RCA Engineer

Vol. 30 No. 3 May/June 1985

". . . effectively reduced the differences within a group of testers."

". . . decreased line scrap five percent."

"Numerical literacy, the ability to communicate statistically, is no less important than the ability to speak or write succinctly. . ."

"Fewer than two out of every thousand fail. . ."

"I think statistics are just as lovely as they can be. . ."

". . . strong trend of decreasing scrap."

"It is in the glorious columns of ascertained facts and legalized measures that beauty is to be found. . ."

". . . decreased process loss of 0.29."

"Deliberate action does not, in general, guarantee the desired result. . ."

". . . the control chart for variables is one of the simplest and most powerful."

". . . variability due to setup was drastically reduced."

"Current specs are near-optimal. . ."

". . . threefold reduction in defects."

statistics in manufacturing

RCA Engineer

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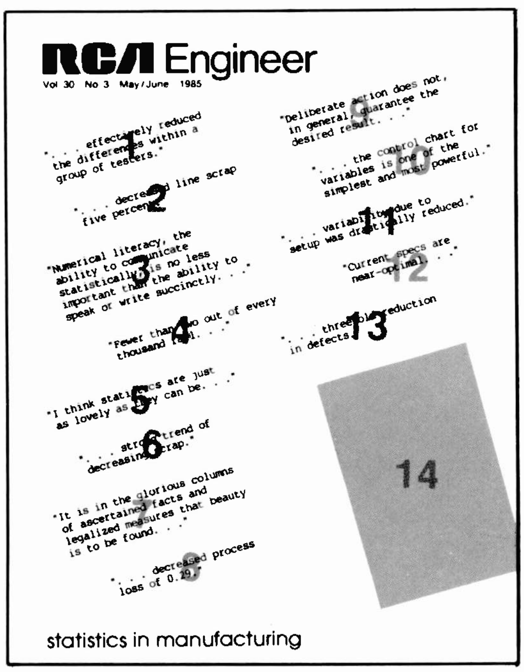


About our cover . . .

Like snatches of overheard conversation, our cover quotes tease the imagination and provide just a glimpse of what you'll find in the statistics articles in this issue.

1 Stein/Turpin/Whitcomb, page 24
2 Armour/Kleppinger/Morey/Pitts, page 44
3 Hunter, page 8
4 Stein, page 6
5 O. Henry, *The Handbook of Hymen* (*see Sharp, page 32)*
6 Gunter/Tadder/Hemak, page 54
7 O. Henry, *The Handbook of Hymen* (*see Sharp, page 32)*
8 Gunter/Tadder/Hemak, page 54
9 Coleman, page 16
10 Shecter, page 38
11 Coleman, page 16
12 Sharp, page 32
13 Coleman, page 16
14 Tucked inside the back cover of this issue is a poster on the graphical display of statistical information.

Cover design by RCA Engineer Staff

□ 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 among various groups at RCA □ To create a community of engineering interest within the company by stressing the interrelated nature of all 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.

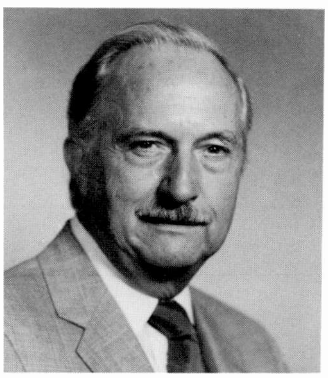
The statistical approach to manufacturing

The need for major improvements in overall manufacturing efficiency and product quality is becoming a serious national effort. The use of statistical methods to evaluate and optimize product designs, manufacturing processes, and purchased material and components is central to this thrust.

Coupling of statistical techniques with engineering and scientific resources provides a powerful tool for reducing product costs and improving quality and reliability. The development of statistical models of critical processes combined with design of experiments and statistical process controls, have become effective techniques for improving products and processes. These methods can lead to fewer end-of-line product rejects, reduction in costly scrap, reduction of warranty claims, improvement in operator efficiencies, and in the long run reduce the paperwork necessary to control manufacturing quality.

Although statistical methods have long been known, they are more recently being applied to the total product development cycle. The articles in this issue will highlight some of RCA's programs that are using statistical methods. The days of improving quality by tightening outgoing specifications and increasing product testing are past. Use of statistics and engineering expertise to narrow product distribution variables to meet customer needs is the wave of the future.

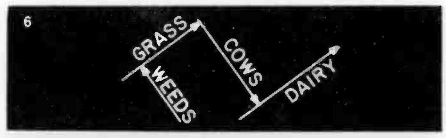
James L. Miller

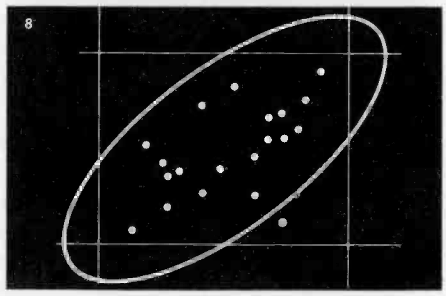


James L. Miller
Staff Vice President
Manufacturing and Materials Research
RCA Laboratories

RCA Engineer
Vol. 30 | No. 3 May | June 1985

in this issue...
statistics in manufacturing

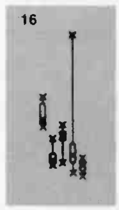


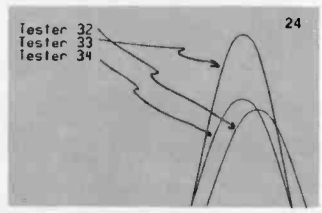


■ **Stein:** *"We must educate ourselves and each other, be open to new ideas and new philosophies, communicate our successes and failures, and dig in and try again."*

■ **Stein:** *"We shouldn't attempt to return to the days when America was king of this type of manufacturing. It is necessary to take a holistic approach: to increase the value added, to encourage small, custom production runs."*

■ **Hunter:** *"The leap forward to real competitiveness requires the application of statistics in all of its modern modes."*





■ **Coleman:** *"The first concept to grasp about metrology is that any measurement comes from a measurement system, not from measurement equipment alone."*

■ **Stein/Turpin/Whitcomb:** *". . . statistics is also the only way to achieve control over the entire measurement process, not just over some components of the test system."*

32

$$f(x_i,y_i) = \frac{\lambda\,|\,x_i\,|}{\pi^2(x_i^2 + y_i^2)(x_i^2 + \lambda^2)}$$

■ **Sharp:** *". . . it is possible to sensibly predict the misalignment results in terms of a statistical distribution."*

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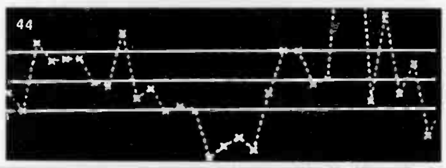
38 OUT OF CONTROL PROCESS (SPECIAL CAUSES PRESENT)



■ **Shecter:** *"Among the wide variety of statistical quality control tools that can be applied to improve or maintain high process yields, the control chart for variables is one of the simplest and most powerful."*

■ **Armour/Kleppinger/Morey/Pitts:** *"SPC is a tool for efficiently directing engineering and production efforts to correct real problems and not waste time repairing a process that doesn't need attention."*

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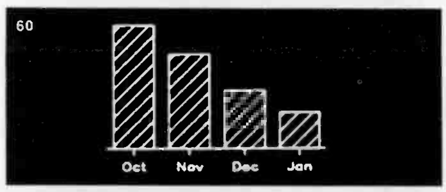
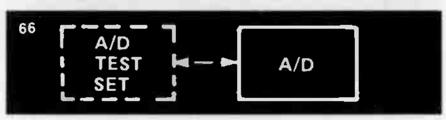
54 **EVOP**

■ **Gunter/Tadder/Hemak:** *"Scranton screening operations are now running at the highest quality levels ever achieved . . ."*





■ **Kleppinger:** *"Use of the laser defect scanner has resulted in significant reductions in wafer particle counts in production."*

■ **Hynes/Dunlap:** *"As new generations of phased array radar systems move into the manufacturing stage, additional areas of automated testing are presenting new challenges."*

■ **Keith:** *"All in all, there is a strong and lively interaction between recreational mathematics and other disciplines."*

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in future issues...
30th anniversary issue
computer graphics
mechanical engineering

Introduction to this special issue

These are exciting times. It seems that we are living in the middle of a new industrial revolution. Consumer goods are being mass-produced today whose level of technical sophistication was unthinkable only 20 years ago. More remarkable, these sophisticated products are being delivered with a higher degree of reliability than their simpler predecessors.

These changes do not come about without difficulty. Products, manufacturing processes, and indeed whole companies are faced with the imperative: join the new revolution or collapse and fail. It is not possible to stand still and repeat the triumphs of a previous generation. It is necessary, rather, to do business in a new way. The new way promises productivity and harmony in the factory, utility and reliability in the product; all of it at lower cost. Yet, this is not an easy revolution to join. Explanations of how to join, what to do, which consultants to hire; all of these are plentiful, yet success is elusive.

One reason that it is so difficult to pin down this new industrial revolution is that several discrete revolutions are taking place simultaneously:

- In factory organization and sociology, where production workers become part of the process design and management team.
- In information handling, where computers manage factory information, scheduling, inventory, and work-in-process flow.
- In production machinery, where automation promises faster, more consistent, less expensive assembly.
- In design, where manufacturability is a primary criterion for the structure and configuration of new products.

To embrace one of these tools to the exclusion of the others is as sure a path to failure as it would be to embrace none. Yet, even with all of them in place, something fundamental is missing.

A key to the effective use of these tools is the revolution taking place in the use of quantitative methods in manufacturing. Statistics, modeling and simulation, measurement science—all of these disciplines are central to an enhanced understanding of what is really going on in a manufacturing process.

This ability to measure the process, to determine whether it is producing high quality product, to indicate where improvement, repair, or adjustment is needed, to doggedly follow up and make the necessary changes, and to do so in a quantitative, objective, defensible manner is the triumph of the new industrial revolution.

This is not meant to imply that there is no room left for intuition, for great design, or for art. In fact, the enhanced ability to manufacture sophisticated, intricate things at low cost and with exceptional quality has freed designers to let their imaginations soar. The flood of new products that are both beautiful and useful is the result.

Where to now? Widespread understanding and application of statistics in the factory is not common in the United States. In many circles, it is unheard of. Where it has been tried, sometimes it didn't work and was dismissed as a bad idea. We must educate ourselves and each other, be open to new ideas and new philosophies, communicate our successes and failures, and dig in and try again. That is the purpose of this issue. If you read these pages and pick up one good idea, make one new contact among those for whom statistics have worked, or make one improvement in a factory process, this issue will have been worthwhile.

Philip G. Stein
Senior Member, Technical Staff
RCA Laboratories

About this issue

When Philip Stein agreed to serve as guest Technical Editor for this *RCA Engineer* issue, I knew that his assistance would go beyond the acquisition of manuscripts. Not only does Phil know the topic well, he understands how a magazine is produced. He gave his attention to every statistics article in the issue.

Part of the satisfaction of putting together the *RCA Engineer* derives from seeking new ways to engage your interest in a theme. Getting Phil Stein to help is one way of doing this. His contributions are clearly evident.

With this issue we include a poster on Graphics for the Display of Statistical Data—another way of engaging your interest. The idea for the poster began with Associate Editor Mike Lynch. Phil then enlisted the help of Dave Coleman and Bert Gunter. The challenge we faced in designing this poster was to make it useful as well as attractive, and I feel we've done both.

* * *

A note to future authors: We want your files. This is our first issue where all manuscripts were received as computer-readable files. This scheme permits more editing time and considerably reduces time spent rekeying the text.

Authors in five locations (Indianapolis, Palm Beach Gardens, Scranton, Moorestown and Princeton) produced their articles using available computing facilities (minicomputers, micros, word processors and the mainframe) and shipped copies to the editorial office in Princeton via telecommunications or internal mail. For this issue, most files were partially cleaned-up on a VAX computer at the Labs, then transmitted to a Wang word processing system in our offices. We look forward to when we can do almost all clean-up on the larger machines, then receive, intact, clean files on a PC.

Our file specifications are few: Keep it as simple as possible. If there is elaborate formatting in your file, we would prefer that you send us a duplicate that has been stripped of formats. (However, to capture the keystrokes, we would accept all extraneous control characters and formatting.) In all cases, mail us a printout of the document.—*TEK*

Is this issue just for statisticians?

Definitely not.

We hope that every RCA engineer, scientist, and technician can learn something from this issue about the applications of statistics to RCA's design and manufacturing operations.

Most of the statistical work in a design lab, manufacturing engineering office, or on a factory floor is done by the people who work there, and not by professional statisticians. In every case, some knowledge of statistics would improve the quality of this work. In the best possible world, a professional statistician would be available to act as both teacher and advisor. He or she would assist in setting up appropriate data gathering and analysis procedures, provide training in their use, and help to alert users to situations where difficulties could arise.

Most people who use statistics in their jobs do not have a professional statistician available. In these cases, how much training and experience do they need in order to handle these specialized tasks well?

Fortunately, for all but the most specialized problems, the mathematics is not difficult. The use of statistics in engineering, design, and manufacturing does, however, require a change in the way we think about things and look at the world, and this takes time and application. In fact, most of the training consists of learning how to plan the collection of data, how to collect it, how to look at it, and how to think correctly about what it means. We are concerned with a new way of thinking here, of how to modify our systems and approaches to doing things that we have done in other ways for a long time.

It is appropriate to ask "how much training?" when talking about teaching the mathematics and techniques of statistics, but it is not techniques that we need to teach. Rather, we need to teach the view of the world that they represent. This demands that we think of this training as a *process*, and that we ask, instead, what kind of ongoing system of coursework and reinforcing consulting structure must we set up to help people actually apply the ideas in their work. Those organizations that have been most successful in the application of statistics use a mixture of classroom training, experience with using the techniques at work, and interaction with others who are learning.

We hope that you enjoy this special issue, and that it will stimulate you to learn more, so that you will be better able to apply statistics profitably in your job.

The list below is a short bibliography for you to use if you can't get immediate training, or if you want to supplement it.

P. G. Stein
D. E. Coleman
B. H. Gunter

Ishikawa, Kaoru, *Guide to Quality Control*, Asian Productivity Organization, Tokyo (1983). Available from UNIPUB, New York. Elementary and non-mathematical text on gathering and analyzing engineering data.

Box, G.E.P., Hunter, W.G., and Hunter, J.S., *Statistics for Experimenters*, John Wiley & Sons, New York (1978). Beginning-level text emphasizing how statistical strategies for designing experiments yield more precise results and reduce experimental cost. Text for CEE course on Design of Experiments.

Guttman, I., Wilks, S.S., and Hunter, J.S., *Introductory Engineering Statistics*, John Wiley & Sons, New York (1971). Comprehensive mathematically-oriented text with many applications in all areas of engineering work.

Box, G.E.P. and Draper, N.R., *Evolutionary Operation*, John Wiley & Sons, New York (1969). Written for the engineer desiring to systematically optimize manufacturing processes. Clearly presents simple statistical tools in the context of engineering decision making.

Velleman, P.F. and Hoaglin, D.C., *Applications, Basics and Computing of Exploratory Data Analysis*, Duxbury Press, Boston (1981). Beginning-level, practical presentation of exploratory (mostly graphical) techniques of data analysis. Portable FORTRAN and BASIC listings included.

Ehrenburg, A.S.C., *A Primer in Data Reduction*, John Wiley & Sons, Chichester, England (1982). In between Ishikawa and Guttman et al. in scope and depth. Clearly written explanations of many data analysis concepts.

Statistical Quality Control Handbook, published by the Western Electric Company (1977). Exposition of classical control charting techniques filled with many practical manufacturing examples.

P.G. Stein

Japanese industrial productivity threatens new market

The Japanese have punched a hole in a uniquely American industry, and the man on the street may find this latest turn of events especially hard to swallow.

According to the latest industrial reports from Japan, another indigenous American industry had better look out. First it was shipbuilding, then steel, then autos and consumer electronics. Now, under the watchful eye of the Ministry of International Trade and Industry (MITI), the widely respected Japanese industrial capabilities are being focused on the lowly donut.

By now, the Japanese success story is familiar to millions of Americans, especially to those still out of work. The Yankee monopoly on high-volume, low-cost mass production is a thing of the past. By what seems to be a magic combination of good management, a willing and able work force, aggressive capitalization, and the use of modern statistical methods, the Japanese have shown in industry after industry, in plant after plant, that they can make higher-quality products than we can, and can do it at lower cost. Recent documentation of this trend in the air conditioner industry strongly supports this notion.[1]

Abstract: *Statistical control of an industrial process is shown to be the cornerstone on which modern, efficient, low-scrap manufacturing must be based. Using specific examples from a highly productive cost-effective Japanese industry, the author demonstrates that the application of statistics in the factory is crucial to the economic success of American manufacturing.*

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Reprint RE-30-3-2

Tohoshiro Nishiaki, MITI's donut expert, was recently interviewed by this author during a coffee-soaked whirlwind tour of his country's newest industrial facilities. "Our people are not as creative as yours," he said, "so in order to be competitive in the donut market, we have had to rely on price and quality to attract customers."

And the Japanese *have* been able to perform the same quality miracles with donuts that they did with cars and stereos. Anyone who has ever gotten a jelly donut with no jelly in it knows the frustration facing the average American donut lover. "Weight of filling is just one of over fifty variables we use for statistical process control," said Mr. Nishiaki. "By using formal problem-solving methods, such as the Fishikawa bone chart[2] and scatterplots,[3] our manufacturing staff has identified these causes of variation and, with the total support of management, the variation has been systematically eliminated. The result is our new donut, which we have named the quality circle."

Figure 1 shows a portion of a fishbone diagram for donut manufacturing.

The most amazing result of this technological achievement is that these uniform, delicious donuts actually cost less. Why is this so? The Japanese factory has greater capital investment, more inspectors, and many more design and manufacturing engineers than its counterpart in the United States. The labor rates are roughly comparable, and there's not much difference in the amount of automation. What makes the operation so profitable is the fantastic productivity that results from a plant-wide, top-down commitment to quality. Scrap and rework, a daily fact of life in American industry, are virtually unknown to the Japanese donut makers. By designing capable processes, by using statistics to keep them under control, and by insisting that vendors of incoming materials do the same, only one or two donuts out of every *thousand* fail to make it to the breakfast table.

Can America catch up?

Frederick P. Duncan, founder of one of the world's largest donut chains and president of the American Toroidal Pastry Institute (ATPI), says that we must first put our industries on an equal footing. "The Japanese donut industry is actually supported and run by its government. Manufacturers get special treatment, low-cost loans, and tie-in discounts from the chocolate and shredded-coconut suppliers. It's no wonder they can dump their products here at the unreasonable prices that they do. We can't compete without some help from our own government. An import duty of, say, 50 percent on plain and honey-dip and 35 percent on filled and iced might give our domestic industry a chance to get back on its feet." No mention was made of cinnamon.

Harvard lecturer Robert B. Right, author of *The Next-To-Last American Frontier*, says "There is no way we can match the Japanese or emerging third-world countries in high-volume mass production of donuts. We shouldn't attempt to return to the days when America was king of this type of manufacturing. It is necessary to take a holistic approach; to increase the value-added, to encourage small, custom

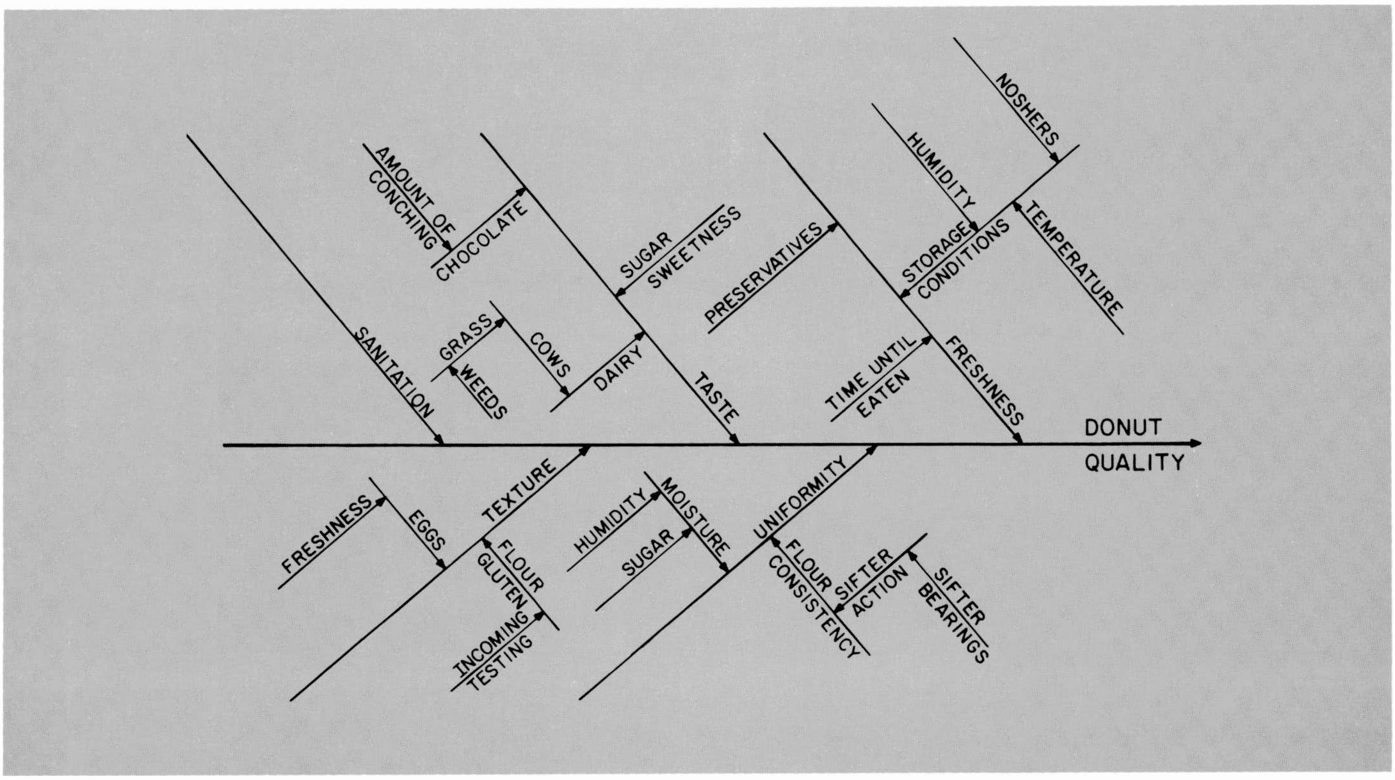

Fig. 1. *Fishbone diagram of donut manufacturing.*

> ### Research methods
>
> The author gained eight pounds in the preparation of this report.

production runs. For example, the production of individually monogrammed donuts, using a computer-driven laser donut engraver, might give the industry the boost it needs to be competitive."

There seem to be as many ideas for how to compete with the Japanese as there are writers and lecturers in the field. One thing is certain, though: something must be done before the United States has no more native bakeries. As Mr. Nishiaki said, "Now that our donut program is now under way, we plan to look at the bagel industry." New York Mayor Ed Koch was unavailable for comment.

References

1. Garvin, David, *Quality on the Line*, Harvard Business Review (September/October 1983).
2. Ishikawa, K., *Guide to Quality Control*, Asian Productivity Organization (1982).
3. Rayl, M., and Stein, P.G., "Factory data vs. factory information," *RCA Engineer*, Vol. 28, No. 4, pg. 81 (July/August 1983).

J.S. Hunter

The technology of quality

Statistics is a language, the mechanism for creating and communicating quantitative concepts and ideas.

To remain competitive with other industrial nations, and particularly with Japan, American industry will have to pay greater attention to the quality of its products and to the efficiency of its production processes. This overall product-process problem can be encapsulated into the single word "quality." Most of the origins and the solutions to America's quality problems rest with management.

Today's "quality" activities

American management has already devoted considerable resources to changing its point of view with respect to quality. Through short courses and other exhortations most of today's managers have come to recognize that productivity and quality are not antithetical, and that both management and worker have shared responsibilities for quality. The highest echelons of management have thus become personally committed to the pursuit of quality, and have restructured their organizations to make "quality" both a staff and a line function.

Vendors are now asked to demonstrate proof of their product quality, purchasing departments are encouraged to reduce the number of vendors, and "just in time" (Kanban) production inventory methods are being inaugurated. "Quality circles" and other parcipitative management procedures are being introduced, while the worker on the production floor is encouraged to "do it right the first time" and to become a self-monitored, quality-conscious individual.

Unfortunately, commitment, reorganization, and motivation on behalf of quality, in and of themselves, are incapable of closing the performance gaps that separate most American and Japanese industries from each other. Also required are heavy infusions of quality *technology* of both a hardware and software variety.

Hardware quality technology is the introduction of modern production equipment, CAD/CAM systems, robotics, computers, new manufacturing processes and designs. Many quality technology hardware investments have already been made and more are planned. In these days of strong competition industrial management can be quickly persuaded into constructing new facilities and purchasing new equipment. In this context, management decision making is easy. Part of what is needed is capital, and remarkably that appears to be in good supply. And should local resources of engineering knowhow appear insufficient, management can always arrange joint ventures with foreign competitors.

Much more neglected and more difficult to acquire are the "software" aspects of quality technology, that is, the ability to create new knowledge on how to improve one's products and processes. Management is now faced, not with a decision making process, but rather with a learning process that requires both the leadership qualities of a dean and the learning capacities of a student.

Creating new knowledge

Classically, new knowledge has come from research and development laboratories, and considerable additional resources are today being invested by American industry in R&D, one novel consequence being occasional collaborative arrangements between universities and industry.

But new knowledge on behalf of quality also arises from within manufacturing. One explanation of the success of Japanese manufacturers in increasing both product quality and process efficiency is their ability to create useful information using data gathered from within manufacturing. This ability is perhaps the most important characteristic of quality technology software not yet fully appreciated by American management. The key question then becomes, "What can American management do to enhance the knowledge-gaining abili-

Abstract: *The production of information-laden data is essential to the improvement of both product quality and process efficiency. The classical histogram and Shewhart chart are but two of many graphical devices for the study of historical data to secure quality improvement information. New information is also created through process and product design experimentation. Statistically designed experiments provide for the study of the influences of several factors varied simultaneously, and can be used to "block" unwanted sources of variability. The language and tools of statistics are essential components to any learning process that involves the use of measurements. Industrial competitiveness requires the application of statistics in all of its modern modes.*

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Reprint RE-30-3-3

ties of its product design and production personnel?"

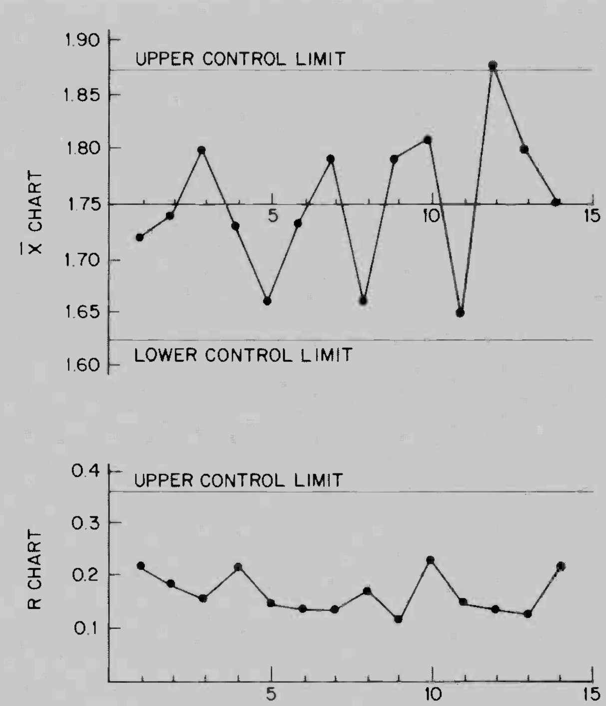
A clue to the answer rests in the Japanese commitment to an educational program designed to aid both managers and workers in the arts of problem definition and problem solving, coupled with the language and tools of statistics.

When Dr. W. Edwards Deming instructed Japan's upper management in the rudiments of industrial statistics in the 1950s,[1] his lectures were used as templates for vastly extended educational programs for all levels of personnel. These lessons were augmented by Prof. Kaoru Ishikawa, who insisted on the careful statement of objectives, on the construction of cause-and-effect diagrams, on the use of Pareto charts, and most especially on the graphical displays of data.[2] The combined contributions of Deming and Ishikawa have resulted, very simply, in a vast educational program in the scientific method applied to quality problems.

The term "scientific method" sounds pretentious, but few other descriptions seem adequate. This Deming-Ishikawa approach is methodically used within Japan to attack myriad problems of quality, both small and large. The areas of application are product design and production. The objectives are to meet all immediate quality and production requirements and to reduce process and product variability while simultaneously creating knowledge useful for the enhancement of product quality and process efficiency. Over time, and in a fashion analogous to the growth of a great reef, huge foundations of practical knowledge are gradually created from within the design and production functions. Here is the software characteristic of quality technology that managers in America must grasp and apply.

Today, teaching statistical methods for quality improvement is on the increase in the United States. Unfortunately much of this effort is aimed at expounding arts of statistics that were common at the end of World War II. American industry has seemed content to import back from the Japanese the very same statistical tools that Dr. Deming elucidated for them forty years ago. Some of these more classical statistical tools continue to be of great importance, most particularly the Shewhart quality control chart.

Other tools are now in less frequent use, in particular acceptance sampling procedures arranged to allow product with a fixed percent defective (AQL) to be passed. Acceptance sampling procedures, though soundly based on mathematical principles and still of value, contribute to the notion that quality can be inspected into a product, and that management can afford to ship a "few" bad items. The shipment of bad items enhances the attitude of "let the next guy catch the defect." The mindset associated with acceptance sampling procedures is contrary to the notions of never ending improvement, and to the learning process.



Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	1.84	1.73	1.83	1.62	1.63	1.66	1.86	1.67	1.72	1.92	1.67	1.86	1.75	1.70	
	1.62	1.82	1.97	1.76	1.73	1.68	1.82	1.58	1.82	1.69	1.72	1.93	1.85	1.75	
	1.77	1.75	1.72	1.84	1.58	1.58	1.72	1.62	1.78	1.88	1.63	1.80	1.87	1.66	
	1.63	1.64	1.88	1.70	1.64	1.80	1.75	1.75	1.84	1.75	1.57	1.94	1.74	1.88	
Sum	6.86	6.94	7.20	6.92	6.58	6.92	7.15	6.62	7.16	7.24	6.59.	7.53	7.21	6.99	
Average	1.72	1.74	1.80	1.73	1.64	1.73	1.79	1.66	1.79	1.81	1.65	1.88	1.80	1.75	
Range	0.22	0.18	0.16	0.22	0.15	0.14	0.14	0.17	0.12	0.23	0.15	0.14	0.13	0.22	

Chart parameters: $n = 4$, $\bar{\bar{X}}$ 1.75, $\bar{R} = 0.17$

Fig. 1. *Shewhart X bar and R control chart.*

The Shewhart control chart

Much emphasis is currently being placed on the Shewhart control chart, a method for sequentially plotting a regularly measured response.[3,4] An illustration is given in Fig. 1. Here a sample consisting of four observations (measurements on some important quality characteristic) is taken, and the sample average and range of the observations plotted sequentially. The objective

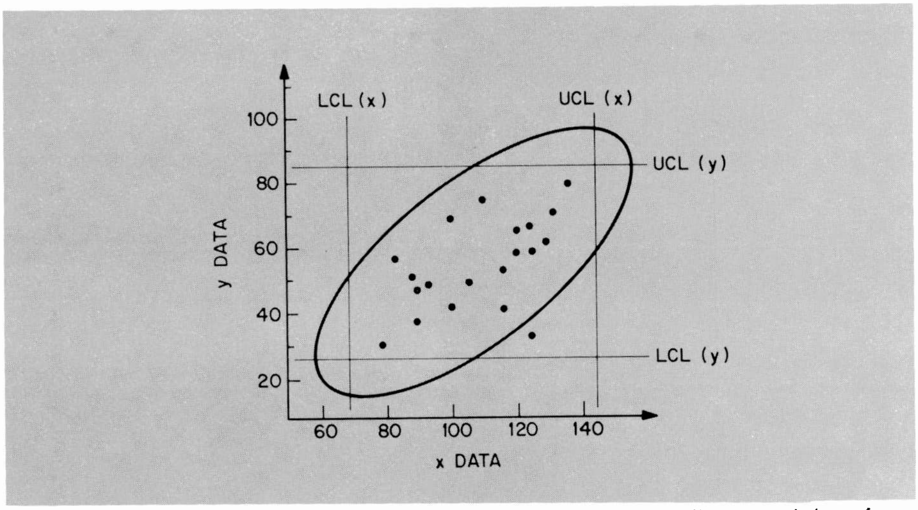


Fig. 2. *Bivariate Control Region. Note the point outside the ellipse, and therefore out of control. One-variable at-a-time control limits (the rectangle) would not signal an out-of-control condition.*

of the chart is to establish and then maintain process stability. Stability does not mean the complete elimination of all product variability. There must always remain an intrinsic variation among items produced. This is natural to the manufacturing process. Stability does mean producing product on target with only intrinsic variability about the target allowed.

A Shewhart control chart is established by first collecting twenty or so samples of four observations each when the process appears "well behaved." The average and range are computed for each sample, and then the grand average (X bar) and average range (R). Upper and lower control limits (the 3-sigma limits) for future averages and ranges of four observations each are then constructed using simple tables. In Fig. 1 a subsequent sequence of sample averages and ranges has been plotted. At time position 12 an average is observed to fall above the upper control limit. The chartist is now required to find an *assignable cause* for this unusual event (unusual for a process supposedly on target) and most important, to make sure the event cannot happen anew. A plotted range beyond its control limits is a signal that the variability of the process has changed, and once again the assignable cause, and cure, are required. Over time, most external causes leading to shifts in both mean level and variability of the process will be uncovered and eliminated. The process is then declared to be under "statistical control."

Once the Shewhart control chart is established, its graphical simplicity makes it a most valuable instrument for process control. Not only is the historical progress of the process displayed for all to see, but the requirement that assignable causes be identified and eliminated forces workers to take an aggressive attitude towards maintaining the quality of their work. The elimination of many assignable causes is often beyond the abilities or capacities of the worker. Shewhart control charting in the absence of active management participation then quickly becomes aimless makework. The control chart is a tool for *both* worker and management.

Shewhart control charts can be designed for percentage data, for counts, and for other statistics. The charts have found application in offices, the service industries, and in fact, whenever data are sequentially observed. The Shewhart control chart had its origins in the early 1930s, and it remains to this day a valued statistical tool.

Multivariate control charts

Much has happened in the practice of statistics over the past fifty years, and it is important that today's manager be alert to other control charting techniques that may be of value. For example, consider the case where each manufactured item has two measured quality responses (say, paper tear strength and fiber content). Common practice is to construct and evaluate two separate Shewhart control charts, one for each response. An opportunity frequently neglected is to co-plot the data, and to establish a control region appropriate to both responses considered simultaneously. The boundary of the bivariate control region is a circle or, should the two measured responses be correlated, an ellipse. An illustration is given in Fig. 2. Note how the control ellipse both includes and excludes regions contained within the rectangle formed by the superpositioning of the two separate one-factor control boundaries. Once the bivariate control region is obtained, the worker merely co-plots the data and notes whether each plotted point falls within the control ellipse. A bivariate control chart provides more appropriate, and often dramatically different, signals than those offered by the separate univariate charts. In general, whenever univariate charts are used in the absence of bivariate charts, information on process performance is lost, and misinformation frequently offered.

If bivariate charts are so valuable, why, one might ask, haven't such charts found wider use? Arithmetic is the answer. Hotelling's T^2 statistic must be calculated to establish the bivariate control boundaries.[4,5,6] This expression and its associated arithmetic may appear formidable, but they are not. Today's hand-held calculator or desktop computer is easily programmed to complete the necessary arithmetic and graphics within a few seconds.

Managers must recognize that the simple hand-held calculator is destined to revolutionize the applications of statistics on the production floor.

Since Hotelling's T^2 is not limited to two measured responses, the computer also offers the opportunity to contemplate multivariate control chart procedures. In practice, the factory worker would place the several measured responses into the hand-held or desk-top calculator. The calculator would compute T^2, and could be programmed to 'beep' whenever an unusual value of T^2 was obtained. If the sequential values of T^2 are plotted, they can be compared against upper (and lower) bivariate or multivariate control limits. Monitoring today's processes with one-variable-at-a-time methods is to throw away information.

Additional control charts

Other methods for the graphical processing of sequentially recorded data also need emphasis. Of great practical importance is the CuSum (Cumulative Sum) chart.[7,8,9,10] An illustration of a usual time plot along with a CuSum plot is given in Fig. 3. Clearly, signals are offered to the eye by the CuSum chart that are not readily apparent from the original time plot. The CuSum, plotted on the vertical axis, equals:

$$\sum (Y_t - T)$$

where Y_t is the observation recorded at time t, and T is some convenient constant, usually the target value for the response being measured. When the process is on target the CuSum wanders about zero. Should the response mean move away from T by a constant value D, the CuSum adds D, with each subsequent observation yielding a pronounced change in slope of the CuSum plot, rising or falling depending upon the sign of D. To help distinguish between a random walk while on target, and a true change in slope, a V-mask is often placed a fixed distance in front of the last plotted CuSum point. A V-mask is shown in Fig. 4.

To illustrate the construction of the V-mask, consider the data given in the following table.

Thirty sequentially recorded observations.

Target value $T = 19$.
Standard deviation $\sigma = 0.25$.
The data are listed in columns.

18.98	19.03	19.09
19.38	19.13	19.55
18.57	18.99	19.31
18.76	18.91	19.37
19.21	19.58	19.15
19.05	19.27	19.38
18.84	18.95	19.28
18.50	19.65	18.81
19.16	19.05	18.93
18.94	19.40	19.02

The target value for the items being measured is $T = 19.00$ and the standard deviation of the measurements is $\sigma = 0.25$. Let the shift in mean D away from the target value be approximately equal to the standard deviation. (When the ratio D/σ is approximately unity, then standardized CuSum graph paper will have its horizontal and vertical axes scaled as illustrated in Fig. 4.) The standardized V-mask, with semi-angle $\theta = 26.50°$ and placed $D = 7$ units horizontally in front of the last plotted observation, is displayed in Fig. 4. So long as the entire CuSum plot falls within the arms of the V-mask, no signal of change away from target is given. In Fig. 4, a signal is noted at time position $t = 14$.

In general, the parameters of the V-masks are functions of the size of the shift in mean D relative to the standard devia-

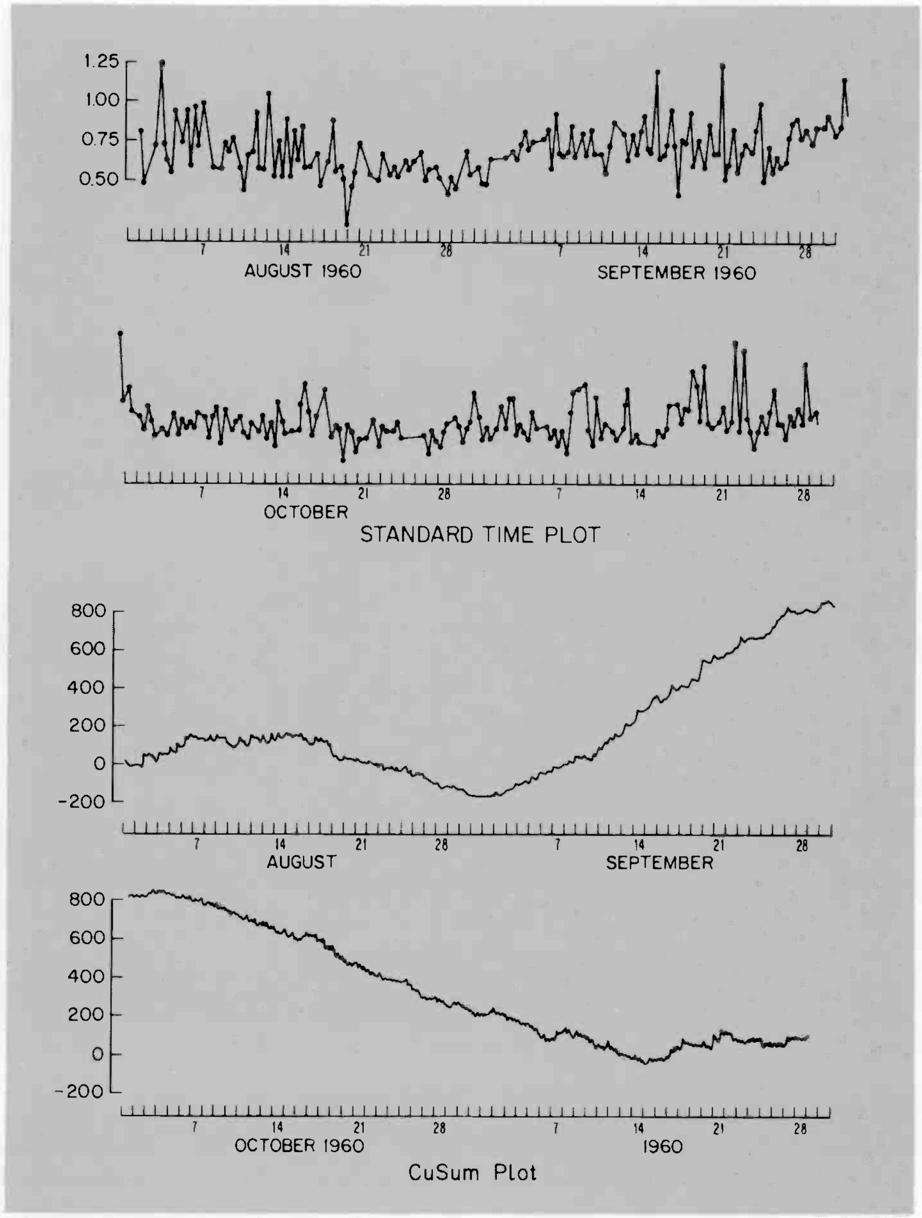


Fig. 3. *Standard time plot and its associated CuSum plot.*

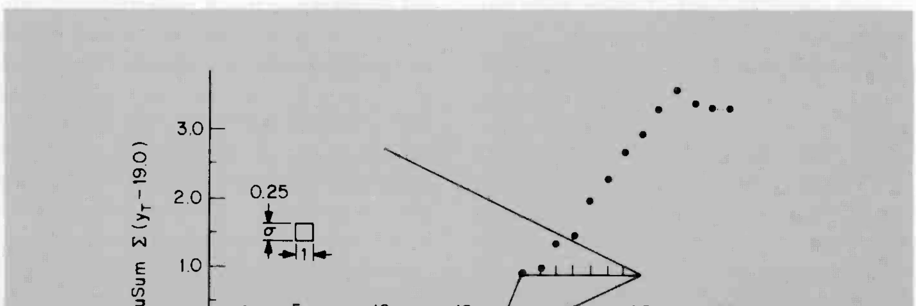


Fig. 4. *CuSum plot with V-mask for indicating out-of-control signals.*

Batch Yields

Batch No.	Yield %	Batch No.	Yield %	Batch No.	Yield %	Batch No.	Yield %
1	69.0	11	69.5	21	74.2	31	68.3
2	67.5	12	72.6	22	68.9	33	70.2
4	70.4	14	70.9	24	70.6	34	70.6
5	67.8	15	69.1	25	69.8	35	66.8
6	69,3	16	68.3	26	70.8	36	72.7
7	70.7	17	69.9	27	68.0	37	68.0
8	70.0	18	71.3	28	67.2	38	65.6
9	68.4	19	67.8	29	72.8	39	69.2
10	68.2	20	66.2	30	71.7	40	69.5

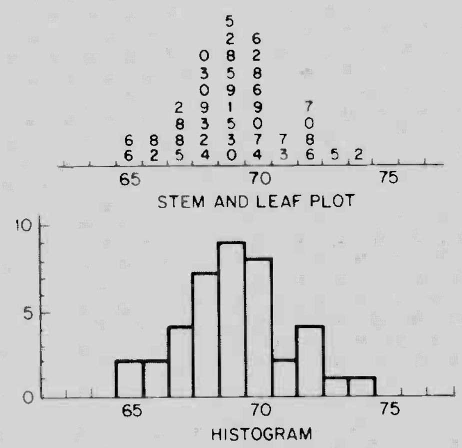
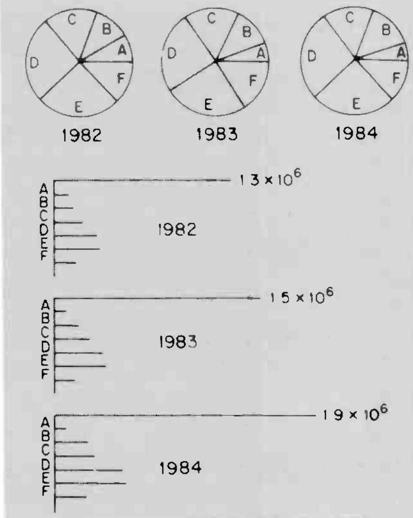


Fig. 5. *Histogram compared with Stem and Leaf plot of the same data.*



Market Share

	1982	1983	1984
A	1.08	0.83	0.95
B	1.44	1.88	2.53
C	2.17	2.50	3.01
D	3.25	3.54	5.01
E	3.43	3.75	5.12
F	1.62	2.50	2.38

Dollars $\times 10^6$

Fig. 6. *Pie charts for market share in three years, and an alternative presentation that shows more information. Note that it is very easy to compare magnitudes from different years in the second set of graphs, and impossible to do so in the pie charts.*

tion of the process, and to the risks of false signals. The *V*-mask may be modified to control for deviations from target of a given sign. The CuSum may also be adapted to percentage data and count data. The CuSum plot with its various control boundaries is currently finding wide use in the process industries.

