tools available for certain application-specific integrated circuits. Present tools not very useful for linking customer to design. Requirements and specifications not coded or indexed to be easily retrievable.	Automated tools that generate design specification available. Tools more effective than today. Improved data bases reduce user time requirements. The manufacturer's facility acts as an extension of customer's business. Better indexing and classification of specifications for automatic retrieval.	Product specification to product documentation automated. Natural language interfaces available for CAD/CAM. Tools link customer to supplier. Full system simulations available. Optical disk storage of specifications with sophisticated indexing and retrieval available.
7. Artificial Intelligence Tools (Various Forms)		
Only a few expert systems in use for requirements and specifications; these are used to communicate specifications between the manufacturer and customer, and to optimize system configuration. Artificial Intelligence (AI) not extensively applied to requirements and specifications.	Expert systems for verifiability and testability limited to systems engineering tools. Tools in place for well understood problems. Integration of requirements and specifications with manufacturing process.	Expert systems for automatic generation of specifications. Systems with limited reasoning for product improvement. Inference technology for ill-defined problems. Integral part of workstations.

14. Modeling/Simulation/Prototyping (Including Software Prototyping)		
Stand-alone tools available for prototyping and for user interfaces to larger systems. Modeling tools for performance simulation are good. Existing systems functionally simulate facility operation. Tools for modeling printed wiring boards are limited because requirements and specifications are ill-defined. Present tools inadequate for simulation of specification.	Tools available for validation of requirements and specifications. Advances in AI allow automation of process. Integration of stand-alone tools continues. Total prototyping done by software simulation. Common specifications emerge for simulation modeling.	Tools available to model customer's use of product. Tools using knowledge-based software used to model production process. All designs modeled prior to production. Highly sophisticated techniques needed. Cost analysis of design decisions in common use.
	DESIGN	
2. Design Automation Tools		
Super-minicomputer capabilities at workstations. Producibility, reliability, testability issues not fully addressed. Islands of automation. Software design automation only beginning. Little capability in software simulation.	AI software transports concepts from designer to engineer. Workstations approach mainframe capability. Extensive three-dimensional graphics capability. Computer-aided design tied to manufacturing data base. Producibility, reliability, and testing issues increasingly addressed. Increasing emphasis on subgroup tests and built-in test. Lower-cost hardware and software, but complexity increases. System simulation available.	Fully integrated capabilities available (analog/digital/mechanical/software). Self-healing and built-in test algorithms. Some automatic part replacement during manufacture. Some supercomputer capabilities. Test programs generated automatically. Massive optical storage of data. Two debates emerge: (1) Will workstations replace central computers (and still guarantee data base integrity and security)? (2) Will AI be used extensively to generate key alternatives?

CURRENT AND FUTURE STATUS OF KEY ELECTRONIC MANUFACTURING TECHNOLOGIES
(continued)

STATUS TODAY	WITHIN 5 YEARS	WITHIN 10 YEARS
5. Computer Capability (Software and Hardware, Mainframe to Microprocessor)		
Computer power well ahead of design applications. RISC and Very Large Scale Integration chips make extremely fast workstations. Machine-intensive speed still too slow for performance and fault simulation and modeling. Software behind hardware. Standardization needed. Some linkage to factory floor.	Lower-cost, faster workstations. Massive mainframe capability available without reentry. Pattern recognition capabilities. Speaker-dependent speech input. Direct communication to factory and other data bases. New languages and algorithms needed.	100-MIPS workstations and distributed data processing common. Speaker-independent speech systems emerge. Key issue is complete integration of manufacturing function. One-pass design becoming conventional.
6. Artificial Intelligence Tools (Various Forms)		
Limited stand-alone, rule-checking, "design adviser" prototypes. Still have to "correct by construction." Systems so limited that true AI capabilities not fully realized.	"Design advisers" available using conventional processors. AI assistance for component selection, producibility, and selection of analysis and test. Embedded natural language interface provides design documentation from specifications. Engineering works at functional level. CAD synthesizes, simulates, tests, and optimizes designs.	Knowledge systems guide engineers throughout design cycle (analysis, reliability, and simulation). Best systems are discipline-unique. Multidiscipline cognizance begins to appear, but multidiscipline "reasoning" not available. Loop between design and manufacturing closed (provides feedback for heuristic learning). Debate on AI's role sharpens: "assistant to" versus "master designer."

