RCA Engineer

Vol. 29 No. 2 Mar./Apr. 1984

MANUFACTURING

Cover photograph © 1984 Dave Repp

Manufacturing is massive and dynamic.
Our cover shows assembly line 10 at Bloomington, Indiana, where the RCA 19-inch color television set is assembled. The woman in the foreground stands at the beginning of the line, which stretches into the distance. She is putting the receiver chassis into the set. Other operations down the line include installation of a tuner assembly and keyboard assembly. Behind the photographer, an elevator delivers product from the lower level, where the picture tube and the cabinet are assembled before they go to line 10. Tickets attached to the sets allow manufacturing specialists to check performance data and permit troubleshooting. A daily computer tabulation is kept and cross-referenced by set serial number.

Jim Chrena, Administrator, Technical Training, Bloomington, and a photographer himself, spent the lion's share of time directing events that led to this issue's cover. Ben Borman, RCA Consumer Electronics Division Vice-President, Manufacturing, contributed the back cover photos. In addition, CE Editorial Representative Larry Olson, along with CE's Jack Drake, Len Schneider, Frank McCann, Judy Fleming, Malcolm Cobb contributed time, ideas, and photographs that helped us present this array of CE manufacturing images. Our thanks also to Frida Schubert, New York, for her assistance.

—MRS

RCA Engineer

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• To disseminate to RCA engineers technical information of professional value • To publish in an appropriate manner important technical developments at RCA, and the role of the engineer • To serve as a medium of interchange of technical information between various groups at RCA • To create a community of engineering interest within the company by stressing the interrelated nature of all technical contributions • To help publicize engineering achievements in a manner that will promote the interests and reputation of RCA in the engineering field • To provide a convenient means by which the RCA engineer may review professional work before associates and engineering management • To announce outstanding and unusual achievements of RCA engineers in a manner most likely to enhance their prestige and professional status.

J.L. Miller

Innovative manufacturing means higher quality, lower cost

In journals as well as at current manufacturing, engineering, or business meetings, increasing interest is centered on the status of manufacturing in this country as compared with other societies.

The challenge is to produce goods of ever higher quality at ever lower cost. Innovative manufacturing approaches are necessary to maintain a competitive position in established products. In view of the complexity, tight tolerances, and small dimensions required for future products, this requirement becomes even more important. Increasingly the determining factor in new-product success is the ability to manufacture that product effectively.

Many U.S. companies making a variety of products, from automobiles to semiconductors, are implementing significant changes in their operations. The pattern that constantly emerges is a need for close cooperation and interaction among departments. Major changes in one segment without complementary changes in others will produce low or sometimes negative returns. Therefore, such factors as design for assembly, automatic assembly and test, statistical process control, factory information systems, Just-In-Time materials, and RCA/vendor interaction all become key and complementary to major improvements in manufacturing.

RCA has been at the forefront of new-product innovation and development for years. To maintain a leadership position, technical resources are increasingly being directed to the development of advanced manufacturing systems. The establishment of a Manufacturing and Materials Research organization at the David Sarnoff Research Center and the formation of advanced manufacturing efforts at division satellite laboratories attest to RCA recognition of these needs.

This issue of the *RCA Engineer* touches on some of the developments aimed at manufacturing improvement.

James L. Miller
Staff Vice-President,
Manufacturing and Materials Research,
RCA Laboratories

RCA Engineer

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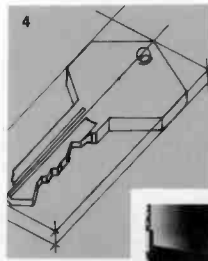
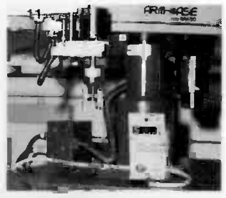
in this issue ...
manufacturing

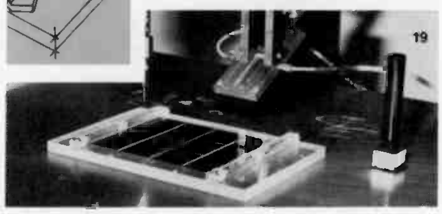
■ **Cobb:** *"Research has shown . . . that assembly costs are fundamentally established in product design."*

■ **Aceti/Carroll:** *"This project would become the first large-volume robotic assembly system within RCA."*

■ **Baldo:** *"This paper describes the research that established the robot as a development tool, and includes a brief discussion on its production line implementation as a major goal."*



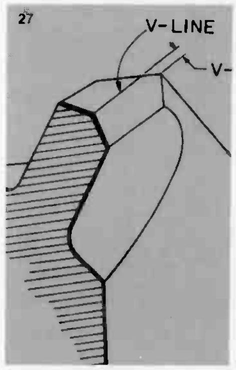


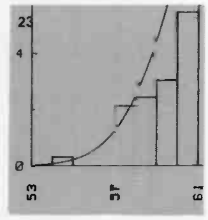


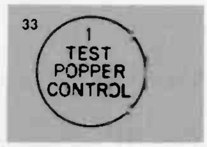
■ **Bennett, *et al.*:** *"The incorporation of statistical process control in the manufacturing operation has generated a better understanding of what makes the product work."*

■ **Coleman/Stein:** *"The activities and benefits described here are but a fraction of the successful work using statistical production engineering techniques carried out by the people at RCA's VideoDisc cartridge plant."*

■ **Gaylord:** *"A Factory Information System (FIS) is used to collect data, convert it to information, and communicate the information to people so they can use it to make decisions."*







■ **Platt:** *"Production control need only make a small change to its view of manufacturing in order to take advantage of the cycletime-enforcing mechanism in an Aggregate Inventory Management system."*

■ **Hakala/Wierschke:** *"Contaminant control has to be approached as if the part were a large semiconductor circuit wafer rather than a modified audio stamper."*

■ **Kleppinger:** *"The use of a laser-defect scanner to detect particles on silicon wafers has brought a new dimension to the evaluation of LSI process and equipment."*

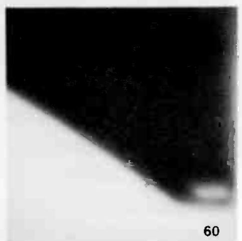
■ **Gale/Covey:** *"With some knowledge of the geometry under study, dimensional information well below the classical resolution limit can often be obtained . . . ."*

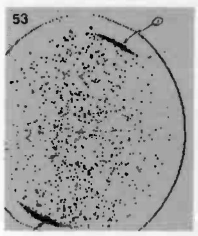
■ **Doerschuk/Moscony/Weber:** *"For very high resolution masks, a novel etch-tank modification is used . . . ."*

■ **Arnold:** *"The management believed that there were real rewards to be gathered if RCA could release the quality and productivity ideas that we were confident were present in the workforce."*

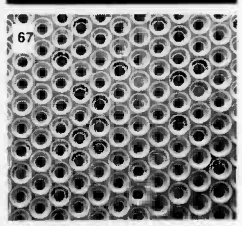
■ **Alexander/Riggs:** *"Just-in-Time prescribes no single methodology or technique."*

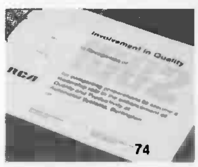
■ **Hotmire:** *"An effective and efficient method of handling the large amount of variable measurement data . . . has been determined."*





80 **Just-in-time**





82 **Satisfying the need**

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in future issues...
automating the engineer's workplace,
technical excellence,
materials technology

M.F. Cobb

Design-for-assembly is the key to increased productivity

A new software system provides the design engineer with an effective method for incorporating into the product design the requirements for efficient assembly.

In our society, manufacturing is the major contributor to the wealth-producing activities that establish our standard of living. Recently, other countries seeking to raise their standard of living have begun to effectively compete with the U.S. in a world market. Studies of these new competitors show that manufacturing productivity is a key indicator of a nation's ability to compete.

Historically, productivity has been increased through innovation, price increases, and large investments in capital equipment; however, in recent years, increased competition has limited price increases, and higher interest rates have diminished returns from capital. The most innovative product with the most up-to-date manufacturing methods will not attain its profit goals if it cannot be efficiently manufactured.

Abstract: *In a competitive market such as consumer electronics, companies can no longer afford the lost profit opportunities and low productivity resulting from redesign cycles required to correct assembly problems. Research has shown that 70 percent of the product's cost is determined during design and only 20 percent during actual production. In other words, to achieve maximum productivity, design and manufacturing must be considered as one continuous process. The task then is to blend advanced technology—and the creative efforts of the design and manufacturing engineer—into the new product, without sacrificing time to market. To assist in this effort, a system called "Design for Assembly" or "UMASS" has been developed by Dr. G. Boothroyd and his associates from the University of Massachusetts, in collaboration with the University of Salford Industrial Center in England. This paper is a brief discussion of this "Design for Assembly" system.*

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Reprint RE-29-2-1

Many companies, recognizing the diminishing returns of conventional productivity-improvement remedies, have placed greater emphasis on the study of assembly. Traditionally, assembly problems have been regarded as product oriented, to be solved during the production process. Research has shown, however, that assembly costs are fundamentally established in product design.

In general, the ease with which a product is assembled is dependent upon communication between design engineers (in different disciplines) and manufacturing. Ineffective communication, absence of guidelines, and the design engineers' lack of manufacturing experience can create serious manufacturing problems. As a result, productivity suffers and profit goals are compromised.

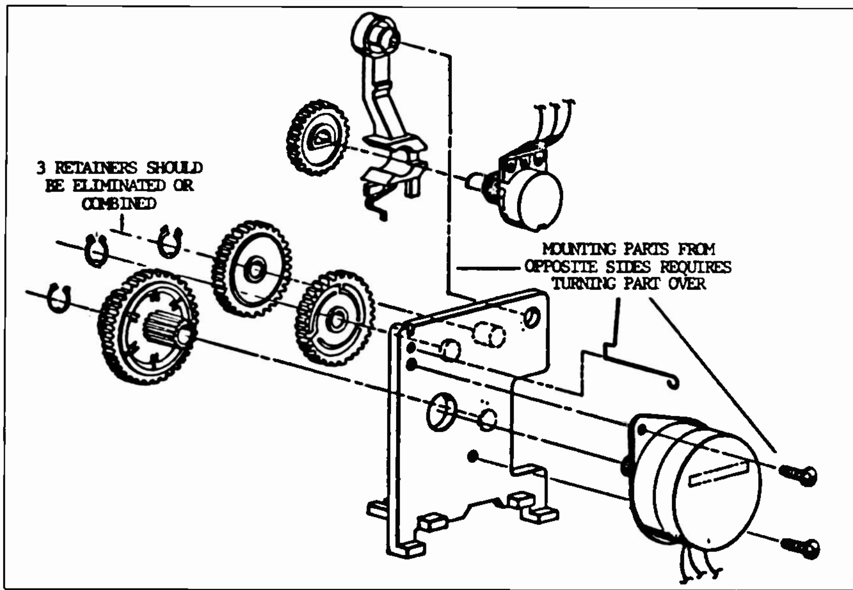
In an attempt to eliminate these problems within the VideoDisc player, RCA Consumer Electronics' Manufacturing Technology was given the responsibility of working in concert with Design to provide information that would result in a player that would:

- Provide the necessary function at the lowest cost;
- Be compatible with the manufacturing system;
- Assemble easily; and
- Achieve high "first-pass" yields through manufacturing.

To achieve these goals, everyone involved needed to know the requirements for effective assembly early in the design cycle. However, because of the vast amount of information involved in manufacturing, it was difficult to develop *comprehensive* assembly guidelines for design. Consequently, an inordinate amount of time could be spent in meetings defining assembly requirements on a part-by-part, assembly-by-assembly basis.

The "Design for Assembly" program

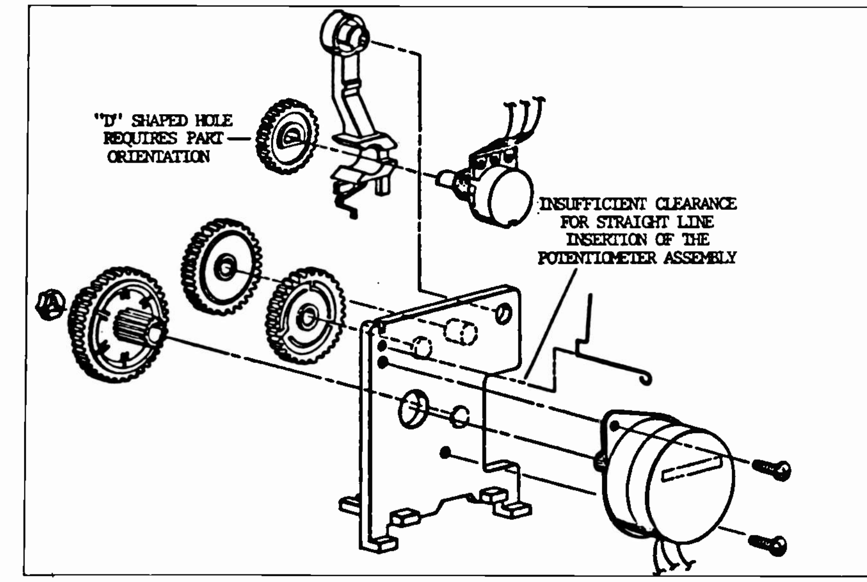
During this time, we became aware of a system called "Design for Assembly," or "UMASS," developed by Dr. G. Boothroyd at the University of Massachusetts under a grant from the National Science Foundation. "Design for Assembly" is the result of approximately 15 years of research at the University of Massachusetts, in conjunction with the University of Salford in England. Recently, the UMASS system has been developed into a series of six interactive microcomputer software programs compatible with the IBM Personal Computer in a 128K configuration. Before getting into the actual details of the system, I would like to relate a recent example as an illustration of the system's potential value.



		AUTOMATIC ASSEMBLY	MANUAL ASSEMBLY
ASSEMBLY EFFICIENCIES, %		3	22
WORK-STATIONS	MANUAL	2	5
	TOTAL	9	5
COSTS PER ASSEMBLY (CENTS)	HANDLING, INS'N ETC.	35.06	36.94
	BASIC MACHINE	12.6	7
	OPERATOR & SUPERVISOR	20	-
	TOTALS	67.66	43.94
TOTAL ASSEMBLY TIME, S		-	92.35

NUMBER OF DIFFERENT OPERATIONS = 9
TOTAL NUMBER OF PARTS = 12
THEORETICAL MINIMUM PARTS = 10
REQUIRED ASSEMBLY RATE = 3

Fig. 1. *Arm-drive gear assembly and related UMASS analysis summary. Failure to achieve the theoretical minimum number of parts is the main determinant for further analysis.*



		AUTOMATIC ASSEMBLY	MANUAL ASSEMBLY
ASSEMBLY EFFICIENCIES, %		3	26
WORK-STATIONS	MANUAL	1	4
	TOTAL	8	4
COSTS PER ASSEMBLY (CENTS)	HANDLING, INS'N ETC.	24.12	27.94
	BASIC MACHINE	11.2	5.6
	OPERATOR & SUPERVISOR	20	-
	TOTALS	55.32	33.54
TOTAL ASSEMBLY TIME, S		-	69.85

NUMBER OF DIFFERENT OPERATIONS = 9
TOTAL NUMBER OF PARTS = 10
THEORETICAL MINIMUM PARTS = 9
REQUIRED ASSEMBLY RATE = 3

Fig. 2. *Gear assembly as released to production, incorporating some UMASS recommendations that reduced assembly time by 22 seconds, but did not achieve the theoretical minimum parts count.*

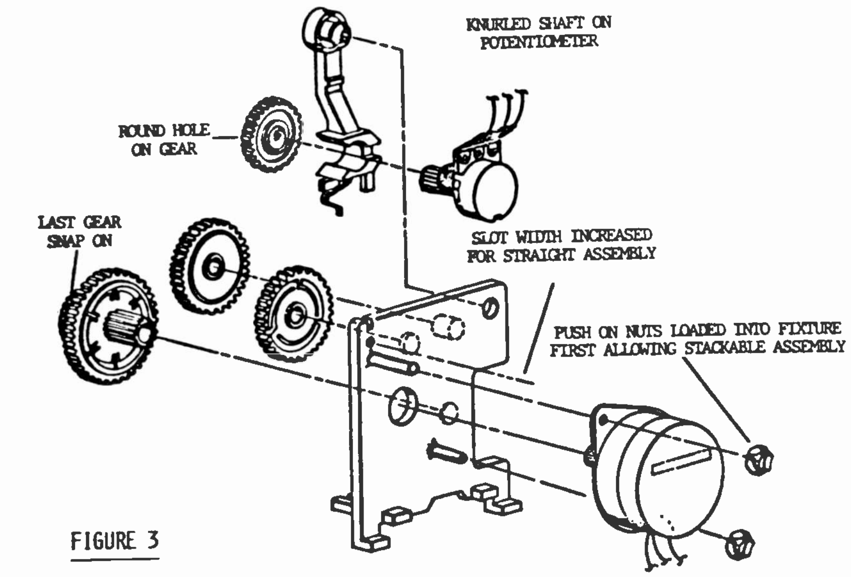
Design for assembly and robotics

During the development of the 1983 VideoDisc player, the arm drive (Fig. 1) was identified as a mechanism having high potential for assembly by robotics. To enable the robot to achieve the desired output, engineers from Manufacturing Technology, Product Design, and RCA Laboratories, made several recommendations for simplifying the assembly. Figure 2 is the assembly as released to production, incorporating a few of the recommendations. The changes eliminated two retainers and substituted a push-on nut in place of the third retainer, resulting in major improvements in the ease of assembly. These studies and recommendations required approximately 300 person hours and $6,000.00 in tooling costs.

To evaluate the "Design for Assembly" system, we requested Dr. Boothroyd's analysis of the arm drive assembly (Fig. 1). The results were impressive. Dr. Boothroyd's recommendations closely paralleled our previous studies, but required only 12 hours, instead of 300 hours. Further, if either study had been performed at the design-concept stage, the $6,000.00 die cast tool, and related ECN and print change costs would not have been required.

Accompanying Dr. Boothroyd's recommendations was a software analysis and summary of results. This summary, with its assignment of relative measurements to design parameters, amplifies the value of the "Design for Assembly" system.

The analysis summaries shown with the assembly drawings can be used to compare design alternatives. They provide direction for achieving the lowest-cost assembly. Figure 3 is the gear assembly modified using the suggestions and recommendations



		AUTOMATIC ASSEMBLY	MANUAL ASSEMBLY
ASSEMBLY EFFICIENCIES, %		5	52
WORK-STATIONS	MANUAL	1	2
	TOTAL	7	2
COSTS PER ASSEMBLY (CENTS)	HANDLING, INS'N ETC.	16.29	13.77
	BASIC MACHINE	9.8	2.8
	OPERATOR & SUPERVISOR	20	-
	TOTALS	46.09	16.57
TOTAL ASSEMBLY TIME, S		-	34.43

NUMBER OF DIFFERENT OPERATIONS = 8
TOTAL NUMBER OF PARTS = 9
THEORETICAL MINIMUM PARTS = 9
REQUIRED ASSEMBLY RATE = 3

Fig. 3. *Recommended gear assembly achieving a stackable assembly and the theoretical minimum number of parts. The parts count was reduced by three and assembly time was reduced by 58 seconds.*

within the design-for-assembly guidelines. For all studies, the lever and potentiometer were considered as pre-assembled. Combining the three summaries in Fig. 4 illustrates the potential value that can be achieved by simplifying the assembly and eliminating parts. The savings shown are significant and achievable. These savings, if initiated in the original design, could be realized without capital investment, and without pilot runs, prototypes, or time-consuming group discussions.

Use of the system

This is not meant to imply that the software is creative. Rather, it is an easy-to-use interactive system that forces the designers to systematically review and consider each part in an assembly as to need, geometric relationship, ease of handling, and method of assembly. By assigning relative quantified values to criteria such as design efficiency, assembly time, and the theoretical minimum number of parts, the system provides direction to improve assembly and shows the relationship between a product's ease of assembly and its cost. In this sense, the software encourages the designer to be as creative as possible in examining the best options.

The six software programs are independent and can be used in any sequence; however, the procedure illustrated below is possibly the most time efficient:

Tips & practice

- Become familiar with design alternatives

↓

Design for automatic assembly

- Achieve discrete part reduction
- Achieve layered assembly
- Simplify part mating to require the fewest degrees of part rotation
- Provide part locators to reduce assembly time

↓

	No. parts	Manual assembly efficiency (%)	Assembly time (sec)	Relative % cost reduction	Increase pieces/ hour	Productivity (%)
Arm drive 1 Gears retained with 3 snap retainers	12	22	92.35	BASE	40	BASE
Arm drive 2 Gears retained with (1) locknut	10	26	69.85	24	52	+ 30
Arm drive 3 3rd reduction designed for snap-on Pot gear redesigned to eliminate end-to-end orientation Mounting bracket cutout enlarged to allow perpendicular insertion of the lever & pot assembly Changed sequence of assembly loading pushnut into fixture first—achieving a stackable assembly	9	52	34.43	63	105	+162

Fig. 4. *Comparison of the three summaries, illustrating the main factors relating to reduced product cost and showing a potential gain in productivity of 162 percent.*

Assembly system economics

- Test the assembly to determine the most economical method of manufacturing

Either design for manual assembly . . .

- Optimize part geometry for manual assembly

Or design for automatic handling . . .

- Optimize part geometry for feeder design
- Estimate cost of automatic part-handling equipment
- Estimate cost of part-insertion equipment

Machine simulation

- Evaluate the effect of part quality on machine downtime
- Determine optimum buffer size
- Determine optimum number of support operators

Tips and practice

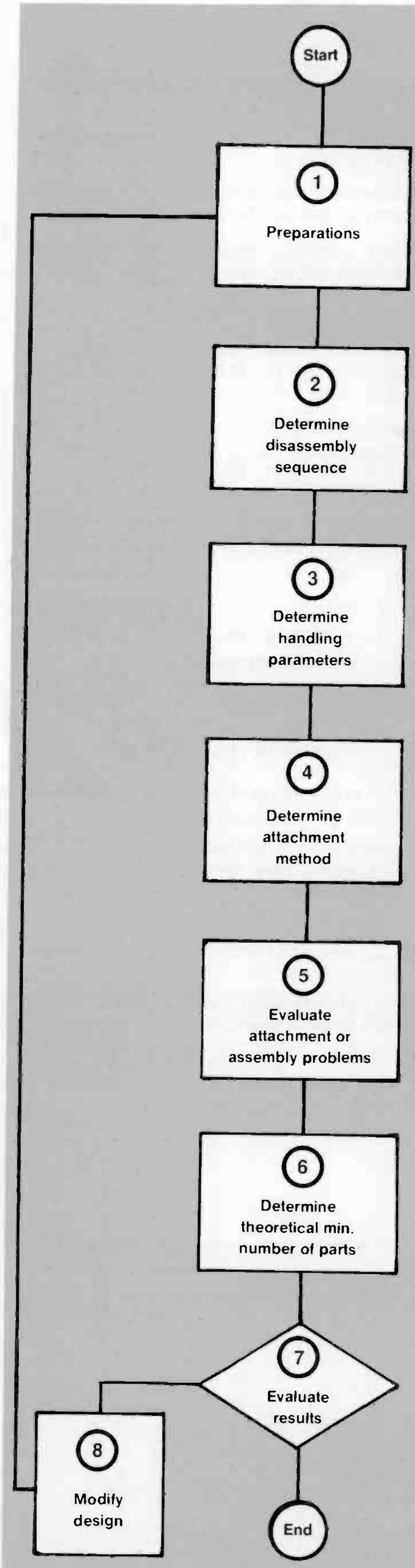
In this program, the user is provided tips to assist in assessing the features of individual parts for automatic handling. In addition, sample parts with a variety of geometric shapes for which part-handling codes have been determined are displayed. The user is then tested for selection of significant feature determination and part-size envelope. A pass/fail grade is displayed at the end of each attempt. This testing and prompt feedback assists the user in gaining familiarity and confidence with the methodology used in the "Design for Automatic Assembly" program.

Design for Automatic Assembly

This is the main program to be used for optimizing a product for manufacturing. The actual procedure for analyzing a product is relatively straightforward, as all inputs are the result of prompt statements and interactive screen displays. The flow chart (box) illustrates the procedure, and highlights the important elements in each step.

During execution, the program will determine for each part its general fastening method, geometric part relationship to insertion axis, physical size, envelope shape, amount of symmetry or asymmetry, potential handling or feeding problems, and poten-

"UMASS" design for automatic assembly procedure



1. Concept drawings, final drawings, assembly drawings, sample parts, exploded three-dimensional views, and if possible, prototype
2. Determine disassembly sequence, and enter the part names and number of parts in their sequence of disassembly
3. Evaluate each part geometrically for:
   (a) Handling
   (b) Feeding
   (c) Orienting
4. Determine method of attachment:
   (a) Screwing
   (b) Riveting
   (c) Snap fit
   (d) Bending or crimp
   (e) Bulk deformation
5. Evaluate each part attachment or fastening method for assembly insertion problems due to:
   (a) Alignment
   (b) Obstructions
   (c) Nonlinear motion during insertion
   (d) Resistance to insertion
6. Determine theoretical minimum number of parts. Parts should be combined unless:
   (a) They move during the assembly operation
   (b) A different material is required
   (c) They are required for assembly of other parts
7. Review and evaluate results printout for:
   (a) Cost
   (b) Minimum number of parts
   (c) Assembly efficiency
8. Use subprograms as necessary
   (a) Part design for automatic handling
   (b) Provide part locators
   (c) Quantity of parts reduction

Table I. *Basic assembly systems description.*

Code	Description
MA	Manual assembly using an in-line free-transfer machine with one buffer space between each manual work station.
MM	System MA, with mechanical assistance provided for the operators in the form, for example, of parts presentation devices.
AI	Indexing of synchronous automatic assembly machine; a rotary machine with six or fewer work stations, otherwise an in-line machine.
AF	In-line free-transfer or nonsynchronous automatic assembly machine with optimum buffer storage space for work carriers between each work station.
AP	In-line free-transfer or nonsynchronous assembly machine with robot work stations and parts presented in hand-loaded magazines; the number of work stations and the number of parts assembled at each station determined by the required assembly rate; the complexity of robots (three to six degrees of freedom) determined by the number of operations to be carried out by each robot.
AR	Two robot arms, each with six degrees of freedom sharing one work fixture; the parts presented in hand loaded magazines.

tial insertion problems due to obstructions or nonlinear assembly motions. From this information, the program determines relative values for assembly time, equipment cost for automatic and manual assembly, design efficiency, and the theoretical minimum number of parts.

The unique program capability to predict a *theoretical minimum number of parts* for a design is an important part of the UMASS system. Following considerable study, the approach adopted was that separate parts should be combined into one part, unless one of the following criteria are met:

1. Because the part *moves* during the operation of the assembly, and the movement cannot be achieved through a combination of parts in a flexible material.
2. Because a *different material* is required or because the part must be *isolated* for insulation purposes, and so on.
3. Because the part must be *disassembled* or because it must be separate to allow *assembly* of other parts.

It is important at this point in the program that the designer not be concerned with technical feasibility, but with identifying potential parts for elimination. For example, referring to Fig. 1, the three gear retainers are not justified by any of the three criteria and therefore should be eliminated.

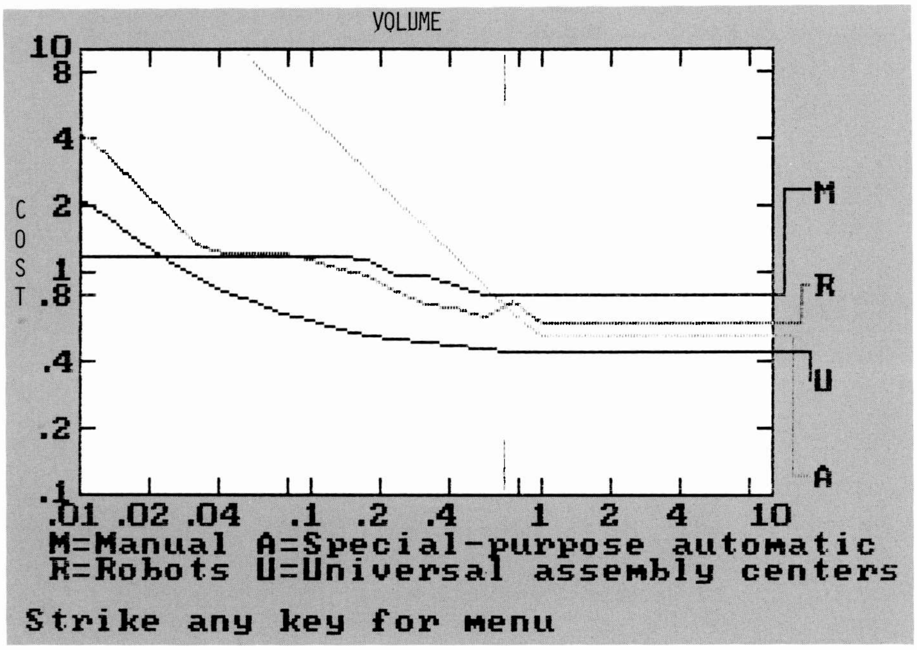


Fig. 5. *Plot, relating assembly cost to assembly systems, that considers factors of volume, parts quality, economic climate, and the number of parts, style variations, and design changes.*

Whether or not the parts are eliminated will depend on the creativity of the engineer.

The theoretical number of parts is then combined with values derived for discrete part assembly time and a comparable ideal part assembly time, to determine the design efficiency of the assembly. This efficiency is given as a relative value, reflecting how effectively an assembly has achieved the design guidelines. It also can be used to compare alternate designs. This does not mean an assembly should achieve a design efficiency of 100 percent. In fact, the typical electromechanical assembly efficiency will approximate 25 percent to 30 percent.

At the end of the Design for Automatic Assembly program, a results summary is displayed, comparable to Fig. 1, which gives a breakdown of the total cost for both manual and automatic assembly. Prior to or after the summary is displayed, the opportunity is provided to change cost and volume parameters to reflect actual costs or to evaluate future cost impact.

This feature provides the opportunity to quickly model and evaluate the cost effectiveness of different assembly concepts. In addition, the program provides a list of all parts in the assembly with their handling and insertion cost. In this way, the assembly cost associated with each part can be studied to determine how the total cost is distributed and to identify problem areas where changes would be most beneficial. Parts are listed for redesign if they are unnecessarily expensive to feed or impossible to feed and orient automatically. In these cases, a five-digit code is given for the part; the code can be used in the "Design for Automatic Handling" program to obtain suggestions for redesign.

During the analysis process, it should become obvious that maximum system efficiency and productivity will be realized only when the requirements of the manufacturing system and product design are integrated.

Assembly system economics

Assuming the Design for Assembly program has been completed and has resulted in parts reduction, has provided for mating part locators, and has led to the achievement of a layered assembly, the next step would be to determine the most economical method of manufacturing. To accomplish this, the "Assembly System Economics" program uses mathematical models to assimilate approximately thirty fixed and variable parameters of the assembly and work climate to determine the most economical assembly system from those listed in Table I.

During operation of the program, all parameters are shown on an interactive screen display. The option to change any value provides an opportunity to quickly model and evaluate the system sensitivity to a variety of conditions.

When the data base presented is satisfactory, the program will calculate and list relative assembly cost for each manufacturing system. The system also provides a graph (Fig. 5) that illustrates the assembly cost of manufacturing systems plotted against annual production volume per shift.

Design for Automatic Handling

This program is used to analyze individual parts for automatic feeding and orienting. Numerous suggestions for design changes are presented, allowing parts to be automatically handled more efficiently.

Design for Manual Assembly

This is used when automatic assembly cannot be justified. The program is similar to the automatic assembly program. Emphasis is again placed on the elimination or combination of parts, and simplification of the part-orienting required for assembly.

Assembly Machine Simulation

The effect of four parameters on the performance of an automatic assembly system are investigated in this program. These parameters are:

- Machine cycle time;
- Parts quality at each work station;
- Average time to clear a stoppage due to a faulty part; and
- Number of service operators available.

The first program is a graphical simulation of an automatic assembly system with five work stations, four buffer storage spaces between each work station, and one operator to clear malfunctions due to defective parts.

The second program is a free-form numerical simulation. In this program, buffer space between work stations, number of operators, time to clear malfunctions, and the ratio of defective parts at each station can be specified. In both systems an on-screen display shows the total system output and the percentage of downtime resulting from defective parts.

The ability to model a manufacturing system provides an efficient tool for determining the system size and studying the operating behavior in relation to parts quality. Additionally, the program provides a tool for studying the cost effectiveness of increased parts quality versus system downtime, and the resulting loss of product.

Summary

Several major companies such as IBM, DEC, Xerox, and General Electric are using "Design for Assembly" and reporting material and labor savings of 25 percent to 30 percent. A similar system in notebook form was developed by Hitachi in about 1975. The fact that they understand and apply the principles of design for assembly is clearly demonstrated in their products.

Within RCA, the "Design for Assembly" program was implemented by Player Manufacturing Technology and is being used in the VideoDisc player program by Product Design, Manufacturing Technology, and RCA Laboratories Manufacturing Research. The goal was to provide not only operating hardware, but a system that would allow interaction of ideals, and sharing of analysis between Design and Player Manufacturing Technology.

To expand the performance of the personal computer and achieve the sharing of ideals, required a network system with a common storage. The network chosen was "Corvus Omninet" with Constellation software and a Corvus Winchester disc for mass storage. The Omninet is a shared-access local network using RS422 twisted pair cable, which can be 4000 feet in length and handle 64 devices. The network uses "bus topology," which means that stations can be added anywhere along the network by tapping into the trunk line.

The network system as installed consists of:

Work station

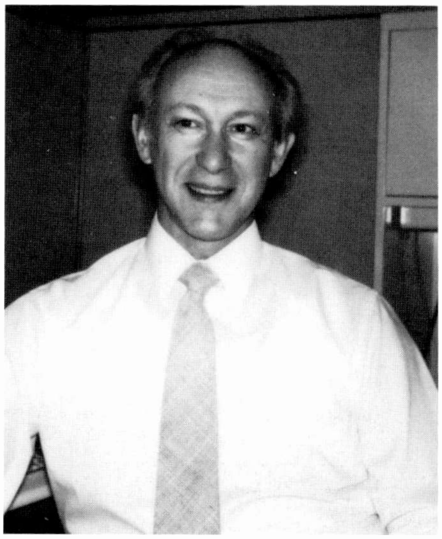
- IBM PC 128K configuration
- IBM DOS 1.1
- Dual disc drive
- Color graphics adapter card
- RGB color monitor
- Epson 100 dot-matrix printer

Network

- 20 Mb Corvus hard disc
- Transporter card for each IBM PC
- Omninet disc server with Constellation software

With this system, the analysis results from the "Design for Assembly" programs are stored on a common sector of the hard disc. Access to the sector directory provides a list of all analysis results that can be retrieved for review or further analysis. Collision is avoided by a modification to the "UMASS" software that assigns a user prefix to the file name. This allows multiple access, and also allows additions or changes to be made to previous analyses without changing the original analyses. In this manner, all the information is shared and there is no duplication of effort when more than one analysis of the same assembly is desired.

"Design for Assembly" has been an effective tool for product analysis and improved



Malcolm Cobb joined RCA in 1979 as Senior Industrial Engineer in the VideoDisc Player Manufacturing Technology Department, where he is project engineer coordinating the efforts between Design and Manufacturing Technology to reduce player manufacturing cost. As part of this responsibility, he recently implemented the "Design for Assembly" program.

He received his B.S. Degree from the University of Tennessee in 1961. Since then he has accumulated a wide variety of Industrial Engineering experience, serving as supervisor of a wage incentive program for Eaton-Yale Inc., and as project engineer at Hamilton Beach and Magnavox. Most of his assignments in consumer electronics have involved the implementation of new products into manufacturing. Mr. Cobb is an active member of the Institute of Industrial Engineers, currently serving on the Board of Directors of the Indianapolis Chapter.

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part design for assembly. Equally important has been the development of a common language between research, design, and manufacturing technology. This common language has been the catalyst for increased cooperation and understanding necessary to achieve the common goal of increased manufacturing productivity.

Acknowledgments

The author would like to acknowledge A. Sproul for the software enhancements and system maintenance that made the total system operational; J. Aceti for his continued support and use of "UMASS" in advanced player design at RCA Laboratories; and Doctors G. Boothroyd and P. Dewhurst at the University of Massachusetts for their assistance and cooperation.

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J.G. Aceti | C.B. Carroll

Robotic assembly of the VideoDisc player's arm drive

Electromechanical assembly—an elusive task for robots, and a lucrative area for manufacturing—has begun at RCA.

In April 1982, the VideoDisc Player Manufacturing Technology group at RCA Consumer Electronics and the Electromechanical Systems Group at RCA Laboratories proposed a prototype subassembly as a candidate for robotic assembly. The subassembly was a VideoDisc arm drive to be used in RCA's prototyped J-line player, scheduled to be assembled in the Bloomington plant. This project would become the first large-volume robotic assembly system within RCA. The obstacles to implementation present a double-edged sword, both technological and economic. But, correspondingly, the rewards for meeting the challenge will be a two-pronged solution to lagging U.S. productivity.

Robotic assembly today

Electromechanical assembly presents a formidable task to robotic system designers.

Abstract: *Competitiveness in manufacturing allows only the progressive and flexible companies to survive. Robots will play a role in the factory of the future as the flexible muscle driving the manufacturing process. This is the account of RCA's first introduction of a robot into the production environment of electromechanical assembly. It involves interesting economic and technological issues, and shows cooperation among groups at RCA Consumer Electronics and RCA Laboratories.*

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Programmable mechanical arms have accomplished many industrial tasks—such as spray painting, welding, and part handling—where the task does not require the exacting accuracy of assembly. Assembly requires more of the system—an additional degree of flexibility, adaptability, precision, and in general, sensory feedback mechanisms similar to a human assembler on a production line.

Assembly and inspection of product account for 40 percent of direct labor in the radio and television industry.[1] Many of the "simple" tasks performed by these workers actually require a complex interaction among sight, hearing, and touch that is difficult if not impossible for an electromechanical system to integrate and mimic. Moreover, robotic system designers must pay particular attention to the part-feeding methods that provide the robot with oriented and accurately positioned parts (see box, page 12). And even before that, careful consideration should be given to the design of parts for automatic handling. A more extensive review of this subject is covered in an article by Malcolm Cobb, elsewhere in this issue. Understandably, application of robots for assembly-line work has been minimal—amounting to a little over 5 percent of the robotic systems operating nationwide. A recent survey conducted by *Assembly Engineering* magazine showed that 13.3 percent of the 1,000 assembly plants participating in the study used robots and that 28.3 percent of those robots were part of the assembly line. The other 71.1 percent were used for part handling, electronic component assembly, arc welding, stand-alone operations, inspection, spot welding, fastening, wire harness assembly, and calibration.[2]

Economic and political issues

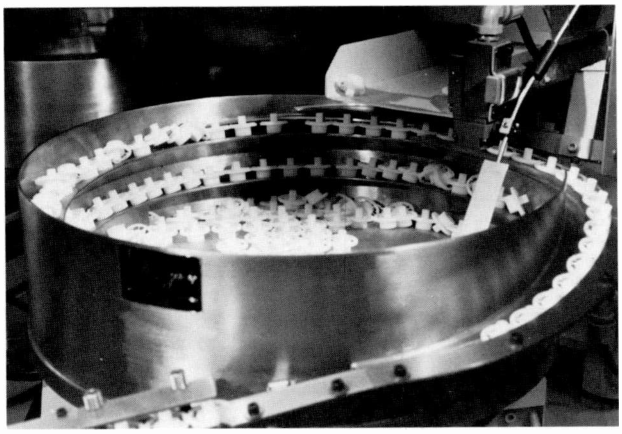
With the impressive array of tasks being performed and the potential economic advantages, why are only 13.3 percent involved in robotics? There are several reasons:

- Risk associated with new machinery
- Labor conflicts
- Inadequate project proposals

Understanding the risk

Those involved with providing, justifying, or using assembly automation equipment have associated the risk of using robotics with that of using uncompromising hard automation—machinery uniquely designed for a specific product, with little possibility for future modification. To a great extent, the difficulties associated with hard automation are appropriate, but the flexibility, reprogrammability, and reduced cost of modern robots have diminished the uncertainty of bringing automation into the factory. Robots can reduce both economic and technological risk—the economic risk of having automated assembly costing more than manual assembly and the technological risk of being inflexible to product improvements. An understanding of the economics when using truly reusable "off the shelf" equipment proves profitable by shortening the payback for each application. When all avenues of savings are consid-

Orienting and feeding parts



Part feeding is a technology that has lagged behind the advanced automation systems it supports. Neither flexible nor sophisticated, part-feeding equipment is usually constructed by artisans working in small specialized shops with welding torch and hammer.

The most common feeding method, bowl feeding, provides the builder with versatility to handle many different parts, and provides the user with many years of reliable service. Being the lowest-cost feeding method, designers should prepare for automating the assembly with bowl feeders by following some guidelines for part design.

Not all parts can be bowl fed. Delicate, sticky, light, tangled, or abrasive parts are generally not bowl fed. For most parts the overriding concern is geometry, and in particular, symmetry. If a part is either symmetric or grossly asymmetric, then feeding will be easier and more efficient.

Dr. Geoffrey Boothroyd, of the University of Massachusetts in Amherst, has researched this subject quite thoroughly and has produced a handbook called "Feeding and Orienting Techniques for Small Parts." Although the text is all-encompassing, three rules can be stated to cover most design problems:

1. Avoid projections, holes, or slots that will cause tangling with identical parts when placed in bulk in the feeder. This may be achieved by arranging that the holes or slots are smaller than the projections.
2. Attempt to make the parts symmetrical to avoid the need for extra orienting devices and the corresponding loss in feeder efficiency.
3. If symmetry cannot be achieved, exaggerate asymmetrical features to facilitate orienting or, alternatively, provide corresponding asymmetrical features that can be used to orient the parts.[6]

Providing the bowl builder with well-designed parts simplifies the bowl design and supplies the factory with a more reliable and efficient system.

ered, a window appears on the production volume scale (typically between 0.25 million and 2 million parts per annum) where robots compete favorably with manual labor and hard automation.

In addition to the typical costs associated with getting a robot up and running, an economic analysis includes the varying costs associated with auxiliary equipment (that is, fixtures, part-feeding mechanisms, vision systems, automatic tools) essential to support the assembly robot. For assembly applications, these costs can amount to three times that of the robot itself. With knowledgeable foresight, robotic assembly can still be had with minimal risk. Considering the robot by itself:

> "Robot manufacturers estimate that it will cost (average) about $6 per hour to operate a robot, based on a two shift operation and a useful equipment life of 8 years. If direct labor costs are around $16 per hour in a five-day, two shift operation, then justification is no problem . . . . This will give a payback period of less than two years for most robots . . . ."[3]

Labor conflicts

Due to insignificant unemployment relating directly to robots, few real conflicts have erupted between labor and management. Many robotic applications, especially in the metal-working industry, have replaced hazardous or tedious jobs without much complaint. But eventually, as large numbers of robots begin working on the plant floors, serious problems could erupt. Proper training programs can benefit the workers and the factory by channeling personnel into new and more appropriate jobs as system operators, programmers, and maintenance experts.

Inadequate proposals

When proposing the use of robots, it is essential that manufacturing engineers outline the potential risks and savings for management. Increased use of robots will occur not by the justification methods of the past but by outlining the additional savings beyond reduction of labor and increased quality. The value of robots as reusable tools must be considered, as must the value of increased flexibility gained by manufacturers who must constantly deal with consumer demand, part quality, and seasonal production variations.

In addition, the proposal should adequately define the need for maintenance personnel capable of supporting robotic systems, and show an increased awareness of the safety issues involved.

Robotic assembly within RCA

To dispel some of the reservations and to consider the possibilities, groups at RCA Laboratories are investigating various phases of flexible manufacturing. Flexible manufacturing, in a practical sense, is the means to vary the manufacturing process to accommodate changing market demands, product changes (within a family of products), without additional capital expenditure or labor. In particular, the area of robotic assembly is being studied for application in RCA's manufacturing facilities. What better way is there to learn and apply new-found knowledge than by doing a "real" job?

Designing the product for automation assembly

The initial task was to consider the feasibility of robotically assembling a 24-piece subassembly, the VideoDisc arm drive. After consideration, our first response was that the product could indeed be robotically assembled, but not economically. Several small external retaining rings, set screws, and a 3/8″ long extension spring presented formidable assembly tasks for the mechanical arm. Thus, we attempted to modify the design to one that is easier to assemble.

Applying a disciplined set of guidelines (Fig. 1), we designed a simplified product. The principal improvements were:

- Fifty percent reduction in part count
- Layered assembly
- Elimination of set screws and retaining rings
- Elimination of extension spring

Of course, there was no reduction in the capability or quality of the product (Fig. 2).

Today we would have taken the new design and quantitatively analyzed the improvements. Using a software package called *Design for Automatic and Manual Assembly,*[4] an assembly efficiency would be derived for comparison among any suggested improvements. Design-for-assembly cannot be overemphasized as a critical point in the design-for-manufacturing process. Not only is there a savings in part cost but also a drastic reduction in assembly time.

> "Experience shows that it is difficult to make large savings in cost by the introduction of automatic assembly in the manufacture of an existing product. In those cases where large savings are claimed, examination will show that often the savings are really due to changes in the design of the product necessitated by the introduction of the new process. It can probably be stated that, in most of these instances, even greater savings would be made if the new product were to be assembled manually. Undoubtedly, the greatest cost savings are to be made by careful consideration of the design of the product and its individual component parts."[5]

Less inventory, increased reliability, and higher quality are also realized without any additional capital investment if assembly is considered during the design phase. In addition, it is appropriate to design for automatic assembly by specifically allowing for automatic feeding/handling of components. Simple modifications may be made at this point for the purpose of robotically or automatically handling the part.

Modeling the assembly

Having a workable model, a strategy for assembly must be considered within the limits imposed by manufacturing. For the gearbox, the production rate was naturally a critical issue. One system working one shift had to produce 1,400 assemblies—one about every 20 seconds.

Knowing approximate execution times for various robot maneuvers, a machine-time schedule can be readily constructed. The user must creatively determine the sequence of events and must discover if any auxiliary equipment (that is, fixtures, vision, tactile feedback, etc.) will be employed. For maximum flexibility, a minimum amount of tooling should be considered. On the other hand, additional tooling can be used effectively to "buy time" by assisting the robot. Typically, dedicated hardware is required to feed parts to the robot (that is, bowl feeders, magazines, pallets). Unlike the robot, dedicated hardware is not easily reusable, and therefore, is less economical for medium-volume applications.

After many attempts, a scenario, or sequence of events, for assembling the gearbox was produced that called for an assembly time of under 20 seconds, and required a minimum amount of dedicated hardware (Fig. 3). In this case, hardware was used only to apply grease, accurately position parts, pre-mesh the three gears, and automatically apply screws. The scenario also required that:

- The potentiometer, lever, and gear be manually assembled—the design did not allow efficient use of the robot for this assembly.
- The three reduction gears be premeshed and a palnut accurately located below the cluster (a palnut is a formed sheet metal nut that is pushed rather than turned on a shaft).

1. Strive to minimize number of parts.
2. Select a base to which other parts will mate, that is, design the product in layers to allow each part to be assembled from above.
3. Ensure that the base part has features that facilitate locating and securing of mating parts.
4. Use liberal chamfers, tolerances, tapers, and rounded edges where possible.
5. Avoid expensive and time-consuming fastening operations, such as screwing, soldering, and so on.
6. Assure that parts remain in an oriented form from vendor to factory floor, or be certain that parts can be easily fed by conventional means.