An additional modern charting technique is the EWMA (Exponentially Weighted Moving Average) chart, a simple method for plotting sequential data that weights historical data less as the data become older. The EWMA stands between the Shewhart and CuSum charts in its capacity to produce signals useful for process control. The EWMA is, in turn, one of a large class of time series models (such as the ARIMA models of Box & Jenkins,[7]) useful for controlling industrial processes. Still another charting technique now used at Western Electric, is the QMP (Quality Measurement Plan) chart.[8] All these charting techniques have a place in modern quality technology.

Graphical data displays

The eye is the primary avenue of communication to the mind, and graphical techniques for the display of quantitative information are among the most valued tools of modern statistics. Certain graphical displays are much preferred over others. For example, the eye is quite skilled at detecting small changes in the lengths of lines, when the lines are parallel and start from the same base. This skill can be effectively used in constructing histograms in which the height of each line equals the frequency of some measured response at different settings located along a horizontal axis. However, histograms are often displayed as a grouping of rectangles, and on other occasions as groupings of rectangular prisms. These alternative methods of eye-display are not preferred. The eye is not skilled at appreciating slight differences in areas, and if the rectangles have different base widths, this form of histogram can lead to confusion. The eye is even less able to appreciate differences in volumes, hence volume displays should be avoided.

A valuable graphical device for recording a long list of data is the "stem and leaf" plot. Figure 5 compares a standard histogram against a "stem and leaf" plot of the same data. Note how the decimal digit of each observation is recorded on the stem-and-leaf plot. This plot provides a picture of the data equal in information to that of the histogram while simultaneously not losing any numerical detail.[9]

The pie chart is a poor graphical display device for comparing numerical information. The observer doesn't know whether to compare the angles, the areas, or the lengths of the circular arcs. All these geometric measures bear a fixed relationship to one another, but each is differently appreciated by the eye. Further, the eye is a poor judge of the differences between pie-chart sectors, both within a single pie chart, and even more poorly between pie charts. A graphical alternative to comparing pie charts is illustrated in Fig. 6.[10]

Multivariate graphical displays of many numerical measurements can be shown in a "metroglyph." The symbols on a weather map are examples of metroglyphs. Stem and-leaf plots are a form of metroglyphs, and there are many others: box and whisker plots, castles and trees, and Chernof faces. In quality control, the recent work of Gary MacDonald at General Motors is of particular interest. Here measurements on many different characteristics of production line items are viewed simultaneously with respect to their control limits in metroglyphs that have the appearance of snowflakes or stars.[11] [*Ed. note: The center poster shows examples of all these techniques.*]

Data vs. information

In most manufacturing processes vast quantities of data are gathered from the production floor on a wide variety of responses and carefully stored in a computer. Can modern statistical methods, using the computer, uncover useful information from these numerical records? Yes and no.

Unfortunately, most stored production data are the archival record of measurements made at some transitory historical moment. The value of these old data as information relative to today's quality questions fades rapidly as time passes. The very quantity of these data is itself often a handicap with poor data, cheaply acquired and too voluminous, serving to dissipate the contributions of good data. Some statisticians call the analysis of historical production data PARC analysis: Practical Accumulated Records Computations. Read the acronym backwards.

The statistical analysis of historical production data is analogous to mining an ore in which only a very small percent of desired mineral is present: there is much data but little information. Many other difficulties can be encountered. Important factors may not have been measured, or measured with time or space lags that are unknown. Other observed factors, correlated with unmeasured important factors, will give the impression of having influential effects when in fact the observed factor is merely the surrogate for the unknown influential factor. Historical production data are usually rife with missing and abberrant values and prone to poor measurement quality. PARC analysis is an appropriate title.

Data management, by which we mean the collection, storage and retrieval of numbers, is important but secondary to the need to provide information that will answer questions. With a computer there are many ways in which data can be displayed, both tabular and graphic. The purpose of most analyses, though, is not data displays, descriptive as they may be, but the construction of forecasts and the development of useful mathematical models—the creation of information. Many managers save their production data in the hope that tomorrow's questions can be answered with yesterday's numbers. The creation of information more properly proceeds by first asking the questions and then organizing for the necessary numerical information.

Passive vs. active statistics

It is not widely recognized that control charts, acceptance sampling procedures, and methods for analyzing of historical data all represent the *passive* use of statistics. They play a role analogous to that of a physician who, on visiting a patient, sits and listens to what the patient has to say. Of course a great deal can be learned through listening. But obviously much more can be learned through active questioning and testing. So, too, with industrial processes. "Quality" managers must learn to interrogate their industrial processes, that is, invoke the *active* uses of statistics. Statistics in its active mode requires the planning of experiments.

Experimental Design

A proposal to experiment with an on going production process can stimulate a variety of reactions on the part of a production manager, ranging from outspoken hostility, through scorn, to trepidation. To many managers, "production" and "experimentation" are at opposite poles. Nevertheless, it is a fact that experimentation goes on in every production process: a small variant tried here, another small change there, "small" because any large change might have immediate deleterious consequences on throughput or quality. Of course, small changes usually have small effects, and the investigator's problem then becomes one of detecting the effect of an induced change. Given the variability of product and measurement that attends most industrial processes, investigators are lucky indeed if they can state with any confidence that any effect, good or bad, has occurred. Thus, in most industrial processes, changing the process (experimentation) has become an informal procedure, with much data generated, but little information acquired. Worse, after a sequence of many *ad hoc* changes an attitude of "that 'ole black magic" begins to replace logic.

Required in this industrial situation is the application of a little "enlightened empiricism." In brief, the application of simple statistically designed experiments.

Planning a useful experiment requires a well-defined question, the selection of factors to be varied, and responses to be measured: all good experimental as well as statistical practices.

Managers should know that in statistically designed experiments the measured response is always influenced by two types of factors: studied factors and blocking factors. Studied factors are those chosen by the experimenter in order to determine their influences. Blocking factors are phenomena such as batches and machines—factors that become part of the statistically designed experimental program because one recognizes, in advance, that they are likely to add noise, confusion, or in a word, *error* to the observed response. Consider the following simple example.

In a study of two different types of NO_X sensors an engineer obtains ten sensors of Type A and ten of Type B, and places these instruments in the exhaust systems of twenty different automobiles. The resulting data are displayed in Fig. 7a. On viewing both the spread and over-

Type A	Type B
72.1	74.0
68.2	68.8
70.9	71.2
74.3	74.2
70.7	71.8
66.6	66.4
69.5	69.8
70.8	71.3
68.8	69.3
73.3	73.6

$n_A = 10 \quad n_B = 10$

$\bar{y}_A = 70.63 \quad \bar{y}_B = 71.04$

$\bar{y}_A - \bar{y}_B = -0.41$

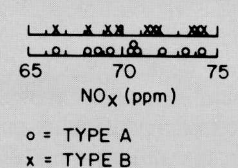


Fig. 7a. *Comparing two sensors.*

NO_x Sensor Experiment II

NO_x in ppm

		Type A	Type B	A − B
Car	1	72.1	74.0	−0.8
	2	68.2	68.8	−0.6
	3	70.9	71.2	−0.3
	4	74.3	74.2	+0.1
	5	70.7	71.8	−1.1
	6	66.6	66.4	+0.2
	7	69.5	69.8	−0.3
	8	70.8	71.3	−0.5
	9	68.8	73.6	−0.5
	10	73.3	73.6	−0.3

n = 10 pairs

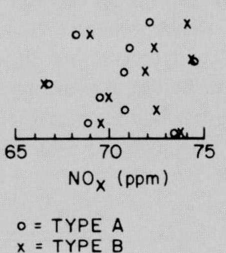


Fig. 7b. *Comparing two sensors with blocking.*

lap of the A and B data there is little evidence that a difference between the Type A and Type B sensors exists. The experiment has been poorly designed. The differences in the combustion systems of the cars has been allowed to influence the comparison between the two types of sensors.

Suppose instead (and here we use the same data for illustration purposes), each of ten cars had been equipped with both sensors. Then the comparisons between A and B could be made for each car separately. The difference between the sensors could be measured regardless of whether a car had high or low emission qualities. The differences between the cars would be eliminated from the analysis. The data for this blocked experimental design are displayed in Fig. 7b. A difference between sensors A and B appears real. The blocked experimental design is superior to the unblocked design.

The data in this example were analyzed graphically. A more precise numerical analysis is very simple and can be left to a technician.

In the real world A and B, the studied factors, could represent an old versus a new method of manufacture, or two different tools, two different ingredients, two different temperatures, or simply two different treatments of interest to the experimenter. The classification "cars," the blocking factor, could represent different workers, coils of wire, furnace heats, days of the week, or any identifiable source of variability beyond the control of the experimenter. Both treatments are run within each block. The key point for the manager to remember is that through careful planning the information content of experimental data can be increased tremendoulsy.

But even when blocking factors have been taken into account, it is usual to find the experimenter studying only one factor at a time. Most industrial managers are simply unaware of the important fact that with statistically designed experiments it is easy to study the consequences of varying more than one factor at a time, and in fact, it is strongly encouraged.[12] Such experimental programs are called "factorial designs," and it is common to study four or more factors simultaneously in as few as eight well-designed experiments. Further, the data-taking sequences can be arranged to reduce (block) unwanted sources of variability. Statistically designed experiments have been used successfully in every science.[13]

Remarkably, although statistical experimental designs are easy to plan, conduct, and analyze, they are currently seldom used by production personnel. This failure represents a serious loss of opportunity to learn about quality improvement on the production floor with production personnel performing the role of experimenters. Production process experimentation has been formalized into a statistical procedure called EVOP (Evolutionary Operation), a contribution of G.E.P. Box.[13]

Theory SIGMA

The variety of statistical tools available to the production manager, and managers in general, is impressive. However, modern statistics is much more than a collection of tools and computing protocols to be used here and there. Statistics is a language, the means for creating and communicating quantitative concepts and ideas. Managers insist that their staffs speak and write succinctly. Numerical literacy, the ability to communicate statistically, is no less important. Since most quality problems are characterized in numerical terms, their description and analysis require the highest levels of language possible. The appropriate language for most quality problems is the language of statistics. The ability to employ both the language and tools of statistics on behalf of product quality and productivity will identify tomorrow's "quality" manager. Management must couple good organization and motivation with quality technology if American industry is to remain competitive.

Conclusions

Quality technology has obvious hardware aspects. Equally important, however, are its software aspects, that is, the production and analysis of meaningful quality information, not mere data. In addition, today's "quality" managers recognize that they are part of a learning process that involves both quantitative information and concepts. As leaders and as students they know how much can be done even with very simple statistical tools, but that to leap

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ahead of their competition they must learn and apply new arts and languages.

Most important of all, today's 'quality' manager applies the scientific approach to problem solving: the careful quantitative statement of the problem, the exhaustive review of the historical data, the numerical forecast of what can be accomplished, and the creation of new quantitative information. The modern manager will find the role of statistics pervasive.

What can be done today? Certainly today's manager should ensure that the teaching of statistics to "quality" personnel is not merely a repetition of what was offered at the end of World War II. In particular, although the Shewhart control chart remains the essential first tool of analysis, today's industrial manager must plan to go beyond. If today's "quality" managers and their staffs merely relearn the statistical arts of their World War II predecessors, they will never catch up with their competition. The leap forward to real competitiveness requires the application of statistics in all of its modern modes.

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D.E. Coleman

Measuring measurements

We use measurements routinely in the factory, in design, and in engineering. We rarely, if ever, measure the quality of the measurements themselves.

What were you thinking about the last time you stepped on a bathroom scale? If you are like most of us, you were thinking about how you would like to lose a few pounds. Or, maybe you are one of the few and fortunate who would like to gain a few pounds. In any case, you were probably not thinking about metrology, the science of studying and understanding measurements. You might wonder, "Why should I think about metrology while standing on the bathroom scale?" While it cannot be expected to help you lose or gain weight, a serious consideration of metrology would help you understand much more of what is behind that number glaring up at you from the scale. It might even help you justify why it is not what you would like it to be.

The first concept to grasp about metrology is that any measurement comes from a measurement *system*, not from measurement equipment alone. In other words, the weight shown on your bathroom scale is the result of more than the mere existence of you and the scale. It is the consequence of many existing and "setup" conditions, plus the weighing procedure followed. We might call this the "measurement process description." For weighing on a bathroom scale, the measurement process description might include:

(a) How long it has been since your last meal.
(b) What you are wearing.
(c) How long it has been since you washed your hair.
(d) Where you are standing on the scale.
(e) Whether you are leaning forward to read the scale.
(f) Whether the scale is on a level surface.
(g) Whether the scale has been calibrated, and when.
(h) The display precision of the scale (2-lb. steps or 1-lb. steps), etc.
(i) What time of year it is.

From this example, we can see that measurements come from a measurement system; making measurements is a process. That is why we speak of a process description, as would a manufacturing engineer. The product of a measurement process is not television sets or satellites, but numbers. Just as we are concerned with quality and productivity for goods and services sold by RCA, we do well to concern ourselves with the quality of our measurements and the productivity of our measurement systems. We do not make a profit directly from measurements, but we do gain knowledge and understanding from them.

Abstract: *Measurement systems are used throughout RCA, and the results obtained from them are used daily to make important decisions. Yet, it is rarely appreciated that making measurements is a process whose product is numbers. The quality of measurements and productivity of measurement systems are rarely assessed. The advantages of measuring measurements are discussed in this article, and three recent RCA case studies are given to show the enormous benefits that can be obtained.*

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Relevance to manufacturing

In similar ways, the measurement process descriptions in RCA's manufacturing plants influence the quality of the measurements. RCA has complex electronic test equipment in virtually every department of its plants. The day-to-day use of this equipment may or may not reflect good metrological practice. Important decisions that determine product quality and manufacturing productivity are based on these measurements. Let us consider a few manufacturing departments.

The consequences of bad measurements in the quality control department are plain and are serious in the short term. If the QC department rejects good manufactured product, productivity drops immediately, and profit suffers. If the QC department accepts bad product, field returns and warranty costs eventually rise, and poor customer relations can result. In both cases, in the longer term, the opportunity to gain manufacturing process knowledge is lost, and misunderstanding of the manufacturing process may even result.

The periodicals serving the QC field are filled with advertisements touting the outstanding precision of various measurement equipment. Unfortunately, most of these advertisements do not consider the impact of the measurement process description on the precision of measurements.

Hence the QC community is subjected to unrealistic claims. They stem from the use of "short-term replicate" measurement procedures: set up the tester carefully with the unit to be tested, test it, and test it again—without changing anything. Naturally, the "precision" of the tester can be expected to be excellent under such conditions. However, such circumstances do not reflect how the tester will really be used. To realistically assess measurement precision, we must mimic the conditions of actual use.

The quality of measurements also affects the manufacturing and manufacturing engineering departments. Both departments make decisions on how to modify manufacturing processes based on measurements of product taken on the floor. Suppose Line 1 uses Process P1 to make product, and tests it on Tester T1. Line 2 uses Process P2, and tests it on Tester T2. A systematic bias in Tester T2 toward a specification limit might indict Process P2 (showing a higher defect rate), even though Process P2 may produce more consistent product, and closer to the nominal. Greater variability in Tester T2 might lead to the same (wrong) conclusion. These types of wrong decisions have short-term to moderate-term consequences. A good process might be given up for a poorer process, simply because the actual process performance could not be assessed correctly.

Bad measurements hurt design engineering in ways that usually have long-term consequences. Nominal and worst-case analyses done on CAD systems may not "live up to their names" because the measurements of components themselves may be considerably biased or variable. For example, a minimum, maximum, and nominal value for the inductance of a specially purchased head in a VCR may be calculated from tests on sample heads. If the inductance measurement process was shifted, a design decision to increase the level of current going through the head may be made—even at the expense of resulting picture degradation due to saturation. The design modification would unnecessarily compromise picture quality, which could make the VCR less attractive to the consumer. The modification could hurt manufacturing productivity as well, since it would reflect a situation different from reality.

Later in the product development cycle, when prototypes are tested, measurement errors can wrongly reject or accept whole designs, or lead to nominal and limit specifications that do not optimize performance.

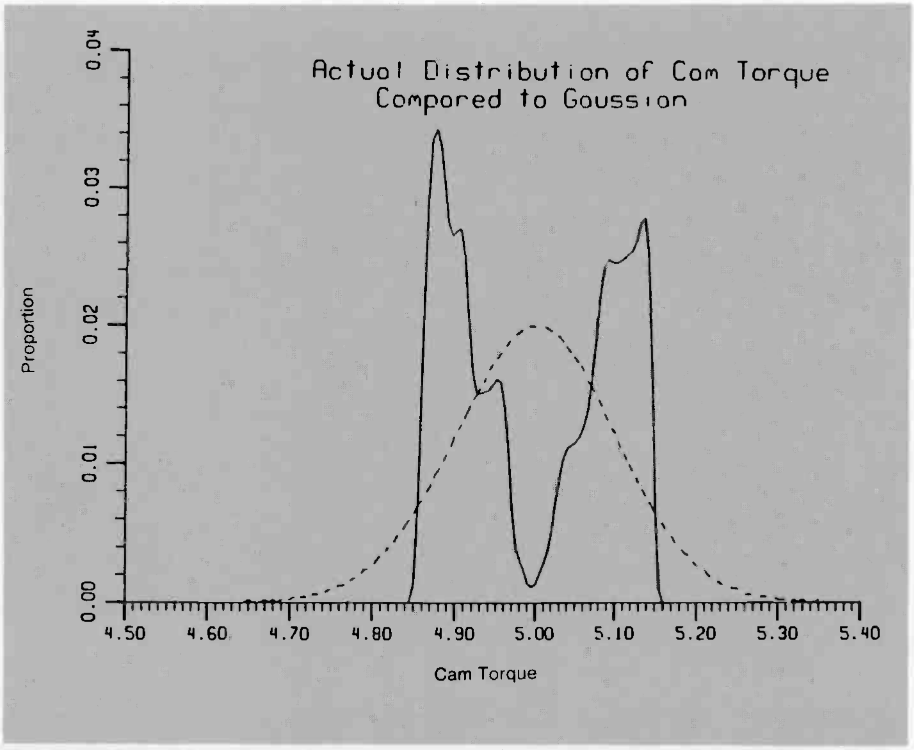

Fig. 1. *Distribution of cam torque compared to a Gaussian distribution with the same mean and standard deviation. The distributions are completely dissimilar.*

For example, two competing VCR head designs might be evaluated as follows: Record ten videotapes from identical video sources—five on heads of Design 1, and five on heads of Design 2. The resulting tapes may be evaluated quantitatively or subjectively by playing them on a standard playback VCR. But suppose the heads on the playback VCR have a physical bias downward on the tape. Then a similar bias in head Design 1 may result in test results that declare that head Design 1 is superior to head Design 2 (*e.g.* better signal/noise, tracking) even though the opposite may be true.

Present dangers

For the engineer and scientist interested in good measurement understanding and control, a host of dangers await. These include:

(1) The summary of a distribution by an absolute statement of tolerance.

(2) Technology that removes people from individual measurements, including fast personal computers, spreadsheets, and databases.

(3) Belief in the sanctity of computer output.

The summary of a distribution by an absolute statement of tolerance is a natural attempt to reduce the description of a complex function shape to a simple statement—but it is often inadequate. A typical example is a dimensional tolerance on a part. The distribution of cam torque may be bimodal (double-peaked) and truncated, as shown in Fig. 1, yet the cam may be advertised as having a torque of 5 ± 0.1 dyne-cm, based on the simple computation: sample arithmetic mean = 5, sample standard deviation = 0.1. The stated interval, 5 ± 0.1, would contain about 68 percent of the torque measurements if the measurements were distributed according to the Gaussian distribution. But for the actual distribution, the statement 5 ± 0.1 is simply wrong. The interval 5 ± 0.1 contains, in this case, about 53 percent—not 68 percent—of the torque measurements. More significantly, 5 ± 0.1 is misleading. It does not communicate the peculiar and important shape of the cam torque distribution. The practical consequence of a shape like this is that the cams should probably be segregated into two groups—each with about half the variation.

Similarly, manufacturers of measurement equipment commonly misstate measurement accuracy. Measurements have a distribution, whether taken over the short term or over the long term. Measurement system performance is *not* properly characterized by simple ± 1, 2, or 3 standard deviations from a mean. It is properly characterized by careful statement of the

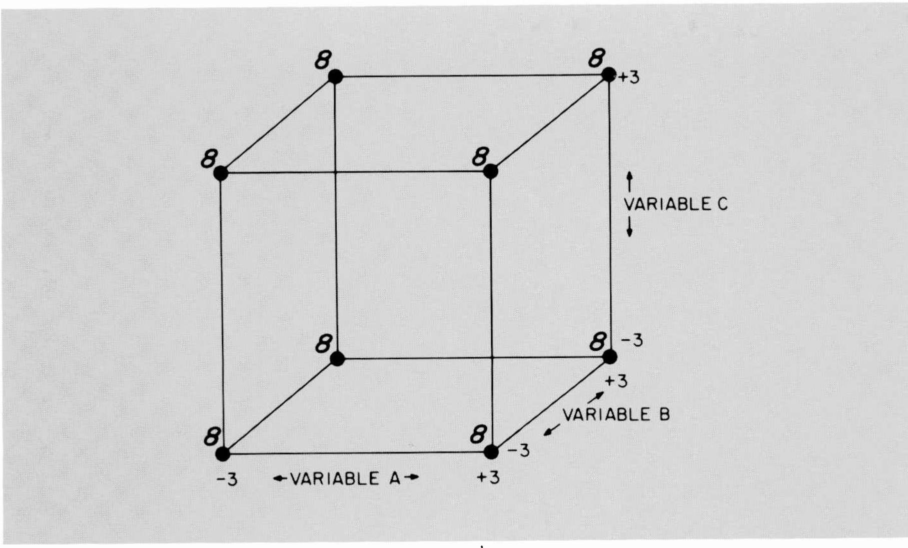

Fig. 2. *Graphical representation of the 2^3 factorial experiment design used to estimate the effect of A, B, and C on performance measure P. As indicated, eight units were to be built with each of the eight possible +3 combinations of settings of A, B, and C.*

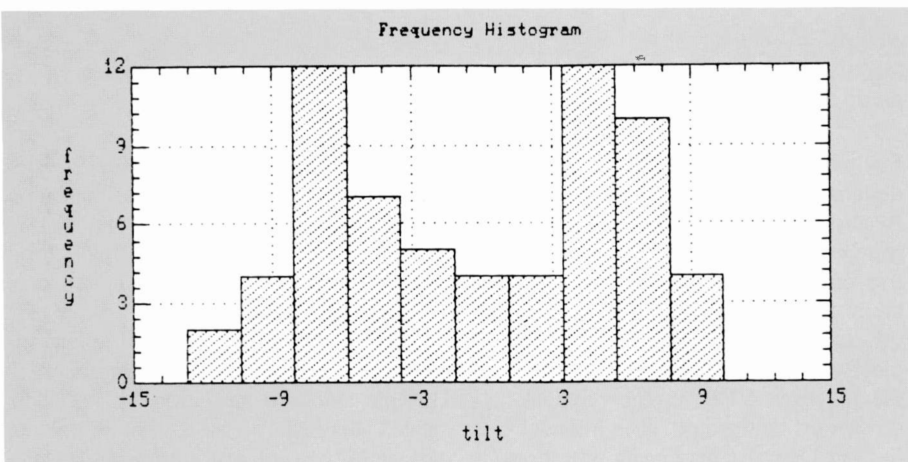

Fig. 3. *Actual distribution, in histogram form, of control variable A. Variable A was supposedly set to* +3, but post-experiment measurements gave readings very different than those two values.

measurement conditions, a set of percentile levels—*e.g.* 1 percent < -3, 5 percent < -2.5, 10 percent < -2, etc., and perhaps a description of the distributional form. Therefore, a fairly comprehensive study is required to properly characterize measurement performance.

Another prevalent and growing danger is the use of sophisticated electrical hardware (such as personal computers and customized CPU+ROM systems) and software (such as spreadsheets and databases) that remove people from individual measurements and observation of the measurement process. This is dangerous because the test for "reasonableness" can be lost.

Integrity in using measurement systems starts with the question, "Are these measurements reasonable?" A negative weight, a current of 5 amperes in a thin filament, a vacuum of 10^{-15} Torr in a cathode ray tube are all silly—but only as judged by a person who is paying attention to whether the measurements make sense. More computers, more spreadsheets, and more databases make it easier and easier to stuff wrong data away, tabulate them, and analyze them—without ever knowing that they are wrong. Fortunately, there is a growing and evolving selection of statistical analysis software available for microcomputers. Many of these packages let the user plot the data this way and that, and check for reasonableness.

A problem that has always gone hand-in-hand with using computers is a variation on an old myth, "If you saw it in print, it must be true." Many people believe that if they see data in a nicely formatted, nicely printed computer printout, then they must be true. Perhaps more subtle is the pressure to believe data appearing somewhere in the middle of a very large computer printout. It is as if by calling into question a part of the printout, you are calling into question the truthfulness of the whole thing, and that printout represents a lot of work! But there is no inherent sanctity to computer output. The old warning of "Beware GIGO (Garbage In-Garbage Out)" is not strong enough. There are very many ways of putting in good data and having the computers spit out bad results.

RCA case studies

Three case studies are presented here to demonstrate the use of some techniques of statistical metrology. Each case study is taken from a manufacturing/support project on which the author worked within RCA. Additionally, readers can consider Philip Stein's article on ATE in this issue to be a case study. The nitty-gritty technical details are inappropriate for an article of this type; an attempt is made to build conceptual understanding, and to encourage readers to apply these concepts to their own situation.

Plant Z

One of the more important strategies employed in the effort to better understand a complex manufacturing process is to design and run deliberate, off-line experiments. This is in contrast to a passive approach, where we would pore over and try to analyze data taken from day-to-day production, hoping that patterns and relationships might emerge.

Such deliberate experimentation was done at RCA's Plant Z (unnamed for proprietary reasons). We were interested in the effect of three "control variables," *A*, *B*, and *C*, on a measure of performance, *P*, especially because values of *P* that were too low comprised the chief source of rejects. We designed an experiment with each variable set to ± 3 (see Fig. 2).[2] Rather than sample production for units that had variable settings at the appropriate levels, we decided to specially build units at those levels. We thought that as these three control variables varied in normal product, some other (perhaps more important) variables might be subject to change, and affect *P*. (Such a variable could, in fact, constrain the "control variables" that we had identified.) We built the experimental units on the same fixtures as ordinary production, so as to produce units otherwise typical of ordinary product. The only difference was that the three control variables on the units were set to ±3 as the units were produced.

Unfortunately, things were not what they seemed to be. Figure 3 shows the after-the-fact measurements of one of the three control variables. The measurements depart considerably from ±3, and the same is true of the other measurements obtained. What caused this? Each variable was not simply measured to be ±3 on each special unit; it was deliberately set to be ±3. Of course, such deliberate action did not and does not, in general, guarantee the desired result. The possible reasons that the after-the-fact measurements were not found to be ±3 are thus two-fold: (a) the measurement system used in the setting procedure was inaccurate, so the variables were not actually set to ±3; (b) the after-the-fact measurement system was inaccurate. There was evidence that (a) was the problem.

Strategy and technique

We were using a linear model to explain *P*. For example,

$P =$ constant $+ a$ (variable A) $+ b$ (variable B) $+ c$ (*variable* C)

was the simplest form of our model. The metrological problem we experienced is called the "errors in X" problem (X is the matrix of control variable settings), and it has an undeservedly small place in the statistical literature.[3] Our strategy for dealing with it was as follows:

(1) Have many replicates (we had eight units built and measured at each of the $2^3 = 8$ combinations of ±3).

(2) Do regression analysis of the results, rather than standard analysis of variance estimates of the coefficients (which assumes no errors in X). For the regression analysis, use the best measurements of the control variables available, and estimate sensitivity to the errors in the control variable measurements.

(3) Do measurement capability studies of the measurement system used while setting the control variables, and of the measurement system used after-the-fact. We actually never took this advised step, because there was such strong belief that the former measurement system was at fault.

Despite the metrological problems, which put the usefulness of the entire experiment at risk, we were able to make important discoveries of the effects of *A*, *B*, and *C* on *P*. These discoveries led to manufacturing process adjustments that immediately caused a threefold reduction in defects that had been due to inadequate levels of *P*. Had we not been aware of the metrological considerations (including the need to measure variables that had been nominally set to known values), and had we not followed the strategy described, we would have learned nothing from the experiment, or (worse) come to the wrong conclusions.

Computer display monitors

For computer display monitors, "quality is key." This quality has to be beyond that required for entertainment displays. The users of a computer display monitor are likely to look at the monitor for up to six or seven hours a day at short range and will be expecting relatively high resolution on a nearly static image. In each of these respects, they will be more demanding than the user of an entertainment unit who typically looks at the display for at most a few hours each day, at a greater relative distance, will not consciously examine the display for resolution, and will be watching a dynamic image.

One measure of quality of color display is the size of misconvergence errors among the three primary colors: red, green, and blue. All color monitors from all manufacturers have misconvergence errors. Ongoing manufacturing process improvement is always directed toward reducing misconvergence and other errors. The author was involved in a task force that (among other things) analyzed misconvergence errors.

Our natural concern when we first started to obtain misconvergence data was the reliability of the data. The data were obtained using Convergence Measurement Equipment (CME) developed at RCA Laboratories and in the VCDD plant at Lancaster, Pa. The CME is microprocessor-based, and the algorithm it uses to measure misconvergence has a certain amount of self-checking to reduce measurement error. However, the misconvergence errors could conceivably depend on the CME setup procedure. These errors due to setup of the measurement system would be real, and would be appropriately measured by the CME, but they are not of interest to us. We wanted to study the performance of the computer display assemblies, not the performance of a measurement system that employed the CME.

> **Summary of results of 700 independent evaluation reports of measurement equipment supplied from 12 different countries**
>
> Proportion of all equipment deemed unsatisfactory in various categories:
>
> **1.** Outside manufacturers' specifications under manufacturer-supplied "ideal" reference conditions: 27 percent.
>
> **2.** Outside manufacturers' specifications under simulated (manufacturer-approved) environmental conditions: 64 percent.
>
> Note that nearly two thirds of the measurement equipment did not perform to specification under conditions agreed to by the manufacturer. In other words, the measurement systems were inadequate for the specifications, or (equivalently) the specifications were too narrow for the measurement system.
>
> These evaluations were performed by independent standards bureaus under the SIRA Instrument Evaluation Panel (SIREP).

Strategy and technique

The CME is in great demand and is a one-of-a-kind piece of equipment. Moreover, obtaining misconvergence data from it is very time consuming. Nonetheless, we chose to pay a price of fewer data on the various assemblies in which we were interested in order to get some nominally "redundant" data. We thought that our unfamiliarity with the CME measurement system warranted the price.

We decided to get two types of nominally redundant data: (1) short-term measurement variability (STMV) data, and (2) long-term measurement variability (LTMV) data. STMV data were obtained from one assembly measured repeatedly on the CME

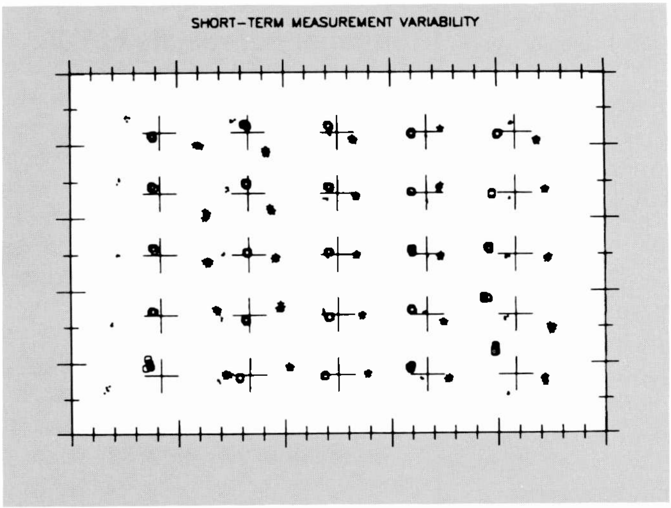

Fig. 4a. Short term measurement variability (STMV) in misconvergence is shown in this exaggerated-error plot. The "plus signs" indicate reference points on the face of the tube, and are about one inch apart. The misconvergence symbols are on a much exaggerated scale.

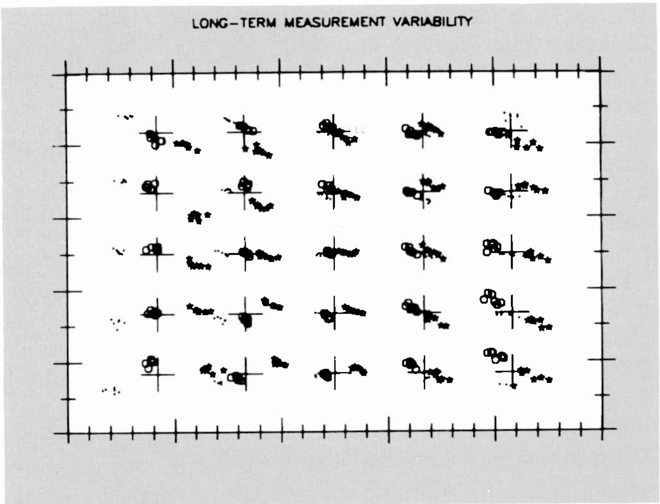

Fig. 4b. Long term measurement variability (LTMV) in misconvergence, using the same exaggeration as in Fig. 4a. Whereas the former figure showed great consistency in repeatedly measuring the same assembly, this figure shows the disturbing effect of setup. We decided that this level of measurement system variability was too great to remain uncorrected.

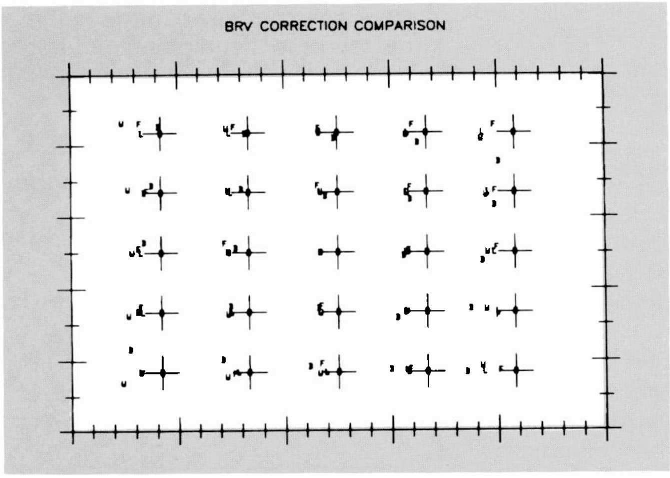

Fig. 5. Blue-to-red vertical line misconvergence error of 0.2 millimeters in the center "induces" error elsewhere on the display. These amounts are estimated by multiplying 0.2 times the candidate correction factors computed by regression for the three empirical datasets (L, F, and B), and obtained by the Wojtowicz computer simulation (W). These four candidates were evaluated and selected from for our final set of correction factors.

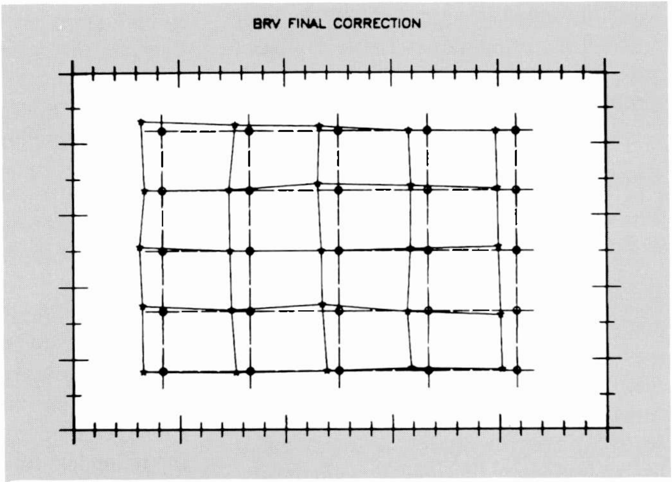

Fig. 6. The final set of correction factors selected for blue-to-red, vertical-line misconvergence in the center. Note the slight deviations from rectangularity. Similar sets were obtained for horizontal-line misconvergence, and for the other color separations—in both the vertical and horizontal directions.

with all setup conditions preserved: the assembly was left in the CME fixture, the CME components were left in place, and the operating conditions of the CME and assembly (including focus voltage) were left the same from measurement cycle to measurement cycle. LTMV data were obtained from the same assembly as the STMV data, but the full setup procedure was performed each time, and the measurements were obtained on different days, interspersed with measurements on other assemblies. This allowed for change in the placement of the assembly in the fixture, change in CME component configuration, and change in operating conditions, including focus voltage. In all cases, the focus voltage was set by the user of the CME so as to achieve optimum spot focus at the upper left corner of the display. The (discrete) beam bender, which is also sometimes used to affect convergence, had been locked in place during production of these assemblies, and it was not adjusted.

We collected STMV and LTMV data because we anticipated how we would interpret them: STMV data would represent the "ultimate capability" of the CME, short of algorithm or hardware modification. LTMV data would represent the actual measurement capability of the measurement system involving the CME. It is the actual measurement capability with which we have to live. Alternatively, if we saw that the LTMV was much greater than the STMV, something having to do with the measurement process description could potentially be made more consistent. Then we would be able to obtain closer-to-ultimate capability, without having to redesign CME software or hardware. This is a standard use of a mea-

Variance Components As Part Of Successive Measurement Capability Studies Of The Small Parts Measurement System

M.C.S Number	(a) Setup Variability in Microns Squared (proportion of LTMV)	(b) Ultimate Capability =STMV in Microns squared (proportion of LTMV)	Ratio of (a) to (b)	Area(s) Where Effort Should Thus Be Focused
1	1.1593 (89%)	.1173 (11%)	8	Setup
2	.1131 (61%)	.0712 (39%)	1.6	Either
4	.0501 (80%)	.0145 (20%)	4	Setup
6	.0023 (22%)	.0060 (78%)	.3	Ultimate Capability

Fig. 7. *Variance components from successive measurement capability studies of the small parts measurement system. This shows, in time order, how the variability due to setup, and variability representing ultimate capability, were reduced. The ratio of the variability estimates indicates where engineering effort might be most profitably focused.*

surement capability study such as that which we were performing.

Figures 4a and 4b show the considerably greater variability of the LTMV data compared with the STMV data. We did not know what part of the measurement process was introducing the variability, but we did notice that it was somewhat systematic. First of all, although the CME setup procedure was supposed to ensure that the center would be converged (zero misconvergence), it was not converged to within the ultimate CME measurement capability. That is, the bias away from zero for both sets of data could not be explained away by the variability in the STMV data; the bias was real. Not only could we not ignore the bias, but a pattern was observed. When, for example, blue-to-red misconvergence was to the right and down at the center of the display, it tended to be similarly biased at the other positions on the display.

We decided to take a nonstandard approach in response to discovering a large LTMV/STMV difference—one that would exploit the systematic nature of the misconvergence errors. Rather than attempt to identify and then reduce or eliminate the source(s) of variability within the measurement process description, we decided to let measured center misconvergence serve as a proxy variable for the actual cause of center misconvergence. This is analogous to using the amount of stretch of a spring in a spring scale as a proxy for weight. In this case, we hypothesized that perhaps some variation in focus voltage or unintentional bumping of the beam bender during CME setup might have caused the change in misconvergence, but we really did not care what it was that caused the change, as long as we could remove most of the change.

We obtained four sets of data with the CME measurement system to carry out our strategy of using a proxy to help correct the data: long-term variability ("L") data (which we already had), "F" data taken repeatedly on one assembly where focus voltage was deliberately changed before each set of measurements, "B" data taken repeatedly on one assembly where the beam bender was deliberately but randomly (slightly) adjusted, and "W" data from a computer simulation study done by P. J. Wojtowicz. On each dataset but the last we did a simple linear regression on a per-color-separation and per-location basis of horizontal and vertical misconvergence as a function of the proxies: center horizontal and center vertical misconvergence. A sample of the results is shown in Fig. 5. As can be seen, the correction factors obtained from the regression did not all agree. We used criteria such as symmetry, regularity, and physical sensibility of any given set of four candidate correction factors to select our final correction factors. One of our selections is shown in Fig. 6. All of our correction factors were later cross-validated on other assemblies.

The "moral" of this case study is that we deliberately checked measurement capability, both long term and short term. We were then able to concentrate our attention on setup problems, and use defendable (not *ad hoc*), effective techniques to characterize the measurement error observed, and then remove it. We did this without even identifying the exact nature or cause of the variability in the measurement process. This data correction algorithm is now routinely used for CME data.

Measuring small parts

John Beltz and Bob Covey at RCA Laboratories were working, recently, to provide complex instrumentation for one of RCA's plants. The plant needed equipment that could be used to obtain measurements of very small parts. The precision desired was in the $5 \mu m$ range, so the wavelength of light was an inherent limitation. The system they developed was based on solid-state imaging, a microprocessor, and sophisticated software. The level of sophistication of the software and power of the microprocessor were such that measurements of (x, y) positions of edges of the part at many different locations could be combined by multiple regression analyses. The result was an implicit length "measurement" of a section of a part never actually observed by the imager.

Strategy and technique

In the final refinement stage of the measurement system, the gross repeatability of the system was poorer than Beltz and Covey thought should be attainable. Resisting the natural temptation to twiddle indefinitely with algorithm variations and parameters, they decided to seek a more systematic approach. With the aid of Philip Stein and Steve Miller of RCA Laboratories, they mapped out a fully nested exper-

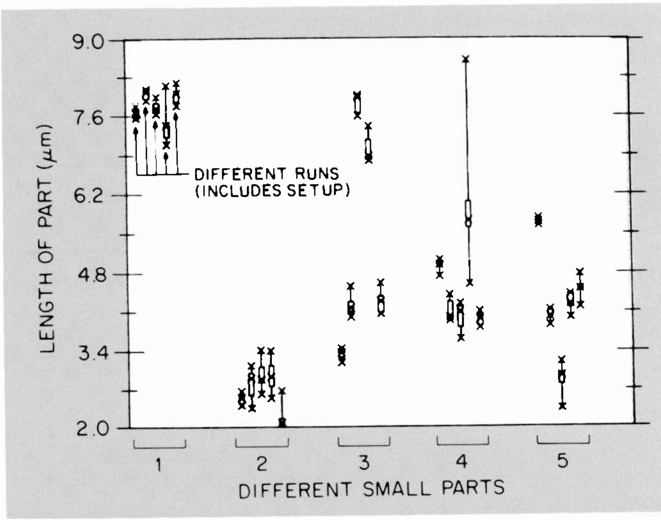

Fig. 8.a Graphical ANOVA (ANalysis Of VAriance) qualitatively conveys the same information as variance components analysis. The boxplots can be read as follows: the box represents the central 50 percent of the data, the X in the box is the median, and the "whiskers" go out to the minimum and the maximum of that set of data.

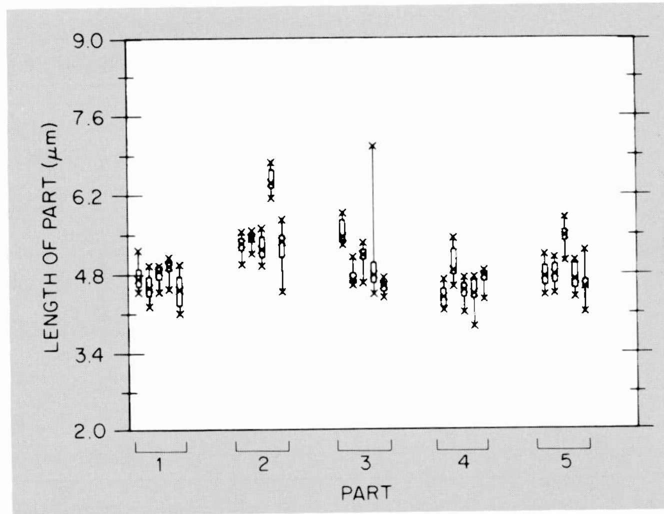

Fig. 8b. The impact of the cleaning station was to reduce variability from run to run. This reduces the primary source of setup variability: dirt on the small parts. Dirt was still present, but Beltz and Covey decided to extrapolate better, "robustify" the algorithm to be less sensitive to dirt, and make some other minor changes to improve ultimate capability.

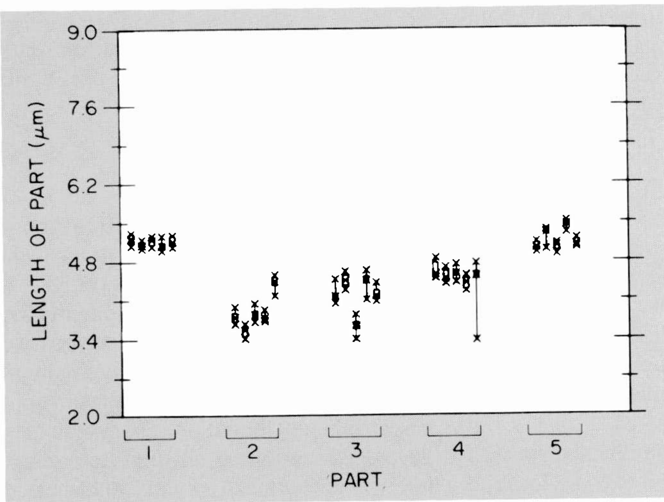

Fig. 8c. *Multimate capability was improved by a factor of five by better extrapolation, regression robustification, etc. More work was now needed on the cleaning station to further reduce variability due to setup (the small parts were still too dirty).*

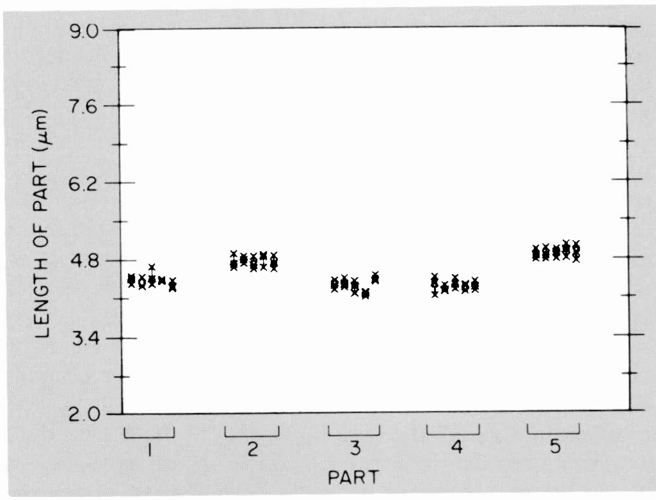

Fig. 8d. The best performance of the small parts measurement system, by far, is seen subsequent to the improvement in cleaning station (and other minor changes). Setup variability was reduced by a factor of 25, resulting in a (final) total measurement system standard deviation of

$$\sqrt{(.0023 + 00.60)} = 0.09 \text{ microns}$$

with unimodal and Gaussian-like error.

iment design for a measurement capability study of the small parts measurement system.[4] The design was:

(1) Select five "representative" small parts.
(2) Place the first one in the measurement equipment fixture, all the while following the usual measurement system process description.
(3) Compute the measurement of interest.
(4) Measure it again four more times, without disturbing the small part in any way.