11. Data Base Technologies (Organization, Size, Integrity, Consistency, Security)

Poor data base management interfaces. Manual intervention common. Most are hierarchical, with key indexes that are distributed rather than relational. (Relational data base management is available but not being used.) Weak data integrity and security common. Good basic technology not consistently applied. Data explosion exacerbates problems. Distributed capability beginning. Object-oriented DBMS beginning.	Graphics data bases common. Size of data bases requires that they be distributed, which causes data integrity and security problems. More relational data bases. AI (object-oriented) data base models emerge. Software not fully integrated with AI systems. Manufacturing and test requirements in data bases.	Data base machines have high performance and high capacity. Packaged solutions allow mainframe to communicate with workstations. Data easily moved via high-speed communications. Several companies have all drawings converted to electronic data bases for design, test, and manufacture. Standard representations of software design begin to develop based on transportable, object-oriented, programming languages. Debate over central versus distributed data bases. Major issues are data consistency, integrity, and security.

13. Modeling/Simulation/Prototyping (Including Software Prototyping)

Electronic equipment modeling and simulation available, but mechanical systems not as advanced. Different vendor standards for data storage; thus, many components remodeled by original equipment manufacturers. Technologies emerging for prototyping real-time software applications. Initial models of design-for-assembly available. Many programs require services of competent engineer to analyze data from program. No simulators that mix analog and digital modes.	Mixed digital and analog simulation. Whole system simulation of integrated circuits with millions of gates. Better interaction of timing and functional simulation using AI systems. Certain domains have 100 percent modeling, simulation, and prototyping. Better three-dimensional modeling systems available. Integrated producibility and testability tools more common. Model accelerators introduced. Increasing recognition that modeling, simulation, and prototyping greatly reduce costs. First pass design success becoming common.	Standards and translators allow component models to come from component manufacturers. Simulation is more fully integrated (chip/system/software). Top-down system simulation begins to emerge, with "bodies of knowledge" rather than data bases to drive the design. AI systems develop a path from requirements and specifications to the prototype hardware and software. Software maintenance accomplished via requirements changes. All documentation generated automatically.

CURRENT AND FUTURE STATUS OF KEY ELECTRONIC MANUFACTURING TECHNOLOGIES (continued)

STATUS TODAY	WITHIN 5 YEARS	WITHIN 10 YEARS
25. Data Networking and Security		
Ethernet and Manufacturing Automation Protocol (MAP) systems available. Many systems not very robust. Good dedicated local connectivity. Wide-area access requires large computer interfaces. Engineering workstations networked. Few standards. Optical standards emerging. Very few transparent data access tools available, though strong capabilities are available. A few firms link computer-aided design for electronic design, fabrication, assembly, and test at multiple factories, globally.	100 megabits per second data rates. MAP/TOP (Technical Office Protocol) standards accepted. Other standards emerge. Interoperability still a goal, not an accomplishment. Level of granularity refined. Closer coupling between engineering and manufacturing. Costs decline and network transparency improves. Fiber optic networks common. Distributed data tools improve.	Standards allow multivendor interconnection and better user interfaces. Much work still needed to allow interoperability. The importance of security finally understood. Full broadband interconnectibility incorporated into local- and wide-area networks, MAP, TOP, Open System Interconnect, and ISDN. Increased conformance and finer levels of granularity with enhanced semantic capabilities and more concise standards not fully available. Communicating computers the norm for new workstations.

EXTERNALLY ACQUIRED COMPONENTS

Problems associated with externally acquired components are the most often cited among defense contractors today. The Navy's "Best Manufacturing Practices Survey" identifies numerous component-related problems—including solderability, part age, and part marking--as widespread throughout the defense electronics industry. These quality control problems pose serious barriers to the future factory.

