DOE/DP/00392--T1

International Technology Research Institute

JTEC/WTEC

JTEC/WTEC Report on

Benchmarking Foreign Electronics Technologies

Charles W. Bostian, Virginia Tech.
David A. Hodges, UC Berkeley
Robert C. Leachman, UC Berkeley
Thomas B. Sheridan, MIT
W.T. Tsang, AT&T Bell Laboratories
Robert M. White, Carnegie Mellon University

December 1994

**International Technology Research Institute
Japanese Technology Evaluation Center/World Technology Evaluation Center
Loyola College in Maryland
4501 North Charles Street
Baltimore, Maryland 21210-2699**

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

This document was sponsored by the National Science Foundation (NSF), the Advanced Research Projects Agency, and the Department of Energy of the United States Government under NSF Cooperative Agreement ENG-9217849, awarded to the International Technology Research Institute at Loyola College in Maryland. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the United States Government, the authors' parent institutions, or Loyola College.

JTEC/WTEC

Michael J. DeHaemer, Principal Investigator, JTEC/WTEC Director
Geoffrey M. Holdridge, JTEC/WTEC Staff Director and Series Editor
Bobby A. Williams, Assistant Director
Catrina M. Foley, Secretary
Aminah Batta, Editorial Assistant

George Gamota, Mitre Corporation, Senior Advisor to JTEC/WTEC

International Technology Research Institute at Loyola College

R. D. Shelton, Director

The Government reserves for itself and others acting on its behalf a royalty free, nonexclusive, irrevocable, world-wide license for governmental purposes to publish, distribute, translate, duplicate, exhibit, and perform any such data copyrighted by the contractor.

Copyright 1994 by Loyola College in Maryland. The U.S. Government retains a nonexclusive and nontransferable license to exercise all exclusive rights provided by copyright. JTEC/WTEC final reports are distributed by the National Technical Information Service (NTIS) of the U.S. Department of Commerce. Information on ordering JTEC/WTEC reports from NTIS is included on the inside back cover of this document.

Table of Contents

Foreword	i
1. Manufacture of Integrated Circuits <i>David A. Hodges and Robert C. Leachman</i>	1
2. Human-Machine Interface Technology <i>Thomas B. Sheridan</i>	15
3. Wireless Technology <i>Charles W. Bostian</i>	29
4. Data Storage <i>Robert M. White</i>	41
5. Optoelectronics <i>W.T. Tsang</i>	57
APPENDIX: "Flat Panel Display Technologies in Japan" <i>Larry A. Tannas</i> (update of 1991 JTEC study, published in February 1994 issue of <i>Information Display Magazine</i>)	75

reprint
removed.
ds

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

FOREWORD

This report was prepared to help define the proposed National Electronics Manufacturing Initiative (NEMI) of the Electronics Subcommittee of the National Science and Technology Council. This initiative is intended to help American industry compete in manufacturing the user interfaces to the National Information Infrastructure (NII). These interfaces include advanced television receivers, commercial and consumer workstations, and a host of new devices that the fusion of computer and communications technologies will make possible. While the construction of the infrastructure itself is a vast undertaking, it is likely that the user interfaces will provide a greater market. Since much of the investment in this information superhighway is being made by the American public and private sectors, it is only reasonable that American manufacturers should have a fair opportunity to compete for this business.

One aspect of establishing this environment is to benchmark essential technologies versus our foreign competitors. This effort includes identification of the technologies critical to development of user interfaces, location of where the most advanced versions of these technologies are to be found, and determination of the relative position of U.S. industry. Such information can help the NEMI focus investments in research and development in the most effective areas.

This report is the preliminary result of such a study for five essential technologies: integrated circuit manufacturing, optical electronics, man-machine interfaces, electronic memories, and wireless communications. This report was done at the request of ARPA and DOE on a very tight time schedule; the authors only had about a month to do their writing. This result was only possible because the authors were already up-to-date on the international scene in their area of specialty.

We appreciate the opportunity provided by our sponsors, Paul Herer (NSF), Lance Glasser (ARPA), and Wayne Hofer (DOE), to contribute to the Administration's efforts to help American industry. We especially thank our very distinguished authors who dropped everything at a very busy time of year to make these contributions.

Duane Shelton
December 1994

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

1. Semiconductor Manufacturing

Robert C. Leachman and David A. Hodges
Engineering Systems Research Center
University of California at Berkeley
Berkeley, CA 94720

INTRODUCTION

This report has been drafted in response to a request from the Japanese Technology Evaluation Center's (JTEC) Panel on Benchmarking Select Technologies. Since April 1991, the Competitive Semiconductor Manufacturing (CSM) Program at the University of California at Berkeley has been engaged in a detailed study of quality, productivity, and competitiveness in semiconductor manufacturing worldwide. The program is a joint activity of the College of Engineering, the Haas School of Business, and the Berkeley Roundtable on the International Economy, under sponsorship of the Alfred P. Sloan Foundation, and with the cooperation of semiconductor producers from Asia, Europe and the United States. Professors David A. Hodges and Robert C. Leachman are the project's Co-Directors. The present report for JTEC is primarily based on data and analysis drawn from that continuing program. (See Ref. 3)

The CSM program is being conducted by faculty, graduate students and research staff from UC Berkeley's Schools of Engineering and Business, and Department of Economics. Many of the participating firms are represented on the program's Industry Advisory Board. The Board played an important role in defining the research agenda. A pilot study was conducted in 1991 with the cooperation of three semiconductor plants. The research plan and survey documents were thereby refined. The main phase of the CSM benchmarking study began in mid-1992 and will continue at least through 1997.

DEFINITION OF THE TECHNOLOGY

Our study focuses on semiconductor wafer processing as needed to produce VLSI chips including memories, microprocessors, signal processors, other logic, and mixed-signal products. Wafer processing takes place in manufacturing plants known as "fabs". Modern fabs require capital investment in plant and equipment of \$500M to \$1B each. They are the most costly manufacturing plants found in any industry today. The knowledge and skills required for efficient wafer fabrication require further large, ongoing investments. Manufacturing process sequences are exceedingly complex, with 400 or more sequential operations on a wafer over a span of 20 to 60 24-hour days. A gross failure at any step can render a wafer worthless. The salable fraction of the total number of chips on a finished wafer, known as the "chip yield," varies from near zero to 100%, depending on the effectiveness of quality control in avoiding localized defects on chips.

Today's principal VLSI products including memories, microprocessors, etc. are manufactured worldwide using very similar manufacturing equipment and processes. In many cases, 5 to 15 firms world-wide compete in selling interchangeable final products to hundreds of customers. Economic success in wafer fabrication clearly requires maximizing the output of salable products from a large fixed investment. Despite these obvious facts, there is an amazingly large variation in the manufacturing performance of semiconductor firms. The present study is intended to quantify and benchmark manufacturing performance and to identify superior practices in factory operation, organization, and management.

SCOPE OF THIS STUDY AND SOURCES OF DATA

The data and analysis summarized in this report are derived from measurements of manufacturing performance and investigation of underlying determinants of performance at sixteen wafer fabrication facilities in the United States, Europe, Japan and Taiwan. The companies operating these manufacturing facilities are listed in Table 1.1. In selecting participants, we sought access to plants representing a cross-section of the industry, both internationally and in terms of business models and product mix. We asked for access to plants that had been in operation for at least 3 years. Substantial effort is required on the part of each participant; some of those approached declined to participate. Participants who operate multiple semiconductor manufacturing lines generally opened one of their best lines to this study. Firms participate based on written agreement that we mask the identity of individual firms and plants. We report results only in anonymous or aggregated forms. The Berkeley team signs non-disclosure agreements with all participating firms.

Our study has addressed only the wafer fabrication element of the total semiconductor manufacturing cycle. This is the most complex and capital-intensive element. The technologies and processes of packaging semiconductor chips are, however, growing in significance. These latter aspects are well covered in a recent JTEC report. (Ref. 1)

Table 1.1
Companies Participating in the Main Phase
of the Competitive Semiconductor Manufacturing Survey (first 18 months)

Advanced Micro Devices, Inc. (AMD)	Nihon Semiconductor, Inc. (NSI)
Cypress Semiconductor, Inc.	NEC Corp. (NEC)
Delco Electronics, Inc.	Oki Electric Industry, Ltd.
Digital Equipment Corp. (DEC; 2 sites)	Silicon Systems, Inc. (SSI)
Intel Corporation	Taiwan Semiconductor Manufacturing Corp. (TSMC)
International Business Machines, Inc. (IBM)	Texas Instruments, Inc.
ITT Intermetall	Toshiba Corp.
LSI Logic, Corp.	

As the first step, participants complete a fifty page mail-out questionnaire (MOQ), reporting data concerning clean room size and class, staffing levels, equipment counts, wafer starts, die yields, line yields, cycle times, manufacturing systems, etc. over the last four years. From the completed MOQs, we calculate technical metrics of manufacturing performance for each participant. We then rank the participants for each of the metrics.

We observed a great variation in the scores. In an attempt to understand the factors that account for performance differences, we conduct a two-day visit at each participating site. We tour the manufacturing line, interview a cross-section of the staff, and hold a series of sessions to determine the fab's strategies for improving manufacturing performance. We assess each fab's resources for improvement including computer integrated manufacturing (CIM) and information systems, human resources development, deployment of work groups and teams, etc. These more qualitative evaluations of participants' operational practices are then correlated with the performance metrics to identify those practices that underlie top performance.

METRICS OF MANUFACTURING PERFORMANCE

The technical metrics used to measure manufacturing performance of the participants are summarized as follows:

- 1) Average cycle time per wafer layer.
- 2) Average line yield per ten wafer layers.
- 3) Die yields for major process flows, converted into defect densities using the simple Murphy model. The reported defect densities account for all yield losses, including both spot defects and parametric problems.
- 4) Wafer layers completed per 5X stepper per calendar day (considering only layers exposed using 5X steppers).
- 5) Wafer layers completed per operator per working day.
- 6) Wafer layers completed per working day divided by the total head count.
- 7) On-time delivery (percentage of scheduled line items with 95% of scheduled volume shipped from wafer probe on time).

We encountered a wide range in scores for each metric, even though the basic process technology and the major manufacturing equipment in use at the participants was generally similar. Table 1.2 summarizes the best, average, and worst scores for each metric, considering the latest data points we received from each of the sixteen participants, and provides an estimate of the relative ranking of Japanese and US firms in each metric. These data points represent measurements of manufacturing performance in some quarter between the middle of 1992 and the end of 1993, depending upon the participant.

Rates of improvement also are studied for each participant. Scores for each technical metric are computed for each quarter over a period of three to four years. For most metrics, the ranking of participants does not change quickly. We did not find many cases where a last-place participant overtook the leader for a particular metric, although a few participants improved their rankings considerably over the period.

Table 1.2
Summary of Technical Metric Scores,
Competitive Semiconductor Manufacturing Survey (first 18 months)

<u>Metric</u>	<u>Best Score</u>	<u>Average Score</u>	<u>Worst score</u>	<u>Japan vs. US</u>
Cycle time per layer (days)	1.2	2.6	3.3	0
Line yield per ten layers (%)	98.9	92.8	88.2	++
Murphy defect density - (defects/cm ²)				Overall: ++
0.7 - 0.9 micron CMOS memory	0.28	0.74	1.52	
0.7 - 0.9 micron CMOS logic	0.28	0.79	1.94	
1.0 - 1.25 micron CMOS logic	0.23	0.47	0.96	
1.3 - 1.5 micron CMOS logic	0.21	0.61	1.15	
5X stepper throughput (5X layers completed per machine-day)	724	382	140	+
Direct labor productivity (wafer layers completed/operator-day)	63.0	29.6	8.0	+
Total labor productivity (wafer layers completed/total staff-day)	37.7	17.6	3.3	++
On-time Delivery (% of line items with 95% of die output on time)	100%	89%	76%	--

Average and worst scores are calculated after discarding the worst data sample for each metric.

Legend:

- ++ Japanese fabs are almost uniformly superior
- + Japanese fabs are generally superior
- 0 Superior/inferior fabs are not distinguished by region
- US fabs are generally superior
- US fabs are almost uniformly superior

Perhaps the most striking phenomenon observed in our measurements concerns the initial defect densities for process flows, i.e., the defect densities realized in the first quarter after transfer of the process flow into manufacturing. We recorded a factor-of-ten range in initial defect densities. Those fabs with poor starting points tend to have faster rates of

improvement, but not nearly fast enough to overtake those with good starting points, at least not for several years, as those with good starting points also make steady if somewhat slower progress reducing defect densities.

ANALYSIS OF PRACTICES UNDERLYING MANUFACTURING PERFORMANCE

Our main objective in the CSM survey is to identify those operational practices that underlie leading-edge manufacturing performance. Summarized below are the operational practices that distinguish those fabs achieving best or near-best scores in one or several of the metrics described above. (For the sake of brevity, we refer to such fabs as the "leading" fabs.) But before summarizing our findings in that regard, it is only fair to acknowledge that our analysis does not account for several strategic factors concerning product design and fab design that may strongly influence manufacturing performance.

First, the restrictiveness of product design rules can have a strong influence on observed die yields and hence on our calculated defect densities. Issues of overall business strategy influence the choice of design rules and affect the priority attached to the different metrics of manufacturing performance. We made no attempt to normalize defect density scores for differences in design rules and/or overall business strategy among the participants.

Second, the range of sizes of fabs in our survey, in terms of wafer starts, spans a factor of almost fifty. Small fabs generally have inferior labor and equipment productivity scores, because of the indivisibility of machines and operators, and because of the tendency to install extra equipment to avoid situations in which a particular process step must be performed by a one-of-a-kind equipment type. We made no attempt to normalize productivity scores to account for fab size.

Third, the assignment of older-generation of processing equipment to newer-generation process flows may result in lower values for several metrics than would be possible with newer equipment. While yields may be lower for the strategy to employ older processing equipment, capital costs are lower as well, and so the strategy might turn out to be economically competitive or even superior to the strategy that employs solely new processing equipment. We made no attempt to normalize metric scores for the generations of equipment applied.

With these strategic factors aside, we now turn to the various operational practices we found to be correlated with good manufacturing performance (in terms of the manufacturing metrics we have defined). These practices may be categorized into four basic types of practices at which a fab must excel in order to realize excellent manufacturing performance.

First, a fab must have computer systems providing strong process control, excellent data collection and excellent data analysis capabilities. The fab must be able to expeditiously

pinpoint the causes of yield loss and the sources for losses of wafer throughput. The fab must be able to promptly recognize when processing is being done incorrectly, or better yet, prevent misprocessing entirely with equipment and system controls and procedural checks.

Second, a fab must have an organization that not only executes the manufacturing processes well, but also is very good at problem recognition and at problem solving. Semiconductor manufacturing is characterized by immature processes and immature processing equipment with relatively short lives, and by continuing increases in complexity. Opportunities to improve yields and/or wafer throughput are always present. Thus manufacturing has a major engineering element as well as an operational character. This means a fab must continually improve the technical competence of its organization and continually foster a teamwork approach to recognize problems, devise innovative solutions, and implement them quickly and successfully. Not only engineers but also operators and technicians must participate in problem recognition, process improvement and problem solving, and they therefore must possess basic engineering skills as well as technical knowledge of the manufacturing processes and equipment.