Using this series of five measurements, we could estimate the STMV for the measurement system. We then:

(5) Removed the first small part from the equipment.
(6) Set up the second small part in the equipment.
(7) Measured this part five times in rapid succession, and so on.

After each of the small parts had been measured similarly, five times, we again set up one of the five small parts in the equipment, and it was measured rapidly five more times. Similarly, we remeasured the other four parts. Then we quintuple-measured all five small parts for three more rounds. This made a total of five rounds of measurements, each involving the same five small parts, each small part measured five times in rapid succession for each round. We were able to estimate the LTMV for the measurement system from the differences in average measurement value obtained for each rapid succession quintuple. The STMV was estimated from the differences of individual measurements from quintuple averages. Similar nested designs were used later to help guide the efforts of Beltz and Covey. Figure 8a shows the result of the first measurement capability experiment study.

What was gained by following this protocol? First, by testing five small parts in parallel we were able to pool results on several small parts rather than risk jumping to conclusions on the basis of results from just one small part. This is merely common sense. More subtle and powerful was the ability, using this nested design, to estimate variance components—by which we partitioned the total variability observed into different explanatory sources. We found that 71 percent of the total variability was due to differences in small parts. This variation was innocuous. The parts *do* vary. Out of the remaining variability, variance components analysis "extracted" how much was due to setup (89 percent), and how much was due to ultimate STMV capability (11 percent). Thus, eight times as much measurement variability was due to effects of setup than was due to the performance of the equipment itself (see Fig. 7), though even that performance was worse than desired. Figure 8a illustrates this graphically.[5] Not only was there considerable variation of measurement of a part when it remained in the equipment, but with each setup entirely different measurements often were obtained.

It turned out that when the small parts were handled, even when handled carefully, they got dirty. "Dirty" on a dimensional scale of micrometers means that dust particles looked (to the imager) like boulders. Beltz and Covey immediately sought ways to clean the small part as a step of the measurement system—just prior to taking images of the small part from which to compute a measurement. Happily, although finding a suitable cleaning strategy turned out to be far more difficult than anticipated, the success in their endeavors (and in implementing some other minor modifications) can be seen in Fig. 8b. This figure shows how the variability due to setup was drastically reduced by Beltz and Covey. Note how much better aligned the boxes are in each clump representing a single small part.

Beltz and Covey were also able to improve the ultimate measurement capability by, among other things, switching from an extreme extrapolation method using ordinary least squares to a neighborhood extrapolation using a robust least squares.[6] Figure 8c shows the results of this improvement in ultimate measurement capability. Note how much shorter the boxes are.

With more acceptable ultimate capability, setup variability remained the primary source of measurement system variability. Beltz and Covey therefore focused their efforts primarily on improving their cleaning station. Figure 8d shows how much more consistent the small parts measurement system became—an entirely different measurement capability than was originally achieved, thanks in part to the metrological studies.

Conclusions

Measurements enter all phases of work and life. However, hardly any of us ever measure measurements. Problems with measurements are commonly thought to belong to spectrometrists who try to identify minute chemical quantities, or the operators in Purchased Material Inspection (PMI) who inspect incoming material. Actually, problems with measurements are epidemic. They cloud understanding, and they reduce quality and productivity in RCA's plants—and in the rest of RCA. We can take safeguards by:

(1) Recognizing that measurements come from measurement systems.

(2) Deliberately conducting measurement capability studies according to statistically designed experiments.

(3) Analyzing the data correctly afterwards.

Such thorough and careful protocols for the use of measurement systems, if widely instituted, could save RCA millions of dollars per year.

Acknowledgments

Philip Stein, a full-time metrologist at RCA Laboratories, first piqued my interest in metrology, and did some of the work described in the case studies. All of the work described in the article was jointly done with Russell Barton, John Beltz, Bob Covey, Bert Gunter, and Peter Wojtowicz of RCA Laboratories, and with Kathy Conoley-Busald, Bob Hagmann, Dave Hutchins, Mike Mindell, Mike Renfro, and Russell Willner at various RCA divisions.

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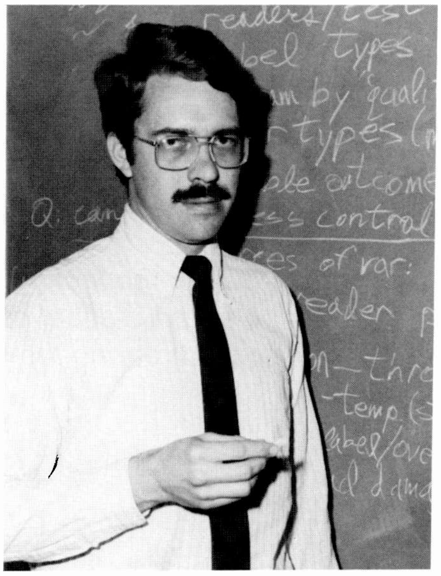

David E. Coleman has more than eleven years' experience in developing mathematical software. He received his BA in Applied Mathematics/Computer Science from Harvard University, and his MS in Statistics from Princeton University. Since then he has done mathematical modeling of nuclear fusion load capacity for the Federal Department of Energy. Since becoming a Member of the Technical Staff at RCA Laboratories in 1981, he has designed statistical software, participated in leading statistical process control projects, and codeveloped new statistical methodology for VCDD.

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Philip Stein | Larry Turpin | Brian Whitcomb

Statistical control of television chassis ATE

We have shown, in the factory and here in print, that measurement science and statistical control of measurements can be used effectively to reduce the differences among a group of testers.

RCA's television factories use highly integrated automatic test equipment (ATE) to align and test television chassis. The continuous operation of this equipment and its ongoing calibration are crucial to maintaining production. This paper describes a project to place a group of similar testers at the Juarez factory under central measurement control. This ensures proper calibration, and means that each tester will operate so that it is consistent with all others of its type.

The approach utilizes a novel application of statistical control techniques such as those advocated by W. E. Deming and others for the control of factory processes.

Abstract: *RCA's television factories use highly integrated automatic test equipment (ATE) to align and test television chassis. The continuous operation of this equipment and its ongoing calibration are crucial to maintaining production. This paper describes a project to place a group of similar testers at the Juarez factory under central measurement control. This ensures proper calibration, and means that each tester will operate so that it is consistent with all others of its type.*

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A group of chassis was selected to be measured once or twice per day. Measuring the ability of testers to consistently measure this standard group of chassis indicates tester trends, which are then automatically corrected if necessary.

We call this standard group *correction chassis*, and the process is called ATE correction. The process of isolating correction chassis data from the product test data stream, analyzing these special data to determine the state of calibration of the testers, developing correction factors, and applying these factors to ongoing measurement of product is all carried out by computers.

What problems are we addressing?

Any measurement process, manual or automatic, cannot exist in an information vacuum. The process of comparing measurements made by one process or apparatus with those made to a presumably higher accuracy and precision is called calibration. Every measurement process is subject to two major sources of error, regardless of how well it was designed and maintained:

- Measurement bias, or drift. In this type of error, small changes in the internal standards of the measuring equipment add up over time to produce an offset, or difference, between today's measurement and one made previously.
- Random measurement noise. In this type of error, repeated measurements of the same object will vary, even if the object remains exactly the same. Some random noise is absolutely unavoidable. It is a fact of life and a natural property of the universe. In some cases, though, measurement processes are noisier than they have to be.

When two or more testers in a factory are testing the same product, it is an unavoidable, inherent fact that different testers will yield different answers. While the differences may be small, they may have a large effect on product accept/reject decisions when the product itself is near a specification boundary. When these differences are large enough to influence product decisions, it is necessary to control and minimize them. At the same time, it should also be possible to monitor the operation of the testers to indicate other faults as well as breakdowns. The process described here can do all of these things.

How can this be accomplished?

Several approaches to implementing this control have been proposed. The use of

Measurement capability study

It is a well-known fact that if you measure something twice on an ATE, you will get two different numbers. Is the difference significant? Do you accept the product thus tested, or do you reject it? One needs data to make some intelligent decisions.

The capability of the ATE measuring process was characterized to aid in answering these lingering questions. A *Measurement Capability Study* was performed. The questions answered by this study were:

- How much of the measurement difference can be assigned to the product being tested (TV chassis)?
- How much can be assigned to the ATE measurement system?
- How much to the test fixture contacts and interconnections?
- How much to the warm-up drift of the test chassis?

The process capability study consisted of five CTC121 chassis being tested repeatedly in random order. Each chassis was measured after a two-minute warm up, ten times in a row. The chassis was then removed from the test fixture and another was inserted. This was done once for each of five chassis in a random order; then the entire process was repeated eight times, yielding 400 complete test runs. The chassis were numbered 1 through 5. The random order was:

4	5	2	3	1
5	2	1	4	3
4	3	1	2	5
3	2	5	1	4
5	4	1	3	2
3	1	4	2	5
3	2	5	1	4
4	2	3	1	5

Each complete chassis test run consisted of 240 measurement results (test specifications). The raw data for each result were recorded for each chassis (240 X 400). The raw data were processed by several statistical techniques in an effort to determine the amount of measurement variability of the 240 parameters per chassis and to assign causes to each component of variability.

Linear regression was used to measure temperature drift and to remove the effect of that drift from the data. Variance component analysis was used to separate and assign causes of measurement variation. Blame could be partitioned among the unit under test, the test fixture, and the test instruments contained in the ATE.

Results from this measurement capability study indicate that for some tests, the measurement process has small errors with respect to the product's allowed specification range. Other measurements were noisier and were identified as candidates for improvement. The statistical analysis of the data from this designed experiment was used not only to point a finger at the offending variation, but often to give hardware and software engineers valuable insight into the reason for the variation, thus leading quickly to solutions.

statistical control was chosen because it did not require new hardware engineering and seemed simpler, but statistics is also the only way to achieve control over the entire measurement process, not just over some components of the test system.

Two alternate methods worth discussing are self-test and higher-echelon calibration. In self-test, standards are built into the ATE and are connected and measured under software control. Instruments are then automatically adjusted or corrected according to the results of self-test measurements. In higher-echelon calibration, standards are kept, either as components or whole assemblies, whose measurement values are well known and stable. These standards are then brought to each tester in turn and the instruments within each tester calibrated accordingly.

One difficulty of these approaches is that many of the tests in RCA's television chassis ATE are already measuring at the state of the art for signal/noise, speed, etc. It would therefore be necessary to extend the art even further in order to build self-test or higher-echelon standards.

The biggest drawback of both of these methods, however, is that they address only the test instruments, not the whole measuring process. Within an ATE, many circuits, switches, and connections are needed to connect between each test point on the unit under test and an instrument input or output. These additional circuits, switches, and connections can add both measurement bias and random noise, which are inherent parts of the process. A statistical approach measures not only data values, but also measures the noise itself. In this way, the entire measuring process is characterized and tested.

As an example, suppose a test pin that normally makes good contact to the underside of the unit under test becomes contaminated or corroded. In some cases, stray capacitance is enough to couple the test signal into the measuring circuit and allow the test to proceed. This might produce approximately the right measurement, but with additional noise. The result would be that good product will be occasionally rejected, but unless the rejects become very frequent, the tester might not be suspected. In this case, the statistical method will detect an *increase in measurement noise*, which would not be detected by a nonstatistical calibration scheme.

A second example demonstrates an added benefit of statistical monitoring of the measurement system: the ability to detect malfunctions that might otherwise go unnoticed. Suppose a buffered analog-to-digital converter broke during self-test or calibration in such a way that it retained its current reading and could not make new

ATE CORRECTION REPORT

DATE 23 JAN 1985
TIME 12·26·42

TEST NUMBER	TESTER OR CHASSIS	ERROR CONDITION	CONTROL INDICATOR	REFERENCE NUMBER	% CFACTOR APPLIED
1	T02	Slow Drift up	0 000	9 00	0
	C04	Drift up	0 000	15 00	47
2	T02	Extreme Shift Down	-5 217	-1000 00	-1
	T01	Extreme Shift Down	-4.743	-1000 00	-12
29	T03	None	-1 126	0 00	4
	C03	Slow Drift Down	-0 463	-1.00	50
30	T01	None	-0 810	0 00	0
	C03	Slow Drift Down	-0 129	-1 00	47
31	T01	Extreme Shift Up	3 669	1000.00	-6
	C01	None	0.808	0.00	50
33	T02	Large Shift up	2.832	100.00	20
	C04	None	0.374	0 00	43
35	T01	Extreme Shift Down	-5 502	-1000.00	32
	C05	None	-2.933	0.00	46
48	T01	Extreme Shift Down	-5 667	-1000.00	0
	C01	None	-1 477	0 00	50
62	T02	Become Noisy	2 117	2000.00	-2
	C04	None	1 137	0 00	48
63	T01	None	0.191	0.00	5
	C05	Slow Drift up	0 032	1.00	46
64	T02	Become Noisy	1 610	2000.00	-4

Fig. 1. *Sample of a typical report from the correction algorithm. Tests with no problems are not shown. The control indicator shows the number of standard deviations the current measurement is away from the average. The reference number shows which control charting rule has been violated.*

ones. It would pass a simple self-test because it was stuck on a reading of the internal standard and therefore would appear to be functioning properly. If the value of the self-test parameter was within the acceptable range for product testing (and it should be if the self-test is well designed), then the defect might never be detected. With the statistical approach, the *lack of measurement noise* would be detected by the calibration algorithm and reported as a failure.

What the system does

The basic operation of this correction scheme is very similar to a calibration process. Each day, or sometimes each shift, a correction chassis is measured on each tester. The data from each such correction run are sent by wire from the tester's computer to the factory information system (called FACTS in the Juarez television chassis plant). The calibration data are processed by the central computer and returned to each ATE as correction factors. The ATEs then apply the corrections to measurements made on all product as it is tested.

A report generator program is provided on the FACTS system to allow factory test engineers to follow the results of the calibrations and to receive reports of testers that are not in statistical control.

Looking under the hood

This process is not an ordinary calibration scheme. The chassis used as "standards" are not basically different from those being tested, so they are not inherently more stable or accurate. To use these ordinary chassis, we rely on the strong properties of numerical averages to help us out. Even though the value of any given measurement made on a standard chassis is no more accurate or stable than that from any production chassis, the long-term average of many repeated measurements *is* more stable. By using five chassis, and by measuring each chassis many times, we are able to use the long-term average *of the chassis averages*, thus giving us a powerful stabilizing effect. There is therefore no physical "standard;" rather there is an ongoing history residing in FACTS memory that is the "standard" for each measurement.

FACTS also keeps an ongoing history of the standard deviation, or measurement noise, for each tester and chassis. New measurements of the correction chassis are compared with the long-term averages. If the new measurements are very far from the average, or are much noisier or quieter than recent history indicates, the tester is considered to be "out of control," and this information is included in a printed report. Figure 1 is a page from one of these reports. The correction chassis can also drift or become defective, and the chassis' control history is used in exactly the same way, to indicate that our "standards" are working and are in control.

Each day, a test engineer measures one standard chassis on each of the three ATE testers on production line C1 in Juarez. A computer-generated list of random numbers indicates which chassis gets measured on which tester.

One regular ATE test checks for the presence of the normal under-chassis IF shield by looking to see if a test probe is grounded. Correction chassis have been modified to have a conductive area touched by that test probe that is not grounded but is pulled up to a unique positive voltage. The ATE is thereby notified that a standard chassis is in place. This causes several changes in the normal test procedure:

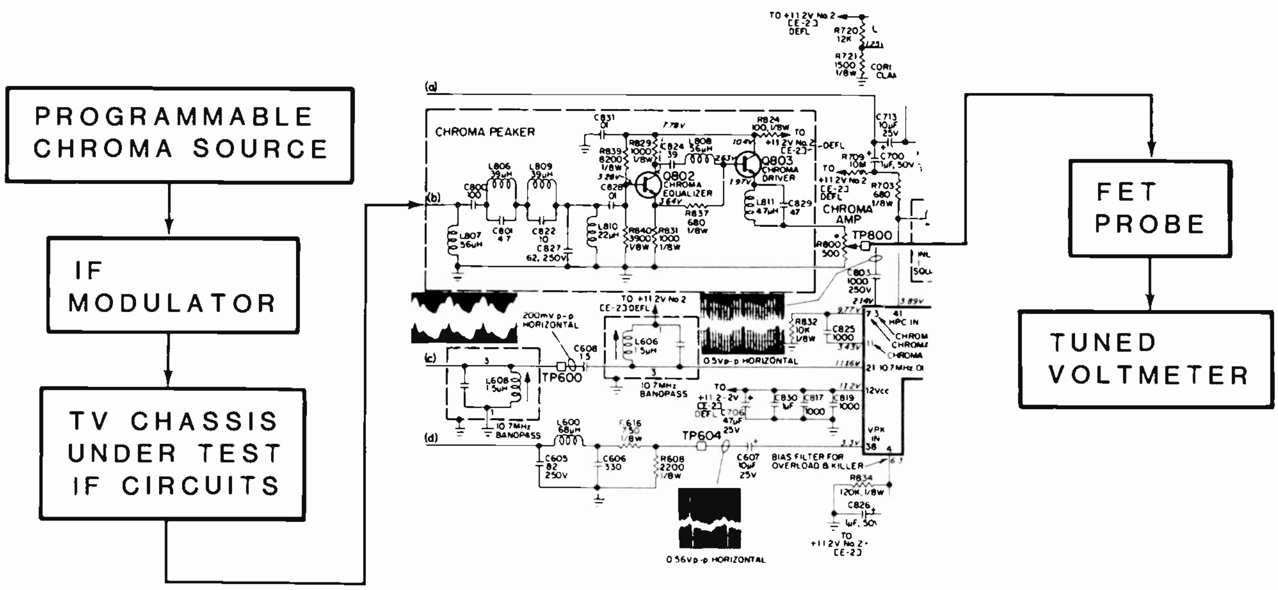
- Automatic alignment is suppressed.
- The test results are not rounded off as they usually are.
- The test results are not included in production summaries normally accumulated by the ATE and by FACTS.
- The results are sent to FACTS as soon as the tests are complete.

Within the FACTS computer, a real-time task has been "sleeping," and is awakened by the arrival of the data. If other standard chassis are run at the same time, their data are queued by FACTS until the task is ready to sleep again. The data are checked for correctness, the tester and chassis are identified, and the statistical algorithm (see box) is invoked. When the algorithm is finished, it leaves a unique array of correction factors to be transmitted back to each tester. This array is then "trimmed" in two ways. It is compared, test by test, to a maximum allowed correction and a minimum allowed correction. The maximum allowed correction is determined from the measurement capability study (see box) and other considerations.

We are using the measurement of peaker tilt as an example (see sidebar). The allowed product range is ±20 percent (peaker tilt is measured in percent), for a total range of 40 percent. Analysis of error sources shows that a test system might have a total measurement error from all system causes as large as ±0.5 tenths of that range, and the maximum allowed statistical correction is set to be about 1.5 tenths of that range. The minimum allowed correction provides a hysteresis or deadband to prevent the correction program from constantly "diddling" with the tester results in response to normal statistical noise in the correction process. The magnitude of this deadband is also determined from the measurement capability study.

All during this process, the correction factors have been kept within FACTS as

A typical test, and the attendant measurement statistics



The chroma peaker tilt test is the measure of the chassis' IF and chroma peaker circuit's frequency response. The response is measured just before the chroma signal enters the chroma/luma IC, where it is demodulated. The accompanying drawing shows a block diagram of the test setup, along with the schematic diagram of the circuit being tested. The circuit's gain is measured at five frequencies: 3.08 MHz, 3.33 MHz, 3.58 MHz, 3.83 MHz, and 4.08 MHz. Peaker tilt is calculated and reported as the ratio of the gains at 3.83 and 3.33 MHz, minus 1, and is expressed in percent.

A chroma source module is programmed to generate the chroma at the specified frequencies and to drive an IF modulator. The error of this chroma source for tilt is directly proportional to any error in the waveform as measured at the output of the chroma peaker circuit. This error would be expected to be less than one-quarter of one percent due to drift with time.

The chroma waveform from the chroma source drives an IF modulator and is then applied to the IF input (link cable from the tuner) of the chassis.

The IF modulators are not flat in frequency response and can change with time and temperature. Modulator response is a first-order error in the waveform at the chassis chroma peaker output. IF modulators vary from test system to test system. Attempts to realign IF modulators for absolute chroma flatness can create larger errors in the lower-frequency video response, where accuracy is also desired.

The ±0.5-dB specification on total modulator tilt can therefore introduce a one-percent tilt from test system to test system over the chroma frequency range. Because the chassis IF circuit is under automatic gain control, amplitude errors of the modulated test signal are not significant.

We now have a signal with expected error applied to the unit under test and available at the chroma peaker output. This is shown in the accompanying diagram.

Now consider measurement error. The chroma peaker output is high-impedance, and measurement loading exists at TP800. From test system to test system this loading is characterized and should vary only slightly (less than one-quarter of one percent).

The measurement path contains a module for gain and multiplexing as well as the measurement module that converts the chroma waveform amplitude to a proportional dc voltage, much like a selective-level voltmeter or a spectrum analyzer. The dc voltage is then converted by an analog-to-digital converter. Any tilt or bandwidth error from test system to test system due to time drift, temperature change, or module replacement directly affects the error of the test.

This measurement error could be as great as 1.5 percent if rigorous calibration is not followed over the life of the test equipment.

The limits for chroma peaker tilt on the CTC131 chassis are ±20 percent; any tilt greater than this would indicate incorrect or defective components. A measurement error of 3 percent accumulated from all system causes from test system to test system is an obvious concern. Hardware attempts to correct this would require offsetting the error, which may be moving, with constant recalibration.

RESPONSE VARIABLE: RAW

SOURCE OF VARIATION	SUM OF SQUARES	D.F.	MEAN SQUARE	F-RATIO
MAIN EFFECTS	1248.9388	6	208.15646	60.816857
TESTER	611.89697	2	305.94849	89.388651
CHASSIS	539.14342	4	134.78586	39.380243
2-FACTOR INTERACTIONS	151.52486	8	18.940607	5.5338575
TESTER CHASSIS	151.52486	8	18.940607	5.5338575
RESIDUAL	366.22645	107	3.4226771	
TOTAL (CORR.)	1766.6901	121		

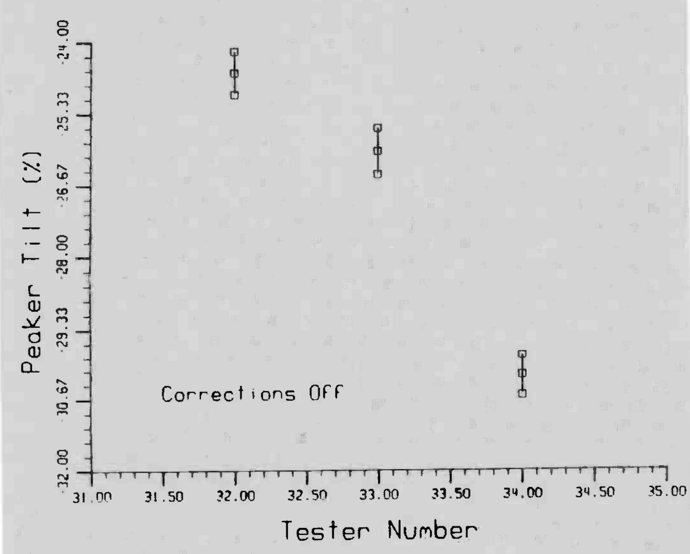


Fig. 2. *Data from effectiveness study, before correction. The table is from an unbalanced two-way analysis of variance (ANOVA). The graph shows the mean value of peaker tilt for each tester, with a 95-percent confidence interval.*

RESPONSE VARIABLE: CORRECTED

SOURCE OF VARIATION	SUM OF SQUARES	D.F.	MEAN SQUARE	F-RATIO
MAIN EFFECTS	539.51524	6	89.919206	17.894883
TESTER	55.570645	2	27.785323	5.5295761
CHASSIS	455.54856	4	113.88722	22.664773
2-FACTOR INTERACTIONS	192.31658	8	24.039573	4.7841319
TESTER CHASSIS	192.31658	8	24.039573	4.7841319
RESIDUAL	537.65957	107	5.0248558	
TOTAL (CORR.)	1269.4914	121		

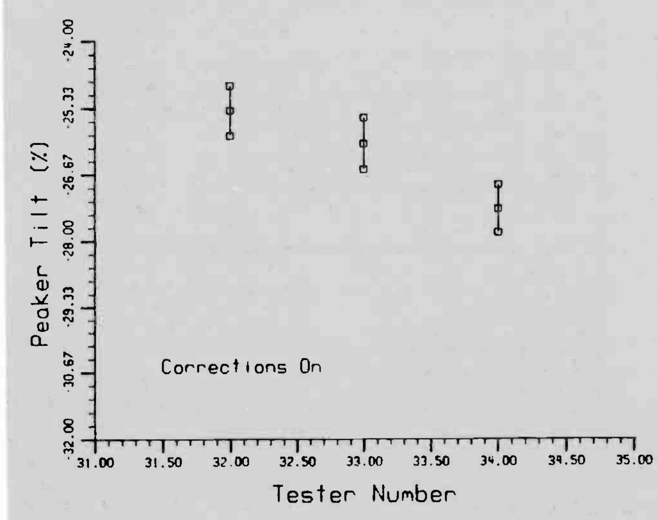


Fig. 3. *Data from effectiveness study, after correction. Note the decrease in the F ratio for TESTER, although the tester differences are still significant. Note on the graph that the means are much closer to each other.*

additive constants. Some tests, however, require that the correction factors *multiply* the test results. Those factors that are applied by multiplication are converted at this time, and then the entire table of factors, along with the information as to whether each is additive or multiplicative, is sent back to the appropriate ATE by FACTS. Tests that are not to be corrected are sent additive factors of +0.0.

Correction is supported by several other software features in the ATE. An engineer can turn the wholesale application of correction factors on or off, display the factor for any given test, send a message to FACTS about system status, and print out a list of all factors currently loaded. When a tester is first powered on, or when a new ATE program is loaded from floppy disc, the software sends a special message to FACTS requesting a new download of the current correction factors. Production can continue at this time, and corrections will not be applied until the download is finished. This enables ATEs to support production even if FACTS is unable to service a request.

Results

The program had only been in use for a few weeks when this report was written. Nevertheless, many studies of effectiveness were conducted before the system was turned on. The results reported here are from both effectiveness studies and real online experience.

Effectiveness studies

Before the system was placed into actual use, many months of data were taken on the correction chassis' history. Several versions of the control algorithms were tried and tuned, but the correction factors were not transmitted to the factory floor. During this time, a simple but powerful test of effectiveness was developed that materially aided the tuning process.

Taking the raw data from a day's correction chassis run as a proxy for actual production, we corrected the chassis readings according to the correction factors calculated from the previous day's data. The correction chassis, as run, are just like ordinary ones. We corrected those data using measurements that had not yet "seen" that day's runs and had not included them in the history. This was an identical measurement environment to the one in which we expected to run production chassis every day.

Figures 2 and 3 show the results of an analysis of such an effectiveness study. For the purposes of demonstration here, we have shown data from test 51, peaker tilt. The measurement details and error analysis of this test are shown in the accompanying box. Figure 2 shows the analysis of raw data. An unbalanced two-way analysis of variance procedure was run, using chassis and tester as the independent variables. The figure shows the ANOVA table, followed by an I-bar graph of the means by tester surrounded by a 95-percent con-

Tester control algorithm

The underlying principle of operation of the correction system is embodied in the control algorithm carried out by the FACTS computer. The computer program is set up to treat each of the 240 possible tests separately, so here we will talk about what happens for any one test.

There is a group of correction chassis, now numbering five. These chassis are measured by different testers according to a random sequence, and each of the three testers sees at least one chassis every day. The calibration value for each test is embodied in a long-term exponentially weighted moving average (EWMA) of that test as measured on all five standard chassis, and a test history is maintained by the computer, which contains the last 30 measurement values and the last 30 standard deviations.

When a new measurement arrives from the factory floor, the chassis and tester are known to the algorithm. The EWMA for that *chassis* is subtracted from the measurement, which yields, as a difference, a first estimate for a *tester* offset (or error).

What does this mean? If the chassis did not drift at all, but was instead some kind of perfect standard, any difference between the measured value and the expected standard value would thus be due to an error made by the tester. Since the chassis is not perfect, we use the chassis EWMA as the best estimate of the true chassis value. The tester error thus calculated is not perfect either, but it is now just our first estimate of tester error.

How good is this first estimate? We compare it with the *tester* EWMA, our best long-term estimate of tester error. This comparison is done with a simple statistical test; how many standard deviations away from the tester EWMA is our new tester value? If the new tester value is statistically close to the tester EWMA, it is included in that EWMA and in the history for that tester, and the algorithm proceeds. Let's follow this path for now. We now have a new best estimate for the tester offset. It's not exactly equal to the most recent measurement, however, since the history of past measurements has been included.

We therefore are left with a residual error, the difference between the current measured offset and the current best estimate of the offset. This difference is then assumed to be due to a change in the *chassis!*

We now turn around and do the same maneuver to the chassis data. The new value for chassis error is compared to the chassis EWMA, and if it is statistically close, it is included in the chassis history. This procedure could be repeated more times, but in fact it stops here.

What happens if either the tester offset or the chassis error is *not* statistically close to its respective EWMA? These data are included in the history anyway, but may be moved closer to the EWMA before being included so as not to have their full impact on the history. At the same time, an entry is made in a journal file indicating the unusual condition. This will later be made into a printed report (see main article, Fig. 1), which can be used by a test engineer to spot tester troubles (perhaps before they affect production), or troubles with one of the "standard" chassis.

fidence interval. The figure captions provide a brief explanation of how to interpret the analysis.

In Fig. 3, we again perform the unbalanced two-way ANOVA and look at tester means, only this time with the corrections turned on. The differences between the testers have been greatly reduced, although the differences are still statistically significant.

Online data

Figure 4 has three curves, one for each tester, similar to daily Juarez production data with corrections turned off. The curves are estimates of the underlying *chassis* distributions, and if the testers were unbiased, the three curves would be the same. Figure 5 shows data similar to those found in production with corrections turned on. It is easy to see that roughly the same level of improvement was made to the tester results in production as was done during the effectiveness studies. In this case, of course, applying the corrections would affect the reporting of chassis as having passed or failed the ATE tests.

Summary

This project is not complete, even though we have good results to demonstrate what we have just discussed. Our correction algorithm doesn't always work as well as it did here, and seems to be oversensitive to rapid step changes in measurement values. We are still in the process of refining the system so that it operates smoothly in the production environment, with the intent of applying it to all ATEs in all product lines in the Juarez factory.

We have shown, in the factory and here in print, that measurement science and statistical control of measurements can be used effectively to reduce the differences (bias) among a group of testers without resorting to self-test hardware or higher-echelon calibration. In addition, capability studies using the same principles have led test engineers and programmers to assign causes to sources of measurement noise and thus eliminate them.

Special thanks for this project go to Dave Coleman for algorithms, Jim Grayson for FACTS system code and many helpful consultations, to John Lufkin for making many changes to the ATE computer software to make this system work, and to Larry Byers, Al Crager, Ray Jordan, Sergio Torres, Nancy Gates, Guillermo Gonzales, and Alfonso Dena for ongoing support, encouragement, and help.

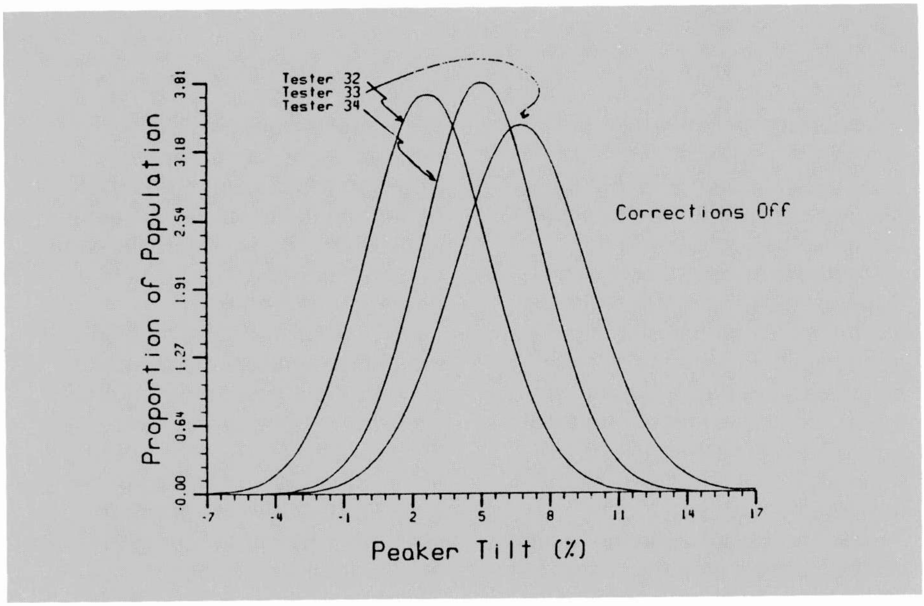


Fig. 4. *Data as they would look like in production, before correction. The graphs are estimates of the distribution of product as seen by each tester. They have been forced to appear Gaussian. Note the differences among testers.*

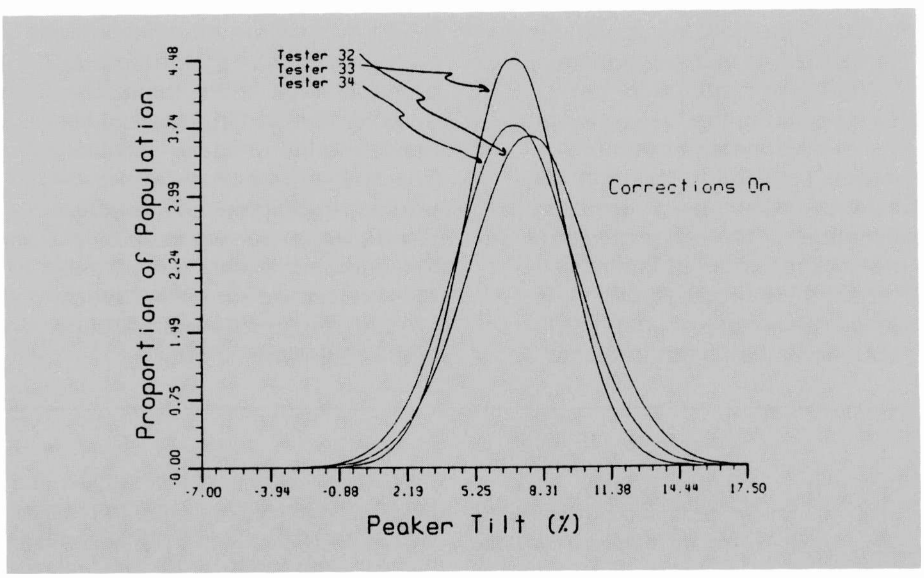


Fig. 5. *Data as they would look like in production, after correction. Note that the testers measure the product with much less bias. The graphs are estimates derived from data on about 1000 chassis actually measured by the testers.*

Do we add corrections, or do we multiply?

Consideration of this issue took far more time and effort than we would have believed possible. In practice, some tests are corrected by addition, others by multiplication. The decision as to which to do is made by a test engineer and then coded into the FACTS system and transmitted, along with the corrections themselves, to the ATE computers.

Tests that themselves are ratios, such as readings of an analog-to-digital converter that reports the ratio of an unknown voltage to an internal standard, are best corrected by multiplying. In this way, a 10-percent correction to a high test value and a 10-percent correction to a low test value are both applied in the right way. If corrections were added, a 10-percent correction added to a high value might be a 15-percent correction when added to a low value.

If the reported value of a test is allowed near or through zero, however, multiplied corrections have little or no effect in that region, even when we want corrections to have the same magnitude of effect regardless of the value of the data being corrected. In that case, we have to add.

What's more, some multiplicative correction must be *added*, for example when the reported value is in decibels. Corrections are kept additively in FACTS, and the tester control algorithm operates entirely in the additive domain. The multiplicative ones are transformed on their way to the ATE computers.

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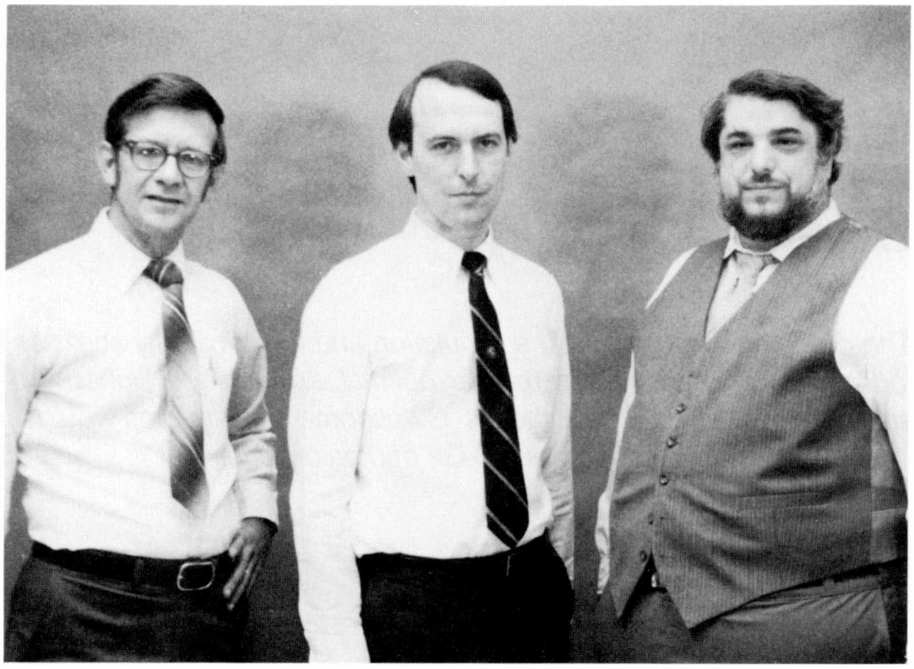

Authors, left to right, Turpin. Whitcomb and Stein

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M. C. Sharp

A stochastic model of electron gun grid alignment procedures

The numerical results from the simulation and the sensitivity analyses indicate that current specs are near-optimal, e.g., writing tougher specs (larger diameters) for the G1-G2 alignment fixture pins would cause a noticeable fraction of G1-G2 grid pairs to fail.

"Let us sit on this log at the roadside," says I, "and forget the inhumanity and ribaldry of the poets. It is in the glorious columns of ascertained facts and legalized measures that beauty is to be found. In this very log we sit upon, Mrs. Sampson," says I, "is statistics more wonderful than any poem. The rings show it was sixty years old. At the depth of two thousand feet it would become coal in three thousand years. The deepest coal mine in the world is at Killingworth, near Newcastle. A box four feet long, three feet wide, and two feet eight inches deep will hold one ton of coal. If an artery is cut, compress it above the wound. A man's leg contains thirty bones. The Tower of London was burned in 1841.

"Go on, Mr. Pratt," says Mrs. Sampson. "Them ideas is so original and soothing. I think statistics are just as lovely as they can be."

—O. Henry, The Handbook of Hymen

Abstract: *The distance between the centers of corresponding grid apertures (grid misalignment) affects electron gun performance. Grid misalignment is not directly observable in an assembled unit; consequently, a model is required to quantitatively predict it. Grid dimensions are measurable, and of course the steps of the assembly procedure are known. Therefore it is possible to sensibly predict the misalignment results in terms of a statistical distribution.*

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Reprint RE-30-3-6

RCA manufactures millions of electron gun assemblies each year. Their performance depends, among other things, on how accurately the grid apertures are aligned. The grid is a small metal stamping with three beam holes, or apertures. The grids must be assembled accurately. Each hole in each grid must line up with corresponding holes in other grids so that an electron beam can pass directly through the combination.

Misalignment can cause unbalanced flare and other undesirable performance characteristics in the completed kinescopes. This problem is becoming noticeably more serious with the tighter alignment tolerances needed for display and high performance entertainment tubes. Therefore, it is important to understand the detailed sources of misalignment so that they can be properly addressed.

There are several known sources of aperture misalignments. These include errors in aperture locations during grid manufacture, improper alignments prior to beading (final mount assembly), and shifts in grid positions either during or after beading. These shifts can in turn either be "mechanical," as caused by bent or loose (and moving) parts, or "thermal," as caused by thermal stresses and distortions during gun operation. In this study the PI17 mount and the current production assembly procedure are examined; analogous studies of other mounts and alternative assembly procedures are underway.

Statement of the problem

During aperture alignment, the grids are placed with the two outer apertures on pins mounted in mandrels. The nominal pin separation (0.520 inch) is defined by the mandrels. However, even in an "ideal" beading fixture the pins are made smaller than the grid holes in which they are to be located by $R - r$, where R is the radius of the aperture and r is the radius of the pin. The pins can also move slightly in the mandrels, so the axis of each alignment pin can lie anywhere within a circle of radius Δ from its nominal position. In total, the center of an aperture must lie within a circle of radius $\Delta + R - r$. If a grid, G1, with an aperture spacing (between outer apertures) not equal to 0.520 inch is placed on the pins, the pins will move to try to accommodate this grid error. When a second grid, G2, is next placed on the pins, the pins again will try to accommodate the aperture spacing of the second grid as well as the first. It is clear that, because of manufacturing errors in the grids, it is possible that either grid will be in error to such an extent that it will be unable to be placed on the pins. Moreover, even if each grid separately fits, the combination may not.

Stochastic geometry as applied to G1, G2 grid tolerancing

The result of aligning an outside aperture, (*e.g.*, the blue or red aperture) is two circles (*i.e.*, the apertures of the G1 and G2 grids), of radii R_1 and R_2, placed so they enclose an alignment pin of radius r. In Fig. 1, the distance between aperture centers u is the "misalignment" parameter of interest.

Because of dimensional variations, u is stochastic, *i.e.*, the actual u in a specific G1-G2 gun is a function of the particular dimensions of the grids that "happened" to be selected and the vagaries of the alignment procedure that "happened" to be executed.

The purpose of the stochastic model is therefore to derive the probability density function of u, *i.e.* $f(u)$. Given $f(u)$, misalignment properties can be derived, *e.g.*, the average misalignment, median misalignment, max-min misalignment, etc.

Analytic approximation

In this section the problem rationale will be discussed, but the geometry of the computer simulation plus a presentation of a "worst case" analysis will be postponed.

During aperture alignment, the grids are placed with the two outer apertures on pins mounted in mandrels. The design pin separation is 520 mils, but the pins can accommodate slack (via pin movement in the mandrel, and because the pins are smaller in diameter than the apertures) up to about one mil. Thus the endpoints of the line between pin centers can be anywhere in the "dumbbell" of Fig. 2.

For future reference, we define the origin of our coordinate system at the nominal center of the left-hand (LH) pin, and the X-axis to be the line connecting the nominal pin centers.

A grid (G1, G2) consists of three nominally identical circular apertures, of radius R, (12.7 mils), nominally collinear, with outside center-to-center spacing d (520 mils). Real grids, of course, display variation in dimensions (Fig. 3).

Therefore, individual symbols R_l, R_c, R_r are required for aperture radii.* Since the real center-to-center outside aperture spacing is rarely equal to d, a symbol, l, is used for this value.

Real apertures might also be significantly out-of-round—e.g., ellipses rather than circles. This was considered, but data on two perpendicular aperture radii allowed us to neglect out-of-round as a practical matter. Mechanics exist (see Kluyver) for "converting" circles to ellipses if necessary.

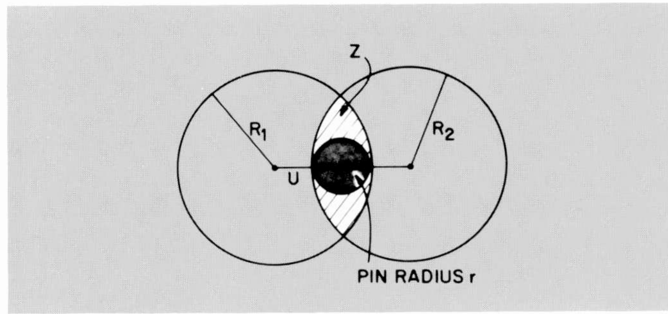


Fig. 1. *Two grid apertures placed on a pin.*

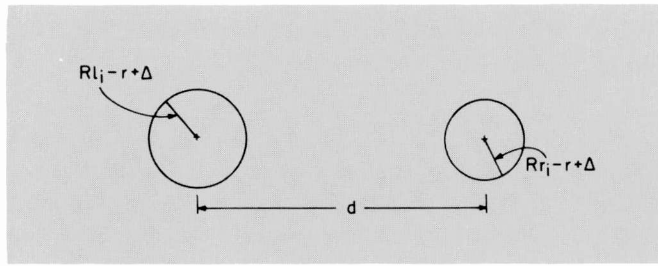


Fig. 2. *Possible locations for outside apertures of a grid.*

In all cases the subscripts 1,2 will identify G1, G2, if necessary.