FABRICATION

16. Modeling/Simulation/Prototyping (Including Software Prototyping)		
Able to simulate specific processes with producibility rules; in some cases, can simulate whole plants. Used to fine-tune equipment and process before manufacturing. Many products available for simulation today.	Software and hardware available for most jobs, including metal and chemical processes. Automatic generation of real-time design-to-cost feedback systems. Producibility validation available.	Automated generation of fabrication process derived by modeling product from design data. Three-dimensional modeling integrated with fabrication system and test data bases.
18. Automated Statistical Process Control (Real Time)		
Some operational systems being used, but product and process specific. Current systems limited by available sensors and software. Limited real-time systems, with off-line statistical analysis.	Real-time data collection and distribution; closed-loop process control. AI and knowledge-based systems available for problem solving. Applications paced by management acceptance.	Statistical process control becomes "part of" actual fabrication process. Operation with no human intervention. Systems supported by computers with optical array processors and ability to predict production performance for a broad range of products.
22. Robotics, Flexible Equipment, and Data-Driven Automated Tools		
Equipment, including sensors and software, available. Individual equipment very flexible and programmable, but not easily linked. Systems for large volume production not cost effective for small batches. Material handling and processing tools most advanced.	Design data base-driven flexible manufacturing systems (FMS) with multiprocess automated tools, using intelligent robotics and three-dimensional space modeling for improved accuracy. Robots for small-batch production just becoming available.	Industry standard equipment available, which can be integrated through total process control systems. Broad use of FMS for low-volume production, with cooperative robots and adaptive, distributed controls. Off-line programming with automated tool-to-tool logistics.

CURRENT AND FUTURE STATUS OF KEY ELECTRONIC MANUFACTURING TECHNOLOGIES (continued)

STATUS TODAY	WITHIN 5 YEARS	WITHIN 10 YEARS
26. Data Networking and Security		
Limited local connectivity, using existing standards. Interfaces between Computer-aided design and fabrication available, but no accepted high-level design language. Most working systems are company proprietary. A few MAP networks are installed at 10 Mbps.	Standard high-capacity data networks available--10 to 20 Mbps. Factory equipment will lag network capability. Proliferation of communications standards, particularly at interfaces of computer-aided manufacturing to management information systems and to test. Local and some wide-area network capability.	Advanced distributed relational data base technology available. Full broadband interconnectivity on both local- and wide-area basis; transmission up to 100 Mbps, as required.
	ASSEMBLY	
3. Design Automation Tools		
Program generators for automatic parts placement on printed wiring boards. Setup/teardown time a barrier to efficiency. Most manufacturing requirements not linked to computer-aided design.	Design for manufacture integrated into computer-aided design. Automated product routing. Direct programming of many assembly machines. Better algorithms. Tighter process control. Manufacturing-oriented data base management systems.	Optimized assembly. Reduced human intervention. More flexible machines. Computer-aided design systems consider alternative processes and costs.

17. Modeling/Simulation/Prototyping (Including Software Prototyping)

Assembly schedule modeled. Work flow rarely modeled. Stand-alone systems used. Special training necessary. Animation available. Production balancing and inventory management common.	AI permits dynamic scheduling systems. Statistical process cotrol integrated more fully. Graphical reporting increasing. More design guidelines in workstations.	Discrete simulation language for real-time modeling, which results in major gains in processing efficiency. Tools easier to use in design concept stage.

19. Automated Statistical Process Control (Real Time)

Continuous monitoring with mainframes and personal computers. Most statistical process control uses manual inputs. Little testing during assembly. Vision systems primitive. Improved sensors needed. Equipment actuators needed.	Yield increases via mix-and-match assembly. Some noncritical visual inspection automated. AI-coached problem resolution.	Optical array processors integrate statistical process control. Product "aging" predicted. Design rules consider visual inspection systems. Wide application of AI. Data-driven automated tools common.

21. Component Mounting and Connection

High-volume applications (printed wiring board, cable, harness). Automated equipment available for SMT and PWB (top and bottom placement). Sequencing, lead-forming, wire-wrap, automatic wire-bonding control. Pick-and-pack now available. Solder inspection is problem.	SMT becomes assembly focus. 15-25 mil spacing. Solder inspection remains as problem. Some three-dimensional assembly emerging. Smaller components complicate job. Lower volume applications.	SMT with 5-10 mil spacing. Flexible substrates common. Chip-on-board technology common. Producibility/automation integrated into design process. Multiple-chip modular packaging. Fewer "components." New interconnection techniques required. Lot size=1. Customization at final test or point of sale.