Third, and closely related to the second area, the fab must have the internal technical talent as well as the requisite support from vendors to expeditiously make modifications to product, process, and equipment in order to implement changes that have been identified by problem-solving efforts as desirable or necessary to improve manufacturing performance.

Fourth, and finally, a fab must have effective procedures for managing the introduction of new process flows. The economic life of many process flows is three to four years, with unit prices for products of the flow declining rapidly over this period. Thus it is economically important to realize high throughput of the process flow early in its life, and to fairly frequently introduce new process flows into the fab. This means the fab must become expert in each new process flow and its required equipment as soon as possible, ideally before it transfers to production, so as to realize good yields and good wafer throughput early in its life and to quickly ramp to better yields and higher wafer throughput thereafter. Even if a fab is proficient in the above three types of practices, a poor start with a new flow may leave the fab too far behind to catch up before the market value of the output has mostly drained away.

Table 1.3 provides a tabulation of particular operational practices of these types, the impacted metrics, and comparisons of the overall rankings for Japanese vs. US manufacturers. These rankings include some weight added in recognition of the intensity or effectiveness of practice. As can be seen, the practices are organized into categories titled CIM and Information Systems, Organizational Practices, Formal Procedures, Process and Technology Improvements, and Production Control.

In the area of CIM and Information Systems, the leading fabs collect and analyze large amounts of data, enabling them to trouble-shoot their manufacturing processes and equipment quickly and comprehensively.

Table 1.3
Summary of Effective Manufacturing Practices

<u>Practice</u>	<u>Metrics Influenced</u>	<u>Japan vs. US</u>
<i>CIM and information systems</i>		
SPC	Defect Density, Line Yield	++
Equipment efficiency measurement	Equipment throughput, cycle time, labor productivity	++
Visual displays of SPC charts, equipment tracking, etc.	Line yield, defect density, labor productivity, equipment throughput	+
Automation of data logging	Cycle time, defect density, labor productivity, equipment throughput	++
Auto recipe download and/or display	Line yield, cycle time, defect density, labor productivity, equipment throughput	0
Automated feedback control at photolithography	Defect density	0
Yield correlation analysis	Defect density	++
In-line electrical measurements	Defect density	+
In-line particle measurements	Defect density	+
Automated trouble messaging and automated assistance for trouble-shooting	Cycle time, line yield, equipment throughput, labor productivity	-

Legend:

- ++ Japanese fabs are almost uniformly more effective
- + Japanese fabs are generally more effective
- 0 The most effective practitioners are not distinguished by region
- United States fabs are generally more effective
- United States fabs are almost uniformly more effective

Table 1.3 (cont.)
Summary of Effective Manufacturing Practices

<u>Practice</u>	<u>Metrics Influenced</u>	<u>Japan vs. US</u>
<i>Formal Procedures</i>		
Formal procedures for new process introductions	Defect density, line yield, equipment throughput	++
TPM program	Equipment throughput, cycle time, line yield, defect density, labor productivity	++
<i>Organizational Practices</i>		
Exchange of engineers with development fab	Defect density, line yield, equipment throughput	++
Integration of engineering groups	Defect density	++
Integration of engineering and manufacturing staff	Equipment throughput, line yield, defect density	++
Operator and technician improvement teams	Equipment throughput, cycle time, line yield	++
Mentoring by senior engineers and supervisors	Defect density, line yield, equipment throughput	++
Mentoring by senior operators	Line yield, cycle time, equipment throughput	++
Extensive leadership training	Defect density, line yield, equipment throughput	++
"Stretch" goals	Defect density, line yield, equipment throughput, labor productivity	++

Table 1.3 (cont.)
Summary of Effective Manufacturing Practices

<u>Practice</u>	<u>Metrics Influenced</u>	<u>Japan vs. US</u>
<i>Process and Technology Improvements:</i>		
Machine modifications to automate load/unload or wafer handling mechanisms	Line yield, cycle time, labor productivity, equipment throughput	++
Machine modifications to reduce particle counts	Defect density, cycle time, labor productivity, equipment throughput	++
Process flow re-design	Defect density, cycle time, line yield, equipment throughput	+
Product re-design	Defect density	++
Machine lights and audio alarms	Cycle time, equipment throughput, labor productivity	++
Linked photolithography cells	Defect density, cycle time, equipment throughput	0
Automated interbay lot movement	Cycle time, labor productivity	++
<i>Production Control</i>		
Kanban	Cycle time, labor productivity	--
Computerized dispatching	Cycle time, labor productivity, on-time delivery	--
Production planning based on measured equipment capacity	On-time delivery	--

All participants in our study have embraced statistical process control (SPC) as a means of detecting manufacturing problems and improving process performance. Almost all provide automated notification of out-of-control conditions. The leading fabs rigorously manage

their SPC programs, retiring unneeded control charts and adding new ones recognized as desirable, adjusting control limits as appropriate, adjusting frequencies of measurements to focus efforts on the most critical areas, and maintaining an effective training program.

SPC measurements are made both of product wafers and of machine conditions, such as particle counts of machine exhaust flows or of blank wafers passed through the machine. The leading fabs have information systems that automatically provide assistance for responding to out-of-control situations, such as auto-display of corrective action guidelines, automatic disabling of equipment or process, automatic notification of the responsible engineers, etc. SPC measurements also are used to trigger preventive maintenance and tool or material replacements.

All of our participants have engineering databases to which they upload some amount of metrology data, SPC measurements, and production tracking data (such as which machine was used to process a lot, which operator attended to it, which batch of chemicals was used, etc.). The leading fabs upload more data, and they have automated the upload of much of these data using bar codes or magnetic cards and sensors.

The top fabs efficiently perform end-of-line yield analyses by integrating their engineering database with the database of die yields and parametric measurements taken at the end of the manufacturing line. Automated statistical correlations are made between die yield results and the data uploaded to the engineering database described above, in order to ascertain what characteristics are common to low-yielding wafers. Leading fabs feature yield improvement groups that build yield models specifically for their fab, perform extensive wafer map analysis of yield patterns to find clues to the types of processing equipment where losses were incurred, as well as carry out statistical correlation analyses as described above. The leading fabs document their findings for each major event of yield loss, and save these findings in a database for future reference.

Leading fabs also are increasing their efforts for in-line yield analysis using digital image processing and laser scanning machines to conduct particle inspections of partially-processed wafers. Wafer maps showing the distribution of particles are classified so as to obtain clues concerning the equipment source of the particles; SPC procedures are instituted for particle inspections, for which out-of-control incidents trigger partitioning analyses to pinpoint the source of particles; and end-of-line die yields are statistically correlated with in-line particle measurements of the product wafers.

The leading fabs make effective use of computers to prevent processing errors. Automated recipe download is installed at most or even all processing equipment in leading fabs. "Smart" lot-machine interfaces have been installed by some leading fabs, whereby the computer system prevents one from tendering the wrong lot or the wrong recipe to the machine. In addition, "smart" lot and reticle racks also are used at one participant to highlight the correct lot and reticle to be used. A couple of leading fabs also have automated the feedback control of photolithography exposures based on critical dimension measurements.

In the area of organizational practices, the leading fabs practice considerable integration of sustaining engineering staff with development engineering staff in order to make the introduction of new process flows more successful. The top fabs exchange engineers with the development fab that is the source for their new process flows, sending their own engineers to development before time of transfer, or receiving engineers from development at time of transfer, or both. Considerable engineering hours are invested in the transfer of a new process technology rather than merely in its development. For example, at a number of leading participants, the development fab will continue to run the new process in parallel with the production fab for some period of time in order to provide equipment backup and useful reference data. These steps are taken to ensure the fab has expertise in new process flows right from the moment they enter production, as well as to ensure that new flows and their associated processing equipment are installed, configured and operated to provide the desired results.

The leading fabs have organized the various types of sustaining engineers into more integrated departments of product engineers, process engineers and equipment engineers so as to promote interdisciplinary problem-solving and shared accountability. This integration of what are traditionally distinct engineering groups comes from the recognition that solving yield and throughput problems requires a variety of expertise as well as consideration of many trade-offs, and that specialists in one engineering area will benefit from increased knowledge of related areas. These integrated organizations also feature substantial efforts to mentor technical staff to higher levels of responsibility and higher levels of technical knowledge, e.g., mentorship of junior engineers by senior engineers, mentoring of technicians by engineers, etc.

At leading fabs, improvement projects are not merely the domain of engineers. Improvement teams of operators and technicians are formed and guided by managers and engineers to address and solve manufacturing problems appropriate to their knowledge and experience. This team activity at leading fabs is an essential strategy for training employees and for upgrading their skill and knowledge levels. Umbrella programs such as TQM and TPM are used effectively as a means of rallying and focusing team efforts, and especially for training in formal methodologies for problem-solving. The leading fabs have very large numbers of improvement teams, with nearly every technician and operator involved in improvement projects. Virtually all technicians and even many operators are sent to classes run by equipment vendors in order to increase their equipment knowledge.

TQM (Total Quality Management) focuses improvement efforts on product quality. TPM (Total Productive Maintenance) focuses improvement efforts on equipment productivity. The two paradigms are thus complementary, and tend to drive different kinds of improvements. While most of the leading fabs had embraced TQM first and then TPM later, this is probably a historical artifact reflecting the relative ages of the paradigms.

The resulting acquisition of skills and knowledge leads to a more productive division of labor in leading fabs. Operators in leading fabs perform preventive maintenance and minor

repairs of processing equipment, help design SPC charts, and participate in trouble-shooting efforts following formal methodologies. Technicians are thus freed to focus on major maintenance and repairs, improvement projects, training, and the documentation of equipment-related procedures. In turn, engineers are freed to focus most of their time on major improvement projects rather than on trouble-shooting exercises.

The leading fabs engage in extensive mentoring and employee development at all levels, with senior managers developing managers, senior engineers developing the engineers working with them, right down to senior operators and technicians developing operators in each equipment bay. In lieu of hiring professional supervisors, leading fabs promote experienced line workers to positions as group leaders, where their knowledge and experience makes them suitable to serve as mentor to workers in their area. At these fabs, there is extensive and continuing leadership training for engineering and manufacturing managers, all the way up to the executive officers.

Not only do the leading fabs establish programs for continuous improvement, they also set ambitious stretch goals for improvements in productivity and quality that force systemic improvements, and they do extensive technical planning, project and team planning and mentoring to realize those goals. Many of the factors just mentioned closely parallel the successful practices of world leaders in automobile assembly, as described in Ref. 2.

In the area of formal procedures, the leading fabs have established formal procedures governing the transfer and introduction of new process flows. There also are efforts at leading fabs to modularize process design, whereby new processes make use of proven modules from previous-generation processes, where feasible to do so. Such procedures serve to maximize the likelihood that new processes provide favorable yields in the first quarter of production, and that volume may be ramped quickly.

While all of our participants use SPC as a formal procedure for in-line measurement of quality, and all of our participants make efforts to measure equipment availability and utilization, the leading fabs have formal procedures for the measurement of true equipment productivity rather than merely its utilization. The leading fabs also have formalized the improvement of procedures for equipment maintenance, operation, analysis and training under the TPM paradigm.

In the area of process and technology improvements, the leading fabs make useful modifications to processing equipment to reduce downtime, to reduce particles, to reduce wafer breakage or scratches, to reduce handling, to reduce machine setups, to reduce the need to process test or pilot wafers, and to reduce unit processing times. They have the necessary expertise on-site, they obtain support from equipment vendors as required, and they have an organizational structure that integrates process and equipment engineers so as to deduce the most prudent equipment modifications to make considering the desired process characteristics. The leading fabs have installed lights and audio alarms on the processing machines to focus attention on idle or malfunctioning machines.

Photolithography at the leading fabs is performed in linked cells achieving superior die yields, low rates of rework, low cycle times and high throughput.

Sometimes, modifying the equipment is not the most effective solution to a yield problem. The leading fabs also make changes to product designs or process flows for increased manufacturability. Such changes reflect an organizational structure that integrates product, process and equipment engineers, enabling them to identify and make trade-offs between potential equipment and product changes.

Special mention should be made of the application of standard mechanical interface (SMIF) technology, involving the implementation of portable micro-environments for processing equipment and lots. We have seen one participant, using an older and much more modest clean room than other participants operating comparable process flows, obtain world-class die yields. The introduction of SMIF technology clearly extended the economic life of this older fab and thus constitutes a very good technological improvement. The isolation of each machine from the rest of the fab also facilitated staged and selective upgrading of the equipment set in the fab.

Special mention also should be made with respect to the leading fab in terms of cycle time. Over several years, this fab has steadily re-arranged its layout to break up the standard farm-type layout in favor of smaller cells of equipment handling a smaller variety of operation sequences. While in the past cell-type layouts have been resisted by many fab designers for fear of lost equipment utilization, this same fab is also our leader in 5X stepper throughput. This fab has demonstrated that a more cell-type layout represents a technological improvement, in that cycle times can be reduced while achieving leading-edge equipment throughput.

Finally, in the area of production control, the leading fabs perform automated production planning based on measured equipment capacity and cycle times to achieve high levels of on-time delivery. Re-planning is performed frequently and swiftly to keep up with revised intelligence on market demand and customer orders. On the factory floor, both Kanban and computer-assisted dispatching (lot sequencing) are used by leading fabs to improve cycle time as well as on-time delivery.

SUMMARY

Japanese plants examined as a part of the semiconductor manufacturing study on the whole are much more effective in implementing preferred manufacturing practices. Management and workers share a firm commitment to continuing improvements. As a consequence, quality and productivity measures for those plants are excellent and improve steadily. While a few US plants achieve similar excellence, the majority of US plants fall far behind the leaders.

Our prescription for US competitiveness calls for the high quality management and leadership frequently seen in research, product definition, finance, and marketing by US firms to be matched in manufacturing.

REFERENCES

1. Kelly, et al. *Electronic Manufacturing and Packaging in Japan*, JTEC Panel Report, (Draft) July 1994.
2. Womak, Jones, Roos: *The Machine that Changed the World*, Rawson Associates, 1990.
3. Leachman, et al. *The Competitive Semiconductor Manufacturing Survey*, Report CSM-08, Engineering Systems Research Center, University of California at Berkeley, September 1994.

2. Human-Machine Interface

Thomas B. Sheridan
Massachusetts Institute of Technology
Cambridge, MA 02139

DESCRIPTIONS OF THE TECHNOLOGY

Human-machine interface technology is naturally classified as to whether it is: (1) a display of information conveyed from the machine to the human senses, and whether this display, in turn, is by means of vision, hearing, haptic senses, or by other means; or is (2) a means for the human to give commands, effect control actions, or otherwise communicate information to the machine, and whether this communication, in turn, is by means of manual control devices, head or other body control devices, speech, or myographic/EEG/ERP inputs to the machine.

Human-machine interface technology can also be classified as to whether it is essentially hardware, software or systems integration. Accordingly the subsections below entitled "Machine Display to Human Senses" (p. 16) and "Human Command and Control of the Machine" (p. 18) deal with (1) and (2) above. These are followed by sections entitled "User Interface Software Devices and Techniques" (p. 20), and "Teleoperation and Virtual Reality" (p. 20), the latter describing integrative techniques. In the software interface category supervisory control is a relative newcomer given attention, and in the system integration category teleoperation and virtual reality are discussed.

It should also be noted that the focus in this report is on information exchange and not on energy exchange between human and machine. The latter may be important in interfacing humans with bicycles, human-powered aircraft, hammers, etc. but these days is less important when electrical and other forms of energy are available.