Dimensional data on grids allows the empirical construction of appropriate probability density functions (pdfs) f_{l-d}, f_R, and so forth, describing variations, namely:

1. f_{l_i-d}, the pdf of the outside aperture spacing as referenced to the nominal pin separation d. This is a one dimensional pdf, *i.e.*, the outside aperture centers are considered to be an X-axis. Data show that we can assume that f_{l_i-d} is a Gaussian "normal" distribution with mean zero and standard deviation σ_l, *i.e.* f_{l_i-d} is distributed $N(0,\sigma_l)$.
2. The aperture radii pdfs are all equivalent, *i.e.*, $f_R(R_{l_i}) = f_R(R_{c_i}) = f_R(R_{r_i})$ and can be assumed to be distributed $N(R,\sigma_r)$.
3. $f_{X,Y}\left[\dfrac{h_i - l_i}{2}, k_i\right]$ is a pdf of the two-space deviations of the center aperture's center from the nominal location. This pdf can be assumed to be bivariate normal with zero correlation coefficient, *i.e.*, the horizontal or X-errors are distributed $N(0,\sigma)$, and are independent of the vertical or Y-errors, which are distributed $N(0,\sigma)$.

Consider placing G1 on the alignment fixture. To do this requires:

1. $R_{l_l}, R_{r_l} \geq r$, *i.e.*, the outside apertures have to be larger than the pins.
2. $|l_1 - d| \leq R_{l_l} + R_{r_l} + 2\Delta - 2r = \delta$ (say). In other words, an amount of slop δ is available, because (a) the pins themselves have Δ "accommodation room," and (b) an aperture of radius $R > r$ will still be over the pin if the aperture center is anywhere within $R - r$ of the pin center. But if $|l_1 - d| > \delta$, the grid is too long or too short to fit over the pins.

The probability of individual grids not meeting requirements (1), (2)—*i.e.*, grids that literally cannot be "aligned"—was calculated. It is very, very small. In the rest of this discussion it is assumed that grids will fit.

In summary, placing G1 on the pins amounts geometrically

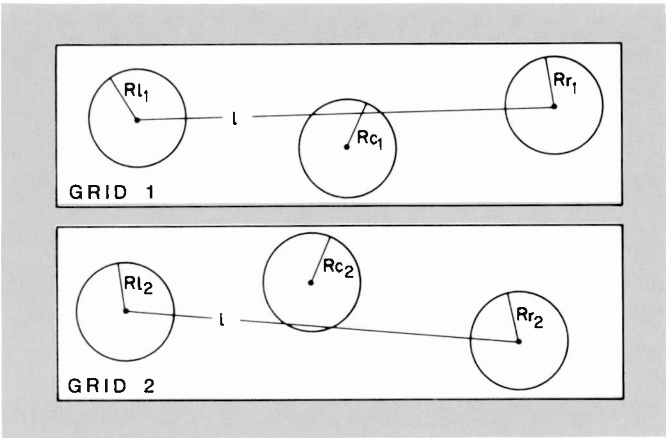


Fig. 3. *Notation for grid dimensions.*

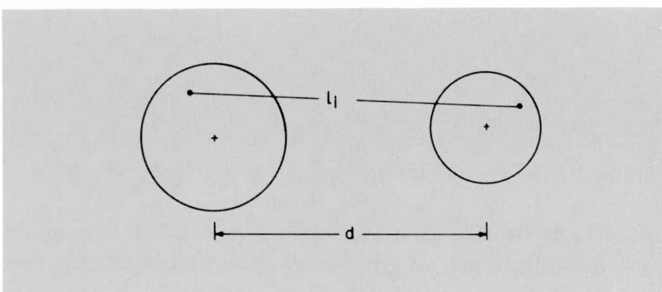


Fig. 4. *Schematic of grid "stuffing."*

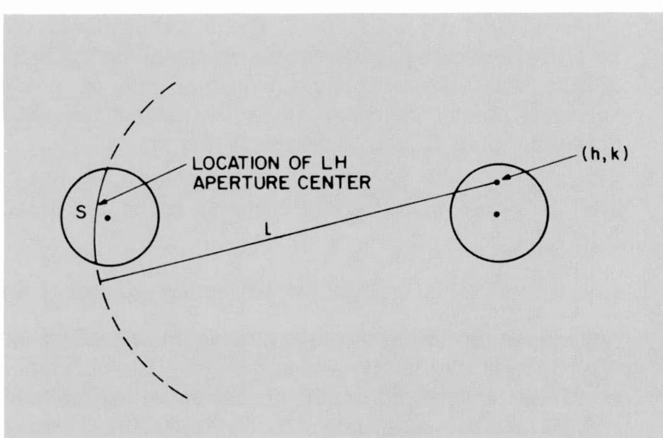


Fig. 5. *Location of LH aperture center given fixed RH aperture center.*

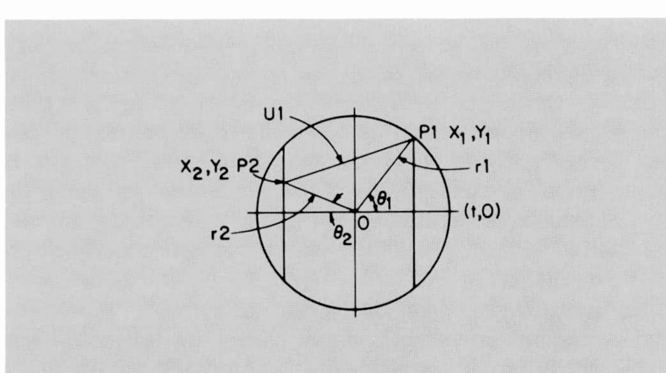


Fig. 6. *Approximate model of grid locations.*

to "stuffing" a line segment of length l_1 into a dumbbell of length d, bell radii $\Delta + R_i$, such that both ends of the line segment are within the respective bells (see Fig. 4).

For a given l_1, there is in general a region in which this is possible, *i.e.,* there are "choices" as to where the grid is placed. The actual feasible region is constructed in the next section. In this section, an approximate analytical solution is pursued instead. An approximate analytical solution is reasonable because the data say that $\sigma_l \gg \sigma_r$, *i.e.,* manufacturing variation in spacings greatly exceeds variation in aperture radii.

Now consider placing G2 on the pins, given that G1 has already been placed. (The same dimensional constraints apply, of course, to l_2 and R_{l_2}, R_{r_2} of G2.) The presence of G1 on the pins imposes added constraints on G2. The slop δ is not available to G2. Specifically, G2's left-hand aperture center must be such that $R_{l_1} + R_{l_2} - 2r > 0$. See Fig. 1.

Thus, it is possible for a particular G1 and G2 to be an "illegal" pair, even though G1 and G2 are themselves feasible. The probability of this was calculated and it is very small, so in the balance of the discussion it will be ignored.

Next, the analytical approximation is developed for $f(u_1)$, the center-to-center left hand aperture "misalignment" probability distribution. By symmetry, $f(u_3) = f(u_1)$, *i.e.,* both outside aperture misalignments have the same pdf. The density $f(u_2)$ of center apertures will be discussed after $f(u_1)$ is derived. (But note that $f(u_1) \neq f(u_2)$. In fact, u_2 must be "worse" due to the alignment process itself: center apertures are most affected by the non-collinearity of the grid.)

Consider a dumbbell as in Fig. 4 in which we are placing a line segment (a grid). Suppose that the RH aperture is at an arbitrary (legal) point (h,k). Then, really, the LH aperture center must be somewhere on the circular arc S drawn a distance l from (h,k) and intersecting the LH bell. See Fig. 5.

However, l's are $\approx$ 520 mils and the bells are only about 1 mil in radius. Therefore, the arc S can be approximated by a vertical chord.

The LH G2 location is approximated in the same way, where both chords are constrained to be in a circle of radius $R_{l_1} + R_{l_2} - 2r = \rho$ (say). The radius ρ is stochastic, that is to say, randomly varing from grid to grid, but in order to derive $f(u_1)$, we first derive it for a fixed ρ, and then consider ρ as variable.

In Fig. 6, then, we randomly choose horizontal or X-offsets. Given X, we randomly choose appropriate vertical or Y-offsets. Having thus constructed appropriate P's, we compute $f(u_1)$ given that $u_1 = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$.

Now we must define what we mean by "appropriate."

Consider first an X-offset. These X-offsets arise from the slop variable $l_i - d$, which our data say is normally distributed. The LH X-value is a "random fraction" of $l_i - d$ (because the rest of $l_i - d$ was used on the RH). There is no reason to suspect a bias between left and right, so the pdf we are looking for should be:

- ☐ Symmetric about (0,0)
- ☐ Like a Gaussian but "fuzzier" (because the slop is not split equally between ends, but only tends to be assigned equally).

We select the Cauchy distribution as reasonable under these circumstances, so

$$f(x_i) = \frac{\lambda}{\pi\ (\lambda^2 + x_i^2)}\ ,\ i = (1,2). \qquad (1)$$

Rayleigh densities

Consider two independent normal distributions $f(x)$, $f(y)$ with means zero and common σ. Then consider $u = \sqrt{x^2 + y^2}$, $v = x$.

By change of variable calculus, the Jacobian $= \frac{u}{\sqrt{u^2 - v^2}}$, and:

$$f(u) = 2\int_0^u \frac{u}{\sqrt{u^2 - v^2}}\left[\frac{1}{2\pi\sigma^2}\right] e^{-(1/2\sigma^2)(v^2 + u^2 - v^2)}\, dv.$$

$$= \frac{u}{\sigma} e^{(-u^2/2\sigma^2)} = \text{Rayleigh.} \qquad (1)$$

Thus, the "random normal vector" has a Rayleigh distribution.

Now consider the vector difference (sum) between two such vectors. From Kluyver,* the distribution function F of two vectors of fixed length a_1, a_2 with random orientation is:

$$F(u,2) = u\int_0^\infty dx\ J_1(ux)\ J_0(a_1x)\ J_0(a_2x). \qquad (2)$$

Now let a_1, a_2 have Rayleigh densities, i.e.,

$$f(a_i) = 2\gamma_i a_i e^{(-\gamma_i a_i^2)},\ (i = 1,2).$$

Then the resultant cdf $F(u)$ is:

$$F(u) = 4\gamma_1\gamma_2 u\int_0^\infty dx\, J_1(ux)\int_0^\infty da_1\,[a_1 e^{-\gamma_1 a_1^2} J_0(a_1x)]\int_0^\infty da_2\,[a_2 e^{-\gamma_2 a_2^2} J_0(a_2x)]$$

but

$$\int_0^\infty dy\, y^{(\nu+1)} e^{-\alpha y^2} J_\nu(\beta y) = \frac{\beta^\nu}{(2\alpha)^{\nu+1}} e^{(-\beta^2/4\alpha)}$$

Re $\alpha > 0$, Re $\nu > -1$.

For us, $\nu = 0$, $\alpha = \gamma_1$ or γ_2, $\beta = x$. This implies

$$F(u) = u\int_0^\infty dx\, J_1(ux) e^{[-(\gamma_1 + \gamma_2)/(4\gamma_1\gamma_2)]x^2}$$

but

$$\int_0^\infty dy\, y^{(\nu-1)} e^{-\alpha y^2} J_\nu(\beta y) = 2^{(\nu-1)}\beta^{-\nu}\gamma\left(\nu, \frac{\beta^2}{4\alpha}\right).$$

For us, $\nu = 1$, $\alpha = \frac{\gamma_1 + \gamma_2}{4\gamma_1\gamma_2}$, $\beta = u$.

This implies

$$F(u) = \gamma\left(1, \frac{u^2\gamma_1\gamma_2}{\gamma_1 + \gamma_2}\right)$$

But

$$\gamma(1,x) = 1 - e^{-x}$$

$$F(u) = 1 - e^{-[(\gamma_1\gamma_2)/(\gamma_1 + \gamma_2)]u^2} = \text{Rayleigh.}$$

This direct derivation is due to J. Economou.

* Kluyver, J.C., "A Local Probability Problem," *Netherlands Acad. Wetensch. Proc.*, Vol. 8, pp. 341-363 (1906).

λ is a parameter numerically determined from the $l_i - d$ variance.

Note that X_i is really confined to the interval $(-\rho,\rho)$, *i.e.*, eq. 1 is truncated, but this will be ignored (recall that virtually no grids "want" to lie outside this interval).

Now consider a vertical displacement y_i, given that X_i has been drawn. We can't know what y_i is, but it is reasonable to assume that all possible angles θ_i (see Fig. 6) are equally likely, *i.e.*, give an available vertical "slop" for skewing the grid, we assume that the actual skew is "random."

If all θ's are equally likely, then $(y_i \mid x_i)$, the pdf of y_i given x_i is also Cauchy with parameter $\mid x_i \mid$, *i.e.*

$$(y_i \mid x_i) = \frac{\mid x_i \mid}{\pi(x_i^2 + y_i^2)},\ i = (1,2). \qquad (2)$$

Note that y depends on X, *e.g.*, if $X \approx \rho$, then $y \approx 0$, *i.e.*, if the grid is barely long enough to fit, the skew will be minimal. Conversely, if $X \approx 0$, then y has an amount ρ of room for variation. This is realistic, and in fact the $X - Y$ dependence is the chief reason why simple models are not sufficient (see center aperture discussions).

Hence, the pdf of aperture center locations (x_i, y_i) is:

$$f(x_i, y_i) = \frac{\lambda \mid x_i \mid}{\pi^2(x_i^2 + y_i^2)(x_i^2 + \lambda^2)} \qquad (3)$$

For misalignment u_i, we need the squares of $(x_1 - x_2)$ and $(y_1 - y_2)$, but these are also Cauchy, since the Cauchy is reproductive. Therefore, define $x = x_1 - x_2$, $y = y_1 - y_2$ and then

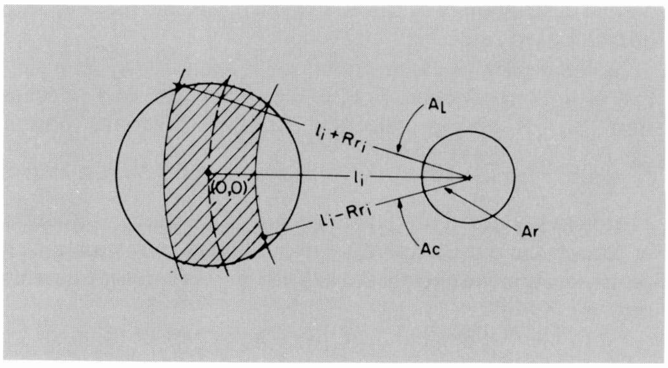


Fig. 7. *Feasible region for LH aperture placement.*

$$f(x,y) = \frac{\alpha \mid x \mid}{\pi^2(x^2 + y^2)(x^2 + \alpha^2)} \qquad (4)$$

where $\alpha = 2\lambda$.

The "misalignment density" $f(u_1)$ is then found by straightforward change of variable techniques given that $u_1 = \sqrt{x^2 + y^2}$ with the result:

$$f(u_1) = \frac{4\alpha}{\pi^2 u_1\sqrt{\alpha^2 + u_1^2}} \sinh^{-1}\left[\frac{u_1}{\alpha}\right],\ (u_1 > 0) \qquad (5).$$

PDF for the distance between two points dropped randomly in a circle.

Consider a circle of radius S with a point P_1, fixed on the circumference. P_1 is fixed on the circumference because of Crofton's theorem from stochastic geometry.† This results in the differential equation:

$$dS = 2\frac{(P_1 - S)}{V}dV, \qquad (1)$$

where

P_1 = Prob (u_1 < separation of $P_1, P_2 < u_1 + u_1$) when P_1 is fixed on the boundary of V,

S = Prob (u_1 < separation of $P_1, P_2, < u_1 + u_1$)

V = Area of the circle.

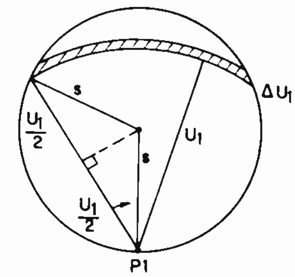
In other words, Crofton's theorem allows one to derive the pdf of (u_1) for two random points from the pdf,

$f(u_1 \mid P1$ fixed on the boundary of the circle).

For u_1, $V = \pi s^2$ and $dV = 2\pi s ds$.

For infinitesimal Δu_1, the area of the shaded annulus is $2\nu u_1 \Delta u_1$, where $\nu = \cos^{-1}\left(\frac{m}{2s}\right)$.

† H. Solomon, "Geometric Probability," Regional Conference Series in Applied Mathematics, Ch. 5 (1978).



Hence equation 2 is:

$$dS = 2\frac{[2u_1\Delta u_1 \cos^{-1}(u_1/2s)]}{\pi s^2}\frac{2ds}{s} \qquad (2)$$

By rearranging terms, eq. 2 together with the boundary condition $S = 0$ when $s = \frac{u_1}{2}$ results in the answer:

$$f(u_1 \mid s) = \left(\frac{2u_1}{s^2}\right)\left\{\frac{2}{\pi}\left[\cos^{-1}\left(\frac{u_1}{2s}\right) - \frac{u_1}{\pi s}\sqrt{1 - (u_1^2/4s^2)}\right]\right\} \qquad (3)$$

for $(0 < u_1 < 2s)$.

Thus equation (3) is the pdf of the distance u_1 between two points randomly dropped into a circle of radius s.

Equation (5), with a numerically appropriate α, is thus the "answer" to outside aperture misalignment. From eq. 5 any desired description of u_1 can be extracted, *e.g.*, the mean u_1, σ_{u_1}, quartiles of u_1, etc.

Now consider misalignment of center apertures, u_2. It is plain that a random selection of u_2 is the vector sum of a selection from eq. 5 and a selection from a bivariate normal $f_{X,Y}\left[h - \frac{l_i}{2}, k\right]$, (from the collection of pdfs shown above). That is to say that center apertures are off because of variations in placing the outside apertures over the pins plus variations in center location with respect to the line between outside aperture centers).

From the dimensional data, the normal part of the error has $\sigma \geq$ the (eq. 5) part. Also, of course, we are in effect averaging over two error sources. One is selected from a source assumed random, the other is not random, but the averaging process itself tends towards normal, so for practical purposes u_2 was considered as the vector difference between two random normal vectors—*i.e.*, vectors in which the X and Y components are distributed independent normal. This perspective fits the simulation results in the next section quite well.

The pdf (u_2) in this case is a standard result, namely the Rayleigh density (see sidebar):

$$f(u_2) = \frac{u_2}{\sigma} e^{-[u_2^2/2\sigma^2]}, \qquad (6)$$

where σ is numerically appropriate given the dimensional standard deviations of pdf's (1), (3) from above.

Computer simulation

Although eq. 5 and 6 are reasonable analytical answers to G1-G2 misalignment, a computer simulation (conducted by S. Miller, RCA Laboratories), was also written because:

- ☐ No approximations are required, this making the numerical results theoretically superior,
- ☐ The sensitivity analyses are now computationally feasible, so that the effect of different fixture dimensions, different grid specs and dimensions, etc., could be handily examined, and
- ☐ The simulation serves as a basis of comparison for other simulations of other (proposed and real) alignment procedures.

The simulation routine starts by selecting for G1 LH aperture a random point in the "feasible region" for LH aperture location. The feasible region, shown in Fig. 7, is reasoned out as follows:

1. Any outside aperture center must be in the bell of the dumbbell constructed in Fig. 3.
2. Imagine the RH aperture to be at the center of the RH bell, $(l_i,0)$. Then the LH aperture center must be on the arc A_c intersection with the LH bell.
3. But the RH aperture doesn't have to be at $(l_i,0)$, it can be anywhere in the right bell.
4. Therefore the intersections of arcs A_l, A_r with the LH bell define the feasible region for the LH center aperture (cross-hatched area in Fig. 7).

Having located G1 legally according to the Fig. 7 criterion, the simulation then locates G2 according to its Fig. 7 region, plus satisfying the constraint (see above) that the resultant $u_1 \leq R_1 + R_2 - 2r$.

The numerical results from the simulation and the sensitivity analyses indicate that current specs are near-optimal, *e.g.,* writing tougher specs (larger diameters) for the G1-G2 alignment fixture pins would cause a noticeable fraction of G1-G2 grid pairs to fail.

Worst case analysis

Although the above results are considered the "best" estimates of $f(u_1)$, no accounting is made of possible mechanical/thermal perturbation effects on aperture locations. For example, because $l - d$ is normally distributed, aperture centers tend to depart little from nominal.

If, however, major distortions are present, our model is inadequate. For this reason, an alternate perspective was constructed.

In this perspective, the only constraint on LH aperture locations P1, P2 is that they are physically possible, *i.e.,* P1 and P2 are within $R_{l_1} + R_{r_1} - 2r = s$ of one another so that a physical pin could accommodate both grids. This is not really the *worst* case, it is one in which all aperture spacings are equally likely rather than displaying a central tendency as they do above. Again, the RH constraint is needed. Subject to this constraint, P1, P2 are located randomly.

Thus, there are two steps to the analysis:

1. Derive $f(u_1)$ for two points dropped randomly into a circle of radius s.
2. Allow s to be stochastic, *i.e.,* regard $f(u_1)$ as an $f(u_1 \mid s)$, and then integrate over the pdf (s) so that

$$f(u_1) = \int f(u_1 \mid s) f(s) ds.$$

Technically, this step is called "mixing" (on s).

The result of step (1) is standard (see sidebar) with the result,

$$f(u_1 \mid s) = \frac{2u_1}{s^2}\left\{\frac{2}{\pi}\left[\cos^{-1}\left(\frac{u_1}{2s}\right) - \frac{u_1}{\pi s}\sqrt{1 - (u_1/2s)^2}\right]\right\}, \quad 0 < u_1 < 2s \qquad (7)$$

To mix eq. 7 on s we assume, for simplicity, that s varies uniformly over an interval $(0, W)$. Then by straightforward integration we arrive at the worst case $f(\nu)$:

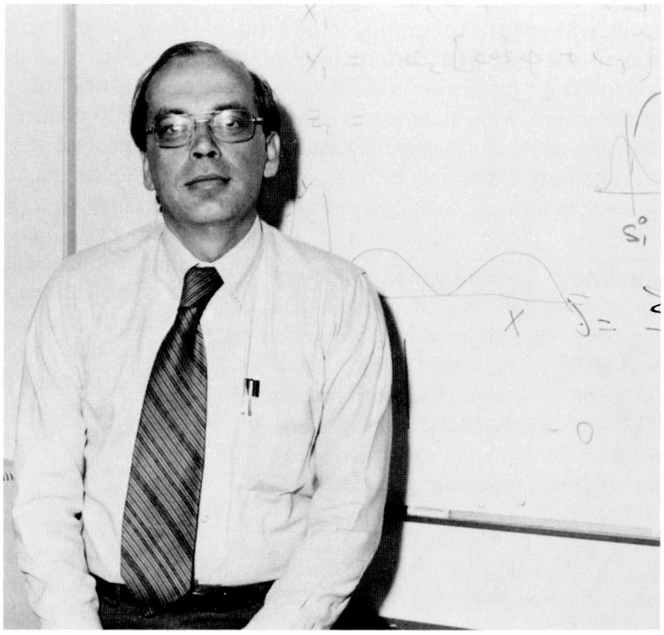
$$f(\nu) = \frac{16}{\pi}\left\{\sqrt{1 - \nu^2} - \frac{1}{3}(1 - \nu^2)^{3/2} - \nu \cos^{-1} \nu\right\}, \quad \nu = \frac{u_1}{2W}, (0 < \nu < 1). \qquad (8)$$

Misalignments computed from eq. 8 were, roughly speaking, 50 percent larger than those derived from eq. 5.

Summary

The product of this work is a probability distribution for G1-G2 misalignment, which allows us in a statistical sense, to "see" that which we cannot explicitly measure. (Even if we could observe u's, it would still be an obvious design aid to have a statistical model of u "error sources").

We believe that the result is illustrative of a type of modeling with many applications in kinescope manufacture. If an arbitrary assembly procedure can be described in geometric terms, and if data or reasonable guesses exist for parts variation, then in principle such a model can be derived. Examples might include G3 and G4 alignment, cathode insertions, and mount rotations.



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E. Shecter

Process control for high yields

There is a wide variety of statistical quality control tools, and the control chart for variables is one of the simplest and most powerful.

During the course of manufacturing, many factors contribute to the final product result, with each factor causing some variation in the specified performance parameters. These factors include differences in performance with time on a particular machine, nonuniformity in material (lot-to-lot variation), differences among operators, differences among machines, power variations, differences among suppliers, and so forth. Efforts are made to control each of these contributing factors, but it is still necessary to control the end result. The use of statistical methods offers a cost-effective means to control the process.

Abstract: *Among the wide variety of statistical quality control tools that can be applied to improve or maintain high process yields, the control chart for variables is one of the simplest and most powerful. This type of control chart can be used to measure performance on virtually any process that lends itself to recording values.*

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A process can be viewed as a series of operations that produce a result. This result can either be a product or a service. Thus, a process can be viewed as the operations that produce assembled electronic boards, a complete spacecraft, a solder joint, a weld; or that provide a service, such as placing purchase orders.

In general, a process has some central tendencies as well as a certain amount of variability. The location of the central tendency depends on the number of factors that are involved in the creation of the output and the variability of each factor. The more factors, the greater the variability. The wider the variability of the individual constituents, the greater the variability of the process. Many times we do not know all of the factors, or even which ones contribute the most to the variability. The behavior patterns of these factors are subject to both random variation and "assignable" causes.

Knowledge of the factors and proper process controls enable the process to produce a larger percentage of conforming items and fewer deficiencies, provided we are aware of the process level and variability and make adjustments only when necessary. The process variability, also called process capability, determines the limits within which the process can be expected to perform. If the specifications or requirements are broader than the process capability, then the process can produce a totally conforming product. If, on the other hand, the specification limits are narrower than the process capability, nonconformities will abound unless changes are made to reduce the variability.

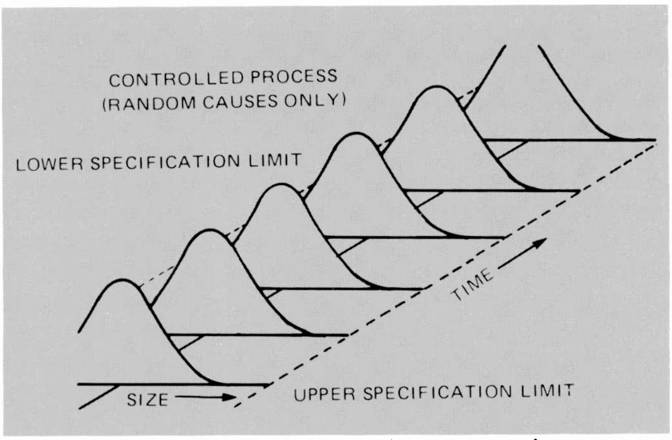


Fig. 1. *This plot shows the behavior pattern of a process that is operating within control. Note that all data lie within the specification limits. Here any variation in data is due only to random causes.*

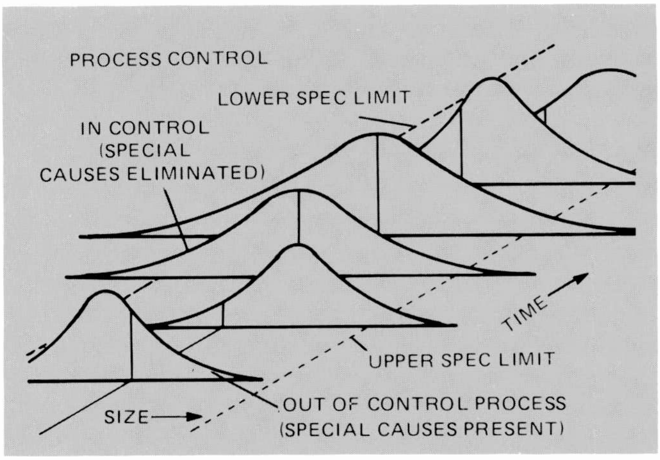


Fig. 2. *This plot shows the behavior pattern of a process that is operating out of control. These curves do not lie within the specification limits.*

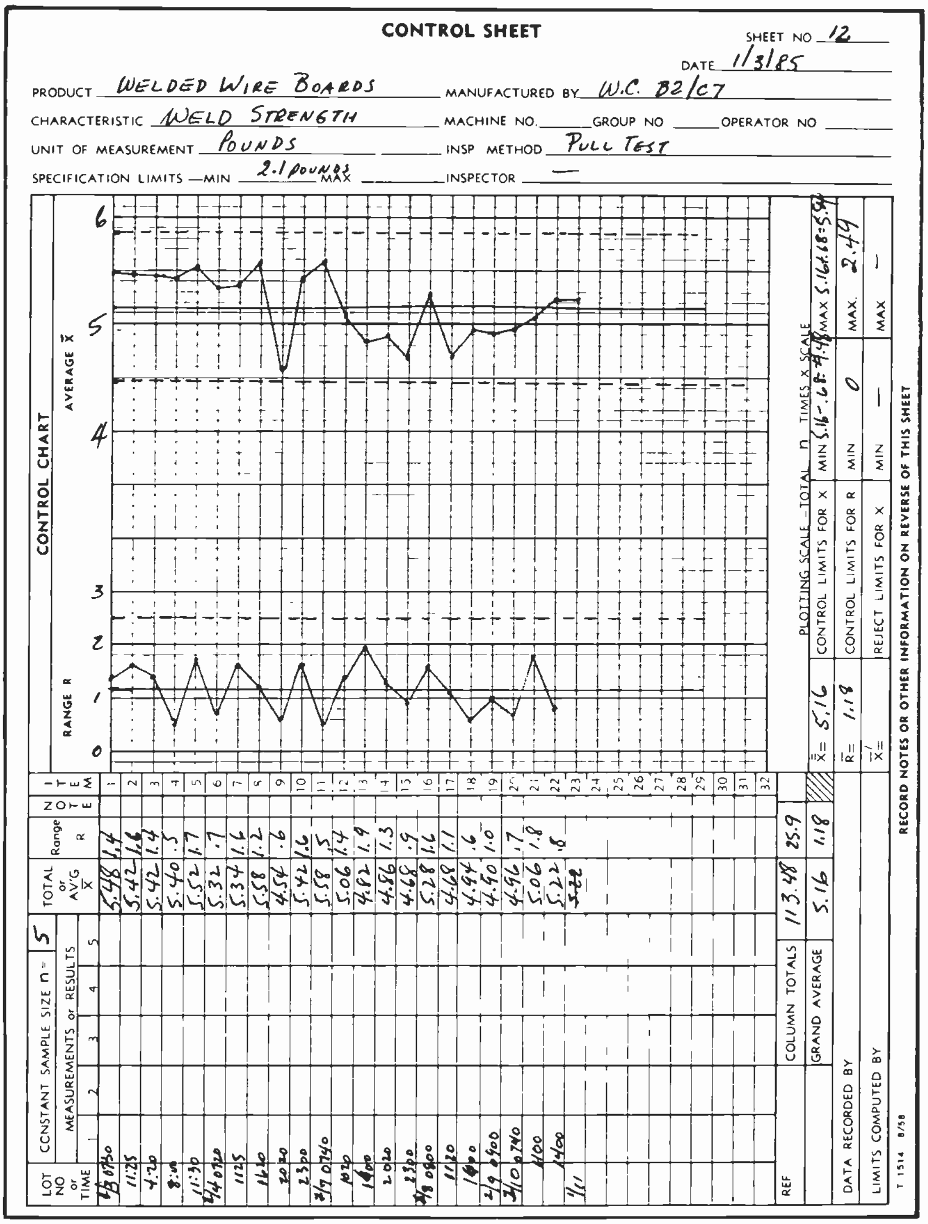


Fig. 3. *Actual weld strength data have been plotted on these average and range control charts. Note that even with the variation in data, they are all within the specification limits.*

The control chart

The control chart is used to detect shifts in process levels or spread. The timely detection of these shifts often enables engineers or process people to determine the physical causes and thus eliminate them from the process. The timeliness is achieved by checking items periodically during the process, and sensitivity to change is achieved by use of the control chart.

A small number of items is selected during the manufacturing process, measurements are taken, and the average, $\overline{X}$, and range, R (largest value minus smallest value), or the standard deviation, σ, of the measured data are calculated. The values are plotted on separate $\overline{X}$ and R (or σ) charts (see Fig. 3). While the parent population or process may not be a normal (Gaussian) distribution, the distribution of averages is normal, and the distribution of ranges is close enough to use rules for normal distributions. Hence the probability that the averages will lie within $\pm 3\sigma$ is 99.7 percent.[1] The likelihood that an average will lie outside these limits is, therefore, 3 in 1000. Thus a point falling outside the $\pm 3\sigma$ limits is highly indicative of a process shift. Control limits are determined using standard formulas shown at the end of this article.

The limits developed using $A_2 \overline{R}$ are equal to three-sigma limits for the average, or $3\sigma_{\overline{X}}$. Limits for the range or standard deviation charts are also essentially $3\sigma'$ limits.[2]

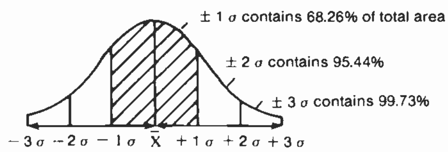
The control limits are established such

"Assignable" or abnormal causes shift the average or the variability and result in higher levels of nonconformance. It is important to be able to segregate these from the random effects that contribute to the variability of the process. Figure 1 is a pictorial representation of a process in control; that is, it is subject to random variations only. Figure 2 represents a process that is out of control, and shows shifts in both level and variability due to the effect of abnormal factors.

Among the wide variety of statistical quality control tools that can be applied to improve or maintain high process yields, the control chart for variables is one of the simplest and most powerful. This type of control chart can be used to measure performance on virtually any process that lends itself to recording values. At Astro-Electronics there are actually three separate welding processes that are controlled in this manner: welding of insulated wire to buttonhead pins that have been press fitted into the boards using opposed-electrode spot welding; parallel-gap welding of part leads to buttonhead pins; and pincer welding of leads to pins.

Wires welded on one side of the board make the interconnections; the parts are welded to the other side of the board using parallel-gap or pincer-type welding. These welding processes are controlled using control charts.

1. The normal or Gaussian distribution has fixed areas or probabilities determined by the number of standard deviation units measured from the average or from $-\infty$.



Thus the probability of a value lying outside of $\pm 3\sigma$ is 100 percent−99.73 percent or 0.27 percent. Therefore the assumption that a point out of $\pm 3\sigma$ is indicative of a shift in the process has a probability of 99.73 percent being correct. The identical probabilities apply if we consider control limits that are placed at $\pm 3\sigma_{\overline{X}}$.

2. The standard deviation for individual values can be calculated from a control chart by:

$$\overline{R}/d_2 = \sigma \text{ or by } \sigma / c_2.$$

The relationship between σ for the individuals and $\sigma_{\overline{X}}$ for the averages is

$$\sigma_{\overline{X}} = \sigma/\sqrt{n}$$

where n is the subgroup sample size. See table at end of article for values of d_2 and c_2.

that a point out of control on the $\overline{X}$ or R chart indicates a process shift. A shift in central value is indicated on the $\overline{X}$ chart, and a shift in dispersion is indicated on the range chart (see Fig. 3). (Texts provide other rules to determine process shifts, but we use one point outside the control limits as the sole criterion for process shifts.)

We selected samples of five, although samples of four or six would have served equally well. Small samples are used because too large a sample can indicate process shifts whose physical causes are difficult, if not impossible, to detect. This is because $3\sigma_{\overline{X}}$ limits become narrow, because they are related to the population σ by the formula $\sigma_{\overline{X}} = \sigma / \sqrt{n}$. Hence, as n increases, $3\sigma_{\overline{X}}$ decreases. The narrowing of the control limits results in frequent out-of-control indications simply because processes do not behave as perfectly as statistical methods indicate. Samples of four or five pieces strike a balance between looking for trouble when none is present or ignoring trouble when it is present. Because weld strength is undesirable when it gets too low, we weren't concerned if the average went out of control on the high side (the weld strength was too high).

A pull test to destruction determines weld strength, and we could not use actual product for our samples, so we selected representative materials. Using the established schedule parameters, we made seven samples which were pull tested using a TJH Hunter tensile tester. Five samples were used to determine $\overline{X}$ and R, and two were saved for possible physical cross sectioning and analysis if weld reliability were to be questioned at a later date.

Samples were selected at the beginning, middle, and end of each work shift. When we started, samples were taken each hour, but as the data showed a relatively stable process, we found that every four hours was adequate. The frequency of sample selection is a function of the process stability. We found that taking the entire sample at once was more practical than selecting them at incremental times. Control chart usage normally requires spreading the sample selection over a small period of production time for a more accurate representation of process average and spread, but where destructive tests are required, the method we used is common.

FREQUENCY DISTRIBUTION ANALYSIS

CELL BOUNDARY	CELL MIDPOINT	FREQUENCY OF OCCURRENCE	f	d	f·d	f d²
6.2	6.1	//	2	5	10	50
6.0	5.9		0	4	0	0
5.8	5.7	//	2	3	6	18
5.6	5.5	++++	5	2	10	20
5.4	5.3	++++	5	1	5	5
5.2	5.1	++++ /	6	0	0	0
5.0	4.9	++++ /	6	-1	-6	6
4.8	4.7	++++ ++++	10	-2	-20	40
4.6	4.5	++++ //	7	-3	-21	63
4.4	4.3	++++ /	6	-4	-24	96
4.2	4.1	/	1	-5	-5	25
4.0						
			n =		Σfd = -45	Σfd² = 321
					E_1 = -0.9	E_2 = 6.42

A = MIDPOINT OF ZERO CELL = 5.1

M = CELL INTERVAL = 0.2

$E_1 = \frac{\Sigma fd}{n} = -0.9$, $E_2 = \frac{\Sigma fd^2}{n} = 6.42$

$\overline{X} = A + mE_1$ $\quad \overline{X} = 5.1 + .2(-.9) = 4.92$

$\sigma = m\sqrt{E_2 - E_1^2}$ $\quad \sigma = .2\sqrt{6.42 - (.9)^2} = 0.47$

Fig. 4. *The frequency distribution of weld tensile tests is shown along with calculations of $\overline{X}$ and σ.*

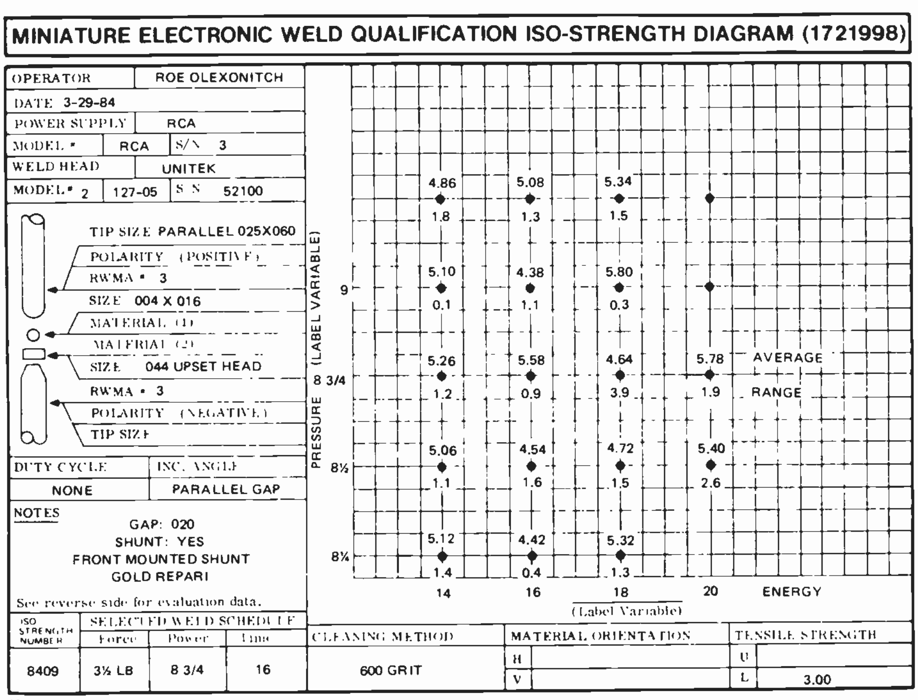


Fig. 5. *The isostrength chart is used to select pressure and energy for a given combination of materials.*

The frequency distribution

For added reliability assurance, a sample of 50 pull tests is performed and the $\overline{X}$ and σ are calculated before running the process. All 50 readings must lie within $\overline{X} \pm 3\sigma$, where the standard deviation is calculated[3] from the formula:

3. In our case, arbitrary criteria are applied requiring that $\sigma_{\overline{X}} < 0.2\ \overline{X}$ (to provide a measure of confidence that the spread is not excessive) and that $(\overline{X} - 3\sigma) < T_L/2$ (where T_L is the lowest tensile strength of the weaker of the two materials being bonded).

$$\sigma = \sqrt{\Sigma (X_i - X)^2 / n-1}$$

Although it is a good idea to plot individual readings (in one corner of the control chart), this is not usually done. Such a frequency distribution is depicted in Fig. 4. The advantage of this plot is to provide an indication of the shape and location of the parent population, which is helpful in understanding the process and the nature of its change. Sometimes, for example, bimodal distributions become evident, or truncation or skewness is displayed. The use of variables in determining product performance or process levels is widely disregarded in many companies. Its application should be encouraged, because these methods can lead to process improvements. (My definition of a process improvement is one in which the variability is reduced and the average is at the center of the specification.)

Establishing the schedule—the isostrength chart

It is desirable to have a stable process in all situations. In the weld process, stability is more likely if the weld schedule is established using the isostrength procedure. This is done using an isostrength diagram made by recording averages and ranges of weld strength of similar materials at selected points of pressure and energy (see Fig. 5). The diagram is used like a profile map. That combination of weld settings near the center of a plateau of weld strengths is selected. The highest values are not necessarily selected—the widest plateau is the most desirable for stability, should there be slight shifts in operating parameters. In addition, the location of the break is noted, and welds that do not pull material when fracturing are considered to be poor. The detailed procedure is defined in Asro-Electronics Specification 1721998.

Process description

Welds made through the teflon insulation bond nickel wire to a gold-plated stainless steel pin (Fig. 6). A process change was introduced because experience showed that the lot-to-lot variability of the gold plating required new weld schedules to be developed for each plating lot. The process is more stable now that welds are made directly to the newly processed pin, enabling the frequency of testing to be reduced.

The part lead is parallel-gap welded to

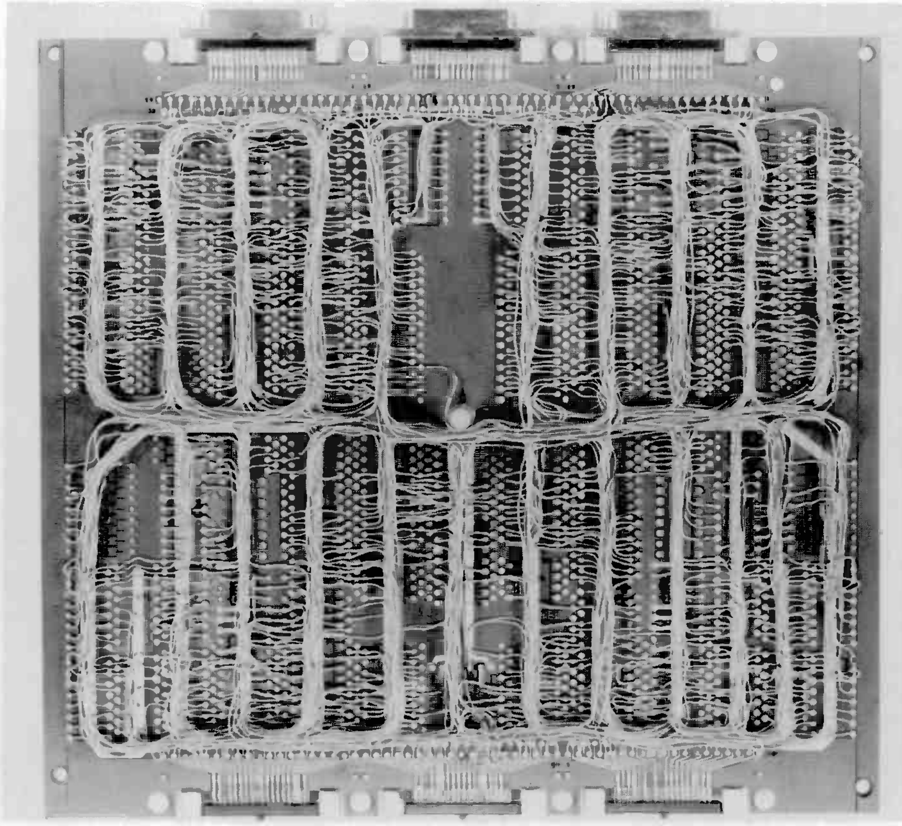


Fig. 6. *Welded wire board showing layout of wires and buttonhead pin terminations.*

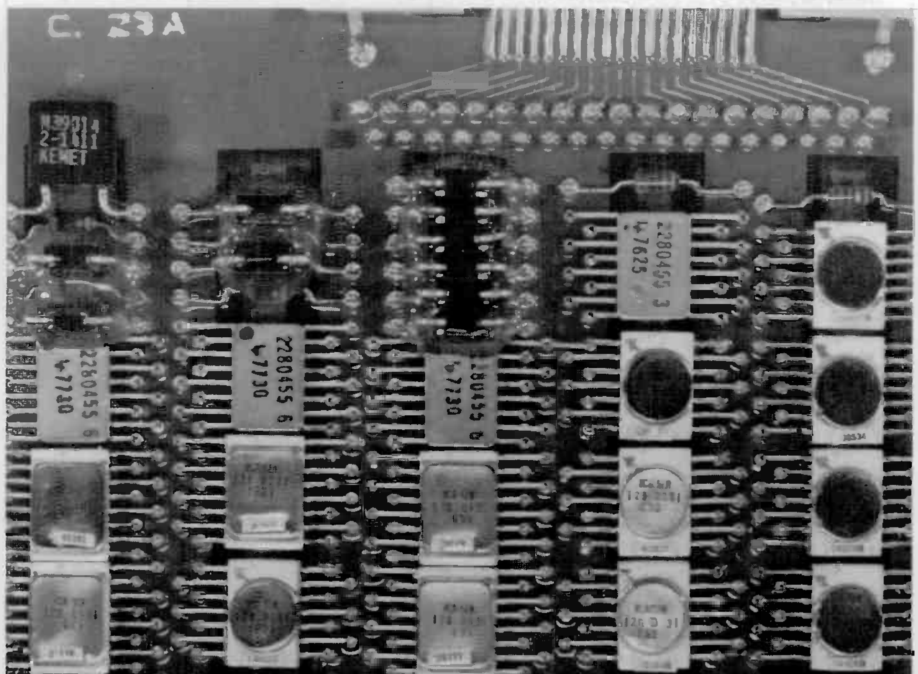


Fig. 7. *Welded wire board showing flat pack integrated circuits parallel-gap welded into position.*

the other side of the pin (see Fig. 7). Representative part leads are used with pins to establish a schedule using the iso-strength chart and the frequency distribution, and to provide the necessary samples for testing. Each unique material lead combination must have a unique schedule for each machine. After the schedule has been established, new lots of the same material only require five samples whose $\bar{X}$ and R plots are within control limits.