CURRENT AND FUTURE STATUS OF KEY ELECTRONIC MANUFACTURING TECHNOLOGIES (continued)

STATUS TODAY	WITHIN 5 YEARS	WITHIN 10 YEARS
23. Robotics, Flexible Equipment, and Data Driven Automated Tools		
Non-PWB applications limited. (Narrow/stand-alone.) Some vision. Some autonomous motion. Individual machines not linked directly. Limited robot flexibility. Need communication protocol standards. Need improved accuracy. Some cable and harness assembly.	Higher precision and accuracy. Intelligent robotics available (force sensing, vision). Flexible manufacturing systems in smaller companies. Better linkage between machines. SMT fully mechanized. More material handling applications. Cable and harness assembly common.	Further improvements in precision and accuracy. Cooperating robots with distributed control. Autonomous "navigation." Flexible manufacturing systems more common. Industry standards promote cost effectivity.
27. Data Networking and Security		
No integrated strategy. Proprietary solutions. High costs for MAP/TOP. Centers of automation (e.g., printed wiring boards, surface mount technology) perform well, but are loosely coupled. Standard application-level interfaces missing between CAD and CAM. (Manual extraction from CAD, manual massage, manual entry to CAM.) Lack of CAM definition standards. Mainframe computer I/O not supportive of CAM and vice versa. Interface is a problem.	Network strategy increasingly defined for entity. Systems installed are low in bandwidth (10-20 Mbps). Fiber optic systems available. More transparent file translators. Significant improvement in intramanufacturing interfaces. Migration under way to token ring (CNA) architecture. Distributed data tools available. Some plants fully networked.	Industry standards recognized. Multivendor interconnection common. Progress slowed by existing capital base. Interface issues solved. Full plant networking common (100 Mbps). MAP is out of date. New broadband and optic technologies emerge.

TEST: PRODUCT AND PROCESS

4. Design Automation Tools

Design automation tools not widely used to test product or process because of limited capability. Present capabilities include autogeneration of tooling, board-level fault isolation, and in-circuit testing. CAD systems can produce component values and circuit test vectors.	Design automation tooling capable of autogeneration of test programs, automatic process correction, and on-board fault isolation. Workstations have integrated design tools, and good links achieved between CAD systems and commercial test systems. Simulated fault testing in the design stage emerging.	Full test generation on a workstation should be possible. Test systems will be integrated into design process. Systems will be capable of automatic chip-level fault isolation. Most products and equipment will have built-in self-test.

6. Computer Capability (Software and Hardware, Mainframe to Microprocessor)

Widespread capability in functional testing using available PCs and minicomputers. Use of maintenance and supercomputers constrained by cost. Data networking to take advantage of mainframes and supercomputers is inadequate.	Parallel processing eases problem of computer power. Better integration of equipment and knowledge-based systems increases capabilities. Integrated networks from design to test.	High-speed functional tests on ECC and GaAs. Software advances driven by AI. Total test program generation. Smart sensors help with fault isolation.

9. Artificial Intelligence Tools (Various Forms)

Very active area of research. Expert systems for component fault isolation available. Robotics and vision are areas that can make contribution. First-generation programs capable of some deep reasoning to derive test data.	Increased complexity of fault-isolation systems. Feedback changes to design for automated learning. Board-level programs become available. Ability to use historical data in automatic test generation.	Automatic generation of test parameters and selection of tests. Systems test themselves. Feedback to design process.

CURRENT AND FUTURE STATUS OF KEY ELECTRONIC MANUFACTURING TECHNOLOGIES (continued)