Mostly today "human-machine interface" means human-computer interface, though traditionally there have been many human exchanges of information with machines which are not normally considered computers, e.g., office machines, medical devices, home appliances, automobiles, aircraft, ships, industrial devices and tools of many kinds, and weapons systems. The difficulty is that computer chips more and more are being interwoven with sensors, actuators and mechanical devices, so that the distinction between "computer" and "machine" is blurred.

A final note up-front is that human interaction with machines involves tight feedback loops. For example, human sensing involves active muscle control of sense organ position, orientation and focus (e.g., in vision the head position, gaze and accommodation) as well as modulation of energy (e.g., in vision, eyelid closure and pupil contraction). Human operation of manual control devices involves sensing in the muscles, tendons, joints and skin. Therefore, while separate consideration of interface hardware components may be easy, functional separation between hardware and software and between human sensing and actuation (display and control) is essentially impossible.

Machine Display To Human Senses

Visual displays. 1. CRT and flat panel display. Driven by the consumer market for higher quality television and microcomputer displays of text and graphics, by far the largest commercial display technology investment has been for visual displays, specifically to improve resolution and general quality in cathode ray tubes (CRTs) and more dramatically of flat panel liquid crystal displays (LCDs) and light-emitting diode (LED) displays.

640 x 480 pixel color CRT displays (VGA standard) are common for full size computer workstations, but somewhat less common in miniature CRTs. Both passive and active matrix flat-panel LCD color displays are common in laptop computers (e.g., 640 x 480 pixel resolution), but brightness is not so high as is the CRT. However 1536 x 1024 active color LCDs have now been demonstrated by ARPA.

The NTSC standard for video is 525 vertical lines, with horizontal resolution determined by the sampling rate. 1000 line CRT video displays, components of what are called "high density TV" (HDTV) systems, have been demonstrated. Larger images require projection systems. A new digital micromirror device (DMD) projection system, based on arrays of tiny mirrors on torsion hinges activated electromagnetically, promises still higher resolution. A system under development by Texas Instruments uses three 2048 x 1152 pixel DMDs operating in parallel.

Under good brightness and contrast conditions the normal eye can resolve dots of better than one minute of arc (which is less than 0.01 inches at three feet or 0.005 inches at 18 inches) or lines at an order of magnitude smaller spacing. Thus the 300 dpi printing (resolution of the normal laser printer) is at marginal resolution for adjacent dots, but 600 dpi or better is required to match visual resolution for lines and larger patterns. Thus the experimental systems described above, when viewed up close, are still not as good as 300 dpi or as seeing real objects.

Resolution is not the only factor demanded of modern display technology. Some others which are important are refresh and update rates. Refresh rate, which is normally 60 Hz (30 Hz interlaced for video) is necessary to stay above the flicker fusion frequency of the eye, i.e., to produce a picture which does not appear jumpy. Update rate has to do with changing the pixels of the image. If every pixel on a full high-resolution computer screen is updated simply by reading from memory, whole new pictures at each cycle (like a picture being moved laterally) can be updated at this rate. However, if the image is also being generated in real time, that activity is likely to constrain image update to a fraction of 60 Hz, though high end workstations can produce video quality moving images.

2. Head-up and head-mounted superposition displays. Head-up displays make use of prisms, half-silvered mirrors or similar means to allow superposition of computer-generated images (generated on CRTs or flat panels, or etc.) onto real world images (direct vision or video). These have been used in aircraft to project a computer-generated runway where the actual runway is expected to be as a pilot is approaching an airport but still above the ceiling. Lately they are being used in a variety of other industrial applications where a person wants to see real objects but at the same time receive information about those objects (e.g., icons or text superposed artificially on the real objects). Maintenance workers undergoing on-the-job training can have pointed out to them by a computer what different machine parts are and what to assemble to what, astronauts can be advised of predicted

trajectories in control of rendezvous or space robots, brain surgeon can have previously worked up CAT or NMR scan data projected onto their view of where they currently are performing surgery.

If the display (of both reality and computer-generated imagery) are not fixed, but are head-mounted (onto a helmet, onto eyeglasses or, as in some experiments, onto the cornea directly), then the real-world image will change as a function of how the observer positions and orients his or her head. In this case there must be some means to measure the head position and orientation and update the computer generated image to correspond to that portion of the 360 degrees of spherical angle the display is currently subsuming. This measurement and correspondence-keeping is essentially impossible with today's computer speeds, especially if head motion is fast and the desired resolution is high.

3. Stereoptical display. Artificial stereopsis is achieved by having two images, one presented to each eye, which correspond to the slightly different images each eye would see as a function of distance. At distances greater than about 3 meters there is little stereopsis effect. The two images can be presented in a single display (e.g., a stereo film or computer-generated image) if color coded (e.g. as red or green) and then selectively filtered by red and green lenses. More popular for computer-generated stereo images is to display alternatively to the two eyes the images for each respective refresh cycle, and then to use liquid crystal shutters to block the alternative unwanted images.

4. Printed images. As suggested above, given sufficient time, images can be printed on paper with resolution approaching that of the eye. Full color realism is still lacking, however, due the difficulty in color mixing of pigments, especially when high speed is necessary.

Auditory displays. 1. Tone generation. Generation of tonal signals is the conventional way for the computer to send information to the ears. The ears have the advantage that the operator does not have to be looking somewhere in particular. Modern aircraft have six or more different alarm signals (stall, ground proximity, fire, etc.) and nuclear or chemical plants may have a similar number (radiation, fire, etc.). Tones are also commonly used to signal that there is some visual warning or alarm message, or to mean that an alarm has cleared (the problem has gone away). The challenge is to make the alarms easily distinguishable from each other and from background noise as well as uniquely recognizable (typically by means of some strong association, e.g., with a fire engine).

New understanding of the function of the pinna (outer ear) in directional perception and the "head-related transfer function" have led to development of 3-D audio techniques which are improvements over ordinary stereo.

2. Speech synthesis. Speech is sometimes combined with tones for alarms (the ground proximity warning is a "whoop-whoop" tone followed by a voice "pull up, pull up!". The telephone companies make extensive use of speech commands and queries, some of them recorded, but more and more synthesized. Speech synthesis is now relatively inexpensive, but for some reason has not been widely accepted for serious use in systems.

Haptic Displays. Kinesthesia (literally, sense of motion in one's limbs) and proprioception (literally awareness of self, referring to limb position) are mediated by a variety of muscle, tendon and joint sensors, which also convey a sense of force. A variety of sensors in the

skin convey forces and displacements applied both normal and tangential to the skin surface, mostly in spatial-temporal patterns, at frequencies up to 400 Hz (but not at DC, the touch senses are high-pass filters!). The term "haptics" refers to all of these senses working interactively with active motor control of limb position.

1. Kinesthetic and proprioceptive display. The importance of motion, position and force and sensing is increasingly recognized as forms of feedback to confirm that a button has been pushed or a control has been set to an appropriate position (force is scaled proportional to position, e.g., in a joystick or steering wheel, or changes suddenly when a discrete action occurs). Kinesthetic and proprioceptive displays can be passive (e.g., spring centering) or active (active motor-generated force feedback in a bilateral master-slave teleoperator system).

2. Tactile display. Though tactile sensing seems to have preceded vision and hearing in nature's evolution of animals, human technologists seem to be getting around to it last. There exist some artificial tactile sensors for robots based on optical, strain gage and other technology. However essentially no acceptable tactile display exists, though currently there is active research and interest in the area. Cursors or master arms that can be dragged over virtual sandpaper come close.

Other display modes. 1. Vestibular displays. Aircraft, ship and automobile human-in-the-loop simulators generate vibration and acceleration cues, typically through use of multi-degree-of-freedom hydraulic mechanisms, e.g., Stewart platforms, such as are used commonly in moving base flight simulators.

2. Olfactory and gustatory display. Though not normally considered part of a human-machine interface, there is no question but that, driven by market forces in the food and perfume industries, technology's ability to synthesize both tastes and smells has made great advances in the last several decades. It is just a question, then, of a machine's ability to convey to the mouth, tongue and nose the appropriate chemicals, either stored or synthesized on demand.

Human Command And Control Of The Machine

Manual and body-actuated control devices. 1. Hard and soft keyboards. Though not "high-tech", hard or conventional keyboards have evolved to provide better haptic "feel" for confirmation of actuation, better orientation to the hands to minimize carpal tunnel syndrome, and smaller size (as in wrist watches).

Soft keyboards (touch screens) are position-sensing overlays to graphic visual displays of keys of icons which, when touched, activate corresponding commands.

2. Mice, tablets, and trackballs. The two-dimensional mouse (integrating a ball rotation to determine position) now takes many forms, including rotation in the desktop plane, and can have multiple buttons.

The electromagnetic tablet is another means to convey position, either isomorphic to wand location or an integral of several passes and lifts (as with a mouse).

The trackball is also common in laptop computers and certain commercial workstation devices for cursor positioning.

3. Joysticks and master-arms. Joysticks are common with one to six degrees-of-freedom (DOF), can have multiple buttons or additional tiny directional joysticks on their tops, and can provide force feedback, vibration, or other haptic feedback as a function of what is being controlled. Joysticks can be near isometric (very stiff, responding to applied forces in any direction) or isotonic (flaccid with no or near-constant spring centering).

Multi-segmented serial or parallel link arms provide positioning in up to seven DOF, including grasp, with active and variable computer-determined force feedback and impedance characteristics (computer-determined, motor-produced and therefore variable spring and viscosity characteristics). More DOF can be active independently if the device is attached to multiple body segments (e.g., fingers, arm, shoulder, head, legs)

4. Unattached gloves and space-trackers. Control devices can also be tracked optically or electromagnetically with no mechanical connection to any base. These resolve 1 mm displacement in a 1 m² cube and 1 degree rotation, but are hindered by objects which occlude or distort electromagnetic radiation.

Speech. Current speech recognition technology is still not satisfactory for most command and control applications. There are three practical problems: (1) robustness with respect to time-continuous connected speech, as contrasted to one word spoken at a time; (2) robustness with respect to different human speakers (or the same speaker on different days as a function of health, stress, etc.); and (3) robustness with respect to size of vocabulary, though the latter is more a matter of memory size. Progress is being made on all three fronts as computer power and cost improve. Given sufficient capability in speech recognition, markets are there for computers to "take dictation" and similar applications.

Myographic, EEG, ERP, GSR, and other physiological signals. The heart and skeletal muscles emit voltage (myographic) signals indicative of muscle force and velocity. The brain emits lower level voltage signals which have characteristic steady state waveforms (electroencephalograms or EEG) or evoked response potential (ERP) driven by a sudden visual or auditory or tactile stimulus indicative of the its state of activation or recognition, etc. The skin increases electrical conductivity (due to micro sweating) with stress. The pupil of the eye dilates with interest in external events. These and other physiological properties and resulting physiological outputs have been suggested as useful inputs to computers, but experience has thus far shown that they need to be calibrated to specific individuals and situations, or averaged over extended time periods to get reliable information.

User Interface Software Devices And Techniques

In addition to the hardware, the human interface is very dependent upon software devices and techniques.

Useability, user-friendliness and software widgets. The first two terms are catchall terms having the same (but nonspecific) meaning, yet at the heart of human-computer interface research and development practitioners. They include a variety of performance and subjective assessment variables such as are mentioned below under psychometrics.

Interest and effort in computer useability and user-friendliness has sparked the development of numerous "software widgets". Since the first Macintosh and later the Windows technology, it has been popular to utilize a variety of icons and metaphors, to assist the user and make the display "user friendly". For example, the desktop metaphor has become very popular: the computer screen becomes a desktop with standard size file icons which can be placed in standard size folder icons, and either can be placed anywhere on the desktop. A wastebasket is there for disposing of trash. Dragging and clicking with the mouse allows grasping and then dragging of any file or folder icon into another folders or into the trash. Pull-down menus expose alternative commands and put tool-like icons in one's "hand" (the cursor) by means of which one may then perform operations normally associated with that tool. When messages must be passed to the reader a standard "dialog box" appear, giving an explanation of some problem and asking for alternative responses or at least a click in the "OK" box to get confirmation that the original message was heard.

Decision aids. Decision aids include expert systems, decision support systems, in-line graphical aids, on-the-job training aids, computerized procedures and check lists and the like. Typically decision aids consist of large data bases of stored "if--then--else" rules, though semantic association networks, "frame" structures, fuzzy logic and neural nets are all having their impact on new ways to infer best decisions or actions from inputs.

Supervisory control. Supervisory control refers to a human observing and controlling a process by means of higher level displays (computer-integrated and typically graphical) information, as well as macro commands (goals, criteria, procedures, constraints, suggestions) at a significantly higher level than the raw sensed data or control signals. The success of supervisory control depends heavily on graphical displays, decision aids and internal models of the process being controlled (on the basis of which to make predictions and determine actions which are "optimal" in some sense).

Teleoperation And Virtual Reality

Teleoperation. Teleoperation means refers to human observation and manipulation of objects at a physical distance though video or other sensing and through robotic vehicles, arms and hands. Historically, applications have been to handling of radioactive materials and operations in space, undersea, mines and industrial application where there is chemical or mechanical hazard. Newer such devices are controlled in supervisory fashion, where the computer mediates between the human and the teleoperator, where the computer closes the control loop through its own local electro-mechanical sensors and actuators.

Virtual environments (or virtual reality, or artificial reality). A virtual environment (VE) system is similar to a teleoperator system in that it involves a human operator and a human-machine interface. It differs, however, in that the teleoperator and remote physical environment are replaced by a computer and synthetic (software) environment: the real environment becomes virtual. The purpose of a VE system is to change the state or behavior of the human operator or of the computer, rather than effecting changes in the physical environment. Traditional examples of VE systems are flight simulators and video games. Newer applications involve head-mounted displays, 3-D audio and data gloves or other haptic displays. In addition to applications in the areas of training and entertainment, considerable attention has been given to the use of virtual environments for mission planning and rehearsal, scientific modeling and simulation, and enhancing the human's ability to interpret and understand complex data sets (e.g., a brain surgeon during

an operation mapping previous MRI scans onto his real-time view of surgical tools and brain tissue).

DEFINITION OF METRICS

The following are lists of metrics believed by the writer to be relevant. Some were suggested by HCI colleagues queried on the Internet. There is currently no single or even small set of accepted metrics for the performance or quality of a human-machine interface, except possibly a numerical or category scale for subjective judgment.