Fig. 1. *General rules for designing a mechanical product for manual and automated assembly.*

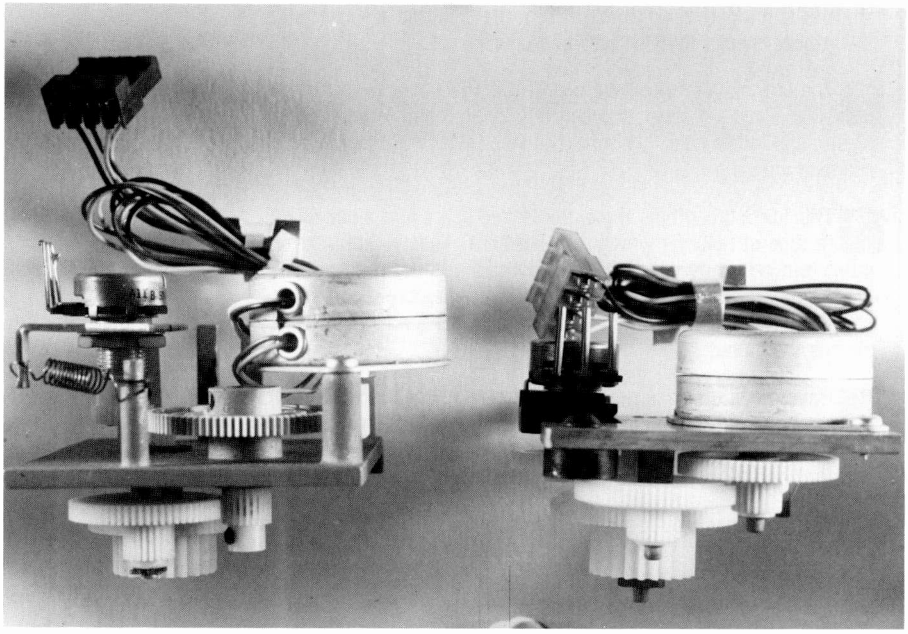
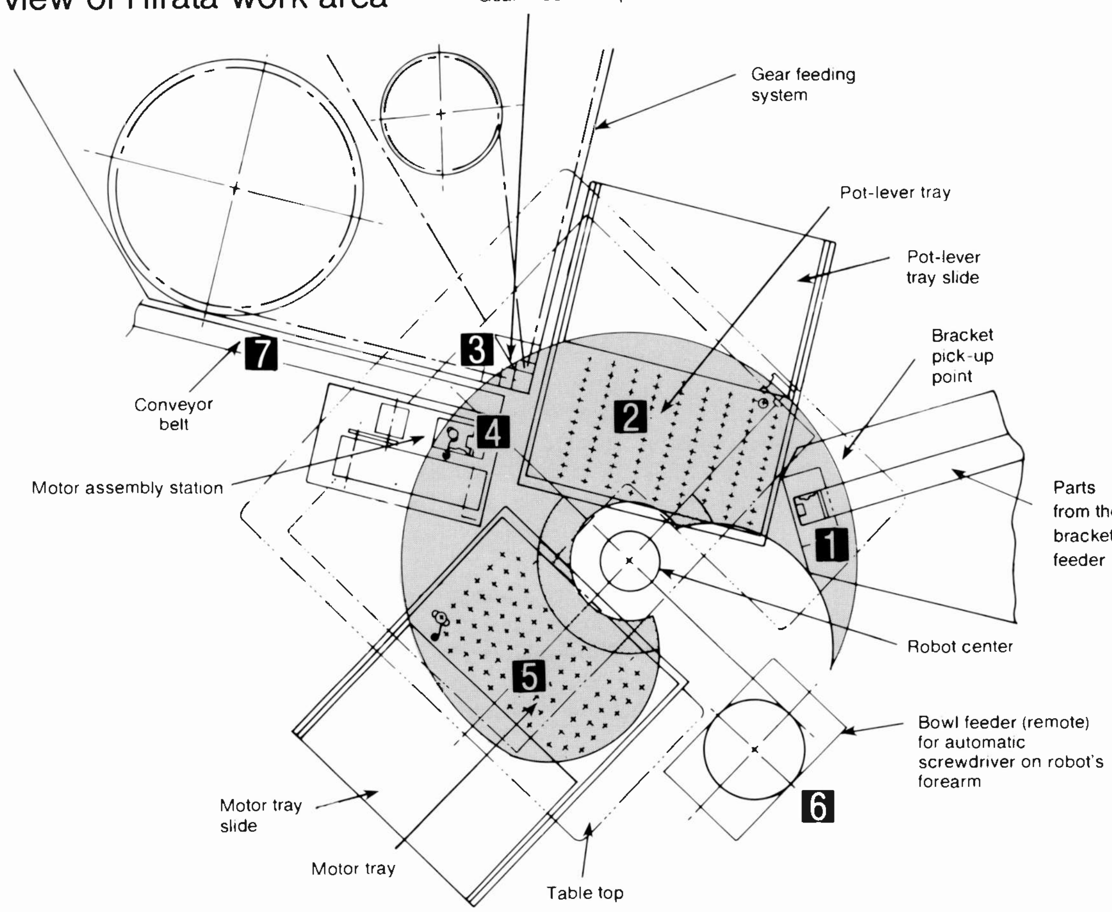


Fig. 2. *Following the design guidelines for assembly, the prototype design (left) was simplified, thereby making automated assembly feasible and manual assembly much faster.*

Overview of Hirata work area



1 The robot picks up a bracket from the bowl feeder's nest. The nest is instrumented to detect the part and test the bracket's three gear shafts for straightness. Failed parts are removed by the robot and rejected. A small amount of grease is also applied to each shaft for lubrication between the rotating gear and metal shaft. The gripper raises the part from the nest and a sensor on the gripper checks that the part is properly held.

2 The arm moves to remove one of the 108 pot-lever assemblies. Each pot-lever is accurately located and retained by a plastic clip in the tray. The arm is lowered until the bracket is snapped onto a pot-lever.

3 This station contains three premeshed gears and a palnut (a type of fastener which is pushed on). The system interrogates four proximity sensors for positive location of each part before the arm lowers the bracket into the assembly. Each shaft on the bracket moves into its mating gear until the longest shaft pierces the palnut.

4 Having captured the gears and the palnut, the robot positions the partial assembly in the motor assembly station. This station is equipped to sense that the pot-lever was properly installed and that one of the two screws is applied in the next sequence.

5 The gripper is moved over and selects one of 108 motors from a tray similar to the pot-lever tray and moves back to the motor assembly station. The motor is moved in a way that meshes the pinion smoothly. While placing the part on the bracket, the system actuates a clamp that will hold the motor in place while the robot positions the screwdriver and applies two screws.

6 A Weber automatic screwdriver mounted on the forearm of the robot is fed screws from a remote bowl feeder via a pneumatic feed tube.The system controller positions the arm and actuates the driver. After fastening a motor to the bracket, the robot swings around to the bracket station to begin the sequence again.

7 Simultaneously, the motor assembly station flips the completed assembly onto a belt conveyor, which moves the part away from the robot. If the robot has successfully completed the assembly, it will travel down the conveyor to an operator for visual and electromechanical inspection. Incomplete assemblies are directed to a rework bin. Incomplete assemblies are caused by parts missing in trays or nests or the robot failing to pick up a part. If a missing part causes a jam, the system will stop and notify the operator via a red rotating beacon. Inconsequential misses are ignored by the robot and sorted on the conveyor, thus minimizing downtime. At the completion of 108 assemblies, the system automatically stops and turns on the rotating beacon. The operator simply replaces the empty trays with filled ones and presses a resume button.

Fig. 3. *Assembly sequence and overview of Hirata work area and ancillary part-handling equipment. The nautilus-shaped area encloses the work area of the robot. The actual robot, the robot controller, and the Weber screwdriver are not shown. Several bowls, for example, the 40" diameter bowl for bracket feeding, are not shown.*

• The motor and its pinion be pre-assembled—the motor manufacturer provided this service.

Prototype testing

Prototype fixtures and software were then developed for the IBM RS-1 robot (Fig. 4), which is an advanced assembly robot. Concepts, cycle times, reliability, and robot performance were all evaluated for the selected scenario. The sophistication of the RS-1 provides the flexibility to modify programs quickly and to experiment with different techniques (See also, J. Baldo's description of Astro-Electronics' IBM robot application elsewhere in this issue). At this point we tried, as an exercise in "devil's advocacy," to identify and work with imperfect parts that statistically are hard to find but, when present, cause an outstanding percentage of problems. Also we looked for handling problems. In this case, we discovered a particular way of wrapping the motor's leads in small bundles to prevent the possibility of their getting caught on a fixture during assembly.

From this stage, with the initial boundary conditions satisfied, a proposal was developed for management that outlined:

• Which robot was required?

• What hard tooling was required?

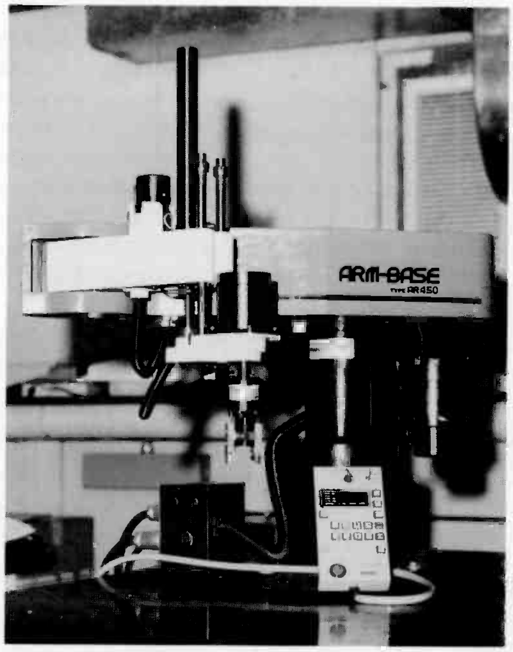
• How much money was required?

For this case, the IBM RS-1 would have been excessively sophisticated in terms of both the robotic skills required and the cost.

A Hirata AR-300 robot was proposed due to its repeatability and low cost (Fig. 5). Also, the Hirata robot is found in several RCA facilities including Lancaster, Indianapolis (Sherman Drive), Princeton, and now Bloomington. This type of robot is called 'SCARA' (selective compliance assembly robotic arm) and is less costly and more suited for certain assembly tasks than the rectilinear-type RS-1. While spherical or cylindrical coordinate robots such as the Puma 600 have roughly isotropic rigidity, the SCARA-type robot is designed to move anisotropically. The SCARA-type robot, therefore, is designed to respond selectively to loads applied at the gripper. The kinematics of the Hirata, which moves in a nautilus-shaped work area (Fig. 3), allows compliance in the X-Y (horizontal) plane, which permits compensation that is helpful when the robot is locating a part in a fixture or hole having a tolerance smaller than the repeatability of the robot, as when pressing a peg into a chamfered hole. But the robot is rigid in the Z (vertical) axis, for pressing, as required for screw driving or press fitting.

IBM 7565 (RS-1 shown)
Coordinate system: Cartesian
Repeatability: ±0.005
Actuators: All hydraulic
Maximum velocity: 40 in/sec
Payload: 5 lbs
Controller: IBM Series 1 computer
Cost: $120,000 typical

Fig. 4. *The IBM 7565/RS-1 robot (Series 1 computer and operator terminal not shown) is one of the most advanced systems available today. Using the system's advanced optical/tactile sensors, the robot is capable of executing complex tasks that require iterative part positioning for precision assembly.*



Hirata AR-300 (AR-450 shown)
Coordinate system: SCARA type
Repeatability: ±0.002
Actuators: dc servo motors
Maximum velocity: 55 in/sec
Payload: 4.5 lbs
Controller: Hirata program controller
Cost: $18,000

Fig. 5. *Hirata AR300/AR450 robot was first manufactured for Hirata's own customized automation equipment. Noted for its low cost and repeatability, it has become favored for small electromechanical assembly tasks.*

Programming the Hirata

The Hirata AR-300 system consists of the robot, controller, and a pendant. The pendant is the user's interface to the system providing teach, programming, and two run modes (step and continuous). The user basically inputs all position points (up to 1,000) and then writes his program in sequential steps (up to 256). For this system a control panel with four control pushbuttons, a counter, and eight status lights was added to simplify the operator-robot interface. The panel also eliminates the ability and need for the factory operator to use the pendant, thus preventing accidental changes in the program.

Position points can either be taught or programmed in, but our experience was that taught points were more accurate and quicker to input than those programmed. Most robots have this peculiarity in that their accuracy is dependent on a buildup of mechanical tolerances, but that once a point is taught the robot can repeatedly move to that same position.

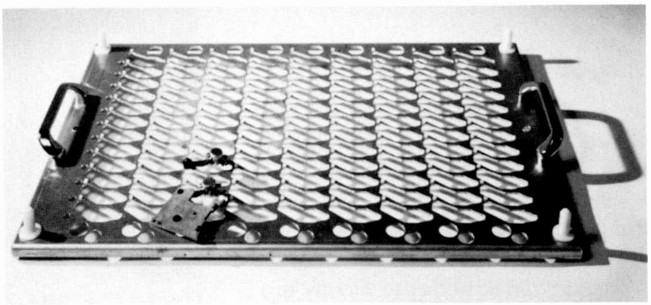
Feeding parts

Hard tooling, as identified in the prototype stage, became the greatest expense in developing this system. The handling, orienting, and feeding of parts as they come from the vendor is a formidable job. The design

The robot-CAD/CAM connection

Feeding an assembly robot accurately positioned parts is a major concern for robotic system designers. Parts sometimes cannot be fed/oriented automatically due to some delicacy of the part. You must then rely on tray feeding, which provides a queue of manually placed and accurately secured parts accessible by the robot. Two such trays were required for the arm-drive assembly system.

Both the motor, with its 16-inch-long wires, and the potentiometer-lever assembly were considered too delicate and too difficult to feed automatically. With the assistance of CAD/CAM facilities available at the RCA Laboratories, trays were developed for the components mentioned. The designer had to both determine and avoid interference problems and "dense-pack" as many parts onto a 16- by 24-inch tray as possible. On the Computervision system, a design was produced, verified, and then downloaded to a Spindle Wizard (computerized numerically controlled milling machine) where two stacks of six trays were machined. A pot-lever tray consists of 108 positions that secure the part and allow clearance for the extended shafts on the bracket (not visible).



The same number of plastic spring clips, which retain the pot-lever, were designed on the same system and downloaded to a Graziano NC Lathe for production.

Software is now available for some CAD systems that not only allows modeling of parts and fixtures but also shows the robot's kinematics. An entire workcell can be animated for analysis before any hardware is purchased. In the future, robot software will be developed in this manner and fed directly to the workcell, eliminating robot downtime for programming. The CAD/CAM-robot system will be a valuable tool in the factory of the future.

of a reliable feeding mechanism is usually best left to those companies who are skilled in the art. If the parts are relatively small and are not delicate, a vibratory bowl feeder is commonly used. This type of feeder has a helical track that passes around the wall of a bowl. When a driving vibration is applied to leaf springs mounted under the bowl, the effect is to cause parts in the bottom of the bowl to climb up the track to an outlet at the top of the bowl. Various devices are welded into the bowl that allow only properly oriented parts to reach the outlet. Delicate parts or parts that tangle, such as motors, are better fed either by magazine or tray.

In summary, the proposal presented for this system included a Hirata AR-300 robot and the following feeding systems:

- Vibratory bowl for feeding brackets
- Vibratory bowl for feeding 3rd-reduction gears
- Vibratory bowl for feeding 2nd-reduction gears
- Vibratory bowl for feeding 1st-reduction gears
- Vibratory bowl for feeding palnuts
- Tray for holding 108 motors (with spares for reloading)
- Tray for holding 108 pot-lever assemblies (with spares for reloading)

In addition, a Weber automatic screwdriver, a nest for meshing the three gears, and a motor assembly fixture had to be built/purchased.

An overview in Fig. 3 shows the placement of feeding mechanisms into the robot's work area. Starting at the bracket feeder and then working counterclockwise the robot follows the scenario presented in the figure.

Safety

Safety of the operator is paramount in the system's design. For this application, the robot's work area was totally enclosed in removable plexiglass sheets. These lightweight shields are easily removable but, if removed, cause all power to be dropped from the arm. Feeding equipment is outside the enclosure and can be replenished without interrupting the system. Additionally, the motor and pot-lever trays automatically move out from the work area on a slide for replacement.

ADAM

To ensure a safe, efficient transfer of the system from Princeton to Bloomington, the engineers and the technicians from the plant visited the Laboratories before shipment. Seeing and working with the equipment in the lab allowed the present users to become familiar with the equipment as well as with programming the robot. They nicknamed their first robot ADAM (arm-drive assembly machine).

After almost two years of development and six months of actual construction, the Hirata system was dismantled and shipped to Bloomington in early November to begin production on the factory floor (Fig. 6).

What we have learned

As of this writing, the arm-drive assembly system has only been operating for a short time. We intend to keep track of the system's performance, and in particular, the reliability of the Hirata robot. Our future work in robotics and design for robotic assembly will be based on our present experiences with this system. In a nutshell, we found our greatest effort and cost was in part feeding, not in programming or using the robot itself.

Part feeding curtails flexibility, increases costs, greatly increases floor space required (as compared with the robot itself), and lengthens the concept to delivery time. Bowl feeding requires that parts remain exactly

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Since 1977, Mr. Aceti has worked for RCA Laboratories, Princeton, N.J., as a Member of the Technical Staff in the Electromechanical Systems group. His work as a Project Leader includes a solar-energy concentrator, computer-based automatic parts-inspection devices for VideoDisc caddies, and flexible manufacturing systems. In 1983, he received an RCA Laboratories Outstanding Achievement Award for his designs of automatic inspection systems for delicate plastic parts. He also holds a U.S. patent for this work.

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Authors Aceti (left) and Carroll.

Charles Carroll is Head of the Electromechanical Systems Research group in the Manufacturing Systems Research Laboratory. He graduated *cum laude* from the University of Florida in 1960, with a BS degree in Mechanical Engineering; in 1966, he received the MSME degree from Drexel University. In 1960, he had joined RCA Astro-Electronics, Princeton, N.J., as a design engineer developing sensor and camera components. After serving as a Lieutenant in the U.S. Army Artillery from 1962 to 1964, Mr. Carroll returned to Astro, and then transferred to RCA Laboratories, Princeton, in 1966.

In 1973, Mr. Carroll transferred to the RCA Palm Beach Division, Palm Beach Gardens, Florida, and worked on products using mini- and microcomputers for hotel/motel management. He rejoined RCA Labs in 1975, and he received an RCA Laboratories Outstanding Achievement Award for work on equipment for optical scanning and readout of the RCA VideoDisc. He then led the mechanical design effort that succeeded in producing early prototypes of a flat-panel television system. Mr. Carroll holds seven U.S. patents.

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the same, thus making modifications to the product impossible—modifications for which the robot could easily be reprogrammed. Part feeding accounted for almost 70 percent of the purchased part costs for the system, leaving only about 20 percent (the robot) reusable, thus decreasing the savings. Bowl feeding requires two to four months for construction while a robot can be programmed in a day or two. However, with all the drawbacks, bowl feeding remains the most cost-effective method for orienting and feeding bulk parts.

In the future, the use of robots for assembly will depend on an improvement in the methods to deliver oriented parts to the robot workcell. Vision and tactile feedback systems are presently too expensive and slow for most applications. In the near future, these systems should be available at reasonable costs and will be fast enough to assist the robot in handling unoriented parts. Still, most applications will require ingenuity on the part of designers, manufacturing engineers, and purchasing department personnel. Parts should be delivered already oriented, such as in egg crates or pallets. Disciplined methods such as the *Design for Assembly* software, previously mentioned, will assist engineers in making parts

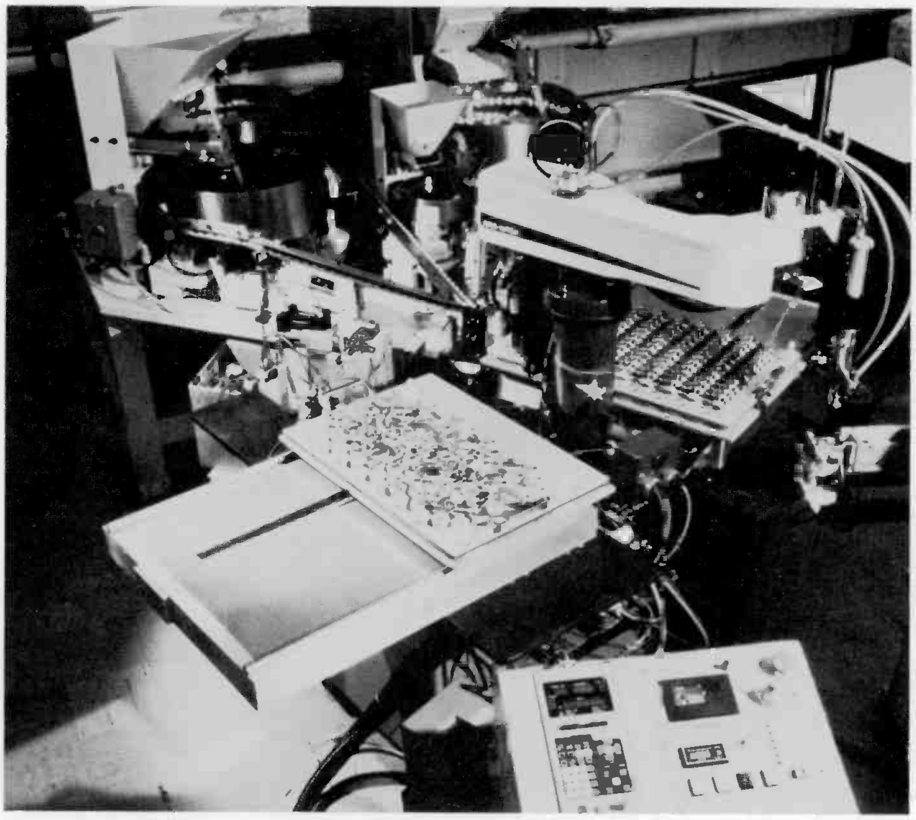

Fig. 6. *The Hirata gearbox assembly system, without its protective Plexiglas envelope, is shown in the Laboratories environment.*

that can be efficiently fed by ordinary means.

Conclusion

From television receivers to VideoDisc players, electromechanical assembly is a vital factor in RCA's future. Competition in this arena is fierce and the winner will provide the consumer with what he wants when he wants it. As flexible manufacturing becomes more of a reality, and robots play a vital part, the competition will become only more aggressive. We must continue to plan and implement effective modern techniques in our engineering and manufacturing.

Acknowledgments

The authors would like to acknowledge Jack Drake, Manager of Player Manufacturing Technology, and Del Baysinger at RCA Consumer Electronics for their continued contributions from inception to completion of this project. Also, Scott Feeser, Associate Member of Technical Staff, Bob Schneller, Senior Technical Associate, and Paul Smalser, Associate Member of Technical Staff, all from the RCA Laboratories, were the driving force behind the systems programming and construction. And finally, Bernie Parambo's suggestions and aid greatly eased the entry into production; he is in the Manufacturing Methods Engineering department at Consumer Electronics.

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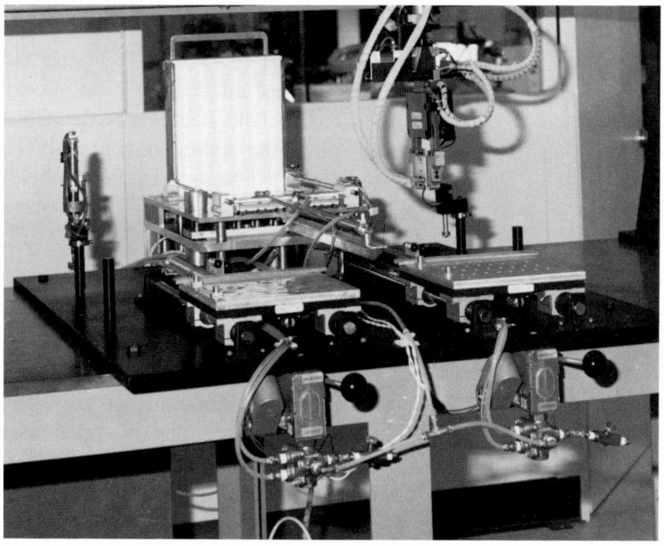
J. Baldo

IBM RS/1 used for solar cell glassing

At Astro-Electronics, labor-intensive aspects of spacecraft solar array assembly are being handled by a robot.



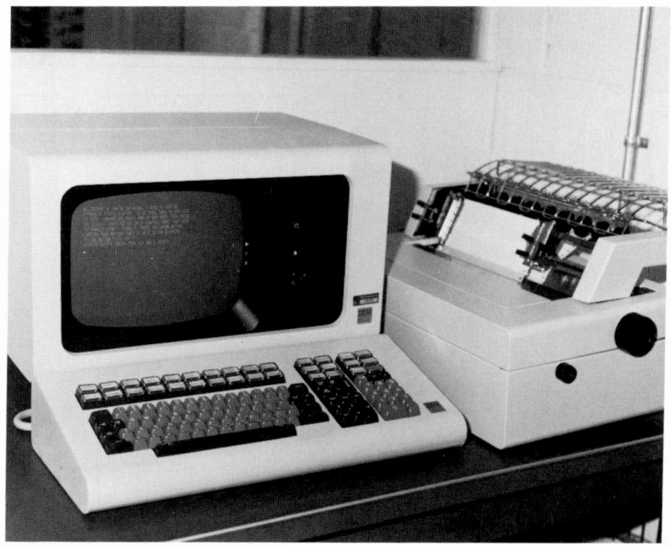


Fig. 1. *The IBM Robot System/1. The photograph on the left shows the manipulator in its rectangular box frame. The system controller CRT and printer are shown on the right.*

The spacecraft solar array is a set of silicon solar cell panels that convert incident solar radiation into current and voltage. This electrical energy (stored in rechargeable nickel-hydrogen or nickel-cadmium batteries) powers the spacecraft voltage busses during partial or full eclipse. The panels consist of silicon solar cells that are fabricated first into submodule matrices, then modules (each a set of submodules), and finally into the panel (a set of modules).

Abstract: *The glassing step in solar array fabrication is a labor-intensive procedure that requires exact deposition of adhesive and accurate placement of the filter glass on the solar cells. Because it is labor intensive and is a repetitive and tedious job for human workers, glassing results in a high incidence of rework. An Independent Research and Development (IR&D) project evolved to address this problem by investigating the feasibility of using intelligent automation for the glassing application. As a result, the IBM RS/1 Robotic System was selected for its versatility and reliability.*

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On the submodule level, filter glasses are "glued" to each cell. These glasses limit the transmission of thermally active ultraviolet radiation, prevent particulate degradation, and avoid moisture contact interference. The glass is a polished fused silica with a magnesium fluoride antireflective coating. A discrete volume of optically clear Dow-Corning 93-500 (DC 93-500) adhesive is deposited onto each cell, then a coverglass is placed atop the adhesive.

This glassing operation is very labor intensive and repetitive, and requires a high degree of rework as well. The repetitive nature of the task, as well as the ease with which intelligent automation can effect a work-intensive, accurate, and reliable system of glassing, make the glassing operation an ideal choice for the RS/1's first application at RCA Astro-Electronics. This paper describes the research that established the robot as a development tool, and includes a brief discussion on its production line implementation as a major goal.

The IBM RS/1

The RS/1 is a six-degree-of-freedom, versatile robotic system (Fig. 1). It can effect translation in the linear X (±9 inches), Y (±29 inches), and Z (±8.5 inches) directions, and in the rotary roll (±135°), pitch (±90°), and yaw (±135°) directions. The maximum linear speed is 40 inches/second; rotary speed is 180°/second. The hydrau-

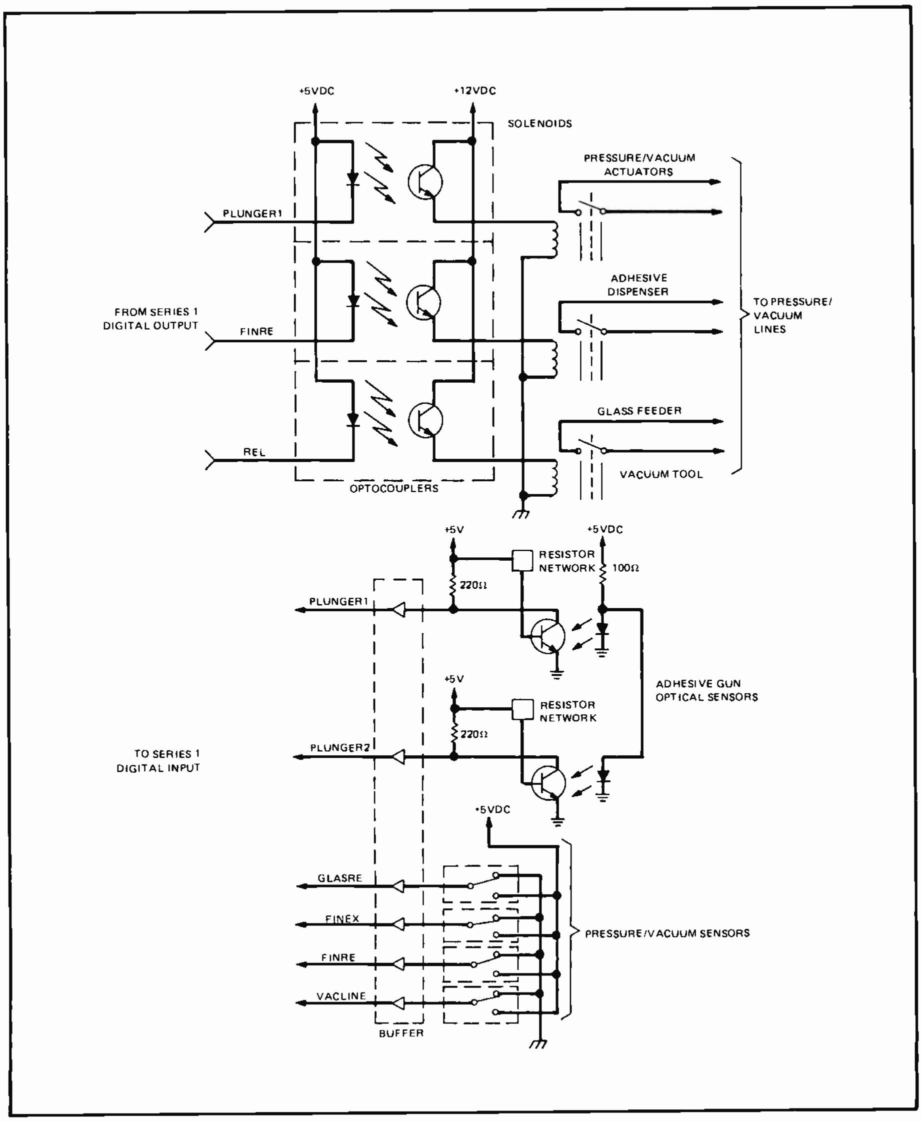

Fig. 2. *Schematic diagrams of the sensor/switches and how they interface with the DI/DO ports of the Series 1 minicomputer.*

lically driven manipulator arm is mounted on rails in a rectangular box frame, and these rails ride on parabolic cams. It is a closed, servo-loop feedback system, and the maximum payload is 5 lbs-force.

The system controller is an IBM Series 1 minicomputer that uses standard IBM EBCDIC (Extended Binary Coded Decimal Interchange Code) protocol. The software is written in AML (A Manufacturing Language) and is interpretive (like Pascal). It is a subroutine-based language that uses data types such as aggregates and strings. Special commands in the software enable the system to handle sensor information; that is, to receive signals from, monitor, and send signals to the digital input/output (DI/DO) ports and the internal/external sensors and actuators.

Internal sensors are those included in the manipulator and involve two types. One type includes strain gauges that enable the robot to sense pressure in the gripper finger pinch (inside gripping surface), tip, and side. The other is a photosensor pair built into the gripper fingers. This pair consists of an IR emitter and phototransistor.[1] External sensors (which are user supplied) include two in-line vacuum sensor/switches, two pressure sensor/switches, and a photosensor pair similar to the finger photosensors.

The development setup

The Series 1 is equipped with 64 DI/DO ports, 32 contact-sense or voltage-sense points via the sensor I/O unit, and 32 voltage-sense points on the processor customer-access panel. Input sensing is supplied by in-line vacuum/pressure sensors that switch on or off for each state, sending a "0" or "1" signal to the DI via the signal lines. A buffer protects the input ports. The input takes $V_{in} \geq 25$ Vdc for an "off," and $V_{in} \leq 8$ Vdc for "on."[1] Digital output signals activate optocouplers. The optocouplers control solenoids that, in turn, control pressure/vacuum actuators (valves). *Npn* transistor switches in the DO provide on/off control for up to 100 mA at 5 Vdc. The schematic representation of the sensor/Series 1 interface is shown in Fig. 2. The pneumatic, optical, and electrical components are consolidated into a junction box that rests below the robot workspace.

A vacuum pickup tool transports coverglass from a pneumatically controlled glass feeder. The robot uses a pneumatically controlled adhesive dispenser to deposit a discrete volume of DC 93-500 onto each solar cell. After all cells in a submodule have adhesive, the robot puts the coverglasses onto the adhesive (Fig. 3). The tools and glass dispenser are controlled by the pressure/vacuum valves and monitored by the in-line sensors.

Sensors and software

The software design is a straightforward application of steps (see the flowchart in Fig. 4). Table I summarizes the sensor information for this glassing application. Calibration posts provide a reference for all tooling and submodule locations. Submodule dimensions and geometry determine a map (which is recorded on a disk) for solar-cell positions.[2]

Feasibility demonstration

On September 1, 1982, approximately six weeks after delivery of the RS/1 robot, the IR&D team gave a conceptual demonstration of solar cell coverglass adhesive dispensing and coverglass placement for members of manufacturing and design engineering IR&D management. The intent of the demonstration was to show both the procedure the robot would follow and the efficiency with which it would work; that is, that it would execute optimum paths and decrease process time. During the demonstration, the robot accurately manipulated the adhesive dispenser over each solar cell and carefully placed the glass onto each cell without breakage.

A 6- by 4-cell module, each cell 2 by 4 cm, was used in the demonstration. Timing of the actual process, conducted at a later time, showed a 63-percent improvement in total time as compared to a manual operation.[3] No consideration has been given, however, for adjusted time that would include normal personnel losses or equipment downtime. Estimates of adjusted time indicate an even greater margin in favor of automatic assembly.

The demonstration included special module-handling mechanisms, the adhesive dispensing applicator, and coverglass handling/placement devices. The electronic and pneumatic controls, as well as the complete software package for the glassing process, were designed and developed in 1982. The robot began production in 1983. This operation results in a substantial increase in the production output and a significant improvement in the quality and reliability of the product.

It has been calculated that, if a year's supply of solar cells and coverglasses (that is, the amount of material that, on the average, the solar array area uses per year) were available for bonding, the automated assembly setup, working 24 hours a day, could complete the glassing operation in less than three weeks. As implemented in the production line, the automatic process now realizes a rate of 6 submodules/hour,[4,5] which translates into a year's supply in less than five weeks. This performance time demonstrates the success of using a reliable automation system.

Manufacturing implementation

The ultimate goal of production line implementation has been realized and involves the use of multiple glass feeders (these preposition six coverglasses) and slider trays for submodule placement and removal. A time-motion study indicates that on the average the robot can glass a cell in 7 seconds, and a human worker takes 19.1 seconds (this includes break and sick time, lunch, and so on).[3]

A brief discussion of vision

When programming the robot to perform its tasks, one must account for the fact that it is totally blind and must "feel" its surroundings. One must define meticulous specifications for tool and object position as well as carefully choose the manipulator's paths. If, however, the robot were able to receive visual feedback, the problem of critical dimensioning and error would be virtually eliminated.

Investigations were conducted in the areas of adhesive processing, artificial intelligence, and visual recognition. Three different vision recognition systems, all of which have some associated artificial intelligence, were selected for further investigation.

A variety of machine vision systems are available commercially. One type provides automatic visual inspection of parts in a production line. Another type is a robotic vision system, which can interface to the robot controller. The system usually consists of a solid-state or vidicon camera interlaced with an image processor and computer.

Conclusions

The IBM RS/1 is a flexible automation tool and a feasible choice for the repetitive task of solar cell glassing. The robot performs a reliable job in less time than a

Table I. *Sensor information.*

Sensor name (in software)	*Sensor type*	*Function*
ADGUN	Optical (internal)	Verifies that the adhesive tool is in the gripper
PLUNGER1	Optical	Verifies that the plunger is fully extended
PLUNGER2	Optical	Verifies that the plunger is fully retracted
VACTOOL	Optical (internal)	Verifies that the vacuum tool is in the gripper
VACLINE	Vacuum	Verifies that there is a vacuum in the vacuum pickup tool line
GLASPRE	Vacuum	Verifies that there is vacuum in the line to preload position on the glass magazine
FINEX	Pressure	Verifies that there is pressure in the pressure line for the glass dispenser finger to extend fully
FINRE	Pressure	Verifies that there is pressure in the pressure line for the glass dispenser finger to retract fully
REL	Vacuum	Verifies that a vacuum is restored to the vacuum tool line after release of the glass

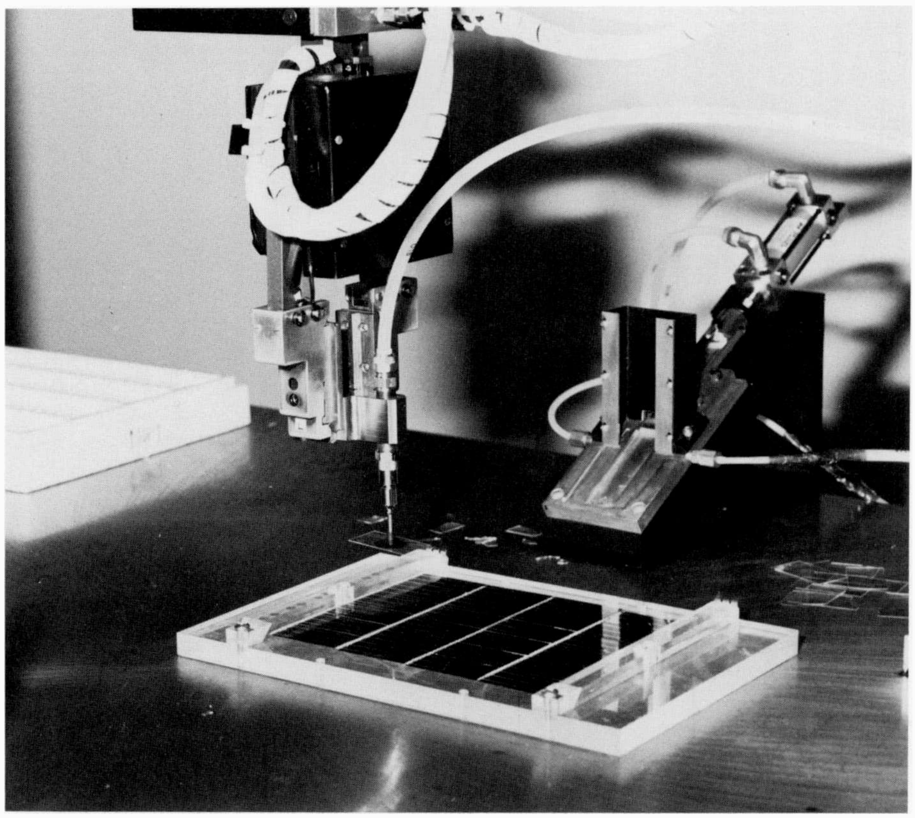

Fig. 3. *The manipulator placing filter glass on a solar cell, using the vacuum pickup tool.*

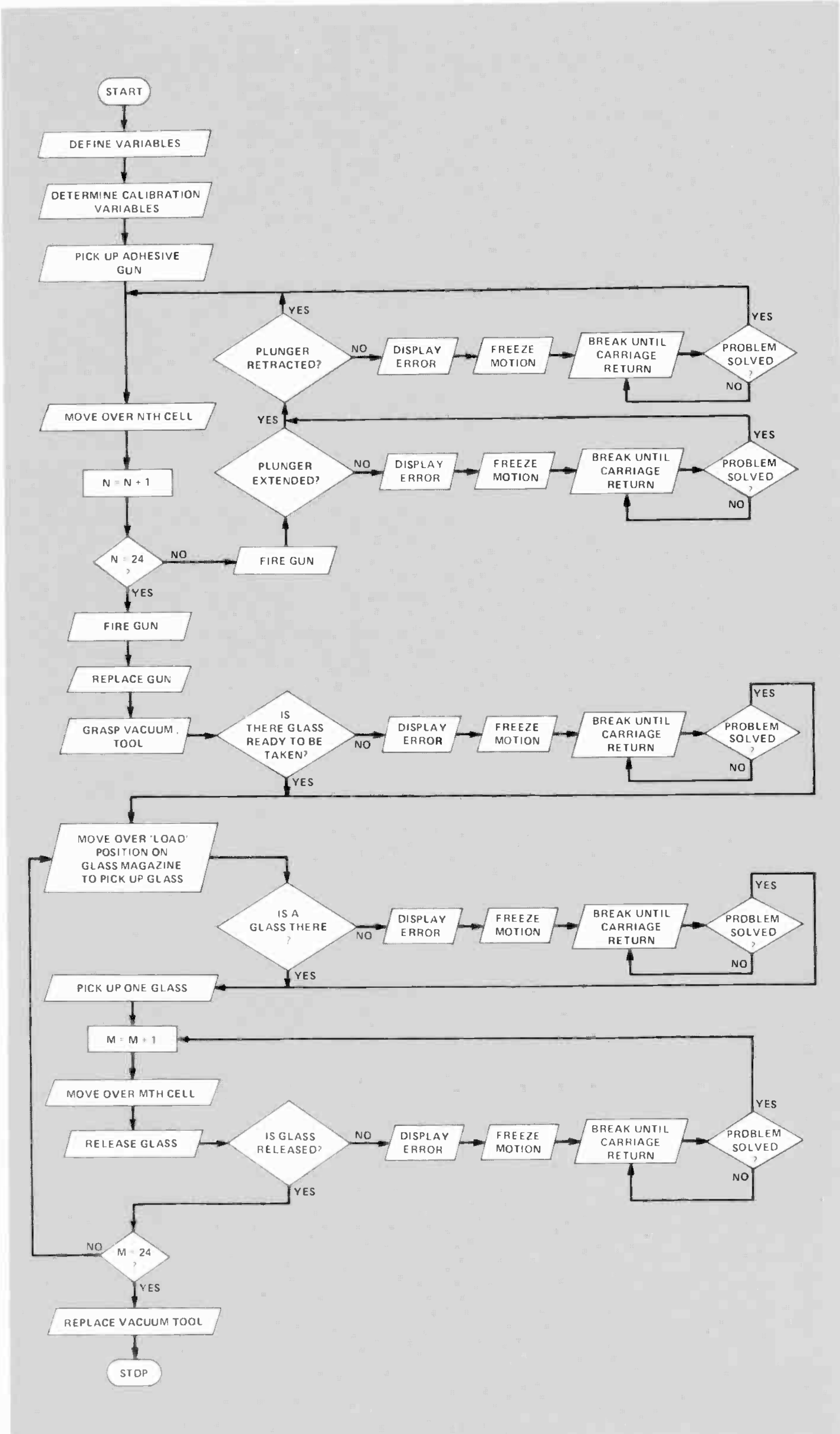

Fig. 4. *This chart illustrates the flow of the software and the rules to guide the robot's "decision-making" process.*

human and can be used for other tasks as well.

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Janise Baldo, since joining RCA Astro-Electronics in 1980, has designed ground station cable networks for testing spacecraft and has developed algorithms and subroutines for running continuous experiments with a lidar (laser radar) system for measuring wind velocity. As a lead engineer in the Power Systems Group, she is now responsible for a variety of solar array research work. Baldo has a Bachelor of Engineering degree in Engineering Physics from Stevens Institute of Technology and looks forward to receiving her Master of Engineering from Stevens in 1985. She is interested in electro-optical research and development as well as robotic applications development.

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Statistical process control: Learning by doing

Statistical process control works for everybody, if everybody works for statistical process control. This Consumer Electronics manufacturing unit has proof!

Virtually everyone in industry is familiar with the term statistical process control (SPC) and the great success the Japanese and U.S. companies such as Chrysler Corporation have had following implementation of such a program. However, little is written on how such a system is implemented. This paper shows how SPC was put into practice at RCA. Commitment to SPC requires a change in philosophy by management, an investment in training the entire organization top to bottom, and time to realize the potential benefits of improved quality and increased productivity in manufacturing, warranty costs, and product share.

Getting started

As a result of attending a workshop at the David Sarnoff Research Center in Princeton, N.J., on "Applications of Statistics to Manufacturing," the operations staff of the VideoDisc Stylus/Cartridge Manufacturing Operations (RCA Consumer Electronics Division) located in Indianapolis, Indiana, at the Rockville Road plant, decided to embark upon a program of SPC in early 1983.

Kickoff training was provided by the Productivity and Quality Assurance group from DSRC and involved key manufacturing, engineering, and quality personnel. The Basic Statistical Toolkit training included discussions of variability, histograms and simple plots, control-charting techniques, and process-capability studies. A commitment of 44 person-days was required for the training of all 22 participants involved over a 4-week period.

Abstract: *Stylus/Cartridge Manufacturing Operations at RCA Consumer Electronics in Indianapolis, Indiana, trained in Statistical Process Control procedures in early 1983. They began applying their education almost immediately and have found several suitable projects since then. One such successful venture is described in this paper. The manufacturing results: a better cartridge at significant cost savings.*

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After completion of the course, there still remained the task of making SPC a part of our everyday worklife. There existed a basic, underlying commitment to understanding and achieving the benefits that were felt possible with SPC. The first step was to choose a problem area in cartridge manufacture that was ripe for initial success. This was important to maintain the momentum towards a change in manufacturing philosophy.

First success

A task force was formed consisting of the manufacturing supervisor, the hourly production group leader, manufacturing engineer, manufacturing technicians, quality control supervisor, quality control technicians, and the Purchased Material Inspection (PMI) supervisor. In a brainstorming session, the group selected the number one quality-related problem at assembly and final audit: rejection because of incorrect force and bias (vertical and lateral tracking force).

At the time of the study, the manufacturing process consisted of a cartridge assembly "build" operation, where the initial force and bias were established, followed by combined 100 percent inspection for force and bias, and a repair operation. The force-and-bias inspection in manufacturing was performed on an optical comparator. The quality inspections, however, were performed on an electronic gauge. The manufacturing inspection equipment had been set to agree on the average with the electronic quality control fixture, but there was not one-to-one correspondence on individual cartridges.

Prior to the task-force meeting, it was agreed to keep control charts of the process—shown by operator—after the assembly "build" and repair operations. A meeting was held to explain the charts to operators to relieve their anxiety. After one week, there was a noticeable improvement on the charts from the assembly fixtures. This could be attributed to the performance feedback given to the operators.

At the first meeting, participants reviewed the control charts, developed a cause-and-effect diagram, ranked the causes, and selected the number one item, staking force, for further study and control charting. The PMI supervisor provided information that showed that the flylead (signal conductor and force spring) had variations in thickness that affected the final force of the assembly. What started out as an assembly issue became a material issue.

The control charting of the assembly and repair operations was continued. Histograms (Fig. 1) and box plots (Fig. 2) of the force and bias were prepared for each operation. The information from the histograms was the most revealing. After assembly, bias was normally distributed and had a tighter range than after repair. This was sufficient evidence to justify elimination of the bias-repair operation—it had become part of the problem. Similar analysis of the force data, however, showed that the repair operation degraded the product distribution.

A process capability study was now performed on force. The results of the capability study showed that it was not possible to manufacture the product to the existing specifications.

This data was shared at a joint meeting with the cartridge management and the design engineering personnel. Analysis by the design engineer found that the VideoDisc player was able to accept the cartridge force at its natural process capability. It was concluded at the meeting to eliminate the inspection and repair operations and to control the process average within one standard deviation of the nominal force specification.

An off-shoot of the above findings was our increased awareness of the real impact of material upon the performance of the cartridge. Purchasing had previously arranged the bulk rolling of the flylead material. Our data clearly showed the effect of the flylead materials's thickness on performance of the cartridge. This led the plant QC Manager to contact the material vendor and, with purchasing, negotiate for process control of the vendor's milling operation—at a cost reduction. The savings to RCA resulting from the implementation of process control at the cartridge assembly operation showed up as direct labor reduction, material cost savings, and improved yields that facilitated further savings at subsequent operations because of the improved process.

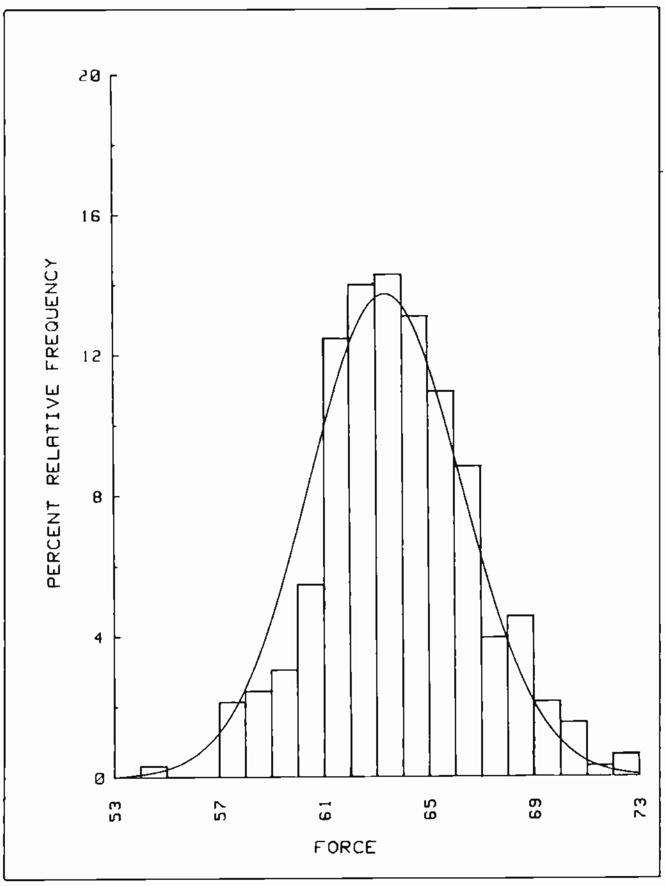

Fig. 1. *Histogram of flylead force, measured after the cartridge is assembled. The process is a normal distribution, but exceeds the design specification of 65 mg. ±7. The specification was changed to control the process within 3 σ limits.*

Success breeds success

After the success with the force and bias problems, several members of the organization enrolled in the RCA Corporate Engineering Education (CEE) course offered on "Design of Experiments." There emerged a small group of highly committed members of the organization who, on their own energies, have spread the "gospel of statistical process control." Although feeling persecuted at times, they have persevered. The support of management and the consultants at RCA Laboratories helped, but ultimately their efforts cannot compare to the personal, day-to-day commitment of the individuals directly involved in manufacture.