STATUS TODAY	WITHIN 5 YEARS	WITHIN 10 YEARS
12. Data Base Technologies (Organization, Size, Integrity, Consistency, Security)		
Separate data bases and libraries, usually not linked. Hierarchical test equipment--configuration and failure, data collection. Test patterns developed and stored with only partial fault coverage. PC and minicomputer data bases used, limited to one product line.	Fifty percent of data bases are relational; knowledge-based data bases used for troubleshooting. Library models become common, shared data bases used by design and test functions. Products with built-in self-test relieve some data base requirements. Data collected and stored across many product lines.	Distributed-test data bases used throughout process. Single library data base for total factory.
24. Robotics, Flexible Equipment, and Data Driven Automated Tools		
Manipulators available to load and unload automatic test equipment. Robotic assemblies do insertion into test fixtures. Quality of software is a problem.	Intelligent robots with vision and force sensing capability. Higher level programming languages available. Automatic probing using vision sensors. Easy reconfiguration. Networking linking design workstation to plant available.	Cooperative robots with autonomous operation standards in place. Suitcase testing available to interface to automated test equipment. Systems highly automated. Automated material handlers for test repair cycle.
28. Data Networking and Security		
A limited amount of networking has been implemented. Lack of standards inhibit interconnectivity.	Greater availability of standards: TOP, MAP, OSI. Local area networks integrated with manufacturing protocol.	Central network for factory of future available. Modeling techniques drive networking. Full broadband interconnectivity. MAP, TOP, OSI, ISDN.

FIELD SUPPORT

10. Artificial Intelligence Tools (Various Forms)

Limited field use for diagnostics, troubleshooting, maintenance, and training. "Early" expert systems operational. Feedback loops are manual.	Integrated field support packages available, including maintenance, repair, training, and early warning. Expert systems with automated feedback loop and custom hardware for data collection. AI coach in CE's hands at customer site.	Systems widely available in industry. Integrated on-line field service systems. embedded in electronic equipment. AI diagnostics built into "mission critical" equipment. Dial-up AI fault identification/repair tutor for customer use.

13. Data Base Technologies (Organization, Size, Integrity, Consistency, Security)

Wide variety of data bases in use today, mainly for specific products and proprietary applications. Distributed monitoring and failure data collection systems. Good basic technology, limited applications software. Engineering and manufacturing data bases used to support field on products currently in production; service bulletins generated automatically.	Relational data bases support design, test, and field operations. Knowledge-based data bases for troubleshooting using on-line communications. Distributed architecture links design workstations and field support AI system. Manufacturing and maintenance history, manuals, and drawings stored and updated digitally--field updates via on-line communications.	Distributed field data bases for each customer engineering activity. Data bases integrated into total factory system using a common "query" language. Automatic generation of service data/documentation. Drawings, tests, and parts data stored and transmitted digitally.

CURRENT AND FUTURE STATUS OF KEY ELECTRONIC MANUFACTURING TECHNOLOGIES (continued)

STATUS TODAY	WITHIN 5 YEARS	WITHIN 10 YEARS
TOTAL SYSTEM INTEGRATION: ALL FUNCTIONS		
29. Total System Integration (Including System Adaptability)		
Many "islands" of automation, loosely coupled. A few totally integrated operations linking order processing, design, manufacturing, shipping, cost accounting, and personnel systems through common mainframe data bases. Existing systems mainly for mid-to-high volume production. Varies widely from company to company and even within the same company.	"Seamless" system integration possible through the use of distributed data bases and high-speed networks. Emergence of complementary vendor systems. Degree of implementation depends on automation throughout factory.	Fully integrated systems available using distributed hardware and data bases, with closed-loop operation and including automated real-time statistical process control. Totally integrated system links component and material suppliers and customers with plant and provides field test and support through on-line communications links.
HUMAN FACTORS		
30. Training Technologies/Process Instruction		
Computer-based training, automated assembly instruction, and some expert systems available. Some on-line process instruction, but no effort to integrate activity as part of total factory. No training for the "total factory."	AI customized training, tailored to individual needs. On-line JIT training systems available.	Most vendor-supplied equipment and systems will contain on-line help and just-in-time training. Natural and graphic languages will be available for on-line "courses." Self-training will cover equipment, process, and associated software; focus will be on both operator and problem solving.