Physical Metrics

- ***Bandwidth and information.*** Shannon information (average logarithm of probability of message) and Kolmogorov information (the most compact possible description of the components of a structure and the procedure for their assembly).
- ***Sampling rate or bandwidth of control.*** These measures specify how much information is communicated or how much variation in action is taken per unit of time. Transient response time and stability measures are closely related.
- ***Magnitude and dynamic range of signal.*** The range from the least perceptible energy (in whatever form) to the greatest, or the lowest rate to the highest. Human vision and hearing sets a formidable standard on dynamic range: the least energy that can be sensed is roughly 10^{-12} times the greatest or saturation limit. For humans a logarithmic mapping is appropriate across all senses (and this physiological fact that differential discrimination is proportional to stimulus magnitude, called Weber's law, is the original basis for the decibel unit).
- ***Size, weight and power requirements of interface hardware.***
- ***Reliability of the interface communication.***
- ***Functional robustness.*** (or in what variety of circumstances will some interface function)

Psychometrics

- ***Testimony of customers or users about interface quality.***
- ***Performance time for a various standard activities.***
- ***Error rate.*** (by some acceptable criterion of what an error is -- not easy to come by).
- ***Accuracy of human action.***
- ***Training time to some standard of proficiency.***
- ***Number of keystrokes or other actions per standardized function.***

- ***Mental workload, processing and memory requirements.*** (The most commonly used measures of mental workload are subjective scales, but there are some physiological indices as well.)
- ***Subjective presence.*** (the sense of "being there" -- as with virtual environments.)
- ***Transparency.*** (can the human operator "see through" the interface to make sense of what is going in the actual controlled process, vehicle or system being controlled?)
- ***Stimulus-response compatibility.*** (meaning the degree to which an action to be taken corresponds in location and direction with the stimulus indicative of the need to take that action.)
- ***User stereotype compatibility.*** (meaning the degree to which the location and direction of pointer movement or other indication on a display or control corresponds to expectation, based on culture, training or whatever -- e.g., increase of a function should be up, or to the right, red means danger, etc.)
- ***Ergonomic or anthropomorphic metrics.*** (namely, does the interface "fit" the physical population of users. There are government-produced software packages as well as handbook data which help ensure such fits.)

Econometrics

- ***Any of the above measures per dollar.***
- ***Comparative effort spent on the human interface relative to the rest of the product or system.***
- ***Extent of interest and activity concerned with HCI:***
 - Number of developers that have usability labs (comparison of countries).
 - Number or extent of publications on interface technology.
 - Number or size of professional meetings on human interface technology.
 - Number of nationals of a particular country presenting papers at int'l meetings.
 - Number of specialists graduated from universities, number of course taught, etc.
 - Citation index counts data relative to HCI

SOURCES AND ANALYSIS OF METRICS

Leaders Relative To The Metrics

Since no single measure has been accepted by the HCI community, this discussion deals with the metrics as a group.

In terms of display hardware, it seems that the Japanese are the general leaders (the Japanese clearly have the laptop computer display market "sewn up") though the US is setting some records [see discussion on visual display hardware above and the February 1994 article by Larry Tannas updating the 1991/92 JTEC study, attached to this report as an appendix]. Such special devices as head-mounted displays seem always first to be

produced in the US, then copied by Japan. With regard to audio hardware (conventional loudspeakers, 3D audio, speech recognition and synthesis) it seems the US is at the forefront of research, but a number of Japanese companies are keeping abreast, as is Philips in the Netherlands.

Haptics is of great interest within the virtual environment research community in both Japan and the US, but it is not clear which large companies or commercial interests are paying attention outside the computer game industry, which is mostly Japanese (Nintendo, Sega).

With respect to formal indices of interest and activity in HCI (this has to be considered more broadly than what is called HCI in the US, which is primarily what was discussed under "software of HCI" above, the US is the clear leader.

I do not see any European country or the EC generally as being leaders in HCI. Curiously in commercial Aviation the Europeans have been the most aggressive in adapting certain new interface automation and display ideas. The Airbus (A320,330,340) flight deck is the most automated (compared to Boeing 747,767, 777 and McDonnell Douglas MD11) allegedly in order to be easier for less-well trained pilots in developing countries to fly. The Airbus also has the worst accident record with regard to human error!

Foreign Roadmaps And Strategies

The Japanese have a tradition of sensitivity to users in designing products for consumer markets, as amply demonstrated by the success of their automobiles in appealing to American car buyers. However they have had no tradition of formal "human factors engineering" as have the Americans (the latter began in defense laboratories during the Second World War) and as have the Europeans to a somewhat lesser extent. Japan is now beginning to change in this respect, and we are seeing the beginnings of human factors in their universities within engineering training.

The Japanese love gadgets, and this is underscored by the Japanese embrace of virtual environment and teleoperation technology. It fits in well with their already-in-place electronic display, robotics and miniaturization capabilities; it is prominent in their national press. For the size of their country they seem to be sponsoring more meetings than the US.

Europe has a tradition of interest in the welfare of workers, due in part to the socialized work arrangements that grew there in the 50s and 60s. This has meant a keen interest in industrial interfaces for production machinery. They have adopted automation and computer-interactive systems in factories, nuclear power plants, etc. with a self-conscious concern about human interfaces. surely more than in the US. The EC project named *Esprit* epitomized this interest in interfaces, especially software interfaces. The Japanese have followed, and the Americans lag behind both, I judge, in concern for factory workers' safety and quality of work life at the machine interface.

Potential Breakthroughs

Large flat panel display. Small flat panel LCD displays, both passive and active, are common, but large ones will depend on bringing costs down. Some believe the market is such that this will occur soon.

Touch or haptic display. As stated above, no satisfactory tactile display exists, but the research interest is such some practical approach may occur soon, likely making use of some kind of electronic LSI- to-mechanical displacement properties. Tiny printed very-high-speed motors exist, but the micromechanics to produce sufficient forces and integrated displacements for tactile display use are still lacking.

3D visual display. There have been some demonstrations of quasi- 3D visual displays based on mechanical vibration of image planes, holography, etc., but none is satisfactory yet. The market in air traffic control, entertainment and other uses is there and waiting.

Video recognition and compression. Active research on recognition and compression of moving images is promising some practical answers.

Computer-based model of the user. This idea is that, in addition to having a computer model of the controlled process (an important part of optimal control and many decision-aiding systems, to have a computer model of the human operator (including identification and specification of capabilities, preferences, current focus of attention, current level or fatigue or stress or alertness, etc.). The computer could then make use of such knowledge about "to whom it is speaking" (much as a human speaker does) and decide when it, the computer, should take over control or otherwise second-guess the human operator.

Direct readout from motor neurons, direct input to nerves. Of course this is done now in a primitive way, but more refinement might begin to bypass the conventional machine interface altogether. It is probably a way off.

Underlying Enabling Technologies

Visual Display. For visual display, electronics and electro-optical physics are clearly the underlying technologies. The Society for Information Display is a good source of information for the state of the art.

Auditory display. As mentioned above, the "hi-fi" industry drives conventional audio. Probably the PC board manufacturers influence developments in speech generation and speech recognition. With improved speech recognition the demands for signal processing speed and power increase greatly, so that progress in A-D capability (DSP chips), parallel computation and large fast-access memories is critical to progress here. The same is true for 3D audio production.

Haptic display and human command and control devices. Haptic (touch and force) display and human command and control hardware and software are closely coupled, and research/development in both is part of teleoperator R&D and therefore closely related to R&D on robotics in general. There is no single application industry for teleoperation. Indeed, in industrial robotics the human interface is not so critical; once programmed the factory robot (supposedly) does its task without human help. The human interface is critical in the many teleoperator applications mentioned above. The underlying technologies are mostly in mechanical position-sensing instrumentation, some of it electromagnetic, some optical.

Software of HCI. HCI software developments are most closely coupled to the personal computer industry and the professional societies coupled to it such as the IEEE.

SIGGRAPH is a major annual meeting as is the CHI (computer-human interface) meeting of IEEE.

Speech recognition is generally considered part of computer science.

BUSINESS AND STRATEGIC FACTORS

To be discussed in subsequent draft of this chapter.

TRENDS

Teleoperation And Virtual Environments

Air traffic control. New display-control technologies, coupled with GPS technology, offer opportunity improved human monitoring and surveillance of aircraft both in the air and on the ground, including both vehicle identification and enhancement of situation awareness in three dimensions. A direct 3D display would be a boon, but progress is occurring without it.

Portable computing. Numerous computer firms are actively developing small computers capable of communicating over radio or optical networks (and with GPS) and accepting hand drawn words or pictures (e.g., the Apple Newton). Such devices, given additional interfaces, can perform many other functions information about which can be relayed to another location. They can be used for monitoring of physiological variables of patients under medical care, connection to optical scanners for taking key data from all kinds of packages and labels in retail stores to get more information, and a means for a person walking at night to indicate to a security alarm system his location on a map, etc.

Data visualization. Advances in virtual environment display and haptic control technology permit an observer to visualizing and understand complex data such as that from radars and sensors on flight vehicles, flow of fluids over aerodynamic surfaces, the interactive forces in molecules, geometrical problems of stress, wiring, or etc. in complex mechanical designs.

Distributed simulation and training. Teleoperation and virtual environment technologies have already been applied on a large scale to training for tactical military operations in the form of SimNet. ARPA is committed to extending and enhancing distributed interactive simulation (DIS) to support theater-wide, "seamless" joint service exercises with tens of thousands of simulated real vehicles, naval vessels, aircraft and human and "semi-automated" participants before the turn of the century. Similar techniques could be applied to forest fire fighting, police and disaster relief operations.

Tele-medicine and tele-education. There are several application areas where teleoperation technologies offer considerable promise. One is tele-medicine, including both tediagnosis and telesurgery, a new "dual-use emphasis by ARPA. The idea is to bring the diagnostic and surgical skills of the physician specialist to the patient no matter where the latter is, making use of new satellite and other high-bandwidth communication technology and telerobotics.

Tele-education means allowing groups of students to participate in real-world scientific or cultural events even though they may occur half way around the world. Dr. Robert Ballard of Woods Hole Oceanographic Institute demonstrated this idea by allowing high school science students to participate in the mission of the Argo-Jason robotic submarine expedition to the bottom of the Mediterranean.

Decision Aids And Supervisory Control

Decision aids. Development of decision aids continues to be a very active field in medicine (the Stanford researchers who started "expert systems" still haven't convinced physicians that computers are better at prescribing mycin drugs), but expert systems are now common in configuring computer systems and many other applications.

A few expert system companies have gone out of business as have some major manufacturers of Lisp-oriented computers, but the field remains healthy, even controversial. It is split by disciplinary orientation. Computer-supported cooperative work (CSCW) is a fashion pushing management, along with older approaches to "decision-support systems" for market analysis, sales, inventory, transportation of goods, etc. Medicine has its own flavor of expert system people who must talk doctor language. Computer-aided design offers a very different set of capabilities to different industry, mostly engineers.

New computation technologies such as neural nets and fuzzy logic contribute here. A neural net enables the learning of any non-linear function from an input-output data set. Fuzzy logic allows elicitation of expertise from a human expert who cannot state rules in crisp quantitative equations or logic.

Supervisory control. Supervisory control is the clear trend in the chemical, oil and process industries, and to a lesser extent nuclear power, because of its conservative stance since the Three Mile Island and Chernobyl accidents (the Japanese, Canadians and Europeans are moving faster than are the Americans because new plants are being built there; they are not in the US). The trend toward supervisory control is also true in aviation, where pilots are becoming "flight managers" interacting with highly computerized "flight management systems". The "glass cockpit" (integrated computer-based instruments rather than electromechanical ones) is characteristic of all new commercial as well as military aircraft. Robotic devices for space, undersea, chemical and toxic environments are more and more being controlled by computer-mediated human-supervisory control interfaces.

The European Community, with its PROMETHEUS and DRIVE PROJECTS, was the first to undertake major projects to improve automobile transportation by means of electronics and communication technology, all of which has important human interfaces. The Americans (with their "intelligent highway vehicle systems") and Japanese have followed suit.

Miniaturization

The steady trend toward miniaturization continues in all forms of electronics and sensors. Miniaturization is compatible with less bulk and less obtrusiveness at the human interface, especially if a device is designed to be carried or mounted or "worn" on the human body (eye glass displays, medical monitoring devices, wrist-mounted radio, TV, or personal communication devices. In the past the Japanese have emphasized miniaturization more in

their universities and research labs. They now have taken over from the US most of the market for small electric motors and related actuators (try to find a department of mechatronics in an American engineering school). The US is waking up on this point, however. Industrial electronics labs in both countries are currently active with respect to ultraminiaturization of computer chips, sensors and devices.

Usability Research

To date, most software widgets are embodied as visual displays, or for vision-plus-mouse actuation. The "widget" idea has simply not found its way to any significant extent into auditory and haptic displays, though I suspect it will soon, particularly as new products and services are offered to market by AT&T and its competitors on the "information highway".

SUMMARY

Table 2.1 summarizes the status and trends in U.S. technology compared to that in Japan and Europe with respect to each of the related areas.

Table 2.1
Relative Status of U.S. Human-Machine Interface Technology

Technology Areas	Basic Research	5 Yr. Trend	Commercialization	5 Yr. Trend
<u>Human factors theory</u>	US ahead	US will continue ¹	NA	NA
<u>Software</u>				
rapid prototyping	US ahead	will continue	US ahead	will continue
interface standards	US ahead	will continue	US ahead	will continue
interface intelligence	US ahead	will continue	US ahead	will continue
<u>User modeling</u>	US ahead	Japan, Eur pulling up	Japan emphasizing Kansei, or user "good feeling" ²	
<u>Natural language interface</u>	US ahead	Japan pulling even	Japan pulling ahead ³	
<u>Advanced input-output</u>				
visual	US ahead	will continue	Japan ahead ⁴	will continue
auditory	US ahead	will continue	US ahead	will continue
haptic	US ahead	will continue	US, Japan even	will continue
virtual reality	US, Japan even	continue	Japan ahead ⁵	will continue
assist handicapped	US, Japan even	continue	US, Japan even ⁶	will continue
<u>Wireless/mobile interface</u>	US ahead	will continue	US ahead	will continue
<u>Group support interface</u>	US ahead	will continue	US, Japan, Eur even	continue
<u>Aircraft systems</u>	US ahead	will continue	US ahead	will continue ⁷
<u>Ground transport</u>	US, Japan even	continue	US, Eur, Japan even ⁸	continue
<u>CAD/CAM/CAE</u>	US, Japan even	continue	US, Japan even	will continue
<u>Manufg/process plants</u>	US, Japan even	continue	Japan, Eur ahead ⁹	will continue

Notes on Table 2.1:

1. Japan is just getting started in human factors theorizing. There has been no such recognized discipline, though they have been implicitly sensitive to human factors in design applications for some time.
2. The new national projects emphasizing quality of life and "kansei" are worth tracking (e.g., at Waseda University). To westerners this looks silly. Commercially it may not be.
3. Japanese natural language recognition systems are excellent, and this all fits in with their "soft engineering" and overt interest in technology to serve people.
4. This is strongly supported by their liquid crystal industry dominance.
5. The Japanese love virtual reality, and seem to take it much more seriously than westerners do. Without question they will dominate the entertainment applications in several years.
6. The Japanese have had national projects like "Silver Robotics" to apply robotics in nursing homes, etc. Much bolder than here in application, but not so successful either.
7. The Japanese aircraft industry is beginning. Needs to be watched closely. They may go in for general aviation aircraft, a total vacuum at the moment here.
8. "Intelligent highway vehicle" technology is a continuing race between Europe, Japan and US. Market acceptance will be fastest in Japan where they love gadgets in their cars.
9. The US has sold off its manufacturing robotics industry in recent years-- essentially all of it. A very frightening fact.

Human interface technology is a complex topic because of the many ways to present information to a person, get command and control information from a person, and because software and integration are just as important as the hardware at the interface. Metrics for benchmarking are many, including physical variables, psychological variables and economic variables. No one or small set of variables are accepted for measuring the quality of a human-machine interface, which makes benchmarking difficult. This reviewer sees the US and Japan leading in different aspects of interface technology.