In the short time since the first success, there have been many other studies and designed experiments. Problem analysis, through designed experiments, is gradually being recognized as the surest path to permanent solutions, rather than the "band-aid" fixes that are often a temptation during crises. The basic truth of controlling the natural manufacturing process cannot be denied.

Lessons learned

The incorporation of statistical process control in the manufacturing operation has generated a better understanding of what

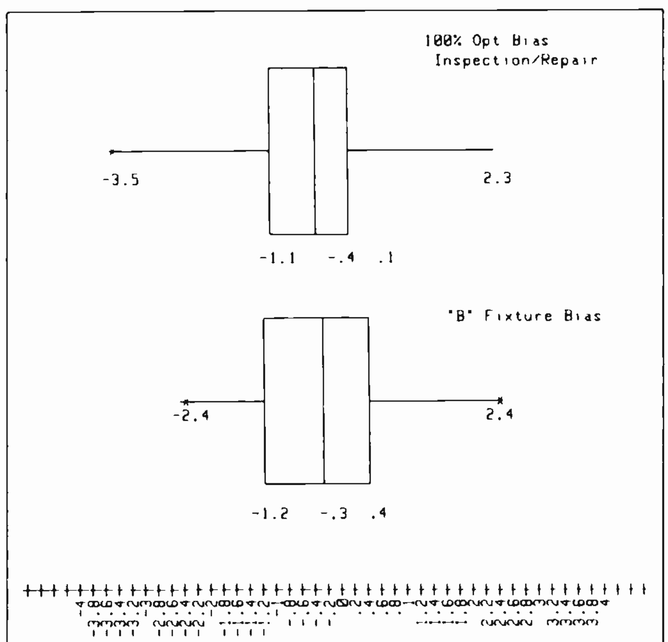

Fig. 2. *Box plots of before-and-after bias repair. Although 50 percent of product is more tightly distributed, the overall distribution is larger. Conclusion—stop the repair, and control the process.*

makes the product work. The necessary change in philosophy involves the commitment of management and the whole organization to SPC. The transition period can be frustrating until it is complete. Those frustrations are eased by the realization that we are making progress and doing what is right.

With the advantage of 20/20 hindsight, there are several things that participants should keep in mind when an organization embarks upon statistical process control. The following list is certainly not complete—but then we have not finished our trip.

- Control charting can only be used to improve the product if one understands the underlying distribution.
- Control charts do provide an excellent historical record of the process. Control charts can also be invaluable in solving problems not directly related to the factor being charted.
- It is critical to know and recognize the capability of the measuring system being used. It is fruitful to do measurement capability studies early—an inadequate measurement system can only obscure problems.
- Progress in a single organization can be frustrated if related organizations are not commited to SPC. Include such organiza-

What is Statistical Process Control?

- Putting a process in pictures—histograms, control charts, graphs for understanding variability.
- Analyzing pictures for deviate behavior—looking at the shape of the distribution and the activity of the mean and range.
- Reacting to warnings given by analysis—doing corrections according to control-chart rules and distribution abnormalities.
- Blending mathematical interpretations with technical awareness of the process.

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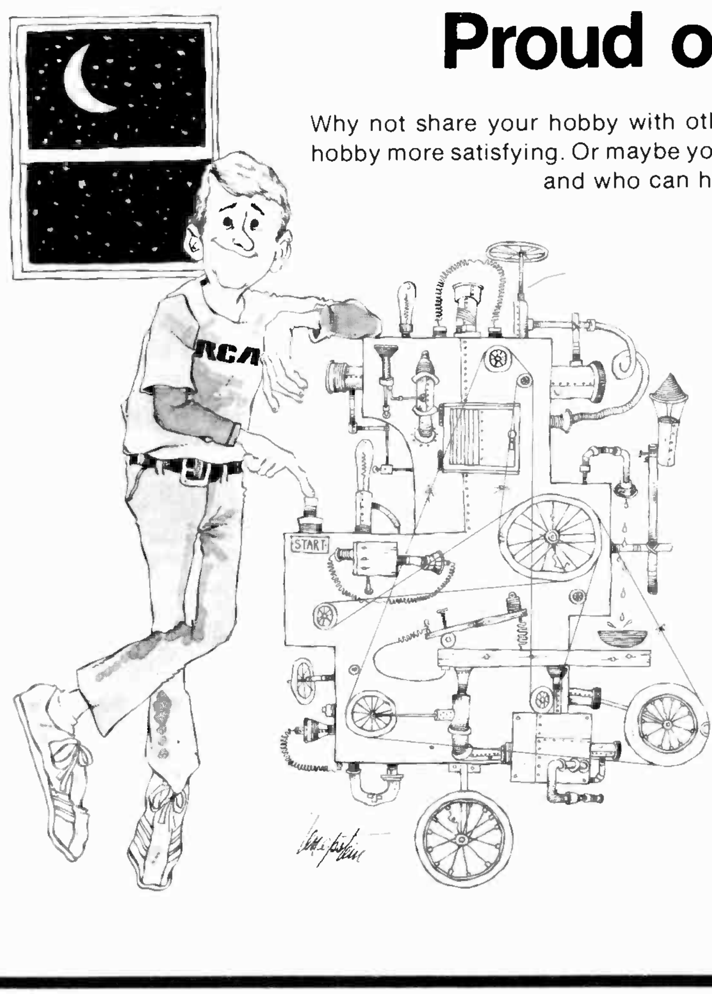
tions in the training sessions along with frequent explanations at meetings of the basic principles being applied. This process is important in building a solid base of support.

- The use of "package" computer-analysis programs by the inexperienced can lead to incorrect solutions. Although the best solution is to have individuals knowledgeable about statistics in the organization, access to strong statistical strengths from consulting groups, such as those at RCA Laboratories, is important.
- Patience, of course, is a virtue. This is the biggest challenge to operating management who are used to making quick decisions. Initially, designed experiments seem to take forever. Once the value of the results becomes evident, the little extra time to get results is worth the wait. As greater knowledge is gained about the process and the product, simpler experiments can be designed that are easier and quicker.
- Believe in SPC. SPC can point out problems even before there are rejects. Ignoring such advance warnings has been adequately demonstrated to be costly.
- The importance of material characteristics on the process cannot be understated. Failure to appreciate this impact can hide or divert attention away from the real causes of process or performance problems.
- It is important that SPC not be viewed as a "Quality Control program." It requires the total organization involvement and commitment to accept the responsibility of reacting to changes in the process without the "crises" of rejects.

Conclusion

The gains possible through statistical process control are real but they do not come without cost. The cost is minor when considering the alternatives. Changes in philosophy and operating style do not come easily. They require commitment, understanding, and patience. The long-term rewards are great and are worth the extra effort.



D.E. Coleman | P.G. Stein

Better yields, better understanding: An example of statistical production engineering

When looking for machining defects in VideoDisc styli, measured at the limits of light microscopy, RCA engineers depended on statistical production engineering to ferret out some of the hidden causes.

Statistical production engineering is an interdisciplinary procedure by which manufacturing processes may be simultaneously improved in both yield and product quality. This is accomplished through studies that increase our basic understanding of how a process works. When we have this understanding, the day-to-day operation of the process becomes more consistent because the effects of adverse changes that occur in any manufacturing process can be corrected.

At RCA's VideoDisc cartridge plant at Rockville Road, Indianapolis, the diamond stylus that reads the video signal from a CED VideoDisc is plated, faceted, assembled into a plastic and metal cartridge, and machined. A recent statistical production engineering effort was successful in helping to improve this manufacturing process, reducing rejects at one near-final step of the process from 15 percent to 2 percent. This effort represented a cooperation between VideoDisc cartridge personnel and statisticians from the David Sarnoff Research Center. Some details of this effort are presented here. They emphasize the concepts and strategy used, so that application of the same techniques to other processes may be easily understood.

The stylus and v-to-p

The cartridge is about the size of a box of paper clips, and one is installed in each VideoDisc player manufactured by RCA in Bloomington, Indiana. Cartridges are also distributed to be sold as replacement parts. The process used to manufacture a stylus is unique, and is particularly hard to understand and control because of the stylus's physical dimensions.

A stylus must be machined with tolerances of fractions of a micrometer (one micrometer is 1/1,000,000 meter, or 0.00003937 inches). It is very difficult to see and measure fractions of a micrometer, even with a good optical microscope or shadowgraph. A micrometer is only as long as two wavelengths of yellow light, and therefore perilously close to the ultimate limits of light microscopy. Similarly, the actual processes used by RCA to machine ("micromachine") the styli are impossible to watch. Only snapshot views can be obtained by aborting the micromachining process to take measurements—and this runs the risk of introducing additional (and uncharacteristic) variation in the process and product.

One problem that has concerned personnel at RCA's VideoDisc cartridge plant involves the faceting and micromachining of two geometric features of the VideoDisc stylus that are supposed to be in the same spatial plane. One of them is called the "v line," and the other is the "prow"—from an analogy to boating (Fig. 1, next page).

The "v line" starts at the back of the bottom part of the stylus which, seen from the rear (the electrode side), is shaped like a "v." It continues forward for the entire length of the shoe (that part of the stylus which rides in the VideoDisc groove.) The prow is the lower front part of the stylus. It steers the stylus along the groove.

The distance between the plane of the v line and the plane of the prow, as optically measured at the apex, or lowest point of the prow, is referred to as "v-to-prow off-center," or simply, "v-to-p." In a geometrically perfect stylus, the v line should end at the prow; a v-to-p of zero is best. V-to-p was one of the major defect classes found at the visual inspection station following final micromachining. It had been responsible for a cartridge reject rate of about 15 percent at that station.

Strategy for tracking down v-to-p

Members of the RCA Laboratories Productivity and Quality Assurance Research group were teamed with staff from the

Abstract: *Working as a member of a team of engineers and other technical people, an industrial statistician can help solve production problems. He or she does this by increasing the understanding of cause-and-effect relationships between process steps and product characteristics. This was done recently in RCA's VideoDisc cartridge plant, with some significant results.*

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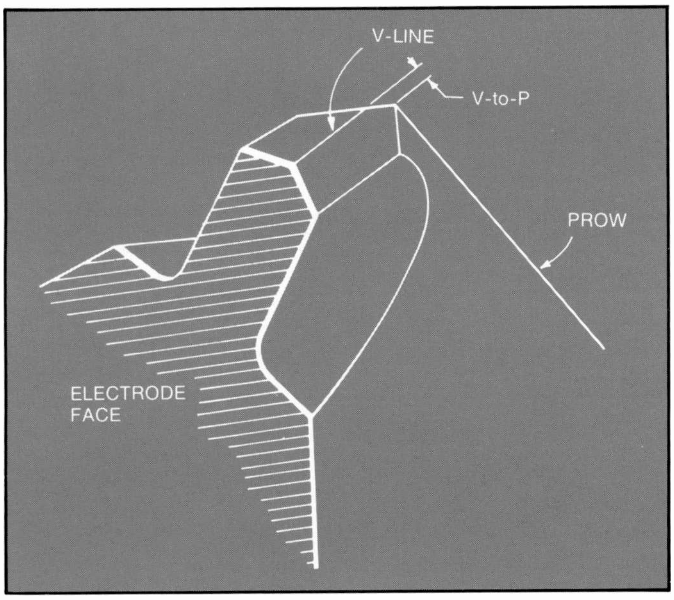


Fig. 1. *The VideoDisc cartridge stylus, with geometric features noted. The "shoe" makes contact with the bottom of the groove. The prow is the leading edge of the stylus. The "v line" runs along the bottom center of the shoe. In a perfect stylus, the "v line" intersects the prow.*

VideoDisc stylus terminology

The following terms are used in the article and describe the different alignment directions of the VideoDisc stylus with respect to the VideoDisc groove.

Lean: angle of the stylus as measured in line with the disc groove.

Azimuth: rotational angle of the stylus as measured between the disc groove line and the normal to the electrode surface. The electrode surface should be perpendicular (90°) to the side of the disc groove, which corresponds to an azimuth of 0°.

Tilt: angle of the stylus to the side of disc groove.

Electrode facet angle: angle on the electrode face from the prow facet to the vertical plane perpendicular to the electrode face.

Prow heading: angle of the heading of the line formed by the intersection of the two prow facets with respect to the disc groove centerline.

Shoulder-height induced angle: v-p offcenter that occurs at setdown on the micromachining tool. It is caused by the different shoulder heights of the tool grooves.

VideoDisc cartridge plant to track down the causes of v-to-p. The ultimate goal was gaining a better understanding of these causes so they could be reduced or eliminated. A number of possible causes of v-to-p had been proposed and, through the use of engineering judgment, partially ranked lists of these proposed causes had been produced. There was general agreement that v-to-p and its causes were poorly understood. Because of the small dimensions and difficult measurements involved, though, it was not clear that the rankings were correct, or that the lists even contained the most important causes!

Divide and conquer

The strategy was to take a methodical and disciplined approach. This was unlikely to find a quick solution to the problem, but would guarantee that at each stage of investigation some knowledge would be gained, thus shrinking the list of possible causes. This "divide-and-conquer" strategy differs from the troubleshooting often seen in manufacturing, which uses a mixture of engineering judgment and experience. In general, the statistical production engineering approach does not promise immediate results. It is therefore inappropriate to expect "quick fixes," but rather to look for an evolutionary improvement due to deeper understanding of the process. These results, though slower, can still be dramatic.

The first step in this divide-and-conquer approach was to determine the primary source (*not* cause) of v-to-p variability. Was it due to v-to-p measurement variation (lack of repeatability)? Stylus variation? Cartridge assembly variation? There are four separate stations of micromachining equipment. Was there variation among them, or were they all performing alike? There are two micromachining media, types N and R, and different micromachining tools are used. Did media or tools contribute variation? Nobody knew for sure. The data available did not point in a clear direction. To answer these questions, a hierarchical, or "nested," study was proposed based on the hierarchy of the micromachining process. This "process capability study" focused on the capability of the existing process to make cartridges free of v-to-p problems, to measure the variability of the existing process, and to split this variability up into its separate sources.

Process capability study

The hierarchy was natural, at least on a gross scale. First, there were four micromachining stations. Second, on each station either of two types of media could be used. These two parameters could be chosen at will for the study. Third, for each type of medium we had some sample micromachining tools all from the same tool production run. Fourth, for each tool we had some typical cartridges. These latter two parameters were sources of variation that were taken as given, and were truly "nested." Calling this situation nested means that while medium N could be run on station 1 or on station 3, the medium of tool 37 could not be changed, nor could we try tool 37 on different stations. Similarly, we could micromachine a cartridge on only one tool—hence on only one medium and on only one station. The structure of the study is shown in Fig. 2. Additionally, some cartridges were measured twice to give an estimate of the measurement error.

Before the study was carried out, some technical staff and some managers were asked to estimate the sources of variation and their relative proportions. This was done in order to get everyone to think in quantitative terms, to see a variety of ideas about the variability, and to enable us to later measure what we had learned from the study. The estimates from this exercise are shown in Fig. 3.

The study was carried out in April, 1983. As the study results in Fig. 3 illustrate, most (71 percent) of the v-to-p problem had its source in cartridge-to-cartridge variability. In other

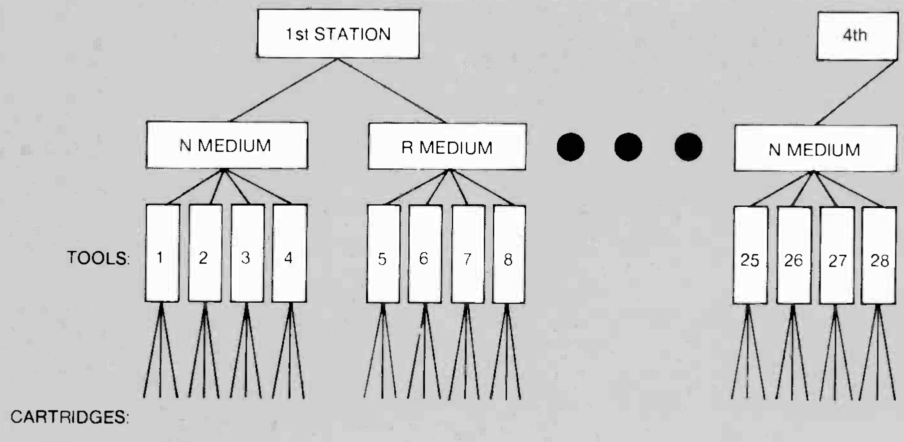


Fig. 2. *Design of the process capability study. The natural hierarchy of the micromachining process is reflected in this designed study. The specific details of how many media per station were used, how many tools per medium type were used, etc. directly entered into the analysis of variance done on the data obtained.*

Source of variability	***Estimated total % of variance***	***Percentage variance predictions and (% off from study)***				
		Person 1	*Person 2*	*Person 3*	*Person 4*	*Person 5*
Station	9	5 (− 4)	5 (− 4)	5 (− 4)	15 (+ 6)	13 (+ 4)
Medium	0	20 (+20)	20 (+20)	30 (+30)	25 (+25)	0 (0)
Tool	18	5 (−13)	40 (+22)	5 (−13)	15 (− 3)	12 (− 6)
Cartridge	71	60 (−11)	30 (−41)	40 (−31)	50 (−21)	50 (−21)
Measurement error	2	10 (+ 8)	5 (+ 3)	5 (+ 3)	5 (+ 3)	25 (+23)

Fig. 3. *What we have learned from the study (4/7/83). Five people in the cartridge manufacturing plant can quantify what they learned from this study. These five gave predictions of variance components for each of the sources of variability identified in the study: station, medium on tool, tool, cartridge, and measurement error. Here are the results in percent of total variability.*

words, the cartridges were different from one another *before micromachining* in an important (and unknown) way. This unknown difference accounted for 71 percent of the variation seen in the v-to-p measurement, while the differences among stations, in the media, in the tools, and in the measurements accounted for only 29%. That this cartridge-to-cartridge difference was the main source of variability was not a great surprise (see Fig. 3), but the extent to which it accounted for v-to-p was new information. This conclusion indicated that efforts should be focused on cartridge-to-cartridge variation first.

To study cartridge-to-cartridge variation, a list of possible causes of v-to-p was needed that indicated what could vary from cartridge to cartridge. To generate this list, some information from the cartridge plant was obtained and, in addition, a modeling technique was used.

Finding an ideal model

Independent of this Statistical Production Engineering effort, Dr. A. Moldovan of the Princeton Labs had developed an "ideal geometric micromachining" model that used a trigonometric formula to compute what machining would occur when a stylus with six specific geometric characteristics came into contact with a tool with one specific geometric characteristic. The model intentionally ignored such phenomena as resonances between stylus and tool, changes in any part of the cartridge other than the stylus during micromachining, nonuniformities in the machining medium, and the crystallographic orientation of the stylus. Moldovan had integrated into the model those characteristics of the stylus and tool that he thought were important and that he thought could be modeled reasonably easily.

Previously, Moldovan had used his model for Monte Carlo computer studies. He made distributional assumptions of interest for the seven geometric variables, and essentially drew values for these variables from the distributions for many thousands of simulated cartridges. His formula gave a predicted v-to-p for each group of seven variable settings. For any choice of distributions of the seven variables—each chosen to represent a manufacturing situation—an approximate distribution of v-to-p could be computed. Additionally, since Moldovan's model includes an

VARIABLE SETTING							V—TO—P THAT RESULTS
VAR: 1	2	3	4	5	6	7	
1	1	1	1	1	1	1	—0:3846
1	1	1	1	1	1	2	—0.2192
1	1	1	1	1	1	3	—0.1140
			.				.
			.				.
			.				.
5	5	5	5	5	5	4	1.0012
5	5	5	5	5	5	5	1.0034

Fig. 4. *Design of the simulation experiment. A 5-to-the-7th full factorial "experiment" was run using Dr. A. Moldovan's "ideal micromachining" model. The data produced by the model took this form.*

T-Ratio	
624	(1) Electrode Facet Right
622	(2) Electrode Facet Left
2205	(3) Tilt
1081	(4) Shoulder Height Induced Angle
3966	(5) Azimuth
3966	(6) Prow Heading
0	(7) Prow to (Normal—to—Disc)
298	(3) & (7) Interaction

The greater the T-ratio, the greater the statistical significance. Greater than 4 is very significant.

Fig. 5. *Results of the simulation experiment. A quantitative ranking of the significance (and impact) of the control variables is given here, based on the regression analysis of the 2187-observation subset of the 15625 observations.*

analytic expression for v-to-p, the importance of the variables could be roughly ranked.

The designed experiment

The approach taken for this study, however, was a little different. In addition to providing some validation for the model, we wanted to rank the importance of the variables, and to quantify their relative importance in manufacturing. At the same time, it was possible to investigate the impact of interaction and quadratic effects as well as the linear effects. This would serve to guide the effort in the next stage of tracking down v-to-p: the performance of a designed experiment in the factory to identify specific cartridge sources of v-to-p problems. To reach this objective, a simple designed experiment was planned for computer simulation: a 5-to-the-7th "full" factorial experimental design, with every possible combination of five settings for each of the seven variables. The five settings were:

(1) low end of spec;

(5) high end of spec;

(3) nominal (spec midpoint);

(2) midway between (1) and (3); and

(4) midway between (3) and (5).

Moldovan's model was used to get all the v-to-p estimates, as shown in Fig. 4.

Since there were no random effects, including measurement error, in this simulation experiment, no repeated estimates were made for any combination of the settings. This design gave us $5\times5\times5\times5\times5\times5\times5 = 15625$ v-to-p estimates. Settings (2) and (4) were dropped, leaving $3\times3\times3\times3\times3\times3\times3 = 2187$ v-to-p estimates from which to make estimates of the linear, interaction, and quadratic terms, using regression analysis. The rest of the v-to-p estimates were used as a cross-validation, to "check the fit" of the mathematical expression obtained from the regression on the 2187 estimates.

The experimental results

The results of this experiment on simulated data are shown in Fig. 5. In summary, the model had a good fit, good validation, and the variables with the most statistically significant contributions to v-to-p were azimuth and prow-heading, tilt (half as significant as azimuth and prow heading), shoulder-height induced angle (half as significant as tilt), electrode facet angles (60 percent as significant as shoulder-height induced angle) and the rest. Quadratic terms were not important, but interactions were somewhat so—the most important of which (tilt and prow-to-normal-to-disc) occurred seventh on the ranked list of effects from the regression analysis.

The next stage of investigation was to statistically design an experiment that would give us estimates of the same terms, but from "real" data—that is, cartridges produced in the VideoDisc cartridge plant. It was impractical to consider actually setting all seven of the simulation variables in the production environment. Selection was made from the most important variables as identified by the simulation experiment, and an experiment was designed using them. Making this choice is not as straightforward as it may seem. In order to use variables that conform to the structure of the designed experiment, the variables had to be able to be set to predetermined values in the factory. The problem of "setting error" was not commonly appreciated in the manufacturing situation. Processes designed to manufacture parts to a nominal value cannot always specifically be changed to be able to set a variable at a predetermined value other than the nominal. In addition, it was now necessary to address the problem of measurement error in v-to-p, and in the variables themselves. The process capability study had, fortunately, shown the measurement error of v-to-p to be relatively small. If the measurement error were unknown, it would be impossible to determine the setting error of the variables.

After considerable discussion about the logistics, priorities, and design, an experiment and a plan for carrying it out were agreed upon. The key variables chosen were azimuth, prow heading, and tilt. The design chosen was a two-cubed full factor-

Setting or selecting? Which is better for a designed experiment?

Should an attempt be made to build samples of a product so as to set control variables at the levels called for by the design, or can the output of routine production generate the range of values required by the design? To answer this question requires judgment and experience on the part of the statistician and the engineer, because there are tradeoffs to be made.

On the one hand, if design points are chosen that are somewhat moderate—that deviate only slightly from the nominal—there will be a risk of seeing only local behavior or noise. This is analogous to looking at a small slice of data that shows roughly linear behavior. The advantage of choosing small deviations is that it will be relatively simple to get samples of the product that have the values required by the design. This can be done either by slight process modifications to set the control variables, or by selecting from existing production.

On the other hand, if more extreme design points are chosen, the study is more likely to see causal behavior through the noise, at the risk of detecting behavior uncharacteristic of possible control variable settings in production.

Setting control variables by modifying the process runs two risks. First, modifying the process will likely change more than just the control variable intended. Second, it is impossible to modify the process to obtain precisely the desired setting. This is due both to setting error and measurement error.

Selection from current product to find samples that conform to the design points runs three risks. First, measurement error prevents us from obtaining precisely the desired setting. Second, a selection of product that has the desired characteristics may be different from nominal product in other, unknown ways. Third it may also be impractical to select from current product. This is often the case for complex designs.

For example, with a 2-to-the-4th factorial experiment design, with settings at the plus/minus two standard deviations from the (nominal) mean, and given that the control variables have a Gaussian distribution, there is a chance of 0.00000057 that any given sample would meet a given design point.

The complexity of these issues and their implications for both statistician and engineer means that it is important to address them early in the process of planning a designed experiment.

ial with eight replicates to protect against setting error, and to help estimate unexplained variability. This design is shown schematically in Fig. 6. Each variable was planned to be set at two settings, its specification low, and its specification high.

The data and results

In August of 1983 the experiment was conducted over a week's period. After all the data had been collected, the results were analyzed. Additional measurements were taken on the styli made with synthetic diamonds, and these were also analyzed. The results of the experiment are summarized in Fig. 7. In brief, it was found that:

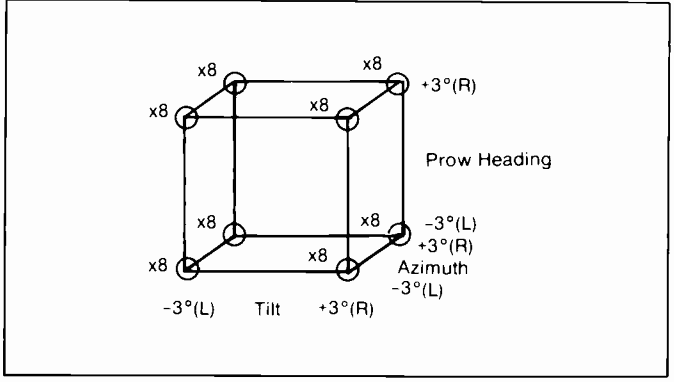


Fig. 6. *Design of the v-to-p experiment. The design of the v-to-p experiment called for eight cartridges to be built for each of the eight possible combinations of tilt (3° L/ 3° R), azimuth (3° L/ 3° R), and prow heading (3° L/ 3° R), totaling 8 × 8 = 64 cartridges for each type of diamond stylus, natural and synthetic.*

1. Setting error was serious—cartridges could not be specially built as desired.
2. Right electrode facet angle, tilt, and azimuth were statistically significant causes of v-to-p for synthetic diamonds.
3. Synthetic diamonds differed greatly from natural diamonds.
4. Right electrode facet angle and left electrode facet angle did not behave with the same degree of importance in affecting v-to-p.

The results of the analysis prompted the cartridge plant people to

T-Ratio	
3.78	(1) Electrode Facet Right
2.15	(2) Electrode Facet Left
2.02	(3) Tilt
3.13	(5) Azimuth
1.52	(6) Prow Heading
1.21	(7) Prow to (Normal—to—Disc)
1.91	(8) Force
1.65	(9) Bias

The greater the T-ratio, the greater the statistical significance. Greater than 2 is probably significant.

Fig. 7. *Results of v-to-p experiment. A quantitative ranking of the significance and impact of both control variables and other variables (measured on the cartridges after the experiment was conducted) is shown here for the synthetic diamond stylus.*

reexamine the faceting and assembly operations, where two of the key variables, tilt and electrode facet angles, were set during stylus manufacturing. These were of particular interest because they were identified as the most important variables by the in-plant experiment, because of the unequal magnitudes of the left and right facet angles, and because of the interaction term of tilt and prow-to-(normal-to-disc).

During this reexamination, it was discovered that the first alignment fixture for prow faceting was skewed. This caused a fixed shift away from the nominal. In order to produce acceptable cartridges further on in the assembly process, the rest of the faceting equipment had been set up to compensate for the hidden shift. Although this appeared to correct a problem, it actually compounded the problem and obscured the fact that there was a problem. The compounding effect was a result of nonlinearities in the impact of one variable on another. Specifically, when the tilt was not zero, the electrode facet angles could not be properly set and measured. This in turn meant that the prow angle could not be correctly set and measured.

Prompt effort went towards correcting not only the primary problem on the first faceting fixture, but the "cascade" of problems that had been introduced because of the first problem. The immediate impact of making these corrections was a reduction of v-to-p rejects from the 15-percent level to the 5-percent level. Subsequent improvements of this sort have reduced the reject level to about 2 percent. This reduction, coupled with the fact that v-to-p causes only a soft failure (over the long term it leads to an increase in noise in one of the stereo channels), means that v-to-p alone no longer justifies an inspection after micromachining.

It is anticipated that other problems, some which now do justify inspection, will be discovered and solved using the systematic methodology of statistical production engineering.

Summary

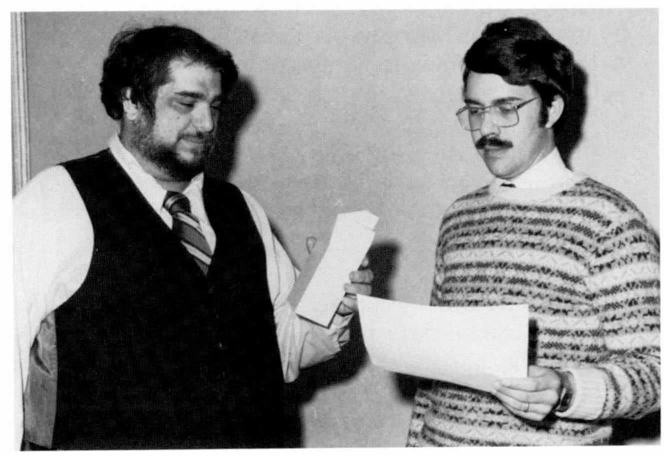
The reduction of the v-to-p problem in the VideoDisc cartridge plant from about 15 percent to about 2 percent was the result of a cooperative effort between Labs industrial statisticians and the managers and technical people at the plant. The contribution of the statisticians was an unbiased, statistically sound, and effective collection of methodologies for investigating the problem. The contribution of the VideoDisc cartridge plant people was commitment to carry out the project at the risk of short-term production losses, technical (especially engineering) expertise, and refreshing candor to keep the statisticians on a path that made sound engineering sense.

The systematic investigation described appears easy. In fact, it was not as simple as it appears. The process capability study turned out different from the way it had been designed. Geometric variables were frequently confused, since they are conceptually difficult to envision and can't be seen directly. Forty percent of the data used in the first computer simulation experiment were discovered to be incorrect. The design of the experiment to study cartridge-to-cartridge variability was completely revised four times.

The activities and benefits described here are but a fraction of the successful work carried out by the people at RCA's VideoDisc cartridge plant, in which statistical production engineering techniques are used.

Acknowledgments

The authors particularly wish to thank Bert Gunter, who did much of the work described herein. Gary Gerhold and Bob McCarthy supported the effort from the start, and Eric Bennett, Bob Goldberger, Terry Beaty, Kathy Conoley-Busald, Dave Hutchins, Mike Mindel, John Rupp, and the many others worked hard to make the use of statistical production engineering in the VideoDisc cartridge plant a valuable day-to-day tool. Anthony Moldovan contributed the geometric model as well as many valuable discussions.



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J.W. Gaylord

Structuring the design of factory information systems

Today's electronic manufacturing operations are complex, highly technical, dynamic systems requiring astute management. The Factory Information System (FIS) supporting this management must be designed with help from system specialists to be "used and useful."

A Factory Information System (FIS) is used to collect data, convert it to information, and communicate the information to people so they can use it to make decisions. The system also assists in changing the decisions into actions that improve productivity by communicating the control directives, derived from the decisions, to appropriate people and machines whose location and tasks are determined by the flow of product. The design of an FIS is thus concerned with the flow of data, information, control directives, and product.

Abstract: *This article describes the methodology of Structured Design as applied to Factory Information Systems (FIS). Structured Design provides four major benefits to the FIS designer and user.*

1. *How the system is used becomes an integral part of the design process.*
2. *The quality of the system is improved because a better "needs analysis" occurs.*
3. *The effort expended to specify the system is reduced.*
4. *Documentation for training system users is produced as part of the design process.*

The author has adapted the techniques of structured analysis used for computer system design[1,2] for use in analyzing and specifying the manufacturing system. The methods were applied to the Automatic Component Insertion portion of the factory information system (called FACTS) at RCA's TV chassis assembly plant in Juarez, Mexico. A broadly inclusive application specification resulted that the Manufacturing Technology Center[3] of the Consumer Electronics Division used as the guide for implementation.

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Product, control, and data flow

The most obvious portion of the design concerns the flow of product because this is physically observable. Product flow refers to the movement of materials, or of assemblies being produced, along well-defined physical paths. For continuously processed materials, these paths are pipes, reactors, storage tanks, and so on. Conveyors, moving belts or hangers, transfer machines, automatic assembly machines, and robots, are some of the paths for assembled products. Product-flow diagrams are essential for plant layout, work-in-process control, and scheduling. They describe the physical plant and form the basis for modeling the dynamics of product movement.

Control flow is less obvious because it is not physically apparent. It is the movement of verbal or written directives that originate at some authority and pass through a chain of command to terminate in a directed action. Control flow begins with decisions and ends with actions. The actions usually directly impact product flow. The decisions usually originate with information derived from the analysis of data.

Data flow is the movement of data through the process of their collection, verification, analysis, conversion to information, and presentation in easily understood form to an authority. Data have always been collected to measure the performance of manufacturing operations. Now, more accurate and larger quantities of data can be collected by the use of sensors and computers. The computers also are used to do much of the data analysis function and to present the derived information in graphical form or summarized in management-by-exception reports.

The relationship between the flow of product, control, and data is illustrated in Fig. 1. Motion around this flow loop is continuous. The objective of all this motion is to learn from each decision how to make the next one better. The shorter the cycle time around the loop, the more chances there are to succeed. The decisions being tested usually come from many people at various levels of the manufacturing organization. The loop thus provides a way of evaluating many decisions simultaneously and studying the interaction between these decisions.

Structured Design encompasses more than just the data and information portion of the flow loop. Control flow and the resulting actions taken with the manufacturing process are included as part of the design procedure. FIS users and designers participate in defining how they will evaluate each type of information, what the resulting directives will be, and who will be responsible for converting these directives to action.

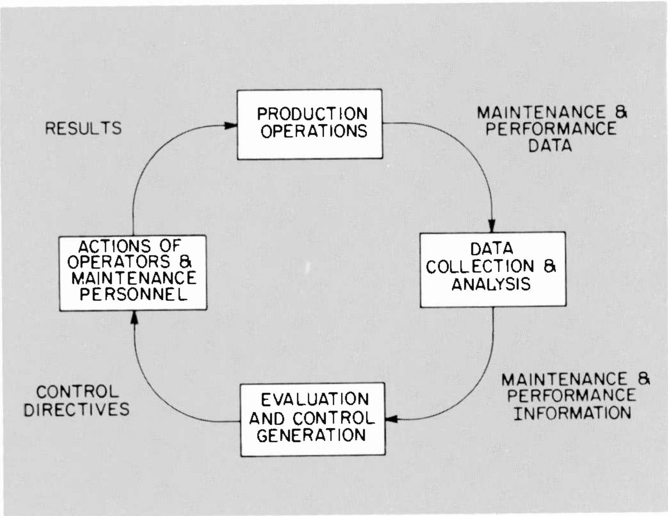


Fig. 1. *The data → information → control-action loop.*

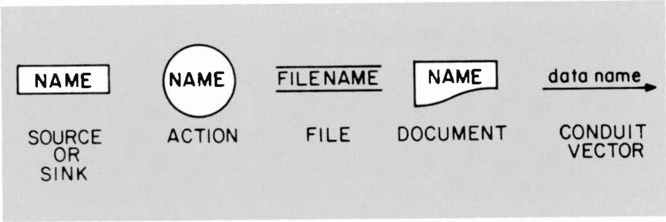


Fig. 2. *Data-flow diagram symbols.*

Fig. 3. *Action symbol.*

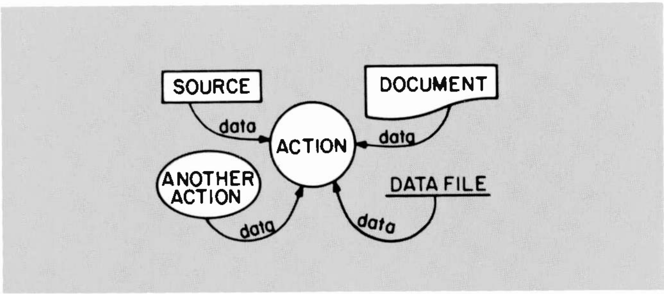


Fig. 4. *Generalized sources of data.*

Because data collection and analysis have become much more economically feasible, the quantity of available manufacturing data has increased. To maintain and improve the quality of these data, better planning to determine the true manufacturing data needs and how to meet them is required. Data, information, and control-flow diagramming—along with the supporting methodologies of mini-specifications, data dictionaries, and mock-ups—are tools for manufacturing people to use to accomplish this planning.

Data-flow diagramming

A data-flow diagram shows data needed for analysis and decision making, sources of the data, what the analysis is, and what is done with the information produced by the analysis. The diagramming technique greatly simplifies manufacturing needs analysis, system design, and eventual system use by providing a common graphical document that people from widely varied disciplines can easily interpret and understand. The data-flow diagram is a set of symbols representing sources and sinks for data, actions taken using the data, data storage files, and documents produced. Vectors are used to tell where and what data are transferred between the symbols.

The symbols shown in Fig. 2 are suggested for manufacturing systems. It is essential for clear and concise communication that the same symbols be used by the many people from different organizations who usually work on a manufacturing system project.

A "source" symbol represents the origin of data. The origin can be a person, machine, or any tangible physical thing that produces data. The "sink" is a repository for data or for the information that is derived from the data. Usually the sink is a machine or person that needs the data to make decisions and exercise control. Sources and sinks are terminators of the data-flow diagram in the sense of initiating the flow and receiving the results. The "action" symbol defines what is done with the data to transform them into more useful information. Actions are identified by a hierarchical numbering scheme that will be described later in more detail. Data storage is represented by the "files" symbol. The file symbol can have an optional "header" to ease diagramming. These files are physically located in computer storage devices (disks, memory, magnetic tapes, and so on). "Documents" can also be used to store data but more often are used to transfer information to a person, who can be thought of as a "sink," for some "action." The "conduit vector" indicates the path and direction of data flow. Its label defines the specific data being conducted.

To illustrate data-flow diagramming, consider the task of defining and documenting what a hypothetical production system such as the familiar popcorn popper should do. The verb "do" implies that the production system will take a series of "actions" to accomplish specific tasks. The first specific task is to test for out-of-control conditions in the popping process. The action symbol is shown in Fig. 3.

The next step is to determine what data the system needs to accomplish the "action." This is always some kind of data from the generalized sources shown in Fig. 4. For the popper control system the specific sources are shown in Fig. 5.

The data-flow diagram also shows where the data and information resulting from the "action" are used. The general case is shown in Fig. 6. The popper-control system with repositories added is shown in Fig. 7.

The symbols of data-flow diagrams are connected together to represent a series of actions. For example, the "test popper control" action can be considered as three separate actions. The first is the collection of temperature data. The second is the processing of these data along with the control limits to establish whether the process is in control. The third is the plotting of a control chart. The data-flow diagram of Fig. 7 is expanded to show this greater detail in Fig. 8.

Data-flow diagrams can thus be expanded by breaking down actions into greater detail. Conversely, they can be contracted into simpler, less-detailed representations by combining multiple actions into a single action. The choice depends on the complexity of the action and the level of detail desired. The rule of thumb is to keep each diagram size small enough to fit on an 8-inch by 11-inch page.

Most systems require a number of diagram levels for adequate definition. The top level uses actions that are very broad in scope. These actions are represented in greater and greater detail in the underlying diagram levels. The diagram levels are designated by a hierarchical numbering system. For example the first level of the "test popper control" action of Fig. 7 is identified with the number "1." In Fig. 8 this same action is divided into three actions. They are identified as 1.1, 1.2, and 1.3.

If a shift occurs in the average measured temperature, the temperature setting of the popper controller has to be adjusted. The first-level diagram of Fig. 7 then would change to include the control loop as shown in Fig. 9. The more detailed data-flow diagram describing the "Reset Thermostat" action would be comprised of a series of detailed actions labeled 2.1, 2.2, 2.3, and so on.

If this were done, the popcorn-popper system would be described by a single first-level and two second-level diagrams, with all of them fitting on three 8-inch by 11-inch pages. These pages, like the contents of a good reference book, provide both a broadly scoped and a detailed description of what is to happen. In addition they lead, like an index, to the necessary supporting documents that completely define the system. These documents are the mini-specification, data dictionary, and mock-ups to be described later in this article.

The second-level actions can be further detailed by creating a third level (for example, 1.1.1, 1.1.2, 1.1.3, ...) and so forth. In this way, any action can be divided into greater and greater detail until it reaches the level necessary for system implementation. The action "symbols" are labeled hierarchically as illustrated so that the documentation can be easily organized.

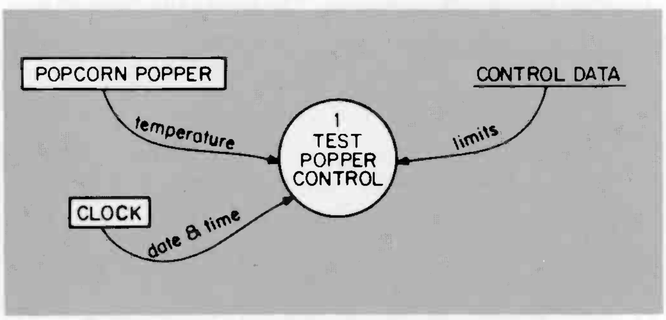


Fig. 5. *Popper control-system data sources.*

A powerful aspect of this methodology is its modularity. An action symbol represents a module. It can be changed without affecting the other modules, and therefore without affecting the total system design. This independence occurs because each action module at any level is a "black box" with certain inputs and outputs. As long as these inputs and outputs remain the same, the system doesn't care what goes on in detail within the action module.

This modularity can be represented on the data-flow dia-

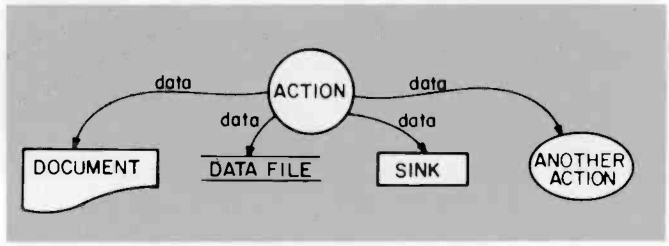


Fig. 6. *General repositories of data.*

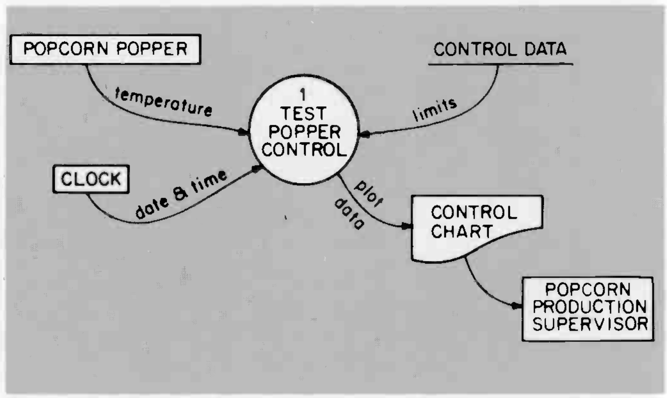


Fig. 7. *Popper-control-system with data repositories.*

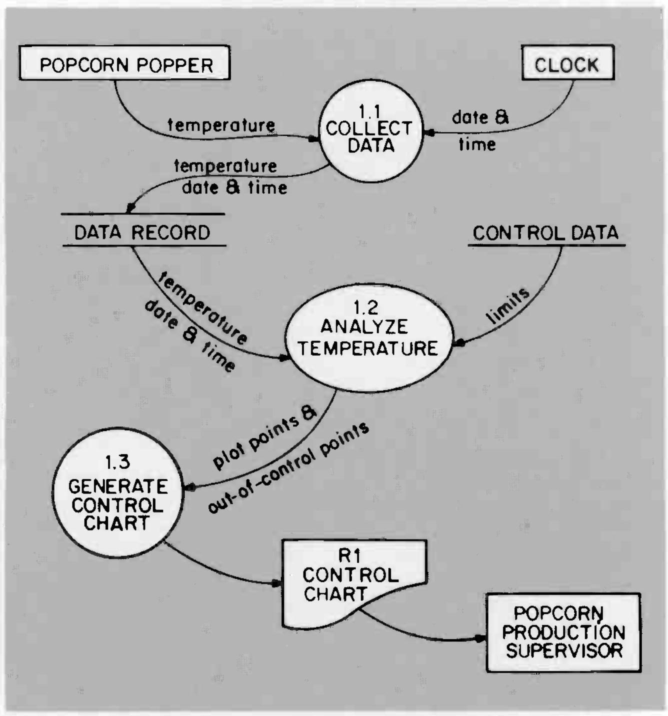


Fig. 8. *Detailed popper-control-system data flow.*

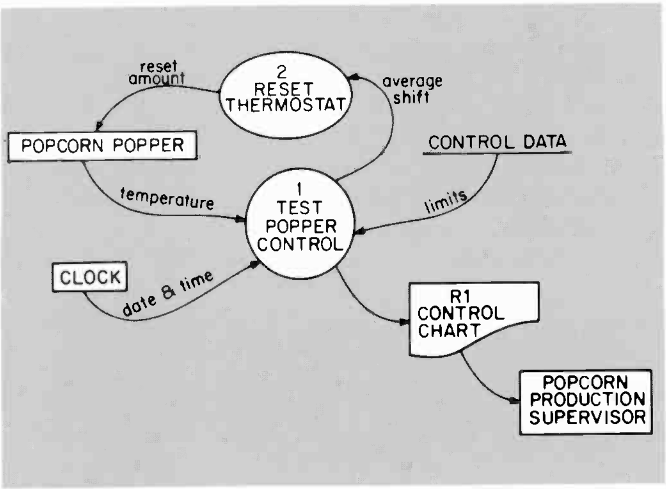


Fig. 9. *Corn-popper data flow.*

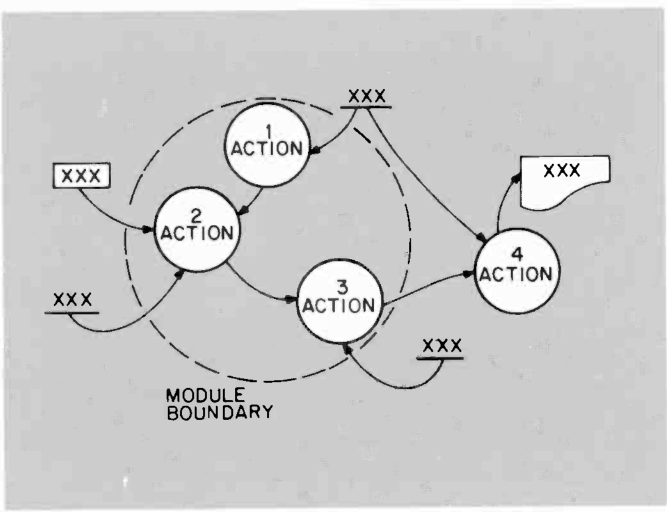


Fig. 10. *Modularity of an area of actions.*

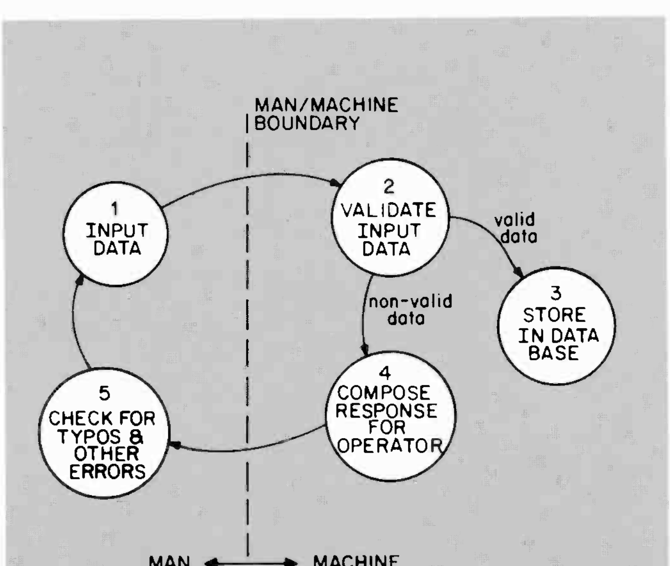


Fig. 11. *The man/machinery boundary.*

gram by boundaries around an action or groups of actions. For example, if the action 1.2 in Fig. 8 is found to use computer resources very poorly, thus slowing down the responsiveness of the popcorn manufacturing system, it can be changed by perhaps making hardware or software modifications. This can occur without the propagation of changes through the rest of the system because the input across the boundary (from the data record and control data files) and the output across the boundary (to generate the control chart) remain the same.

We have seen that actions can be combined or divided. This leads, *a priori,* to the conclusion that the module boundary can encompass a number of actions. This is illustrated by actions 1, 2, and 3 in Fig. 10.