APPENDIX B

Questionnaire Data

Table B-1. ESSENTIALITY

Tech. Number	Number of Respondents Who Rated the Technology			ESSENTIALITY INDEX
	Absolutely Essential	Very Important	Supporting Technology	
1	4	6	3	2.15
2	15	2	0	3.76
3	9	7	1	2.94
5	14	6	0	3.40
6	10	6	0	3.25
7	1	4	1	2.00
8	3	10	2	2.13
9	4	7	3	2.14
10	4	4	2	2.40
11	8	5	1	3.oo
12	1	6	2	1.78
13	2	7	1	2.20
14	10	3	1	3.29
15	12	0	1	3.69
16	4	5	1	2.60
17	6	6	3	2.40
18	6	8	0	2.86
19	6	7	1	2.71
20	5	4	3	2.33
21	9	7	0	3.13
22	8	6	0	3.14
23	8	4	0	3.33
24	5	7	1	2.62
25	12	4	0	3.50
26	10	3	0	3.54
27	13	3	0	3.63
28	8	5	1	3.00
29	13	3	0	3.63
30	5	9	1	2.53

Table B-2. TECHNICAL AND NONTECHNICAL BARRIERS

Tech. Number	R&D Difficulty (Technical)	R&D Time/Cost/ Performance (Nontechnical)	CALCULATED AVERAGE BARRIER
1	4.00	3.50	3.75
2	2.00	2.00	2.00
3	1.00	3.00	2.00
4	3.00	4.00	3.50
5	2.00	2.00	2.00
6	4.00	4.00	4.00
7	3.00	4.00	3.50
8	2.00	4.00	3.00
9	3.00	4.00	3.50
10	1.67	2.33	2.00
11	2.00	2.00	2.00
12	1.30	2.00	1.65
13	1.25	1.63	1.44
14	3.00	4.00	3.50
15	3.00	3.00	3.00
16	2.20	3.10	2.65
17	3.00	3.00	3.00
18	1.00	2.27	1.64
19	3.00	3.00	3.00
20	3.80	3.80	3.80
21	1.00	1.00	1.00
22	1.60	2.50	2.05
23	2.00	2.00	2.00
24	0.00	0.00	0.50
25	0.00	1.00	0.50
26	2.00	2.73	2.37
27	1.00	2.00	1.50
28	1.50	2.00	1.75
29	2.27	2.80	2.54
30	1.00	1.90	1.45

Questionnaire Data

Table B-3. U.S. NET POSITION

Tech. Number	Lowest Estimate of U.S. Lead or Lag	Highest Estimate of U.S. Lead or Lag	AVERAGE U.S. LEAD OR LAG (IN YEARS)
1	-5.00	5.00	2.66
2	0.00	10.00	4.63
3	-5.00	4.00	-0.45
4	-5.00	3.00	1.00
5	-1.50	10.00	6.00
6	-3.00	4.00	3.25
7	-2.00	5.00	3.25
8	-1.00	7.00	3.00
9	-5.00	5.00	3.00
10	1.00	7.00	3.67
11	0.00	5.00	4.00
12	1.00	5.00	2.75
13	0.00	10.00	4.25
14	2.00	3.00	2.20
15	-5.00	3.00	1.75
16	1.00	2.00	1.50
17	-5.00	3.00	2.00
18	-7.00	0.00	-4.10
19	-10.00	-1.00	-4.70
20	-3.00	-2.00	-2.50
21	-5.00	4.00	-1.17
22	-5.00	2.00	-2.80
23	-5.50	-1.00	-4.50
24	-5.00	-2.00	-2.50
25	-5.00	5.00	-0.38
26	-3.00	4.00	1.25
27	-5.00	5.00	0.67
28	-1.00	5.00	1.00
29	-3.00	5.00	-0.39
30	-5.00	6.00	-0.75

Questionnaire Data

Table B-4. CRITICALITY INDEX

Tech. Number	U.S. Net Position	Average Barrier	Essentiality	CRITICALITY
1	2.66	3.75	2.15	8.08
2	4.63	2.00	3.76	3.76
3	-0.45	2.00	2.94	11.76
4	1.00	3.50	2.80	9.80
5	6.00	2.00	3.40	3.40
6	3.25	4.00	3.25	6.50
7	3.25	3.50	2.00	3.50
8	3.00	3.00	2.13	3.20
9	3.00	3.50	2.14	3.75
10	3.67	2.00	2.40	2.40
11	4.00	2.00	3.00	3.00
12	2.75	1.65	1.78	2.93
13	4.25	1.44	2.20	1.58
14	2.20	3.50	3.29	11.50
15	1.75	3.00	3.69	11.08
16	1.50	2.65	2.60	6.89
17	2.00	3.00	2.40	7.20
18	-4.10	1.64	2.86	18.69
19	-4.70	3.00	2.71	32.57
20	-2.50	3.80	2.33	26.60
21	-1.17	1.00	3.13	9.38
22	-2.80	2.05	3.14	19.33
23	-4.50	2.00	3.33	26.67
24	-2.50	0.50	2.62	3.92
25	-0.38	0.50	3.50	3.50
26	1.25	2.37	3.54	8.37
27	0.67	1.50	3.63	10.88
28	1.00	1.75	3.00	5.25
29	-0.39	2.54	3.63	18.38
30	-0.75	1.45	2.53	7.35