[Editor's note: for more information on the display hardware aspect of the human-machine interface topic, see article by Larry Tannas updating the 1991/92 JTEC study on Japanese flat panel display technology, attached as an appendix to this report beginning on p. 75.]

3. WIRELESS

Charles W. Bostian
Virginia Tech.
Blacksburg, VA

You can always tell when a new market is going to be big. Long before companies are able to figure out how to take advantage of it, others are already profiting from it with seminars, market research, executive search, financial and educational services, books, magazines, and newsletters. Wireless communications is going to be that kind of a market. (Schneiderman, 1994b)

DESCRIPTION OF THE TECHNOLOGY

Wireless is an old term for radio now used for a collection of telecommunications services whose common feature is delivery by a radio link. Some wireless products -- like RF (radio frequency) tags that locate people and cargo -- have no wired counterpart. Others -- like cellular telephones -- represent new, inexpensive, and ubiquitous forms of services that with previous technology were available only in very limited quantities. Still others -- like wireless computer networks -- simply replace wires by radio.

Currently wireless is booming. Cellular telephones have succeeded beyond anyone's wildest predictions, and many other wireless products should do the same. Rapid growth, worldwide competition, and multiple alliances between companies characterize the industry. Newsletters, trade magazines, and advertisements abound. The quotation above well describes what is going on.

This report discusses the following wireless services: (1) cellular and satellite-based telephone systems, (2) microwave personal communications services and networks (PCS and PCN), (3) fixed and mobile wireless computer networks, (4) position location systems, and (5) RF tags. Of these, telephones are the most important economically and receive the most attention. The categories are not mutually exclusive; for example, PCS is still evolving and may ultimately replicate all the others.

DEFINITION OF THE METRICS

The current boom in wireless products typifies the change in telecommunications technology from systems that allow sequential exchanges between two parties to those that make individuals part of a network. Most successful wireless products require a supporting network infrastructure. Thus a breakthrough in wireless telephone technology would be economically important only if it could fit into an in-place cellular system or if it justified

building a new network to support it. In this way the wireless industry is significantly different from, say, the computer industry, where a new chip like the 486 can give a company a major advantage and render competing products obsolete. Thus, *standardization* is an important metric for wireless. A country or company that can establish its technology as a market standard has a significant competitive advantage because the standard defines the network infrastructure.

Where a standard exists, the next most important metric is ability to make products that are competitive in the market defined by that standard. Market share is probably the best indicator of this capability. For some wireless services the report applies the metric to particular classes of products (for example, handheld cellular telephone terminals) while for others it applies the metric globally.

Many technical metrics may be used to compare competing communications technology -- for example, system capacity (quantified by the number of voice channels per unit bandwidth) is important in the debate over code division multiple access (CDMA) versus time division multiple access (TDMA) systems for PCS systems. This report avoids these for technologies with widely accepted standards, but includes them for services like PCS where standards are still under consideration. It lumps them under the general heading of capacity and capability, an inexact assessment of a wireless technology's resistance to interference, and ease of deployment.

Another metric that the report considers is a subjective assessment of the quality of a particular supporting technology, for example, radio transmitters for handheld radios. It reflects market share and prevailing opinion about who makes the best products with the most features..

THE STATE OF WIRELESS TECHNOLOGY: SOURCES AND ANALYSES OF THE METRICS

Introduction

This section discusses the current state of wireless technology, describing key technologies and identifying bottlenecks where breakthroughs would be important. It is drawn from articles published in 1993 and 1994, government and industry documents, and informal discussions.

Cellular and Satellite Based Telephone Systems

Ideally, wireless telephones allow an individual to reach the public switched telephone network (PSTN) from any location any time. Their operation depends on a radio link between the telephone handset and a base station (which may be a satellite or a cell site) connected to the PSTN. Terrestrial cellular systems have been deployed for about 10 years; satellite-based systems are under construction. Over 40 million cellular and cordless

phones may be in use by 1996, and some (not all) predictions make the satellite market bigger (Schneiderman, 1994b).

Satellite Systems. The impetus for deploying worldwide satellite telephone systems comes primarily from the United States. American Mobile Satellite Corporation (AMSC) is constructing a system using geostationary satellites, and several operators have filed FCC applications to operate low (LEOSAT) or medium-earth-orbit (MEOSAT) systems. AMSC will begin commercial operations in late 1994 using leased Inmarsat services and marketing through existing cellular providers. It is limited to the North American market, but its competitors are inherently global. Opinions differ about how many proposed LEOSAT and MEOSAT systems will be built, but IRIDIUM and GLOBALSTAR probably will be. While these systems have important international participants, Motorola created IRIDIUM and Loral and Qualcomm created GLOBALSTAR, and both represent U.S. technology. The only likely foreign competitor for these and AMSC is Inmarsat's Project 21, which is not yet fully defined and may not materialize. Japanese geostationary systems seem primarily for domestic use, and R&D efforts may be more for researchers to "keep their hands in" rather than a near-term precursors to commercial operation. A quotation from Schoenenberger (1993) summarizes the European position well: "All of the products depend largely on initiatives led from the USA, with the exception of Inmarsat. There is involvement from European companies, but these are mainly in secondary roles."

The key issues in the coming competition between satellite and cellular systems are economic. Can satellite-based telephone systems compete with the terrestrial cellular network? At least for handsets, satellite seems inherently a more expensive technology, but proponents offer the possibility of a single system with instant connectivity from anywhere, one for which users would presumably pay a premium. The rest of the world seems content to let the U.S. competitors fight it out. European administrations may make it hard for them to operate there.

The principal bottlenecks in satellite telephone technology are the limited battery power and antenna gain available in a handset. (Batteries also dictate cellular handset size and talk time, but the trend toward base stations with ever-smaller geographical coverage continues to reduce battery demands.) Breakthroughs that would produce inexpensive self-phasing array antennas small enough for a handset would significantly improve satellite telephone performance in existing systems, but none are foreseen.

Cellular Systems. Europe and Japan are each covered by a singular digital cellular standard, while the U.S. cellular industry has two. Proponents of the European GSM (*Groupe Speciale Mobile*) see it becoming *the* international standard. As of 1993, 22 countries had operating GSM networks, and 25 non-European countries had adopted or were considering GSM (Déchaux and Scheller, 1993). Another reference (Schneiderman, 1994a) cites 108 licenses allocated or planned in a total of 62 countries. Japan has deployed Japanese Digital Cellular (JDC), and Japanese companies are promoting it without apparent success as *the* Asian standard. Like GSM and JDC, the North American Digital Standard (IS-54) is a time division multiple access (TDMA) system. As of 1991, 52

countries had IS-54 compatible systems; most of these are in North America or the Caribbean (Harte, 1992). Competing with IS-54 are several code division multiple access (CDMA) systems; the best known is Qualcomm's IS-95.

U.S. companies are testing both TDMA (IS-54) and CDMA (IS-95), and there have been recent IS-95 field trials in Europe (where it might become an alternative to GSM) and Asia. CDMA offers some real ("soft handoff") and disputed (system capacity) advantages over TDMA systems (Schneiderman, 1994b). The U.S. leads in CDMA technology, but it is unclear whether this will translate to commercial success. CDMA is still being tested; GSM is installed.

Worldwide, Motorola is the dominant manufacturer of handsets (23% of the market). Its principal competitors are Nokia (Finland) and Japanese companies Matsushita, Mitsubishi, and NEC (30% collective market share).

A few international companies with expertise in both radio transmission and switching systems dominate the European market for cellular network equipment (base stations, switches). Competition here is global; Ericsson has about 40% of the world market (Arnbak, 1993), and Motorola, AT&T, Northern Telecom, and Ericsson together have about 90%. Currently GSM handsets are scarce in Europe. Motorola is the leading supplier; together with European manufacturers Nokia and Ericsson it controls 90% of the market. Matsushita (Panasonic) is the leading Japanese vendor, but the Japanese market share is insignificant (Schneiderman, 1994a). This could change if GSM handsets become a commodity product and Japanese mass manufacturing and marketing skills become important.

The Japanese domestic cellular market is already large and growing rapidly, with 1.6 million subscribers now, and 10 million subscribers expected by 2000. Motorola has sold network equipment and terminals to Japanese users, but dollar figures and market share are not publicly available (Kawajiri, 1993). Currently no foreign manufacturers make handsets in Japan (Schneiderman, 1994b).

System capacity is a potential bottleneck for cellular systems. Breakthroughs that would allow existing systems like GSM to serve more users via smaller cell sites and more intensive frequency reuse would be more significant than new technologies that would require new network standards or architectures. Digital signal processing (DSP) techniques for interference reduction are thus potentially important, and this is an area where the U.S. leads.

Personal Communications Services (PCS) and Networks (PCN)

PCS and PCN are names for new services in the 2.0 GHz band that are still being defined. They will provide voice and data links to small, short-range, hand-held terminals. In a sense, the FCC and its counterparts are making spectrum available and letting the market decide its uses. Depending on who is making the predictions, PCS services will range from

a lower-cost more personalized replication of existing cellular services (one where people rather than telephones will have numbers that follow them everywhere) to completely new interactive computer networks that, for example, will allow a room full of personal digital assistants (PDAs) to set up a network without human intervention. Other scenarios make PCS simply "cellular for pedestrians" -- i.e., systems with little or no provision for handoff that will work only when the handsets move at pedestrian speeds. In this situation, the distinction between cellular-like PCN phones and cordless telephones might disappear.

A well-defined PCS voice service in Japan is the Personal Handy Phone (PHP) which will become operational in 1994 with 14 million potential subscribers, the number of analog cordless phones now in use. PHP is a single handset that works anywhere: a cordless phone at home or work and a cellular phone everywhere else. As a cordless phone it can easily connect with an office PABX. A wireless PABX is essentially a miniature cellular network, and PABX operation is a clear priority of the PHP system. PHP's appeal outside Japan is uncertain.

Chip sets and other PHP components are being exported to Japan by California-based Pacific Communications Sciences, Inc. (Schneiderman, 1994a). This is consistent with efforts by Japanese companies to find U.S. partners to develop terminals to meet the demand for high speed (64 kbps or more) data services that are "virtually undeveloped" there (Kawajiri, 1993).

The European counterpart to the PHP is the DECT (Digital European Cordless Telephone) standard. DECT is designed for wireless PABXs and supports ISDN. DECT shares many features with GSM. Europe also has an 1800 MHz GSM-based digital cellular standard in DCS1800. In September, 1993, Mercury One-2-One, jointly owned by US West and Cable and Wireless began marketing a DCS1800 system in the U.K. Its proponents see it as a likely vehicle for cellular network expansion in the rest of Europe and in the U.S. (Hadden, 1993)

The risk to U.S. technological leadership is that these GSM-derived standards will fill a PCS standards vacuum and become de facto U.S. standards for PCS. This would not automatically relegate U.S. companies to second class status, since Motorola at least is very competitive in the existing European GSM market. It could keep the U.S. lead in spread-spectrum (CDMA) systems from translating into commercial success in the PCS market.

Fixed and Mobile Wireless Computer Networks

The distinctions (other than in marketing) between wireless local area and wide area networks and between wireless fixed and mobile data services are indistinct, as are those for fixed and mobile services. Perhaps the difference is in marketing. All wireless networks allow personal digital assistants or laptop computers to communicate wirelessly with other machines. The potential market is 20-26 million users and worth \$21.5B in 2000 (Schneiderman, 1994b). U.S. companies such as Motorola and BellSouth Enterprises have aggressively promoted an array of systems like RAM, EMBARC, and ARDIS that operate

in the 900 MHz band. Motorola is leading in the development of a family of intelligent wireless modem cards (PCMIA cards) that will fit slots in a variety of digital devices. Service is already available via CDPD (cellular digital packet data, an open specification that uses cellular channels to transmit 19.2 kbps data) and through several competing proprietary systems. GSM provides for data services up to 9.6 kbps, but these are apparently not yet fully implemented. In the wireless network area, the U.S. is leading, Europe comes in second, and Japan is not a major factor.

Position Location Services for Vehicles

Electronic technologies for communication and navigation have much in common, and wireless communications systems can locate a vehicle and report that location to the driver and to a dispatcher. While it is possible to do location via dedicated radio systems (through the cellular network, for example), the U.S. Global Positioning System (GPS) continues to set the world standard for accuracy, and the rapid decline in GPS receiver prices makes alternatives economically unattractive. While there is concern that GPS, which is a military system, could be withdrawn from civilian use in time of national emergency, no one has proposed a viable commercial alternative. Inmarsat has considered an augmented system that would equip their satellites to transmit GPS-derived data and provide their customers with greater accuracy and (perhaps) greater reliability. It is unclear if this will be built or that it threatens U.S. dominance in position location technology. Japanese companies (particularly Sony) threaten to dominate the market for GPS receivers, as they do most other consumer electronics products except for wireless.

Vehicular position location systems that report to dispatchers typically rely on GPS (or Loran-C) for their navigation information. The largest of these is U.S. Qualcomm owned OmniTRACS, which uses leased satellite capacity for communications. Commercial arrangements usually involve Qualcomm and a local satellite provider. EUTELTRACS is the European version.

RF Tags: Identification and Tracking Systems for People and Goods

RF (radio frequency) tags are small radio transponders (transmitter plus receiver) which respond when interrogated by a radio signal. Their applications include security badges for workers, identification tags for laboratory animals, and markers for railroad cars. While both U.S. and European companies offer competitive products, European companies are ahead in developing innovative uses for RF identification technology. This is a consequence of their focus on standards. Smart cards and railroad RF identification systems are two examples where Europe adopted standards early. As in other wireless areas, Japanese companies are looking to the U.S. for technology and seeking teaming arrangements with American companies, particularly for the Intelligent Vehicle Highway Systems (IVHS) market..

BUSINESS AND STRATEGIC FACTORS

The markets for wireless encompass North America, Europe, Japan, and the rest of the world. Japan, the U.S., and Europe compete primarily in North America and the rest of the world. The U.S. competes primarily with Europe in Europe and with Japan in Japan. This finding follows a broader analysis based on patents which notes that "Traditionally the US market has been far more important for Japanese telecommunications equipment exports than European markets, although some big adjustments can be observed for the 1980s. The Japanese market is of growing importance for US exports, but is still totally unimportant for the exports of E.C. countries" (Schmoch and Schnöring, 1994).

TRENDS

Japanese R&D efforts in telecommunications seem focused primarily on intelligent optical fiber networks. Except for a few minor satellite projects, wireless is absent (and not mentioned by name) from a series of reports about Japanese telecommunications policy and R&D issued by the Tokyo branch of the Office of Naval Research. This is consistent with a report that "Japanese companies are looking first to the U.S. for RF data communications technology to a great extent due to U.S. innovation in this area." (Kawajiri, 1993) Japanese researchers are working on innovative uses for satellite channels (for example, ways to allow satellite subscribers to receive the same ISDN services that are available to optical fiber subscribers), but the emphasis is on treating the satellite link as another kind of cable rather than as a wireless connection to enhance the mobility of the user. Much Japanese wireless R&D focuses on network issues rather than on radio technology.

But Japanese researchers are not inactive in wireless. Schmoch and Schnöring (1994) report a rapid rise in the number of Japanese European Patent Office (EPO) patent applications beginning in 1984-85. There was a corresponding jump in US EPO patent applications in 1986-87. The only European country to show an increase was Great Britain. It remains to be seen whether increased Japanese patent activity in Europe will translate into a change in the Japanese competitive position.