The bounded area can be considered as a module that can be changed independently, as long as the type of data transferred by the vectors crossing the boundary does not change. The boundary can also define a physical area where the described actions take place. For instance, it may represent a specific machine, department, or building of the plant complex. Systems designed with the aid of structured methodology can automatically provide the desired independence between organizations by using the boundary concept and simultaneously tie the organizations together through the data-flow paths (conduit vectors).

To preserve the advantage of modularity, whatever crosses the boundary must remain invariant. The boundary is also a very convenient way to specifically define the interface between people, machines, and orgânizations. This helps to clarify system user responsibilities during needs analysis and later during the start-up of production use. The use of boundaries to separate men and machines is illustrated in Fig. 11. The area to the right of the boundary is the computer system. The area to the left is the human environment. Data that cross the boundary into the computer must originate with people. Data from the computer, intended for people, cross the boundary in the opposite direction. To design and optimize the human interface of a computer-based system, one only has to address the problems defined by the data flow across the boundary. This greatly simplifies the interface problem by specifically defining what the issues are and where they occur. When the system has multiple users, in different locations, and at different organizational levels, the boundary technique helps communicate and clarify these issues.

Modularity is an intrinsic quality of data-flow diagramming. If data-flow diagrams are used to define what a system should do and the system is so implemented, it will be inherently modular. This means the system can more easily evolve as needs change with time.

Mini-specifications

The mini-specification is a detailed description of a single "action" described in a data-flow diagram. The label of an "action" symbol suffices for the broadly scoped data-flow diagram, but is not detailed enough to adequately define how the action is to be carried out. The term "mini" relates to the narrowly detailed scope of each specification.

A mini-specification accompanies every "action" symbol of the data-flow diagram. Each mini-specification is identified by the same number as its corresponding "action" symbol. For example, the Corn-Popper Data-Flow diagram of Fig. 8 has an action symbol labeled, "1.1 Collect Data." The mini-specification for this action would be identified as, "1.1 Collect Data Mini-Spec."

The form of the mini-specification should be as simple and concise as possible. It is the primary document used by software engineers to create programs that accomplish the desired "action." It is usually written in a structured format called "structured English" to conform to modern programming objectives of portability and documentation. If structured English is used, the programmer has an easier job converting the specification into the specific structured software language(s) used for the system.[4]

Structured English consists of a set of key words written in a format that adds meaning to the key words. The most common format is indentation. Every level of indentation indicates a subset of commands that are to be executed until a logical conclusion is reached. The basic key words and their logic are shown in Fig. 12.

The level of command-line indentation, combined with the key words, conveys the logic form to be used. Other ordinary English words are also used to increase the information content of the commands and to make the specification more intelligible.

There are four basic forms of logic required to define the actions of a data-flow diagram. They are serial commands, branching commands, repetitive-looping commands, and looping commands with internal exits. These various forms are discussed in the following paragraphs.

Sequentially executed serial commands are written as a column of left-justified statements at the same level of indentation. Figure 13 illustrates a mini-specification composed of the serial-command sequence for the action symbol "1.1 Collect Data" of Fig. 8.

Decisions are a major function of any computer-based manufacturing system. Decisions involve "branching" to the various alternatives available for action after a "test" is made. The decision logic and key words for branching commands are also shown in Fig. 12. The key word combinations of "IF" and "OTHERWISE" or "WHEN" and "ELSE" describe single-choice branches. Multiple-choice branches can be made by combining single branches or by using the key word "SELECT."

Branching commands are needed for many applications. For example, suppose that when the corn-popper manufacturing system tries to store the data record referred to in Fig. 13, the power to the disk is turned off and the store cannot be executed. The system designer should take care of this contingency by adding a branch to the end of the mini-specification. The command sequence shown in Fig. 13 would then appear as Fig. 14.

The third form of logic is repetitive looping. This is the repeated execution of the same command or series of commands until a test condition is met. The key words and logic for looping are also shown in Fig. 12. The test that ends the repetition can be done before or after the series of commands is executed. If it is done before, the key word is "UNTIL" or "WHILE." If the test is made after the loop is executed the key words are "REPEAT UNTIL" or "REPEAT WHILE." As an example, to make the whistling more effective the mini-specification could read the way it's given in Fig. 15.

The commands within the loop in this example are designated by indentation under the "until"-condition test statement. After the indented loop has been executed six times, the program exits the loop and shuts down the popper.

The fourth form of logic needed for manufacturing system control is the loop with exit shown in Fig. 12. To illustrate loop with exit, suppose a response is required from the popper operator prior to shutting down the popper. This would be a way to save the in-process product. Since the operator may on occasion

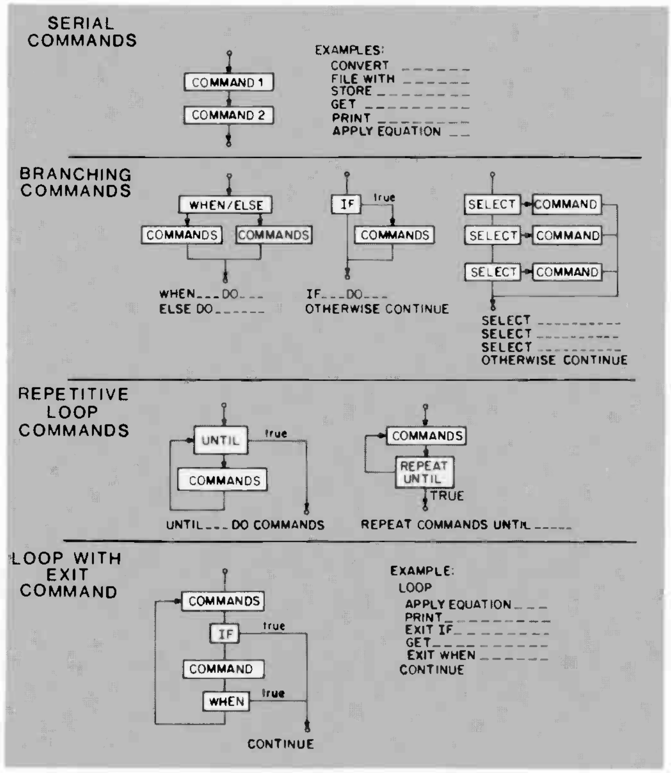


Fig. 12. *Structured-English key words and logic.*

Request temperature reading from popper
Store temperature in data record
Request date and time from clock
Store date and time in data record
Store data record on disk
Continue

Fig. 13. *1.1 Collect data mini-spec.*

Request temperature reading from popper
Store temperature in data record
Request date and time from clock
Store data and time in data record
Store data record on disk
If data record is stored
    Continue
Otherwise
    Blow whistle for 10 seconds
    Shut down popper
Continue

Fig. 14. *1.1 Collect data mini-spec with branch.*

```
Request temperature reading from popper
Store temperature in data record
Request date and time from clock
Store data and time in data record
Store data record on disk
If data record is stored
    Continue
Otherwise
Until 6 times
    Blow whistle for 10 seconds
    Wait 60 seconds
Shut down popper
Continue
```

Fig. 15. *1.1 Collect data mini-spec with branching and whistle control.*

```
Request temperature reading from popper
Store temperature in data record
Request date and time from clock
Store date and time in data record
Store data record on disk
Loop
    If loop done 6 times
        Shut down popper
        Exit loop
    Exit if data record is stored
    Otherwise
        Blow whistle 10 seconds
        Wait 60 seconds
        Exit if operator shuts off popper
    Otherwise continue loop
Continue
```

Fig. 16. *1.1 Collect data mini-spec including branching, whistle control, and shutdown.*

not be present when the whistle blows, it is also necessary that the whistling be limited to six blasts and not continue indefinitely. It is also necessary to shut down the popper automatically if the operator does not return to avoid damage to the equipment.

The mini-specification could now appear as in Fig. 16.

The mini-specification thus becomes a very concise document of detailed commands configured in a format consistent with modern structured programming. The format also imposes modularity. This is best illustrated by the logic diagrams of Fig. 12. Each of these diagrams have only one starting and one ending point. Between the start and end points, a module has been defined that is independent of any other logic intrusion. This independence, like the modularity imposed by the data-flow diagram, makes software changes and growth much easier.

```
C1 Production calendar
    For each year (A8)
        For each day (A8)
            For each shift (I1)
                Shift length in hours (F2.1)
C2 Configuration file
    For each machine in plant
        Machine ID (I2)
C3 Recipe to model cross index
    For each recipe ID (A4)
        Model name (A10)
D1 Machine data
    For each machine
        For each shift
            Machine ID (I2)
            Shift date (A8)
            Shift ID (I1)
            For each recipe used
                Recipe ID (A4)
                Production output (I4)
R1 Monthly production output report
    For each month
        For each model
            Model name (A10)
            Units produced (I-4)
            Units per machine hour (I4)
```

Fig. 17. *Example data dictionary.*

The data dictionary

The data dictionary describes the contents of files and documents represented on the data-flow diagram. These files and documents are usually defined on the diagram and in the data dictionary by the same letter-number combination. The letter identifies the type of data stored in the file or the type of document, and the number identifies the specific contents. Common letter prefixes used are:

D = Data from manufacturing operations, machines, and so on;

S = Standards for the manufacturing operation that are relatively constant;

C = Configuration data describing the contents of the factory;

PR = Process recipes; and

R = Reports.

The user defines these prefixes to meet the needs of the particular system. An example of a data dictionary is shown in Fig. 17.

The alphanumeric code to the right of dictionary entries defines the type and precision of the data stored. These codes are not the same as FORTRAN field specifications that include the spaces for signs, decimal points, and so on. The user can also define these codes to meet specific needs. The codes used in this example are:

A = Use alphanumeric characters.

I = Use integer numbers.

F = Use fixed-point (decimal) numbers.

The number associated with these letters tells how many characters or numbers will have to be stored for each entry. For example, A8 means the entry for this data is composed of 8 alphanumeric characters. I2 means two integers.

For fixed point, the number to the left of the decimal tells how many whole integers are used and the number to the right of the decimal tells how many digits are to the right of the decimal. For example, F2.3 means it is a fixed-point number with 2 whole integers and 3 digits in the fractional part (for example, 54.358). A minus sign placed after the code letter is used to show that the number can be negative. The absence of a sign means that only positive numbers can occur. For example, the UNITS PRODUCED filed in R1 is shown as (I–4). This means production is anticipated to be as large as tens of thousands, requiring four integers to quantify the magnitude. The (–) means that because of scrap, the magnitude of the units produced can occasionally be negative.

The data structure is inferred by the form of the data dictionary. Like the mini-spec, the data dictionary uses indentation to denote subsets of data. This relationship is a particularly valuable guide to setting up the owner-member relationships of the database or file system used for data storage.

During the needs-analysis phase of a Factory Information System Design the data dictionary grows, along with the data-flow diagram, mock-ups, and mini-specs, to describe the required system. The data dictionary becomes the document that describes the content of the manufacturing database. It is used as the guide for database design because it inherently contains not only the required data but the data structure (relationships).

The mock-up

The mock-up is a prototype report, chart, graph, or plot that describes by example the exact form and content of the documents to be produced by the system. The mock-up is very easy for system users to appreciate and understand. The popcorn-production system produces a control chart for the superintendent (see Fig. 8). The mock-up of this chart is shown in Fig. 18.

Procedure for implementation

Doing a Structured System Design using data-flow diagrams, mini-specifications, data dictionaries, and mock-ups is not a nice, straightforward, serial set of tasks. The value of this methodology is its recognition that the creative planning process occurs from looking at a problem both broadly and in detail, and from var-

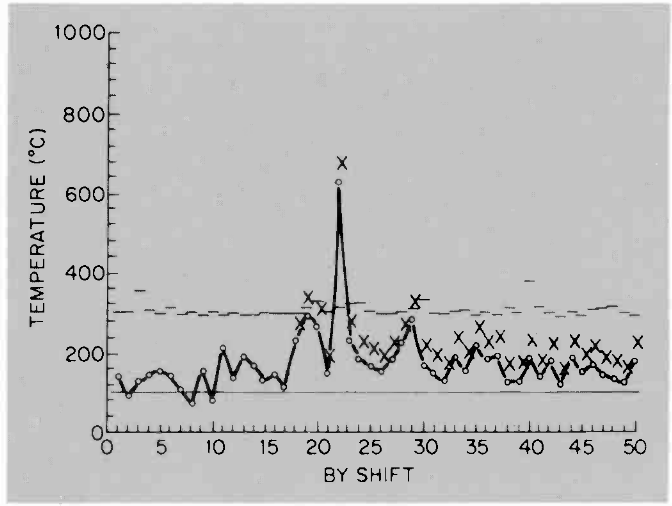


Fig. 18. *Popcorn-popper control chart mock-up.*

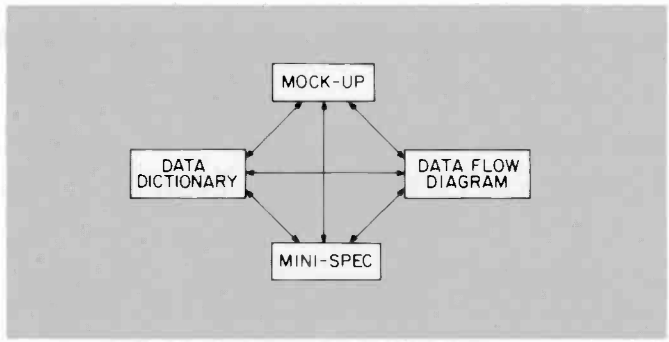
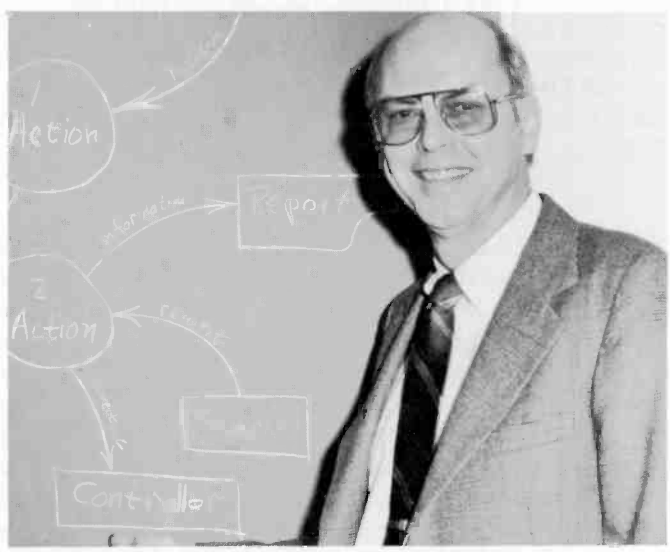


Fig. 19. *Procedure for structured systems design.*



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ious viewpoints simultaneously. A technique the author uses to accomplish this is to lay out on a desk four piles of the above documents with work room in the center. Each pile contains the same type of document. The engineer achieves the system design by moving within the data-flow diagram and mini-specification piles to produce varying degrees of detail and from pile to pile for varying viewpoints. This technique is illustrated in Fig. 19.

Acknowledgments

Evolving a methodology involves some trial and error. Those people who participate have to carry, in addition to the stress of their own tasks, the frustration of dealing with new ways of communication. The author is grateful to Jim Grayson and Nancy Gates of the CE Manufacturing Technology Center, to David Coleman, Duane Piper, Donald Fisher, Stuart Golin, and Tom Stiller at the Laboratories, the ACI production organization managed by Peter Krolow at Juarez, and to the FIS organization headed by Ray Jordan, also at Juarez for their patience and constructive ideas as this methodology evolved.

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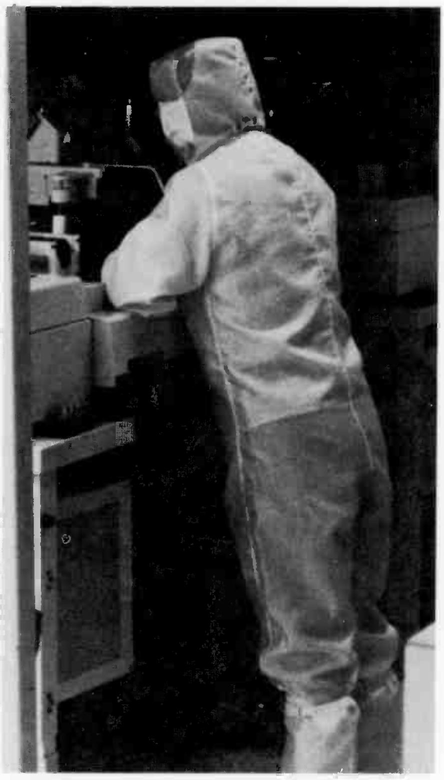

Analysis of lot cycletime in microelectronics manufacture

Knowledge of cycletimes is important to both manufacturing and production control.

Within the solid-state industry, product is moved through circuit-fabrication processing in groups of 24 to 96 units called "lots." These lots, while following the same general type of process flow, adhere to predefined sets of operations called processes. Each process is a unique route whereby raw silicon is turned into a group of identical finished circuits. Each process derives its uniqueness from the number of steps, sequence of steps, or the amount of time necessary to perform the steps. Measurement of the elapsed time consumed in processing, or cycletime, is one measure of the effectiveness of the manufacturing process.

Cycletime can be defined as the elapsed time that a wafer lot uses in traversing a report point, or location (Fig. 1). It is measured by taking the difference between the time a lot moves into a location and the time it moves into the next location, relative to a production calendar that eliminates weekends, holidays, and other non-production time.

In the linear circuit fabrication area at RCA Solid State Division in Findlay, Ohio, an online computer system called PMC (Process Monitor and Control) collects logistics data on the movement of product. The software system was written by the Solid State Technology Center and runs on a Data General Eclipse 300 minicomputer. This logistics data has been extracted for analysis by manufacturing supervision using a combination of system-supplied utilities and user-written BASIC language programs.

Abstract: *The manufacturing perspective from RCA Solid State Division in Findlay, Ohio, is given here. Periodic surveillance of microelectronics-circuit-lot cycletimes, on a by-type and by-location basis, will indicate the degree of control present, the room for improvement, and the changes in operating conditions in manufacturing. Use of scheduling algorithms separate from management control methods will allow better, on-time production of wafers by type.*

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Cycletimes: Two points of view

Knowledge of cycletimes is important to both manufacturing and production control. Management-control methods concentrate on creating a repeatable, dependable performance from a system composed of a multitude of people, processes, and "gremlins." Sometimes the methods even succeed. The result is a performance that varies, but averages to a repeatable set of values in both cycletime and yield to good product.

Manufacturing supervision concentrates on providing a continuous flow of events without detailed regard for the identity of the specific product in the flow. This Aggregate Inventory Management (AIM) system is designed to cause normal results for all product at all times, relying on the proper and timely injection of materials into the line to cause the proper output mix. AIM uses exception conditions to cause remedial action. Therefore, a need arises to know what is meant by "normal," relative to product movement.

Production control, on the other hand, views manufacturing on the average, treating cycletime as a repeatable, machine-like phenomenon that will deliver specific product to specific customers in a precisely stated time. Use of the average value as

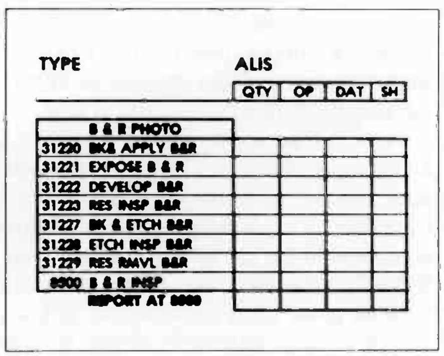


Fig. 1. *An excerpt from a lot card. "Base-and-resistor" photoengraving is one of fourteen locations, representing 8 of the 100 operations, in a simple bipolar process.*

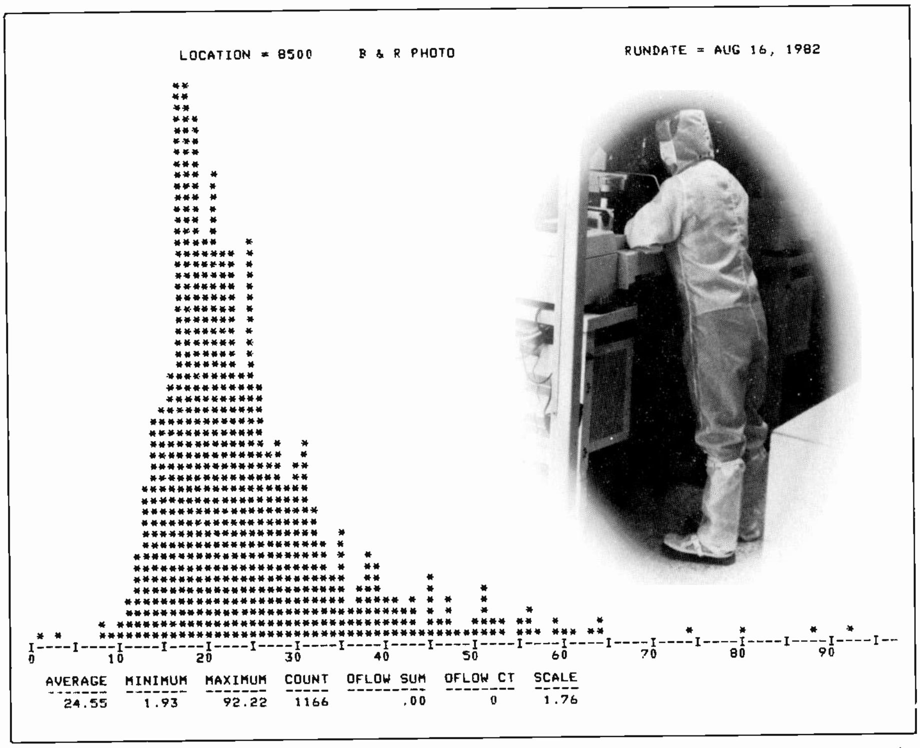


Fig. 2. *Location-8500 graph. The distribution of lot cycletimes through base-and-resistor photoengraving is given. Theoretical cycletime is about 8 hours. Each asterisk represents 1.76 lots in the multi-asterisk columns.*

the scheduling-model cycletime, therefore, guarantees that about 50 percent of the product being scheduled will arrive before it is needed, and 50 percent will arrive after it is wanted. The implication is clear. Manufacturing control systems must be separated from scheduling systems, although the relationship between the two must be maintained. A suggestion on what this relationship might be is contained in the conclusion of this article.

Surveying and analyzing lot cycletimes

Periodic surveillance of lot cycletimes on a by-type, by-location basis will indicate the degree of control present, the room for improvement, and the changes in operating conditions in a manufacturing area.

At the type level, a move through a location represents a standard and calculable amount of work called "theoretical" cycletime. The average actual cycletime compared to the theoretical time is a "multiplier," often used as a figure of merit without proof of its applicability. In practice, it is more instructive simply to analyze the distribution of actual cycletimes without reference to theoretical cycletime. To the extent that types are nearly identical in processing, aggregates by product or process can be made, to generate larger data samples that can reveal patterns more easily.

For ease of analysis, the cycletime data is presented in graphic form. In the attached examples, the data was rationalized for presentation on single sheets of paper. A maximum of 50 vertical quantity buckets and 100 horizontal time buckets are displayed for any event (Fig. 2). The vertical buckets were ratioed so that the mode, if greater than 50, equals 50, and all other buckets are proportional. Time is treated differently. Because we knew beforehand that a 4-day (96-hour) horizon will fit 99 percent of the lots, the elapsed hours were displayed as found, except that lot times in excess of 96 hours were cumulated in bucket "97." In this way, no time distortion was introduced, permitting direct visual comparison of time distributions from one location to another. Total cycletimes, whose values range from 8 to 25 days, were displayed in shifts, on a straight "divide-by-8" basis.

Simple statistics are displayed: number of lots, gross average time, total hours cumulated in bucket "97." After publication, a net average time is calculated by rejecting cycletimes on the somewhat arbitrary minimum/maximum limits set visually as not being part of the "normal" flow of product. The rationale for rejection is that times below a clearly definable minimum processing time are "catch-up" reporting, and excessively long times are the offsetting unreported lot movements, or are "engineering-hold" conditions and not a part of regular scheduled processing.

Visual inspection of the resulting rationalized graphs revealed that:

1. Theoretical cycletime becomes apparent as the minimum time on the graph, assuming that in a large sample some few lots will, by chance, move in theoretical time (Fig. 2).
2. As with any manually controlled system, times distribute themselves in a skew-normal curve, with a right-hand tail of significant length that, in turn, increases the arithmetic average well above the median time (Fig. 3).
3. The range of the curve and the slope of the left-hand side of the distribution are an accurate presentation of the amount of conscious control being exercised over product movement. The more effective the management that is being exercised, the more highly modal is the curve; the less, the more randomly are events distributed.

   A shop that runs FIFO (First In, First Out) concentrates on moving product through an operation in the order of arrival and as soon as possible. Since there must be some minimum processing time, the closer to that minimum that lots move through the operation, the less time they are simply waiting around to be processed; therefore, the more effective is the management control that is orchestrating that move. Please note that "management control" embraces operator training, proper equipment, materials, manpower, guidance and motivation, and not just a whip and a chair.
4. Cyclical events can be seen as multimodal distributions, as, for example, in the case of a long processing time through a limited facility that accumulates randomly arriving product for release in large waves (Fig. 4).
5. Production lots contain different circuits for different customers. At a given facility, the lots arriving may not be process-compatible, meaning that they must constitute their own batch because of differences in gas flow, time, temperature, and so on. Even when they are compatible, units are not interchangeable between lots. Therefore, in building a batch load, each lot must be loaded in such a manner that its iden-

tity can be maintained, allowing subsequent resegregation into its original lot. Being only human, one tends to "cherry pick"; one runs lots in the order that causes the least physical and/or mental effort. Since "cherry picking" violates FIFO processing, it is a constant source of frustration to the supervisor as he attempts to minimize its continual reappearance.

The modality of the curve and the slope of the right-hand side of the distribution will generally indicate the "bunching" effect of high-volume types when viewing an aggregated sample (Fig. 3). High volume at close to minimum time, with a gradual falloff of volume to the longer times, seems to indicate that a high-volume type will "capture" a processing system and will release it only after exhausting the inventory of that type. This release is followed by another capture by the next highest volume type. The extreme times will generally belong to minority types that tend to be ignored even when no change in set-up is needed, acknowledging the greater mental effort necessary to combine unlike types to generate a full batch, and then to split them back to individual lots after processing (see point 3 above on effective management).

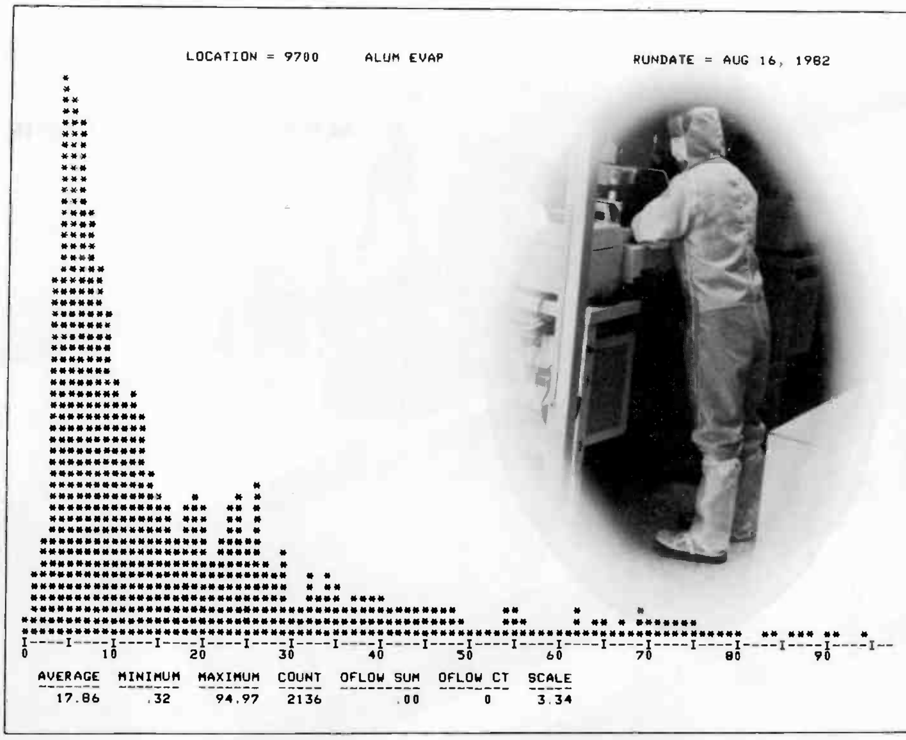


Fig. 3. *Location-9700 graph. Aluminum evaporation, a bottleneck facility, exhibits the "capture" phenomenon. Theoretical minimum is about 1.5 hours. Compare the mean of 17.86 hours and the median of about 12 hours to the minimum.*

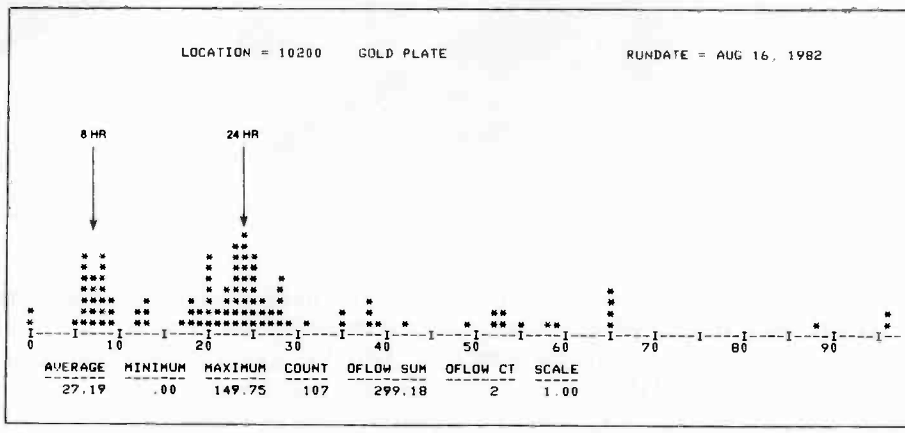


Fig. 4. *Location-10200 graph. The gold-plate operation in the tri-metal process section is the subject. Manning only on first shift leads to product release within 8 or 24 hours of arrival.*

Corrective action

Analysis of the resultant graphs can give rise to a variety of corrective actions:

1. Where a significant theoretical cycletime is observed, a radical process change is required to improve throughput time. This often requires an infusion of capital. For example, if 13,000 angstroms of silicon dioxide must be deposited on each wafer, doubling the deposition rate would cut the cycletime roughly in half. Usually, the deposition rate is already at the maximum for that type of machine, requiring that a new, and more expensive, machine be purchased. Running smaller batches more frequently could also reduce the waiting portion of cycletime, but again, more machines would have to be obtained.
2. Multimodal distributions can be analyzed for the cause of the cyclic effect. It may be due to a manpower allocation or a critical, long-process-time facility that restricts smooth flow. Again, a dollar-for-time tradeoff decision can be made (Fig. 4).
3. A location whose normalized average is many multiples of theoretical cycletime is probably a bottleneck facility. As such, it will permit constant flow of product, but the maximum output rate is very close to the average arrival rate, causing a relatively high and constant average throughput time. Either an additional facility must be provided to increase the output-to-arrival ratio (assuming an efficient processing method is in place), or a management method must be installed to ensure that lots are moved in the proper priority sequence, for example, FIFO, type-sensitive, and so on, to meet plant objectives.

An aluminum deposition system capable of processing 750 units per day is matched to an arrival rate of 750 per day. While capacity is theoretically sufficient, arrivals are never exactly linear, allowing dead time on the system. Surges of product then cause inventory buildup, even though the average arrival rate remains constant. Mechanical breakdowns will cause product to accumulate also, thereby generating queue, or wait, time for each lot until overtime or sheer effort is focussed to reduce the backlog. When such a condition arises, a distortion to cycletime is introduced.

Deposition of a protective layer of silicon dioxide on the almost-finished wafer permits later handling of the individual circuit in the assembly process, and imparts desired electrical or reliability characteristics.

The movement of product through the facility must be ordered by management according to priority until the cause for delay is eliminated (Fig. 3).

Available management tools

Exception lot report

One management tool that can readily be developed is an exception lot report. Each lot is tested against a by-type time limit appropriate to that location. The limits are arrived at pragmatically from normalized actual history. Those lots that exceed the limit are flagged to supervision for investigation and expediting. The effect is to "chop off" the right-hand tail of the curve before the extended cycletimes can degrade average performance. Another result is to narrow significantly the range of times within a location. This in turn reduces the advantage of a total inventory prioritizing system (for example, AP/D), since LIFO (Last In, First Out) processing no longer gains great chunks of time advantage.

AP/D, the activity planner/dispatch system, is a vendor-written system that plans intended activity, then monitors actual performance. The monitoring function is provided by comparing the planned time for completion of a lot to the remaining actual time. The highest ratio of planned to actual time indicates the most urgency, and hence determines the lot to be moved first. Where a process moves in essentially random order, accelerating a lot to the head of a line will gain time. However, in a tightly controlled process, the difference between minimum and maximum times will be small, reducing the gain to be made by expending exceptional effort. The major problem associated with such a system is that it has a single-valued priority scheme. When volumes are low relative to capacity, any priority scheme will move product. Near capacity, when a customer-oriented priority becomes critical, the single-valued lateness measure will give false priorities since, historically, due dates are not maintained in the hectic atmosphere of day-to-day survival.

At the same time, priorities are established for all lots at all locations. Some lots may be acceptably late in view of volume, while others are critically late. Yet all locations and all lots clamor for attention by the very existence of a list. Since a lot may be anywhere within the six to ten operations comprising a logistics system location, much supervisory effort is required to find the #1 lot, do something extraordinary to it, then find #2, all the while trying to avoid disturbing the "normal" flow of product—all of this while attempting to sort out system-generated priorities from management-directed priorities. An exception report places effort in areas where supervisory action can make a difference, where abnormal things are happening (or failing to happen), and the report ignores areas where things are happening normally. It also looks only at lots that are already abnormal, ignoring the rest. Since supervisory effort is also a scarce resource, effective rationing means applying it where it can return the most value—in correcting the correctable.

An aggregate inventory management system using exception reporting is always more economical of effort than a 100 percent line-item system, and is generally more dependable in its application across shifts and supervisors, since all supervisors are reacting to the same known set of abnormalities.

Graphs

A second tool is the periodic publication and comparison of the graphs. Any shift in centering or change in shape or range signifies a change in manufacturing conditions. Analysis of these changes will determine whether corrective action is needed, help indicate the type of action needed, and equally important, limit the action to those areas that will benefit. This analysis can be aided by publication of relevant figures of merit such as average lot size, number of types and processes active, minimum/maximum number of lots of a type, and so on. If desired, statistical analysis is available to test the significance of an apparent change, or to predict future behavior of product under projected conditions.

The primary tests to be applied are calculating the mean and standard deviations of the new and old distributions. The null hypothesis then tests, to whatever level of significance desired, the existence of true change. Bear in mind that this system is designed to be used for rapid evaluation and corrective action. There is no substitute for an experienced supervisor who can look at a set of histograms, offset his feel for changes in product mix, discount weather and operator attendance, and arrive at corrective action necessary to restore baseline performance.

This analysis can also be used to aid in overall ontime delivery of product. When manufacturing is operating under an AIM system, lots will be processed in random order through operation sequences with the AIM controls designed only to keep all product moving in an orderly manner. The output total cycletime is, therefore, a normal distribution about an average value, ranging from a low of theoretical cycletime to a high of slightly greater distance from average than the low. A spread above and below average of 30 percent of the average is not unusual (that is, a 15-day average will deliver product within a range of 10.5 to 19.5 days after its start date).

The etch and inspect line. Chemical etch sinks and rinse tanks are on the right. Binocular microscopes on the left are under laminar flow to combat particulate contamination.

Summary

Average cycletime, by-type operation, sequence time limits, and continuing analysis of cycletime performance must be used as a part of an Aggregate Inventory Management system designed to stabilize and improve product-delivery cycles, or detect and correct problems early on.

Production control need only make a small change to its view of manufacturing in order to take advantage of the cycletime-enforcing mechanism in an AIM system. The start dates of product into a line must use a "percent-of-delivery" concept to inject material such that a stated percentage of the product will be available by a desired date for delivery to a customer or offshore plant (Fig. 5).

This apparent addition of up to 30 percent more cycletime is not in fact an addition. It is simply a recognition of what will happen anyway so far as product delivery is concerned. Because the manufacturing-line speed controls remain unchanged, no additional inventory is created over the present method. If all types were instantaneously switched over to a promise-date starting schedule, there would be a self-correcting blip in the line while the "50-percent late" lots cleared to sales. This condition would last about one cycle while AIM and capacity limits returned the line to a smooth, dependable flow of product.

This graphic analysis of cycletime is now being adapted for use with the IC-10 sys-

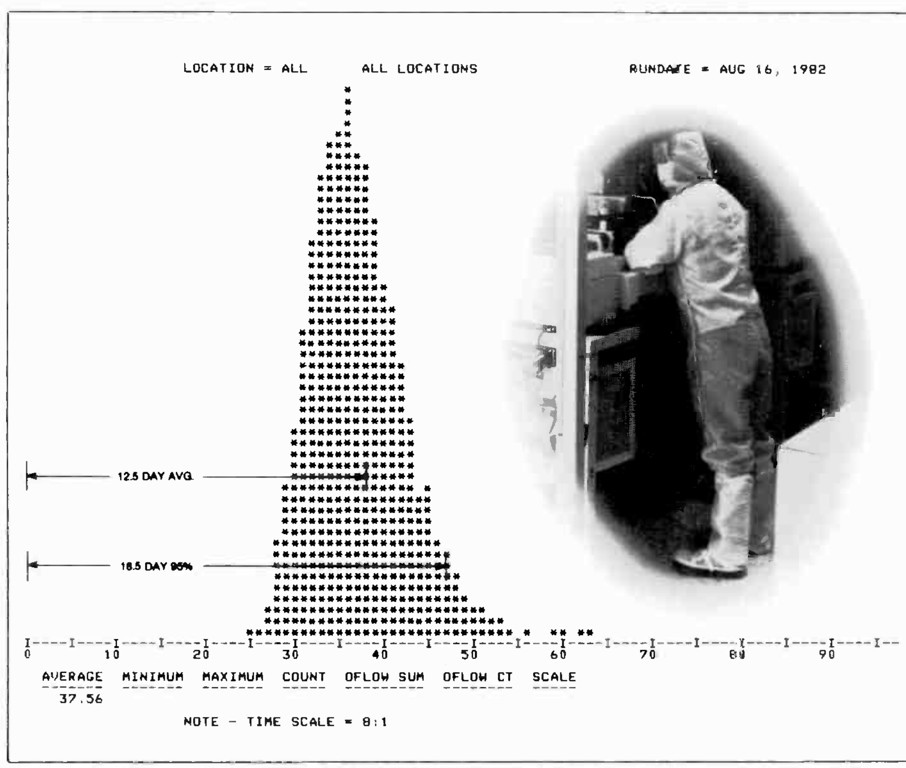
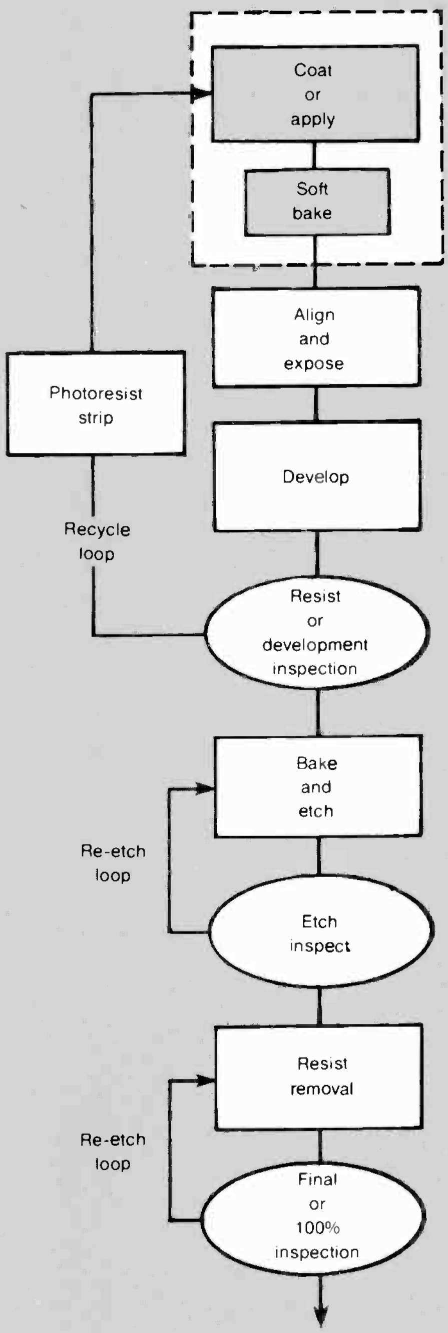


Fig. 5. *Location-all graph. Total cycletime from raw silicon to untested circuits is represented. Manufacturing controls movement on a 12.5-day average performance. Production control should inject material into the line 19 days prior to need.*

tem, the SSD logistics system replacing PMC. It will then be made available to all locations within SSD for use by local management as the need arises.

Photoresist flow diagram



Photoresist is deposited and spun onto the wafer in a smooth and even coat.

The wafers are baked, after the coating process, to remove any residual solvent left in the resist and to improve the adhesion of the resist to the wafer.

The current mask pattern is aligned to the wafer, or to the previous pattern or patterns, and the wafer is exposed to ultraviolet light.

Unpolymerized resist (resist that was not hardened during exposure) is washed off.

The wafers are inspected, after development, for flaws in the current photoresist pattern such as misalignment, scratches, pinholes, and so on. Rejects are stripped of photoresist and sent back through the recycle loop shown.

The wafers are baked again to ensure that the resist is hardened and moisture free. They are then immersed in an acid. In the areas that are not covered by photoresist, the oxide or metal is etched away.

The wafers are inspected, after etching, for flaws in the etch process. Wafers that have not been etched long enough are re-etched until they are clear.

The wafers are immersed in a solution to remove the no-longer-needed photoresist.

Wafers are inspected to ensure that all the photoresist has been removed. Wafers that have not been completely stripped are reprocessed back through resist or chemistry removal.

Photoresist flow diagram. Diagram of the photoengraving process. Alignment is to tolerances of 1 to 5 microns. Etch and resist removal increasingly is achieved using plasma technology instead of wet processing.

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D.F. Hakala | D.J. Wierschke

Matrixing for VideoDisc

Strict attention to process control and microcontaminant control are required to manufacture copper and nickel metal parts of sufficient quality to meet VideoDisc needs.

The prime responsibility of the VideoDisc Matrix Department at Rockville Road, Indianapolis, Indiana, is to convert the recorded copper substrate received from mastering to some large number of stampers. Stampers are the electroformed nickel parts that are clamped to the press mold to provide the actual molding surface itself. In addition, the Matrix Department produces the plated copper material that is used by mastering as the recording medium.

Electroforming is a modification of more conventional plating techniques in which the detail of the surface being plated upon is replicated in the surface of the plate. A passive layer on the parent part permits ready separation of the plated daughter part. This is different from most plating operations where adhesion of the plate to the substrate is usually important.

Economical production of the stampers requires the use of a fan-out process that reuses parent parts several times so that, as the original recording is replicated to the master, mother, and finally stamper level, the "family" grows rapidly in size. Fan-out refers to the number of times each parent part can be reused. An overview of the metal-part process flow is given in Fig. 1.

Abstract: *The initial master copy is recorded on a plated copper substrate produced in the Matrix Department. After recording, nickel electroforming is used to replicate this copy to make press tooling in a fan-out process. The processing steps required to do this are decribed, along with material and process control requirements.*

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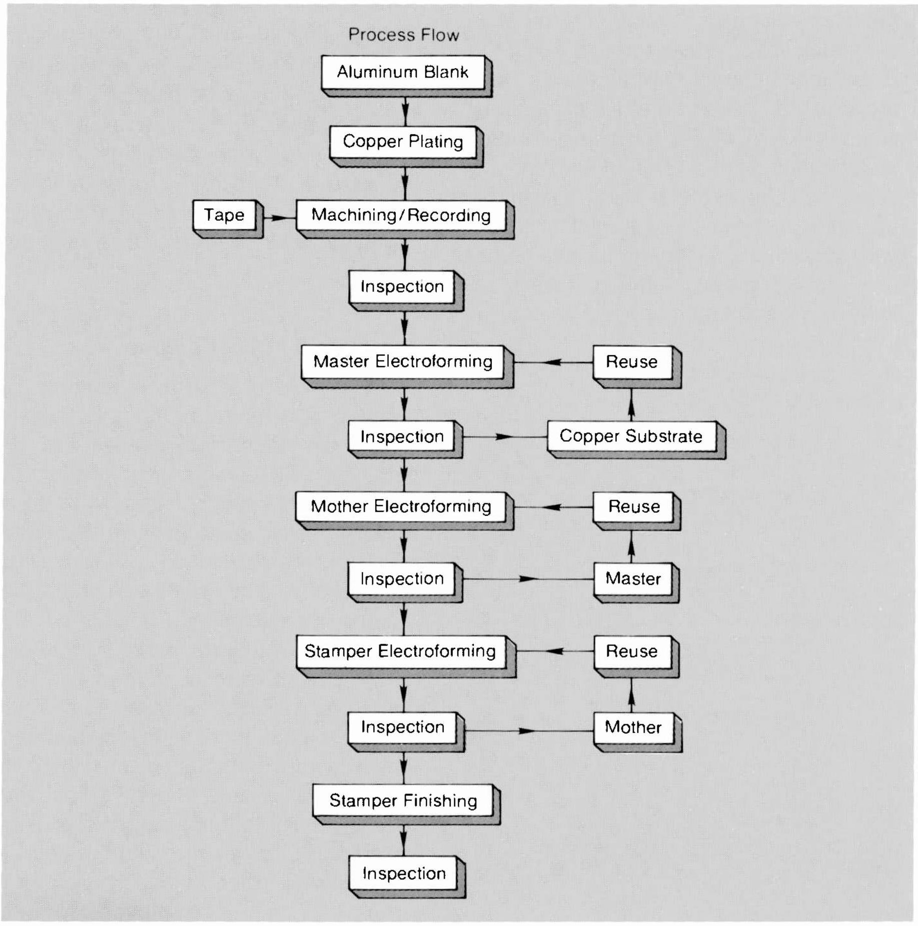

Fig. 1. *VideoDisc metal parts manufacture process flow.*

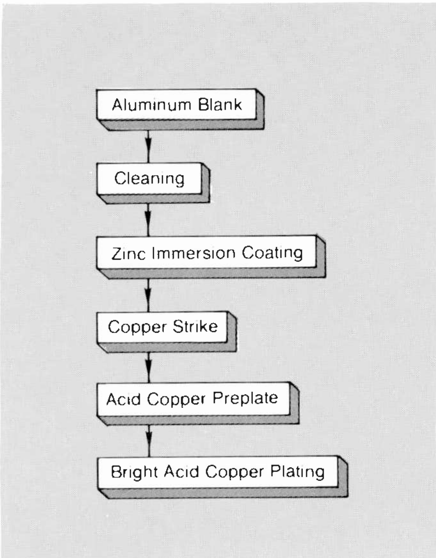

Fig. 2. *Copper plating sequence.*

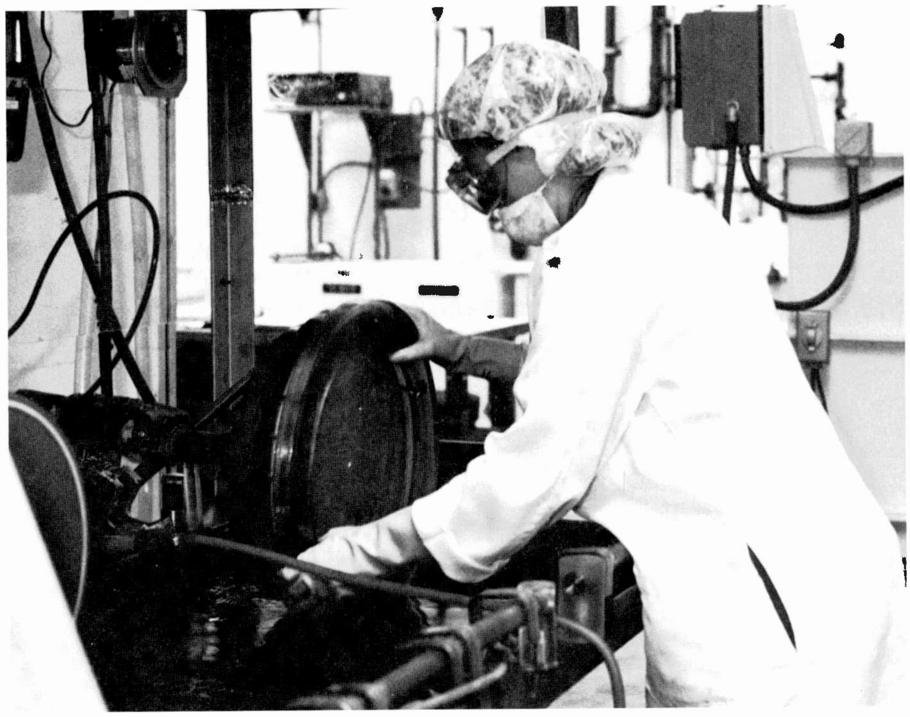

Fig. 3. *Bright acid copper plating bath. The operator loads a preplated aluminum blank onto the plating head for plating of bright copper deposit. The deposit is used as machining medium for VideoDisc mastering.*

Manufacturing process

Copper preplate

The VideoDisc matrix department first becomes involved in the process of manufacture of the VideoDisc when an aluminum blank (14.5 inch diameter, 0.5 inch thick) is electroplated with a layer of extremely fine-grained copper that is 1/15,000 of an inch thick. This is done through a series of cleaning and plating steps that begin when the blank is received from the mastering area (Fig. 2). Initially, the blank is rinsed and cleaned with a pad to remove any debris left from the leveling machining operation. It is soaked in an alkaline cleaner with ultrasonic agitation, rinsed, and dipped in a second cleaning solution. This is followed by another rinse, a dip in 50-percent nitric acid, a rinse and drying. The blank is dipped in the zincate immersion-coating solution, rinsed, and again dried.