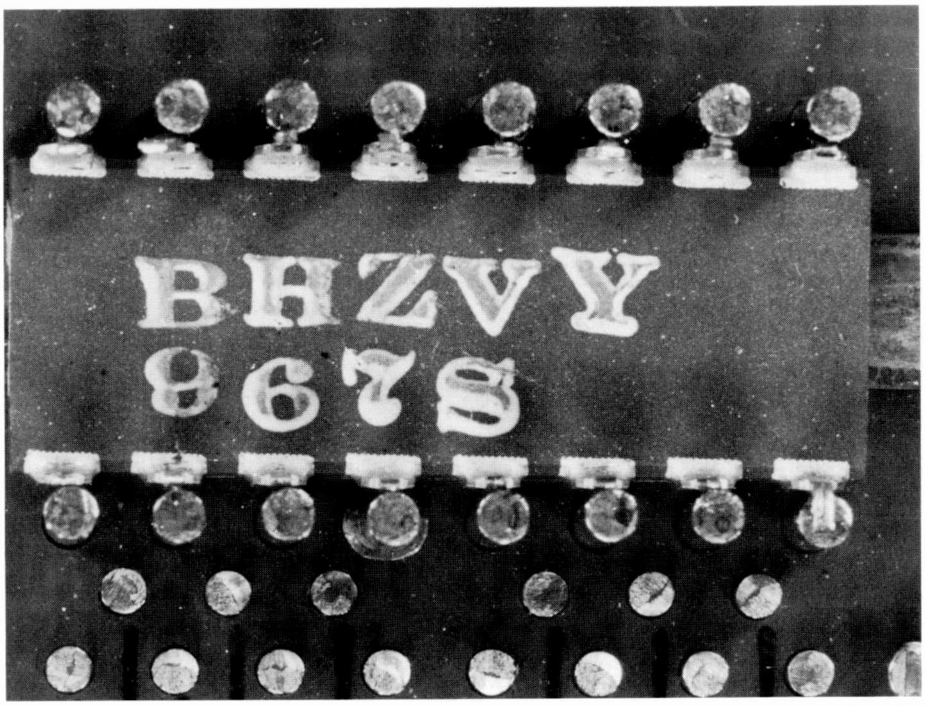


Fig. 8. *Top view of integrated circuit (dual-in-line package) illustrates how leads are pincer-welded to button of buttonhead pins.*

Basic Control Chart Calculations

$$UCL_{\bar{X}} = \bar{\bar{X}} + A_2 \bar{R} \qquad UCL_{X} = \bar{\bar{X}} + A_1 \bar{\sigma}$$

$$LCL_{\bar{X}} = \bar{\bar{X}} - A_2 \bar{R} \qquad LCL_{X} = \bar{\bar{X}} - A_2 \bar{\sigma}$$

$$UCL_{R} = D_4 \bar{R} \qquad UCL_{\sigma} = B_4 \bar{\sigma}$$

$$LCL_{R} = D_3 \bar{R} \qquad LCL_{\sigma} = B_3 \bar{\sigma}$$

$$\sigma' = \frac{\bar{R}}{d_2} \qquad \sigma' = \frac{\bar{\sigma}}{c_2}$$

where A_2, D_3, D_4, d_2 and c_2 are a function of the sample size and are determined from tables below:

Sample Size	n	A_2	D_3	D_4	d_2	A_1	B_3	B_4	c_2
	2	1.88	0	3.27	1.128	3.76	0	3.27	.5642
	3	1.02	0	2.57	1.653	2.39	0	2.57	.7236
	4	0.73	0	2.28	2.059	1.88	0	2.27	.7979
	5	0.58	0	2.11	2.326	1.60	0	2.09	.8407
	6	0.48	0	2.00	2.534	1.1	0.03	1.97	.8686

The pincer weld is used to weld part leads to the side of the pin (Fig. 8). The design may require installation with the part body against the board and leads bent upward and running parallel and adjacent to the corresponding pin to which they are to be welded. Similar procedures for weld schedule determination are used for this process, and the control charts are also similar.

Summary

Statistical methods are used at Astro-Electronics to control several welding procedures to assure proper weld strength. The control chart technique involves taking a

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small number of samples (in our case four or five items) periodically throughout the production process. The frequency of sample selection depends on the stability of the process behavior, with longer intervals between sample selection for more stable processes. In our application, the weld strength of the samples is tested via a pull test to destruction (two untouched samples are set aside for later analysis, if necessary). The average measured weld strength of each sample group is plotted, and the range of measured values of each sample (i.e., the largest minus the smallest value) is plotted on a separate chart. Control limits are set for each using statistical methods. Points outside the limits on either chart indicate a shift in the process. Thus engineers can determine the cause of the shift when it is first detected and eliminate it. This results in a higher percentage of conforming product and thus higher yields through process controls.

Acknowledgments

I wish to acknowledge the assistance of Maury Wells, quality engineer at RCA Astro-Electronics, for his critique and recommendations on an early draft of this paper. I also wish to thank Carol Coleman, technical writer at Astro-Electronics, for her perceptive and critical review of the material and for reorganizing the paper into a more readable format.

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N. Armour | R. Kleppinger | R. Morey | K. Pitts

Statistical process control for LSI manufacturing: What the handbooks don't tell you

If you are planning to use Statistical Process Control (SPC) to eliminate the bugs in your manufacturing process, read this article first. Palm Beach Gardens found some things out about SPC that you won't find in any of the books.

Palm Beach Gardens, a manufacturing plant for Solid State Division, fabricates wafers containing integrated circuit devices. The specific parts include many large scale integration (LSI) and high-reliability devices. The processes involved are complex; each wafer fabrication may involve up to 400 process steps. Several years ago, statistical process control (SPC) was chosen as a tool to control the processes to produce higher yielding wafers. A benefit of statistical process control is its ability to distinguish random, expected, variation in a process from variation caused by a systematic source (see sidebar).

Abstract: *Solid State Division's Palm Beach Gardens LSI manufacturing plant implemented Statistical Process Control (SPC) several years ago, and had less success than they expected. They found that this lack of success was partly due to not verifying assumptions critical to the effective use of SPC and not evaluating the data taking process itself. Once the non-process problems were correctly identified and solved, attention could be focused on solving the process problems. The benefits include accurate engineering information and improved yield.*

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At periodic intervals in the manufacturing process, samples of some critical parameter are measured, and the average and range (or standard deviation) are calculated. Control charts (graphs) of the average, X-bar, (with ± 3 standard deviation control limits) and the range , R, (also with ± 3 standard deviation control limits) are updated every time a sample is taken. A major criterion for a process being "in control" is that 99 percent of all observations will lie within these ± 3 standard deviation control limits. Another major criterion is that the process mean (average) show no trends. For example, eight consecutive averages above or below the overall average signal a statistically significant shift in the average.

Statistical process control won't cure your process problems. The methods, however, can alert you to situations where something has shifted or gone out of whack. SPC is a tool for efficiently directing engineering and production efforts to correct real problems and not waste time repairing a process that doesn't need attention.

After the initial application of statistical process control at Palm Beach Gardens,[1] we recognized that following the instructions in the handbooks was not enough. Although 140 processes were charted, with most of the charts following the techniques described in standard quality control handbooks,[2,3] few processes exhibited statistical control for any length of time. We were only partially successful in our efforts to bring more processes "in control." Consequently, we began an intensive effort to determine the reasons for lack of control and to correct the problems we found.

To simplify the task, only those processes deemed critical to production line and circuit probe yields were selected for this program. The number was limited only by the resources available. For bulk CMOS processing this resulted in the selection of the processes shown in the sidebar.

Production process engineers were assigned to each of these processes to characterize them and to make the changes necessary to get a controlled process. As these analyses progressed many questions were raised that had to be answered:

1. How should we be sampling product?
   a. Should we measure product wafers or monitor wafers?
   b. How many measurements must we sample?
   c. When we can measure both across the wafer and on different wafers, which should we do?
   d. When can we combine machines and processes?
2. Does current product match the control limits we are using?

Statistical process control

All processes vary. When manufacturing LSI wafers or any other product, measurement of either the product or the process will show inevitable, inherent variation due to unintentional process changes and random variation. When we attempt to control a process, for example to control resistivity by adjusting a dopant level, we measure the controlled quantity, resistivity. The result of this measurement is used to adjust the dopant concentration to keep resistivity fixed.

Ongoing measurements of resistivity, however, will show this inevitable process variation even if everything is working well. By conducting studies, statisticians and factory people measure the inherent amount of variability.

Statistical process control (SPC), as used in this article, is a procedure for monitoring process *variation* and generating information about the health of that process. If the process mean (average, or X-bar) shifts more than would be expected due to normal variation, we know something significant has happened to that process. Similarly, if the process variation (calculated as standard deviation or range) shifts more than would be expected due to normal variation, we know that something significant has happened to that process. The mean and variation are usually plotted on *control charts*, which allow simple and rapid visual detection of these problems. A "control chart" is a graph of a statistic (an average, a range, a percentile, not the data itself) of a process parameter over time that is plotted as each sample is taken so that out-of-control behavior will be immediately evident. Control charts also include bounds, or control limits, to determine if a point is within acceptable limits of random variation. The bounds for the present process are determined from past data (at least 25 sample points).

SPC will therefore tell us when a process changes. It is a sensitive, powerful tool for *monitoring* a process and generating alarms when the process data show trends. SPC is especially powerful because it senses these trends in the presence of natural process variation. If a process produces acceptable product and SPC shows no changes, it will still produce acceptable product. SPC by itself can't make the product better, or bring it into specification if it is out.

3. Do our measurements make sense?
   a. Are they consistent from operator to operator? From day to day? From machine to machine?
   b. Do the measurements correlate with the parameters we measure on the finished wafer?
4. What are the sources or assignable causes of our out-of-control problems?

We will discuss the general issues here, what questions come up repeatedly, and how to answer them. We will then show, using specific examples, how these answers were implemented at PBG and what effect they had.

Several of the concerns we had with implementing SPC are based on the mathematical assumptions. The underlying mathematics of SPC involve the following assumptions:

1. Averages of measurements of a process variable follow a *normal* distribution.
2. The averages are calculated from a *random sample.*
3. The sample comes from a *uniform* or homogeneous population.

To apply SPC to our production processes, we must sample product so as to obey the rules listed above. This isn't as easy as it sounds. How do we know the averages are normal? What constitutes a random sample? Can we use the middle wafer in each boat? Where is the major source of variability—within a wafer? Between wafers?

We also have other important concerns not directly related to the mathematical assumptions: How much do we trust our measurements? Are they consistent from machine to machine, operator to operator, day to day? We are currently measuring product for every lot. Is this right? Do we have to change our methods of monitoring? Should we measure product (actual wafers) or a control (monitor wafers)? Do we have to change the process? In general, we answered the questions as follows.

Does the average follow a normal distribution?

Since all the probabilities for determining "in control" versus "out of control" are based on the average following a normal distribution, it is essential that we check to be sure this assumption holds. If the averages *don't* follow a normal distribution, we may be reacting too frequently or too infrequently. To assess qualitatively whether averages follow a normal distribution, check the shape graphically by plotting histograms. The plots of the averages should be symmetric and bell shaped. To test more rigorously whether the averages are normal, use a Kolmogorov-Smirnoff statistic. Non-normality indicates we have problems to track down. Possible sources are:

1. Sampling.
   a. Combining measurements across something inappropriate, for example, two different machines.
   b. Sampling locally (across a wafer) rather than globally (across many wafers).
   c. Sampling across a region with systematic differences (front and back of a furnace).
2. An out-of-control process.
3. Measurement error.

Non-normality doesn't tell us much. The other areas of investigation listed below give better clues. For example, P+ diffusion doping had averages that were not normally distributed. We used other methods to discover that the high values were due to a measurement problem and the low values were due to a process problem.

Random sampling: Does it have to be random?

Is it legitimate to put a sample at the beginning and the end of the lot when you fully expect there to be differences between the beginning and the end? Only if the differen-

Processes identified for SPC

Gate Oxide (Thickness)
Field Oxide (Thickness)
Silicon Nitride (Thickness)
Polysilicon (Thickness)
P-well Oxide (Thickness)
Polysilicon Doping (Sheet rho)
Undoped CVD Oxide (Thickness)
P+ Diffusion Doping (Sheet rho)
N+ Diffusion Doping (Sheet rho)
BPSG (Thickness)
P+ Source/Drain Implant Doping (sheet rho)
N+ Source/Drain Implant Doping (sheet rho)
P-well Implant Doping
Gate Photo and Etch (Length) (Sheet rho)
Active Area Photo and Etch (Length)

Gate oxide, silicon nitride, P-well oxide, undoped CVD oxide, field oxide, polysilicon, and BPSG are all furnace operations to deposit films 500 to 10,000 angstroms thick.

P+ diffusion doping, N+ diffusion doping, and polysilicon doping are furnace operations to change the resistivity of a surface.

P+ source/drain implant doping, P-well implant doping, and N+ source/drain implant are all ion-implant operations where a surface resistivity is changed by adding ions.

Photo and etch for both gate and active area involve the imprinting, developing, and etching of an image on the surface of the wafer.

ces that you get are about the same size as your measurement error or the same size as ordinary sample-to-sample variability.

It is reasonable, when controlling a process that varies systematically, to place the samples systematically. However, one must constantly check to make sure the system isn't drifting. At PBG, we defined "constantly" to mean every 25 to 50 samples, which typically means between once a week and once a month.

All the furnace operations are sampled with evenly spaced wafers front to back, yet systematic variations across the furnace are not uncommon. By placing the sample systematically, one can check for the differences and correct the problems. This checking must be done independently of the typical X-bar and range charts; X-bar and range are not designed to detect systematic differences in the sample. (See the sidebar for details on how to check for differences across a sample.)

What determines the sample frequency?

One of the most frequently asked questions is how many measurements? Do you make several close together in space (multiple measurements on a wafer), or do you use several spread across the lot (several wafers)? Is there a right or a wrong place to sample? Do you sample every lot? Every hour? Every time the machine is set up for a process? How do you compare measurements on a wafer to measurements between wafers?

The answer lies in how the measurement behaves. One must collect and analyze data (a pilot study) to find how many measurements to make. If the wafers vary little from one to another, but the variability across the surface of a wafer is large, then we need to sample points across the surface. In this case, the total sample size is the number of measurements, whether they are on one wafer or five.

Conversely, if the variability across the surface of the wafer is small, but there are large differences from one wafer to another, we need to base the sample on multiple wafers. Multiple measurements on an individual wafer should be averaged and treated as one measurement. Similarly, if the machine is shut down for cleaning twice a shift, the sample probably should not combine measurements from before and after cleaning.

While you are checking such variability as within-local sample vs. across-global sample, you should also find out how repeatable your measurements are.

Questions like these—how do you determine the appropriate sampling plan—occur in every application of statistical process control. Multiple measurements close together in space or time vs. multiple measurements separated in space or time is invariably a key issue. The only way to answer them is to collect some data and analyze it. An appropriate analysis technique in this case would be components of variance, although a straightforward comparison of the variabilties of repeated measurements, local disturbances (say over the surface of the wafer), or variability over larger area should answer the basic question.

Once you have determined the major source of variability you can sample four to six points from the source. For example, in photolithography, the variability across a wafer was the same as the variability between wafers. The sample chosen was two measurements on each of two wafers, a sample size of four. For P+ diffusion, the variability of resistivities across a wafer was much smaller than the variability from wafer to wafer. The measurement equipment required multiple points on a wafer. The solution was to use the average for each wafer as the sample, with the total number of sample points equal to the number of wafers measured.

How do we evaluate our measurements?

If you don't know how accurate your measurements are, it's difficult to evaluate the process information you need to control the process. A great deal of information can be obtained by a few simple, designed experiments. (See the article in this issue by D. Coleman.) Key issues to address are:

1. The setup of the equipment—what varies from one measurement to another on the same equipment with the same operator?
2. Operator differences—does everyone do it the same way?
3. Short-term repeatability—measure samples more than once.
4. Long-term repeatability—measure several samples more than once over hours or days, perhaps on different test setups.
5. Differences from one piece of equipment to another.

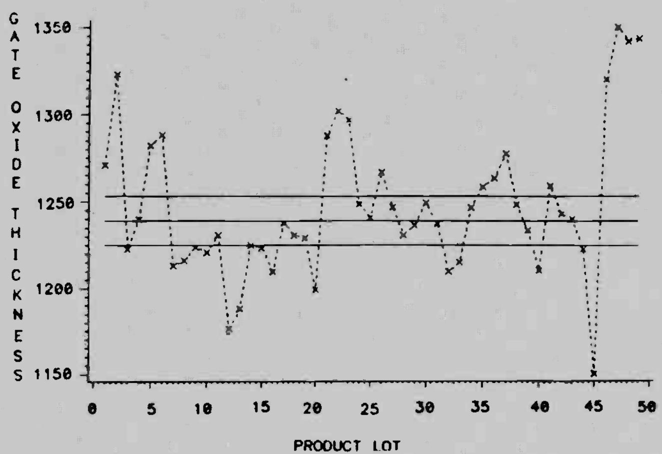


Fig. 1.

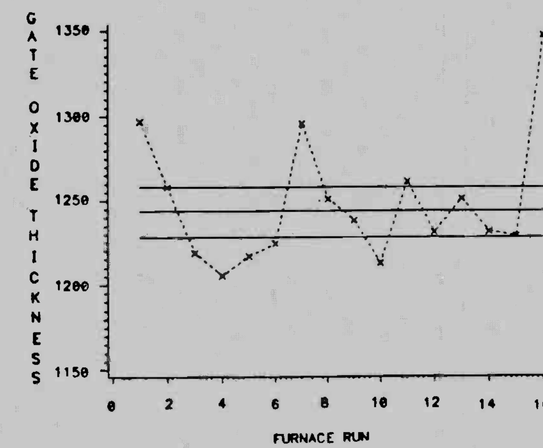


Fig. 2.

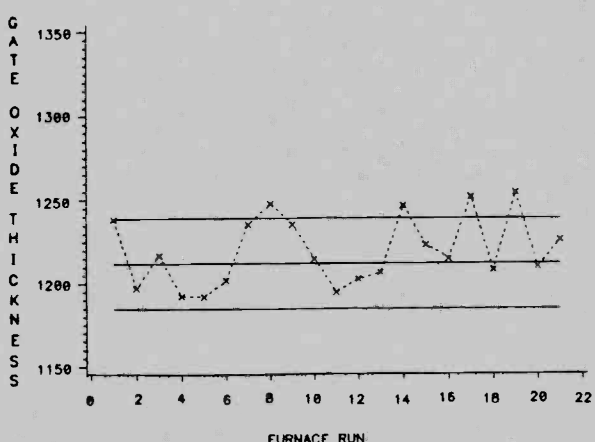


Fig. 3.

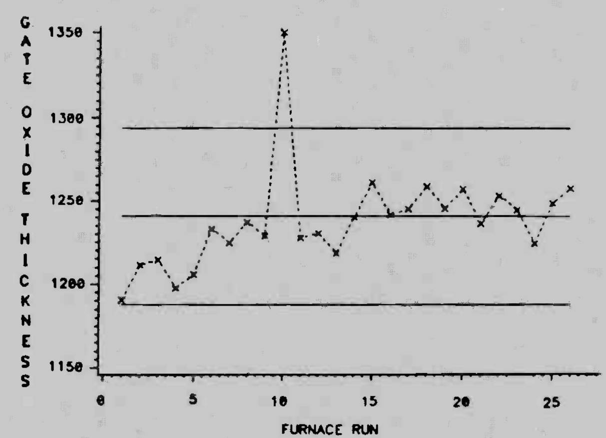


Fig. 4.

In all four figures, the plots are X-bar charts for gate oxide thickness, measured in Angstroms. Each point marked by an X is the average for a sample. With one exception, the sample from which the average is calculated is a furnace run. The center solid line represents the overall average of the process, and the upper and lower lines show ± 3 standard deviations for the average (the upper and lower control limits). If all the assumptions for statistical process control are met, a process that is in control will have 99 out of 100 points inside the ± 3 sigma (standard deviation) limits. There are many other tests one can apply to a process to test whether it is in control, but unless very few of the points fall outside the upper and lower control limits, additional tests are moot.

Figure 1 shows very few points inside the lines; Fig. 2 shows a few more; Fig. 3 shows more improvement; and Fig. 4 shows all but one of the points within the limits. The probable cause for the point that is extremely high is either incorrect time in the furnace or specifying the wrong process. Figure 4 demonstrates another out-of-control situation—trends. In this case, the thickness measured after the initial furnace runs was lower than the desired target of 1240 to 1250 Angstroms: therefore, the trend was a conscious adjustment to the process. For the four graphs, the width of the control limits around the average should not be compared directly, since different numbers of measurements were averaged in the four graphs. (The limits will be narrower when one averages more points.)

A typical experiment would be to measure five samples on all equipment three times. Analysis will determine measurement error (repeatability) and equipment biases.

For example, in the gate oxide investigation, we compared calibration methods on two different types of microscopes. One type was much more prone to calibration error and was also more variable. To eliminate measurement-induced problems, we chose to use the more stable microscope.

Product (every lot) vs. process (every run)

Most manufacturing measurements are done on a lot basis to ensure that the product will meet specifications. Frequently, process control requires a different way of collecting the information. Any time you run multiple lots together through an operation, you should monitor them together, not separately. A prime example of this at PBG is furnace operations. In the past, the sampling was done by product lot rather than sampling what product was processed in the furnace together. With experience, we found that sampling process lots rather than product lots was better in almost all instances.

Monitor wafer vs. production wafer

Another issue of concern is whether to measure product (actual wafer) or process (monitor or control wafer). To check the processes individually, we at PBG use monitor or control wafer measurements. This way we can monitor individual process steps without the data being confounded by those processes that preceded the process under test.

For example, in the gate oxide operation, we are growing a layer of oxide whose thickness we want to measure. We chose to measure monitor wafers so we have accurate information on how the furnace behaves. Thus, the control charts are not distorted by previous processing.

Is the process in statistical control?

After we determined the correct sampling and measurement methods, we then checked to see whether the process was in control over time. We found that many processes had problems in run-to-run variability. Since we had done the work to ensure valid sampling, we could then focus on correcting process problems.

Each of the examples cited here had at least one of the statistical or measurement problems described above. In the four specific examples below, all but the P+ source/drain implant needed some process improvements. Thus, to develop useful control charts, one needs to investigate both setting up the charts and whether the process is in control.

Specific examples

To illustrate some of the problems and solutions, we will use four examples of critical processes that we examined in the fourth quarter of 1984. These processes are gate oxide (a high-temperature oxide growth process), P+ diffusion (doping a layer of the wafer, also at high temperature), P+ source/drain implant (doping via implanting ions), and photolithography (printing images on the wafer and etching to get patterns). For all these processes, we examined the issues discussed above: sampling, product vs. process, normal probabilities, process under control, and measurement. Each example had minor problems in some areas and major problems in others.

Gate oxide thickness

The critical issues were sampling (both product vs. process and sampling with systematic difference across the furnace), and improved process control.

The original sample scheme measured three product wafers per lot. For this operation, a lot was one of several boats in the furnace, and each boat contained several wafers. Each boat was plotted separately on the X-bar and range charts, regardless of how many boats were in the furnace run. Runs varied from one to four boats. Furthermore, if two small lots were combined in one boat, the sampling plan was selected arbitrarily by the operator.

Another consequence of not monitoring the furnace on a run-by-run basis was the difficulty in assessing systematic difference from the front to the back of the furnace. Since wafers are loaded in a last-in-first-out (LIFO) sequence, front-to-back differences are not uncommon. The process can be adjusted to eliminate differences, but we must know if differences exist and if so, how large they are.

Problems that can be caused by incorrect sampling are illustrated in Fig. 1, where an incorrect X-bar chart (based on lots) had 65 percent of the lots out of control beyond the ±3 sigma limits. (Recall that if the process is in control, fewer than 1 percent of the averages will fall outside of these limits.) With corrected sampling (using educated guesses to determine what lots were in a run), the X-bar chart (Fig. 2) had half of the runs out of control. Clearly, sampling wasn't the only problem.

A sampling plan, based on furnace runs, placed a monitor wafer in each of four zones across the furnace. We used monitor wafers for two reasons: you can always run them, even if you have only one lot, and the monitor wafer can be measured on a more accurate microscope. The resulting chart is Fig. 3.

This chart still has some problems—33 percent of the lots are out of control. The improvement from Fig. 2 to Fig. 3 is due to consistent monitoring of the furnace; we were now able to see furnace problems when they occurred and to react to them.

With the new sampling plan, we could check for differences across the furnace. As suspected, there was a systematic difference (Fig. 5). The boats on the extremes (1 and 4) had thinner oxide than the boats in the center (2 and 3).

Engineering tests determined the source, or assignable cause, of the out-of-control points to be inadequate control of the temperature cycle. New quartzware was installed that allows nearly continual monitoring of the temperature (autoprofile thermocouple). The statistical process control

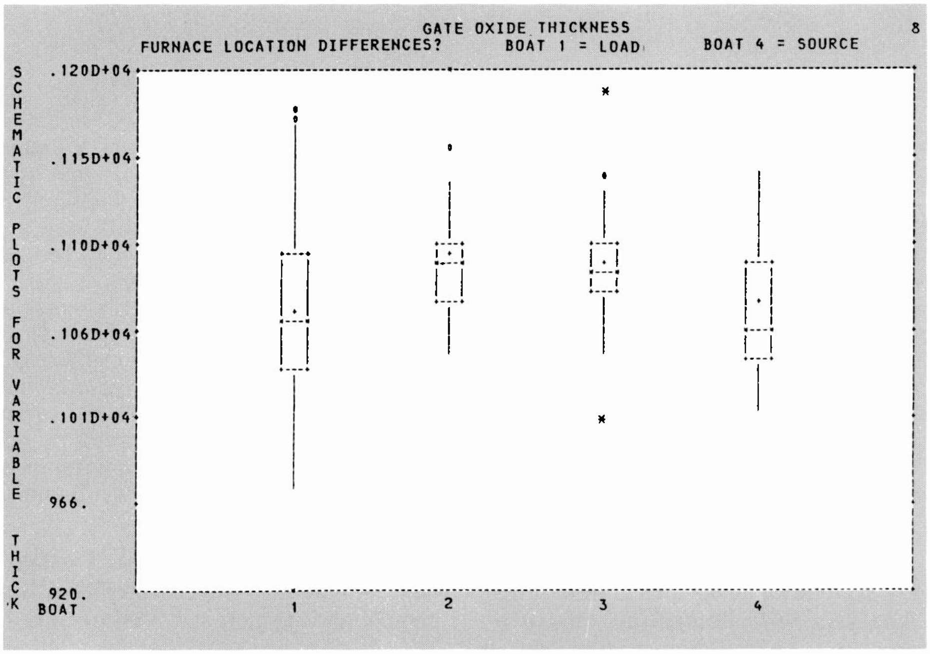


Fig. 5. Gate oxide furnaces frequently show thickness differences across the furnace. This is one common pattern where the center of the furnace (boats 2 and 3) is different from the extremes (boats 1 and 4). Other patterns include one of the extremes (either the load or source end) being low or high. Uniformity across the furnace is a problem common to many of PBG's critical processes (gate oxide, silicon nitride, CVD oxide, polysilicon, BPSG, and so on).

chart showing the much improved process is Fig. 4.

P + *source / drain implant*

The critical issues were measurement and test equipment. Examination of the source drain control charts revealed that the source/drain implant processes were not in control (see Fig. 6). Several possibilities were suggested:

1. Furnace variations (lack of control on an old furnace).
2. Wafer-to-wafer variability (the sample was three points on one wafer, which assumes variability across the wafer is larger than wafer-to-wafer variability).
3. Measurement accuracy and repeatability (using an unreliable four-point probe to measure the resistivity).

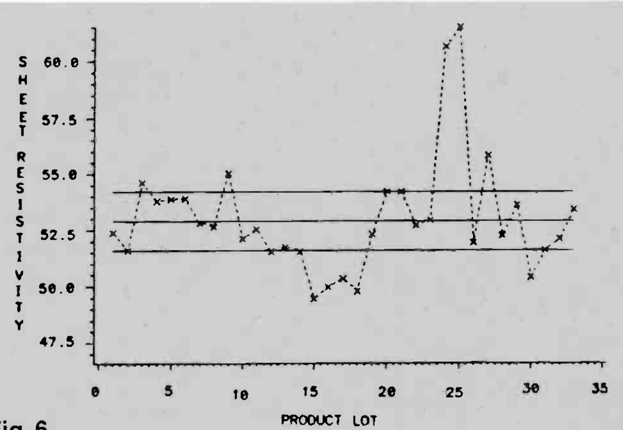


Fig. 6.

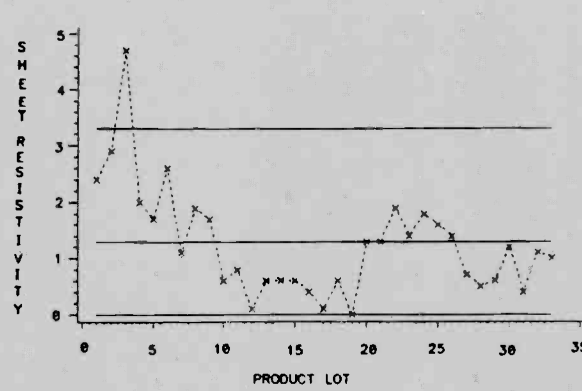


Fig. 7.

X-bar and range charts for P+ source/drain implant. Again, the Xs represent averages of individual measurements for a lot. The solid lines are the overall average (the center line), and the ±3 sigma limits for the average. Note that many points fall outside the 3 sigma limits for the X-bar chart, but that all but one point are inside for the range chart. The parameter being measured is sheet resistivity in ohms per square on a monitor wafer.

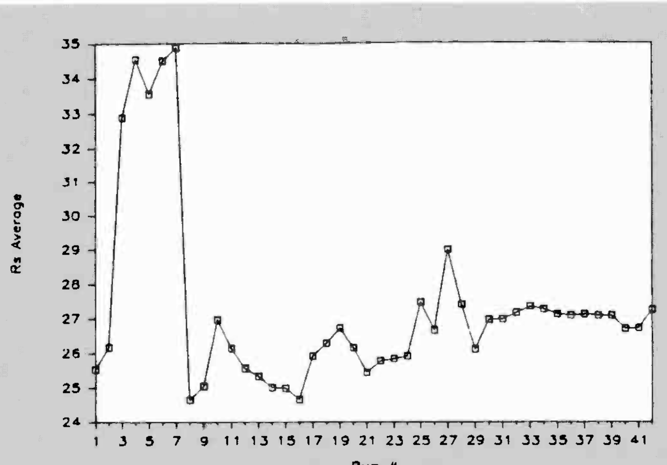


Fig. 8.

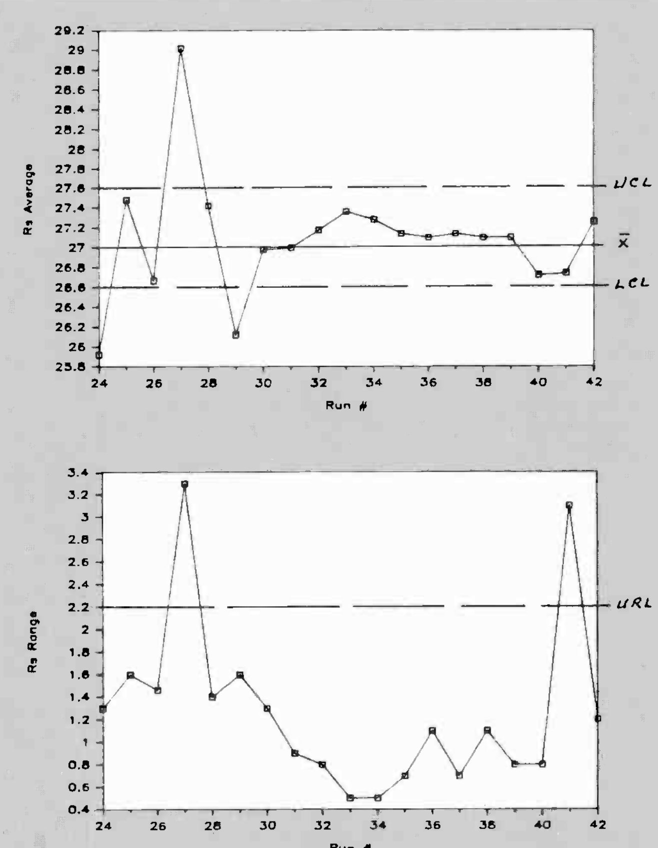


Fig. 9.

Sheet resistivity with the new equipment and test procedure. In Fig. 8, sheet resistivity (labeled Rs) varies considerably. As operators learn the correct procedures, the average stabilizes. Figure 9, X-bar and range charts demonstrate a process close to control.

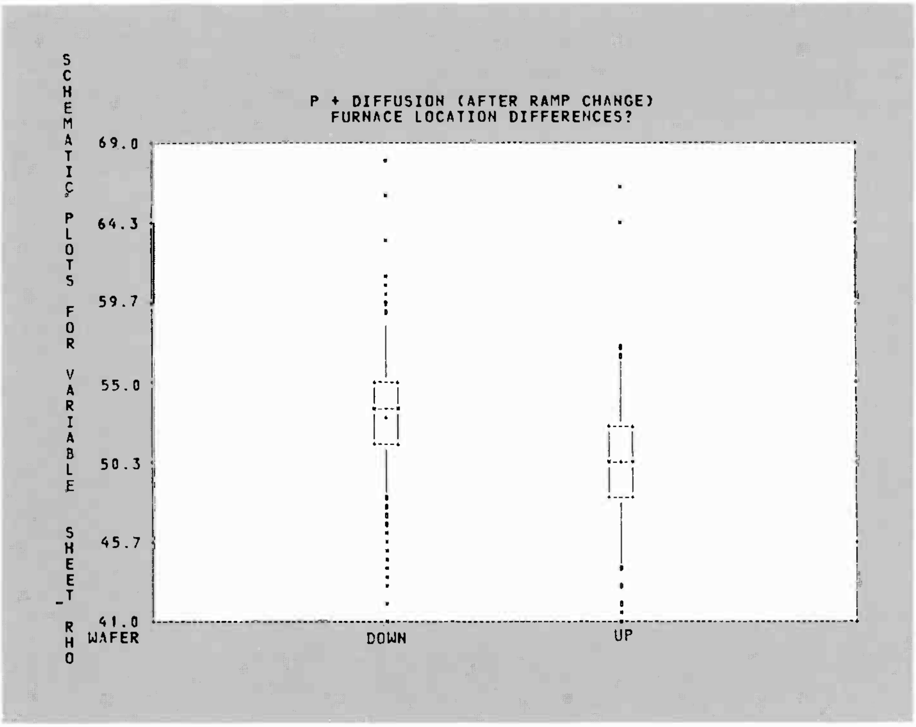


Fig. 10. Boxplot of furnace differences for P+ diffusion. In P+ diffusion, the boxplot demonstrates several problems. Many points are unusually far away from the boxes (marked by "*" and "0"). In addition, the downstream wafer is consistently higher than the upstream wafer. Both these problems violate assumptions for statistical process control (averages should follow a normal distribution, no systematic differences in the sample averaged).

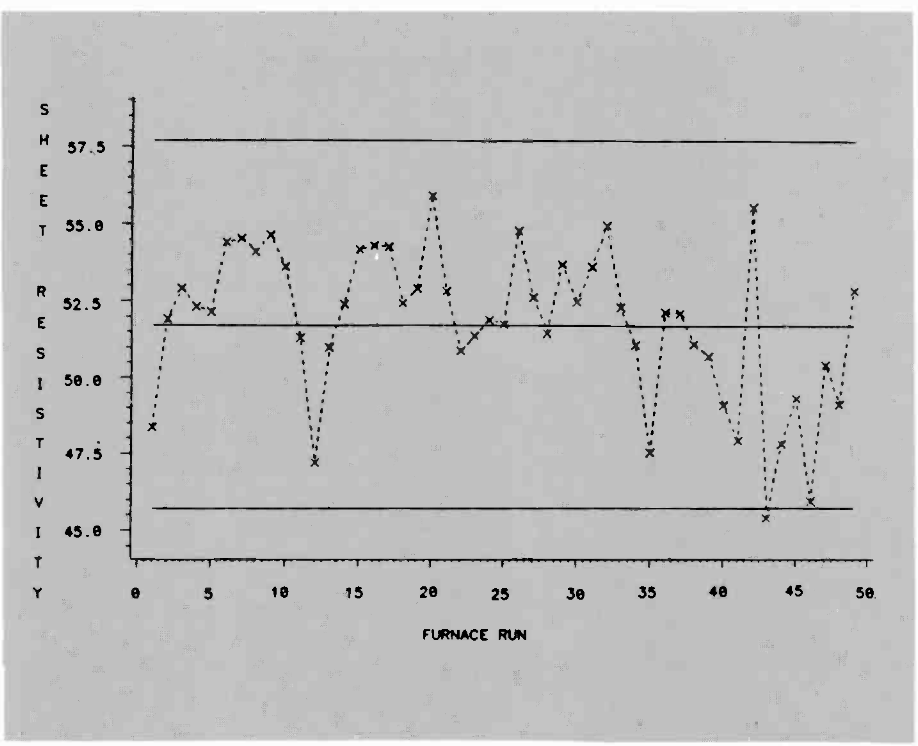
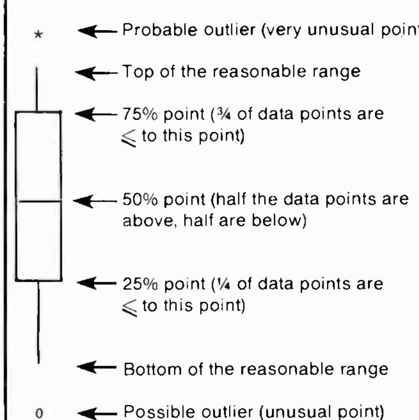


Fig. 11. X-bar chart for P + diffusion: The Xs represent the average sheet resistance for each furnace run. The solid lines are the overall average (center line), and the ±3 sigma limits for the average. Note that only one point is outside the limits. Since we know (from the box plots in Fig. 10) that we have some nonnormality in the data and the furnace has differences from front to back, the control chart may yield misleading clues to in-control vs. out-of-control.

Systematic differences

The most frequently used mathematical technique to check for systematic differences is analysis of variance, or ANOVA (see any standard statistical text). A graphical technique, heavily used in this project, is the *box-plot.* A boxplot is constructed from the 25-percent, 50-percent (median), and 75-percent points of the data. An algorithm for detecting unusual observations is also applied. See the diagram for an illustration.

Explanation of Box Plots



To compare machines, regions in a furnace, or different aligners, we can compare boxplots. A good rule of thumb (given 20 data points or so in each plot) is that if the boxes overlap, there is probably no statistical difference. If boxes don't overlap, you should worry. We start to concern ourselves when the 25 percent line of the higher box is above the 50 percent line of the lower box (See Figs. 4 and 10). For Fig. 5, the outside positions (1 and 4) are equivalent, and the inside positions (2 and 3) are equivalent, but the outsides are different from the insides.

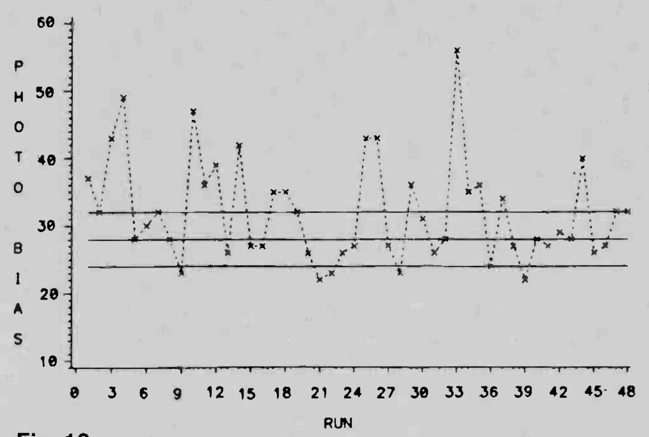


Fig. 12.

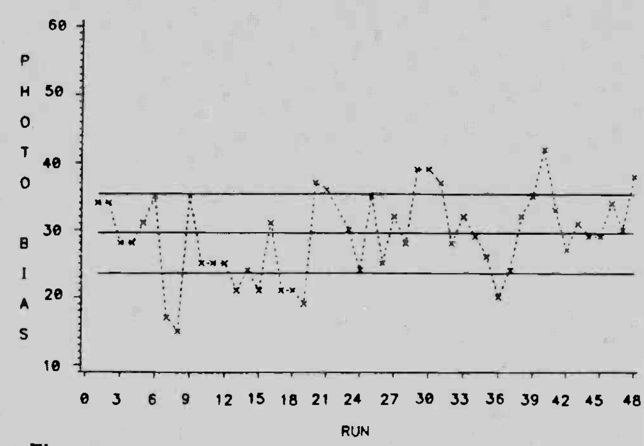


Fig. 13.

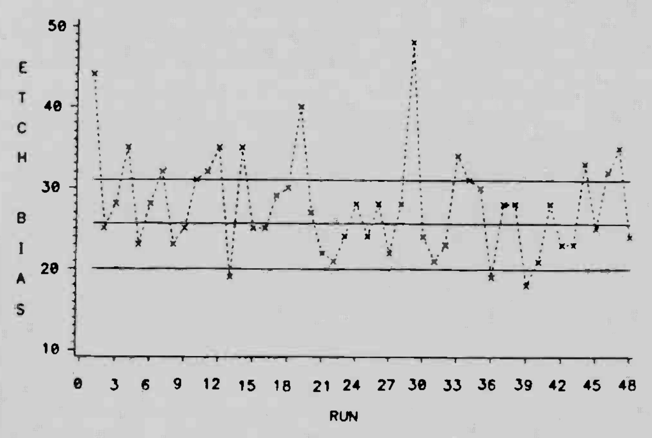


Fig. 14.

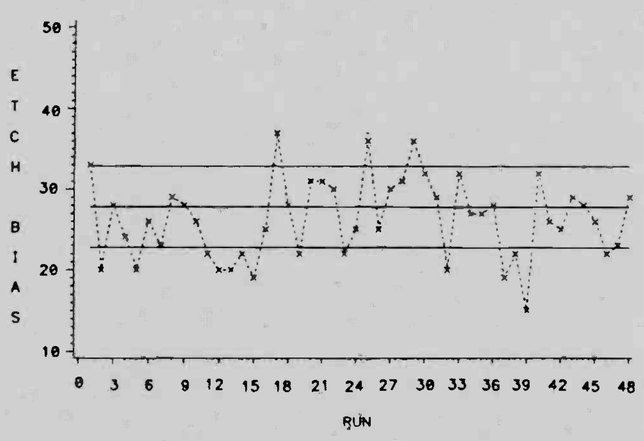


Fig. 15.

Figures 12-15 are X-bar charts for the photo and etch steps in photolithography. Figure 13 shows clear improvements in the photo process with the elimination of some mask-related problems. Figure 15 shows minor improvements for the etch process. As in previous graphs, the Xs represent the average for a lot, the solid center line, the overall average, and the outer solid lines, the ± 3 sigma limits for the average. If the process were in statistical control, 99 out of 100 points would be inside the limits (inside the solid lines). At best, these processes run in control 60 to 70 percent of the time, rather than 99 percent of the time.

4. Actual operation of the implant machine (we strongly hoped the implanter was operating correctly!).

Our investigations demonstrated clear problems with measurement and testing (furnace and four-point probe). The control chart data suggested the major problem was the variation between runs (lots) instead of variation over the half wafer being tested, since the range chart (Fig. 7) looks all right, but the X-bar chart (Fig. 6) has many points outside the control limits. In addition, sheet resistivity, as measured on the completed wafer, didn't demonstrate the same lack of consistency from lot to lot. We suspected (1) non-uniform heating of the wafer in the furnace being used and (2) testing errors with the four-point probe used to measure sheet resistance.

To solve the measurement and testing problems, we obtained a rapid optical annealer to replace the furnace and set up a more sensitive four-point probe (the Prometrix OmniMap) to measure five points over a full wafer instead of three points formerly measured over a half-wafer with a less sensitive probe. The data collected initially show a learning curve for using the new equipment and procedures (see Fig. 8, runs 1-30). The data then rapidly settle down, allowing calculation of control limits (see Fig. 9). We now have a process that is in control.

P+ *diffusion*

The critical issues were sampling (across wafer vs. within wafer, systematic difference across furnace), measurement, and process improvement.