Concerning the European market, it is appropriate to quote a European source

"With a clear lead in digital and RF microelectronics, Japanese and U.S. manufacturers are poised to dominate the supply of advanced digital terminals for GSM networks — a major consumer market with much competition, but only a peripheral system impact. In the core area of total systems engineering and standardization, U.S. manufacturers and operators appear highly divided about the additional merits of various technologically advanced options for radio access, digital modulation, and networking . . . A single convincing first-generation alternative to GSM on the world market, similar to the U.S. AMPS standard, which in the analog era captured about two-thirds of all mobile subscribers worldwide, has yet

to merge in the United States...Arguably, the active presence of U.S. Bell Operating Companies (BOCs) in the operating consortia licensed by countries committed to the GSM standard can be taken as an American acknowledgment of the dominance of European manufacturers in the rapidly growing market for digital mobile network technologies. Conversely, the awards of such licenses in several EC countries can also be seen as a European acceptance of greater American operator experience and marketing skills. (Arnbak, 1993)

While efforts at developing so-called third generation mobile radio systems are under way in the U.S., Europe, and Japan, the Europeans seem perhaps the most serious about it. Their goal is called UMTS, for Universal Mobile Telecommunications System.

SUMMARY

The picture that emerges from this study is one of intense global competition in four markets: North America, Europe, Japan, and the rest of the world. The Japanese are important players only in their own domestic markets. American companies compete in all, and European companies are not competing in Japan. Global alliances are common, with American Motorola and European Ericsson dominating the equipment side, and American BOC's playing important roles on the service provision and business sides. Europeans clearly lead in establishing single standards and getting behind them, but American manufacturers can profitably make equipment to the European standards.

The tables that follow compare key elements of U.S. wireless technology with their Japanese and European competitors. The column arrangement in each case is the same as in Table 3.1.

Table 3.1.
900 MHz Terrestrial TDMA Telephone Systems

Item Compared	With respect to U.S., Europe is		With respect to U.S., Japan is		The world leader is
	Absolute Position	Rate of Change	Absolute Position	Rate of Change	
International acceptance of standard	Far ahead	Holding Steady	Far Behind	Losing ground	Europe (GSM)
Network equipment for all standards	Even	Holding Steady	Behind	Holding Steady	U.S. and Europe
Handheld terminals	Behind	Holding Steady	Behind	Holding Steady	U.S.
System design tools	Ahead	Improving	Far Behind	Holding Steady	Europe

Table 3.2.
CDMA Terrestrial Cellular Telephone Systems

Item Compared	With respect to U.S., Europe is		With respect to U.S., Japan is		The world leader is
	Absolute Position	Rate of Change	Absolute Position	Rate of Change	
Overall technology	Behind	Holding Steady	Behind	Holding Steady	U.S.

Table 3.3
Satellite-Based Telephone and Messaging Systems.

Overall technology	Behind	Holding Steady	Behind	Holding Steady	U.S.
-----------------------	--------	----------------	--------	----------------	------

Table 3.4
PCS and PCN

Development of Standard	Ahead	Improving	Behind	Falling further behind	Europe
RF technology	Even	Holding steady	Behind	Falling further behind	
Large-scale deployment	Slightly ahead	Losing lead	Slightly ahead	Losing lead	Europe

Table 3.5
Fixed and Mobile Wireless Computer Networks

Development of standard	Ahead	Holding steady	Behind	Holding steady	Europe
Large scale deployment	Even	Holding steady	Behind	Holding steady	

Table 3.6
Position Location Services for Vehicles

Space segment	Far behind	Losing ground	Far behind	Losing Ground	U.S.
Receivers	Behind	Holding steady	Even	Gaining	

Table 3.7
RF Tags

Standards	Ahead	Holding steady	Behind	Holding steady	Europe
Technology	Even	Holding steady	Behind	Holding steady	

Table 3.8
Supporting Technologies for Handheld Wireless Products

Transmitters	Behind	Holding steady	Behind	Gaining	U.S.
Receivers	Even	Holding steady	Behind	Holding steady	

REFERENCES

Arnbak, J. 1993. "The European (R)evolution of Wireless Digital Networks. *IEEE Communications Magazine* 31(9): 74-82.

Déchaux, C. and R. Scheller. 1993. "What are GSM and DCS ?" *Electrical Communications* 2nd Quarter 1993:118-127.

Hadden, R. 1993. Mercury One-2-One: The Catalyst for Change in Telecommunications Services. Seventh IEEE European Conference on Mobile and Personal Communications. Brighton, England. December 13-15, 1993. IEE.

Harte, L. 1992. *Dual Mode Cellular*. Bridgeville, PA: P.T. Steiner Publishing Company

Kawajiri, M. 1993. Wireless Data Communications Terminals. Japan FY94 Industry Subsector Analysis. U.S. Embassy, Tokyo.

Schmoch, U. and T. Schnöring, 1994. "Technological strategies of telecommunications equipment manufacturers: a patent analysis." *Telecommunications Policy* 18(5): 397-413.

Schneiderman, R. 1994a. For Offshore Wireless Markets, the Accent is on Rapid Growth." *Microwaves and RF*. August. 33-49.

Schneiderman, R. 1994b. *Wireless Personal Communications*. New York: IEEE Press.

Schoenenberger, J. 1993. "Satellite Personal Communications Networks." Third European Conference on Satellite Communications. Manchester, U.K., November 2-4, 1993. IEE. 128-132.

GLOSSARY

AMPS	Advanced Mobile Phone System (analog cellular standard)
AMSC	American Mobile Satellite Corporation
ARDIS	Proprietary mobile data system
BOC	Bell Telephone Operating Company
CDMA	Code Division Multiple Access
CDPD	Cellular digital packet data
DCS1800	European GSM-based digital cellular standard for 1.8 GHZ
DECT	Digital European Cordless Telephone
DSP	Digital Signal Processing
EMBARC	Proprietary mobile data system
FCC	Federal communications Commission
GLOBALSTAR	Proposed LEOSAT Satellite System
GPS	Global Positioning System
GSM	European Digital Cellular Standard
Inmarsat	International Maritime Satellite Organization
IRIDIUM	Proposed LEOSAT system
IS-54	Proposed US TDMA Digital Cellular Standard
IS-95	Proposed US CDMA Digital Cellular Standard
ISDN	Integrated Services Digital Network
IVHS	Intelligent Vehicle Highway Systems, "smart" highways
JDC	Japanese Digital Cellular Standard
LEOSAT	Low Earth Orbit Satellite
MEOSAT	Medium Earth Orbit Satellite
PABX	Private Automatic Branch Exchange (an office telephone system)
PCMIA	An industry association with a standard for wireless modem cards for computers
PCN	Personal Communications Networks (equivalent here to PCS)
PCS	Personal Communications Systems (equivalent here to PCN)
PDA	Personal Digital Assistant
PHP	Personal Handy Phone (Japanese PCS system)
PSTN	Public Switched Telephone Network
RAM	Proprietary mobile data system
RF	Radio Frequency
TDMA	Time Division Multiple Access

4. Data Storage

Robert M. White
Carnegie Mellon University
Pittsburgh, PA 15213

with assistance of
Norm Talsoe, NBT Consulting

DESCRIPTION OF THE TECHNOLOGY

Data storage typically refers to the secondary and tertiary storage devices in a computer system. The data storage industry is approaching \$100B. The hard disk drive segment accounts for about \$47B, with magnetic tape at \$42B and optical disk drives at \$6B. The U.S.'s share in this market is 40% largely because of its dominance in hard drives and data tape drives.

The enormous growth of this industry over the past decade has been associated with the increases in processor speeds that enabled workstations and PCs. In the next decade, the growth of multimedia and networking will demand even more storage capacity. Will the technology be able to support this demand? The answer appears to be yes. The current areal density on a hard disk is about 300 Mbits/in². The U.S. industry has set a goal of 10 Gbits/in² by 1998, and the indications are that this can be done. The industry has also set a goal of 1 Tbyte/in³ for tape storage.

The principles of magnetic recording are captured in Fig. 4.1. Data is stored in the form of changes in the direction of the magnetization of a magnetic medium. For the case shown here, the magnetization lies in the plane of the medium. There had been a good deal of talk about perpendicular recording, but it appears that longitudinal recording will prevail at least until the turn of the century.

Hard Disk Drives

The media used in hard disk drives currently consists of a thin (300 Å) cobalt alloy film such as CoCrTa or CoCrPt. The alloy composition and the deposition conditions are controlled to produce the desired crystalline texture and grain size which, in turn, govern the magnetic properties such as magnetization, coercivity, and noise characteristics. Higher recording densities require higher coercivities. Coercivities are currently in the range of 1800 oersteds.

Fig. 4.1a. Basic geometry of a magnetic recording system

Fig. 4.1b. Basic geometry of a magneto-optical recording system

The transitions are written into the medium by the fringing fields from an electromagnet. Originally, and still in many cases, the data is "read" out using the same electromagnet which inductively senses the magnetic fields fringing out of the media where transitions occur (see Fig. 4.2). This output voltage is therefore proportional to the relative velocity between the electromagnetic transducer, or head, and the media. The head is supported over the spinning disk on an air bearing that enables high relative velocities, and therefore, fast access to data.

Figure 4.2. Fringing fields associated with a recording pattern having 100,000 flux changes per inch, as imaged by a magnetic force microscope

Both heads and media have undergone major changes over the past decade. The media has evolved from coatings containing iron oxide particles to the thin metal films mentioned above. In the early 80's most heads consisted of ferrite cores with coils that were hand-wound. In 1981 IBM introduced a thin-film version of an inductive head. Since the cost of this new technology was high, it has taken the industry a number of years to make the transition. One of the attractive features of a thin film head is that its pole material, permalloy, has a higher saturation magnetization than ferrite and, therefore, can write on higher coercivity media, which translates to sharper transitions and higher densities. Since heads saturate at the gap, a lower cost approach to having a head with a higher saturation is to line the gap of a ferrite head with a high saturation material. The Japanese have adopted this metal-in-gap, or MIG, approach.

The thin film head has been modified more recently by the addition of a magnetoresistive (MR) material in the gap (see Fig. 4.3). The resistance of this material is sensitive to a magnetic field, in particular, the field produced by a recorded transition. This magnetoresistive effect provides higher sensitivity than inductive readout, and is therefore quickly becoming the preferred head technology for higher density drives.

Figure 4.3. Thin film head showing incorporation of MR sensors

Data Tape Drives

The second storage market with significant U.S. presence is that of data tape drives. These systems have two basic designs -linear and rotary. And among each there are two major tape formats. Linear systems have 1/2" tape, as in the IBM 3490 cartridge drive, or 1/4" tape as in the Quarter Inch Cartridge (QIC) systems. The rotary systems have evolved out of video and audio systems. There are 8mm systems, such as Exabyte, that derive from 8mm helical scan video, and the Digital Data Storage (DDS) systems based on 3.8mm digital audio technology (DAT). A 1/2" rotary technology has recently been introduced. Unlike disk systems, in tape systems the heads and media are in contact.

Optical Storage

Optical storage encompasses read-only optical systems such as the 4.72" CD-ROM, write-once systems, and erasable optical systems. In the CD-ROM systems, the data is impressed on a disk by a stamping process and read out by means of a solid state laser. This has become a popular medium for distributing system documentation and software. In write-once systems the user is provided with a medium whose state may be irreversible changed by the application of local heating by a focused laser beam. This change may be from an amorphous to a crystalline state, or it may involve actual deformation of the material by local melting. The media is typically an alloy of tellurium. The data, once created, may be read many times by a lower power laser.

The most popular technology for erasable optical storage is based on the magneto-optic effect. The medium consists of a disk coated with a magnetic film, typically a rare-earth-transition metal alloy, whose magnetization is perpendicular to the plane of the disk. Writing is done by locally heating the medium in the presence of a biasing magnetic field. The heating allows the magnetization within the laser spot to orient itself, up or down, in response to the bias field. Read-out is accomplished by measuring the change in the polarization of a laser beam upon reflection from the disk. If the direction of the magnetization is "up" the polarization is rotated one way, if it is "down" it is rotated the opposite way.

Since these optical systems all employ laser beams, one does not have the very close "head-to-disk" spacing problem faced by magnetic recording systems. Therefore the media may be removable and interchangeable, a distinct advantage.

METRICS

The objective of this study is to benchmark the U.S. storage industry against its Japanese competition. The primary metrics we shall use for this will be the product specifications:

- areal density in Mbits/in²
- linear density in bits/in (BPI)

- track density in tracks/in (TPI)
- data rate in Mbits/sec

Areal density is the basic figure-of-merit for magnetic recording and measures the efficiency in using the storage area.

Linear density measures how close the magnetic transitions can be spaced. To achieve sharp transitions requires higher coercivity media, which, in turn, requires heads with a higher saturation magnetization. High linear densities also require lower flying heights.

Track density is a measure of how well one can position the head. High track densities also imply narrower tracks which mean less signal and more off-track noise, all of which presents more challenges to the signal processing, and a demand for lower noise media.

Data rate is a combination of the linear density and the rotational speed of the drive. Higher data rates mean greater noise and resultant higher error rates associated with the increased band width. To handle this reduced signal-to-noise ratio requires more sophisticated coding and error correction.

These four metrics apply to all the storage devices we are discussing. There are also additional metrics that apply to the specific types of storage systems. For hard disk drives the **flying height** is becoming a very critical parameter that reflects one's ability to master interface tribology.

For tape systems we might add the **search speed** as an additional metric.

As these definitions indicate, collectively, they measure the level of control that a company, or country, has over the five fundamental technology areas:

- heads
- media
- head/disk interface
- data recovery
- servo

ANALYSIS

Leaders

As a source of data for **hard disk drives** we took the 1993 Disk/Trend Report compiled by James Porter and Robert Katzive. This data was sorted to distinguish between U.S. and Asian manufacturers. From the resulting database the various drive characteristics were compared by using scatter plots to indicate comparative trends. Since the 3.5" product has the largest volume in the market, it was used as the basis for comparison.

The linear densities and track densities are shown in Fig. 4.4. The bit density comparison suggests that the U.S. is slightly more aggressive on BPI than its Asian competitors.

The track density comparison shows that although the US had higher track densities in the past, the Asian drives are now comparable to the U.S.

In Fig. 4.5 we show the resulting areal density and the manifestation of this density on the total capacity of a 3.5" drive. The U.S. lead in linear density gives it the lead in areal density and results in more drives with higher capacities.

The data rates are shown in Fig. 4.6. The fact that the U.S. drives have higher data rates suggests that U.S. companies are more active in high performance markets. These higher data rates partially reflect the trend toward higher rotational speeds as also shown in Fig. 4.6.

Another interesting way of benchmarking the U.S. and Japan is to compare their use of thin film head technology. The charts in Figures 4.7 through 4.9 show that the U.S. made earlier use of thin film technology and is ahead of Japan in using magnetoresistive (MR) technology. However, this use is from only one company, IBM, at this point. The indications are that Asia is still trying to extend MIG technology. *Caution needs to be exercised at the extremes of the charts since the sample size may be small and not indicative of the real world.* For example, the Head Usage chart for U.S. Drives showing 100% MR in '94-95' is for only 6 drives. Again the comparison between head usage and BPI suggests that Asia is pushing MIG to higher BPI than the U.S. The U.S. is more rapidly converting to thin film technology followed by MR. For TPI, Asia shows 4 drives designed with MIG heads at 3000-4500 TPI whereas the U.S. has already made the transition to thin film or MR at those track densities. Data rate comparisons also show the U.S. pushing to higher data rates and making the shift to TF and MR earlier.