The zincated blank is preplated in a copper pyrophosphate bath at a low current density using live entry. Upon completion of this step the blank is rinsed, inspected, and given a second preplate in an acid copper bath, after which it is rinsed, inspected, dried, and put in storage until needed.

Bright acid copper plating

As the mastering department requires copper substrates for recording, the preplated blanks are taken from storage and prepared for bright acid copper plating. The bath is an acid copper sulfate with a proprietary organic addition agent that refines grain size. The preparation consists of cleaning the blank with an abrasive pad under running water, dipping it in a heated alkaline cleaner solution, rinsing it, and dipping it in a 10-percent sulfuric acid solution. After rinsing, the blank is mounted into an especially designed plating case, which in turn is mounted on the plating tank, and the blank is given a final rinse with 5-percent sulfuric acid before being lowered into the plating solution with live entry (Fig. 3). After a plating cycle of four hours, the blank is removed from the tank and the plating case, and then rinsed, dried, and inspected. Accepted substrates will be sent to mastering for machining.

Nickel electroforming

The nickel electroforming steps are similar for masters, mothers, and stampers (Fig. 4). Details are given below.

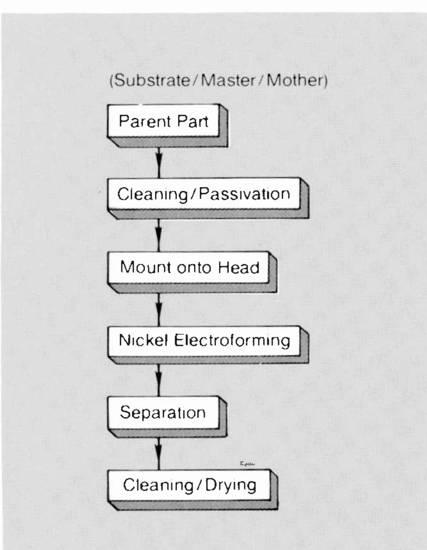

Fig. 4. *Nickel electroforming sequence.*

Electroforming of the master

Once the substrate has been recorded, it is returned to the matrix department for fan out to stampers for use in disc pressing. First, a careful inspection of the recorded surface of the substrate is performed for any defect known to cause a problem in playback of the disc. The inspection is done with a high-intensity light and an optical microscope in a Class-100 clean room. When the substrate has passed inspection, the preparation for electroforming of the first stage of the fan begins when the substrate is placed under running deionized water, and the outside edge is roughened to create a mechanical bond to the electroformed master.

The substrate is then soaked in a solution of alkaline cleaner and potassium dichromate to clean and passivate the copper. After this, the substrate is rinsed in deionized water and mounted in a case that, in turn, is mounted on the plating tank. After the protective shield has been removed

Fig. 5. *Nickel plating bath. The parent part is loaded onto the nickel plating tank for deposition of an electroformed daughter part. The daughter will be the reverse image of the parent.*

Fig. 6. *Inspection station. The parts are inspected for defects using a grazing incidence light inspection, which highlights microscopic defects.*

from the front of the electroforming case, it is lowered into the nickel plating solution (a typical sulfamate nickel bath) and rotation is started (Fig. 5).

After a preplate at low current density, the current density is raised for the remainder of the plating cycle. Upon completion of plating, the substrate is removed from the tank as well as from the electroforming case, rinsed well, and dried completely. At this point, the substrate/master composite is moved to a room where the nickel master is removed from the substrate. Each of the parts is placed in a container and sent to the first face-inspection station where both parts are inspected. Any part that has a defect that is known to cause a problem in playback of the disc is rejected at this time. The entire operation occurs in clean rooms, with Class-100 environments used where the part face is exposed.

Electroforming of mothers and stampers

The production of mothers from masters and stampers from mothers to complete the fan out is identical in all respects except for length of plating time and the current density. In both of these fan-out steps, the parent part is nickel and is prepared for electroforming in the same manner. It is rinsed with deionized water, soaked in an alkaline cleaner with ultrasonics, rinsed, and finally dipped in 10-percent sulfamic acid to neutralize any remaining alkaline cleaner and to activate the surface.

Following another rinse in deionized water, the part is dipped in a potassium dichromate solution to passivate the surface, rinsed, and mounted on another especially designed electroforming case. The case is lowered into solution, rotation is started, and the rectifier is turned on. The current density is initially low and later raised for electroforming both mothers and stampers.

At the completion of the electroforming cycle, the composites are removed from the solution, rinsed with deionized water, and removed from the electroforming case. The composite is rinsed again and taken to the separation room where the two parts are dried, separated, and placed in clean containers before being sent to the first face inspection. Both parts are checked at inspection for defects (Fig. 6).

Finishing operation

After a stamper has been accepted at the first face-inspection station, it goes through a series of finishing operations to prepare it for mounting in the press mold. These operations consist of applying a protective coating to the recorded surface, grinding and polishing the back surface to remove even the smallest nodule, punching a hole exactly in the center of the recording, and coining the inside and outside edges to fit the press mold (Figs. 7-10). After these operations are complete, the stamper is cleaned and re-inspected to assure that no damage has occurred during the finishing operations. Upon acceptance, the stamper is stored in individual containers until needed for disc production.

Quality and process control

The microscopic groove and signal-element geometries of the VideoDisc must be replicated faithfully in the electroforming operations. Small defects on the face of a metal part will result in a corresponding defect in the disc. Building the quality into the parts requires use of extensive fluid filtration of plating baths, cleaning solution, and rinse water. Clean rooms—rated at the appropriate class—and work stations are employed at the various points of the operation. Bath chemistries are carefully controlled by process-control technicians.

The parts themselves are inspected to conform to stringent criteria. Microscopic defects on the face and back of the part are examined by a low-angle bright-light inspection as well as an optical microscopic inspection. Diffracted light from the groove structure is easily perturbed by surface imperfections and observed easily by a visual inspection. Physical measurements on concentricity and thickness are also conducted.

Fig. 7. *Coating application. The stampers that must be handled through finishing operations have the front face protected by application of a protective plastic film.*

Fig. 8. *Stamper backfinishing. The stamper backs are ground and polished to a smooth surface in an automatic finishing machine.*

Fig. 9. *Centering operation. The stamper concentricity is established by a centerhole punch using a video camera focused on a "recorded-in" centering ring.*

Fig. 10. *Coining die. The mechanical profile of the inner and outer edges of the stamper is formed in a coining operation. The forming allows a match between the stamper and the press-mold geometries.*

Material requirements

The bath chemistry control and process control is required to maintain the material properties of both the copper and nickel plates. The copper for machining requires a plate that is so fine grained that it is almost amorphous. Moreover, it must be resistant to recrystallization, and it must be in a narrow hardness range.

The nickel must be produced with low internal stress to prevent distortion, it must be ductile for long service life on the mold, and it must be reasonably fine grained and hard at the recorded surface. These requirements are sometimes contradictory and an optimum compromise condition is determined.

Summary

The disc quality is only as good as the quality of the stamper from which it is pressed. The microscopic geometries associated with a VideoDisc place far greater demands on the electroforming process than normally encountered. Contaminant control has to be approached as if the part were a large semiconductor circuit wafer rather than a modified audio stamper. Mechanical properties are crucial to long service life in the press operation..

Donald J. Wierschke joined RCA "SelectaVision" VideoDisc Operations in 1980 as a Member of the Engineering Staff assigned to the Matrix Department. He came to RCA with 11 years of experience in precision nickel electroforming in the field of optics. Since then, he has been transferred to Development Engineering with primary responsibilities in the area of nickel electroforming.

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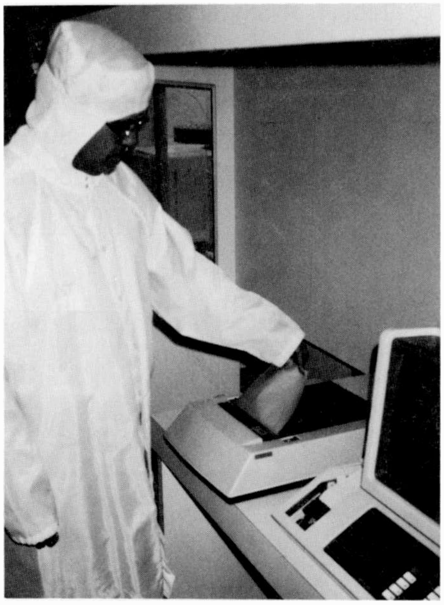

Laser-based defect particle counter used in LSI production

At the Solid State Division's production facility in Palm Beach Gardens, Florida, engineers are using laser equipment to detect micron-sized particles and defects on semiconductor wafers—and they're tracking down the causes using statistical evaluation of the information.

As the feature size of integrated circuits continues to decrease, the particulates left on wafers during processing become increasingly important. Current methods of controlling wafer particles rely on a visual inspection by operators. Since this method is subjective, any data collected will vary from operator to operator and from day to day. This article will describe the use of a laser-based defect scanner at RCA Solid State Division in Palm Beach Gardens, Florida, as a production-process monitoring tool and as a process- or equipment-evaluation tool.

Equipment description

The laser defect scanner depends on the principle that a particle lying on a surface will scatter any "light beam" hitting it. By placing a detector so the scattered beam is intercepted, the presence of a surface particle can be electronically recorded.

RCA Solid State Division at Palm Beach Gardens first used a laser defect scanner in 1981. This equipment was developed by the RCA Laboratories in Zurich, Switzerland, and provided valuable initial data in a production environment. Subsequently, a Tencor Surfscan™ laser defect scanner was installed at RCA-PBG. This system consists of a scan unit with cassette-to-cassette batch-wafer handling, a control unit with a computer and internal printer, a video monitor, and a remote video printer. More detailed information concerning the Surfscan is given in the sidebar (page 55) and in the references.

Abstract: *Control of particle defects on silicon wafers during chemical cleaning has been established using a laser defect particle counter. This, coupled with equipment changes, has resulted in an hundred-fold reduction in particulates on wafers.*

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Reprint RE-29-2-9

Test procedure

To determine the particulates generated by any process, the following procedure was used:

1. Obtain unopened cassette of substrate wafers, and laser-scan the wafers using the test-parameter limits noted in the sidebar (page 55).
2. Subject full cassette of 25 wafers to the process being evaluated for particulate generation.
3. Laser scan using the test-parameter limits noted in the sidebar.
4. Analyze and plot data using an HP35 computer, graphics plotter, and statistical graphics software.

This procedure has been used to evaluate the particles generated by wafer chemical clean processes, MOS gate oxidations, silicon nitride deposition, polysilicon deposition, borophosphosilicate glass depositions, and wafer-cleaning sink equipment.

Production wafer cleaning monitors

Weekly laser-scan monitoring of the production clean sinks was carried out using a 25-wafer cassette. The results are summarized for each type of wafer chemical clean process in Table I. All clean sinks except #13-5 (the only sink with a point-of-use filter on the rinse dryer) showed a high particle count the 9th week.

An investigation revealed that the main deionized water filters needed to be changed. Even sink #13-5 with a point-of-use filter showed a rapid increase in particle count before the main filters were changed (see Table II). In fact, the bacteria count at the rinse-dryer inlet was much greater than 3 colonies/cubic centimeter on Wednesday morning (the wafer particle count was 945). The bacteria count was down to 0.22 colonies/cc the following Monday (the total particle count on this wafer was 160). Although the particle count found on the sink with a point-of-use filter recovered within a few hours after the main filters were changed, it took days for the other sinks to recover.

Data is currently being collected, using three wafers strategically placed in a cassette, so that a statistical process-control

Table I. *Average total particles added by process (>1μm).*

	Sink number						
	13-5	8-4	2-5	5-4	6-3	3-5	7-4
Process	Caros rinse, SC2 rinse, Rinse-dry	SC1 rinse, SC2 rinse, Rinse-dry	SC1 rinse, SC2 rinse, Rinse-dry	SC1 rinse, SC2 rinse, Rinse-dry	SC1 rinse, SC2 rinse, Rinse-dry	Caros rinse, Rinse-dry	Caros rinse, Rinse-dry
Week	*Average total particles added by process (>1μm).*						
1	255	1076	434	—	—	—	—
2	225	1980	522	—	—	—	—
3	75	—	—	—	208	36	251
4	300	—	—	—	—	—	—
5	350	602	—	994	—	—	—
6	155†	594	238	947	1182	283	360
7	145	254	183	305	1922	118	383
8	77	1303	446	1799	736	90	68
9	171	1696	1328	—	2185	1091	—
	(Main DI filter-change completed)						
10	160	470	391	—	1137	784	75
11	88	164	157	575	540	**	138
12	158	774	705	740	374	203	113
13	99	613	248	708	1032	221	24
14	204	275	359	*	*	260	50

* Sink down for repairs.

** Laser scanner down for repairs.

† Point-of-use DI filter installed on DC13-5 rinse-dryer.

Table II. *Average total particles added by process (>1μm).*

	Sink number						
	13-5	8-4	2-5	5-4	6-3	3-5	7-4
Process	Caros-SC2	SC1-2	SC1-2	SC1-2	SC1-2	Caros	Caros
Week/Day/Shift	*Average total particles added by process (>1μm).*						
9/Mon/-	171	1696	1328	—	2185	1091	—
9/Tue/1	259	1798	1352	1938	—	—	139
9/Tue/2	402	—	—	—	—	—	—
9/Wed/1	945	2072	—	—	—	—	—
	(Main DI filter-change completed)						
9/Wed/2	244	—	—	—	—	—	—
9/Thu/1	104	1245	1053	—	—	754	—
9/Thu/2	302	—	—	—	—	—	—
9/Fri/1	118	—	548	—	—	826	—
9/Fri/2	163	—	—	—	—	—	—
10/Mon/1	160	470	391	—	1137	784	75

Surfscan user information

The Surfscan divides a wafer into square cells approximately 0.55 mm on a side for wafer video mapping. When a cell has a defect, its relation to the eight surrounding cells is analyzed to determine the type of defect as follows:

1. If the center cell touches no more than one defective cell, it is classified as a *point defect*.
2. If the center cell touches two to four defective cells, it is classified as a *line defect*.
3. If the center cell touches five to eight defective cells, it is classified as an *area defect*.

Only non-patterned wafers can be used on the present Surfscan, since any pattern is a surface discontinuity that is counted as a defect.

The Surfscan user-set test parameters for these laser scanning tests were:

- Defect size—$1 \mu m^2$ (minimum particle that can be "seen").
- Edge exclusion —6 mm (width of annular zone at wafer's edge to be excluded from measurement - 0.236 mil).
- Point-defect limit—9999 (maximum acceptable number of cells containing a point defect).
- Line-defect limit—9999 (maximum acceptable number of cells belonging to line defects).
- Area-defect limit—9999 (maximum acceptable number of cells within area defects).
- Haze limit—9999 (maximum acceptable average haze in ppm).

The parameter limits set are printed on the internal printer followed by the number of point defects, line defects, area defects, total defects and haze value for each wafer.

Table III. *Laser defect particle counter use in LSI production. Note that the system shuts down when counts go over the limit.*

	Sink number					
	2-5	**8-4**	**5-4**	**6-3**	**3-5**	**13-5**
Process	SC1-SC2		SC1-SC2		Caros	Caros-SC2
	Rinse-dry,		Rinse-dry,		Rinse-dry,	Rinse-dry,
	POU filter		----		----	POU filter
	Limit = 50 particles		Limit = 125 particles		Limit = 50 particles	Limit = 150 particles
Day	*Average total particles added by process (>1μm).*					
1	31	61	70	40	30	39
2	40	44	851	36	26	53
3	26	52	67	39	13	196
4	23	66	38	22	78	46
5	29	40	74	29	12	18
6	17	36	92	260	30	48
7	21	34	31	---	18	183
						89
8	18	34	70	50	10	20
9	42	35	50	36	14	124
10	598	384	507	38	11	22
	15	30	107			
11	27	98	>10K	33	19	72
			64			
12	11	36	13	17	21	63
13	322	12	8	29	18	380
	7					70
14	27	16	26	68	20	59
15	9	26	20	15	29	48

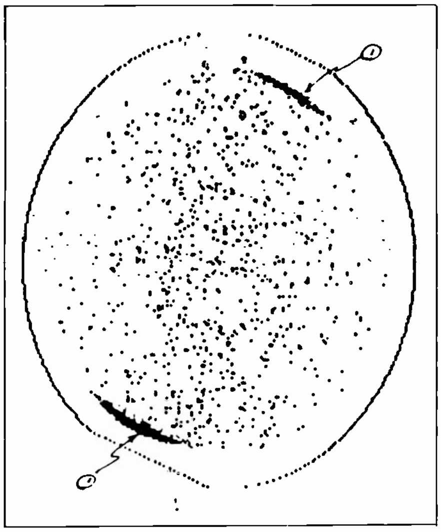

Fig. 1. *Heavy particle counts on opposite sides of wafer resulted from the use of a "dirty" cassette during chemical cleaning.*

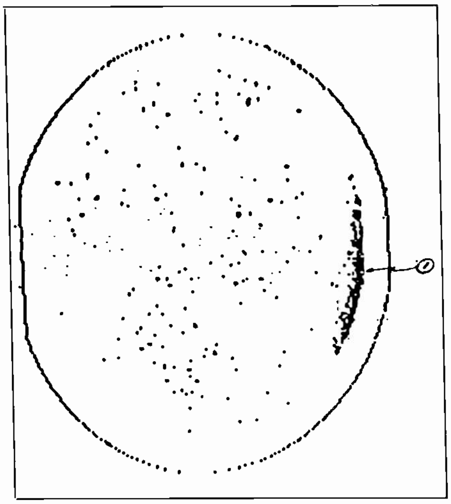

Fig. 2. *A heavy particle count on this wafer was due to a hand touching the wafer prior to chemical cleaning. The picture was taken after cleaning.*

chart can be used to control the wafer particle counts of clean sinks.[2] The wafers are pre-sorted to a maximum count of 10 (the count averages about 2 to 3 defects greater than 1 μm). Daily checks are taken on each sink with defect limits imposed according to the type of equipment used. Whenever the defects have exceeded the limits, appropriate corrective action has been taken to reduce the defects. Table III shows the impact on wafer particles using this daily control coupled with equipment changes. Statistical process-control limits are calculated when sufficient data has been collected.

During these tests we readily identified several dirt patterns. The first pattern, seen in Fig. 1, due to the use of a dirty cassette, shows the transfer of this dirt from a cassette to a wafer during etching and rinsing. The second pattern, shown in Fig. 2, displays the results when an operator's hand touched several wafers while transferring wafers from the incoming carrier to a cassette. Again, cleaning did not remove these particulates. The third pattern, shown in Fig. 3, is the result of the wafer face coming in contact with the belt-transfer system.

Wafer clean evaluations

Through the use of the Surfscan, the average wafer particulate count was significantly reduced on a Caros-SC2 clean sink by:

1. Installing a 0.2 micron point-of-use filter in the rinser-dryer deionized water line and putting a bleed line in at the rinser-dryer water inlet.
2. Changing the rinser-dryer cycle so that the rinse time was increased from 50 s to 120 s, the minimum DI resistivity was increased from 8 megohms to 12 megohms, and the dry time was held at 120 s.
3. Changing the main plant's deionized water filters.

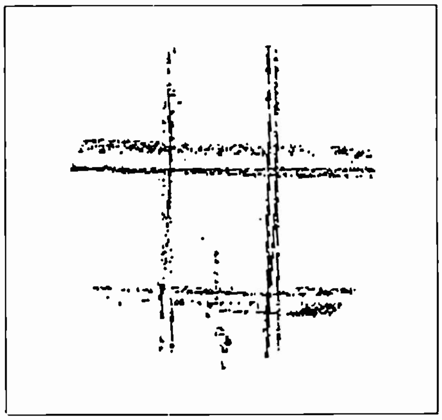

Fig. 3. *Belt tracks on the wafer surface are due to the wafer being placed upside down on the automatic belt-transfer system.*

Figure 4 shows the average wafer particle count before and after making these changes. Similar improvements have been made on other clean sinks using the laser defect scanner to monitor particle reduction.

Rinser-dryer evaluation

The laser scanner was used to compare a new rinser-dryer to one already being used.

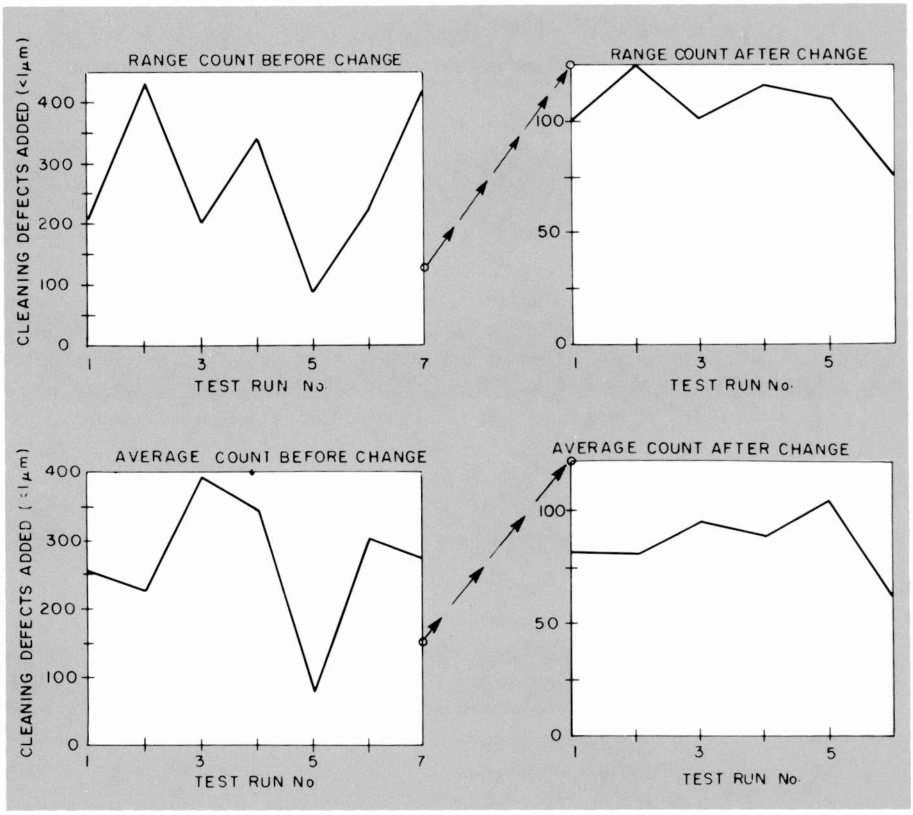

Fig. 4. *This shows the effect on wafer particulate count of modifying the chemical clean process by installing a 0.2 micron point-of-use filter in the rinser-dryer deionized water line along with a bleed line at the rinser-dryer water inlet, and changing the rinser-dryer cycle.*

Data was collected by chemically cleaning two cassettes of wafers simultaneously, and then placing one cassette in the test rinser-dryer and the other cassette in the standard rinser-dryer. During this test period, the test rinser-dryer always gave lower average particle counts (Fig. 5). Subsequent changes in the standard rinser-dryer cycle eliminated this difference.

Evaluation of a four-cassette rinser-dryer being used in production revealed that the wafers furthest from the lid are always cleaner, even when a point-of-use filter is used (Fig. 6). Our conclusion is that this is due to the deionized water-spray pattern in this equipment.

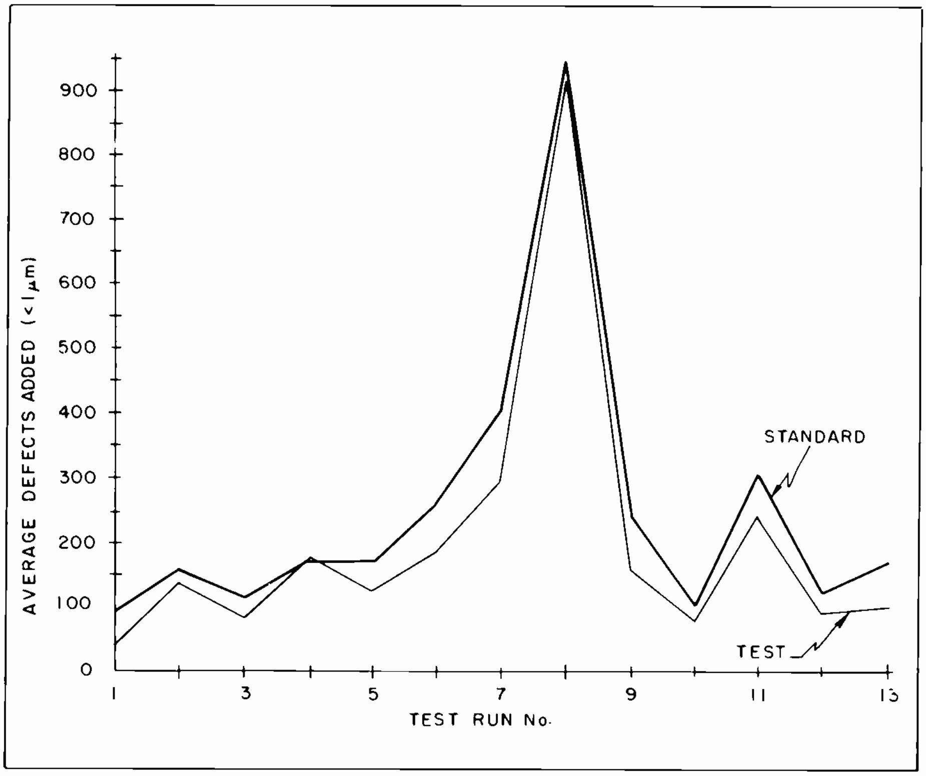

Fig. 5. *Comparison of wafer particulates added during wafer chemical cleaning, using different dryers.*

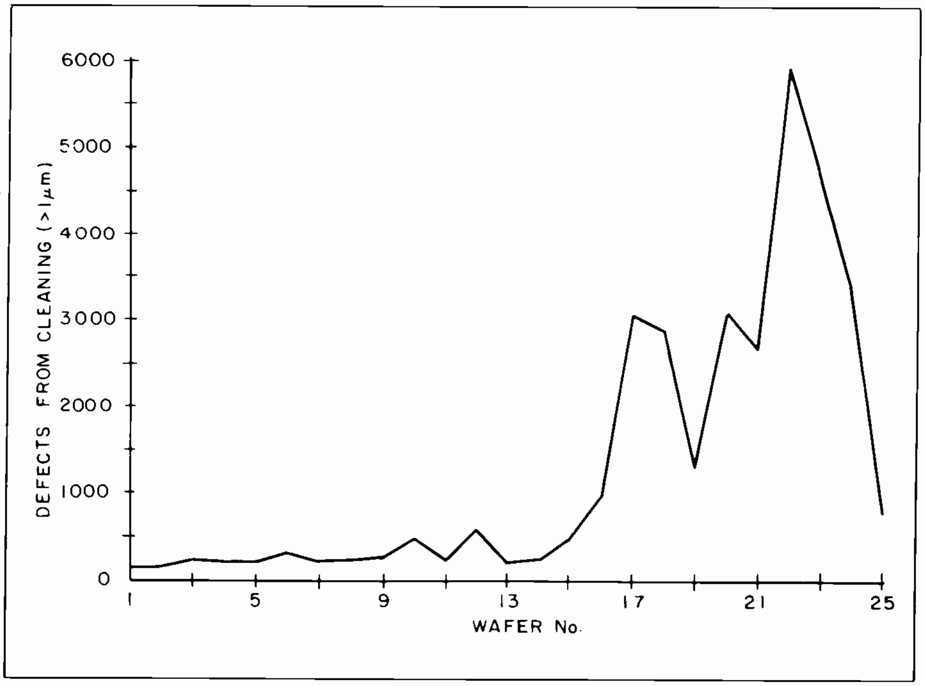

Fig. 6. *Particles added using a four-cassette rinser-dryer. The difference in wafer particulate count for each wafer across a 25-wafer cassette is shown.*

Oxide growth furnace evaluation

The number of particles added to each wafer in a 25-wafer cassette was determined, using the following typical gate-oxide-anneal furnace operation:

1. Transfer wafers from the cassette to the quartz boat.
2. Load boats onto the oxidation furnace paddle.
3. Load the furnace and "steam grow" 1000 angstroms of oxide at 875°C (pyrogenic steam system).
4. Unload the furnace.
5. Place boats from the oxide furnace on the annealling furnace paddle.
6. Load the annealling furnace and heat the wafers at 1050°C in a forming gas atmosphere.

Laser scanning revealed that the two to three wafers at either end of the cassette had an excessively high particle count (Fig. 7). This same pattern occurred for five separate test runs. This particulate pattern is probably caused by the gas flow patterns in the furnaces.

Silicon nitride deposition evaluation

The number of particles added to each of 25 wafers positioned periodically across the boat of a low-pressure chemical vapor deposition (LPCVD) silicon nitride system was determined using the following test procedure:

1. Grow a 1000-angstrom thermal oxide on newly opened substrate wafers and measure the number of particulates on each wafer.
2. "Tweezer load" these oxidized wafers into the silicon nitride deposition boat.
3. Deposit ~600 angstroms of silicon nitride.
4. Unload the boat and remeasure wafers for particle counts.

Figure 8 shows that the wafer particle count is high at the furnace entrance (door end) and continues to increase across the boat. Many of the wafers in this run showed a particle streaming pattern across the wafer (Fig. 9). Deposition process variables are

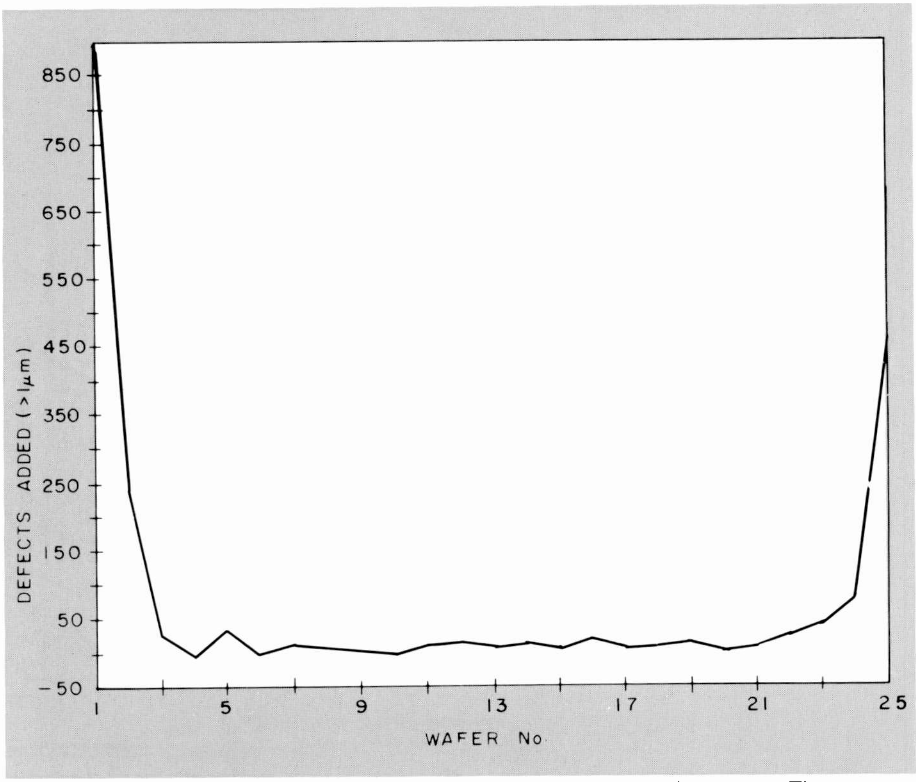

Fig. 7. *Particles added during an MOS gate-oxidation-anneal process. The excessively high wafer-particle count seen in the first and last two to three wafers was reproduced over several test runs.*

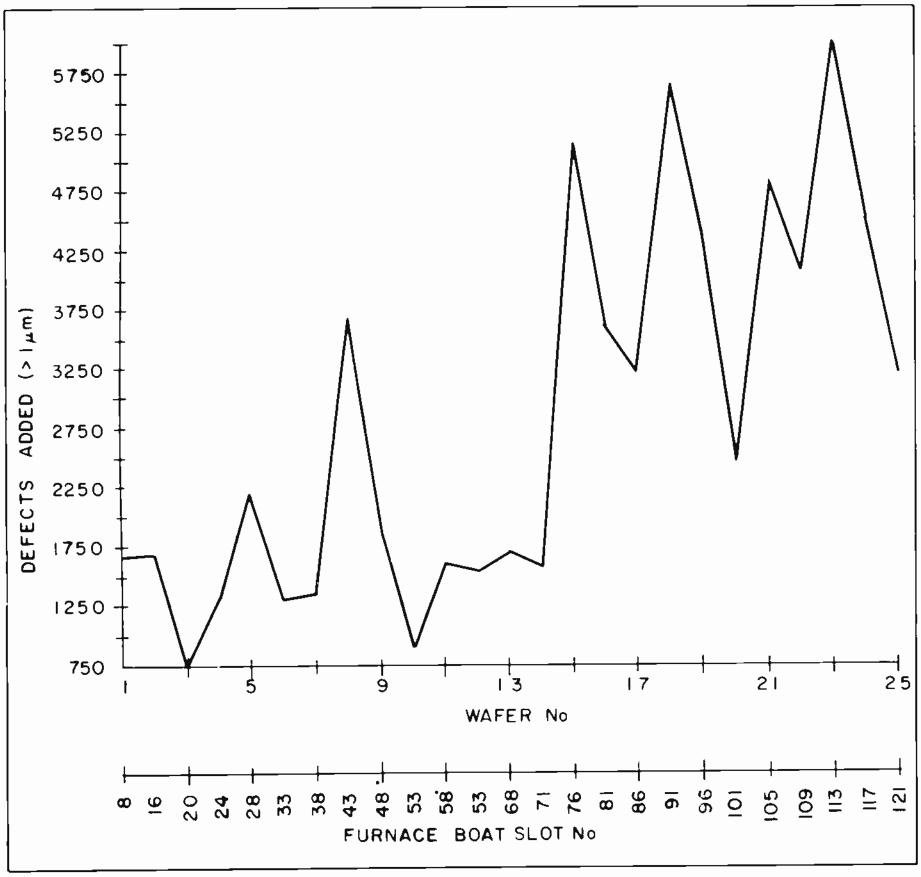

Fig. 8. *Particles added across a boat during a low-pressure chemical-vapor (LPCV) silicon nitride deposition.*

currently being evaluated to reduce this overall wafer particle count.

Polysilicon deposition evaluation

Initial attempts to evaluate polysilicon layers were unsuccessful due to excessive surface scatter that overloaded the detector. This was corrected by adding the gain control option Tencor now has available. The gain control reduces the detector gain to an acceptable scan level, at some expense to minimum detectable particle size. Measurements after this modification suggest that not only the particle count but also the haze value will be useful in obtaining better-quality polysilicon.

Chemical vapor deposition evaluation

The first laser-scan evaluations of a borophosphosilicate glass deposition showed a particle pattern identical to the deposited glass-thickness coloration pattern. This was eliminated by increasing the minimum defect size from 1 to 3 microns. However, the addition of the PMT control is a more direct method of obtaining the same results.

Photoresist process evaluation

Preliminary tests show the laser scanner can also be an effective tool in controlling wafer particles during the various photolithography processes. However, a more detailed study is required before specific process improvements can be identified.

Summary

The use of a laser-defect scanner to detect particles on silicon wafers has brought a

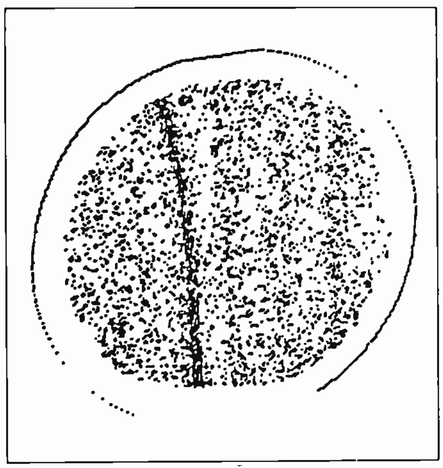

Fig. 9. *Particle-streaming effect seen over many of the wafers from a LPCV silicon nitride deposition.*

new dimension to the evaluation of LSI processes and equipment. Processes or equipment that generate high particle counts can be objectively determined and prioritized. The effect of process or equipment changes on wafer particle defects can be rapidly and effectively determined. Almost any LSI process step can be evaluated for particle generation. This equipment can readily be used to control particle generation as evidenced by the chemical cleaning process evaluations in production at Palm Beach Gardens.

Acknowledgments

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M.T. Gale | R.L. Covey

Image sampling and analysis technique for high-resolution measurement of micrometer-sized features

If one has a priori *knowledge of the shape and transmissivity of a microscopic object under study, one may measure features of that object* far more accurately *than the theoretical optical resolution limit alone would permit.*

The optical measurement of features with micrometer-sized dimensions is becoming an increasingly important requirement in many areas of the fabrication and testing of modern, high-technology products. It is often desirable to measure, by optical means, physical dimensions to an accuracy comparable with or smaller than the limits imposed by the classical theory of physical optics (the Rayleigh criterion). This is frequently the case when restricted access to the part limits the numerical aperture and thus the classical resolving power of the image-forming optics. With some knowledge of the geometry under study, however, dimensional information well below the classical resolution limit can often be obtained by suitable sampling and subsequent analysis of the image-intensity pattern.

Abstract: *Optical techniques for measuring micrometer-sized features during fabrication or testing are often hampered by restricted physical access, limited numerical aperture (N.A.), and insufficient resolving power of the image-forming optics. With some knowledge of the geometry under study, however, dimensional information well below the classical resolution limit can be obtained by suitable sampling and analysis of the image-intensity pattern. Using the example of a stylus tip, the paper describes a technique using a photodiode array and an optical system with an N.A. of 0.45 for measuring certain features to an accuracy of approximately 0.2 μm (Rayleigh criterion of about 0.8 μm) at a working distance in excess of 10 mm.*

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The technique described here is suitable for measuring opaque or even semitransparent objects with relatively simple geometrical features that can be considered two-dimensional for the purpose of the measurement. A translatable linear photodiode array is used for sampling the image pattern. Such arrays and suitable digitizing electronics are commercially available and inexpensive, and the output signal can be readily processed by a modest computer such as a low-cost personal computer (PC) or single-board computer (SBC).

After briefly outlining the theoretical background behind the approach, this paper describes a practical measurement system that demonstrates the capabilities of the technique. The example used is the measurement of certain features of a stylus tip having dimensions of approximately 4 μm. An accuracy of less than 0.2 μm is achieved using imaging optics with a numerical aperture (N.A.) of 0.45 and (objective) working distance in excess of 10 mm. The Rayleigh criterion for such optics is about 0.8 μm.

Theoretical background

The basic measurement technique relies on the fact that, for a single opaque edge under incoherent illumination, the 50-percent point of the light-to-dark image transition defines precisely the location of the geometrical edge. In practical terms, this means that for an imaging system with relatively low N.A., a "blurred" image of an edge can be sampled and analyzed to obtain positional information with a resolution much finer than the extent of the blurring. Although a coherent illumination system could also be used (the geometrical edge then corresponds to the 25-percent transition point), the use of incoherent light avoids many of the problems of coherent noise (speckle, severe dust diffraction patterns, and so on) that can lead to considerable errors in a sampling technique of this type.

The response of the optical system is conveniently considered in terms of the point-spread function[1]—the image-intensity distribution pattern resulting from a single point source in the object plane. Figure 1 shows the basic optical system consisting of an illuminator and imaging optics. If the source is an extended white light, such as an incandescent lamp and if the condenser has a numerical aperture similar to that of the imaging optics, the illumination can generally be considered as incoherent.

For an aberration-free, circular-aperture imaging system, the intensity distribution (diffraction pattern) about the image of an object point is given by (see Fig. 1)

$$I(y,z) = P(y,z) = I_o\,[2J_1(r')/r']^2 \quad (1)$$

$$r' = (2\pi/\lambda)\cdot NA \cdot r \cdot M \quad (2)$$

where

$P(y,z)$ = Point-spread function

I_o = Peak image intensity at $y = y_o$, $z = z_o$

$J_1(r')$ = First-order Bessel function

r' = Normalized radial coordinate

λ = Wavelength of light

N.A. = $n \sin \delta$ = numerical aperture of the imaging system

r = Radial coordinate = $[(y-y_o)^2 + (z-z_o)^2]^{1/2}$

M = Magnification

The image form (the Airy pattern) is circularly symmetric and space-invariant. For incoherent illumination, the image of a general two-dimensional object can be computed by summing the intensity contributions from all points in the object plane.

The Rayleigh criterion, generally taken as the resolving power of an image-forming system, is concerned with the resolution of two point images. The points are said to be resolved if the central maximum of one image-diffraction pattern falls on the first minimum of the other. For incoherent illumination this gives a minimum resolved separation of

$$s = 0.61\ \lambda\ /\ \text{N.A.} \tag{3}$$

Figure 2 shows the Rayleigh resolution criterion s as a function of numerical aperture for a light wavelength, λ, of 0.6 μm, which is typical for the maximum response of a system using a silicon detector with an incandescent lamp and infrared (heat) filter combination.

The image of a long, straight edge is found by integration of the point-spread function along a line and is shown in Fig. 3 as a function of numerical aperture. The image blurring is of a magnitude similar to the Rayleigh criterion. The geometric edge corresponds to the 50-percent peak intensity, independent of the numerical aperture. Detailed analysis shows that this is true even in the presence of moderate defocusing and axial aberrations (spherical and chromatic). It is also valid for short line segments, provided their lengths are greater than λ/N.A. The exact position of an edge can thus be found by sampling the blurred image at a number of intervals sufficient to derive an accurate determination of the 50-percent peak-intensity point.

Similarly, the accurate measurement of a two-dimensional object of known geometry is considerably simplified if the object can be reduced to a number of line (edge) segments (this is often the case for objects of practical interest). The position of any point on a line segment is given by the 50-percent image-intensity point, provided no other segments lie within a circle having a radius of approximately λ/N.A. For more complex objects where this is not the case, a detailed computation of the image-intensity patterns is required to relate the geometric outline to the image pattern. Partly transparent objects may be treated in much the same way. With incoherent illumination, a very good approximation is achieved by correcting the results obtained for an opaque edge with the object transmissivity.

The accuracy to which the 50-percent image-intensity point, and thus the geometric edge location, can be determined is limited by a number of considerations. For an otherwise perfect experimental system, a lower limit is set by the digitizer resolution at the analog measurement-computer interface. For example, Fig. 3 shows that, for an optical system with an N.A. of 0.4, the image intensity change is about 10-percent per 0.1 μm around the 50-percent point. A 4-bit (16-level) analog-to-digital conversion enables the 50-percent point to be determined to about ±3-percent accuracy, and thus the edge location (in the object plane) can be determined to about ±0.03 μm. An 8-bit digitizer could provide twice this precision. However, in practice, experimental limitations such as measurement noise, nonuniformity in the illumination and in the detector response (including "array noise"), and the dimensional accuracy of the detector array are dominant. For an N.A. of 0.4, a resolution of ±0.2 μm is readily achieved in practice, and further reduction is possible with ideal objects and measurement environments.

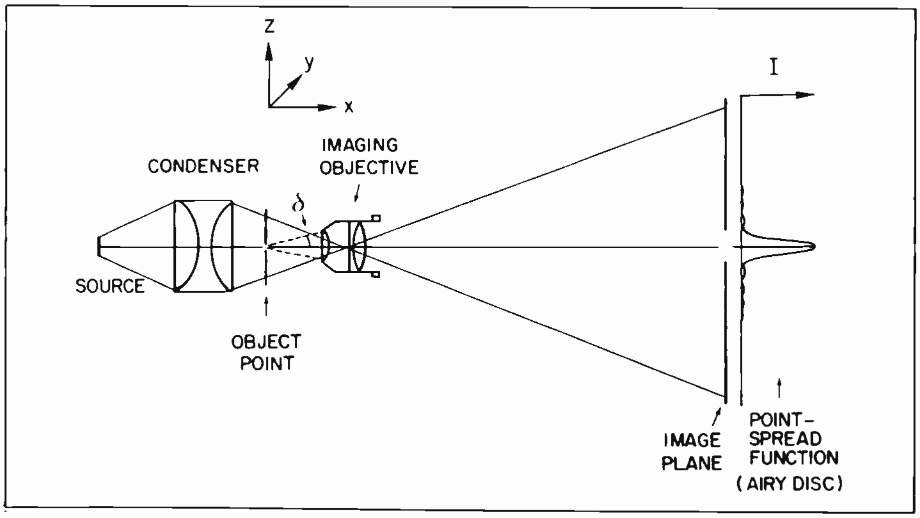

Fig. 1. *Image of a point source by an optical system with transillumination. The image plane coordinates are y and z, with the image centered at (y_o,z_o). The coordinate along the optical axis is x. Numerical aperture is NA = sin (δ) in air.*

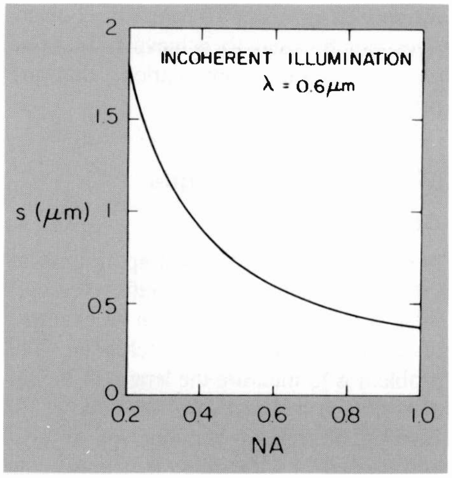

Fig. 2. *Plot of the Rayleigh resolution (s) versus numerical aperture (N.A.) of the objective.*

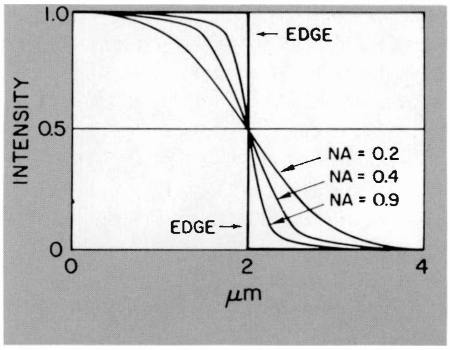

Fig. 3. *The image of an opaque edge by diffraction limited optics under ideal incoherent illumination.*

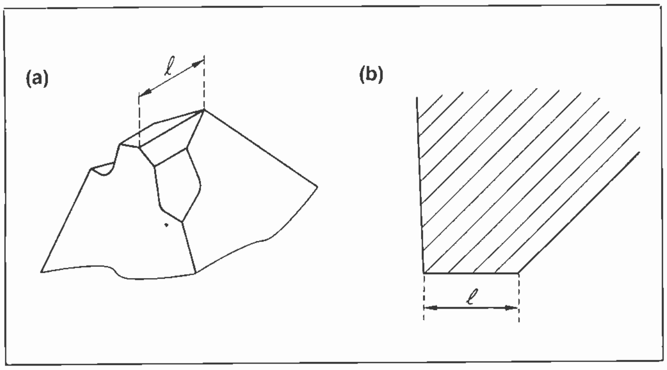

Fig. 4. *Shaped stylus tip (from References 2 and 3):* **(a)** *inverted view in three dimensions,* **(b)** *projected side view.*

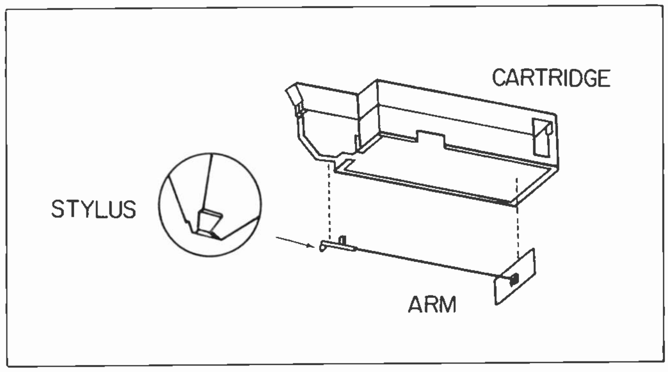

Fig. 5. *The stylus shown in relation to the cartridge (from Reference 2).*

The power of this approach lies in the fact that the resolution is achievable at relatively long working distances. Modern microscope objectives with N.A. values of about 0.4 are available with a working distance in excess of 10 mm. Other objectives can be used to achieve resolution/working-distance combinations that are otherwise unattainable.