We had two concerns regarding sampling. First, we had a LIFO system, where we suspected large differences from the front to the back of a furnace. Since the source for the P+ starts to diffuse immediately, wafers that were first in and last out received a heavier dose. In addition, the temperature at the door end was much cooler than the rest of the furnace.

Second, we measure multiple points on a wafer for more than one wafer. What was the appropriate sample? With large wafer-to-wafer differences, the answer is two wafers. (Although two wafers may not be sufficient for the normal probability assumption in SPC, we are currently constrained by the size of the furnace to only two monitor wafers.)

Data analysis revealed another complication, however—a systematic difference front to back, which overwhelms the within-wafer variability. Figure 10 is a boxplot of upstream vs. downstream differences. Although the boxes are not completely distinct, a run-by-run comparison shows the downstream wafer was always lower than the upstream wafer by 5 to 7 ohms. Since we can have only two monitor wafers per run, we don't really know whether we had a sampling problem of large wafer-to-wafer variability or a control problem of large front-to-back differences. Engineering tests and process characterization revealed we had some of each problem.

An adjusted process, which allows the temperature to stabilize, shows improvements, but retains the front-to-back difference. In this case, we need to do further analysis, removing the systematic front-to-back difference, and then re-evaluating the within-wafer vs. between-wafer variability to determine the correct sample basis.

Due to surface problems, we occasionally had wild measurements. The solution to the problem, etching a surface oxide, removed the bad measurements. Measurement errors are the source of the high values identified as unusual points by the boxplot referred to above (Fig. 10).

Process changes were needed to improve the consistency across the furnace and the consistency from run to run (see Fig. 11). More engineering attention is still needed to eliminate the front-to-back differences.

Photolithography

The critical issues were process vs. product and measurement. The photolithographic process is complex. In the pattern forming stage, we worry about the mask, coater (applying a film), aligner, and developer. In the etch stage, we are concerned with the etching machine and the result from the previous developing stage. Previously, the factory monitored the actual dimensions, looking at develop and etch measurements without accounting for mask differences or coater/aligner/developer effects. We were measuring the product, not the process. Charts are now organized by process (etch process, for instance) rather than a having a separate chart for each product line. Part of the plant monitors a high volume product to check on the process steps; the rest monitors a special "standard" mask, designed to check the process.

In addition to defining the correct parameter to monitor, we spent considerable time evaluating the measurement process—do the microscopes read the same? Do they have systematic differences? What were our actual mask measurements? They were not what the vendor told us they were. The improvements due to correct mask measurements and microscopes that are better calibrated are demonstrated in Figs. 12, 13, 14, and 15. The major improvement is in the photo process (mask inaccuracies).

We are now focusing on process improvement. The assignable cause of the photo points that are out of control appears to be aligner problems; the assignable cause for the etch points that are out-of-control appears to be incorrect modifying of etch settings.

Conclusions

Is SPC worth the effort? What can you gain? In dollars and cents, some of the process improvements have had a dramatic effect on yield. A properly-centered, consistent process in P+ diffusion has improved circuit probe yield from 42 percent to 48 percent, decreased the parametric reject rate from nearly 60 percent to 0 percent, and decreased line scrap 5 percent. We expect similar improvements from improved control of the remaining critical processes.

Furthermore, our efforts ensure that the charts are accurate tools to focus attention on the process changes that will yield the most improvement. The essence of statistical process control is to focus attention on real problems, not random variability. Our previous control charts, due to sampling, measurement, and monitoring problems, either did not alert us to real problems, or caused us to react to problems that were not inherent in the process. With the sampling/measurement/parameter problems solved, we now have charts that allow us to identify and solve the remaining process problems. We anticipate quicker results for our engineering effort.

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Left to right: Kleppinger, Armour, Pitts (seated), Morey.

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B.H. Gunter | A.L. Tadder | C.M. Hemak

Improving the picture tube phosphor screening process with EVOP

Some simple statistical approaches were used at Scranton to force the phosphor screening process to give up information about itself that was then used to improve it.

The purpose of this article is to describe some statistical approaches to manufacturing improvement that have demonstrated significant benefits at the Video Component and Display Division's Scranton picture tube manufacturing facility, but whose applicability within RCA could be widespread. We also want to discuss the nontechnical aspects of our work. This effort involved the close cooperation of three separate organizations: Scranton Manufacturing/Engineering (A.L. Tadder), Scranton in-process Quality Control (C.M. Hemak), and RCA Laboratories Manufacturing Technology Research (B.H. Gunter). We believe that whatever success we had was at least as much due to the ways we found to work together as to the technology we applied, so we'd like to describe how our working relationship helped catalyze our success.

The area on which our work focused was the phosphor screening operation. While more complete details of this process will be given below, briefly what it involves is applying, exposing, and developing three photosensitive phosphor slurries—for the green, blue, and red stripes— to the inside of the picture tube faceplate (also called the "panel"). This is a tricky operation requiring precise control of the slurries' chemical and physical properties, maintenance of tight registration and exposure control, and well maintained equipment.

When we started this work in March 1984, we found the process already to be in a state of good statistical control (as evidenced by the consistency of results over time), but improvement was required to reduce costs and meet the ever tighter demands of the marketplace and evolving technology. While our efforts were underway, from April to November, screen room process rejects were cut nearly in half (Fig. 1). Of course, other ongoing process improvement efforts were simultaneously occurring (better phosphors, equipment improvements, changes in slurry composition), but we feel it is significant that better slurry control was achieved despite the fact that during this period, new and more-difficult-to-manufacture product types were introduced. Additional improvements were realized in non-slurry-related categories (*e.g.* handling, equipment-related problems), aided, we believe, by the ability to react more effectively to problems because of the decreased process "confusion" level. Scranton screening operations are now running at the highest quality levels ever achieved, even in the presence of the most stringent requirements and most difficult tube types ever experienced. Moreover, the statistical approaches we applied *cost essentially nothing*.

How was this done? The answer is that we added to the plant's ongoing efforts some simple statistical approaches—involving ideas that can be learned and used at any RCA location—to force the Scranton screening process to give up information about itself that we then used to improve it. The technique is called EVOP, which is short for evolutionary operation.[1,2,3] It has been around for over 25 years, but seems to have been little known or applied outside the chemical process industries.[2]

Of course, Scranton's phosphor screening operations *are* chemical processes, so EVOP was clearly applicable. The techniques can be used to improve any process, however, and we may indeed try them on some distinctly nonchemical processes at Scranton.

The essence of EVOP is that any manufacturing (or service!) process can be made to produce not only product, but also information about itself that can be used to improve process "health," product quality, and hence, productivity. To do this, one

Abstract: *This article describes some statistical approaches to manufacturing that have demonstrated significant benefits at the Video Component and Display Division's Scranton plant. Also discussed are the technical aspects of the work.*

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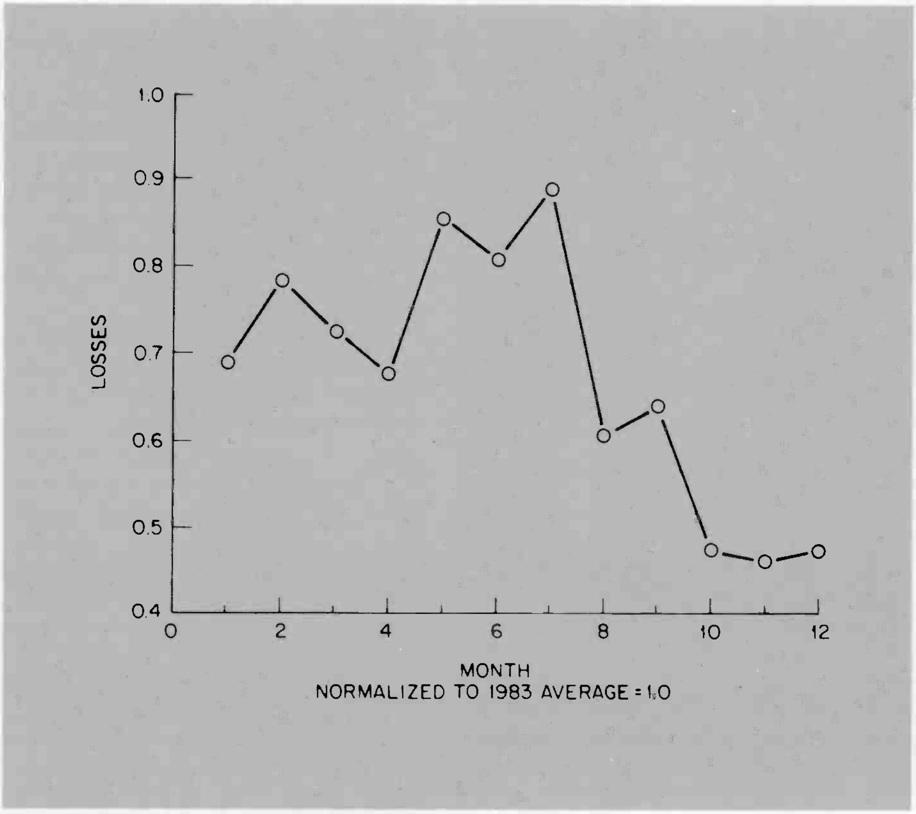

Fig. 1. *1984 screen room 2 process losses.*

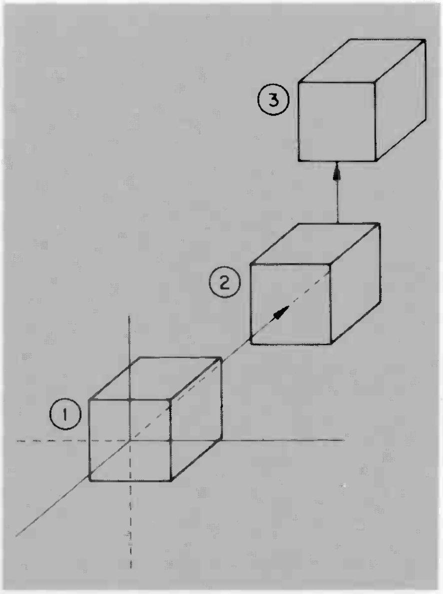

Fig. 2. *A schematic representation of three EVOP cycles. The results of previous cycles are used to determine the best direction for improvement of the next cycle.*

makes small changes in key process variables and uses the resulting slight changes in yields (or in some measured product characteristic, if possible) to determine the effects. Statistics is necessary because only small changes are made so as not to upsetting production. Normal process "noise" would overwhelm the ability to detect these effects if conventional "one variable at a time" methods were used—especially when interactions among variables are present. The factors being investigated are varied in a carefully predetermined pattern chosen according to statistical principles to give the most information at least cost. The data thus obtained are then statistically analyzed to quantitatively describe what effects the changes had and therefore how to modify nominal settings in order to improve results. These cycles of small changes, analysis, and modification of nominal settings are repeated until no further improvement can be achieved (see Fig. 2). It is important to note that these changes are made as part of normal production operations over an extended time period. They do not represent one-shot experiments. For example, approximately 250,000 panels were processed for the three EVOP cycles in Scranton.

Optimal (or nearly so) settings for the process variables are thus determined. Of course, if optimal settings exist at the outset, no improvement will result. But this is rarely the case, even in long-established operations. The ideas can also be extended to optimizing for several characteristics simultaneously so that one aspect (*e.g.,* throughput) isn't improved at the cost of another (*e.g.,* maintenance costs). In this way, overall process quality and productivity are improved.

One other point should be made: EVOP is an *active* approach to manufacturing improvement as distinguished from the passive observational techniques of traditional data collection and reporting systems. Small changes are deliberately made in order to force the process to react. This considerably extends the power and flexibility of process improvement efforts, because any process variable can be chosen for investigation, not just those variables that are being monitored as part of routine data collection efforts. In fact, as those who have struggled to make sense of piles of historical data know, this is often the only way to obtain pertinent process information; existing "happenstance" data are often too contaminated with extraneous noise to be useful for process improvement.

EVOP isn't for everyone. Generally speaking, a manufacturing process must already be in a state of statistical and management control, process documentation must be in order, and the required process information must be reliably obtainable before an EVOP program should be contemplated. Especially important is that any necessary process measurements (including yield figures at an inspection point) be properly defined and adequate. Though this is often taken for granted, it frequently happens that what is being measured may be more measurement "noise" then process behavior. Without these prerequisites, more can be gained simply by eliminating the disturbances and problems that prevent the process from operating to its full capability. Indeed, any improvement from an EVOP program may be "washed out" by the waste and inefficiency of the excess variability of a process that is frequently out of control. But when stable operation is the norm, further process improvement can be gained only by changing the process settings-or by investing in major process upgrades. Quite often, the improvements obtainable by an EVOP program can help pay for such major changes, or even make them unnecessary In such cases, EVOP is a powerful and practically costfree technique to improve process performance.

Scranton phosphor screening: Some background detail

At present, the Scranton plant has two separate phosphor screening rooms. There are some equipment differences between the two rooms, but the processes are essen-

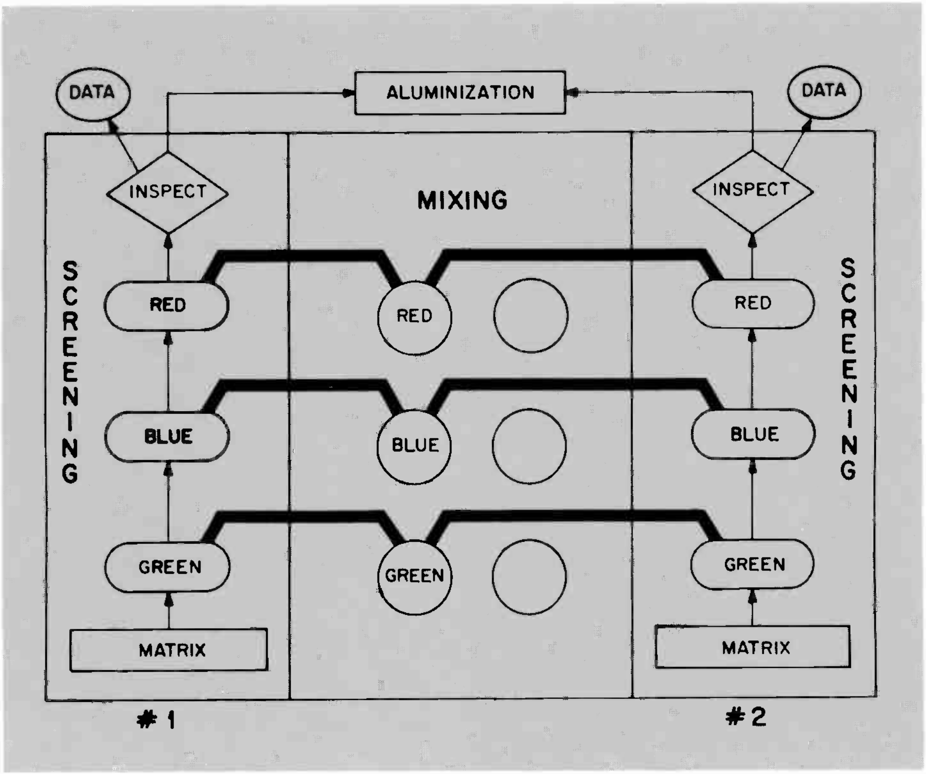

Fig. 3a. *Scranton mixing/screening operation.*

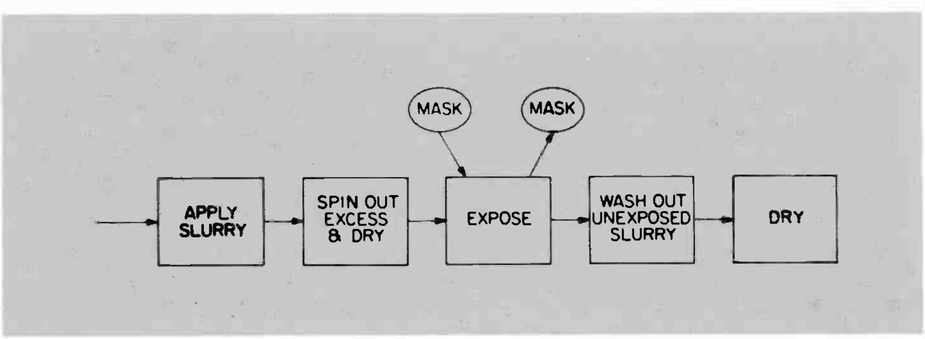

Fig. 3b. *Process steps necessary to print each of the three colors on a panel.*

tially identical. Furthermore, the area where the phosphor slurry is prepared for both rooms is separate from the screening area. A simplified schematic of the overall mixing/screening operation is given in Fig. 3. Fig. 3a shows in greater detail the sequence of steps required to print each color on the panel.

Our goal was to alter the composition of the three separate slurry soups to reduce slurry-related defects as determined by visual inspection of the screened panels immediately after screening. For proprietary reasons, we shall omit the details of the compositions. It is sufficient to describe how the procedure worked for each slurry separatelyand that three aditives per slurry were used. As indicated above, the three colors are mixed and deposited independently of each other, and the visual inspection can distinguish defects by color. So we simply "EVOPed" all three colors simultaneously and independently.

The slurry is a mixture of numerous chemicals. Included are three surfactant additives—call them A, B, and C—which are used to help make the slurry smoother and more able to wet the panel surface. These are added in very small amounts, but have an impact on how uniformly the slurry flows and coats the panel. The photographs in Fig. 4 show some of the defects that result when there are problems. All these defects directly affect product quality, because they are clearly visible when assembled into a finished tube and illuminated by an electron beam. Unfortunately, they are difficult to see when an inspection light is used before the panel is assembled into a picture tube, and the cost of scrapping and reclaiming the tube after the electron gun is inserted and the tube is exhausted and sealed is much higher than the cost of reclaiming immediately after screening. Consequently, improving in-process quality has a major impact on productivity. If by adjusting the levels of the additives, process performance could be improved, the resulting economic benefit would be important beyond the immediate reduction of scrap costs in screening.

With this as motivation, we began to examine how the levels of the three additives were determined. To take advantage of the first-hand knowledge available, we talked with many key process personnel. We found that there was a great deal of knowledge, but that systematic statistical studies had not been been done in the laboratory or on the line. Furthermore, the traditional one-variable-at-a-time approaches that had been used could not reveal interactions. The engineers, chemists, and technicians who worked with the process knew that interactions were important.

On the basis of this information, it appeared that the EVOP approach could be beneficial. To assure smooth operation of the program, we wanted to fully explain to key process technical personnel how the approach would work and benefit from their expertise on how to set initial process levels and make "small" changes without significantly interfering with production. We also needed to set up a procedure for making the necessary changes to the slurry in the mixing room on a specified schedule, and for capturing the relevant inspection results and assembling them for evaluation. While none of this was technically complex, the logistic details to to do it smoothly were extensive. We held many meetings, spent time talking with technicians and production workers on the production floor and in the slurry mix area, and carefully documented the procedures that were agreed upon. Such attention to detail can be tedious, but is absolutely necessary to assure the success of such a program. We all feel that this extensive on-site communication was the key to the subsequent smooth operation of the EVOP program.

How the EVOP program worked: Some technical details

(Note: Reference 3 provides a readable explanation of this and other statistical designs.)

For each of the three additives A, B, and C, "standard," "low," and "high" levels were

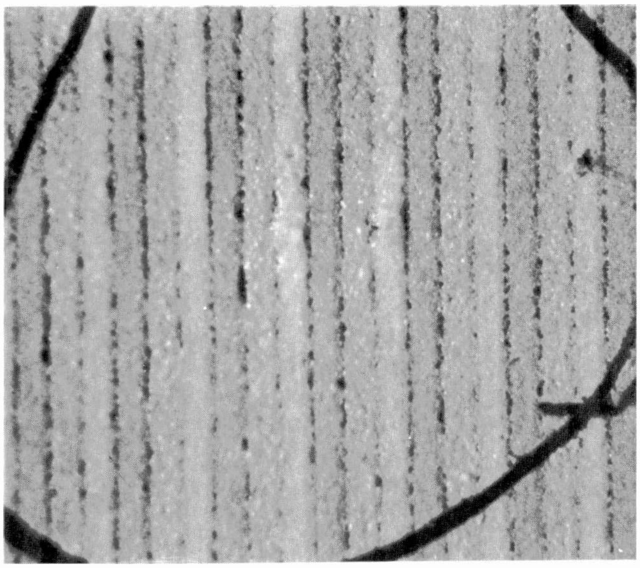

Fig. 4a.

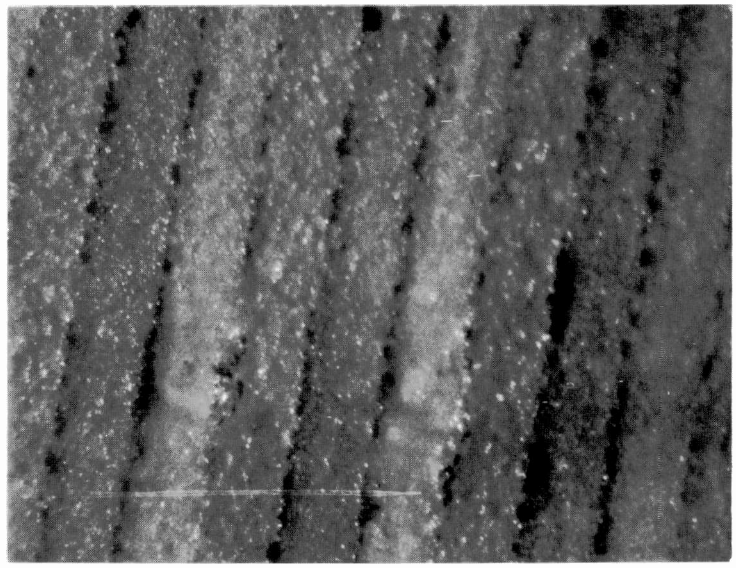

Fig. 4b.

Figure 4a is a 20X and 4b a 50X magnification of a phosphor nonuniformity caused by a failure of the phosphor slurry to smoothly flow and coat the panel. Note that the defect appears only every fourth line—i.e. one color only. In this case it was green. This will cause dark spots in the green phosphor in the finished lighted tube.

determined, denoted by 0, −1, and +1, respectively. The 0 standard level was chosen at what was currently considered to be the desired nominal. The −1 and +1 settings (the "+" will be omitted hereafter) were chosen to be small changes (−1 a little less; 1 a little more) that would not significantly affect production, but would nevertheless have an observable impact if the effect were of practical significance. Actually, we chose the magnitude of these changes based on adjustments that previously had been made from time to time to counter problems.

It is not necessary that the actual levels used be equally spaced. During one EVOP cycle, for example, for one of the slurries we used values of 0.09 for low, 0.15 for standard, and 0.27 for high for additive "A" (these are parameters for the computer program Scranton uses to compute the slurry "recipes").

If all three levels of each of the three factors were run in all possible combinations, there would have been 3^3 or 27 different possible combinations to run. Not only was this impossible from a practical standpoint, but it was also unwise from a statistical standpoint. A great deal of redundant information would have been produced. Our interest was in finding a direction to go for process improvement. For this purpose, it was sufficient to look at the $2^3 = 8$ combinations of high and low settings only. In addition, we decided to run the "center point" of standard settings twice (essentially once per week, because the entire $8 + 2 = 10$ runs required about 14 days of production) as a check to see if any major changes in process results occurred that were not attributable to the different additive combinations. If such changes occurred, these center point runs would have helped us "correct" the data so that we could still see what was going on (the technical term for this is "blocking"). If not, the replicated center point would give us a feel for what kind of random change was present to compare with the "effects" due to our deliberate variations in slurry composition.

It is useful to visualize this "design" in the following way (see Fig. 5): Consider each possible combination of low and high settings for the three additives—that is, of −1s and 1s—as a point in three dimensions. The eight combinations are: (− 1, − 1, − 1), (1, − 1,−1), (−1,1,−1), ... (1, 1, 1) along with the center point at (0,0,0). It is easily seen that these nine combinations lie at the corners and center of a cube whose center is at the origin, (0,0,0). Each corner (and the center) represents a particular combination of additives that was mixed in the slurry and run in production. The screening inspection yields for each combination then provided the "response" data to evaluate the effects of these changes.

Analysis of the data does *not* proceed on a day-to-day basis. In order to be able to detect the effects of the changes in a noisy background, results are averaged over all the days. This has a simple interpretation in terms of our experimental cube. The effect of any of the changes is estimated as the difference between the average of the

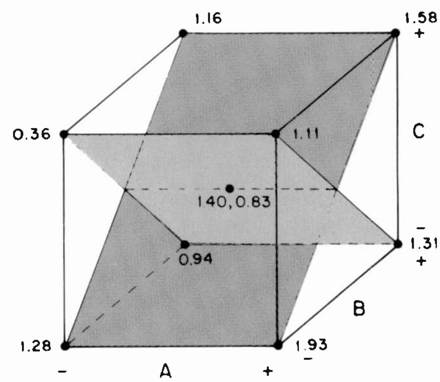

Fig. 5. *A geometric picture of the B-C interaction. The interaction is the difference in the averages of the points on the two diagonal planes.*

results when the change is on the high side and the average of the results when the change is on the low side. (For the more mathematical reader, we note that this is exactly equivalent to a formal least-squares estimation procedure for this kind of balanced two-level design.) Geometrically, this means that the "main" effects of the three chemicals are measured as the difference between the averages on the high and low faces of the cube in each of the three dimensions. Note that this means that the data at any one setting does multiple duty. This is the source of the "efficiency" of statistical design and analysis over the usual one-variable-at-a-time approaches. For the illustrative data given in Fig. 5—which would represent the results from a typical EVOP cycle—the effects would be computed as shown in Table 1.

Table I.

Name		Effect	
	"+" Average	"–" Average	Effect ("+" or "–")
A	1.73	0.91	+.82
B	1.25	1.15	+.10
C	1.05	1.34	–.29
AB	1.11	1.29	–.1
AC	1.20	1.19	–.01
BC	1.4	0.93	+.53
ABC	1.20	1.19	.01
error (from replicated center point)			.20

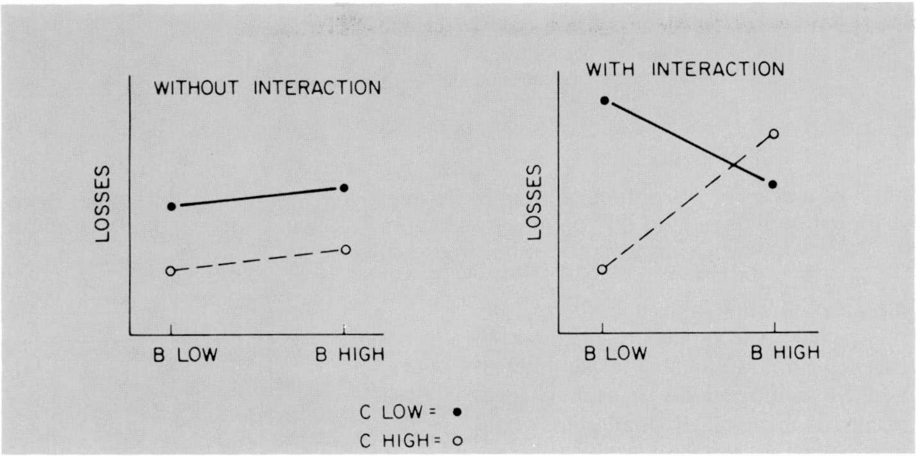

Fig. 6. *Graphical interpretation of the interaction between slurry additives B and C. Note that the effect of B going from low to high level depends on whether C is at its high or low level.*

In Table I, the "+" and "—" signs prefixing the effects represent the effect in going from the high to low level. For example, the −0.29 value for chemical C means that on the basis of these data, going from the low to high level of chemical C results in a decreased process loss of 0.29. The +0.82 for A means that the estimated effect of going from a low to high level of A is to increase losses by 0.82.

The AB, AC, BC, and ABC effects are interactions. They represent the "nonadditivity" of making more than one change simultaneously (due to synergy or interference among the chemicals). Figure 6 gives a simple graphical interpretation of the interaction between B and C. Interaction effects between pairs of variables in this design are easily computed as the difference in averages between diagonal planes on which the product of the variables are positive vs. those on which they are negative. For example, the effect of BC is computed as the average of the four values at (−,−,−), (+,−,−), (−,+,+) and (+, +,+) minus the average of the values at (−,+,−), (+,+,−), (−,−,+), and (+,−,+). Figure 5 pictures the two diagonal planes represented by these two sets of four points. The three-factor ABC interaction effect (which, as is usually the case for such designs, is negligible) is computed as the difference in averages between the two tetrahedrons on which the three-factor product is positive and negative, respectively.

The error estimate for this design is computed as $\sqrt{2}/2 \times$ the magnitude of the difference between the two center points, and represents approximately one standard deviation of the uncertainty in the above estimates due to typical process noise. It is important to keep in mind that the results obtained above are estimated from real process data. Such data contain the effects of the usual "random" variations that occur in the process as well as the slight effects due to the deliberate changes that were made. Thus there is uncertainty in our estimates of the effects due to the fact that when we repeat conditions, slightly different yields will result. The change in yield when we repeat the nominal levels of chemicals helps us determine what the noise level is.

While sophisticated (and somewhat more powerful) statistical procedures such as multiple regression or analysis of variance are available to analyze these data, one consequence of running a well-designed EVOP program is that usually such sophistication is unnecessary. Simply by scanning the list of effects, it is obvious that the amount of A and the interaction between B and C stand out. The rest of the effects are roughly equal and much smaller, and are most likely just the result of random process noise. A rough rule of thumb is that only values that are twice as large in magnitude as the effect error estimate are likely to be real. By this criterion we see again that only the A and BC effects appear real.

The payoff: Making changes to improve the process

Once the EVOP analysis is complete, the time for the payoff arrives. Until this point, nothing had yet been done on a permanent basis to improve the process. We therefore all got together again to discuss the meaning of the results and the changes that should be made. For example, for the illustrative data given here, the positive A effect clearly would mean that to reduce losses, the level of A should be reduced. The positive BC interaction would mean that either B should be increased and C decreased simultaneously, or vice versa. This would have the effect of making the interaction value negative. Due to the marginal negative value for the C effect, it is likely that the best bet would be to increase C (this would tend to lower losses if the C effect were real) and decrease B. In our case, when changes were to be made, how far to go was left up to the process engineering personnel. Because EVOP cycles make only small changes, we would not expect the predicted effects to hold over large changes in the chemical additions (nonlinearity would likely foul up the predictions). A reasonable decision would be to move the new process nominal center point to the (−,−,+) point of the EVOP cube, and to begin a new EVOP cycle around this point, both to confirm the previous results and to explore whether still further change could be beneficial.

Over the course of several months, three EVOP cycles were run. By the end of the third cycle, we were unable to effect any more improvement: we had "optimized" the additions of the three chemical additives we were investigating. The overall results—as measured by the strong trend of decreasing scrap—appear to have been positive.

Conclusion

This EVOP program was only a beginning. Further work could undoubtedly be done in the screen room, but right now we are looking at other areas where potential benefits are greater. The screening area is running better than it has ever run before, and it would be inappropriate to continue to concentrate resources there. Through our success and the smoothness of this project, we have convinced other managers that the EVOP approach can help them. Perhaps more important, we have demonstrated that statistical approaches to process improvement can be valuable adjuncts to existing engineering efforts. We have also demonstrated that the three separate organizations we represent can pool their expertise and work together to produce results that none could have achieved separately. What is required is long-term commitment to the effort, significant time spent on site at the plant learning and communicating about the process, and the ability to manage the procedures required in a production environment. Because these conditions are present at Scranton, we look forward to continuing our work together to help RCA's Video Component and Display Division remain the leader in its marketplace.

Acknowledgments

We did not do our work alone. Our success was to a great extent due to the cooperation and expertise of many people in the Scranton screen room. We would particularly like to thank Larry Ditty, Process Engineer in charge of the chemical mixing area, who helped set up and run the program; Jack Ostir, who worked with us to ensure that production personnel were on board; and Bob Murray, without whose advice and encouragement we would have made a thousand mistakes. Bert Gunter would also like to thank Mike Borosky, Jim Lupini, and all the other operations personnel for putting up with all his questions and helping him to understand what was going on.

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R. Kleppinger

Wafer particle reduction in LSI production

The laser defect scanner in use at Palm Beach Gardens has resulted in a significant drop in the number of particulates left on wafers after processing.

The reduction of particulates left on wafers during processing has resulted in a significant increase in circuit probe yields at Solid State Division's Palm Beach Gardens plant. This was accomplished by using a laser defect particle counter technique.[1] This article will discuss the methods used to reduce and control wafer particulates in a production environment.

Equipment design

The Tencor Surfscan laser defect scanner is being used at Palm Beach Gardens to detect wafer particles 1 micromillimeter or larger. 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.[2]

Equipment calibration is checked using a "Calibration Standards" wafer supplied by Tencor. This wafer has arrays of etch pits in an oxide layer, and is used to determine continued sensitivity.[3] Although this does not furnish an absolute defect size it does insure that the equipment sensitivity does not change.

Abstract: *The reduction of particulates left on wafers during processing has resulted in a significant increase in circuit probe yields at Solid State Division's Palm Beach Gardens plant. This was accomplished by using a laser defect particle counter technique. This article will discuss the methods used to reduce and control wafer particulates in a production environment.*

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Test procedures

The following test procedures have evolved during the reduction of process particle generators:

1. During the initial analysis stage an unopened cassette of 25 substrate wafers are laser scanned using the test parameter limits. The cassette of wafers is then subjected to the process being evaluated and re-scanned using the same limits.

2. Once the process has been characterized using the 25-wafer test sample, the test sample is reduced to three wafers, and the process is monitored daily. These wafers are presorted to a maximum count of 10 (the count usually averages two to three defects greater than 1 micromillimeter). The three wafers are placed in a cassette, subjected to the process being tested, and rescanned using the test parameter limits. During this testing period a maximum limit is established and procedures are developed to maintain the process below this limit.

3. The final method involves the use of a single test wafer measured before and after subjection to the process being controlled. In this case, the production line operator running the process does the wafer particle testing using the parameter limits. If the total particle count added by the process exceeds the maximum limit, the operator shuts down the process and cleans the equipment in the manner previously developed. Product is not run through the processing equipment until a new particle test meets the limits. Currently, this test method is preformed daily.

Photoresist processing

Positive photoresist process data collection started in April 1984. The following process steps are measured daily using the three-wafer test procedure : bake-coat (the two HMDS bake ovens and six coater track testing was separated by December), seven aligners, one developer, and a test combining all four steps with the photoresist exposed. Figure 1 shows the progress in reducing particulates. Figure 2 shows the particle reduction of the four separate processes since December. The processes and equipment were modified to reduce particle generation by:

1. Minimizing the number of hand wafer transfers.
2. Reducing the nitrogen back fill pressure of the HMDS bake ovens.
3. Continuously cleaning all cassettes.
4. Installing 0.2-micromillimeter filters in the photoresist lines.
5. Installing a hot plate soft bake system after coating instead of the tunnel bake system.
6. Cleaning the aligner track and prealigner with acetone every shift.
7. Installing point-of-use filters for the develop solution.
8. Installing point-of-use 0.2-micromillimeter deionized water filters.
9. Installing an on-axis wafer spin dryer that rinses to a minimum resistivity.

Figure 3 is an example of the graphical particle tracking technique used during this period. The limit has been imposed on the data from the beginning, even though it may not have been applied then. The increase in particles in October was the result of abandoning a cassette clean-

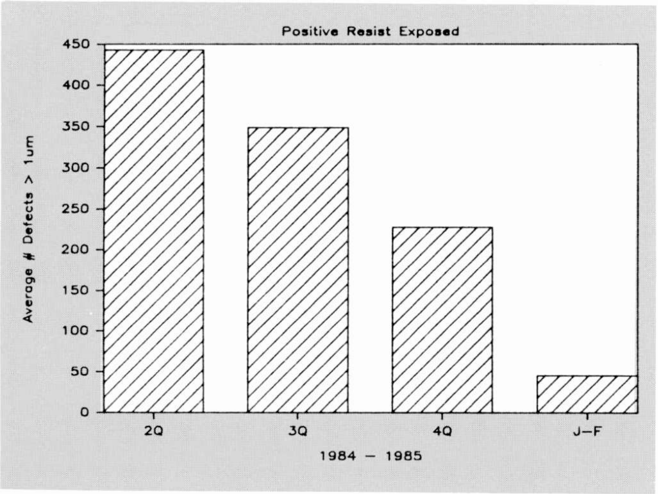

Fig. 1. *Wafer particulates added when processed through all photo steps.*

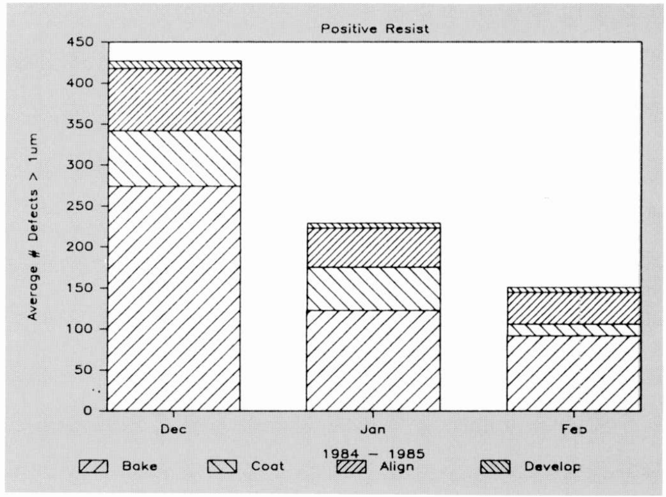

Fig. 2. *Stacked bar chart of four individual positive resist process steps.*

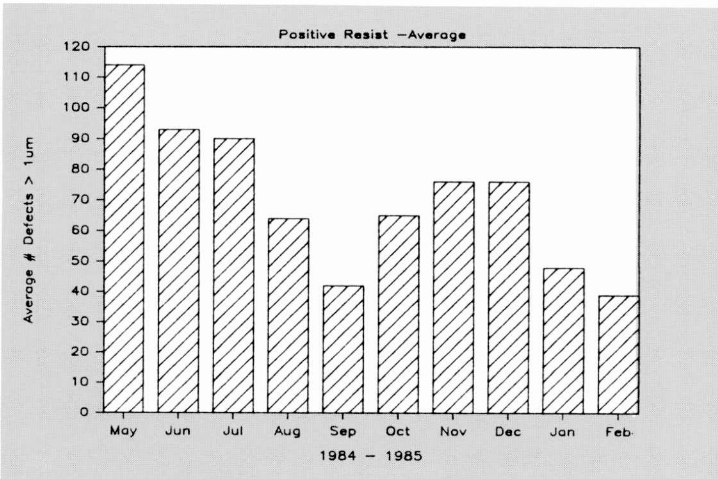

Fig. 3a. *Average number of defects added by photo aligner step.*

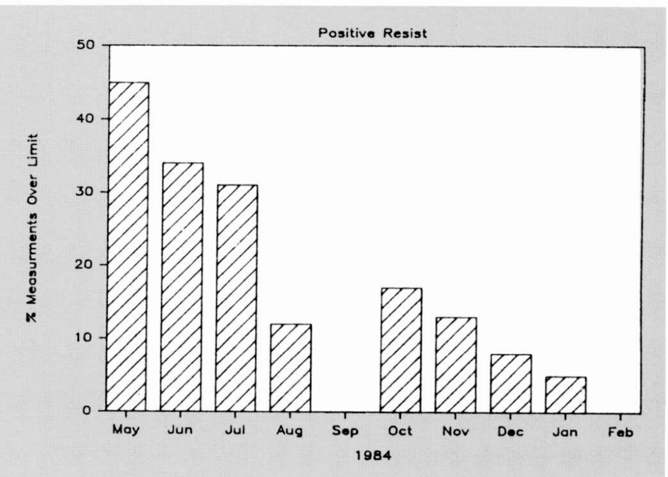

Fig. 3b. *Percent of measurements over specified limit for photo aligners.*

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 and is counted as a defect.

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

- Defect size—1 μm^2 (smallest 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).
- Area-defect limit—9999 (maximum acceptable number of cells within area defects).
- Haze limit—9999 (maximum acceptable number of cells containing a point defect).
- The paramteter limits set are printed on the internal printer followed by the number of point defects, line defects, are defects, total defects and haze value for each wafer. The total is the sum of the point, line, and area defects. Only the total defect data is presented.

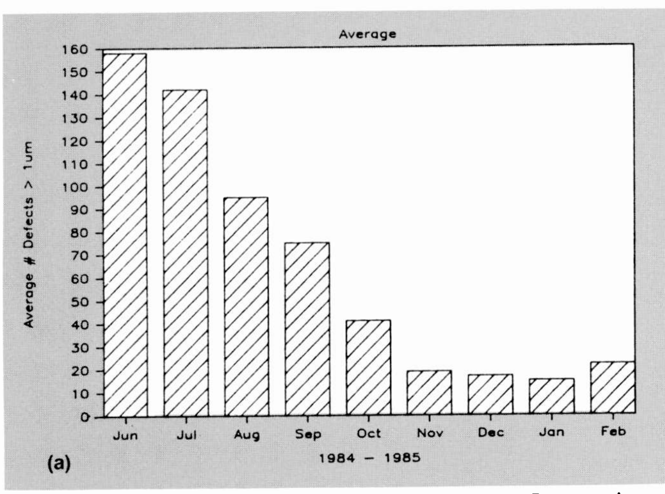

Fig. 4a. *Average number of defects added by Caros clean sink.*

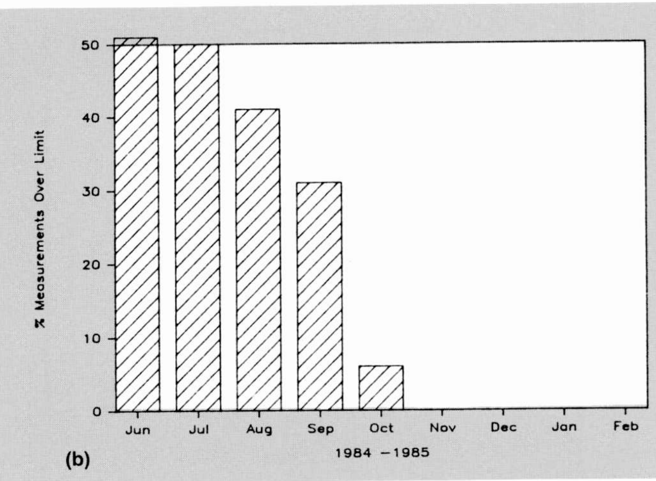

Fig. 4b. *Percent of measurements over specified limit for Caros clean sink.*

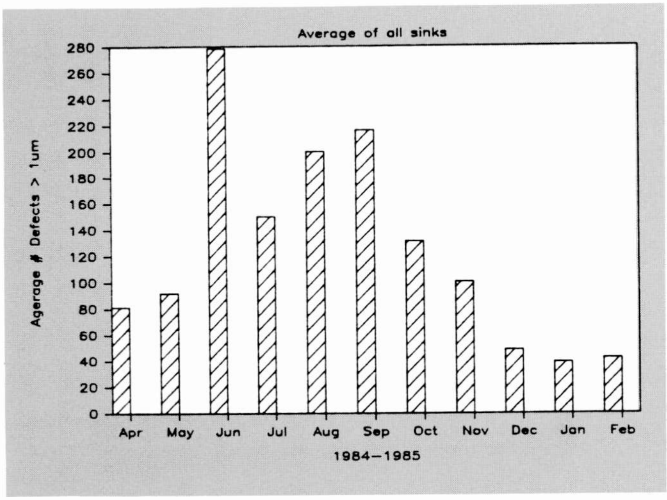

Fig. 5. *Average number of defects for all production clean sinks.*

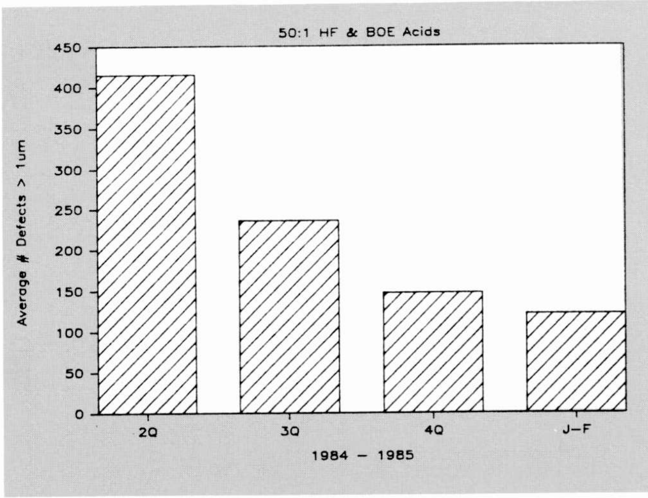

Fig. 6. *Average number of defects for specified clean sinks.*

ing process that was impractical for production. The effect of using new cassettes that could routinely be cleaned in production is seen starting in January.

One of the major particle generators in a positive resist photo room is the brittleness of the positive resist. This requires continuous cleaning of equipment to minimize these photoresist particulates. Since negative photoresist is not brittle, aligner particle counts are low (three to five defects are typically measured). However, other negative photoresist process steps still can contribute to high counts.

Wafer clean processing

By April the three-wafer test procedure was being used with maximum limits on most production wafer cleaning sinks (Caros, SC1-SC2, and Caros-SC2 cleans). During the first half of the year various cleaning stations were modified to reduce particle generation by:

1. Installing on-axis wafer spin dryers that rinse to a minimum resistivity.
2. Adding a deionized water bypass trickle flow to the rinser dryer.
3. Installing point-of-use 0.2-micromillimeter deionized water filters.

At the same time, equipment cleaning procedures were developed to return particle counts below the maximum limit. By November the single wafer test procedure was instituted on 12 different production cleaning stations. Figure 4 shows the graphical particle tracking technique for one sink during this development period. Again the limit has been imposed on the data from the beginning, even though it may not have been applied then. By doing this, the progress in reducing particulates can be seen. The progress in reducing particulates on all clean sinks is seen in Fig. 5. The increase from July to September is partly due to room airborne particle problems.