Appendix C
R&D SUMMARY

This Appendix lists the companies, universities, and other organizations that questionnaire respondents cited as leaders in research and development. The list reflects their judgment; exclusion from the list does imply that the organization is not an R&D leader, and inclusion does not imply the endorsement of the Panel on Strategic Electronics Manufacturing Technologies.

DESIGN AUTOMATION TOOLS

Air Force Materials Laboratory, Apollo, Applicon, AT&T, Boothroyd Dewhurst, Brigham Young, Calma, Carnegie Mellon, Cednetix, CIS-Toulouse, Computer-x, Daisy, Digital Equipment, ECAD, Ford, Fujitsu, Futurnet, General Motors, Georgia Tech, Hitachi, Hewlett-Packard, IBM, Industrial Technology Institute, Intel, Kyoto U., Makino, McDonnell-Douglas, Mentor Graphics, MIT, Motorola, NCA, NCR, NEC, NTT, Philips, Rensselaer Polytechnic Institute, SCI Systems, SDL, Silicon Graphics, Silvar-Lisco, SSI, Stanford, STI, Sun Microsystems, Texas Instruments, Toshiba, UC-Berkeley, UCLA, U. Illinois, U. Maryland, U. Michigan, U. Rhode Island, U. Texas, U. Waterloo, Valid Logic

COMPUTER CAPABILITY

Advantest, Apollo, Apple, AT&T, Boeing, Carnegie Mellon, CNRS-Toulouse, Control Data, Cray, Defense Advanced Research Projects Agency, Digital Equipment, ETA, Ford, Fujitsu, Generad, General Motors, Hewlett-Packard, IBM, Intel, Intergraphics, MCC, McDonnell-Douglas, MIT, Motorola, NCR, North Carolina State, Prime, Rita Electronics, Seattle Silicon, Sematech, Sentry, Silicon Compiler Systems, Stanford, Sun Microsystems, Tail EDA, UC-Berkeley, UCLA, U. Illinois, U. Michigan, University of Southern California

ARTIFICIAL INTELLIGENCE TOOLS

Air Force Materials Laboratory, Angol, Arizona State, AT&T, Bell Labs, Cambridge, Carnegie Mellon, CNAS, Consortium on AI, Digital Equipment, Fujitsu, GE, Hewlett-Packard, IBM, McDonnell-Douglas, MIT, Mitsubishi, National Bureau of Standards, Naval Research Labs, NEC, Purdue, Rockwell, Rutgers, SEI Corporation, Stanford, Sun Microsystems, Symbolics, Syracuse U., Tektronix, Teradyne, Texas Instruments, Tokyo U., Toshiba, UC-Berkeley, U. Illinois, U. Maryland, U. Massachusetts, U. Michigan, U. Pennsylvania, University of Southern California, Xerox, Yale U.

DATA BASE TECHNOLOGIES

Advanced Manufacturing Inc. (AMI), Allied Bendix, AT&T, Boeing, Brigham Young, Control Data, Digital Equipment, DPGM, Generad, General Dynamics, Grumman, Hewlett-Packard, Honeywell, IBM, Initial Graphics Exchange Specification, Kodak, LSI Logic Corporation, McDonnell-Douglas, MicroSoft, MIT, Oracle, Progress, Purdue, Rockwell, Schlumberger, Stanford, Sun Microsystems, Tektronix, U. Connecticut, U. Florida, U. Illinois, U. Maryland, University of Southern California