Experimental technique

General

In this section, the practical application of the above results to a specific measurement problem is described as an example of the capabilities of the technique. The problem is to measure the length of the tip of a shaped stylus of the form shown in Fig. 4. The stylus is mounted on an arm and housed in a cartridge that limits side access to a minimum distance of about 9 mm (Fig. 5). Further details on the stylus and cartridge can be found in references 2 and 3.

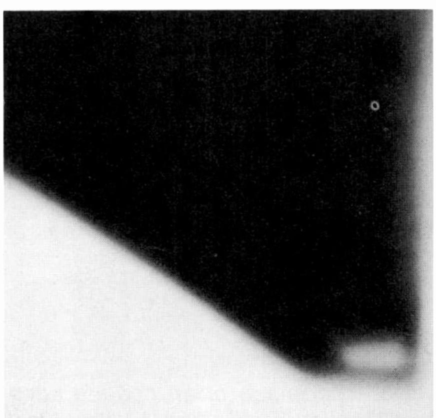

Fig. 6. *A stylus image as projected by a 50× LWD objective and 10× eyepiece, and observed with a 1-inch Vidicon. The nearly parallel stylus planes near the tip form a "window" that transmits light that is accepted by the microscope objective and seen as a bright spot.*

The stylus tip length is typically 4-5 μm. An automated measurement with an accuracy of approximately 0.2 μm rms is desirable since the length is a critical parameter in the stylus fabrication and subsequent performance. Although access to the stylus tip from below (Fig. 5) is unrestricted, the optical view presented is that of a complex three-dimensional object. Measurement of the stylus tip from this viewpoint requires a high-power microscope (~1000-times magnification, N.A. of about 0.9) with a small depth of focus and working distance. Under these circumstances, positioning tolerances are then very severe and the possibility of damage to the stylus and microscope objective surface, due to inadvertent contact, becomes significant. The side view of the stylus tip (Fig. 4b), however, presents a simple geometric object that can be treated as two-dimensional and opaque. The stylus can then also be viewed in transmission, producing a high-intensity image suitable for detection and scanning by a linear photodiode array. A low-power, long-working-distance objective easily clears the cartridge housing and projects an image that can be sampled and analyzed to obtain the required measurement accuracy.

Figure 6 is a photograph of a stylus sideview projection on a 1-inch vidicon. The objective lens has a numerical aperture of 0.45. All edges are blurred by optical diffraction. The region near the tip is partially transparent, but this causes no real problem in measurement as long as the transmissivity is taken into account. Moreover, in Fig. 6, the blur in the vertical edge increases away from the tip. This is due to the finite thickness of this edge along the optical axis. This thickness increases away from the tip, but presents no great difficulty since the point-spread function remains nearly circularly symmetric for imperfect focus.

Measurement system

Figure 7 shows the essential measurement system. The cartridge is dropped into a mechanical fixture and the stylus arm lowered into a V-groove holder mounted on an *xyz*-axis translation stage. No physical contact is made with the stylus itself. The mechanical arrangement is such that the stylus tip is initially located reproducibly within a volume of about 500×500×500 $(\mu m)^3$. The function of the translator is then to center the stylus tip in the optical field of view and perform focusing by using information from the image sensor array. The translator is driven in three directions by stepping motors with a 1-μm step increment. A computer first analyzes image data, then routes a pulse train sequence to the proper stepper-motor drivers.

The illuminator consists of a dc-driven 50-watt quartz-halogen lamp focused by a 0.3 N.A. condenser optic onto the region of the stylus tip. A dielectric heat filter with a cut-off at $\lambda = 0.75$ μm minimizes heating and thus thermal expansion effects of the stylus and the end of the stylus arm. The illumination is uniform to less than 5 percent within a central field of 125 μm diameter.

In choosing the N.A. of the condenser, a compromise was made between desired intensity and incoherence on one hand, and depth-of-focus on the other. With the N.A. of the condenser less than that of the objective, the illumination is not strictly incoherent. Yet increasing the condenser N.A. decreases the geometrical depth of focus (as distinguished from the diffraction-limited depth of focus, which only depends on the objective N.A.), and leads to excessive blurring of the vertical edge (Fig. 6) away from the tip.

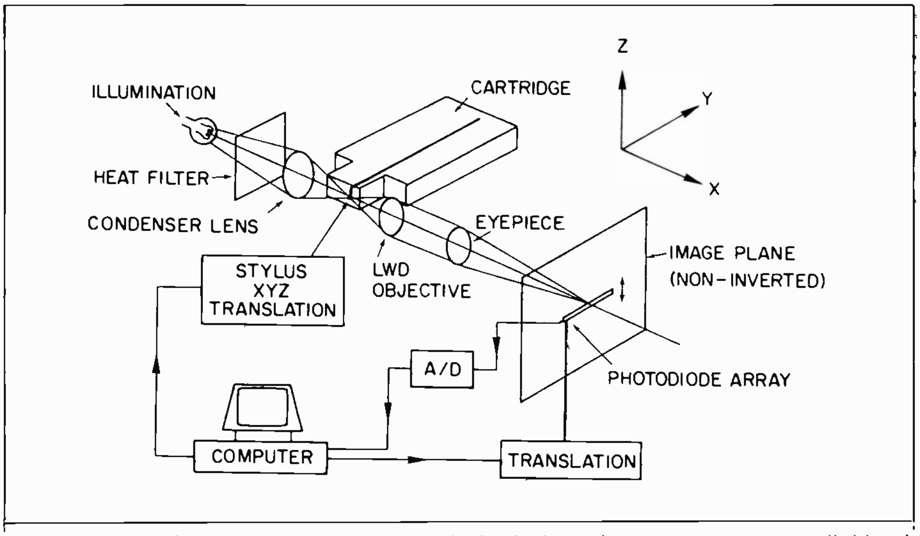

Fig. 7. *The basic measurement system. A single-board computer accepts digitized data from the photodiode array, and provides the proper pulse trains for operation of the stylus (x,y,z) and detector (z) stepping motors.*

The stylus imaging optics uses a long-working-distance objective (Bausch & Lomb 50×, 0.45 N.A., 12.5-mm working distance) to clear the cartridge housing and a 10× eyepiece to project an erect image of the side of the stylus onto the detector plane with a total magnification of about 200×. Although the diamond stylus material is nearly transparent (except for reflection losses), the high refractive index, complex geometry, and surface finish are such that it closely approximates a high-contrast, opaque object suitable for the image analysis described above. Close to the tip, the diamond transparency is evident (Fig. 6). In this region, it is necessary to ensure that the digitizing level defining the edge is greater than the transmissivity. In practice, a digital level of eight (corresponding to an analog signal level of about 53 percent) is used for the horizontal tip line, while a digital level of seven (corresponding to 47 percent) is used for the other edges (away from the tip).

In the image plane, a linear silicon-photodiode array (EG & G Reticon) is aligned horizontally, parallel to the base of the stylus tip (Fig. 8). The array consists of 1728 individual elements, each 16 μm high and spaced 15 μm apart. The array has a total length of about 25 mm. It is electronically scanned and sampled with a repetition rate of about 30 ms. At the 200× magnification, an individual Reticon element corresponds to a square of about 0.08 μm in the stylus (object) plane. The detector array is mounted on a z-axis motorized translator with a 1-μm increment, corresponding to an equivalent 0.005-μm step size in the stylus plane.

The output data from the photodiode array is digitized (4 bit) and input to an Intel 88/25 SBC through the A/D converter. The Intel uses an 8088 CPU with an 8087 coprocessor that handles floating-point math operations. The computer analyzes the data and controls the translation stages to center and focus the stylus and to perform the image-measurement scan. The software is written in PL/M-86 on an Intel development system, then compiled and burned into PROMs.

Measurement procedure

The measurement of the stylus tip length is composed of two operations: (1) finding, centering, and focusing the tip and (2) scanning the image to obtain the data required for determining the tip length. Figure 9 illustrates the steps involved in finding and centering the stylus tip; the photodiode-array output is shown as a function of time (corresponding to element number or position) and is measured initially without a stylus present to obtain the 100-percent intensity level.

Upon initial insertion of the cartridge, an out-of-focus, off-center image is typically presented at the image plane (Fig. 9). If the photodiode array does not sense some portion of this image, then the stylus must be moved around until it does (additional discrete photocells in the image plane having also been used to increase the initial field of view). Based on the array signal, the stylus is translated along the y-axis until the out-of-focus image is roughly centered along the array (Fig. 9b). The image is then focused by moving the stylus tip along the x-axis until the slope (sharpness) of the diagonal image edge is maximized (Fig. 9c); some vertical translation (z-axis) and further centering may be necessary during this operation to maintain a tip image intersecting the array. Finally, the

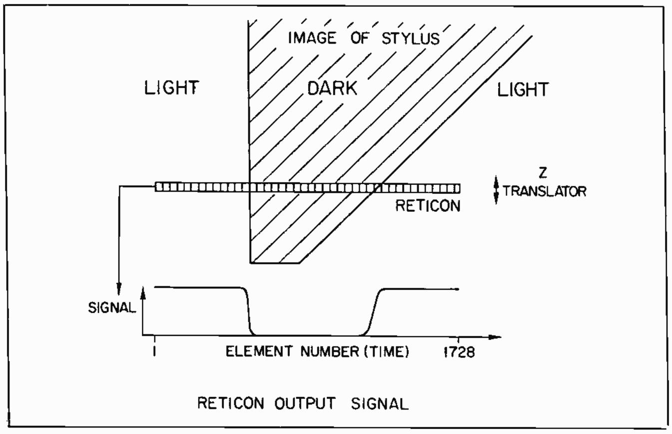

Fig. 8. *Schematic diagram (not to scale) of the image plane showing the stylus shadow and the corresponding photodiode array (Reticon) analog-output signal.*

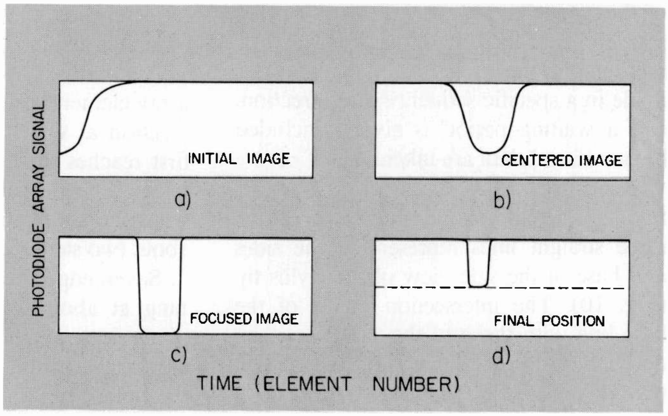

Fig. 9. *The process of finding, centering, and focusing of the stylus tip. The stylus (x,y,z) translators are used in these operations. In the final position (d) best possible focus is attained, but the tip shadow may not be exactly at the 50 percent intensity line.*

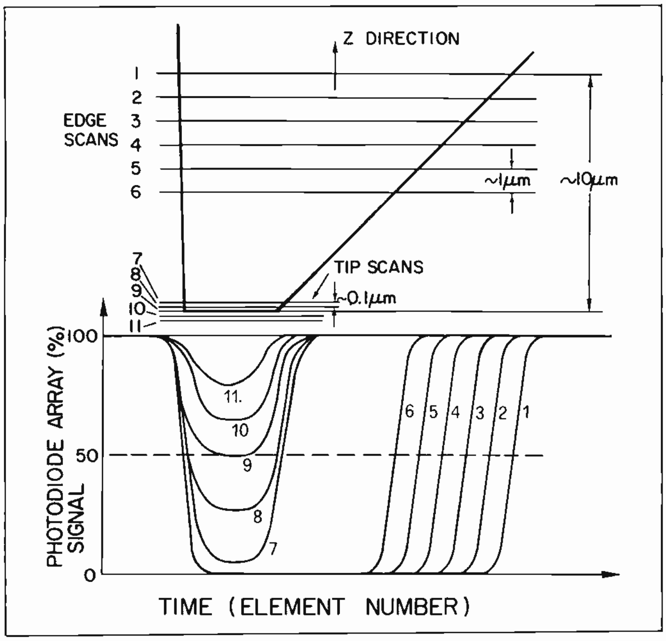

Fig. 10. *The tip and edge scan measurement operations showing both an image plane schematic and the corresponding analog signals. All dimensions are referred back to the stylus object plane. Only the photodiode array is moved during these operations.*

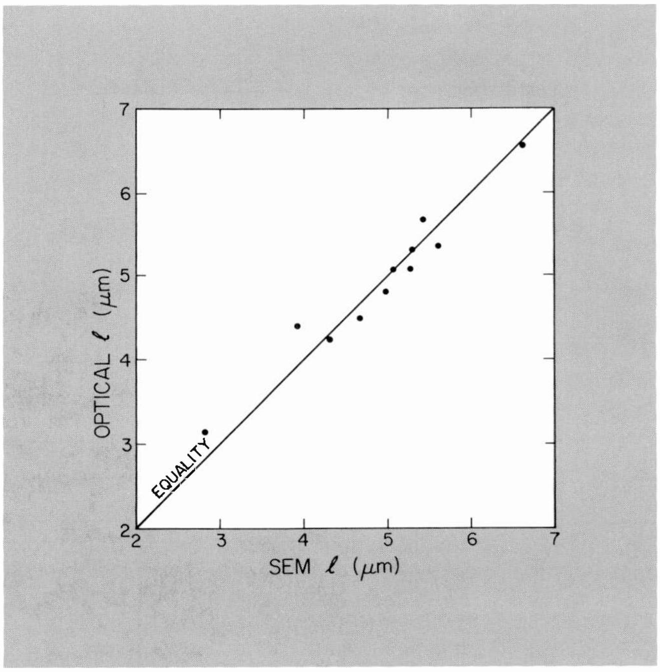

Fig. 11. *Comparison of optical and SEM measurements over a range of 3 to 7 μm.*

stylus tip is moved upwards until the intensity of the tip reduces to about 50 percent of the peak intensity (Fig. 9d). The stylus tip is now focused and centered to an accuracy of about 1 μm along all axes, and the image-scan measurement can begin.

With the stepping-motor stages presently being used, there exists a significant amount of mechanical crosstalk between axes. Moreover, stage vibrations persisting for tens of milliseconds are induced by the square-wave stepping-motor excitation. Both the crosstalk and internally induced vibrations approach the 1-μm level. Great care has therefore been taken to minimize the effect of these mechanical imperfections on the searching and focusing processes. The final motions of the stylus stages are always made in a specific sequence and direction, and a waiting period is always included before critical data are taken.

Basically, the measurement proceeds by finding the slopes and intercepts of the three straight lines representing the sides and base of the side view of the stylus tip (Fig. 10). The intersection points of the base line with those of the two sides then determine the base length. As outlined in the previous section, the edge positions are given ideally by the 50-percent peak-intensity points. With an effective illumination wavelength of about 0.6 μm and a numerical aperture of 0.45, an edge transition typically shows a slope of about 10 percent per 0.1 μm (in the object plane). The accuracy in locating the three straight lines is improved by applying linear least-squares fitting to the data from a number of scans at varying heights. Only the photodiode array is translated between scans—the stylus remains stationary during the actual measurement.

The photodiode array begins in the vicinity of the tip, where several scans are taken at approximately 8-step (0.04 μm) intervals. For each of these scans, the minimum image intensity is stored as the tip recedes (Fig. 10), and the height of the 50-percent level is found by a least-squares fit to determine the height of the tip base (which is assumed to be horizontal).

Alternatively, several suitable Reticon array elements are chosen, and the vertical position at which each of these elements first reaches the 50-percent intensity level is determined as the array is moved away from the tip. A finer tip scan interval of about two steps (0.01 μm) is then required.

Seven edge scans are then taken, beginning at about 2 μm above the tip (all dimensions are referred to the stylus plane), as shown in Fig. 10. Prior to scans 2 through 7, the photodiode array is moved an additional 200 steps (1 μm in the stylus plane) in the positive *z*-direction. Scan 7 is therefore taken at about 8 μm above the tip.

For each scan, the locations (*y*-positions) of the two stylus edges are determined, giving seven (*y,z*) pairs for each line from which a best straight-line location is determined by least-squares fitting. Finally, the length of the tip base is obtained from the intersections of the three determined lines. Additional useful data on the angles between the lines are also available from this measurement.

Results

A measurement system of this type has been constructed and extensively tested. A reliable standard for the stylus tip length is difficult to obtain—the most common technique is to measure scanning electron microscope (SEM) photographs of the stylus tip. The internal consistency of such measurements on styli in cartridges is typically no better than 0.2-μm rms. For the optical measurements, an internal consistency (10 to 20 measurements on a single cartridge) of better than 0.2-μm rms is obtained. Figure 11 shows a comparison of the optical measurement versus the SEM measurement for a number of cartridges. For these and other measurements, an rms deviation of less than 0.2 μm is found (a small systematic error is likely because of the difference in the way the stylus tip is measured). Overall, the optical stylus measurement can be said to have a present accuracy that certainly exceed ±0.2 μm rms.

Such accuracy can only be attained if the stylus is free of contamination because a stylus shadow composed of only straight lines is assumed. The presence of dirt in areas where data are taken might result in marked deviations from straight-line behavior. The present software recognizes such discrepancies when they occur, and flags the measurement as being invalid. In future software versions, bad data points will be eliminated, and a second linear least-squares fit will be performed for remaining data. This will eliminate the effects of stylus contamination provided it is sufficiently local (size less than about 0.5 micrometers).

A totally automated cleaning system that shares Intel SBC with the measurement system has been developed. However, in perhaps one out of ten cases, the stylus remains too dirty to measure after machine cleaning. Even though the system recognizes contamination and signals for recleaning and remeasuring, a machine-cleaning failure rate of less than 1 in 50 would be more desirable. This will be a major focus of future work.

The measurement speed is a further important consideration for practical applications. The system as described above requires a total measurement time ranging from 20 to 30 seconds, including loading and unloading of the cartridge. Approximately half of this time is involved in finding and focusing the stylus tip, and the remainder in the actual measurement. The translator movements account for most of this time (about 75 percent). The stepping motors are operated at rates of up to 1000 steps per second. With better stages and motors, rates approaching 2000 steps per second could be attained, and stage crosstalk reduced. Sinusoidal (rather than square-wave) motor excitation would reduce mechanical vibrations, so that waiting periods for data acquisition could be reduced or even eliminated.

Robert Covey joined the Manufacturing Systems and Technology Research Laboratory of the RCA Laboratories in 1980 as a Member of the Technical Staff. He has worked primarily on VideoDisc-related projects. He has participated in the development of methods for automated image sampling and analysis, and has developed an exact theory of VideoDisc diffraction that has been successfully applied to optical testing and laser playback of VideoDisc masters.

He obtained his BS degree in Physics from M.I.T. in 1962. He earned his Ph.D. in Physics from the University of California at Berkeley in 1970. After graduation, he worked on postdoctoral research projects in optics and spectroscopy at the University of Maryland, University of California, at Berkeley, and the U.S. Naval Research Laboratory, where he obtained an NAS/NSF Research Fellowship. He then joined industry, where he worked in the design and production of optical parts and coatings.

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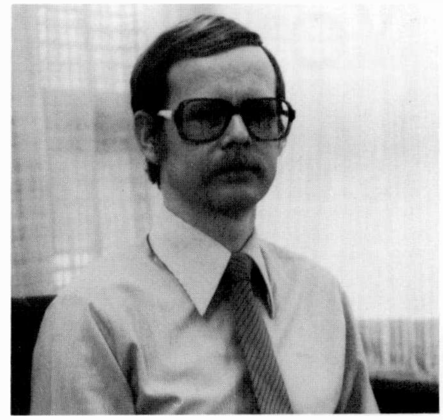

Michael Gale joined Laboratories RCA Ltd. in Zurich, Switzerland, in 1969 after receiving BA and MS degrees in Physics and Optoelectronics from Cambridge and Essex Universities (England), respectively. He has worked on a number of applied optics projects including surface-relief microimages, high-resolution image sampling and analysis, and development of a single-chip CCD color camera. A number of technical publications, 11 issued patents and an RCA Laboratories Outstanding Achievement Award have accompanied this work.

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Conclusions

An optical measurement technique has been described in which geometric features of micrometer dimensions can be measured to high accuracy by the use of an imaging optics of numerical aperture 0.45 and working distance in excess of 10 mm. A precision of better than $\pm 0.2 \mu m$ has been demonstrated for the system, compared to the classical Rayleigh resolution criterion of about 0.8 μm. The long working distance enables the measurement to be carried out on objects with restricted physical access, realizing a precision that would otherwise be unattainable.

The method described is generic: that is, the basic technique of measuring "blurred" images by sampling and analysis is applicable to many types of high-resolution measurement problems, and is capable of making angle and length determinations on any optically opaque object with straight lines for boundaries. If the transmissivity is known, correction for objects containing partly transparent areas are straightforward. With minor changes in the algorithms, curved boundaries could also be determined to this degree of accuracy provided certain aspects of the shape are known beforehand.

Acknowledgments

The authors are grateful to I. Gorog for frequent illuminating discussions and suggestions during the course of the work. The assistance of J. P. Beltz and W.J. Mitchell with the electronics and software, and of J. Csercsevits, A.L. Witchey, J.S. Palopoli, and W.C. Henderson with the mechanical construction and testing of the equipment, is also acknowledged.

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E.E. Doerschuk | J.J. Moscony | D.M. Weber

Shadow-mask etching for data-display tubes

The packing density of apertures in the high-resolution data-display tube's mask is three times that in the conventional entertainment tube's mask. RCA engineers overcame the formidable manufacturing challenges by making ingenious changes in the metallurgical specifications and in the etching process.

Since the beginning of commercial color television in 1950, the shadow-mask color picture tube has been the overwhelming choice of receiver manufacturers as the display medium for transmitted TV signals. Over the years, color picture tubes have undergone many improvements. In the manufacture of the newly designed color picture tubes, the shadow mask itself has undergone a steady evolution to more complex designs that have kept pace with the ever-growing needs for improvements in tube contrast, beam convergence, and focus. These tube requirements have also necessitated significant equipment improvements involving capital investment of many millions of dollars to manufacture the new shadow-mask designs.

Initially,[1] masks used in 70° and 90° beam-deflection, delta-type tubes (tubes with masks having round apertures and dot screens) were etched so that the width of the steel strip was parallel to the observer. This is termed vertical etching. However, with the advent of precision inline tubes (tubes having slit type apertures and line screens), masks are etched so that the width of the strip is perpendicular to the observer. This horizontal etching process is necessary to prevent distortion of the slit, which occurs in vertical etching at the lower portions of the mask, due to the entrapment of ferric chloride etchant in the resist overhang. This entrapment does not occur with horizontal etching because the etchant is flushed through the aperture. As improvements have led to increased electron-beam deflection, from 70° to 110° tubes, the aperture geometry, formability of the metal, warpage, and magnetic coercivity of the mask material have all become more critical.

Abstract: *The masks for RCA Video Component and Display Division's high-resolution data-display tubes differ from the conventional entertainment-type masks in critical ways outlined in this article. Moreover, the manufacturing process had to be altered to meet the greater demands posed by this new mask. The authors cover metallurgical considerations, modifications to the etching process, geometric considerations and more, in an effort to compare the conventional manufacturing parameters and the newly developed parameters for the data-display-tube application.*

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Table I. *Comparison of typical critical dimensions for various delta-type masks (see Fig. 1).*

Dimension	*Mask type*			
	Standard entertainment	*Medium resolution*	*High resolution*	*Ultra-high resolution*
A (mm)	0.70	0.40	0.30	0.20
B (mm)	0.33	0.19	0.14	0.09

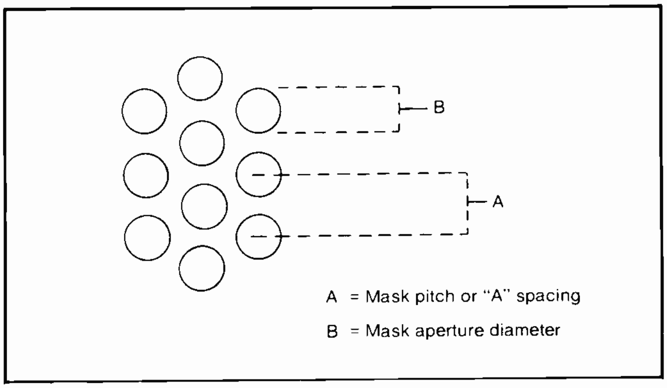
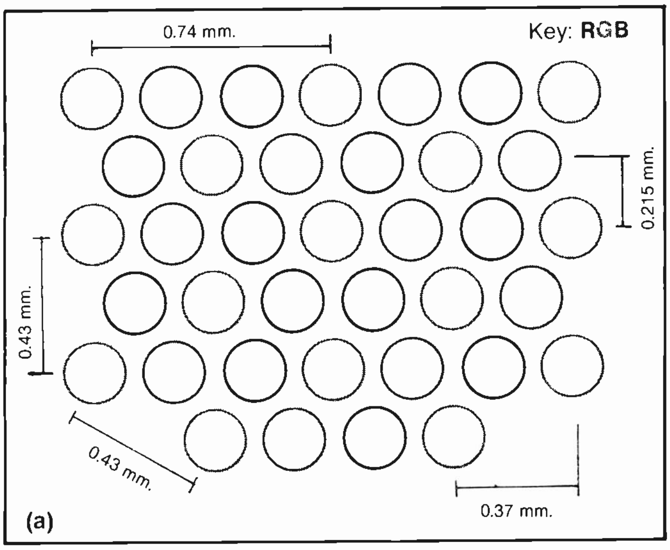
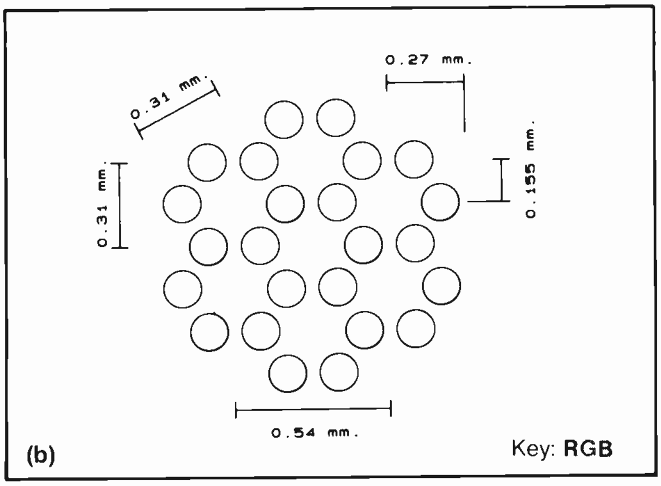


Fig. 1. *Critical dimensions for delta-type masks. Both the aperture spacing and the aperture size determine the degree of resolution in data-display cathode ray tubes.*

Data-display tubes

Even with all these design- and material-related changes in entertainment-type tubes, there appeared on the horizon a new and





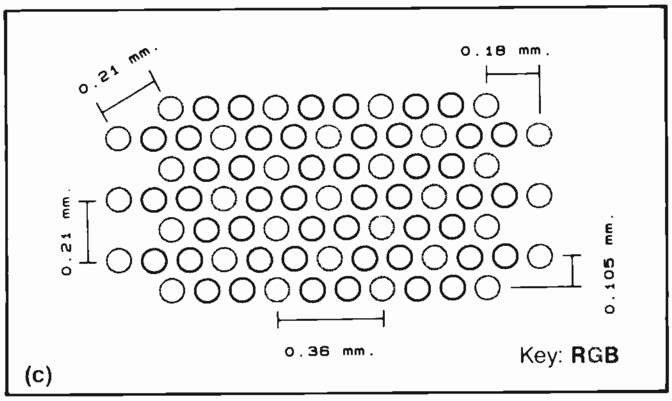


Fig. 2. *Comparison of typical screen structures for display tubes.* **(a)** *Typical medium resolution screen structure,* **(b)** *typical high resolution screen structure for RCA data displays, and* **(c)** *typical ultra-high resolution screen structure.*

even more challenging type of picture tube. Today, this tube has become a reality and we find ourselves in a new era of data-display color picture tubes. Data-display tubes are made in medium-, high-, and ultra-high-resolution versions. These tubes are used as the display medium for personal computers, arcade, and home games. The manufacturing of shadow masks for these tubes presents formidable challenges, which have been successfully undertaken by RCA Video Component and Display Division (VCDD).

Figure 1 and Table I show some critical dimensions for typical standard-, medium-, high-, and ultra-high-resolution dot masks as viewed from the gun side. Figure 2 shows the various illuminated screen structures obtained from the use of medium-, high-, and ultra-high-resolution masks.

A pictorial comparison from the screen side of an RCA 13V/90°COTY mask and an RCA 13V/90° high-resolution display mask is shown in Fig. 3. The packing density of apertures in the high-resolution mask is three times that of the conventional entertainment mask. Thus, it is obvious that artwork requirements and etching yields are severely tested by the increased number of mask apertures per unit surface area of the mask. Of course, the mask cannot have a single imperfection that would adversely affect the screen quality. Similarly, the visual uniformity must be acceptable in the flat and formed state. These are the basic manufacturing challenges that VCDD faced.

Metallurgy

In the early phases of etching high-resolution data-display masks at RCA, it was found that the use of conventional rimmed steel (0.10 percent carbon, cold-rolled steel) resulted in masks with poor uniformity. Also, masks showed a further degradation in uniformity after the annealing and forming operations. A significant improvement in flat and formed mask uniformity was achieved when aluminum-killed (AK) cold-rolled steel was used in place of rimmed steel. Figure 4 shows a flat mask aperture made from rimmed steel and aluminum-killed steel respectively. It is obvious that the edge defining the aperture for the AK steel is superior to that of rimmed steel. The ragged apertures in rimmed steel partially account for the poor mask uniformity.

A comparison of the chemical compositions of rimmed and AK steels is shown in Table II. The impurity levels for the AK steel are somewhat lower than for rimmed steel. Further, the impurities in AK steel are uniformly distributed throughout the body of the material. In the case of rimmed steel, the carbon content is higher (0.10 percent) and there is an anisotropic distribution of all the impurities, giving rise to uneven etching and nonuniform stretching of the metal. Nonuniform stretching during the mask-forming operations can also be due to a metallurgi-

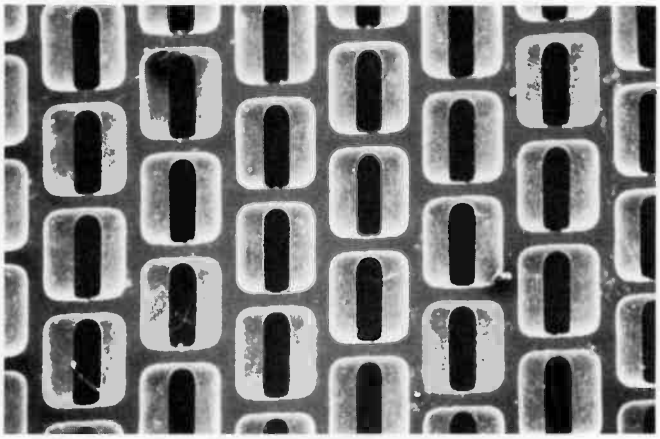
Table II. *Typical percent chemical composition of rimmed and aluminum-killed steels.**

	C(%)	Si(%)	Mn(%)	P(%)	S(%)	Cr(%)	Cu(%)	Al(%)	Fe(%)
Rimmed steel	0.10	0.10	0.25-0.50	0.040	0.050	**	**	**	†
Aluminum-killed steel	0.006	0.05	0.25-0.50	0.020	0.020	0.05	0.08	0.02-0.08	†

* Single values are maximum allowed.

** Not detectable

† Remainder



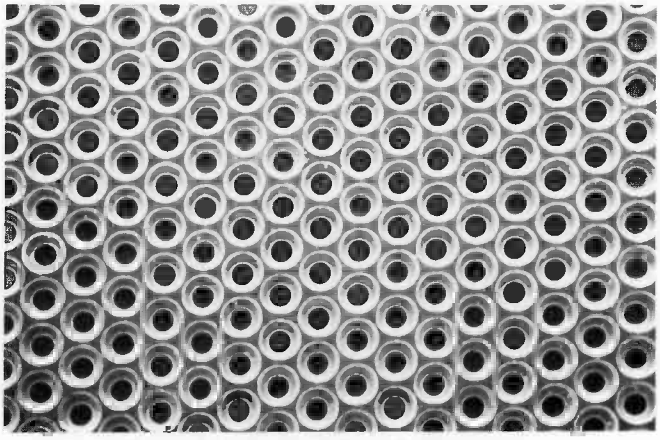


Fig. 3. *Comparison of equivalent areas for 13V/90° COTY and 13V/90° high-resolution display masks. The number of high-resolution display apertures is three times the number of apertures per unit area in entertainment-type masks.*

cal property termed yield-point elongation (YPE). Figures 5a and 5b show tensile plots of materials with and without YPE. A comparison of the information in Fig. 5 shows that AK steel can easily be annealed to remove YPE. This positive characteristic is another reason for selecting AK steel for data-display-tube shadow masks.

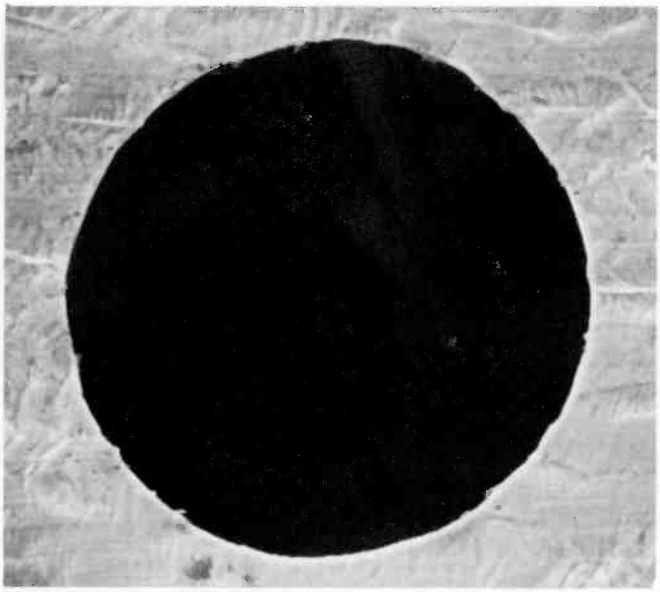
Accommodating the new mask designs

Single-step data-display mask etching

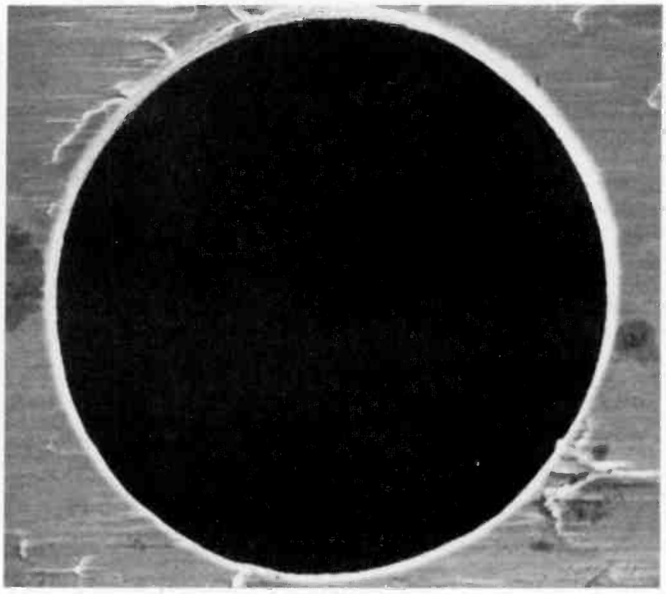
Other factors besides the metallurgical considerations can affect mask and aperture uniformity. Aperture visual and dimensional characteristics are also determined during etching by equipment configuration, process conditions, and artwork image-size design. For entertainment-type masks, these parameters are well established for efficient high-yield production. Extensive tests on pilot and manufacturing equipment have shown, however, that these entertainment-mask parameters must be modified to accommodate the small-aperture, fine-pitch, data-display mask designs. A comparison of the entertainment-mask aperture geometry versus the more demanding data-display mask aperture geometry leads to conclusions on the ideal etching processes for these new masks.

Entertainment-mask aperture geometry

Figure 6a shows the typical finished aperture geometry for entertainment-type masks. This geometry provides good visual uniformity, process control, and acceptable electron-beam clearance. The critical features of the geometry in Fig. 6a are a large



(a)



(b)

Fig. 4. *Comparison of rimmed steel and aluminum-killed steel display mask apertures.* **(a)** *Rimmed steel display aperture, and* **(b)** *aluminum-killed steel display aperture. The rimmed steel apertures are characterized by ragged edges. This condition is not present on aluminum-killed steel and produces better visual uniformity in the finished mask.*

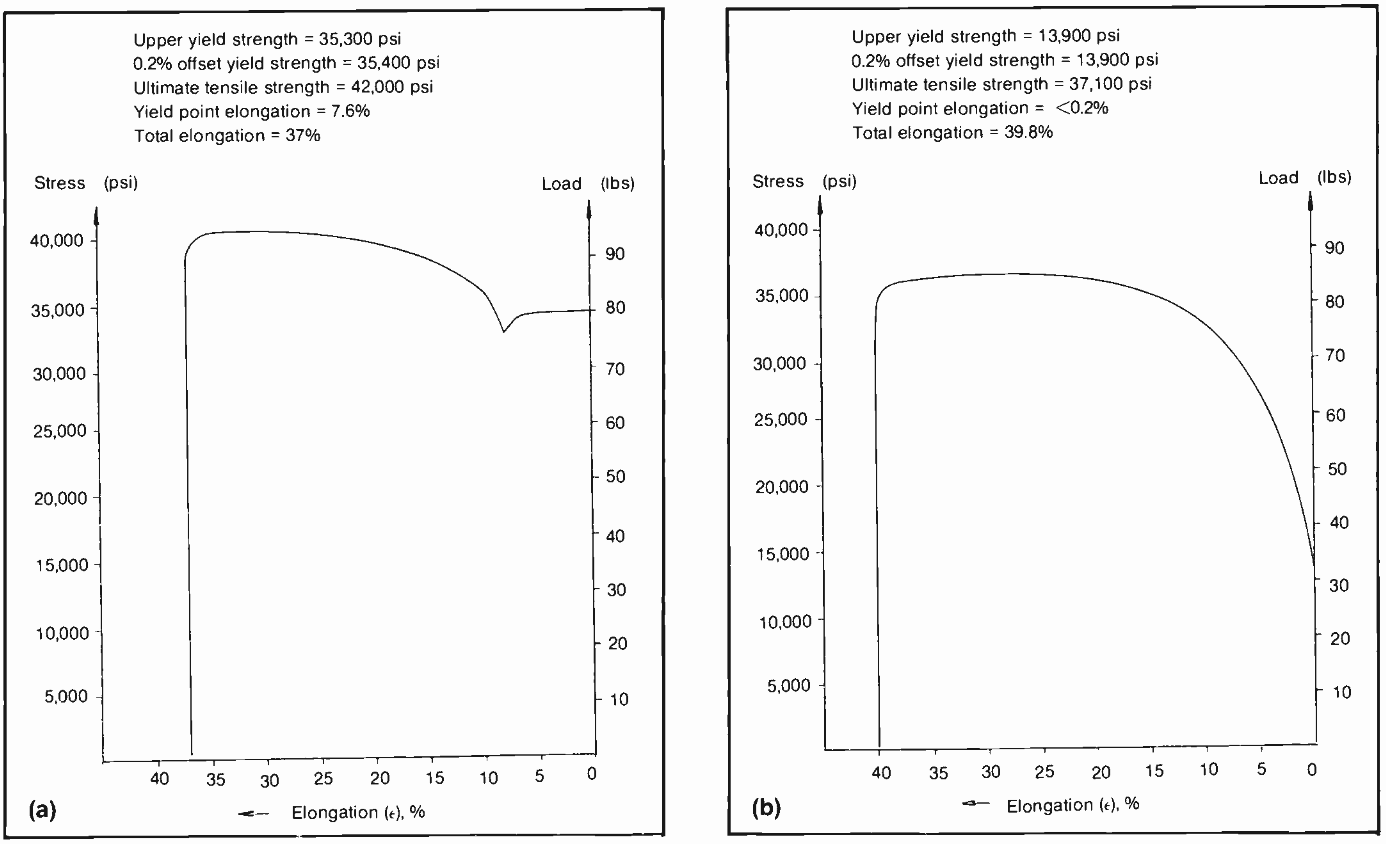


Fig. 5. *Comparison of the stress versus elongation curves (after annealing) for* **(a)** *rimmed and* **(b)** *aluminum-killed steel shows a discontinuous feature termed yield-point elongation (YPE) in the rimmed material that is not present in the aluminum-killed steel. YPE is a source of nonuniformity in the formed and blackened mask.*

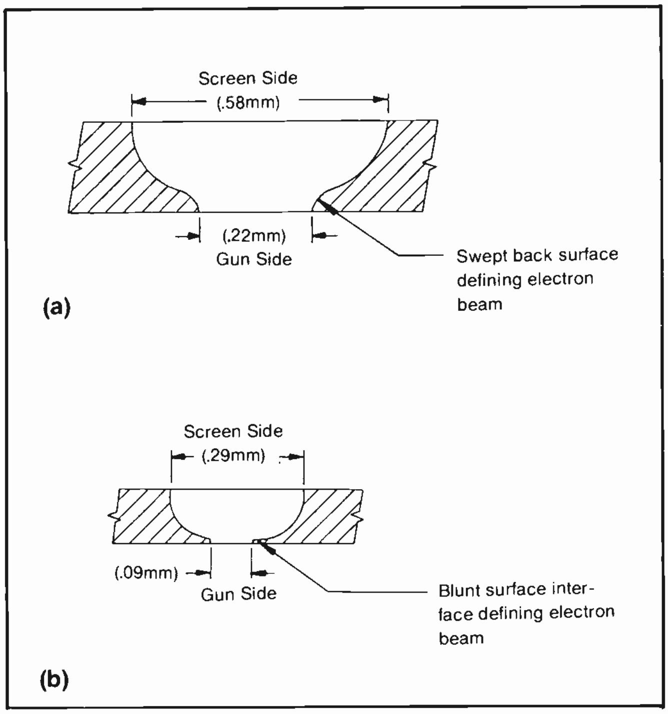


Fig. 6. *Comparison of aperture geometry for* **(a)** *entertainment and* **(b)** *data-display masks shows the data-display geometry has smaller screen size openings, more screen side etching depth, and more blunt surface interface defining the electron beam.*

screen-side aperture opening where 75 percent to 80 percent of the etching is done from the screen side, and a swept-back surface where the gun- and screen-side openings meet during etching. This aperture geometry provides slow-changing surfaces for good process control during etching. Good visual uniformity also results from the smoothed, swept-back opening that defines the electron beam. Aperture openings are large enough to prevent undesirable surface light reflections observed during mask inspections. Also the mask's finished aperture dimensions are such that the required artwork image sizes are well within state-of-the-art limitations.

Data-display mask-aperture geometry

Initial attempts at etching data-display-type masks by use of the conventional entertainment-type manufacturing parameters met with failure, due to poor mask uniformity. Subsequent tests on pilot equipment showed that this poor uniformity was related to the data-display mask-aperture geometry. Specifically, the gun and screen openings, and the geometry of the intersecting surfaces where they meet during etching cause a nonuniform appearance in the finished mask. This condition is exaggerated by artwork-required image sizes that fall outside of current entertainment-mask state-of-the-art limits.

Figure 6b shows the empirically determined preferred aperture geometry for data-display-type masks. Critical features of this geometry that distinguish it from the entertainment-aperture configuration include the following: (1) screen-side openings are small because of the mask design pitch; (2) 85 to 90 percent of the etching is accomplished from the larger screen-side opening;

(3) a blunt surface where the gun- and screen-side openings meet defines the electron beam; and (4) the screen-side opening is "hollowed out" to minimize surface light reflections that could affect mask uniformity. These characteristics are necessary to achieve the best visual and dimensional quality for the data-display product with maximum process control.

Etch modifications for data-display mask etching

The modifications to the conventional entertainment-type mask etching process, required to produce the data-display masks, were determined by two factors. One factor was the need for more screen-side etching, as shown in the optimum aperture geometry specified in Fig. 6b. This increased screen-side etching reduces surface reflections that affect uniformity, and provides the desired electron-beam clearance. The other factor identified for modification was the geometry and surface configuration of the gun- and screen-side surfaces where they intersect during etching. This point eventually defines the electron beam.

Increased screen-side etching. It was determined that etch-machine equipment modifications would be the most effective method for achieving the increased screen-side etching. The most critical part of the etching process takes place before the gun- and screen-side surfaces meet, and "breakthrough" of the surfaces is achieved. After "breakthrough" occurs, the intersecting surfaces of the aperture are cleaned out and no more penetration from the screen side alone is possible. For this reason, modifications were made to the equipment to adjust the ratio of the gun-side to screen-side etching *before* "breakthrough" occurs.

On the manufacturing line, gun-side nozzles that dispense the etchant were changed to reduce the etchant flow rate. Extenders added to the spray manifolds of the screen-side nozzles, however, in effect moved the nozzles closer to the strip. Pressures on both sides of the strip were adjusted to obtain adequate, uniform coverage under this new set of conditions. Equipment and spray pressures after "breakthrough" were not changed. These modifications produced the desired increase in screen-side etching without unmanageable adverse effects.

Modified openings. The need to modify the geometry and surface configuration of the gun- and screen-side openings where they meet during etching was approached in a slightly different way. A series of pilot etching tests, unrelated to data-display mask etching, was performed to determine the effect of etchant temperature and concentration on aperture geometry for entertainment-type masks. Visual and dimensional analysis of aperture geometry for these masks showed that the gun- and screen-side intersecting openings defining the aperture at particular temperatures and concentrations were similar to the desired configuration for data-display masks. Of course, these ranges were undesirable from an entertainment-mask production standpoint because current production rates would be significantly reduced. They were, however, judged to be acceptable for data-display mask production.

Laboratory tests were also run during this period to determine the effect of etchant temperature and concentration on steel surface roughness. These tests showed that the improved uniformity ranges found in the entertainment-mask aperture geometry tests correspond to the smooth etch regions defined in this testing. These results are shown in Fig. 7.

An optimum temperature/concentration combination for data-display mask etching was selected based on the pilot entertainment-mask aperture-geometry etch tests, and the curves in Fig. 7. As indicated previously, the intent in selecting this combination was to produce the optimum aperture geometry and surface configuration where the gun- and screen-side openings intersect and define the electron beam. Tests were run with these conditions, which confirmed that a more desirable data-display mask-aperture geometry with improved mask uniformity could be produced.

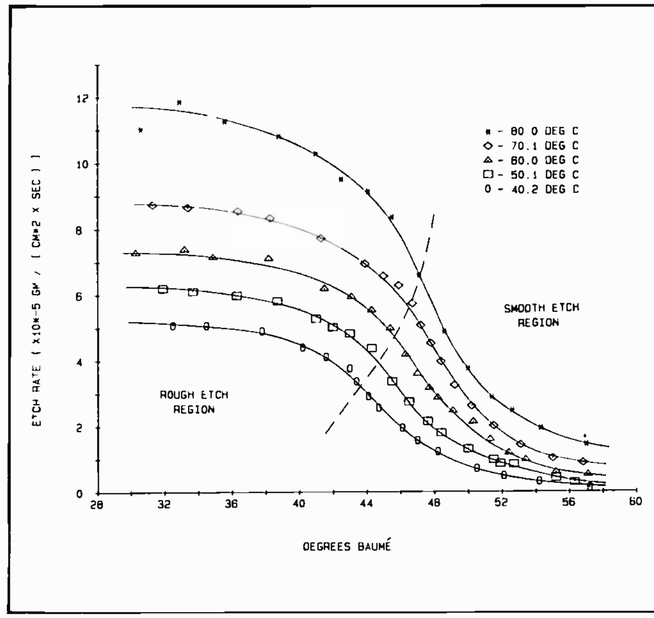


Fig. 7. *Baume and temperature-combination curves for smooth and rough etch. The sections of curves to the right of the dotted line define the regions where smooth etch and improved mask uniformity are obtained.*

Significant improvements have been made in RCA data-display mask uniformity with these equipment and process modifications. Work is continuing in this area to realize further improvements in the single-step data-display etching process. Another area of etching technology that may need to be utilized for data-display mask production involves two-step etching techniques. In addition to the single-step process described, RCA VCDD is exploring these two-step techniques.

Two-step etching

A more theoretical examination of the mechanics of etching reveals why the etch process modifications to single-step etching, previously discussed, improve display-mask uniformity and aperture geometry. This examination also suggests other more complicated equipment and process modifications that could be used to produce high-quality data-display masks.