Acid etch processing

The three-wafer test procedure was implemented in April on three 50:1 hydroflouric acid and two buffered-oxide etch stations. During the year these etch stations were modified to reduce particle generation by:

1. Installing on-axis wafer spin dryers that rinse to a minimum resistivity.
2. Adding a deionized water bypass trickle flow to the rinser dryer.
3. Installing point-of-use 0.2-micromillimeter deionized water filters.
4. Installing recirculating acid bath system with 0.2-micromillimeter filters.

By November, the single-wafer test procedure was instituted with limits. Cleaning procedures similar to those for the clean stations are used. Figure 6 shows the progress in reducing particulates on these acid sinks.

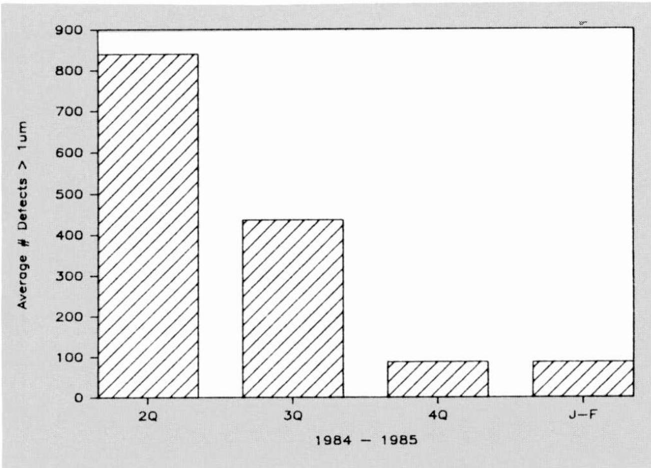

Fig. 7. *Average number of defects for plasma descum process.*

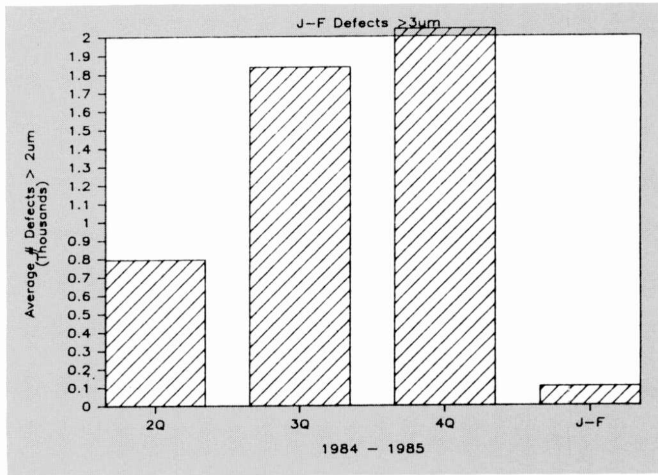

Fig. 8. *Average number of defects for borophosphosilicate glass deposition.*

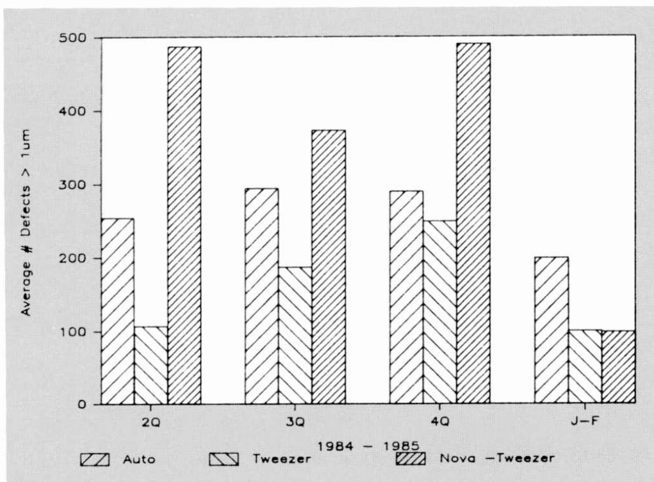

Fig. 9. *Average number of defects for ion implanters.*

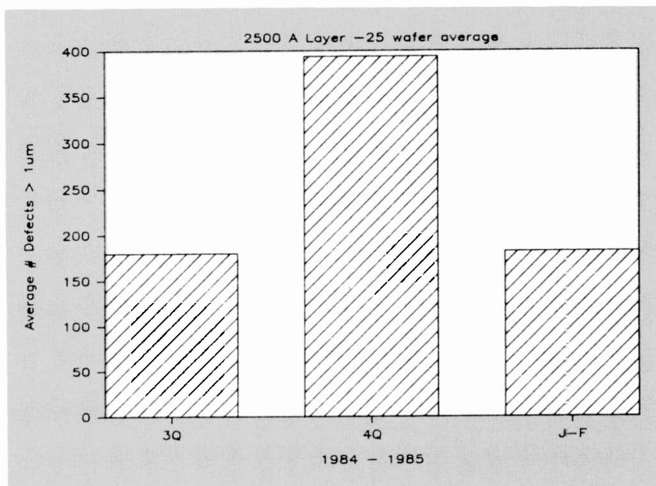

Fig. 10. *Average number of defects from silicon nitride deposition.*

Plasma etching

The plasma descum (plasma photoresist etch) process was evaluated starting in June. Particle reduction was accomplished by removing the metal shield, periodically cleaning the chamber, and etching the quartz boats. Figure 7 shows the progress in reducing particulates.

The plasma nitride and polysilicon Tegal etch systems were evaluated and the single-wafer test method implemented early in November. Alcohol cleaning of the vacuum chamber and tracks every shift was implemented at the same time. As a result, particle counts typically run 40-50 instead of the 300 initially seen.

BPSG CVD layers

Borophosphosilicate glass (BPSG) chemical vapor deposition (CVD) layers were evaluated starting in April. The laser scanner collection-detection method used by Tencor results in layer thickness variations being counted as particulates. To eliminate this anomaly, the minimum defect size was increased to 2 micromillimeters. The January-February data uses a minimum defect size of 3 micromillimeters to further eliminate this anomaly (see Fig. 8). The high false counts using lower minimum defect sizes does provide a different method of indicating the quality of the BPSG layer.

Ion implants

All ion implanters have been monitored weekly since June using the three-wafer test method. These were sub-divided into the following catagories for analysis: two cassette-to-cassette loading systems, two or three tweezer-loaded carrousel systems, and one or two high-current tweezer loading systems. The particle count data is shown in Fig. 9. Initial efforts to reduce silicon chips on one of the cassette-to-cassette loading implanters resulted in excessively high equipment down times. Daily cleaning of readily accessible areas resulted in a substantial reduction in particle counts (from 120 to 89)

Silicon nitride LPCVD

Silicon nitride low pressure chemical vapor deposition (LPCVD) layers 2500 Angstroms thick have been monitored weekly using the 25-wafer test method since August. Initial analysis indicated the major particle generators were due to tweezer wafer loading and insufficient furnace boat and sled cleaning. The increased particle counts seen for fourth quarter in Fig. 10 are the result of environmental problems that are being corrected.

Thermal oxides

Thermal oxide layers from 500 to 1200 Angstroms have been monitored weekly using the 25-wafer test method since August. Since the counts have not been exceptionally high (see Fig. 11), the data

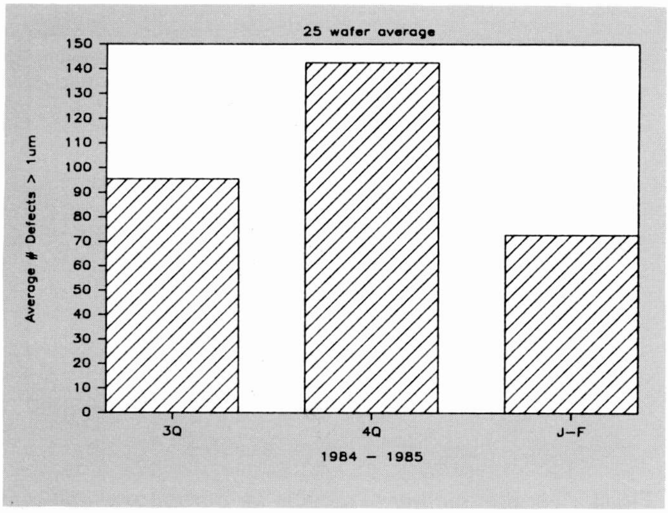

Fig. 11. *Average number of defects from thermal oxidation deposition.*

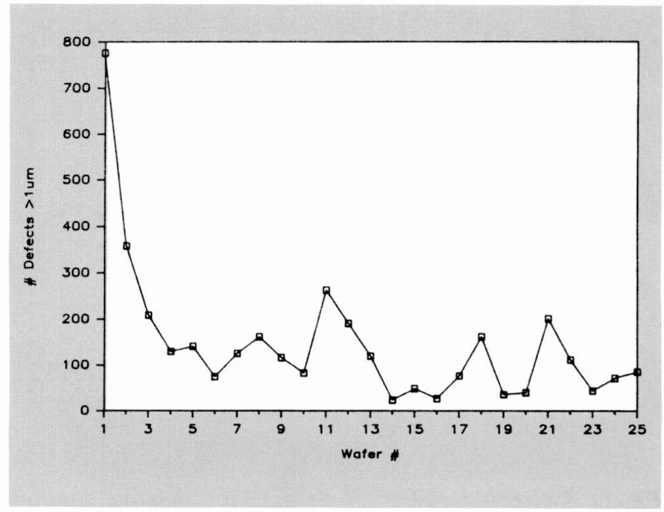

Fig. 12. *Average number of defects from amorphous silicon deposition.*

is recorded and the wafers used for silicon nitride evaluations. Efforts to use a single wafer were not satisfactory since this bypassed the wafer autoloading used at these furnaces. A new method using three test wafers along with 22 dummy wafers to fill a cassette is being tested.

Polysilicon layers

Although polysilicon layers can be analyzed for particulates, the minimum defect size has to be increased to about 65 micromillimeters. The polycrystalline surface structure results in a high background level measurement by the Tencor laser defect scanner, which precludes lower minimum defect sizes.

Amorphous silicon layers can be analyzed using a minimum defect size of 1 micromillimeter. This is due to the more structured surface of this layer, which results in a lower background scattering. Figure 12 shows a 25-wafer test run in the amorphous silicon furnaces.

Summary

Use of the laser defect scanner has resulted in significant reductions in wafer particle counts in production. Process or equipment particle generators have been detected and their effects minimized through using this as an analytical tool. Equally important has been the fact that production operators can also use this equipment to continually monitor and control particle counts at their specific stations. This results in a sensitivity to wafer particulates right on the production floor.

Acknowledgments

The assistance of L. Cornett in collecting and analyzing the data reported here is gratefully acknowledged. L. Jastrzebski was instrumental in finding particle generators in the silicon nitride and ion implant processes.

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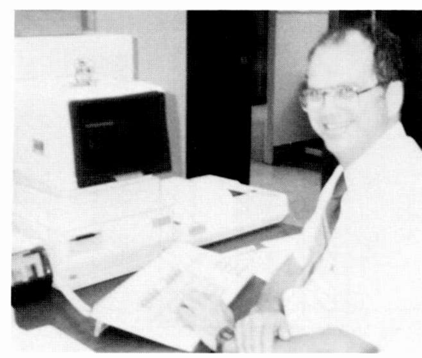

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B.A. Hynes | R.M. Dunlap

Automated testing—the transition to production

At Missile and Surface Radar Division the long test cycles in manufacturing are being reduced through automation.

The heart of MSR's phased array antenna is the phase shifter assembly, which requires tests for insertion loss, standing wave ratio, insertion phase, and phase slope. At the inception of this testing in manufacturing for the first production phased array antenna, a Hewlett-Packard HP-8542 Network Analyzer was used. The test was accomplished in approximately four minutes.

A joint program was recently instituted with an engineering/manufacturing team to develop a go/no go type tester. The go/no go tester (Fig. 1) uses a Hewlett-Packard 9835 computer that controls a phase shifter driver board that in turn feeds phase commands to the phase shifter under test. Each phase shifter's set of test characteristics is summed by the computer to determine a go/no go result. If the unit passes the test, an indication is given as to the range of the phase slope results. A standard deviation measurement (from the established mean) indicates within what group each phase shifter is categorized. A histogram readout is available from the test equipment to indicate actual readings and trends (Fig. 2). With implementation of this test set, total test time has been reduced to 40 seconds.

The next stage of the antenna test involves the test of array modules. The array modules contain 32 phase shifters mounted into a 32-to-1 power divider wired into a printed circuit connector board nest containing eight driver boards, one line receiver board, and one voltage regulator board. The connector board is tested by the DITMCO continuity and open circuits automatic test unit. The driver boards, receiver, and regulator boards are individually tested prior to the array module test.

The initial array module test position, which tested for phase measurements and insertion loss, required four hours to test each array. Also within this test time a VSWR slotted line test must be performed on the array module to electrically test the 32-to-1 power divider. A Hewlett-Packard 9825 computer was initially added to this test position for insertion loss and phase measurements. It drives a test program that calculates mean and standard deviation. If a phase shifter falls outside the acceptable range it will be identified and replacement can take place immediately. To further enhance this test, a series of automatic switches was added to alleviate time-consuming manual switching. The total test time is now 25 minutes (see Fig. 3).

The testing of the ten vertical column

Abstract: *The use of mini and microcomputers in the test activity is not new, but over the years more and more applications have surfaced. At Missile and Surface Radar Division, where both complex digital and analog testing is required, a concentrated effort has been made to reduce manufacturing test times through the effective use of automation and automated test equipment.*

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Fig. 1. *Go/no go test set.*

beamformer assemblies that are assembled into the antenna was originally done with a manual network analyzer. Total test time was eight hours per column. A Hewlett-Packard 9825 computer was integrated into this test position to accomplish the phase measurement (electrical length) of these beamformer assemblies. This reduced the test cycle to two hours. The elbow connector ends of the individual waveguides are machined down to produce a phase match between the four to ten arms of each column beamformer (0.012 inch shaved off gives a 1° phase shift). The cables and the ten cable through assemblies mounted into the antenna are tested automatically using the DITMCO test equipment.

When assembly is complete, the 12-foot diameter octagonal antenna assembly is wheeled to a nearby area known as ANFAST I, where an overall rf analysis is run on the antenna.[1]

Signal processor testing

The modules for the signal processor equipment are tested on a General Radio Model 1792 Logic Test System coupled with a Digital Equipment Corporation PDP8 computer. This test equipment electrically examines all but 200 of the 9000 signal processor circuit modules for each radar system. The testing is accomplished in a go/-no go mode that in 2 seconds lights either a pass or fail light. If the module fails, the program will identify the location of the fault for repair purposes.

The network system

Three of these General Radio logic test positions in manufacturing have been recently integrated into a General Radio 2293 network system (see Fig. 4). This central system contains a DEC 11/23 Computer plus the 2293 central station unit which can operate through any of the three test stations for software checks. Test Method Engineers, working in the network center, write the new programs for each type of circuit module.

These programs are put in queue for entry into one of the test positions when they become available. The network releases the program to a test position, which tests the new program by simulating a fault at each point on the circuit board. It gives the result of the test run on the program in terms of percentage of faults detected. For example, the Test Methods Engineer will see a test result printout of a program exercised by the General Radio net on a test station such as "Your test is 91% effective." The points missed will also be identified. The General Radio network computer has special software that allows it to run five times faster than the test stations. Supporting inputs are received from the Applicon (automatic drafting system) for the wiring information contained in a specific printed circuit board. A DEC PDP 11/23 computer converts the Applicon information to circuit board test information in 15 minutes. This simulation test program input can later be converted to

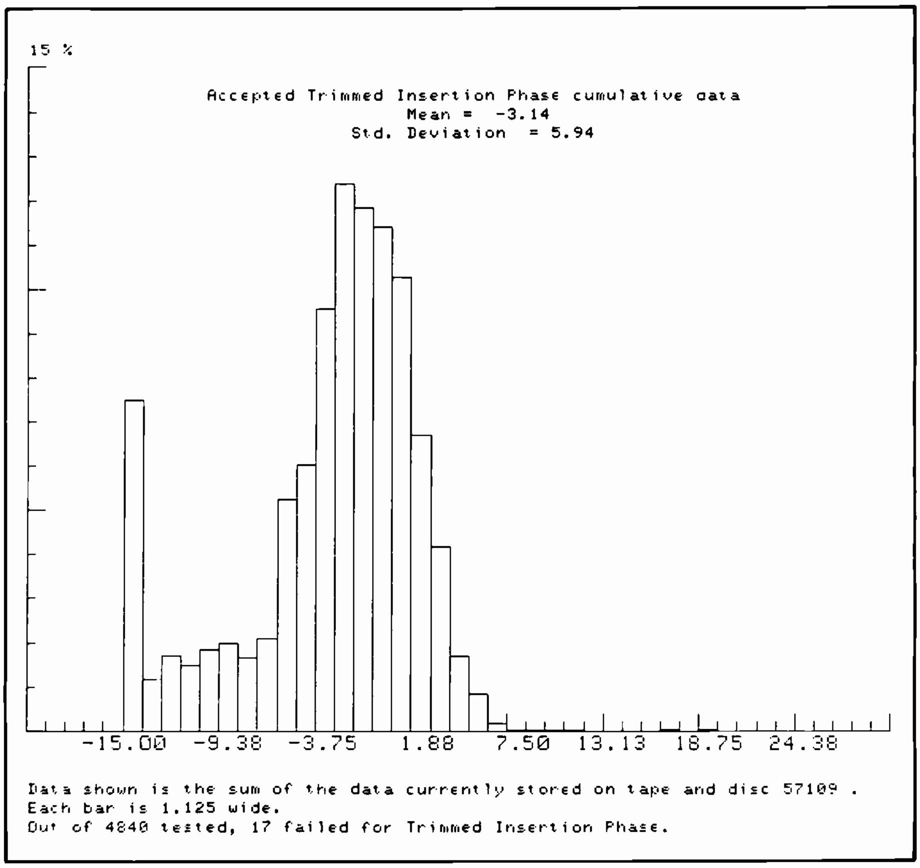

Fig. 2. *Histogram of phase shifter test.*

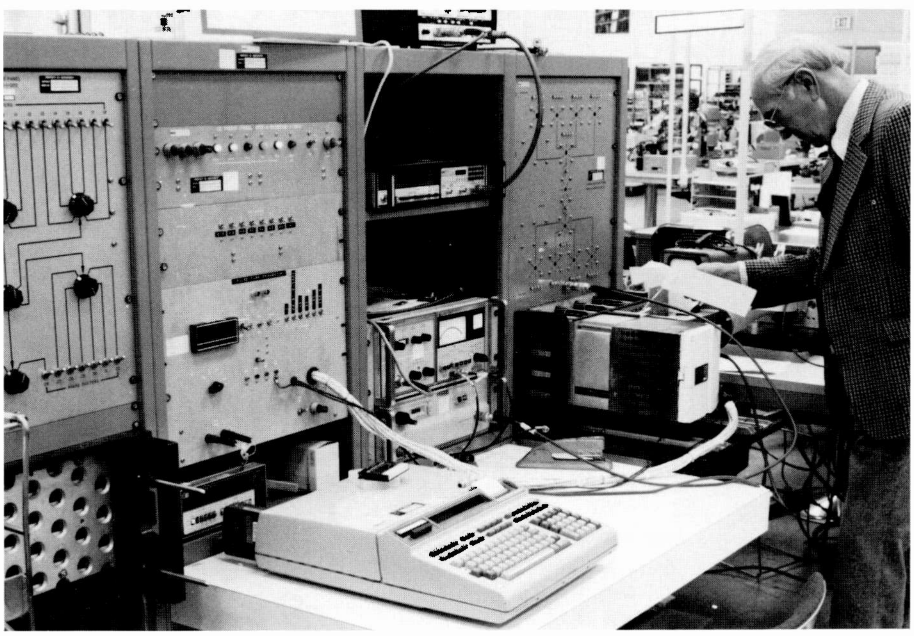

Fig. 3. *Array module test position.*

Fig. 4. *G/R 2293 network.*

Fig. 5. *Power supply test positions.*

actual test programs to save test methods programming time.

Low voltage power supplies

The testing of low voltage power supplies for the signal processor equipment was originally accomplished on two special-purpose test positions (see Fig. 5). Two tests were run. One of these, run prior to close-up of the assembled power supply, tested for functional operation. The test time, including all internal adjustments, was approximately one hour. The second test was an acceptance test that took approximately four hours. This test time has been reduced since the inception of the production program.

The initial review of industry-available test equipment to test low voltage power supplies of the type being built at MSR resulted in a blank. As an interim program, a complex interface fixture was developed to run acceptance tests on the General Radio automated test stations. This proved to be a successful interim measure, reducing test time for acceptance test to 20 minutes. However, this fixture showed considerable wear after a period of usage, and even after it was rebuilt, the fixture continued to require heavy maintenance.

Approximately a year ago a tester capable of meeting our requirements was reviewed with Autotest Co. of San Atonio, Texas. An order was placed for two of these testers, one for Manufacturing's use and one for MSR's Depot operation. Both machines have been received, installed, accepted, and are currently in use in their respective areas. Figure 6 shows the Autotest 3000 in place in the manufacturing area. This equipment, which does the final acceptance test on the low voltage power supplies, tests for all conditions of line and load variation, including dynamic load variation. The total test time now averages approximately 15 minutes per power supply.

Signal processor analog chassis

The testing of the analog chassis for the signal processor has been accomplished on a series of standard test positions. Because of the kind of testing required, the large number of types of chassis, and the small number of chassis per type, automation was not warranted initially. However, as the number of systems released per year increased, the automation of chassis testing became practical. An automated chassis test position was designed, built, and installed in the manufacturing area (see Fig. 7). This position is programmed and controlled by an HP-9836 computer. The test position contains an array of signal stimuli and measurement equipment connected to the computer on an IEEE-488 bus configuration.

System test

The testing of the signal processor cabinets is accomplished at a special system test site using a Perkin Elmer computer with specially designed test software. This test system tests the individual cabinets through an integration program. A signal processor system test is then accomplished on the fully integrated system. Figure 8 shows the test center. The first activity is the exercising of the input/output buffer (IOB) cabinet and the detection track processor. In conjunction with the digital target simulator, the system/subelement test system examines signals received from the detection track processor, then the pulse compression processor, and finally the moving target indicator units, all through the IOB, as shown in Fig. 9. The analog half of test inputs to the signal processor is generated by the waveform generator test set through the intermediate frequency cabinets, also shown in Fig. 9. The analog-to-digital test set then completes the A/D link between halves of the signal processor.

Further advances in automating testing

As new generations of phased array radar systems move into the manufacturing stage, additional areas of automated testing are presenting new challenges. Some of the areas presently under test development are the rf combiner, which requires microwave testing followed by adjustment and then retest, the semi-rigid coax (19,000 per system), the rectangular coax power dividers, and the column beamformer assemblies. In addition to these items, phase shifters and driver modules (19,000 of each per system) require automated testing and laser trimming.

Now that automated testing has come of age and is reducing the cycle time of previously long and complex tests, the next major challenge will be to reduce the cost of the automatic test equipment.

Fig. 6. *UTS 3000.*

Fig. 7. *Chassis auto test position.*

Fig. 8. *Subelement test system.*

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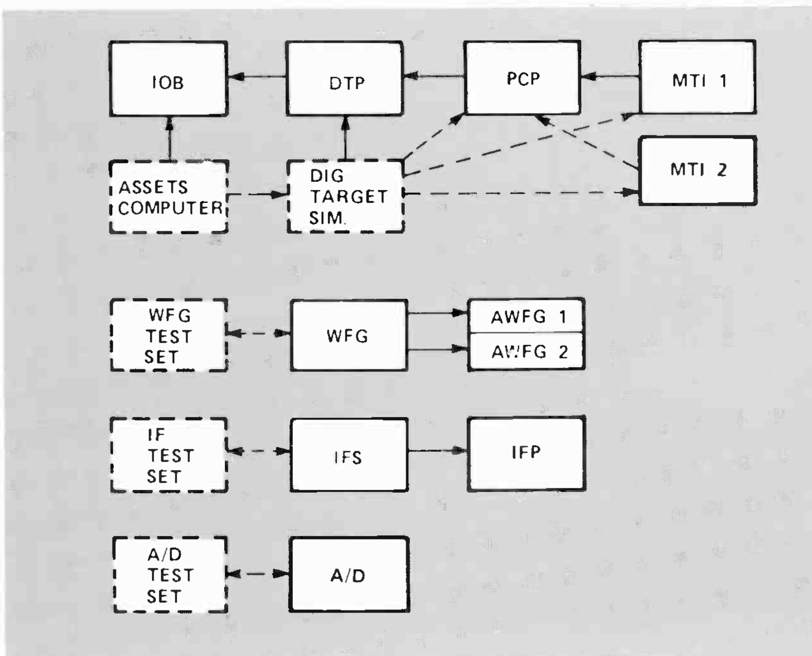

DIGITAL CABINET PRE-TEST	ANALOG CABINET PRE-TEST
1. CAB. WIRING (DIT-MCO)	1. CAB. WIRING (DIT-MCO)
2. BACK PLANES (DIT-MCO)	2. BACK PLANES (DIT-MCO)
3. CABLES (DIT-MCO)	3. CABLES (DIT-MCO)
4. POWER SUPPLIES (MAN/AUTO TEST)	4. POWER SUPPLIES (MAN/AUTO TEST)
5. MODULES (OF 9000 TOTAL ALL BUT 200 GR TESTED)	5. CHASSIS 62/115 (MANUAL TEST)
6. CABS RECEIVE PWR TURN ON PRIOR TO TEST CENTER	6. CABS RECEIVE POWER TURN ON PRIOR TO TEST

Fig. 9. *Signal processor test procedure.*

Authors Dunlap (left) and Hynes.

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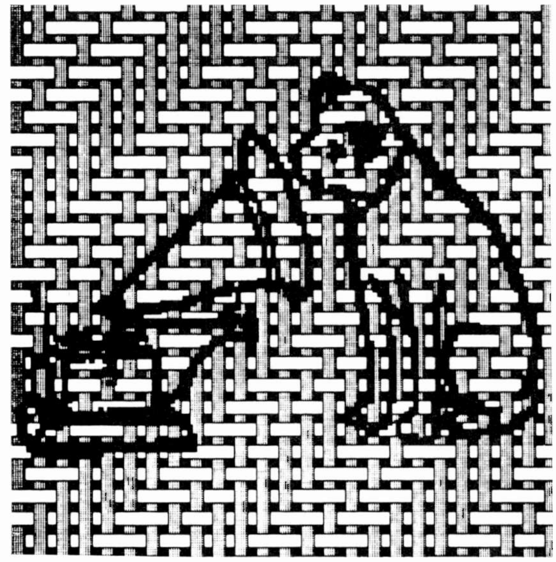
Michael Keith

Recreational mathematics



"The perfect mathematical problem is one that is understandable to an idiot but solvable only by a genius."
—Anonymous

It all started one day in the eighth grade. Waiting for class to start, I doodled in my notebook. The object of my doodling was the Fibonacci sequence—the famous sequence of integers beginning 1, 1, 2, 3, 5, 8, 13 (and so on) in which each number is the sum of the two previous numbers. On a sheet of graph paper, I unsuspectingly wrote the Fibonacci numbers in the following pattern and added up the numbers.

```
1
 1
  2
   3
    5
     8
     13
      21
       34
        55 . . .
-------------
1123595495 . . .
```

Being on familiar terms with the reciprocals of the first few dozen prime numbers, I immediately recognized the sum as the decimal expansion for the fraction 10/89. This unexpected connection between a well-known number sequence and a seemingly-unrelated fraction probably marked the beginning of my fascination with numbers, mathematics, and the playful pursuit of its mysteries.

This hobby has come to be called "recreational mathematics." Unlike some others, this hobby requires very little physical equipment (pencil, paper, and perhaps a few reference books) and is largely a mental activity. It is, however, a rich and fascinating past time. And, like amateur astronomy and amateur radio, it is a field in which "amateur" participants can make real contributions, in the form of correspondence and published results.

In this article, I will briefly describe what recreational mathematics is and how—as an engineer—I continue to benefit from my interest in this hobby.

Abstract: *This article consists of a discussion of the hobby of recreational mathematics, with an emphasis on the aspects of this hobby in which amateur mathematicians can make contributions. The author begins with a definition of recreational mathematics and discusses such topics as problem solving, mathematical beauty, elegance, problem posing, generalization, and overlaps between recreational mathematics and everyday engineering work. A sidebar includes some sample problems, offering the reader a hands-on introduction to the pleasures of recreational mathematics.*

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What is recreational mathematics?

Recreational mathematics may be defined as participation in mathematics primarily for the enjoyment thereof, possibly without any initial thought for the practical application of the results. One might say that it is "math for math's sake." There is an analogy between a recreational mathematician and the "computer hacker." In the positive sense, a computer hacker is one who enjoys the act of computer programming as an end unto itself. So we might call a recreational mathematician a "mathematics hacker."

Martin Gardner, whose "Mathematical Games" column ran for many years in *Scientific American* magazine, is undoubtedly the most famous recreational mathematician of our time. Other famous names in the field include Sam Loyd, H. E. Dudeney, Lewis Carroll, H. S. M. Coxeter, W. W. Rouse Ball, and John Horton Conway.

In Fig. 1 I have listed some of the more popular areas of study in recreational mathematics. As you can see, "recreational" mathematics and "serious" mathematics overlap, and the distinction between the two often gets somewhat blurry. In fact, some areas of now "serious" mathematics (for example, probability theory) were originally studied for largely recreational reasons. It is quite possible, therefore, for a recreational result to find later application in the "real world." I will give an example from my engineering experience later in this article.

Problem solving

Much of the activity in recreational mathematics is inspired by problem solving. By asking "what about . . . ?," we are led to create, examine, and hopefully answer questions about numbers, patterns, or whatever object interests us.

Someone once said that the perfect mathematical problem is one that is understandable to an idiot but solvable only by a genius. Two examples of such problems are shown in Fig. 2. The Four-Color Map problem asks whether every map drawn on a planar surface can be colored with four colors such that no adjacent region has the same color. The Integer Tiling problem asks whether the plane can be exactly covered by a set of square tiles containing one tile each of edge length 1, 2, 3, 4, etc. units. The first of these problems was solved in 1977—a century of mathematical research combined with many hours of computer time finally proved that the answer is "Yes." The tiling problem is, as far as I know, still unsolved, although a fellow RCA engineer, Brian Astle, has discovered a way to construct such a tiling with an arbitrarily small (but non-zero) percentage of the plane left uncovered. This is the best result I've seen to date.

The recreational mathematician also has a keen appreciation for a somewhat vague quality that might be called "beauty" or "elegance" in a mathematical result. As an example, here is a very profound and beautiful problem, called the Problem of Partitions. A *partition* of an integer is the expression of the integer as the sum of one or more positive integers. For example, (1,1,4,6) is a partition of 12 since $12 = 1 + 1 + 4 + 6$. Define $p(n)$ as the number of different partitions of the number n. For example, $p(4) = 5$ and the five partitions of 4 are (1,1,1,1), (1,1,2), (1,3), (2,2), and (4). The problem is to find an explicit formula for $p(n)$. The solution, developed by the English mathematician Hardy and the brilliant Indian, Ramanujan, is:

$$p(n) = \frac{1}{\pi\sqrt{2}} \sum_{k=1}^{\infty} \left[\sum_{\substack{h \bmod k \\ (h,k)=1}} \exp\left[\pi i \sum_{\mu=1}^{k-1} \left[\frac{\mu}{k} - \left[\frac{\mu}{k}\right] - \frac{1}{2}\right] \left[\frac{h\mu}{k} - \left[\frac{h\mu}{k}\right] - \frac{1}{2}\right]\right] e^{-2\pi i n h/k} \right] k^{1/2}$$

$$\Delta \cdot \left[\frac{d}{dx} \frac{\sinh((\pi/k)(2/3 \cdot (x - 1/24))^{1/2})}{(x - 1/24)^{1/2}}\right] x = n$$

This is undoubtedly one of the most amazing results in mathematics. Although it describes a simple arithmetic function, $p(n)$, the formula contains square roots, the numbers $*\pi$ and e, imaginary numbers, derivatives, and hyperbolic trigonometric functions! No simpler explicit formula for $p(n)$ has ever been found.

Since most of us don't have a hundred years to spend on a problem, recreational mathematics problems are usually designed to be solvable with a modest amount of effort. In addition, a good problem should be simple to state, concise, and interesting. Here is an example:

Cards will be turned over one at a time from a deck of cards, and you are to guess beforehand on which turnover the first red queen will appear. What number should you guess to maximize your chance of being right?

Intuitively, the most likely place for the first queen would seem to be somewhere near the middle or maybe a third of the way or so through the deck. The surprising correct answer is that you should always guess the *first* card!

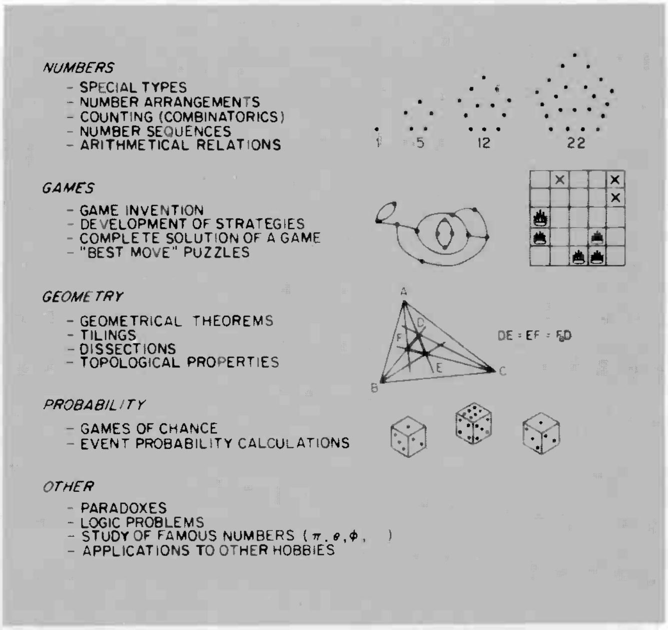


Fig. 1. *Some popular topics for study in recreational mathematics.*

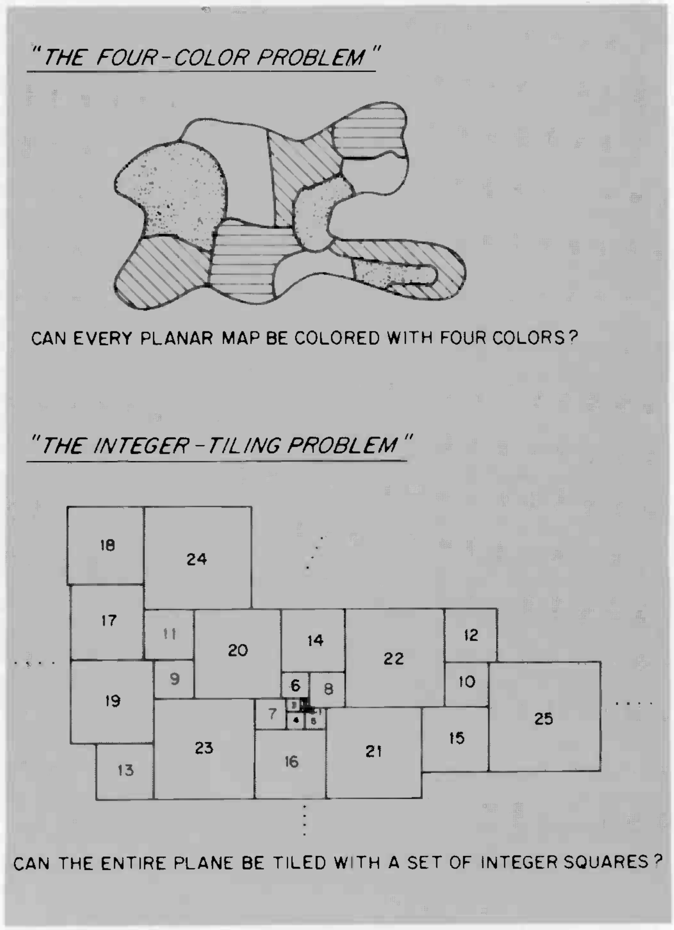
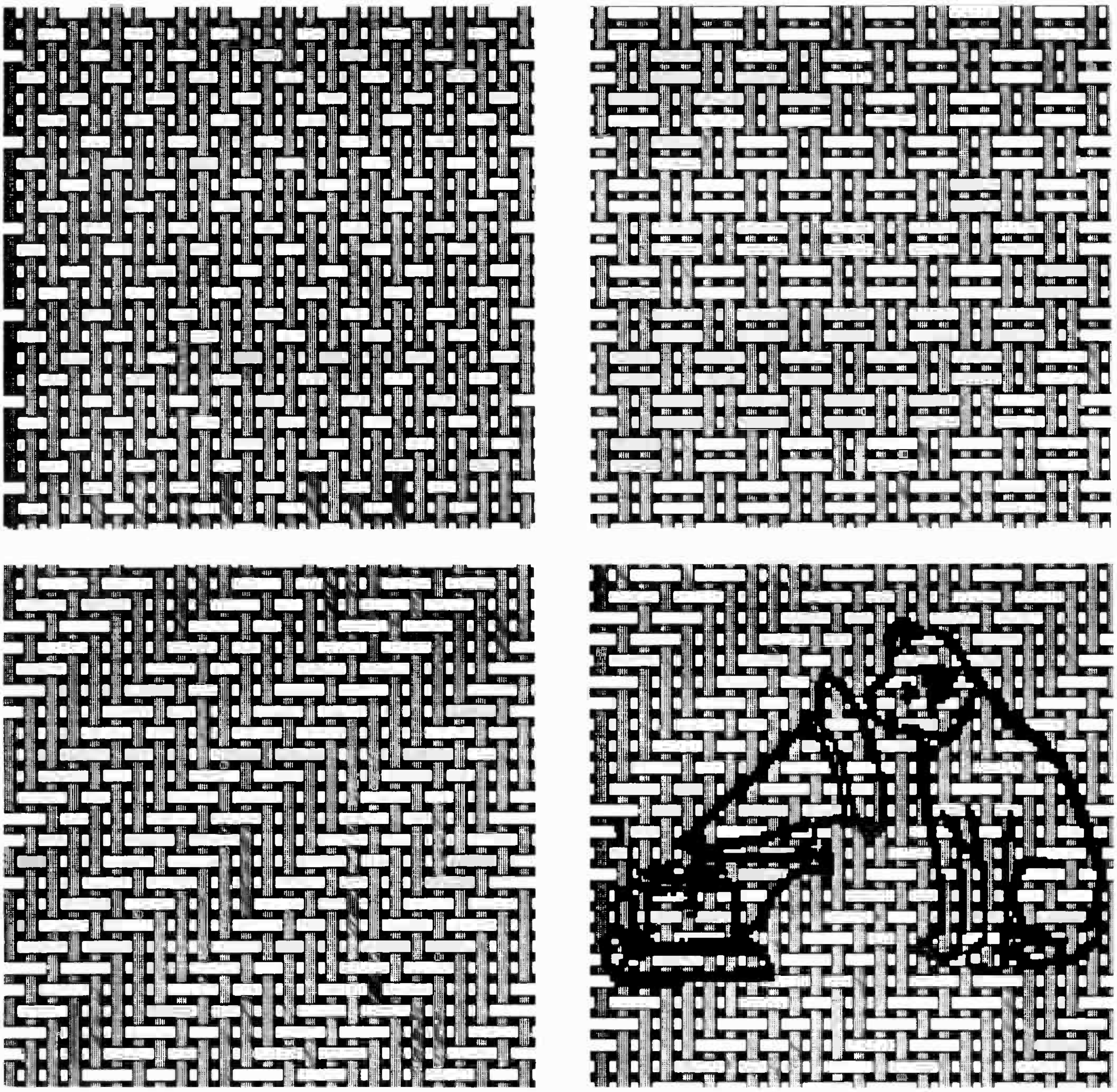


Fig. 2. *Two deceptively simple problems, which are very easy to state but very difficult to solve. The four-color question was answered in the affirmative in 1977 after a hundred years of work by mathematicians. The tiling problem is still undecided, although the answer "almost" has been achieved.*

A practical aspect



In addition to purely intellectual study, recreational mathematics can be applied to other, more practical areas. The above figures illustrate the mathematical analysis and generation of weaving patterns for producing fabrics. Using ideas from geometry, group theory, and combinatorics, it is possible to classify and characterize actual patterns used in real fabrics as well as generate new and attractive designs never before seen. The top two designs, known in the fabrics industry as satinette and duck cloth, respectively, are mathematically classified as "order 4, isonemal" fabrics. The bottom left design is an original order 16 twill based on the first four digits of the number π (try to figure out how!). In these computer simulations, we can also paint designs on the fabrics after they are generated (bottom right).

Here is why. Call the number of cards in the deck n. Let us calculate the number of possible initial arrangements of the deck with the first red queen in the kth position (k=1 to $n'1$). Since the other red queen must be below the first one, there are (n-k) possible positions for it. The remaining cards can be arranged in (n-2)! ways. Thus there are 2*(n-k)*(n-2)! possible arrangements (the factor of two comes from the fact that the first red queen may be either the heart or diamond one). There are, of course, n! possible total arrangements for the deck. Thus the probability that the first red queen is at position k is

$$\frac{2\,(n-k)\,(n-2)!}{n!} = \frac{2(n-k)}{n\,(n-1)}$$

Clearly this expression is largest when k=1, decreasing uniformly to its minimum when k=n-1. Therefore you should always guess the first card. For a deck of 52 cards, the probability that the first red queen is on top is 1/26, decreasing to a probability of 1/1326 that it is the next to last card. The key to the counter-intuitiveness of this problem is that we are asking for *the first* red queen, not just *a* red queen (in that case, of course, all positions would be equally likely).

Another remarkable problem (by John Conway) is the following:

A man, who never left his home town, was nearly 48 years old when he celebrated his first birthday. On what day, month, year, and in what country was he born?

The question asked by this problem, especially the last part, catches the reader completely off guard. This type of problem might be called a "minimum-information" problem, because at first glance it appears that there is not nearly enough information to answer the question. Nevertheless, there is.

The analysis runs as follows. When the calendar was changed from the Julian to the present Gregorian calendar (which more closely approximates the solar year), different countries used various methods to make up the 11 days that the Julian calendar had "slipped." In Sweden, this was done by omitting leap days from 1700 to 1740 (and Sweden was unique in this technique—for example, in America, the 11 days from September 3-13, 1752 were omitted). Therefore the man was born on February 29, 1696 in Sweden, and he celebrated his first birthday on February 29, 1744 when he was 11 days short of 48 years old.

In recreational mathematics, the solution of a problem is usually not the end of the matter; indeed, it is usually only the beginning. Perhaps the method of solution can be simplified or improved. Perhaps a more general solution can be formulated that includes the answer to the problem as a special case. It is even possible for the problem to have other, "surprise" solutions that may not be obvious at first glance. Here is a simple problem with such a feature:

An explorer begins walking from base camp. She walks one mile south, one mile east, one mile north, and one mile west. At this point she arrives back at camp for the first time since leaving. At what latitude is our explorer camped?

The obvious answer is +0.5 miles latitude, and many people would be satisfied with this solution. However, a bit more thought reveals that not only are there other solutions, but there are an

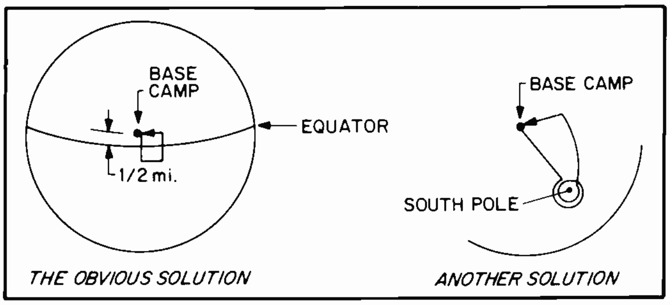


Fig. 3. *Two solutions to the explorer problem—the obvious solution and an infinite family of less-obvious solutions. These two sets of solutions are in fact all the solutions.*

infinite number of other solutions! Try and find some of these alternate solutions before reading any further.

The solution is shown in Fig. 3. Aside from the obvious location near the equator, base camp could be located at any one of an infinity of latitudes just over 1 mile north of the South Pole. The eastward mile would cause our explorer to circle the pole one or more times before going north to a point exactly one mile east of camp. A bit of trigonometry gives us a formula for the distance of camp from the South Pole:

$$\tfrac{1}{2} + \frac{\sqrt{4n^2n^2 + 8n\,\pi}}{4\,n\pi}$$

(for n = 1, 2, 3, ...)

The first few solutions are approximately 1.139, 1.074, and 1.051 miles north of the Pole.

Other popular classes of problems? Maximization or minimization problems. A problem of this type asks for a construction that maximizes or minimizes some quantity. The appeal of these problems is due to the fact that the problem may not have a provable maximum or minimum answer, thus offering a competitive challenge to solvers to continually improve on the current best solution (or prove such a solution to be the best possible). As an example, I offer the following question, which I believe is being asked in print for the first time: What is the maximum score attainable in a single play in the game of Scrabble? The board position and the play itself must be one that is obtainable in a legal game. For definiteness, restrict allowable words to words in some published dictionary. My best solution, using words in the Random House College dictionary, is 1593 points. Can you do better?

Problem posing

In recreational mathematics, problem posing is at least as important an activity as problem solving. Indeed, one mathematician, Paul Erdős (whom I would describe as a serious mathematician with heavy recreational overtones) frequently gives lectures at mathematical conferences that consist solely of new unsolved problems, questions, and conjectures. He even sometimes offers sizable cash prizes for the solutions to ones he is particularly interested in! Such is the enthusiasm of the true recreational mathematician.