MODELING AND SIMULATION

Analogy Inc., Arizona State U., AT&T, Autosimulation Inc., Auto Simulators Inc., Boothroyd Dewhurst, Brigham Young U., CACI, CADRE Technologies, Carnegie Group, Carnegie Mellon, Clemson, Computervision, Control Data, Cornell, Daisy, Digital Equipment, Eaton, Eden, Factrol Inc., Ford, GCA, General Electric, General Motors, Harvard, HHP Systems, IBM (especially Lexington facility), Intel, Intelicorp, InterGraph Corporation, Martin Marietta, Mattel, McDonnell-Douglas, Metha, Metro Graphics, MIT, Motorola, National Bureau of Standards, North Carolina State, Northern Telecom, Penn State U., Perkin Elmer, Pritsker & Associates, Purdue, Santa Clara Univ., Siemens, System Modeling, Tektronix, Therin Co., Texas Instruments, Tylan, U. California, U. Maryland, U. Michigan, U. North Carolina, U. Arizona, U. Illinois, U. Texas, Varian, Westinghouse, Xerox, ZYCAD

AUTOMATED STATISTICAL PROCESS CONTROL

Allen-Bradley, AT&T, Bell Labs, Chrysler, Datamyte, Fujitsu, General Motors, Hewlett-Packard, IBM, Lockheed, Mattel, Matsushita, Mitsubishi, Purdue, 3M, Texas Instruments, Toyota, TRW, U. Arizona, Westinghouse

COMPONENT MOUNTING AND CONNECTION

Arizona State, AT&T, Bell Labs, Boothroyd Dewhurst, Cray, Digital Equipment, ETA, Fujitsu-Amdahl, GE, Hitachi, IBM, Intel, Lockheed, Matsushita, Mitsubishi, Motorola, Philips, Rockwell, UC-Santa Barbara, Texas Instruments, U. Rhode Island

FABRICATION, ASSEMBLY, AND TEST

Adept Inc., AT&T, Carnegie Mellon, Chrysler, CIMLINC, Cincinnati Milacron, Digital Equipment, Fanuc, Fraunhoffer Institutes, GMF Robotics, Hewlett-Packard, IBM, Intelidex Inc., Kearney and Trecker, Komatsu, MIT, Mitsubishi, Motorola, National Bureau of Standards, Purdue, Siemens, Steelcase, Tokyo Institute of Technology, Tokyo U., Toyota, Unimation, UC-Santa Barbara, U. of Kyoto, U. of Osaka, Wasebo U, Yamaha

FACTORY SYSTEM TECHNOLOGY

Allen Bradley, Amdahl, Apollo, Applitek, ASEA, AT&T, Autotrol, Bell Labs, BNN, Boeing, BOSI, Bridge Communication, Carnegie Mellon, Chrysler, Cincinnati Milacron, CNRS (France), Codex, Computervision, Computerex, Concord Data, COS, David Systems, Digital Equipment, Ericsson, Fanuc, Fiat, Ford, Fujitsu, GE, General Motors, Geokeio

U. (Japan), Georgia Tech, Gould, Hitachi, Honeywell, Hewlett-Packard, IBM, ICC Industries, ICL, Industrial Technology Institute, INI, INRIA of France, ISO Committees, Kodak, Lehigh U., MAP/TOP Users Group, McDonnell-Douglas, MicroSoft, MIT, Motorola, National Bureau of Standards, OSI, Product Definition Data Interface, Proteon, Purdue, Rensselaer Polytechnic Institute, SBAG, Schlumberger, Scientific Atlanta, Stanford, Sytex, Tandem, Technical Union (VMI), Technical U. of Vienna, Telecom Systems Development, Texas Instruments, TRW, Ungerman-Bass, U. of Michigan, U. of Victoria (Canada), U. of Waterloo, University of Southern California, Westinghouse

TRAINING TECHNOLOGIES

Apple, Boeing, Arizona State U., Carnegie Mellon, Computer-Aided Manufacturing - International, Chrysler, Digital Equipment, Ford, General Dynamics, General Motors, Hewlett-Packard, IBM, Ingersoll Milling Machine, Purdue, UC-Santa Barbara, Texas Instruments, Toyota, Xerox

NAS NAE IOM NRC

National Academy Press

The National Academy Press was created by the National Academy of Sciences to publish the reports issued by the Academy and by the National Academy of Engineering, the Institute of Medicine, and the National Research Council, all operating under the charter granted to the National Academy of Sciences by the Congress of the United States.

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