Several factors determine the minimum acceptable aperture opening that can be obtained in a given material thickness. First, there is a practical limitation to the minimum clearly defined, developed image size. This, of course, is directly related to the artwork image size. Also, etching unavoidably occurs laterally, under the resist opening, as the material is being etched to the required depth. Figure 8 shows progressive steps in the etching process. In actual practice, lateral etching increases at a rate of 60 to 80 percent compared to the rate of depth etching. Even after the two etched sides meet ("breakthrough"), it is necessary

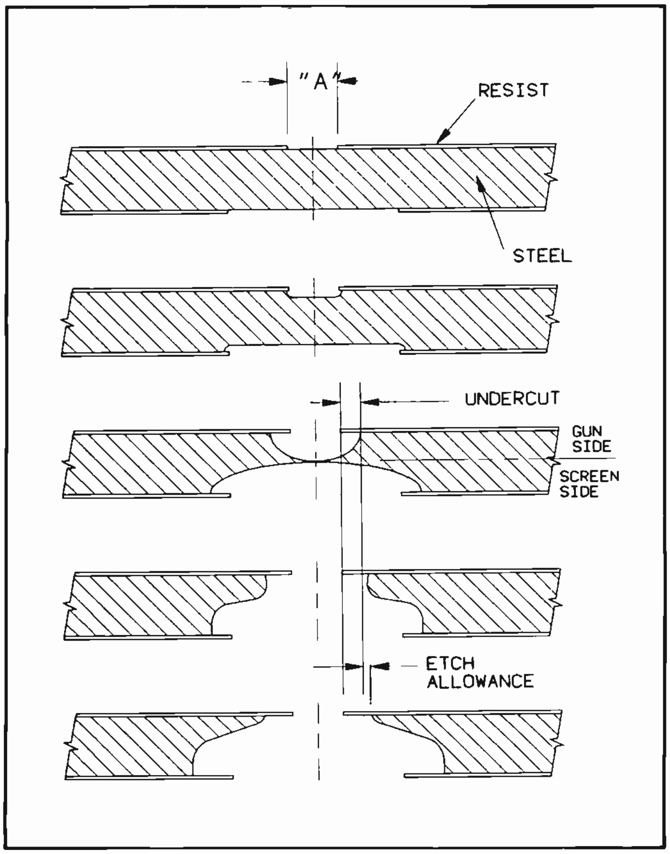


Fig. 8. *Progression of etching. The individual sections show idealized steps in achieving an etched aperture. Key features in establishing aperture geometry are undercut, etch depth, and etch allowance.*

to continue etching to produce the desired openings. This additional etching action further increases the size of the minimum obtainable well-defined etched aperture.

Etching that goes beyond the stencil opening is called "undercut"—as etching depth decreases, the undercut decreases. Therefore, a small minimum opening, whose shape and size closely approximates the stencil opening, can be obtained by etching to a minimum depth from the small-opening side of the material. This side of the mask faces the electron gun and defines the opening through which the electron beam passes. As previously indicated, this effect is accomplished in single-step etching by retarding the etching from the small side while simultaneously increasing the etching from the large side.

The minimum, clearly defined, opening size that can be obtained using single-step etching is equal to about 70 percent of the thickness of the material. If the minimum aperture size required is smaller than 70 percent of the material thickness, more complicated etching procedures must be employed.

Precision etching

To solve this problem, posed by a minimum aperture size that is smaller than 70 percent of the material thickness, we designed and built a shield-like chamber within the overall etch chamber itself[2] (Fig. 9). This equipment allows for a two-step or precision etching process. The enclosure prevents the etchant from contacting the small-opening side until the large-opening side is etched to a predetermined depth. At this point, the material moves out

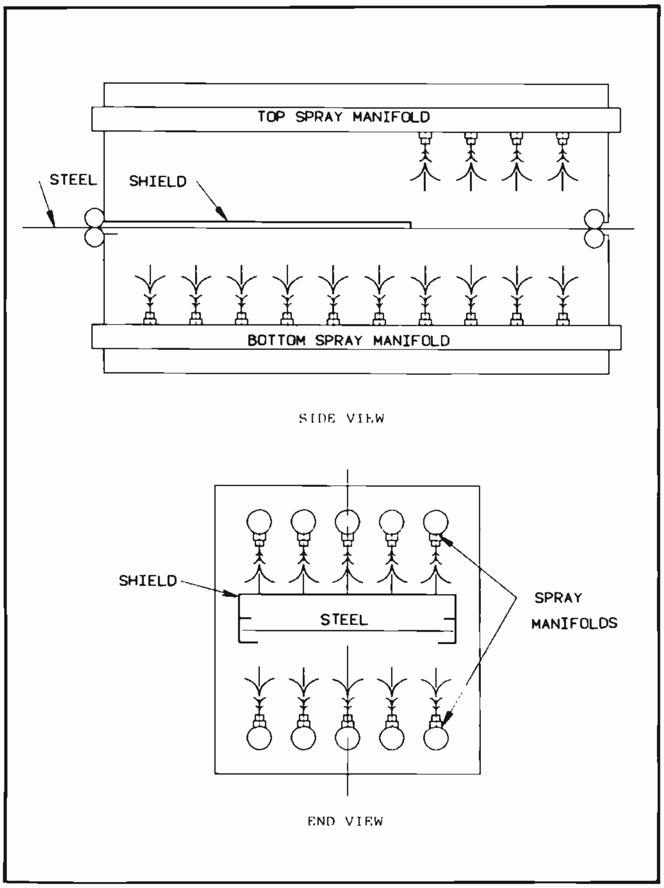


Fig. 9. *Precision etch equipment and process. The cross-sections show the use of a shield-type chamber to achieve very small apertures for ultra-high resolution masks. This relatively simple modification has been shown to be effective in producing good quality data-display masks.*

of the protective enclosure, and the etching process is allowed to take place simultaneously from both sides of the material. But the etchant has been given a "headstart" on the large-opening side.

The prolonged etching of the large-opening side effectively reduces the material thickness so that only minimal etching of the small side occurs before the two sides meet one another. This etching procedure significantly reduces the undercut of the images on the small-image side.

There are special advantages to the RCA two-step etching process that cannot be achieved with one-step etching. Some of the advantages are:

1. Minimum undercut occurs on the small-image side of the strip.
2. Smaller etch allowance (Fig. 8) is needed.
3. The etched aperture more closely approximates the artwork image.
4. This continuous process does not require the application of an etch-resistant coating or other chemicals that retard etching.
5. Missing stencil defects on the small-image side are less critical due to the fact that the enlargement during etching is significantly less, compared to one-step etching.
6. Existing production equipment can be converted to two-step etching in a relatively short time at minimum expense.

Some of the disadvantages with two-step etching are:

1. The productivity for a given etch-chamber length is significantly less.
2. The large-size image undergoes a much greater undercut, which sometimes causes a problem in the separation of adjacent apertures.
3. There is a loss in production flexibility because production of entertainment-type shadow masks with a two-step etching process is not economically practical.

Thus, it is obvious that a two-step etching process will be employed in production *only when there is a sufficient demand to justify the increased cost* for such a sophisticated shadow mask.

Summary

RCA Video Component and Display Division has made significant advances in shadow mask manufacturing technology, to meet the challenges related to the production of shadow masks for data-display tubes. Key factors in this progress have been a better understanding of the etching process, the use of aluminum-killed steel instead of rimmed steel, and relatively minor modifications to existing etching equipment. For very high resolution masks, a novel etch-tank modification is used, which employs a shield-type chamber to reduce the amount of etching on the small-aperture side of the mask.

Even with all of the present and past innovations in processes and equipment to produce color picture tube shadow masks, there undoubtedly will be future challenges associated with the introduction of high-definition television (HDTV) in the years ahead. Currently, color data-display tubes represent a promising business opportunity for VCDD. As this market expands in 1985 and beyond, VCDD plans to capture a sizable market share of this high-technology product.

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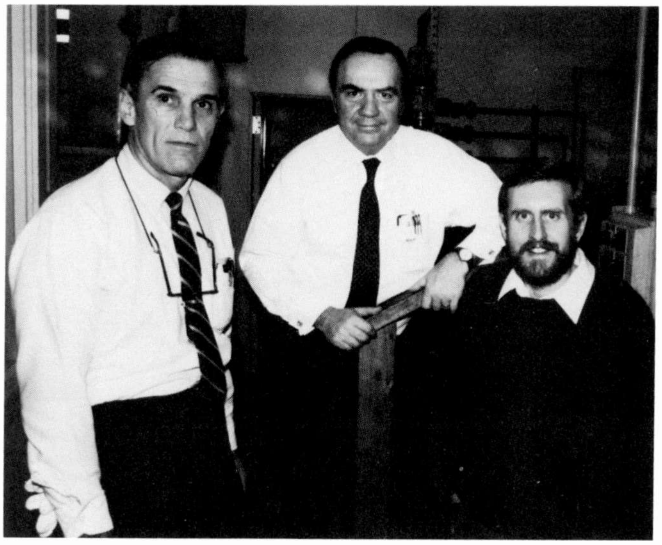

Authors (left to right) Weber, Moscony, and Doerschuk.

Don Weber received a BS in Physics from Lafayette College in 1953. He joined the RCA Color Production Engineering staff at Lancaster in 1956. Between 1956 and 1979 his responsibilities were in various engineering areas, supportive to the solution of manufacturing problems at both the Lancaster and Marion Color Tube Manufacturing plants. This work involved screening, funnel coating, inspection, final panel preparation and exhaust.

In 1979 Don transferred to the Mask Technology/TTL group in Lancaster and is presently a Senior Member Technical Staff. He is responsible for advanced development and coordination of studies relative to improved processes for new mask designs.

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Jack Moscony received a BS and MS in Chemistry from St. Joseph's College, and a PhD in Chemistry from the University of Pennsylvania. He held a David Sarnoff Fellowship at the University of Pennsylvania from 1962-1965. Jack joined RCA in 1957 and from that time until 1962, he worked on materials development projects related to thermoelectric and thermionic energy converters. In 1965 he joined the Chemical and Physical Laboratory at the RCA Lancaster location. As a Senior Engineer and Engineering Leader, he worked on many materials and process programs associated with the production of color television picture tubes.

Since 1979, Jack has been Manager of the Mask Technology group of the Lancaster Technology Transfer Laboratory, and Leader Technical Staff of the Materials and Process Mask group.

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Ernie Doerschuk joined the RCA Color Picture Tube Division in 1973 after receiving a BA in Chemistry from Millersville University. He has been involved since that time in the area of materials and process development for color picture tube shadow mask manufacturing. Ernie has helped in the solution of a broad range of problems including casein-resist development, production start-up of horizontal processing equipment in Barceloneta, Puerto Rico, and development of data-display, full-square, and square-planar mask types for production. He is currently Member Technical Staff, Mask Materials and Process Engineering, Video Component and Display Division.

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T.I. Arnold

Involvement in quality

Automated Systems is improving the quality of its product and improving morale as well as saving money, by calling on its most valuable resource—the manufacturing workforce.

Various international successes in maintaining high quality while increasing productivity have spawned similar efforts by U.S. companies. Everyday a "new" innovative employee participation program is created in hopes of capturing increases in productivity. Because each company has unique problems associated with their specific products, the variety and scope of employee participation programs runs the gamut. Generally, high quality and savings in production costs are the desired primary goals.

One successful program is Involvement in Quality (IQ), used with notable success at RCA Automated Systems. Located in Burlington, Massachusetts, RCA Automated Systems is a high-technology engineering and manufacturing plant employing 1700 people who work exclusively on the design and fabrication of a wide range of military products. The manufacturing sector reflects a high-technology environment in the diversity of processes and the necessity for precision assembly. With annual sales of over 120 million dollars, the production requirements for different products vary from a few units a year to hundreds a month.

These requirements present unique problems in implementing workplace changes that affect overall manufacturing productivity. Traditionally, companies in contraction gain productivity by reducing the existing workforce, but RCA Automated Systems has been growing at a rate of 10 percent per year and has been able to experience real gains in productivity. With the addition of new employees at a constant rate, Automated Systems has had to overcome the "learning phase" drag on productivity. A direct correlation between experience and productivity demonstrated the need for strong on-the-job training and employee participation in the decision-making process.

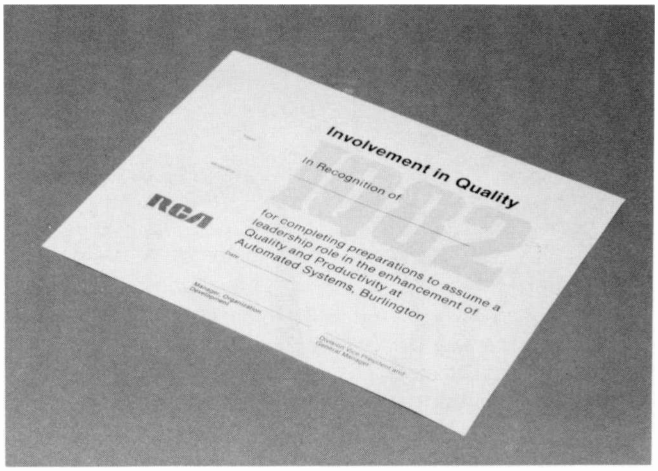

Fig. 1. *Those assigned as moderators received training recognition certificates bearing gold seals.*

The Involvement in Quality program evolved over a two-year period beginning with the establishment of goals and planning for the implementation process. Experiences gained during the early phases were translated into refinements and redefinitions of goals until results came into the desired range. The initial phase consisted of organizing the manufacturing process into groups that reflected the specific products in production..

Participation was mandatory and leaders were plant supervisors. Initial response was positive but with time, the program became reduced to a series of changes that affected and in some

Abstract: *Involvement in Quality (IQ) is an RCA Automated Systems program designed to release the quality and productivity ideas that are present in the workforce. The author describes the preparation, training and kick-off steps in starting the program, and then describes the specific achievements of the program, including quality gains, and the employee rewards system that has been instituted.*

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Reprint RE-29-2-12

cases improved the work climate but did not improve methods, quality, cost, or productivity. Typical improvements implemented during this period included an employee credit union, weekly (as opposed to bi-weekly) paychecks for those desiring the change, and a variety of convenience moves.

The management believed that there were real rewards to be gathered if RCA could release the quality and productivity ideas that we were confident were present in the workforce. Because it was recognized that there would be some up-front expenditures before any payback was realized, an initial budget was established. Thus a second phase or "new" program was structured.

Preparation

The first step in the "new" Involvement in Quality program was to develop and codify the goals. These were determined to be threefold:

1. To increase the participation of employees in workplace decisions, thereby tapping a large but quiescent source of ideas for improvement.
2. To make the job processes faster, easier, less expensive, and/or more consistent.
3. To improve the quality of work and thereby reduce both internal rejections, rework, and the number of escapes.

Training

Recognizing that not all first-line supervisors are adapted to a moderating/facilitating type of leadership, we provided four all-day sessions for all first-line supervisors in both shop and office functions. This training was aimed at increasing their ability to stimulate group solutions to problems as well as their receptiveness to new ideas. Actual problems were solved and the superiority of the group decision over the individual decision was demonstrated as was the effect of the organization on the decision-making process. The plant training manager conducted these training sessions with the Quality Assurance and Manufacturing managers in attendance. The importance of this program to management was further emphasized by a presentation by the Division Vice-President and General Manager. His presentation emphasized that the IQ program was a division effort with support coming from all levels of management. Recognition was bestowed upon those completing these formal training sessions in the form of certificates of completion (Fig. 1).

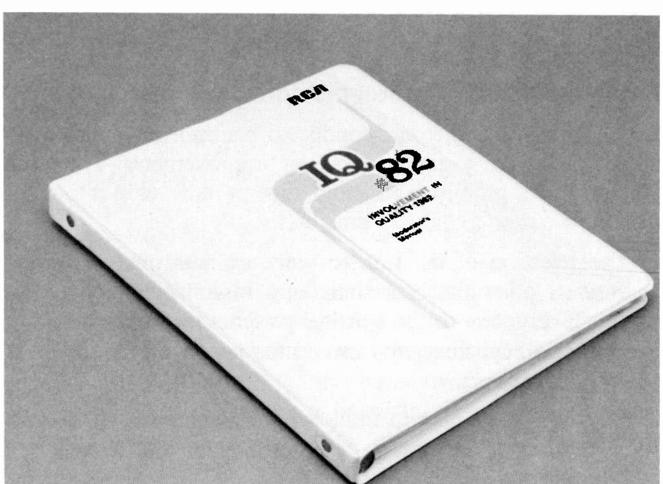


Fig. 2. *The moderators training manual contains complete outlines of all material presented in the four-day training program.*

Moderator for each team

Upon completion of the training program, the Managers of Manufacturing, Quality Assurance, and Training selected the supervisors who would serve as team moderators. These decisions were based on: demonstrated experience, performance in the training sessions, and the amount of enthusiasm and effort it was anticipated they would be able to exact from their personnel. In all cases, the moderator was a supervisor or professional working in the same area as the team members. Figure 2 shows the Moderator's Manual used to guide and formalize the training sessions.

Kick off

Once the organization phase was accomplished, the next step was implementation. A series of large meetings, accompanied by refreshments to enhance the informal environment, were held with all operations personnel. An outline of the mechanics of the program with desired goals was presented. The responsible managers discussed the "hidden storeroom" of ideas we were seeking to use as well as the ground rules that defined the programs. Suggestions were sought that would make a job faster, easier, less expensive, or more consistent. The suggestions had to result in increased productivity, reduced cost, or an improvement in quality.

It was decided that IQ teams would consist of a moderator and six to fourteen members, all of whom would be volunteers. Hourly meeting periods during the working day were provided once or twice each month. Ideas were evaluated by one of two criteria. The first criterion was in reduced costs demonstrated by typical "payback"-type justification that expressed the net annual savings after amortization of the costs of implementation (not including the direct costs of the IQ program).

The second criterion was improvement in Quality. In order to avoid the categorization of non-conformance by a clerical force unfamiliar with the actual condition, our Quality department developed a uniform listing of some 39 objective descriptions of non-conformances that could be invoked by the inspector and easily stored and processed by computer (Fig. 3). As a result of this effort, we were able to post in each work area and in one central area, tabulations showing the number of objective (no opinion involved) and subjective (inspector's opinion) non-conformances found (Fig. 4). These tables were accompanied by line graphs of the non-conformances per unit found each day for each of fifteen different work areas (cable area, printed circuit boards, metal shops, racks, etc.). Thus, the charts give a daily input of quality and the consequent costs of rework, repair, or scrap. In addition to posting the summary data, a quality engineer held a daily review of the previous day's non-conformances with each Manufacturing and Quality supervisor. The data shown on these charts and discussed in the daily review, together with a calculated value of a non-conformance per unit for each work area, serves as the base from which to calculate savings associated with those ideas that provide improved quality, either without or in conjunction with cost changes.

Defects Listing

Objective Defects

1 ADAPTER - DAMAGED, INCORRECT LENGTH
2 ASSEMBLIES - DAMAGED, INCORRECT, LOOSE, MISSING
3 BACKSHELL - LOOSE
4 BANDMARKER - DAMAGED, INCORRECT, INCORRECTLY POSITIONED, LOOSE, MISSING
5 BOARD - CRACKED, DAMAGED, SCRATCHED, WRONG
6 BOOTS - DAMAGED, INCORRECT CONFIGURATION, MISSING
7 CABLE/HARNESS LENGTH - INCORRECT
8 CABLE ROUTING - DRESSED INCORRECTLY, INCORRECT LOCATION
9 CHASSIS - INCORRECT ALIGNMENT INTO RACK OR NEXT HIGHER ASSEMBLY
10 COMPONENT - DAMAGED, INCORRECT, INCORRECT LEAD LENGTH, INCORRECTLY MOUNTED, MISSING, SCRATCHED
11 CONNECTOR - DAMAGED, INCORRECT, LOOSE, MISSING
12 CRIMP - INCORRECT (EXCLUDING LUG)
13 DIMENSION - OUT OF TOLERANCE
14 DOCUMENTATION - INCORRECT, MISSING, SPECIFIES WRONG REVISION
15 FILLERS - DAMAGED, MISSING
16 FLEXPRINT® - MISSING, TAPE DAMAGED
17 HARDWARE - DAMAGED, INCORRECT, INCORRECTLY POSITIONED, MISSING
18 ID LABELS - DAMAGED, INCORRECT, MISSING
19 INSULATOR - DAMAGED, LOOSE, MISLOCATED, MISSING
20 KEYWAY - INCORRECTLY POSITIONED
21 LEAD - COPPER EXPOSED, MISWIRED
22 LEAKTEST - FAILED
23 LUGS - DAMAGED, INCORRECT SIZE, INCORRECTLY CRIMPED
24 MARKING - INCORRECT (EXCLUDING REV. MARKING, BAND MARKER), MISSING
25 OTHER
26 PINS - DAMAGED, MISSING, NICKED, PINCHED, SEATED IMPROPERLY
27 POTTING - INCORRECTLY PLACED, VOIDS
28 REVISION - FABRICATED TO INCORRECT REV., REV. MARKING MISSING
29 SLEEVING - DAMAGED, INCORRECT SIZE, MISSING, NOT INSERTED PROPERLY, NOT SHRUNK
30 SOLDER/BOND MATERIAL - ABSENCES, BRIDGES
31 STAKING - MISSING
32 STIFFENER - INCORRECT, INCORRECTLY MOUNTED, MISSING
33 SURFACE DEFECT - BURNED, FINISH INCORRECT OR MISSING, SCRATCHED
34 TIE STRAPS - DAMAGED, INCORRECTLY POSITIONED, MISSING
35 TORQUE - EXCESSIVE, INSUFFICIENT
36 WIRES - DAMAGED, INCORRECT LENGTH, MISSING
37 WIRE WRAP - EXCESSIVE, INSUFFICIENT, LOOSE, PIGTAILING, SPIRALS
38 GEOMETRIC CHARACTERISTICS - OUT OF TOLERANCES
39 WORKMANSHIP - BURRS, SHARP EDGES, DIRTY

Subjective Defects

50 CONFORMAL COATING - CONTAMINATED, EXCESSIVE, INSUFFICIENT
51 CONNECTOR - TOUCH UP (SCRATCHES)
52 CONTAMINATION - HARDWARE
53 CONTAMINATION - SOFTWARE
54 MARKING - LEGIBILITY
55 SEALANT - EXCESSIVE, INSUFFICIENT
56 SOLDER/BOND MATERIAL - EXCESSIVE, INSUFFICIENT
57 SLEEVING - UNEVEN
58 STAKING/POTTING - EXCESSIVE, INSUFFICIENT

Hybrids Only Defects

70 ALIGNMENT - IMPROPER
71 BALL BOND - DEFECTIVE
72 BOND MATERIAL - EXCESSIVE, INSUFFICIENT
73 CASE/PINS - DEFECTIVE
74 CHEMICAL - DAMAGE, RESIDUE
75 COMPONENT - INCORRECT, MISSING
76 CRACK/CHIPOUT
77 FOREIGN MATERIAL
78 GOLD/GLAZE - POUROUS, INSUFFICIENT
79 MARKING
80 PULL TEST FAILURES
81 RESISTOR - INCORRECT, OVERTRIM
82 SCRATCHES
83 SHORTS
84 WEDGE BOND - DEFECT
85 WIRE LOOP - EXCESSIVE, INSUFFICIENT

Fig. 3. *The list of prevalent defects compromises between an all-inclusive, but unused list of defects, and a list of defects that is too short to be descriptive.*

Reporting

To effect a permanent change on employee's job-related thought processes and behavior patterns, we needed to develop some reporting method that would keep all personnel informed of progress in IQ, acknowledge success, and recognize those individuals on teams that made significant contributions.

We selected three media of communication.

1. IQ-related pictures were posted in the main aisle of the Administration/Engineering portion of the facility.
2. An IQ newsletter was started. The newsletter listed the achievements of the various teams and listed, by name, the individuals who participated.
3. Perhaps most importantly, a reporting board 10 feet high by 30 feet long was set up at the busiest aisle intersection in the Manufacturing portion of the facility. This board consists of fourteen (14) thermometers. Thirteen show the dollar savings (including those attributable to reduced non-conformances) generated by the individual teams while the fourteenth, which is much larger and centrally mounted, reflects the combined achievements of the entire program.

These methods keep the program knowledge current and they result in a high interest level.

Implementation of problems and solutions

Initially, the teams met and conducted brainstorming sessions to record all of the available ideas for improvements. The team would select a promising idea and attempt to develop it to completion. We soon found two drawbacks:

1. The selection of the idea to work on was often made on grounds other than schedule, ease of implementation, and payoff. Emotion or the personal preference or forcefulness of one individual frequently caused the selection of a less-than-optimum project.
2. Developing the idea to fruition often required the assistance of Production Engineers or others not on the team. As a consequence, too many problems without complete solutions were proposed for evaluation.

To overcome these two deficiencies, additional moderator training was given on how to set up a matrix of ideas and actions so

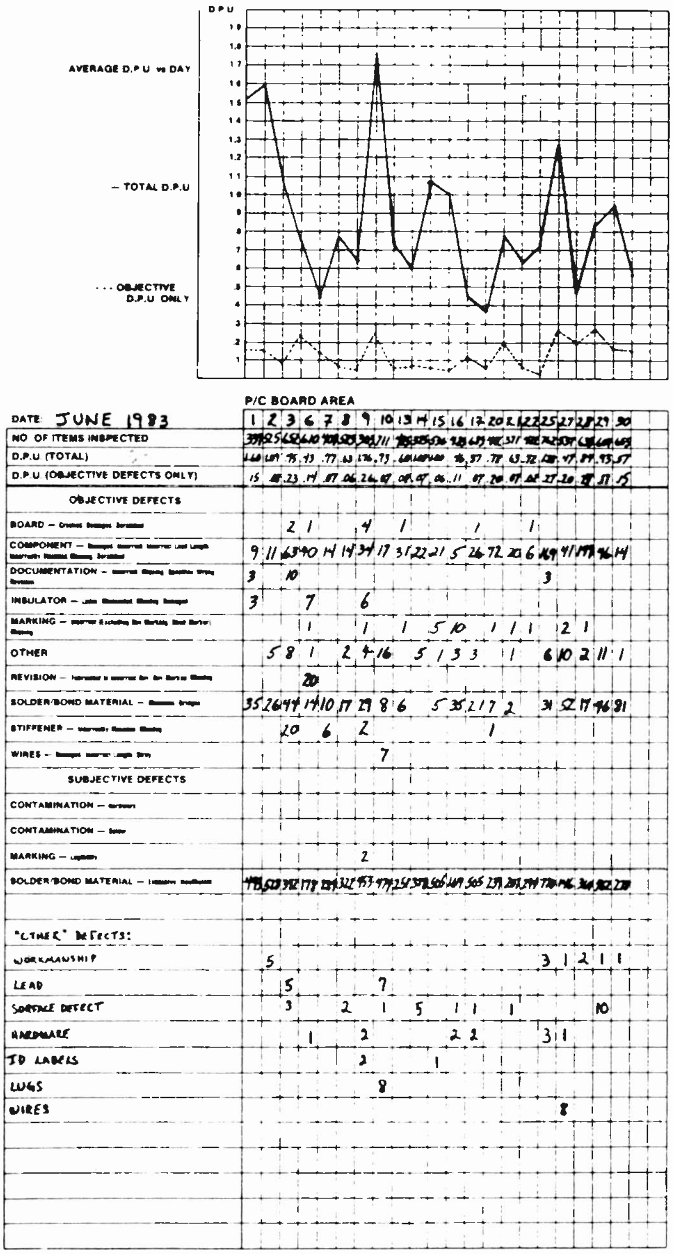


Fig. 4. *Wall charts show daily trends in defects per unit (DPUs) and tabulations of all defects, both objective (no opinion) and subjective (involving inspector's opinion).*

that the most valuable ideas would be pursued. Moreover, teams were encouraged to prepare their ideas in advance of meetings and to follow through with a more complete evaluation.

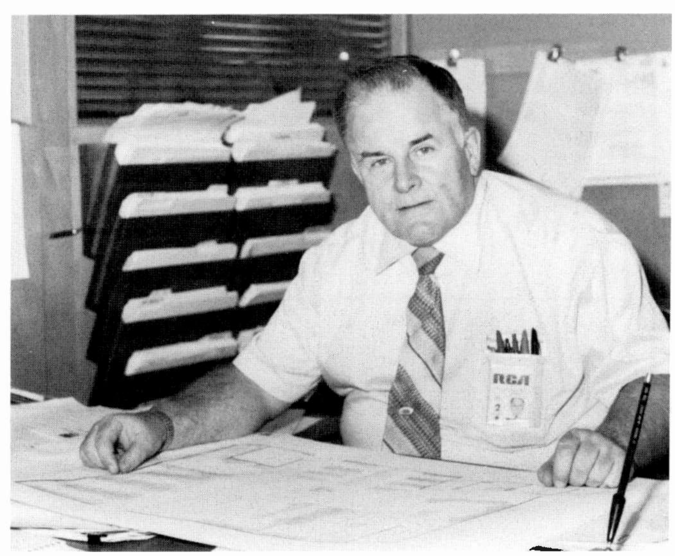
Achievements

Since the revised IQ program has been active, measurable savings have been achieved. Substantial additional savings are involved in changes currently being developed. The ideas that were developed and adopted ranged from simple to complex and from no measurable savings (intangibles only) to tens of thousands of dollars per change per year of production. Three examples were:

1. Baking of circuit boards after "stuffing." If they were on the floor seven or more days after baking and before wave solder, they were rebaked. The IQ team noted that due to changing conditions, virtually all boards were rebaked. Therefore, they proposed that the first bake be eliminated. Savings resulting from this elimination of an operation were over $3,000 per year.
2. Hydraulic transducer labels were serialized manually and an identifying color band was painted on by hand. The team in this area instituted preprinted serialized labels and had a parts vendor mechanically stripe a subassembly with the desired color code. These product and method changes resulted in annual savings of $1,800.
3. Sheet-metal workers were producing templates and using them to produce parts. The templates were then discarded, mislaid, or reconfigured for another job. Reruns of the original job required the fabrication of new, but identical, templates. The IQ team in this area established a file and retrieve system for templates that saved over $2,000 annually.

Quality gains

A reduction in non-conformance (defects) per unit have been experienced in virtually all work centers (Fig. 5). This improvement has been achieved during a period where there has been a substantial increase in the number of items inspected and a significant increase in the number of new operators and inspectors due to new hires, transfers, replacements for retirees, and so on (Fig. 6).



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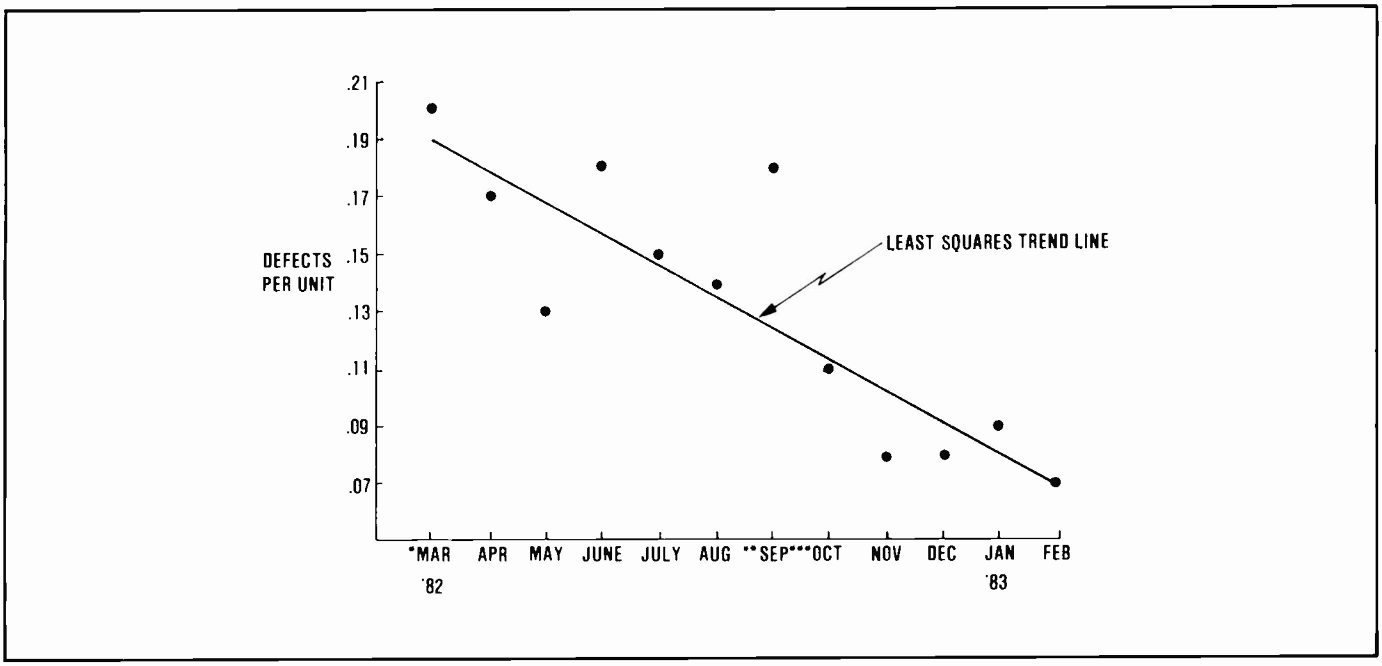

Fig. 5. *The trend in number of DPUs was sharply downward during the first year of the IQ Program.*

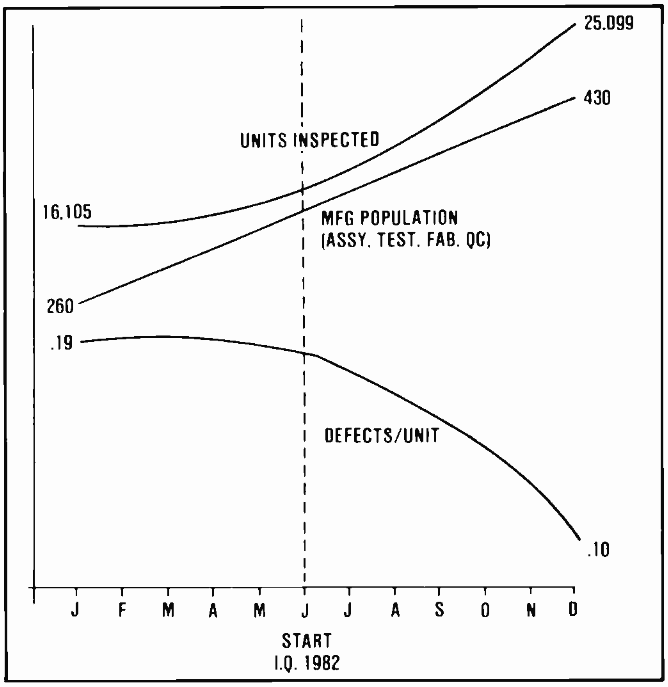

Fig. 6. *A decreased number of DPUs was achieved during the same period that both number of inspections and hiring of less-skilled workers increased.*

Employee rewards system

Management decided that some tangible reward be directed to the employees who had volunteered and had successfully participated in the IQ program. Cash awards to teams, computed at 15 percent of the annual savings, were awarded. These were calculated by computing the figure and dividing it equally among all participants on the team.

$$\text{Individual Award} = \frac{\text{(Teams Annual Savings) (0.15)}}{\text{Number of Team Members}}$$

Each team member is presented a formal invitation to the Award Ceremony. Awards are presented by the Division Vice-President, further demonstrating that the program is supported by management.

The future

The IQ Program has established itself as an integral part of Automated Systems' philosophy. Expansion into non-manufacturing areas is being planned. The program has achieved measurable positive results for the company in quality and cost reduction and for the employees in awards and feelings of team accomplishments. Also, it has proven the old adage that it is always cheaper to "do it right the first time." To this we add "and better." This level of processing and quality remains the goal of RCA Automated Systems.

Online Literature Searching

Did you know that the following databases are available to you for online searching?

Conference Papers Index, 1973 to present—*provides access to records of more than 100,000 scientific and technical papers presented at over 1,000 major regional, national and international meetings each year.*

RCA TAD (Technical Abstracts Database), 1968 to present—*provides access to records of more than 18,000 RCA technical documents, including technical reports, engineering memoranda, unpublished manuscripts, patents, and technical notes.*

Your RCA librarian will be pleased to assist you in searching these databases. . . and many others, too.

Just-In-Time—Making exponential productivity gains

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In today's competitive global market, just to keep even will require much greater productivity gains than have been typical of most U.S. industry. Improvement must be exponential, not incremental. The adoption of Just-In-Time (JIT) is a clear way to make these exponential gains.

Members from Corporate Staff Materials have spent time over the past two years gathering information on Just-In-Time and have put together a presentation on this topic. They are involved in an effort to encourage Just-In-Time pilot projects at RCA. Although a complete explanation of JIT is beyond the scope of this article, some introduction to this topic can be given.

Definition

The most basic definition is this. JIT is an operations philosophy (rather than a system) of producing only the minimum necessary units in the smallest possible production-run quantities at the latest possible time with the objective of achieving plus or minus zero performance to schedule.

Just-In-Time prescribes no single methodology or technique. It simply establishes the goal to pursue, the means to achieve this goal, and the self-evaluation standard for the measurement of success. Waste of all types must be removed from our manufacturing processes in order to have factories function without inventory, inventory that compensates for the problems not yet solved. Look at the causes of inventory: quality problems, set-up time, long cycle times, improper scheduling, inadequate information systems, complexity instead of simplicity, old habits and attitudes. In this sense, inventory is one yardstick of how good a total management job is being done. With layers of inventory slowly peeled away, concentration can then be focused on attacking the most visible evidence of remaining wastes. This waste manifests itself in inventory that is too high, quality that is too low, lead times that are too long, and material that aimlessly moves too much and too frequently around our factories. By analogy we can view inventory as the water level in a pond with a rocky bottom. The rocks represent problems. As the water level goes down, invariably at the worst possible time, the problems are suddenly and unexpectedly exposed. It is better to force the water level down on purpose, expose the problems and fix them now, before they cause trouble.

Abstract: *Just-In-Time is primarily an attack on the manufacturing inefficiencies that excessive inventory causes and conceals. The goal is to strip away inventory, expose problems, and then fix them. To do this carefully and effectively requires a number of complex and interrelated steps. The authors are now encouraging JIT pilot projects at RCA.*

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The elements

The following key elements of Just-In-Time make it a useful system:

- Reduced inventory
- Short set-up times
- Elimination of waste
- Total quality control
- Small lot sizes
- Short-term schedule stability/predictability
- Multifunction workers
- Preventive maintenance
- Emphasis on simplicity
- Highlights problems/opportunities
- Supplier networks

The benefits

The benefits of Just-In-Time are significant:

- Reduced lead time and shortened production time
- Improved customer service
- Reduced material handling
- Increased visibility to management
- Higher quality
- Reduced space
- Reduced capital requirements
- *Increased productivity*

Following is some additional detail on one of the key elements given above.

Total quality control

Total quality control means a lot of things. The emphasis is on defect prevention rather than defect detection. Improved quality is a prerequisite as well as a benefit. Quality must be good to start, but JIT will greatly improve quality.

Statistical process-control techniques are used, with the emphasis on the quality of the process as well as the quality of the product. Fail-safe production techniques are used. We should design the product or the assembly technique so that it is impossible to do any wrong—the "square peg in a round hole" concept. Or use machines that detect problems and automatically stop or light up. Take judgment out of the inspection process. The more these techniques are used, the closer we come to achieving effective 100 percent inspection.

Problems get fast feedback. Problems are made visible with automatic machine shutoffs, warning lights, and so on. Problems are also made visible by low inventory and the constant pressure that the line won't run if everything isn't right; every part is needed.

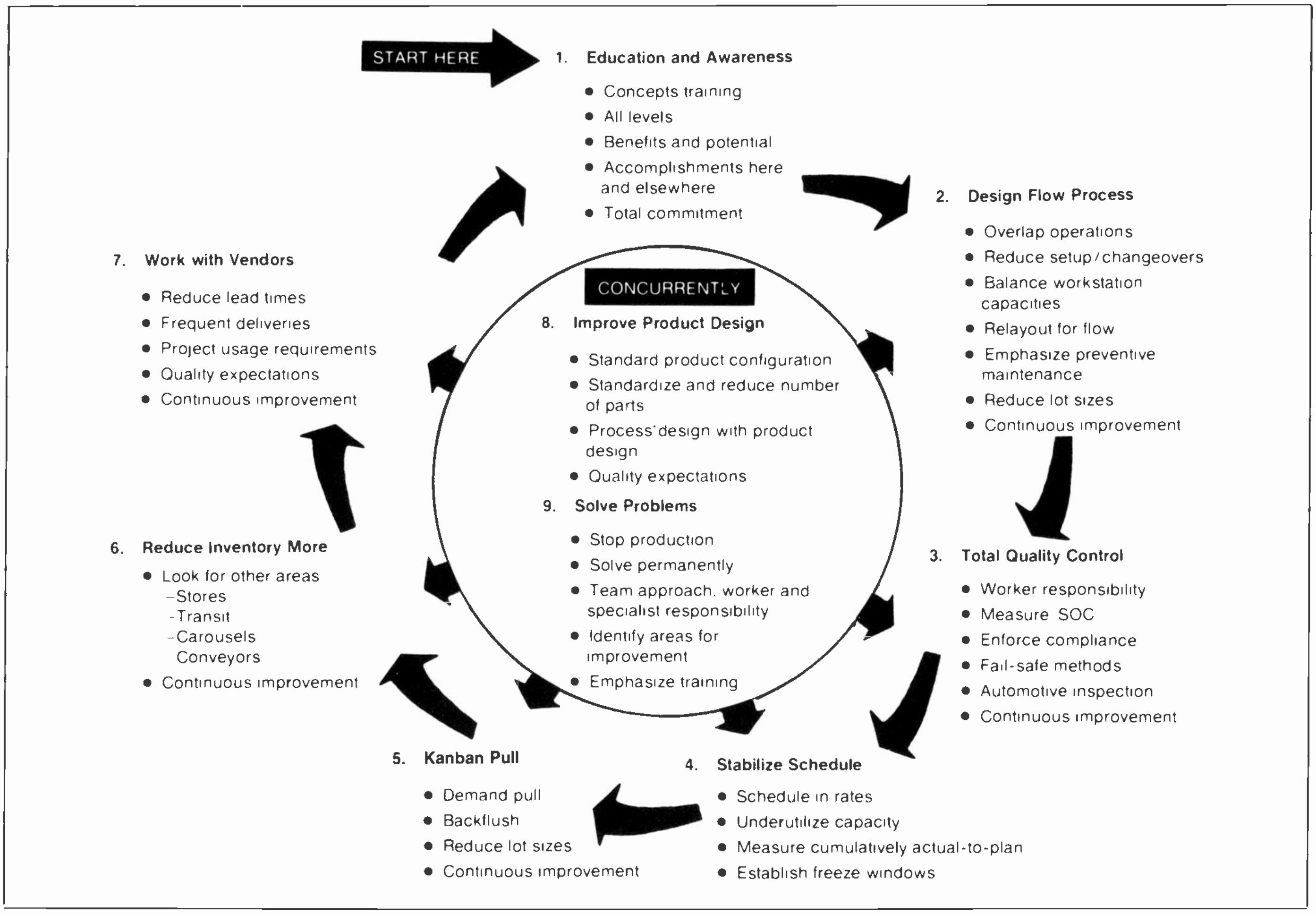

Fig. 1. *Nine steps to improve quality and productivity and accomplish repetitive manufacturing. Note that "kanban" is a simplified control or execution system. Typically, when parts are needed, a kanban (literally, a card) is passed to the preceding upstream workstation. The "kanban" is the only authorization for that workstation to produce parts. Kanban is only a small part of the overall JIT concept.*

Employee involvement is stressed. The worker is encouraged to be responsible for the quality of production and is given tools and a situation that makes him capable of producing parts to specifications. Management provides the necessary work aids, and supports the workers in their endeavor to avoid producing poor-quality products. It becomes a way of life that bad parts never pass from one operation to the next in the manufacturing cycle. There is a habit or philosophy of continuous improvement. Previous programs—we all remember "zero defects"—were different than what we're talking about here. They didn't change the way we operate, so there was no additional need or visibility. Mostly, a slogan campaign held sway. The importance of worker involvement, and the constant emphasis under JIT for the production *worker* to be more responsible for quality, cannot be overemphasized.

Just-In-Time deliveries is not necessarily one of the first steps of a pilot program even though this is one of the most talked about aspects of JIT. It is important first to get our own house in order, to provide the stability that will make Just-In-Time deliveries a contributor and not a problem. And the real intent is not to have suppliers make Just-In-Time deliveries from their own enlarged inventory, but to have these suppliers adopt JIT in their own factories. And the place to start with suppliers is quality improvement followed by Just-In-Time deliveries.

Summary

Major companies in businesses similar to those pursued at RCA are making large investments in, and commitments to, JIT. Through a pilot program approach, these companies are reporting major improvements and are planning a continued and broader implementation of JIT. A chart representing a typical implementation sequence shows nine steps that can improve manufacturing quality and productivity (Fig. 1). Just-In-Time will be more fully explored in a future issue of the *RCA Engineer.*

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J.L. Hotmire

A computerized system for process quality control

Data acquisition equipment, computer hardware and software are enhancing the work done by the Process Quality and Reliability Assurance Group in the Video Component and Display Division, Marion, Indiana.

In May of 1981, a study at the RCA Video Component and Display Division, Marion, Indiana, was made of Process Quality Control variables data to determine the quantity of measurements taken by the QC patrol inspectors during one month. Prompting this study was the recognition that the current method of tabulating and analyzing variables measurements is laboriously time consuming. Requests for data-analysis results by other engineering or manufacturing functions often take too much response time; answers are needed quickly when dealing with a poor or questionable production trend.

A look into the future of the color picture tube reflects the need for the highest quality product that will successfully compete in a market that is already oversupplied. Increased type proliferation, changing tube design and construction, increasing process-equipment sophistication, and tighter process and product specifications have made it imperative to modify the antiquated system of process quality control.

Abstract: *Advancing technology in color picture tube design, construction, and manufacturing makes it imperative for the Process Quality Control Activity to be a progressive service group. To this end, a study was made of QC-sampling techniques and mass-data-capturing systems available through the Hewlett-Packard Company. Several HP computer systems were investigated before finally deciding on the HP 1000 Model 60 Computer System, a high-capacity technical computer system that combines fast real-time responses with powerful software. This system was proposed to and accepted by RCA management and became operational in the fourth quarter of 1983.*

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Michael Mizell, metallurgical sales engineer, and Lawrence Strattner, manager of marketing programs, both of General Electric, stated in a presentation at the Quality Expo TIME '81:

> "Many industries and much of plant management still fail to recognize that a dynamic production process requires living with change. The better one is able to monitor that change, the better chance there is of improving productivity and creating a higher quality product.
>
> There has never been a time when the world has been more quality conscious. Management feels the pressures of the new wave of consumer consciousness, and realizes the consequences of failure to deliver quality. One product that fails or one product delivered to a customer that doesn't live up to expectation can cause the loss of a sale, a customer, or many customers."[1]

RCA management is "living with change." An effective and efficient method of handling the large amount of variable measurement data, which will allow for more rapid feedback of process or product control to engineering or manufacturing, has been determined. A computer-aided system, the Hewlett-Packard 1000 Model 60 Computer System, was proposed and accepted for the Process Quality Control function; HP hardware and system software installation and debugging was completed in November of 1983. Applications software development for use in the system has been an ongoing activity since March.

An electronic spreadsheet software package, an 8-channel multiplexer, and office terminals have been added to the system. These additions are facilitating a more rapid growth of software development and CPU utilization.

Recognizing the need

Control system

Process Quality Control has a number of inspectors that patrol manufacturing operations, monitoring both process and product characteristics; attribute and variables measurements are taken repetitively to determine process control, capabilities, and trends. Measurement data of the various sampling parameters are entered by hand on control charts by the quality control inspectors. Some control-chart applications require plotting of individual measurements, while others require calculations of averages ($\overline{X}$) and ranges (R) before plots can be made. At the end of each month, all control charts are summarized by QC engineering personnel. A "Processing Variables" report using chart summaries is issued for historical purposes by the Management Information Systems and Service (M.I.S.S.) department.

Variables sampling characteristics

A minimum of 24 critical product-related characteristics are routinely audited to determine process control. Control charts are not the only means of communicating product/process conditions to interested personnel; copies of raw data sheets, process-capability studies, time-period comparisons, letters, meetings, and so on are also used.

Data count review

A review of sampling data was made to determine the number of measurements that were taken in a month; process and product sampling by QC engineering and supervisory personnel was not taken into account. Results of the study showed the following interesting conditions:

1. Nearly 100,000 analytical, microscopic, dimensional, and optical variable type measurements are made each month. Over 55,000 of this total are made of opening sizes (phosphor strip width or dot size) of matrixed picture and data display panel/mask assemblies with a Vickers Image Shearing microscope that has an electronic digital readout system.
2. Approximately 83 hours per month of inspector time is involved in control charting graphite pH, percent graphite solids, opening size, and guard-band widths in the matrix activity alone.
3. A large percentage (56 percent) of measurement data is omitted from Matrix control charting. Demonstration of process control is based on sample sizes of four ($\overline{X}$ and R charts), and because of a reduction in the quality control inspection force and tightened inventory control, the required sample size often cannot be satisfied.
4. The QC clerk spends 17 hours each month verifying, summarizing and preparing control charts.
5. Approximately 350 charts are summarized at the end of each month for the "Processing Variables" report.
6. M.I.S.S. cost to produce the "Processing Variables" report amounts to $200 per month.

New tube types and tighter specifications

The advent of higher-resolution tube types and color-data display-tube production dictate more stringent process and product specifications. John Ratay, now Division Vice-President of Manufacturing for the Video Component and Display Division of RCA, wrote in an article for the *RCA Engineer,*

> "Internally, we are attempting to achieve a 30- to 50-percent tightening in tolerances. . . . . Manufacturing engineers continually attempt to tighten one departmental process/product standard per calender quarter. We are working in areas we feel are important to tube performance and process latitude in downstream in-plant operations. This program also will allow us to introduce production mechanization improvements with a minimum of difficulty. If the total systems' tolerances can be reduced, it will be easier to assemble the product, and uniformity and repeatability will be improved."[2]

Fitting the need

Corporate recommendations

The QC measurement data count was reviewed with the Corporate Management Information Systems and Service representative, who has the responsibility for approval of computer system purchases for the RCA Video Component and Display Division. Because of the bulk of data generated, it was recommended that an independent computer system be pursued for Process Quality Control use. Investigation of Hewlett-Packard computer systems was encouraged because of a Corporate purchasing arrangement with that company.