Benchmarking *tape drives* is more difficult because the media is interchangeable. This means the industry more-or-less moves forward together as standards are established. All IBM 3490-compatible cartridges, for example, have 36 tracks; the QIC Industry Association is coordinating a move from oxide media to barium ferrite media. What determines competitiveness is cost and time-to-market, and whether one can establish a standard. This latter feature is why IBM dominates the 1/2" market, and Japan the 4mm and 8mm markets.

Optical storage is dominated by the Japanese. This dominance is due to Japan's large investment in consumer products. This has allowed them to move down the learning curve on optoelectronic components such as lasers and detectors. We mentioned above that Sony has now begun to use magneto-optical technology in an audio product. There are 29 Japanese companies involved in optical storage, while there are only 11 U.S. companies.

Figure 4.4. Bit and track density

Figure 4.5. Areal density and storage capacity

Figure 4.6. Data rate and RPM

Head Usage vs Year (U.S. Drives)

(Sample=186, 3.5" Drives/'93 DiskTrend)

Head Usage vs Year (Asian Drives)

(Sample=101, 3.5" Drives/'93 DiskTrend)

Figure 4.7. Head usage vs. year

Head Usage vs BPI (U.S. Drives)

(Sample=186, 3.5" Drives/'93 DiskTrend)

Head Usage vs BPI (Asian Drives)

(Sample=101, 3.5" Drives/'93 DiskTrend)

Figure 4.8. Head usage vs. BPI

Head Usage vs TPI (U.S. Drives)

(Sample=186, 3.5" Drives/'93 DiskTrend)

Head Usage vs TPI (Asian Drives)

(Sample=101, 3.5" Drives/'93 DiskTrend)

Figure 4.9. Head usage vs. TPI

Technology Roadmaps

Anyone who has visited a Japanese company comes away with a technology roadmap—a ten or twenty year outlook as to which technologies will be important over that time frame. A typical example is shown in Fig. 4.10. This is Fujitsu's view of high-density magnetic recording (from Yoshima Miura, "Advances in Magnetic Disk Storage Technology"). These types of diagrams are very similar from one Japanese company to another.

Figure 4.10. Fujitsu's view of expected progress in hard disk technology. "Step" refers to product generation.

The U.S. recording industry, through the National Storage Industry Consortium (NSIC) has also established a technology roadmap. Both U.S. and Japanese roadmaps show that "maximum likelihood sequence detection" will be used. And both show the introduction of magnetoresistive sensors. One major difference between the two is when perpendicular recording will be introduced. Japanese roadmaps show perpendicular recording appearing at much lower areal densities than U.S. roadmaps.

Concern over the U.S. competitiveness in optoelectronics led, in 1991, to the formation of the Optoelectronics Industry Development Association (OIDA). The major activity of this group has been the development of a technology roadmap. The interesting feature of this roadmap is that it shows magneto-optic technology displacing CD-ROMs. Sony has already introduced a magneto-optical product, the MiniDisc, into the consumer audio market. However, magneto-optic recording still does not readily allow direct overwrite. It is likely to require several generations before an acceptable standard is established.

There has been a good deal of discussion about holographic storage in the popular press lately. But there are still many details to be worked out. The OIDA roadmap shows that holographic storage will be entering the market sometime after the year 2003.

BUSINESS AND STRATEGIC FACTORS

If one were to make a judgment on the data presented above, one would say that the U.S. has a technological edge in disk drives. However, technology alone is not enough to ensure a competitive advantage. One of the major factors affecting success is *timing*, knowing *when* to adopt a particular technology. The U.S. move to thin film head technology, led by IBM was a wise move because of the ease with which one can now introduce magnetoresistive sensors. An example of poor timing is Dysan, who was the premier oxide disk vendor in the 70's and early 80's. Dysan missed the transition to thin film media and has gone out of business. The changing form factors have also represented opportunity for the U.S. But, within the U.S., individual companies have not always timed their production well. CDC, for example, which owned 70% of the 14" disk drive market, missed the transition to 5.25" drives. Even Seagate which introduced the 5.25" drives, missed the transition to 3.5" drives led by Conner Peripherals.

Another factor has to do with investment. The margins in the storage industry have become extremely small. As a result, there is less investment in longer range research. Fortunately, over the last five years, the industry has joined together to support and encourage university research. There is a strong supply of well trained young people entering the field. And, as we mentioned, the industry has established a consortium, the National Storage Industry Consortium (NSIC), which has developed a technology roadmap, and facilitates the exchange of technical information.

TRENDS

The most interesting trend in *hard disk* recording is the increase in the slope of the areal density as a function of time. This is the result of the aggressive introduction of new technology, such as thin film media and magnetoresistive (MR) heads. This trend is likely to continue. One contributing factor to this increase will be the use of giant magnetoresistance (GMR). Just a few years ago, it was discovered that the magnetoresistance of a sandwich of two magnetic films was dramatically different depending upon the relative orientation of the magnetization in the two films. Thus, if the magnetization in one of the films is "pinned" while that of the other is free to be oriented by an external magnetic field (see fig. 4.3), the resistance of the sandwich may change by as much as $\Delta R/R = 10\%$ in a field as small as 10 oersteds. Because it is thought that the antiparallel magnetization confines the current flow through the spin at the electrons, these are called "spin valves". This new discovery has the promise of providing heads with much greater sensitivity than the current MR heads.

In the hard disk market, technology is becoming the critical element. The future leaders will be those who master GMR heads, contact recording, and enhanced data detection codes/high data rates.

The trend in *data tape storage* is also to higher storage densities, particularly for the linear systems as they move to servoed heads.

The OIDA roadmap also shows that the density of *optical storage* will increase by as much as 32X in the future. This would be accomplished by using edge encoding, "super-resolution", and by introducing green and blue lasers.

SUMMARY

The data storage industry is growing rapidly. This growth is being driven by new applications for digital data as well as new technology. The U.S. has strong positions in some sectors of this industry (see comparison chart, Table 4.1). But there are two trends that could threaten this position. One is a cutting back on research by U.S. companies. The other is the trend to manufacture in Asia. This will ultimately undermine the manufacturing infrastructure in the U.S., weakening our ability to commercialize the technologies now being developed in our universities.

Table 4.1
Japan Compared to U.S. in Storage Technologies

	Research	Development	Production
Hard Disk Drive			
5.25"		0	0
3.5"		0	-
2.5"		0	-
1.8"		0	-
Heads	-(GMR)	-(GMR)	-(MR)
Media	-(SmCo)	0	+(Fuji, Showa Denka)
Data Tape Drives			
Linear-1/2"	-(IBM)	-(IBM)	-(IBM)
Linear-1/4"	-(QIC)	-(QIC)	-(QIC)
Rotary-8mm	+	+	+
Rotary-4mm	+	+	+
Optical Storage			
Media	0	+	+
Lasers	-(short l)	+	+

Legend:

+ = Japan ahead
0 = even
- = U.S. ahead

5. Optoelectronics

W. T. Tsang
AT&T Bell Laboratories
Murray Hill, NJ 07974

INTRODUCTION: JAPANESE EXPECTATIONS

In a report prepared in May 1994 by the Telecommunications Council of Japan for the Ministry of Posts and Telecommunications (MPT) forecasts that by the year 2010 it will be possible to use a nationwide fiber-optic network for broadband, interactive communications. The multimedia market is expected to surpass current mainstay industries such as the automobile industry both in terms of sales and employment. Optoelectronic industry is expected to become a new Japanese leading industry. Such optimism is reflected in the estimation of the multimedia markets by 2010. New markets related to fiber-optics networks are expected to reach ¥56 trillion; existing multimedia markets total ¥67 trillion. Thus the total market in 2010 is estimated at ¥123 trillion, with approximately 2.43 million jobs to be created through the construction of fiber-optic networks. A further breakdown of the new markets related to fiber-optics network is given in Table 5.1

The percentages of Japanese GNP and jobs created by the multimedia market, compared with other major Japanese industries, are shown in Table 5.2 and Table 5.3, respectively.

Whether such numbers really bear out or not in the future is not as important as the fact that the Japanese genuinely believe that optoelectronic industry will penetrate widely and deeply in Japan as a whole new key industry in the 21st century.

Such belief led to the present proposal of building a complete "Info-Communications Infrastructure," as it is called, in Japan by 2010. This is in a way similar to the "Information Highway" proposed in the United States, but appears to be much broader according to the Japanese definition. They define this Info-Communications Infrastructure as "a comprehensive entity that encompasses network infrastructures, terminals, software applications, human resources, public and private info-communications systems, as well as social value and lifestyles related to the information of society."

Table 5.1: Multimedia Markets
(approximate values at 2010 prices -- ¥ billion)

Market Area	1995	2000	2005	2010
Terminal	55.4	1,121.5	3,894.8	5,240
Network Operation	11.9	686.5	4,879	13,706.2
Database Service	0.9	51.5	301.8	821.1
Program Distribution	0.9	59.1	756.3	1,458
Tele-Shopping	0	0	1,919.4	5,697.1
Electronic mail publications	0	11.8	757.1	2,460.7
Entertainment Software	0.1	25.4	973.4	3,515.3
Education Software	0.1	20.3	1,233	6,116.5
Other Components	43.3	1,155.5	6,623.9	16,053.9
Total	112.6	3,131.6	21,338.7	56,068.8

Table 5.2
Optoelectronic Industry as Percentage of Japanese GNP

Industries	Production (¥ billion)	% of GNP
Automobile (1990)	39,981.6	4.59%
Electronics, Communications (1990)	26,680.3	3.06%
Consumer Electronics (1990)	4.0	0.7%
Multimedia, Total (2010)	123,000	5.46%

Table 5.3
Jobs Created Through Fiber-Optic Network Constructions

Industries	Employment (millions)	% of National Employment
Automobile (1990)	13.5	2.2%
Electronics, Communications (1990)	9.4	1.5%
Consumer Electronics (1990)	4.0	0.7%
Fiber-Optic Network (2010)	24.3	3.6%

On the other hand, according to the Japanese Optoelectronic Industry and Technology Development Association (OITDA) forecast, which may not have included a multimedia program as ambitious and far-reaching as the above recommendation by the Telecommunications Council of Japan, the optoelectronic industry production will be about ¥15 trillion by the year 2000, of which ¥3.2 trillion will be optoelectronic components and ¥12 trillion will be optoelectronic equipment. By the year of 2010, they estimated the total production will be about ¥35 trillion. This forecast is substantially smaller than the ¥123 trillion forecasted by the Telecommunications Council. Nevertheless, OITDA agrees that optoelectronic industry will be a key Japanese industry in the 21st century.

PRESENT STATUS OF JAPANESE OPTOELECTRONICS INDUSTRY

While all key industries in Japan are suffering economic stagnation in 1993, the optoelectronic industry continued to grow in the area of optical communications systems and optical disks based on semiconductor lasers, optical fibers, optical recordings and other technologies. According to the Japanese OITDA, total industry production for fiscal 1993 (ended March 1993) is ¥3,785 billion, a 7.9% (278 billion) increase over the previous fiscal year. The two main categories are optoelectronic components (up 13% to ¥976 billion) and optoelectronic equipment (up 6.4% to ¥2,809 billion). Table 5.4 shows a detailed breakdown of the various segments of optoelectronic markets and their percentage growth relative to 1992. Optoelectronic equipment represents 74% of the entire market, while optoelectronic components represent 26%. Optoelectronic equipment production rose 6.4% due mainly to the increased demand for optical disks, I/O, and transmission equipment. Optoelectronic components production rose 12.7% due to growth in display devices, optical fibers, and optoelectronic transmission links.

Table 5.4
Production Scale of the Japanese Optoelectronic Industry

In millions of yen.

Product item		1992 FY Production	1993 FY Production forecast	Growth rate
Optoelectronic Equipment	Optical telecommunication equipment	204,585	244,619	19.6
	Optical measuring instruments	24,146	24,691	2.3
	Installation equipment	9,639	10,157	5.4
	Optical sensors	98,851	100,499	1.7
	Optical disk equipment	1,405,377	1,489,710	6.0
	Digital audio disk players	507,095	473,044	-6.7
	Video disk players	137,598	152,458	10.8
	CD-ROM units	59,981	119,562	99.3
	Write-once optical disk & rewritable optical disk equipment	61,111	60,506	-1.0
	Optical disks (digital audio)	454,489	498,191	9.6
	Optical disks (video)	114,825	88,304	-23.1
	Optical disks (CD-ROM)	24,657	37,066	50.3
	Optical disks (write-once, rewritable)	21,658	28,381	31.0
	Others	23,963	32,198	34.4
	Optical I/O equipment	804,872	846,202	5.1
	Printers	528,619	555,188	5.0
	Digital facsimiles machines	151,596	165,034	8.9
	Digital copiers	98,087	99,368	1.3
	Bar-code readers	15,136	15,972	5.5
	Others (array sensor applied equipment)	11,434	10,640	-6.9
	Display equipment (larger than 50")	23,968	24,314	1.4
	Medical laser equipment	2,823	2,980	5.6
	Laser processing equipment	44,356	42,134	-5.0
	CO2 laser processing equipment	26,035	22,603	-13.2
	YAG laser processing equipment	17,247	17,625	2.2
	Other laser processing equipment	1,074	1,906	77.5
	Printing & photosetting equipment	21,000	22,000	4.8
	Other optical equipment	704	1,331	89.1
	Sub total	2,640,321	2,808,637	6.4
Optoelectronic Components	Light emitting devices	140,399	138,715	-1.2
	Semiconductor lasers			10.6
	Gas lasers	42,965	47,498	-4.0
	Solid state lasers	12,004	11,525	12.0
	LEDs	3,683	4,125	-7.6
	Photo detectors (including array sensors)	81,747	75,567	3.9
	Hybrid optical devices	107,366	111,503	2.6
	Optical links	55,727	57,200	28.6
	Display devices	12,669	16,298	24.1
	LCD	385,787	478,657	26.3
	Other flat panel display devices	344,116	434,635	5.6
	Solar cells	15,560	15,710	1.0
	Optical fibers (including cable)	117,662	126,905	7.9
	Fibers for telecommunications			8.0
	Image fibers, light guides, etc.	107,287	115,833	6.7
	Optical connectors	11,510	11,524	0.1
	Optical passive devices	4,786	4,810	0.5
	Other optical components	14,869	15,055	1.3
Sub total		866,335	976,377	12.7
Total for optoelectronic products		3,506,656	3,785,014	7.9

A detailed breakdown of the optoelectronic equipment and components are shown in Figs. 5.1 and 5.2. Changes in Japanese optoelectronic industry production over the last decade is shown in Fig. 5.3.

Figure 5.1. Breakdown of optoelectronic equipment in FY 1993.

Figure 5.2. Breakdown of optoelectronic components in FY 1993.

Optoelectronic Components Semiconductor Laser, Photo Detectors such as Light Emitting Devices (LEDs), Display Diodes, Solar Cells, and Optical Fibers.
Optoelectronic Equipment Laser discs, Optical I/O Equipment (printers, copiers), Laser-Applied Production Equipment, and Laser Sensing Apparatus.

Figure 5.3. Outlook for future production in optoelectronic industries.