> ***"A minimum of 24 critical product-related characteristics are routinely audited to determine process control."***

Hardware objectives

Computer system prerequisites that need to be considered are as follows:

- It must be able to receive measurement data from the Vickers microscope; this electronic instrumentation has the capability of producing binary-coded decimal information (measurements converted to a language the computer understands), which can be fed into the computer systems' data base.
- It must be able to communicate to terminals located a long distance from the computer.
- Vickers data input must be convenient to accomplish.
- The computer must have adequate size to handle both large amounts of data and associated addresses of that data (that is, date, shift, activity, sampling characteristic, panel or tube type, room, machine, position, and data measurement).
- It must be able to handle other service groups requirements, if needed.
- It must be compatible with other computer systems in the Marion, Indiana, plant.

Software objectives

Initial software goals that needed to be considered are listed below.

- Process control and, in particular, measurement analyses that include calculations and specification-limit signals.
- Control trends (graphical output) that track by shift, day, week, month; by machine, room, type, lighthouse bank; and by slurry, graphite, caustic acid.
- Process capability studies that are given by shift, day, week, month; and by all variable characteristics.
- Comparisons (tests for significance) on a shift-to-shift, day-to-day, basis; and on a before-after process change basis; and on a room-to-room, bank-to-bank, machine-to-machine basis.
- Attribute data by the shift, day, week, month.
- Reports on a daily, weekly, monthly basis.
- Departmental attendance records.
- Special purposes, such as visual aids for group meetings, and specific gravity tables.

Hewlett-Packard computer systems

Several HP computer systems were reviewed for possible application to Process Quality Control requirements including the following:

1. System 45 Desktop Computer and two independent Series 80 (HP 85) units for factory terminals.
2. HP 1000 Model 10 L-Series-based system.
3. HP 1000 Model 16 A600 computer system.
4. HP 1000 Model 60 E-Series-based system.

Each of these systems, proposed by HP Sales representatives, was applicable; however, consideration of future needs and desired compatibility with other RCA computer systems limited the selection.

Satisfying the need

Model 60 computer system

The computer system that Process Quality Control selected for use is the Model 60 system; it uses an E-Series central processor, which is an intermediate-performance computer of the HP 1000 family. The Model 60 system is a high-capacity technical computer system that combines fast real-time responses with powerful software allowing multiuse access to large amounts of data.

Operating system software. The RTE-6/VM, real-time executive operating system provides virtual memory for data that will benefit statistical analysis.

Data base management. The Image/1000 provides a complete set of software tools, used to consolidate data files into a single data base to be accessed by many different people. It's for people who don't have and don't need sophisticated programming skills.

Graphics/1000-II. This software has interactive and three-dimensional capabilities.

Mass-storage capability. The system has 16.5 Mb with fixed-disc reliability and integrated tape drive for backup.

Graphics terminal. This is a high-quality display with built-in graphics hard copy.

Printer, 180 CPS. Bidirectional dot matrix serial printer.

DSN/data link. Data-communications interface between the computer and collection devices (DSN = Distributed Systems Network).

Datacap multiplexer. One binary-coded-decimal parallel interface card is for the Vickers microscope output and one 4-channel serial I/O interface card is for the Lear Siegler ADM-5 terminals.

Lear Siegler ADM-5 terminals

During the selection of the data collection system, it was decided to purchase Lear Siegler ADM-5 dumb terminals, primarily, because of the HP/LS price differential. The ADM-5 is an interactive device that is used to enter, display, and send information to a host computer, and to receive and display information from the computer.

Sharing the system

When the software/hardware goals of Process Quality Control are realized, this computer system will be opened to the Parts and Material Quality Control Engineering and eventually to Manufacturing Engineering. Arrangements for their usage have been included in the initial DSN/data-link installation for cost savings.

Mass-storage capability for the system was limited to 16.5 Mb in an effort to satisfy Process QC needs and keep the dollar investment to a required minimum. For Parts and Material QC Engineering to gain access to the system, more disc space will be needed.

Expansion

Every facet of the HP 1000 Model 60 System is expandable. The computer memory, disc memory, number of terminals, printers, plotters, digitizers, instruments, can all be increased as the need arises. Up to 256 devices may be connected anywhere along two DSN/data link cables, and any device may be connected up to 2.5 miles from the computer.

Expansion, since installation, has been limited to the addition of an 8-channel multiplexer, two office terminals and an electronic spreadsheet software package. This has facilitated ease of access to the computer by more than one person at a time, and sets the stage for communication with two other HP 1000 systems at the Marion plant and for secretarial word-processing capabilities.

Summary

A study of the sampling data collected by the patrol inspectors of the Process Quality Control department showed that a sizable quantity of measurements are handled each month. Moreover, a single measuring device, the Vickers Image Splitting Electronic Digital Readout unit, generates about half of the measurements taken by the department. In addition, increasing tube-type proliferation and tighter process and product specifications dictate a progressive quality control function. Because of this awareness, efforts were made to obtain mass data-collection technology, that is, a computer system.

Numerous hardware and software requirements were considered that would enable QC Engineering and Supervision to be more responsive to process and product conditions, trends, other manufacturing support groups, and so on.

The Hewlett-Packard system selected was the HP 1000 Model 60 E-Series computer system, a high-capacity technical computing system that combines fast real-time responses with powerful software. It has unlimited expansion capabilities.

Acknowledgment

I wish to express my appreciation for the encouragement I received, initially from Professor W.L. Seibert (project selection), and then from Professor J.P. Ryan (counseling) at the School of Electrical Engineering Technology at Purdue University at Indianapolis, Indiana. Additional acknowledgments go to F.B. Crow, Manager, Data Analysis and Systems Control, F.C. Farmer, Equipment Designer, Equipment Engineering, and T.L. Newcom, Manager, Data Generation and Analysis for invaluable assistance.

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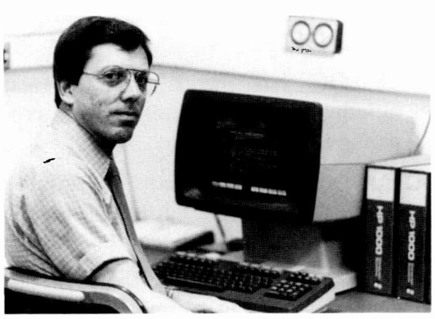

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Bill Hadlock, first *RCA Engineer* editor

William O. Hadlock died on March 11, 1984, after a long illness. He was 73. Mr. Hadlock retired in 1976, after 41 years of service in the radio-electronics business, 20 of them with RCA. Bill is probably best known for his work as editor of the *RCA Engineer,* a journal written by, and distributed to, engineers and scientists at RCA. His service as *RCA Engineer* editor spanned more than 20 years. He was responsible for inaugurating the journal in 1955 and serving as its first editor and publisher; during his tenure, he produced more than 120 bimonthly issues, covering technologies that ranged from television and computers to lasers, space technology, and advanced communications. During that time, he was also Manager of Technical Communications with responsibilities for RCA's corporate technical publishing and technical reporting program and for *RCA Trend* as well as the *RCA Engineer.*

Bill was born in Brier Hill, New York, on February 17, 1911. He attended Clarkson College of Technology and graduated with a Bachelor of Science degree in Electrical Engineering in 1934. In 1934, he joined a newly formed Radio Engineering Group at General Electric where he worked in components engineering, and then on design of battery and farm radios. In 1939, he worked on the design of TV transmitters, and later transferred to Sales Engineering in G.E.'s Electronic Tube Division. During the war, he became Assistant Manager of Commercial Service Activities. In 1944, he inaugurated and produced G.E.'s series of electronic tube manuals.

In 1947, Mr. Hadlock joined RCA, Camden in the Broadcast Equipment Section. His work there included technical editing and writing in conjunction with the sale of TV and broadcast equipment. During this time, he had several papers published in technical journals. In 1949, he was appointed Managing Editor of *Broadcast News,* and in 1950 became Manager of Broadcast and Television Advertising and Sales Promotion. Responsibilities included initiation of a series of nine catalogs on technical broadcast equipment totaling over 1000 pages, production of *Broadcast News,* and planning of trade-paper advertising.

A personal note on Bill Hadlock

I worked with Bill Hadlock for more than 12 years; all of that time he was editor of the *RCA Engineer.* His passing gave me cause to reflect on his role as editor of the *RCA Engineer;* however, I can't speak about that part of Bill Hadlock without reflecting on his larger commitment to communications—in the engineering profession and in RCA. Bill was one of the most enthusiastic spokesmen for quality engineering communications I have ever met. He was probably responsible for helping several hundred of today's RCA engineers start their professional writing careers through his leadership with the *RCA Engineer,* with the Technical Publications Program, and with the RCA proprietary Technical Reporting Program. Throughout all the time I knew him, he never lost his enthusiasm helping a young engineer get started writing his first paper, or for "pushing" an older engineer to write another. We'll all miss that "push."

John C. Phillips

Patents

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Caracciolo, G.T. | Gehweiler, W.F.
Radiation hardened accessible memory—4418402

Commercial Communications Systems

Davis, W.J.
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Hurst, R.N.
Indicator control signal generator for video tape recorder—4413288

McSparran, J.F.
Shock and vibration resistant electrical switch—4423296

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Horizontal deflection circuit—4419608

Muterspaugh, M.W.
Tuning system for a multi-band television receiver—4418427

Tallant, J.C., 2nd | Hettiger, J.
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Willis, D.H. | Clayburn, R.C.
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Barnette, W.E. | Jebens, R.W.
Lens positioning controller for optical playback apparatus—4418405

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Pen and Podium

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Electron and Hole Conduction In the Metal/Tunnel-Oxide/N-Silicon Structure—*Proceedings* of the International Conference INFOS 83, Eindhoven, The Netherlands (4/11-13/83)

W.C. Hittinger
What's Ahead? The Economic and Electronics Outlook: 1984 and Beyond—Presented at American Electronics Association Council Dinner Meeting, New York Hilton, New York (2/16/84)

L. Jastrzebski
SOI By CVD: Epitaxial Lateral Overgrowth (ELO) Process-Review—*Journal of Crystal Growth* 63, 493-526 (1983)

W.H. Meyer | B.J. Curtis | H.R. Brunner
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D. Raychaudhuri
Aloha With Multipacket Messages And ARQ-Type Retransmission Protocols—Reprinted from IEEE International Conference on Communications, Boston, Mass. (6/19-22/83)

H.S. Sommers, Jr.
First-Order Model of the Change with Refractive Index of the Frequency of Semiconductor Lasers—*J. Appl. Phys.* 54(11) (11/83)

E.F. Steigmeier | H. Auderset
D. Baeriswyl | M. Almeida | K. Carneiro
Peierls Instability In The Organic Linear Chain Semiconductor $TEA(TCNQ)_2$—*Journal De Physique,* Colloque C3, supplement au n°6, Tome 44 (6/83)

J.H. Thomas III/J-S. Maa
X-ray Photoelectron Spectroscopy Study of the Surface Chemistry of Freonoxygen Plasma Etched Silicon—*Appl. Phys. Lett.* 43(9) (11/1/83)

J.W. Tuska
Multiplex Wiring with Microcomputer Control—Presented at SAE Intl. Congress & Exposition Conf., Detroit, Mich. (2/27/84)

L.K. White
Planarization Phenomena in Multilayer Resist Processing—*J. Vac. Sci. Technol. B* 1(4) 1235 (10-12/83)

C-H. Wu | R. Williams
Limiting Efficiencies for Multiple Energy-Gap Quantum Devices—*J. Appl. Phys.* 54(11) (1/11/84)

Missile & Surface Radar

F.J. Buckley
Software Quality Assurance and the IEEE Standards Process—Presented at Workshop on Product Assurance Techniques for Embedded Computer Systems, Naval Surface Weapons Center, White Oak, Silver Spring, Md. (1/11/84)

W.C. Grubb, Jr.
Electro-Optics for Non-Electrical Engineers—Presented at Pacific Missile Test Center, Pt. Mugu, Calif. (1/17-18/84)

W.C. Grubb, Jr. | M.W. Buckley, Jr.
Solid-State Electronics for Non-Electrical Engineers—Presented at George Washington University, Washington, D.C. (1/9-11/84)

A. Miklovis
AEGIS—an Overview of the Acquisition—Presented at Philadelphia Chapter of Society of Logistics Engineers (1/25/84)

W.T. Patton
A Planar Near-Field Antenna Test Facility for Precision Alignment of Phased Array Antennas—Presented at National Radio Science Meeting, University of Colorado, Boulder, Col. (1/11-14/84)

Engineering News and Highlights

RCA Laboratories names Lechner Staff Vice-President

The appointment of **Bernard J. Lechner** as Staff Vice-President, Advanced Video Systems Research, has been announced by **Dr. William M. Webster**, Vice-President, RCA Laboratories, in Princeton, N.J. In his new position Mr. Lechner is responsible for RCA Laboratories advanced video systems research, including research on image quality, human visual perception, digital video signal processing and transmission, and high-definition TV as well as research supporting RCA Broadcast Systems and NBC.

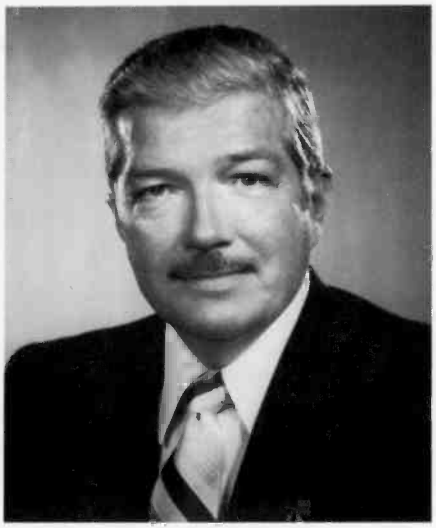
A native of New Rochelle, N.Y., Mr. Lechner received a B.S. degree in Electrical Engineering from Columbia University in 1957. After graduation, Mr. Lechner joined RCA Laboratories as a Member of the Technical Staff working in research on videotape recorders and gigahertz computer circuits. He was named a Group Head in 1967 and has headed research groups working on digitally controlled visual displays, electroluminescent displays, liquid crystal displays, storage displays, and other computer peripheral equipment. In 1971, as Head of the Community Information Systems Research group, he directed pioneering work on two-way cable TV systems and pay-TV systems. In 1974, he became Head of the Color Television Research group that conceived and developed a number of digital TV tuning systems including the Signallock system used in RCA ColorTrak receivers.

Mr. Lechner was appointed Director, Video Systems Research Laboratory, in 1977, the position he held until his new assignment.

In 1961 he received an RCA Laboratories Outstanding Achievement Award and in 1962 was given RCA's highest technical honor, the David Sarnoff Award for Outstanding Technical Achievement, for his contributions to high-speed computer circuitry. He holds seven U.S. patents and has published a number of technical papers.

Volpe named to head RCA Broadcast Systems Division

Volpe



Howe

The appointment of **Joseph C. Volpe** as Division Vice-President and General Manager of the RCA Broadcast Systems Division was announced by **John D. Rittenhouse,** RCA Group Vice-President.

Mr. Volpe succeeds **Joseph B. Howe** who has been named Staff Vice-President and Chief Engineer on Mr. Rittenhouse's staff.

The RCA Broadcast Systems Division, headquartered in Gibbsboro, N.J. produces studio and transmitting equipment for the radio and television industry.

Mr. Volpe has been Division Vice-President, Operations, Broadcast Systems Division, since October of last year. He joined RCA in 1958 and served in a series of engineering assignments with the Missile and Surface Radar unit of the RCA Government Systems Division. In 1971 Mr. Volpe became System Project Manager of the AEGIS Program, a combat weapon system developed for U.S. Navy cruisers. Three years later he was appointed Chief Engineer of the Missile and Surface Radar activity and in 1980 became Director of Product Operations for this group. During 1981 he was advanced to Division Vice-President, Broadcast Transmission Systems at the Broadcast Division.

Mr. Volpe received his B.S. degree in Physics from St. Joseph's College in 1952. He resides in Tabernacle, N.J.

Prior to heading the Broadcast Systems Division, Mr. Howe served as Division Vice-President and General Manager of the RCA Commercial Communications Systems Division since 1981. He was appointed Division Vice-President and General Manager of the RCA Government Communications Systems operations in 1979. Mr. Howe was Chief Engineer of this operation for four years and previously served as Manager, Digital Communications Engineering.

Mr. Howe joined RCA in 1951 as a co-op student while attending college. His early engineering career involved the design of general purpose and special computers for commercial and government applications.

Mr. Howe received his Bachelor's degree in Physics from St. Joseph's College in 1954 and a Master's degree in Physics from the University of Detroit in 1956. He resides in Cherry Hill, N.J.

Karoly is named President, RCA Cylix

The election of **Joseph W. Karoly** as President of RCA Cylix Communications Network, Inc. was announced by **Eugene F. Murphy,** Chairman of RCA Communications, Inc. In his new position, Mr. Karoly will be responsible for the operations of RCA Cylix, a satellite-based, value-added data communications company acquired by RCA Communications in 1982. The company is headquartered in Memphis, Tenn.

Mr. Karoly has served as a director of Cylix since its acquisition by RCA, and has been closely involved in the corporate overview of Cylix operations.

Since 1981, Mr. Karoly has been Vice-President of Finance for RCA Communications. Previously, he was Group Vice-President of RCA Corporation with responsibility for the operations of the RCA Service Company, the Distributor and Special Products Division, and the Picture Tube Division. From 1976 to 1979, Mr. Karoly was President of the RCA Service Company, one of the world's largest technical services organizations. Mr. Karoly joined RCA in 1950 as a budget analyst with the Electron Tube Division and subsequently held various managerial positions in finance, planning and operations in the RCA Solid State Division and the RCA Service Company.

Mr. Karoly succeeds **Ralph R. Johnson,** who will assume the new position of Senior Vice-President, RCA Cylix. Mr. Johnson will be responsible for developing and maintaining relationships with major customers, as well as participating in the development of new areas of market growth for RCA Cylix.

Staff announcements

Group VP

John D. Rittenhouse, Group Vice President, announces the following appointments: **Donald M. Cook,** President, RCA Service Company; **Joseph C. Volpe,** Division Vice-President and General Manager, Broadcast Systems Division; **Joseph B. Howe,** Staff Vice-President and Chief Engineer; and **George D. Prestwich,** Staff Vice-President, Planning and Development.

RCA Communications

Joseph W. Karoly, President and Chief Operating Officer, RCA Cylix Communications Network, Inc., announces the organization of RCA Cylix Communications Network, Inc., as follows: **R. Ronald Burgess,** Director, Employee Relations; **Bryan M. Eagle,** Vice-President, Finance and Administration; **Ralph R. Johnson,** Senior Vice-President; **James L. Magruder,** Vice-President, Operations; **Michael D. Mancusi,** Vice-President, Engineering and Development; **Richard A. Simmons,** Assistant Vice-President, Quality Assurance; and **Ronald L. Young,** Vice-President, Marketing.

Consumer Electronics

Leonard J. Schneider, Division Vice-President, Operations, announces the appointment of **Larry A. Cochran** as Director, Monitor Operations.

Bennie L. Borman, Division Vice-President, Manufacturing, announces the appointment of **Gerald C. Kuckler** as Director, Manufacturing Engineering and Technology.

Gerald C. Kuckler, Director, Manufacturing Engineering and Technology, announces his organization as follows: **Larry J. Byers,** Manager, Test Technology; **John J. Drake,** VideoDisc Player Manufacturing Technology; **John A. Gross,** Manager, Manufacturing Planning and Services; **Horst E. Haslau,** Manager, Equipment Development; and **Larry A. Olson,** Manager, Manufacturing Technology Center.

James E. Carnes, Division Vice-President, Engineering, announces the appointment of **Robert P. Parker** as Director, Signal Systems.

Robert P. Parker, Director, Signal Systems, announces his organization as follows: **James Hettiger,** Manager, RF Systems; **William A. Lagoni,** Manager, Signal Processing; **John F. Teskey,** Manager, Digital Tuning Systems; and **Robert P. Parker,** Acting Manager, Advanced Tuner Development.

Robert C. Arnett, Plant Manager, Bloomington, announces that the VideoDisc Player Manufacturing Operations organization is transferred to the Staff of the Plant Manager, Bloomington. The VideoDisc Player Manufacturing Operations organization will continue as follows: **Gilbert L. Apple,** Manager, Manufacturing Engineering; **Frank P. Hallagan,** Manager, Financial Operations – VideoDisc Player; **Roger D. Peterman,** Manager, Quality Control; and **Robert D. Veit,** Manager, Manufacturing.

Gary A. Gerhold, Plant Manager, Indianapolis Components Plant, announces the appointment of **James R. Arvin** as Manager, Quality Control.

Robert R. Beasley, Manager, Plant Engineering, announces the appointment of **Donald R. Stapert** as Manager, Engineering and Services.

Eugene E. Janson, Manager, Product Safety and Reliability, announces the appointment of **Larry M. Sukey** as Manager, Reliability Engineering.

Gary A. Gerhold, Plant Manager, Indianapolis Components Plant, announces the appointment of **James R. Arvin** as Manager Quality Control.

David R. Crawford, General Manager, RCA Componentes-S.A. de C.V., announces the appointment of **Hector Barrio** as Manager, Manufacturing Engineering.

Government Systems Division

James B. Feller, Division Vice-President, Engineering, announces the appointment of **John M. Herman** as Division Vice-President, Solid State Technology Center.

Laboratories

Robert D. Lohman, Staff Vice-President, Solid State Research, announces the appointment of **Israel H. Kalish** as Head, VLSI Process and Device Research.

Robert D. Lohman, Staff Vice-President, Solid State Research, announces his organization as follows: **Norman Goldsmith,** Head, IC Research Center; **Gary W. Hughes,** Head, CCD Imagers and Systems Research; **Walter F. Kosonocky,** Fellow, Technical Staff; **Israel H. Kalish,** Head, VLSI Process and Device Research; **Walter J. Merz,** Director, Research, Laboratories

RCA, Ltd. (Zurich); **Louis S. Napoli,** Head, VLSI Design Research; **Andrew G. F. Dingwall,** Fellow, Technical Staff; **Charles J. Nuese,** Head, Advanced Technology Research; **John P. Russell,** Staff Scientist; **David E. O'Connor,** Senior Project Manager; **George L. Schnable,** Head, Device Physics and Reliability Research; **Richard Denning,** Staff Engineer; and **Jacques I. Pankove,** Fellow, Technical Staff. Messrs. Goldsmith, Hughes, Kalish, Merz, Napoli, Nuese, O'Connor and Schnable will report to the Staff Vice-President, Solid State Research.

Brown F Williams, Staff Vice-President, Display and Optical Systems Research, announces the appointment of **Arthur H. Firester** as Director, Advanced Displays Research Laboratory.

Brown F Williams, Staff Vice-President, Display and Optical Systems Research, announces the organization of Display and Optical Systems Research as follows: **Carmen A. Catanese,** Director, Picture Tube Systems Research Laboratory; **Arthur H. Firester,** Director, Advanced Displays Research Laboratory; and **Bernard Hershenov,** Director, Optical Systems and Display Materials Research Laboratory.

James L. Miller, Staff Vice-President, Manufacturing and Materials Research, announces the appointment of **Harry Weisberg** as Senior Staff Scientist.

James L. Miller, Staff Vice-President, Manufacturing and Materials Research, announces his organization as follows: **Harry Weisberg,** Senior Staff Scientist; **Istvan Gorog,** Director, Manufacturing Technology Research Laboratory; **Marvin A. Leedom,** Director, Manufacturing Systems Research Laboratory; and **David Richman,** Director, Materials and Processing Research Laboratory.

Istvan Gorog, Director, Manufacturing Technology Research Laboratory, announces the appointment of **Philip M. Heyman** as Head, Advanced Technology Research.

David Richman, Director, Materials and Processing Research Laboratory, announces the appointment of **Aaron W. Levine** as Head, Organic Materials and Lithography Research.

David Richman, Director, Materials and Processing Research Laboratory, announces the appointment of **Dennis L. Matthies** as Head, Materials Applied Research.

David Richman, Director, Materials and Processing Research Laboratory, announces his organization as follows: **Glenn W. Cullen,** Head, Materials Synthesis Research; **Leonard P. Fox,** Head, Materials and Process Engineering Research; **William L. Harrington,** Head, Materials Characterization Research; **Richard E. Honig,** Staff Scientist; **Aaron W. Levine,** Head, Organic Materials and Lithography Research; **Dennis L. Matthies,** Head, Materials Applied Research; **Chih Chun Wang,** Fellow, Technical Staff; and **Robert J. Ryan,** Head, Polymer Processing Research. Messrs. Cullen, Fox, Harrington, Honig, Levine, Matthies and Ryan will report to the Director, Materials and Processing Research Laboratory.

Fred Sterzer, Director, Microwave Technology Center, announces the appointment of **Herbert J. Wolkstein** as Head, Space and Countermeasure Programs.

Fred Sterzer, Director, Microwave Technology Center, announces his organization as follows: **Erwin F. Belohoubek,** Head, Microwave Circuit Technology; **S. Yegan Narayan,** Head, Microwave Device Technology; **Markus Nowogrodzki,** Head, Subsystems and Special Projects; **Barry S. Perlman,** Manager, Design and Test Automation; and **Herbert J. Wolkstein,** Head, Space and Countermeasure Programs.

Charles B. Carroll, Head, Electromechanical Systems Research, announces the appointment of **Albert F. Dietrich** as Manager, Model Shop.

NBC

Steven Bonica has been appointed Vice-President Engineering, NBC Operations and Technical Services, New York, and **Theodore Bruss, Jr.** is Director Broadcast Systems Engineering.

Solid State Division

The Solid State Division organization has been announced as follows: **Herbert V. Criscito,** Division Vice-President, Marketing; **Peter A. Friederich,** Division Vice-President, Industrial Relations; **Larry J. Gallace,** Director, Product Assurance; **Donald W. Gangaware,** Director, Strategic Planning and Services; **Walter J. Glowczynski,** Division Vice-President, Finance; **Robert P. Jones,** Director, Power Operations; **Heshmat Khajezadeh,** Division Vice-President, Standard Integrated Circuit Products; and **Jan A. Shroyer,** Division Vice-President, LSI Products and Technology Development.

Stephen C. Ahrens, Director, Engineering – Standard Integrated Circuits Products announces the organization of Standard Integrated Circuits Engineering as follows: **Charles Engelberg,** Manager, Test Engineering; **Jack L. Jones,** Supervisor, Assembly and Test Support; **Thomas J. McGrath,** Section Manager, Test Engineering – Industrial; **Peter K. Neumann,** Section Manager, Test Engineering – Consumer; **Merle V. Hoover,** Manager, Engineering – Computer, Telecommunication & Industrial Products; **Mandel Glincman,** Section Manager, Industrial Product Engineering; **Otto H. Schade, Jr.,** Principal Member Technical Staff – Analog CMOS Advanced Development; **Joseph F. Siwinski,** Section Manager, Telecommunication Product Engineering; **Victor Zazzu,** Section Manager, Design Engineering; **Lewis A. Jacobus, Jr.,** Manager, Engineering – Logic Products; **Kenneth W. Brizel,** Section Manager, Design Engineering; **Brian J. Petryna,** Section Manager, Product Engineering; **Sterling H. Middings,** Section Manager, Layout Services; **Bruno J. Walmsley,** Manager, Engineering – Automotive and Consumer Products; **Thomas H. Campbell,** Section Manager, Product Engineering – TV; **Max E. Malchow,** Section Manager, Design Engineering – Automotive; **Maurice W. Sloane,** Section Manager, Product Engineering – Automotive; and **Bernard J. Yorkanis,** Section Manager, Design Engineering – TV. Messrs. Engelberg, Hoover, Jacobus, Middings and Walmsley will report to the undersigned.

Gerald S. Worchel, Manager, Wafer Fabrication, announces his organization as follows: **Michael A. Caravaggio,** Manager, Production Maintenance; **William B. Hall,** Manager, Process Engineering; **Thomas J. Lally,** Superintendent, Manufacturing – 1st Shift; **Charles J. McCarthy,** Superintendent, Manufacturing – 3rd Shift; **Roy P. Petersen,** Superintendent, Manufacturing – 2nd Shift; and **Patricia A. Roman,** Manager, Technical Training and Engineering Projects.

William B. Hall, Manager, Process Engineering, announces his organization as follows: **Joseph T. Gershey,** Leader, Technical Staff, Passivation/Photoresist; **Vincent S. Osadchy,** Leader, Technical Staff, Diffusion/Implant; **Daniel J. Smith,** Leader, Technical Staff, Epi/Metals; and **Albert A. Todd,** Leader, Technical Staff, Yield Analysis/Technical Projects.

VideoDisc Division

Jay J. Brandinger, Division Vice-President, Disc Operations, announces his organization as follows: **Harry Anderson,** Division Vice-President, Manufacturing and Engineering; **Paul I. Anderson,** Division Vice-President, Marketing; **F. Donald Kell,** Director, Systems; **Edward B. Knorr,** Director, Finance; and **Robert C. McHenry,** Director, Employee Relations, Rockville Road. Mr. McHenry will continue to report administratively to the Division Vice-President, Employee Relations, Consumer Electronics Division, and functionally to the Division Vice-President, Disc Operations.

Harry Anderson, Division Vice-President, Manufacturing and Engineering, announces his organization as follows: **James W. Critzer,** Director, Materials; **Robert K. Felter,** Director, Manufacturing; **David F. Hakala,** Manager, Process and Material Development Engineering; **Henry D. Olson,** Manager, Plant Engineering and Manufacturing Engineering; **John J. Prusak,** Manager, Process and Equipment Development Engineering; and **Danne E. Smith,** Manager, Product Assurance and Evaluation.

Professional activities

Philadelphia chapter of the IEEE honors RCA employees

Dr. James Vollmer of RCA received a "Centennial Medal" from the Institute of Electrical and Electronics Engineers (IEEE) for exceptional service to the profession. Dr. Vollmer, a Senior Vice-President of RCA, was one of 1,984 outstanding individuals in the U.S. chosen to receive the award, which commemorates the 100th anniversary of the IEEE. Dr. Vollmer and 12 other members of the Philadelphia chapter of the IEEE received the Centennial Medal and Certificate during an awards dinner at the Union League in Philadelphia on February 4.

As a Senior Vice-President for Technical Evaluation and Planning, Dr. Vollmer's responsibilities include evaluating competing technologies and establishing strategic technological approaches for all of RCA's businesses. He is also RCA's primary interface with America's aerospace and defense agencies. Dr. Vollmer joined RCA in 1959 as a physicist in an applied research facility in Camden, N.J., and thereafter served in progressively more responsible executive positions at RCA.

During the February 4 dinner, the Philadelphia chapter of the IEEE also honored three other RCA employees. **Merrill F. Buckley, Jr.,** Administrator of Planning Measurement for RCA's Missile and Surface Radar business unit in Moorestown, N.J. received the Philadelphia section's top award for his service as Vice-President of the IEEE's regional activities. In that capacity, Mr. Buckley, a 30-year RCA employee, coordinates the activities of the 10 IEEE regions, which include some 230,000 members worldwide.

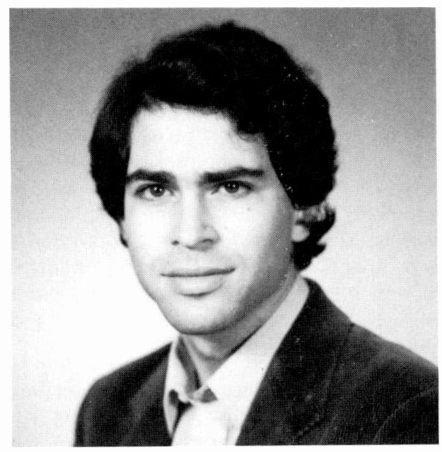
The Philadelphia chapter also presented special awards to **Kent Ringo** and **Barry Fell** of RCA Missile and Surface Radar. Both engineers have been cited for "revitalizing" the chapter's educational program by organizing a highly successful seminar in adaptive signal processing.

Luddy of RCA Broadcast Systems selected for IEEE "Centennial Medal"

E. Noel Luddy, Manager of Consultant Relations for RCA's Broadcast Systems Division, has been selected to receive a "Centennial Medal" from the Institute of Electrical and Electronics Engineers (IEEE). Mr. Luddy will be cited for his contributions to the Institute and the electrical engineering profession as part of the organization's 100th anniversary.

Mr. Luddy was nominated for the award by the Broadcast Technology Society of the IEEE. Mr. Luddy joined RCA in 1951 and held various positions in engineering and product management for broadcast transmitters and antennas until 1967, when he assumed his present position. As Manager of Consultant Relations, Mr. Luddy represents RCA to broadcasting consultants and federal regulatory agencies.

Adelson receives Optical Society's Lomb Medal

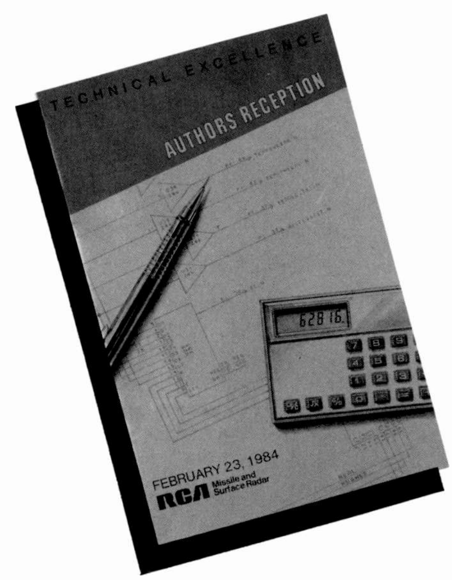


Edward H. Adelson, Picture Tube Systems Research Laboratory, has been designated the recipient of the 1984 Adolph Lomb Medal of the Optical Society of America. The medal is presented biennially to a person who has made a noteworthy contribution to optics before reaching the age of 30. Mr. Adelson is being cited for contributions to understanding in three different areas of physiological and visual optics, namely: temporal responses of the human visual system, color vision, and artificial vision.

Laboratories scientists active in societies

Richard J. Klensch was elected Vice-President of the Princeton Chapter of Sigma Xi in July 1983. He will automatically become Chapter President on July 1, 1984. Moreover, late in 1983, a new society was formed, the Communications and Consumer Electronics Society, which is part of the Princeton Section of IEEE. Mr. Klensch is Chairman of this new society and **Dr. Chandrakan B. Patel,** also of the Laboratories, is Vice-Chairman.

MSR engineers' reception held

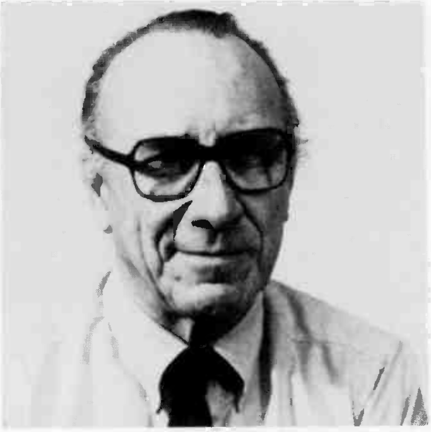


The 117 authors, inventors, and degree recipients during 1983 at Moorestown's Missile and Surface Radar were listed in the booklet shown and honored at a reception. ***Bernie Matulis,*** *Chief Engineer, extended his congratulations, saying that "1983 was without question our biggest year since we've been keeping records of papers presented and published, patents granted, and degrees awarded."*

Burmeister chairs session

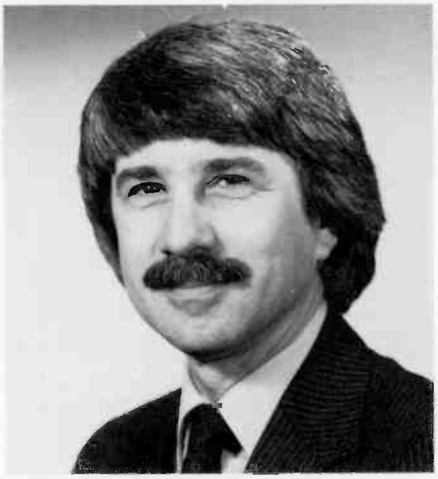
Mark H. Burmeister, Director, PRICE Systems, RCA GSD, chaired a session at the American Defense Preparedness Association "Seminar on the Cost Estimating Process" in Arlington, Virginia, on February 7-8 1984. His session was on the subject of life cycle cost, and included four papers and a panel discussion.

Hughes named Video Component and Display Division Fellow



Richard H. Hughes has been named a Division Fellow on the technical staff at VCDD. The new designation is for persons who have made technical contributions that have had a major impact on RCA's business. Hughes has been a leader in the development of electron guns for picture tubes. He is the first Senior Member Technical Staff to attain the "Dual Career Technical Path" recognition of his outstanding technical contributions. Hughes is a 1939 graduate of the University of Kentucky. He retired from RCA in February after forty years of service.

Bartolini named Fellow by engineering society



Dr. Robert A. Bartolini, Head, Optical Systems, at RCA Laboratories in Princeton, N.J., has been elected a Fellow of the Institute of Electrical and Electronics Engineers (IEEE). Dr. Bartolini was honored "for contributions to the development of optical recording media and systems." He is one of 132 Fellows elected in 1983 from among the IEEE's worldwide membership of over 250,000.

A native of Waterbury, Conn., Dr. Bartolini received a B.S. degree in 1964 from Villanova University, an M.S. degree in 1966 from Case Western Reserve University, and a Ph.D. degree in 1972 from the University of Pennsylvania, all in Electrical Engineering.

Dr. Bartolini, who joined RCA Laboratories as a Member of the Technical Staff in 1966, was appointed to his present position in 1983. He has received three RCA Laboratories Outstanding Achievement Awards for research contributions in developing techniques for plating masters and replicating vinyl holographic tapes, for initiative in the analysis and evaluation of optical recording materials, and for development of a high-density optical information storage system employing an injection laser.

RCA Astro-Electronics engineer earns advanced degree

Martin Meder, Materials Reliability Engineering, has been awarded the degree of Master of Science from Rutgers University. Mr. Meder's advanced studies were funded by the RCA Graduate Study Program. Employees selected for this program are recipients of tuition and book funding, and salaried study time to pursue an employment-related advanced degree. Mr. Meder achieved scholastic excellence by compiling a 3.7 grade average while majoring in Mechanics and Materials Science and is the tenth Astro employee to graduate through this program.

Technical excellence

Fourth-quarter 1983 Missile and Surface Radar technical excellence award winners announced

Fuhr

Gross

Seppanen

Talbot

Timothy D. Fuhr—for establishing unprecedented new accuracy standards for near-field antenna test systems. His efforts in verification of the laser measurement subsystems of ANFAST II were directed toward an accuracy requirement of 0.007-inch rms, 2.5 times better than previously achieved in any near-field systems. His efforts resulted in measured accuracy of 0.0034-inch rms, further enhancing RCA's leadership role in near-field technology.

Samuel D. Gross—for major advances in radar-detection performance-assessment techniques through simulation of target and background signal processing for advanced radars. His interactive simulation program assesses detection performance for extremely low cross-section targets in the presence of a broad spectrum of clutter and interference. This program represents a major advance over current tools and will be a key factor in developing competitive tactical radar designs in the future.

Henry R. Seppanen—for major contributions to the FAA's proposal evaluation processes through introduction of systems engineering disciplines to the Air Traffic Control Advanced Automation System design competition. His personal development of systematic technical evaluation criteria and scoring standards, combined with his comprehensive briefings of the technical evaluation team, provided the FAA with a consistent and systematic approach to technical proposal evaluation and further solidified RCA's position for follow-on work.

William H. Talbot—for development of a major new interface simulator for the EDM-4 radar control computer. Using advanced software design techniques, the program simulates the operation of the new AN/SPY-1B signal processor at real-time speeds and is being used extensively to support development and testing of the AN/SPY-1B tactical software. The performance and availability of Dr. Talbot's simulator have provided significant support to overall EDM-4 system development.

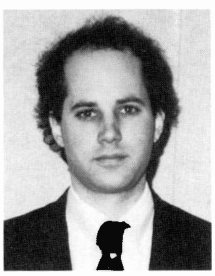
Astro-Electronics engineering recognition team award

Astro engineering recognition team award. From left to right, ***Douglas Mathai, Robert L. Cluna, Susan P. Gregg,*** *and* ***William D. Clark.***

The Engineering Recognition Team Award is presented to **William D. Clark, Robert L. Cluna, Susan P. Gregg,** and **Douglas J. Mathai** for their outstanding and dedicated contributions to the design and implementation of the TIROS ATNAGE test software for the Earth Radiation Budget Experiment (ERBE) and the Solar Backscatter Ultraviolet Radiometer (SBUV) instruments.

The test software and instrument development proceeded concurrently. This presented significant engineering challenges that included the creation of instrument simulators for verifying test software design and a design flexibility requirement to allow for software modification as the instrument designs matured. The cooperative efforts of these team members resulted in project completion on schedule and within budget. The product quality and excellent cooperation afforded the customer contributed to NASA's award of a more significant software contract to Astro.

Astro-Electronics engineering excellence award to Goodzeit



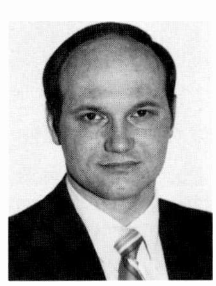
The Astro-Electronics Engineering Excellence Committee is pleased to announce that the Engineering Excellence Award is presented to **Neil E. Goodzeit** for his innovative and expeditious design of the north/south stationkeeping logic for the RCA Satcom H satellite.

Based upon an extensive analysis of flight data from previous Satcom satellites, Neil determined that the interaction between the satellite's flexible solar arrays and the N/S stationkeeping control logic would require a modification to the current control system. Consequently, Neil developed a significantly improved digital filter to prevent the Satcom H control system from responding to and reinforcing the structural oscillations associated with the solar arrays. This improved filter design and two sets of filter parameters were provided to the Flight Software Group less than two weeks after the start of the analysis and design effort. The modified design fit the available ROM space and met the timing constraints of the existing Satcom H microprocessor.

After delivery of his design requirements to the Flight Software Group, Neil continued to refine his analysis. He incorporated improved structural models as they became available and he performed an exhaustive series of frequency-domain analyses and digital computer simulations to confirm the viability of his design modifications. In addition to his analytical work, he supported several meetings with RCA Americom. At these meetings, his clear answers to technical questions helped the customer gain insight into the control system modifications that were being implemented, and into the analyses that supported the design changes.

Neil's improved digital filter and the speed with which it was developed and implemented were instrumental in enabling Satcom H to be launched as scheduled. Subsequent Satcom H flight data indicates that Neil's modified N/S stationkeeping control system is meeting all performance specifications.

Astro-Electronics engineering recognition award to Homco



The Engineering Excellence Committee is pleased to announce an Engineering Recognition Award to **David J. Homco** for leadership and personal dedication in the Planning , Execution, and Evaluation phases of the DMSP F6 early orbit.

Dave's primary responsibility was the planning, writing, and coordination of the F6 Early Orbit Detailed Test Plan (DTP). Although DMSP has used DTPs in previous launches, the DTP for the F6 launch presented two major challenges: F6 was the first flight of the new "D2" series and, for this new series, the Omaha Command and Control Ground System had been completely redesigned. Both of these factors added greatly to the complexity of the DTP generation.

In addition to his DTP responsibilities, Dave assumed a leadership role, in conjunction with his Air Force counterpart, in developing and critiquing the numerous plans, documents, and software listings required for the Air Force DMSP operations in Omaha. In the process of reviewing the ground system products needed for the early orbit operations, Dave was able to provide constructive criticism to the Air Force and their contractors that led to the isolation and definition of several of the problems plaguing the new D2 ground system. His selfless and constructive attitude contributed significantly to a team environment in resolving these problems. He is recognized by his peers as an outstanding contributor to the DMSP efforts and has been singled out in Air Force program office commendations to Astro.

Consumer Electronics third-quarter 1983 technical excellence awards

Dasgupta

Fitzgerald

Monat

Shutts

Dr. James Carnes announced the third-quarter 1983 technical excellence award recipients at Consumer Electronics, Indianapolis, Indiana. Each award recipient receives an appropriately engraved plaque and a reference book of their choice.

Basab Dasgupta—for the development of a better theoretical understanding of yoke parameters. The mathematical basis of yoke phenomena has advanced the state of the art of CE yoke design.

William V. Fitzgerald—for superior motivation, innovation and practical application of theory in the design and development of a chopper power supply for the CTC131 chassis.

Robert A. Monat—for leadership and technical contributions to Consumer Electronics' printed circuit board CAD/CAM program.

Bruce W. Shutts—for the novel combination of digital-television theory and microcomputer technology in producing a unique and valuable keyboard-control system for the developmental CTC141 digital receivers.

Wierschke receives VideoDisc Division technical excellence award

Donald J. Wierschke has been awarded the RCA VideoDisc Division technical excellence award for his contributions to improved plating processes used in the manufacture of VideoDisc metal parts. These contributions have directly impacted the cost and quality of VideoDiscs and VideoDisc styli. Some of his specific contributions include:

- The development of the currently employed high-purity nickel anode material, used in all production nickel plating tanks, which has improved disc surface quality.
- The reduction of lapping disc defects through the implementation of a new tension treatment bath and ultrasonic agitation to replace the deionized water rinse, which has improved stylus quality.
- The characterization of the specific nature of substrate defects, which has given direction to current corrective-action programs.

Don has demonstrated technical excellence by his ability to work effectively as a member of the technical community and by his significant accomplishments in improving the quality of VideoDiscs and styli.

Olsen and Sunshine give technical excellence lectures

In January, **Perry Olsen** and Dick Sunshine of Consumer Electronics teamed up to give two half-hour lectures on their organizations and the various projects on which their groups work. Olsen spoke on Project Engineering and Sunshine spoke on Mechanical Design Engineering. These lectures are part of a series of lectures aimed at familiarizing new engineers with the various organizations within the RCA CE community.

Palm Beach Gardens 1983 fourth-quarter technical excellence award

The 1983 fourth-quarter technical excellence award at RCA Solid State Division, Palm Beach Gardens was presented to ***Wes Morris.*** *Shown, left to right, are* ***Rob Kleppinger,*** *Chairman of the PBG Technical Excellence Committee;* ***Wes Morris;*** *and* ***Thomas Stavish,*** *PBG Plant Manager.*

Wesley H. Morris, a Process Engineer with RCA Solid State Division at Palm Beach Gardens, Florida, was a key member of the team that contributed to the technology for fabrication of radiation-hardened CMOS/SOS integrated circuits. He is honored for successful transfer of SOS low-temperature rad-hard processes from the Somerville Solid State Technology Center to Palm Beach Gardens Manufacturing. He is also recognized for introducing several innovative process improvements that dramatically reduced device leakage and substantially improved radiation resistance, resulting in RCA rad hard devices without equal in the marketplace.

MSR honors 1983 technical excellence award winners

Seated (left to right): ***M.M. Jankowski, Chief Engineer B.J. Matulis, J.D. Fanelle, MSR Vice-President and General Manager W.V. Goodwin, S.D. Gross, J.E. Judd.*** *Standing (left to right):* ***A.J. Link, C. DiMaria, D.L. Matthews, R.D. Clark, A. Cohen, C.W. Laible, J. Drenik, E.J. Kent, N. DeGrandmaison, R. Smargiassi, H.R. Seppanen, T.D. Fuhr, D.E. Maron,*** *and* ***L.R. Miamidian.*** *Absent;* ***W.H. Talbot*** *and* ***G. Nesbit.***

John D. Fanelle *received the annual Missile and Surface Radar technical excellence award, in a special ceremony, from* ***B.J. Matulis,*** *Chief Engineer, and* ***W.V. Goodwin,*** *Division Vice-President and General Manager.*

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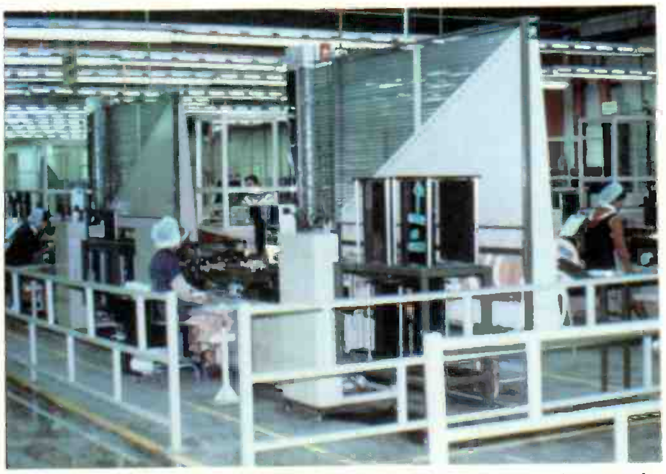

Radial Automatic Component Insertion equipment at RCA Consumer Electronics, Juarez, Mexico

Spray paint robot used in television manufacture at Indianapolis, Indiana

Making RCA TVs (1981) at Bloomington, Indiana

Axial Automatic Component Insertion equipment.

RCA Engineer

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