Optical transmission equipment production rose 19.6% (by ¥40 billion) over the previous year due mainly to growth in trunk line system equipment. Optical disk production rose 6.0% (¥84 billion). Broken down, digital audio disk players with built-in CD fell 6.7% (¥34 billion), while video disk players rose 10.8% (¥15 billion) and CD-ROM units soared 99.3% (¥60 billion). Optical disk (video disk) production fell 23% (¥27 billion), while the production of optical disks (CD-ROM) rose 50.3% (¥12 billion) and that of optical disks (write-once and rewritable) rose 31.1% (¥7 billion). A detailed market percentage breakdown is provided in Fig. 5.1.

The production of display devices grew the most at 24.1% (¥93 billion) mostly due to liquid crystal displays. Optical transmission link production grew 27.6% (¥4 billion). Optical fiber production rose 7.9% (¥9 billion). Semiconductor lasers production rose 10.6% (¥5 billion) due to increased demand for optical transmission equipment, optical disk equipment and optical printers. LED production fell 7.6% (¥6 billion) reflecting the reduced demand for LEDs used in displays. A detailed market percentage breakdown is given in Fig. 5.2.

NEW GENERATION OPTOELECTRONIC TECHNOLOGY IN JAPAN

The new generation optoelectronic technology of Japan can be categorized in four broad areas: optical communication technology, optical information processing technology, optical energy technology, and emerging optical switching technology. Japan believes optical switching will play an important role in the 21st century optical information and communication systems. However, at the current stage, the technology faces two major problems. Devices are not sufficiently identified and matured, and no system configurations have yet been completed. In other words, Japan still does not know what, how and when to do it. It may be waiting for the U.S.A. to figure it out first.

Optical information processing technology consists of the following five major technologies:

1. Optical devices for optical information processing
2. Optical memory technology
3. Optical computing technology
4. Measurement technology for optoelectronic applications
5. Image display technology

Some notable future emphases are: shortening the wavelength for small coherent light-emitting devices; image sensors for high-precision input, mainly HDTV (this required the development of microscopic technologies for CCD image pickup elements such as high pixel density and five pixel size); applying active optical elements to high-precision, high-pixel crystal panels; holographic memory; optical tape drives; stereoscopic glasses used for virtual reality; and stereoscopic images created by laser lightwave front control.

Optical energy technology mainly centers on the industrial applications of various lasers primarily power lasers. Nothing dramatic is anticipated in this area in the 21st century.

By far the most significant, far-reaching, and ambitious development that will affect every aspect of Japanese life-style in the 21st century will be optical communications technology. This technology can be further subdivided into the following:

1. High-speed optical communications technology
2. Optical subscriber systems
3. Image transmission technology
4. Optical devices and electronic circuits for communications
5. Passive optical circuits and components
6. Optical communication measurement technology

In high-speed optical communications, the technology has advanced to 10Gb/S in practical applications, and efforts have begun to standardize in SONET(OC-192). Attention is being increasingly paid to image transmission services for video on demand, network games, remote education, medical treatments and other new services. Figure 5.4 shows the Japanese view of the advancement of optical transmission technology.

Figure 5.4. Advancements in optical transmission technology

As already mentioned above, the Telecommunications Council of Japan report proposes that an "info-communications infrastructure" be built by 2010, including the introduction of fiber-optic subscriber lines throughout the country. According to the report, this plan would generate a multimedia market of ¥123 trillion and create 2.43 million jobs by the year 2010.

The basic plan is as follows:

1. Complete connecting all business facilities and homes via B-ISDN and multi-channel video lines by 2010
2. Forecasted business facilities and homes in 2010:
 - o 7 million business facilities
 - o 54 million homes
3. Forecasted total services lines in 2010:
 - o Three lines per business facility and one line per home
 - o Total 75 million subscribers by 2010

The estimated cost for building such a fiber-optic transmission and subscriber network are given as follows. Each business premise is connected to a network exchange with its own fiber-optic line employing a single-star (SS) arrangement as shown in Fig. 5.5. This consists of a 150 Mb/S bi-directional and video by WDM. For households, a single fiber-optic line is provided to a certain point and then divided to serve several households (up to 16) at the same time employing a passive double star (PDS) arrangement as shown in Fig. 5.6. This scheme consists of 1.5 Mb/S bi-directional and 150 channel video. The total estimated costs for such a network are as follows:

subscriber network	¥ 16 trillion
ATM exchanges, software	¥ 7 trillion
<u>Transmission trunk networks</u>	<u>¥ 10 trillion</u>
Total cost	¥ 33 trillion

Figure 5.5. Single star arrangement.

Figure 5.6. Passive double star arrangement.

For installing the subscriber network under ground, the estimated cost will be ¥42 trillion.

A timetable for the development of service area is proposed:

1. Year 2000: Main cities and "teletopia model cities (% of population covered: 20%)
2. Year 2005: All cities with populations of 100,000 or more (% of population covered: 60%)
3. Year 2010: Completion of nationwide network (% of population covered: 100%)

In addition, by the year 2000, a nationwide fiber-optic network should be installed connecting schools, libraries, hospitals, community halls, and other public institutions. The construction schedule is schematically shown in Fig. 5.7.

Figure 5.7. Construction schedule.

The basic Japanese principle is to establish the fiber-optic network efficiently through the competition of private companies. But the government should formulate policies to promote private investments through fair and effective competition. To reduce the financial burden of private investments, and to accelerate the progress during the initial phase, the government must consider introducing new financing systems, including interest-free loans and tax incentives promoting long-term R&D efforts, and supporting pilot model projects. To complete this discussion, Table 5.5 compares the past, present and future optical subscriber systems in the U.S.A., Japan, U.K., Germany and France. The extent of transformation of the U.S. and Japan into the information age as of 1993 is compared in Table 5.6.

Table 5.5
Development Status of Optical Subscriber Systems

Country	Development and Implementation Status
United States (BOC)	<p>Previously: Installation of remote multiple transmission systems (DLC: digital loop carrier) started in the 1980s.</p> <ul style="list-style-type: none"> • Economy of scale is easily included because of large subscriber areas. <p>Presently: (1) A field experiment started in 1988, principally by BOC, has been completed in half of the district areas.</p> <ul style="list-style-type: none"> • Eleven telephone companies conducted experiments in 46 geographical areas. • A total of 13,000 subscribers participated. • System configurations are chiefly FTTC, and services are conducted by POTS. <p>(2) Wide-band service experiments were conducted in the 1987 to 1989 time frame.</p> <ul style="list-style-type: none"> • Cerritos (CATV/VOD), Heathrow (Digital CATV), etc. <p>Projected: For now, FTTC will be installed. Migration to FTTH will be determined in the future.</p>
Japan (NTT, etc.)	<p>Previously: (1) Since the second half of the 1970s, many experiments centered on image services.</p> <ul style="list-style-type: none"> • 1978: Hi-ovis (interactive optical visual inform. Syo.) • 1981: Closed-area/dedicated systems (Kichijoji, CATV, VRS, high-speed leased lines) • 1984: INS model systems (Musashino, Kasumigaseki, TV telephone, high-speed communications, CATV, VRS, N-ISDN) • 1986: Complex systems (Marunouchi, CATV, N-ISDN) <p>(2) Commercialized installed systems</p> <ul style="list-style-type: none"> • 1982: FV-4M, FV-32M (dedicated image service) systems • 1983: Super digital system • 1987: CT/RT method • 1988: Super CAPTAIN System <p>Presently: (1) Systems for low- and high-speed optical subscribers and FDM multiple optical subscribers are under development.</p> <ul style="list-style-type: none"> (2) An ATM access system is also under development (3) Cooperation in pilot model experiment business <p>Projected: (1) A large number of systems will be installed starting in 1997. Trial tests will be performed in several areas by that time.</p> <ul style="list-style-type: none"> (2) FTTH is to be completed by 2015.
UK (BT)	<p>Previously: At the beginning of the 1980s, R&D centered on wide-band service (CATV).</p> <ul style="list-style-type: none"> • 1982: Milton Keynes experiment (videotex for 18 subscribers) • 1985: Westminster Cable Network experiment (CATV) <p>Presently: (1) The Flexible Access System (FAS) is currently being installed for large-scale users.</p> <ul style="list-style-type: none"> (2) Broadband Integrated Distribution Star, (BIDS), a hub selection CATV system, is currently being tested. (3) The Passive Optical Network (PON) experiment has been completed and commercial testing will be started shortly. (4) ATM PON R&D has been underway since 1988. <p>Projected: Full-scale installation of T-PON (Telephone PON)?</p>
Germany (DBP)	<p>Previously: (1) The BIGFON experiment (CATV, TEL, TV telephone) started around 1983.</p> <ul style="list-style-type: none"> (2) The optical overlay network experiment (high-speed wide-band service) started around 1985. <p>Presently: (1) The OPAL Project experiment (POTS and CATV services) is being conducted at six sites in Germany since 1988.</p> <p>Projected: (1) Three million subscribers are projected to be involved in optical systems by 2000.</p> <ul style="list-style-type: none"> (2) The communications infrastructure in former East Germany will be enhanced. • About 60 billion Deutsch marks will be invested 7 years to 10 years from now. • 300K new subscribers will be added in 1993, 400K in 1994, and 500K in 1995.
France (FT)	<p>Previously: At the beginning of the 1980s, R&D centered on wide-band service (CATV)</p> <ul style="list-style-type: none"> • 1983: CATV experiment in Biarritz • 1984: Plancable Project (CATV, videotex, etc., video communication, etc.) was implemented. <p>Presently: FTTB experiment was started in business areas since 1989.</p> <p>Projected: FTTC experiment start was planned for 1993.</p>

Table 5.6
Transformation to Information Society in U.S. and Japan

	United States	Japan	U.S./Japan
PC/LAN (%)	52.0	8.6	6
PC Popularity (%)	15.8	5.7	3
Database Market (billion Yen)	1,276	216	6
CD-ROM (Multimedia Datamap 1993)	~4,000	~1,000	4
CATV Facilities	11,075	400	28
CATV Subscribers (million)	57.2	1.87	31
Cellular Phones/1000 People	44	13	3

It is also interesting to include here a 1993 study summarizing a technology comparisons between the U.S. and Japan as assessed by Japan's Ministry of Science and Technology and the U.S. Department of Commerce. This is not representative of the present author's view. In fact, the present author does not quite agree with some of the assessments, shown in Table 5.7.

Table 5.7
Japanese & U.S. Government Ratings Comparing U.S. and Japan

	Ministry of Science & Tech. (Japan)		U.S. Dept. of Commerce	
	Today	Future	Today	Future
Information System Electronics:				
Product & Equipment	J	US,J	J	J
Digital Video Processing	-	-	J	J
High Density Data Storage	J	US,J	J	J
High Performance Computer	US	J	US	J
Optical Communication	US,J	J	J	J
Biochemical Science:				
Bio-Technology	US	J	US	J
Medical Equipment	US	J	US	J
Materials:				
Leading-edge Material	US,J	J	J	J
Superconductor	US,J	J	US,J	J
Manufacturing Systems:				
Artificial Intelligence	US	J	US	US,J
Computer Integrated Manufacturing	J	US,J	US	US,J
Sensor Technology	US,J	J	US	J

The status of fiberization of communication networks in terms of terrestrial fiber miles installed in the United States, U.K. and France is shown in Table 5.8.

Table 5.8
Fiberization of Communications Networks

Country	Fiber Installation (1000 km fiber)
Japan (subscribe loops)	6,510 (1,640)
U.S.A. (subscribe loops)	15,810 (---)
U.K. (subscribe loops)	2,340 (---)
France (subscribe loops)	820 (---)

The extent of digitalization of networks as of 1993 are compared in Table 5.9.

Table 5.9
Network Digitalization

Country	Digitalization of Networks
Japan	72%
U.S.A.	65%
U.K.	64%
France	85%

Cable TV subscription information from various countries as of 1993 is shown in Table 5.10.

Table 5.10
Cable Television Subscriptions

Country	% of Total Population Subscribed
Japan, potential households	19.5%
current subscribers	5.4%
USA, potential households	98%
current subscribers	61.8%
Germany, potential households	60.5%
current subscribers	38.3%
U.K., potential households	12.9%
current subscribers	2.8%
France, potential households	27.0%
current subscribers	6.4%

JAPANESE OPTOELECTRONIC INVESTMENTS, R&D, AND FUNDING

In 1990, while only 23% of Japan's optoelectronics revenues came from components (vs. equipment or systems), 60% of the R&D expenses are in components, where they amount to 10% of component revenues. Within the components, semiconductor lasers has the largest ratio of R&D expense to revenues, at 34%. The strong emphasis in Japan on optoelectronic components, especially semiconductor lasers, has led Japan to excel in this area.

The investment breakdowns in telecommunications and broadcasting are given in Tables 5.11 and 5.12, respectively.

Table 5.11
Telecommunications Investment
(¥ million)

	1990	1991	1992
NTT	1,825,121	1,886,839	1,986,000
KDD	57,000	58,718	74,400
Other major telecommunication companies	364,757	413,405	459,624
Value-added telecommunication companies	213,226	239,758	252,720
Total	2,460,094	2,598,720	2,772,744

Table 5.12
Broadcasting Investment
(¥ million)

	1990	1991	1992
NHK	62,800	56,457	67,800
Private broadcasting companies	113,169	138,388	122,630
CATV companies	49,027	65,037	72,031
Total	224,996	260,192	252,461

The average yearly increase in telecommunication investment is about 5%.

The R&D expenses for both telecommunication and broadcasting companies are given in Tables 5.13 and 5.14, respectively.

Table 5.13
Telecommunications R&D expenses
(¥ million)

	1990	1991	1992
All major telecommunication companies	284,829	295,787	315,781
(NTT, KDD)	(282,161)	(289,811)	(310,650)
New Common Carriers	(2,668)	(5,976)	(5,131)
Value-added telecommunication companies	23,397	9,066	10,713
Total	308,226	304,853	326,494

Table 5.14
Broadcasting R&D Expenses
(¥ million)

	1990	1991	1992
Private Broadcasting Companies	2,180	2,190	2,640
CATV companies	201	235	269
Total	2,381	2,425	2,909

The increase in R&D in telecommunications is about 7% from 1991 to 1992.

In 1993, the total budget of the Japanese Ministry of Posts and Telecommunications (MPT) was ¥4.9 billion, which represented only 0.5% of the entire Japanese government public works budget. In 1994, that budget is ¥5.3 billion, still a mere 0.52 % of the total budget. As a result, most of the Japanese funding in communications and optoelectronics comes from loans from Japanese development banks which totaled to ¥164 billion in 1992 and ¥230 billion in 1993. Out of the ¥230 billion in 1993, 60.0 billion were interest-free loans and 10 billion were low-interest loans. In addition to this funding, in 1993 sale of NTT

stocks created ¥1,300 billion. Thus, it is clear that major funding does not come directly from yearly governmental budgets.

SUMMARY

This is a preliminary, brief report on the present status, future plans, investments, R&D and funding sources for optoelectronic technology and industry in Japan. It is intended to serve as a point of comparison for U.S. activities in this area. The Japanese believe in, and plan to work towards, a nationwide fiber-optic network for broadband, interactive communications by the year 2010. They foresee that the multimedia market is going to surpass current mainstay industries such as the automobile industry, both in terms of sales and employment. Optoelectronics is expected to become a new Japanese leading industry in the 21st century.