Problems may arise from completely new topics or by variations or generalizations of existing problems. Here is an example that illustrates this process:

Find a number, greater than one, equal to the sum of the cubes of its digits.

One solution to this problem is the number 153. The next question I would ask is: Are there other solutions? How many? It turns out that it is easy to prove that there are at most a finite number of solutions. The question then is to find *all* solutions (there are only three others—find them!). I would also consider other powers—for example, numbers equal to the sum of the squares (fourth powers, etc.) of their digits. On examining squares, I find there are no solutions, but there are three answers for fourth powers. Next I would wonder about combinations—for example, numbers equal to the sum of the *n*th powers of the digits plus the *k*th powers of the digits, which I denote (n,k) numbers. For example, 90 is a (1,2) number. I

Some problems to try

Here are some original problems for your amusement. The solutions will be published in the July/August issue. Good Luck!

Problem 1. A farmer has 6 hens whose eggs are constantly being devoured by buzzards. He hires an engineer to make some observations; unfortunately, the engineer is also a recreational mathematician, so his observations are somewhat cryptic. After 10 days, the engineer reports the following facts:

1. A hen-and-a-third lays an egg-and-a-third in a day and a third.
2. A buzzard-and-a-half enters a henhouse-and-a-half in a day-and-a-half.
3. A buzzard-and-a-quarter eats an egg-and-a-quarter in an entry-and-a-quarter into the henhouse.
4. There are 13 more eggs in the henhouse than there were 10 days ago.

How many buzzards are there?

Problem 2. A game of checkers has been played and you chance to find the board with all the pieces still in their final positions. There are 11 black and 11 white pieces on the board (all uncrowned). You notice that all 11 pieces of one color are blocked and cannot move. Black moved first in the game.

Who won?

Problem 3. In a randomly chosen year, which occurence is more likely—that Christmas falls on a Sunday, or that Halloween falls on a Friday?

Problem 4. In the following five clues, the letters P through Z represent the integers 1 through 11 (not necessarily in that order, of course). Determine the values of P through Z from the clues (Note: $[x]$ stands for the greatest integer greater than or equal to x).

(a) $P = Q + R = S + T$

(b) $U = Q - R, V = S - T$

(c) $W = ½ (U - V) * (R + (R + T)*[T/V])$

(d) $X = \frac{Q-1}{2} + \frac{R-1}{2} + \frac{S-1}{2} + \frac{T-1}{2}$

(e) Z Chapter $T + Y$ of book number $X + Z$ in the King James Version of the Bible contains a verse with exactly $P^2 - P$ words.

Problem 5. A certain school uses a rather unusual method to pay its mathematics teacher. Each week, Dr. Diophenes is taken to the school mail room and asked to deduce which mailbox his paycheck is in. He is allowed to ask the cashier up to five questions in an attempt to locate his check. The boxes have two-digit numbers. This week, he asks the following five questions about the box number containing his check:

1. Is the tens digit of the number even?
2. Is every digit of the number a divisor of the number?
3. Is the number a "repdigit" number? (A repdigit is a number with all like digits)
4. Is six times the square of the units digit less than the number itself?
5. Is the number a "Lucas number?" (Lucas numbers are numbers in the sequence 1, 3, 4, 7, 11, 18..., where each number is the sum of the two previous terms)

After receiving truthful answers to these questions, Dr. Diophenes thinks for a moment and deduces the only possible mailbox that his check could be in.

What was the box number?

Problem 6. Consider the infinite sequence of integers 2, 27, 271, 2718, 27182, 271828..., where the *n*th term is composed of the first *n* decimals of the number e. Estimate the number of prime numbers that will occur in the whole sequence.

Problem 7. The fraction 2793/7595 has the following remarkable property:

$$\frac{2793}{7595} = \frac{27}{75} \div \frac{93}{95}$$

where the right side of the equation is merely the fraction "split in half." Such a fraction is call a "frac-tion," and must satisfy the additional requirements that the numerator be smaller than the denominator and neither end in 0. Find the only other such 4-digit fraction.

would note that n and k do not have to be distinct—for example, 298 is a (2,2) number. I would next prove the theorem that there are at most a finite number of (n,k) numbers for all n and k, and begin to search systematically for all numbers of these types. I would then go on to three terms or more terms—for example, 336 is a (1,2,3) number. Finally, I would notice that several classes have no solutions—for example, there are no (2) numbers, or (2,3) numbers, or (1,2,2) numbers. I would then ask—is there an infinite number of empty classes? As far as I know, this last question remains unsolved.

I could go on, but I think you get the idea. Starting with an innocent little problem, I have progressed to a deep and unsolved question, with much area for exploration in between. This playful creativity is an integral ingredient of recreational mathematics.

Recreational math on and off the job

Although recreational mathematics is largely recreational, it is also *mathematics*. The tools, techniques, philosophy, and concepts involved often find application in non-recreational settings. Here is one example from my engineering experience.

A fellow engineer at RCA Laboratories was working on remote control systems. He suggested the following scheme. Let the different messages that must be transmitted be encoded with n-bit words with the property that no two messages have code words that are equal under a cyclic permutation. A message is transmitted by continually sending the code word. Such a system has the interesting property that the receiver can, by sampling n bits, decode a message unambiguously regardless of where in the message it begins sampling, and without the need for start or stop bits. The question that arises is: For a given n, how many different code words are there?

After some thought, and some preliminary calculations, I suddenly realized that this problem was equivalent to a recreational problem I had posed and solved a few years earlier. In an equal-tempered musical scale of n tones, how many different chords are there? (A more precise definition of "different" and "chords" would be required to make the correspondence precise, but I will not go into the details here). I was also able to answer other related questions since in fact I had solved an even more general problem than the one asked! Incidentally, the answers for $n = 1,2,3,\ldots$ bits are:

1, 2, 3, 4, 6, 8, 14, 20, 36, 60, 108, 188, 352, . . .

This sequence also has other interpretations—for example, the number of different necklaces with beads of two colors, and the number of irreducible binary polynomials whose degree divides n.

There are many other examples I could give. Ideas from error-correcting coding theory can be used to solve certain problems on Rubik's cube. Recreations involving graphs and trees are related to concepts in electrical circuits. Combinatorial techniques are used by physicists to count lattice arrangements and by chemists to classify compounds. All in all, there is a strong and lively interaction between recreational mathematics and other disciplines.

Conclusion

In this article I have presented a brief overview of recreational mathematics. If you are interested in pursuing the subject further, a vast amount of literature is available—for a start, try some of the publications listed below. Aside from being an enjoyable hobby, recreational mathematics allows one to exercise and develop analytical, problem-solving, and creative abilities—tools that are useful both in and out of the laboratory.

Further reading

Periodicals

American Mathematical Monthly
Fibonacci Quarterly
Journal of Recreational Mathematics
Mathematical Gazette (England)
Mathematics Magazine
Mathematics Teaching (England)

Books

Gardner, Martin, *Wheels, Life, and other Mathematical Amusements*, W. H. Freeman (1983).

Carroll, Lewis, *Pillow Problems and A Tangled Tale,* Dover.
Loyd, Sam, The Mathematical Puzzles of Sam Loyd, two volumes, Dover (1959, 1960).

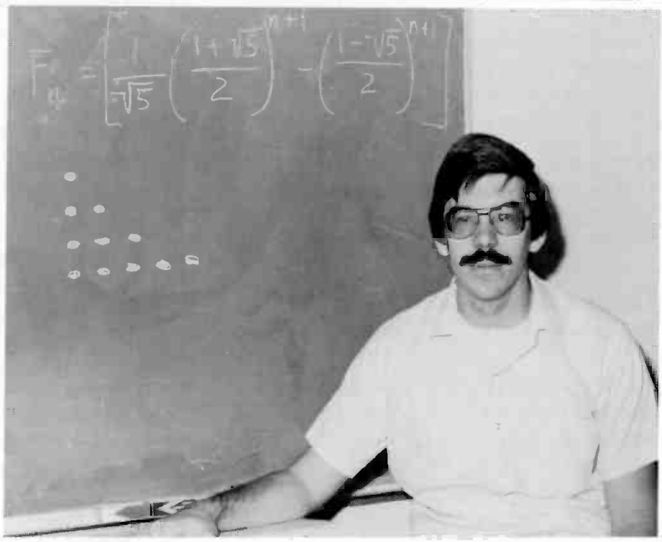
Dudeney, H.E., *536 Puzzles and Curious Problems.*

Ball, W.W.R. and Coxeter, H.S.M., *Mathematical Recreations and Essays*, U. of Toronto Press (1974).

Schuh, Fred, *The Master Book of Mathematical Recreations.*

Polya, G. *How to Solve It*, Princeton U. Press (1971).

Berlekamp, Elwyn R., Conway, John. H., and Guy, Richard K., *Winning Ways*, Academic Press (1982).



Michael Keith is a Member of the Technical Staff in the Digital Systems Research Group, RCA Laboratories. He received his MSEE from Stanford University in 1978 and joined RCA Laboratories in 1980. His research interests include computer graphics, computer music, number theory, graph theory, abstract algebra, logic, and game theory. He is also an avid recreational mathematician and juggler.

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Pen and Podium

Recent RCA technical papers and presentations

To obtain copies of papers, check your library or contact the author or divisional Technical Publications Administrator (listed on back cover) for a reprint.

Astro-Electronics

S. Keck/R. Gounder
Metal Matrix Composite Development for RCA Satellite Hardware—30th SAMPE Meeting (3/85)

J. Maiden/S. Seehra/R. Gounder
Development of Design Data on an Ultra-High Modulus Graphite/Epoxy Composite for Space Applications—SAMPTE Conference (3/85)

N. Valero
Vibration Characteristics of Mistuned Shrouded Blade Assemblies—1985 International Gas Turbine Conference (3/85)

Automated Systems Division

H. W. Grunbaum
Learning Curves—National Contract Management Association, Contract Management Workshop 1985 (3/85)

T. H. Huber
Integrated Electronics for Ground Combat Vehicles—Mechanical Design Course and Automated System Design Course, U.S. Military Academy, West Point, N.Y. (3/85)

M. L. Johnson
Directions in Reliability Testing—Boston IEEE Reliability Group (3/84)

Government Communications Systems

R. W. Johnston/D. B. Carlin
Durable Optical Disc System and Update-Presented at the SPIE Conference, Los Angeles, Cal. (1/85)

RCA Laboratories

D. B. Carlin/J. P. Bednarz/C. J. Kaiser/J. C. Connolly/M. G. Harvey
Multichannel optical recording using monolithic arrays of diode lasers—*Applied Optics*, Vol. 23, 3994 (11/15/84)

C. R. Carlson/J. R. Bergen
Perceptual considerations for high-definition television systems—*SMPTE Journal*, Vol. 93, No. 12 (12/84)

C. R. Carlson/J. R. Moeller/C. H. Anderson
Visual illusions without low spatial frequencies—*Vision Res.*, Vol. 24, No. 10, 14071413 (1984)

D. J. Channin
Optoelectronic performance issues in fiber optic communications—*SPIE Fiber Optic Communication Technology*, Vol. 512 (1984)

J. I. Gittleman/Y. Arie
High-performance Al: polymer: Al trilayer optical disk—*Allied Optics*, Vol. 23, 3946 (11/15/84)

L. Jastrezebski/R. Soydan/B. Goldsmith/J. T. McGinn
Internal gettering in bipolar process; effect on circuit performance and relationship to oxygen precipitation kinetics—*Journal of the Electrochemical Society*, Vol. 131, No. 12 (12/84)

K. Jonnalagadda/Leonard Schiff
Improvements in Capacity of Analog Voice Multiplex Systems Carried by Satellite—*Proceedings of the IEEE*, Vol. 72, No. 11 (11/84)

M. Keith
Computer Science and the Art of Juggling—Annual Joint ACM/IEEE Computer Chapter Awards Dinner (5/85)

V. Korsun/A. J. Stranix
Improving the match between the daily solar insolation peak and electrical peak demand—*Solar Energy*, Vol. 33, No. 2, 171-174 (1984)

M. E. Labib/J. H. Thomas, III/K. D. Embert
The effect of heat treatment on sulfur in an electrically-conductive carbon black—*Carbon* Vol. 22, No. 4/5 (1984)

S. Larach/J. E. McGowan
Adherence of phosphor screens—*RCA Review* Vol. 45 (9/84)

B. J. Lechner
High definition TV—Keynote address at the SID '85 International Symposium, Orlando, Fla., (4/30/85)

M. A. Leedom
The Magic of Japanese Manufacturing—IEEE Society Communication & Consumer Electronics (5/85)

J. R. Matey/J. Blanc
Scanning capacitance microscopy—*J. Appl. Phys.* 57 (5) (1985)

J. I. Pankove, P. J. Zanzucchi/C. W. Magee/G. Lucovsky
Hydrogen localization near boron in silicon—*Appl. Phys. Lett*, 46 (4), (2/15/85)

S. J. Perlow/A. Presser
The interdigitated three-strip coupler—*IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-32, No. 10 (10/84)

H. Schade/Z. E. Smith
Optical properties and quantum efficiency of a-$Si_{1-x}C_x$:H/a-Si:H solar cells—*J. Appl. Phys.* 57 (2) (1/15/85)

P. D. Southgate
A contour deformation model of capacitance videodisc signal pickup—*RCA Review*, Vol. 45 (9/84)

P. J. Stabile/A. Rosen
Silicon millimetre-wave integrated-circuit (SIMMWIC) SPST switch—*Electronics Let* Vol. 20, No. 22, 943-944 (10/25/84)

L. K. White
Approximating spun-on, thin film planarization properties on complex topography— *Journal of the Electrochemical Society*, Vol. 132, No. 1 (1/85)

L. K. White
Characterization and simulation of spin-coated resist contours—SPIE Symposium on Microlithography, Santa Clara, Cal. (3/10/85)

L. K. White/D. Meyerhofer
Image formation in contact-printed PMMA Resist sublayers—*RCA Review*, Vo. 45 (9/84)

Missile and Surface Radar

J. A. Bauer
Leadless Ceramic Chip Carrier Assembly on Ceramic Boards—Surface Mount Technology Seminar

R. M. Blasewitz/M. Gagliardi
Modelling Ada Tasks-An Initial Survey—National Conference on Ada Technology (3/85)

F. J. Buckley
Software Engineering Standards Subcommittee (SESS), Technical Committee on Software Engineering, IEE Computer Society, Status Report, *Computer and Standards*, Vol. 3, No. 4, 159-169 (1984)

W. B. Dennen
RCA's Naval Systems Program—Lunchtime program at Stone & Webster Engineering Corporation's Cherry Hill Operations Center (2/19/85)

L. P. Dorsett
Surface Combatant Passive Survivability Design—Eighth Symposium on Vulnerability and Survivability of Aerial and Surface Targets, American Defense Preparedness (3/27/85)

R. E. Killion
An SOS for ESS—*Quality* (2/85)

R. W. Lampe
Printed CRT Folded Dipole and Related Problems—Invited Lecture (3/15/85)

E. Langberg
Computer-Integrated Manufacturing—American Institute of Industrial Engineers (3/19/85)

S. E. Ozga
VLSI Design—Seminar at Villanova University (3/20/85)

D. C. Schnorr
Surface Mount Technology for Printed Wiring Board and High Density Printed Wiring Development—Surface Mount Technology Seminar (3/21/85)

B. Wieband
CAD/CAM—Linking the Design & Manufacturing Data Base—American Institute of Industrial Engineers (3/19/85)

S. M. Yuen
VLSI, Systolic Arrays, & Real-Time Signal Processing—Valley Forge Research Center, University of Pennsylvania

S. M. Yuen
A New Super-Resolution Spectral Estimation Technique Using Staggered PRFs—IEEE Int'l. Conference on Acoustics, Speech, & Signal Processing (3/85)

Engineering News and Highlights

Robert R. Frederick announces new organization structure

RCA President and Chief Executive Officer **Robert R. Frederick** announced the structure of his organization effective April 1. The operating officers and their organizations (many are newly named) now report to Mr. Frederick exactly as shown in the organization chart below.

Significant changes include the fact that **Richard W. Miller**, Executive Vice President, Consumer Products and Entertainment will now oversee Group Vice President **Jack Sauter's** activities in Consumer Electronics and Video Components and new Group Vice President **James Alic's** added activities in Entertainment Operations, which include RCA Records and RCA/ Columbia Pictures Joint Ventures. Previously, Mr. Miller was Executive Vice President and Chief Financial Officer. Previously, Mr. Alic was Senior Vice President Corporate Planning, with responsibility for the recently created Home Information Systems Division. **Herbert Schlosser** is now Executive Vice President, Entertainment Business Development, reporting directly to Mr. Frederick. **John Rolls** assumes new responsibility as Senior Vice President, Finance, reporting to Mr. Frederick.

Roy Pollack, Executive Vice President, Electronic Products and Technology, adds responsibility for Licensing, Patent Operations, and Engineering to his established responsibilites for Solid State, New Products, and RCA Laboratories.

Eugene Murphy, Executive Vice President, Communications and Electronic Services, was formerly Chairman and Chief Executive Officer, RCA Communications, Inc. In addition to those businesses, Mr. Murphy now oversees RCA Service Company and an International Development Division.

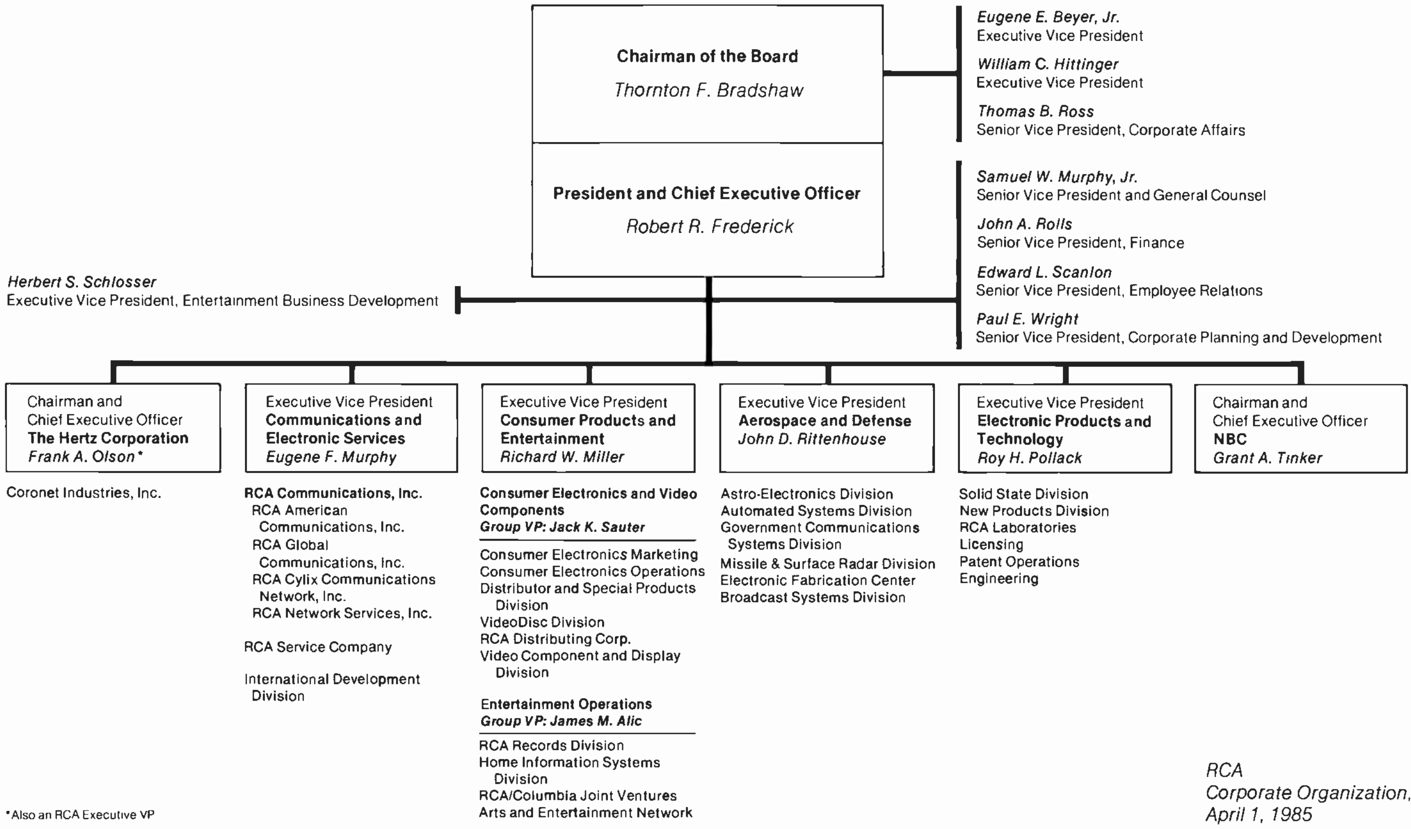
John Rittenhouse, formerly a Group Vice President, is now Executive Vice President, Aerospace and Defense. Within his organization, five business units that comprised Government Systems Division, which formerly reported to Mr. Rittenhouse through **Paul Wright**, now report directly to Mr. Rittenhouse. Four of these units are now Divisions, and the fifth, formerly known as Government Volume Production, is now called the Electronic Fabrication Center. Mr. Wright, as Senior Vice President, Corporate Planning and Development, now reports directly to Mr. Frederick.

Organization notices

Eugene F. Murphy, Executive Vice President, Communications and Electronic Services, announces his organization: **Donald M. Cook**, President, RCA Service Company; **William C. Hittinger**, Acting, International Development Division; **Eugene F. Murphy**, Chairman and Chief Executive Officer, RCA Communications, Inc. Mr. Hittinger will continue to report to the Chairman of the Board but in this acting position will report to the Executive Vice President, Communications and Electronic Services.

Richard W. Miller, Executive Vice President, Consumer Products and Entertainment, announces his organization: **James M. Alic**, Group Vice President, Entertainment Operations (**Michael L. Eskridge**, Division Vice President and General Manager, Home Information Systems Division; **Harry M. Rubin**, Staff Vice President, Strategic Planning and Video Coordination; **Robert D. Summer**, President, RCA Records Division; RCA Columbia Joint Ventures; Arts and Entertainment Network); **Jack K. Sauter**, Group Vice President, Consumer Electronics and Video Components (**Edward A. Boschetti**, Division Vice President and General Manager, Distributor and Special Products Division; **Charles A. Quinn**, Div-ision Vice President and General Manager, Video Component and Display Division; **William E. Boss**, Division Vice President, Distributor and Commercial Relations; **D. Joseph Donahue**, Vice President, Consumer Electronics Operations; **Stephen S. Stepnes**, Division Vice President, Consumer Electronics Marketing; **Arnold T. Valencia**, Division Vice President and General Manager, VideoDisc Division and President, RCA Distributing Corporation).

John D. Rittenhouse, Executive Vice President, Aerospace and Defense, announces



RCA Corporate Organization, April 1, 1985

his organization: **William V. Goodwin**, Division Vice President and General Manager, Missile and Surface Radar Division; **Andrew T. Hospodor**, Division Vice President and General Manager, Automated Systems Division; **Joseph Pane**, Division Vice President and General Manager, Electronic Fabrication Center; **Lawrence J. Schipper**, Division Vice President and General Manager, Government Communications Systems Division; **Charles A. Schmidt**, Division Vice President and General Manager, Astro-Electronics Division; **Joseph C. Volpe**, Division Vice President and General Manager, Broadcast Systems Division; **James B. Feller**, Staff Vice President, Engineering; **James R. Foran**, Staff Vice President, Financial Planning; **Leonard V. Fox**, Staff Vice President, Finance; **Donald L. Gilles**, Staff Vice President, Employee Relations; **Joseph B. Howe**, Staff Vice President and Chief Engineer; **George D. Prestwich**, Staff Vice President, Planning and Development; **David Shore**, Staff Vice President, Strategic Defense Initiative; **Francis H. Stelter, Jr.**, Staff Vice President, Marketing.

Roy H. Pollack, Executive Vice President, Electronic Products and Technology, announces his organization: **Erich Burlefinger**, Division Vice President and General Manager, New Products Division; **Carl R. Turner**, Division Vice President and General Manager, Solid State Division; **William M. Webster**, Vice President, RCA Laboratories; **Jay J. Brandinger**, Staff Vice President, Systems Engineering; **Gordon W. Bricker**, Staff Vice President, Planning; **David J. Gardam, Jr.**, Staff Vice President, Employee Relations Planning; **Allan D. Gordon**, Vice President, Licensing; **John V. Regan**, Vice President, Patent Operations; **Howard Rosenthal**, Staff Vice President, Engineering; **Robert K. Smith**, Staff Vice President, Financial Planning.

Paul E. Wright, Senior Vice President, Corporate Planning and Development, announces his organization: **Levon M. Berberian**, Staff Vice President, Corporate Development; **Kathryn C. Pelgrift**, Staff Vice President, Strategic Planning; **Elizabeth A. Richards**, Director, Marketing Research and Planning; **Robert L. Weinberg**, Director, Business Strategy Development.

John A. Rolls, Senior Vice President, Finance, announces his organization: **Lawrence K. Brown**, Staff Vice President, Tax Affairs; **David I. Brenner**, Vice President and Controller; **Michael A. Cofone**, Staff Vice President, Corporate Information Systems and Services; **Walter N. Coleman**, Staff Vice President Auditing; **Paul C. Colette**, President and Chief Executive Officer, North American Company for Life and Health Insurance; **Brian J. Heidtke**, Vice President and Treasurer.

Edward L. Scanlon, Senior Vice President, Employee Relations, announces his organization: **Donald W. Ponturo**, Staff Vice President, Labor Relations; **William M. Rodgers**, Staff Vice President, Corporate Services; **Edward L. Scanlon**, Acting, Operating Services (**Stanley M. Porfido**, Staff Vice President, Environmental and Facilities Services; **David A. Riggs**, Staff Vice President, Materials; and **Edward L. Scanlon**, Acting, Real Estate); **Edward L. Scanlon**, Acting, Employment, and Organization and Management Resources; **William E. Swartz**, Staff Vice President, Compensation and Benefits.

Americom

James J. Tietjen, President and Chief Executive Officer, RCA American Communications, Inc., announces the appointment of **Harold W. Rice** to the newly created position of Vice President, New Business Development.

Robert E. Smylie, Vice President, Government Communications Services, announces the appointment of **David J. Trautman** as Manager, DOD Systems.

Robert E. Smylie, Vice President, Government Communications Services, announces the appointment of **Doreen R. Jakubcak** as Manager, Federal Systems.

Jack F. Underwood, Vice President, Communications Services, announces the appointment of **Robert T. Krzyzkowski** as Director, Commercial Business Development.

Consumer Electronics Operations

James E. Carnes, Division Vice President, Engineering, announces his organization as follows: **Jack S. Fuhrer**, Director, New Products Laboratory; **Eugene Lemke**, Staff Technical Coordinator; **James A. McDonald**, Director, Display Systems; **Robert P. Parker**, Director, Signal Systems; **Richard A. Sunshine**, Director, Mechanical Design Engineering; and **Willard M. Workman**, Director, Product Engineering.

Robert E. Fein, General Manager, Productos Electronicos de La Laguna—S.A. De C.V., announces the appointment of **Michael E. Miller** as Manager, Resident Engineering.

Gerald C. Kuckler, Director, Manufacturing Engineering and Technology, announces the appointment of **John J. Drake** as Administrator, New Product Manufacturability.

Willard M. Workman, Director, Product Engineering, announces his organization as follows: **Theodore L. Allen**, Manager, Project Operations; **Alfred L. Baker**, Product Manager, Color Television; **Tom W. Branton**, Product Manager, Projection Television; **Todd J. Christopher**, Principal Member, Engineering Staff; **Perry C. Olsen**, Director, Television Product Design and Support; and **Williard M. Workman**, Acting Product Manager, Digital Television.

Perry C. Olsen, Director, Television Product Design and Support, announces the appointment of **Charles F. Hackett** as Manager, Component Engineering.

Electronic Fabrication Center

Joseph Pane, Division Vice President and General Manager, Electronic Fabrication Center announces the appointment of **Robert M. Lisowski** as Manager, Programs Support.

Robert M. Lisowski, Manager, Programs Support, announces his organization as follows: **Dean B. Johnson**, Manager COMSEC Support Engineering; **Joseph Bonacquisti**, Leader, Engineering Support; **Robert A. Myles**, Manager, Configuration Control; **George J. Rogacz**, Manager, Data Control; and **Enrico H. Rossini**, Administrator, Program Services.

Frequency Management and Product Safety

John D. Bowker, Director, Frequency Management and Product Safety, announces the appointment of **Frederick L. Dixon** as Manager, Product Safety, for RCA Corporation.

Globcom

Donald K. Bowker, Manager, Technical Services, announces the appointment of **James Fitzpatrick** as Manager, Office Automation.

Government Communications Systems Division

John F. Serafin, Division Vice President, Program Operations, announces the appointment of **Bill Moore** as Director, Information.

Guy H. Shaffer, Director, Integrated Communications Systems, announces his organization as follows: **Eugene M. Alexander**, Manager, Post Office Programs; **Randolph W. Bickers**, Manager, Computer Network Projects; **David T. Kjellquist**, Manager, Command Support Systems Projects; **Milton H. Lowe**, Manager AN/STC-2 Programs; **Hugh C. Montgomery**, Manager, IRR Programs Management; **Kendall Weir**, Manager, Advanced Communications Programs; **James T. Wright**, Manager, Integrated Communications Systems Programs Management; **Joseph Wylen**, Manager, Programs Support; and **James J. Wynne**, Programs Technical Advisor.

Missile and Surface Radar Division

Joseph T. Threston, Division Vice President, Naval Systems Department, RCA Missile and Surface Radar announces the appointment of **David J. Herman** as Manager, AEGIS Life Cycle Management.

NBC

Steve Bonica, Vice President, Engineering, announces the appointments of: **Bruce Cope**, Manager, Systems Implementation within Broadcast Systems Engineering; **Lon Della Peruta**, Manager, Systems Implementation within Broadcast Systems Engineering; and **Stanley N. Baron**, Managing Director, Technical Development.

RCA Laboratories

Bernard J. Lechner, Staff Vice President, Advanced Video Systems Research, announces his organization as follows: **Peter J. Burt**, Head, Advanced Image Processing Research; **Charles H. Anderson**, Fellow, Technical Staff; **Bernard J. Lechner**, Acting, Digital Video Research; **Thomas J. Bolger**, Staff Scientist; **Charles B. Oakley**, Head, Video Production Technology Research; **Robert E. Flory**, Fellow, Technical Staff; and **Michael D. Ross**, Head, Video Signal Processing Research.

Solid State Division

Jon A. Shroyer, Division Vice President, LSI Products and Technology Development, announces that the Semicustom Operations and the Memory and Microprocessor Operations are combined into one organization. **Charles J. Nuese** will continue as Director, Semicustom and LSI Products and his staff is announced as follows: **James E. Gillberg**, Director, Engineering—Semicustom and LSI Products; **H. Gene Patterson**, Director, Marketing—Semicustom and LSI Products; and **Thomas M. Stavish**, Manager, Manufacturing—Semicustom and LSI Products.

H. Gene Patterson, Director, Marketing-Semicustom and LSI Products, announces his organization as follows: **R. Adrian Bishop**, Manager, Product Markeging—Semicustom and LSI Products; **Henry S. Miller**, Manager, Semicustom Design Centers; and **Ralph S. Hartz**, Acting Manager, Joint Venture Product Definition and Applications.

H. Gene Patterson, Director, Product Marketing—Semicustom and LSI Products announces the appointment of **Ralph S. Hartz**, as Manager, Applications Engineering and Product Definition Marketing. His organization is as follows: **Ralph S. Hartz**, Acting, Product Definition Marketing—Joint Venture; **William H. Schilp, Jr.**, Section Manager, Applications Engineering; and **Paul R. Thomas**, Manager, Product Control.

James L. Magos, Director, Government and High Reliability Operations, announces his organization as follows: **Donald R. Carley**, Acting Mgr., Applications & Product Engineering—SOS Products; **Dale M. Baugher**, Section Manager, Applications and Product Engineering—SOS RAMS; **Edward C. Crossley**, Section Manager, Applications and Product Engineering—SOS Logic; **Seymour Dansky**, Program Manager; **Robert F. DeMair**, Section Manager, Testing Engineering; **Charles E. Farley**, Supervisor, Technical Programs; **Robert W. Nearhoof** Program Manager; **Donald R. Carley**, Acting Section Manager, Applications and Product Engineering—Packaging and LSI Products; and **Marlan N. Vincoff**, Section Manager, Applications and Product Engineering—Standard IC Products.

James E. Gillberg, Director, Engineering—Semicustom and LSI Products, announces his organization as follows: **Al A. Key**, Manager, Product and Test Engineering—Semicustom and LSI Products; **Arthur L. Lancaster**, Manager, Memory Design Engineering; **Richard P. Lydick**, Manager, Development Engineering—Semicustom; and **Joel R. Oberman**, Manager, Systems and Design Engineering—LSI.

Larry L. Gallace, Director, Product Assurance, announces that the title of the Engineering Standards department is changed to the Document Control Center.

Leonard Mineur, Director, Operations Systems and Materials, announces his organization as follows: **Robert E. Brown**, Acting Manager, Data Nomenclature Manufacturing Systems; **Paul J. Herstek**, Manager, MIS—Mountaintop; **Robert J. Jaglowski**, Manager, MIS—Palm Beach Gardens; and **Robert I. Unbehend**, Manager, MIS—Findlay.

Professional activities

Engineers active at Astro-Electronics

John Keigler, Principal Scientist and **Rudolph A. Stampfl**, Manager, Advanced Programs have been elected Fellows of the American Institute of Aeronautics and Astronautics (AIAA).

David W. Gross, Manager, Mechanical Analysis has been appointed to the Technical Committee of the American Institute of Aeronautics and Astronautics (AIAA).

Bruce A. Meberg, Associate Member of the Technical Staff, has been elected Chairman of the Princeton Chapter of the American Institute of Aeronautics and Astronautics (AIAA).

Dr. Raj Gounder, Manager, Special Projects, was chairman of the three sessions on the Spacecraft Structures, Materials, and Processing of the 30th National SAMPE Symposium and Exhibition, March 19 through March 21, 1985.

Dr. Richard Lee, Principal Member of the Technical Staff, has been named President of the Philadelphia Chapter of Korean Scientists and Engineers.

Wolfe nominated to committee

Donald B. Wolfe, Government Communications Systems Division, has been nominated to the Program Committee of the Automation Technology Institute, Inc., Pebble Beach, Cal. This committee will plan the selection of topics and speakers for the 1986 ATI conference.

Karstad is Author of the Year at SSD

Kaare Karstad, Member of the Technical Staff, Solid State Division, has been named the 1984 Author of the Year by that division. The award is based on the number of pages of technical articles published in 1984, the appropriateness of the publications in which the articles appeared, and the degree to which the information in the articles helped the reader become familiar with and use RCA semiconductors.

Braun to head FCC group

Walter H. Braun, Vice President, Systems Engineering and Program Management for RCA American Communications, Inc., has been elected Chairman of the Coordination Working Group of the FCC's Reduced Orbital Spacing Advisory Committee. The objective of the Advisory Committee is to provide the FCC with affirmative recommendations on any actions the Committee should take to effectively implement 2 degree orbital spacing between domestic communication satellites operating on the C and Ku bands.

van Raalte VP of SID

Dr. John A. van Raalte, Director, Display Systems Materials and Processing Research, RCA Laboratories, was re-elected National Vice President of the Society for Information Display (SID). Dr. van Raalte is also Chairman of the SID Convention Committee that organizes the annual SID International Symposia and International Display Research Conferences.

P.E. Licenses

Craig McGirr, Consumer Electronics Operations, has been awarded Indiana Professional Engineer's license number 20957.

IEEE honors two MSRD engineers

George Poletti and **John C. Bry**, Jr., were recognized for their outstanding contributions to the IEEE at the Philadelphia Section Awards Banquet held March 23, 1985.

George Poletti was the Region 2 recipient of the 1984 United States Activities Board Regional Professional Activities Award, and was cited for "contributing most in furthering the professional aims of the IEEE on a national and regional basis." As Region 2 Government Coordinator and the Chairman of the Professional Activities Committees for Engineers, Mr. Poletti espoused the IEEE's technical resources to both the New Jersey and Pennsylvania governor's offices.

John Bry was cited for his "outstanding and dedicated service to the IEEE Philadelphia Section, with particular recognition of the special contributions for Centennial activities." Mr. Bry served the Section in various committee chairmanships and offices, culminating with the Section Chairmanship in 1980.

New Fellows, RCA Laboratories

In recognition of their outstanding contributions, **Sheng T. Hsu**, **Werner Kern**, and **Richard W. Nosker** are appointed Fellows of the Technical Staff, RCA Laboratories.

The designation of Fellow was established by RCA Laboratories in 1959, and is comparable to the same title used by universities and virtually all technical societies. It is given in recognition of a record of sustained technical contribution in the past and of anticipated continued technical contribution.

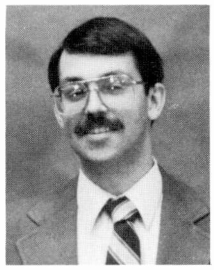
Fellows, Technical Staff:

Charles H. Anderson
Brian Astle
William H. Barkow
Francis J. Campbell
Kern K.N. Chang
Roger L. Crane
Andrew G. F. Dingwall
Robert E. Flory
James J. Gibson
Leopold A. Harwood
Karl G. Herqvist
Sheng T. Hsu
Werner Kern
Ralph W. Klopfenstein
Walter F. Kosonocky
Simon Larach
Richard W. Nosker
Jacques I. Pankove
Dalton H. Pritchard
Allen H. Simon
Harold Staras
Wilber C. Stewart
Thomas M. Stiller
Chih Chun Wang
Hugh E. White
Richard Williams
Charles M. Wine
James P. Wittke

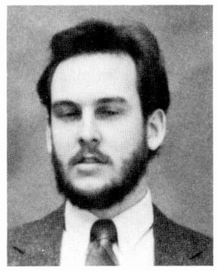
Povenmire wins Findlay award

Ginger Povenmire has been awarded the Findlay 1984 Technical Excellence Award for her outstanding work in the COSMOS Photo Area. She helped reduce the photo recycle rate from 9 percent to a monthly rate of 5.5 percent, she set up a Soft Contact QMOS Photo Process with a higher circuit probe yield and lower P_r than other RCA QMOS photo areas, and she set up a Canon Projection Aligner and established all critical dimension biases for QMOS masks.

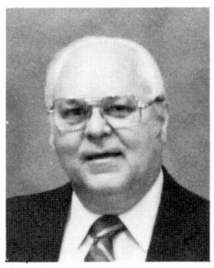
CE fourth quarter awards



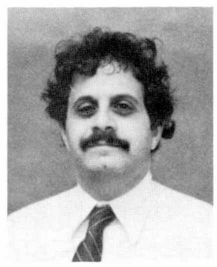
Collins



Culley



Hamrick



Mindel

There were four winners of Consumer Electronics Operations fourth quarter Technical Excellence Awards:

Ronald C. Collins and **Dennis E. Culley**, for the design and implementation of an automatic convergence reading system for COTY yokes. The convergence reader is a computerized test system that controls a yoke core alignment machine. The system automatically adjusts the yoke to achieve the proper yoke/tube setup (YAMing) and then reads the yoke/tube misconvergence at 17 locations. The system reports the convergence data and maintains a statistical history. The ability to make fast, accurate, repeatable convergence measurements is allowing the quality of RCA yokes to be improved from a manufacturing and design standpoint.

George Hamrick and **Michael Mindel**, for the improvement of the solderability of printed circuit boards by process and equipment modifications in the protective coating operation. Through a series of designed experiments and data analysis, they were successful in determining the cause of solderability problems and finding a solution. The water soluble anti-tarnishing chemical spray operation that was added to the process eliminated rework, increased quality, and allowed a 100-percent increase in printed circuit board throughput.

RCA Laboratories honors 44 scientists

Forty-four scientists have received RCA Laboratories Outstanding Achievement Awards for contributions to electronics research and engineering during 1984. Recipients of individual awards are:

Alfonse A. Acampora, for the development of techniques for digital processing of video signals for satellite transmission.

Walter R. Curtice, for the development of advanced techniques for computer simulation of III-V compound field-effect transistors for microwave amplifiers and multigigabit-rate integrated circuits.

Douglas F. Dixon, for contributions to graphics and digital image software for research in consumer electronics products.

Dennis C. Quardt, for the design and development of the "SUPERCAM" system, simplifying the use of CAM equipment and leading to an eightfold reduction in the time spent in producing mechanical parts.

Ronald T. Smith, for contributions to the characterization and understanding of electronic materials by x-ray diffraction.

Gordon C. Taylor, for the development of GaAs power field-effect transistors for K-band and higher frequencies.

Recipients of team awards are:

Zygmunt M. Andrevski, Edward C. Fox, John Kowalik, Theodor M. Wagner, and **Ronald W. Watson**, for contributions to the design and implementation of an assembly system for the optical front-end of a broadcast CCD camera.

John R. Appert, Norman J. DiGiuseppe, Stefan A. Siegel, and **Thomas J. Zamerowski**, for contributions to the development and commercialization of 1.0-to 1.7-um optical detectors and receivers.

Russell R. Barton, David E. Coleman, and **Peter J. Wojtowicz**, for contributions to the development and demonstration of asymmetry and statistical methods for analyzing deflection yokes.

William J.Bischoff, Edward P. Cecelski, James J. Gibson, and **Chandrakan B. Patel**, for contributions in support of the definition of Multichannel TV Sound standards of the United States.

Robert F. Casey and **Hermann J. Weckenbrock**, for contributions to the development of digital signal processing for enhanced NTSC color television display.

John F. Corboy, Jr. and **Robert H. Pagliaro, Jr.**, for contributions to the development of advanced homoepitaxial silicon deposition technology and for support in the transfer of the technology to production.

Alvin M. Goodman, Lawrence A. Goodman, John Neilson, and **John P. Russell**, for contributions to the development of the COMFET—a new power MOSFET with dramatically reduced power disipation—and its successful transfer to production status.

Kenneth W. Hang, Philip M. Heyman, Edward A. James, and **Robert L. Quinn**, for contributions in developing a low-cost, factory-compatible, machine-readable marking system for identifying color picture tubes.

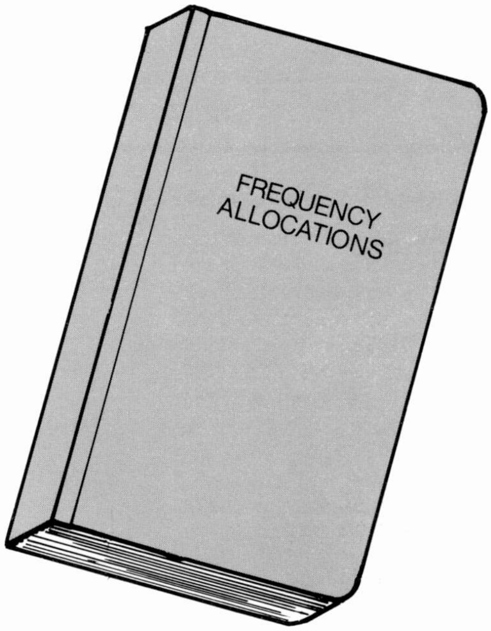
Gunther Harbeke, Liselotte Krausbauer, Edgar F. Steigmeier, and **Alois E. Widmer**, for contributions to the organization of materials and measurements for improved integrated circuit processing.

Alfred C. Ipri and **Roger G. Stewart**, for contributions to the development of novel polysilicon thin film transistors suitable for active-matrix flat displays.

Ralph W. Klopfenstein and **Albert P. Pica**, for contributions in applying a quantiative model of the human visual system to the design of advanced video displays.

Visvaldis Mangulis and **Dipankar Raychaudhuri**, for contributions to the development of unique computer-based analysis techniques for the design of an innovative Ku-band satellite communications system.

New book available: *Frequency Allocations*



The newest edition of *Frequency Allocations* has just been published by the RCA Frequency Bureau. This attractive pocket-sized book contains all international and U.S. allocations and regulations up to November 1984, including the results of the 1979 and 1983 World and Regional Administrative Radio Conferences.

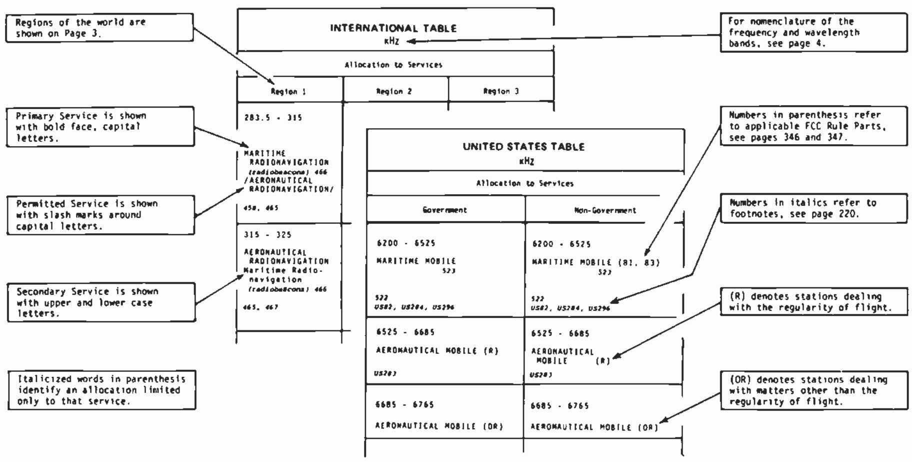
This new edition features:

- Worldwide allocations for all frequencies between 9 kHz and 300 GHz. A world map shows each of the ITU Regions.
- U.S. Government and non-Government allocations printed on studies of potential radio interference.
- Radio service assignments listed by Primary, Secondary and Permitted uses in each frequency band.
- A complete set of international, U.S. domestic, U.S. Government and U.S. non-Government footnotes that help explain or define the limits on certain allocations.
- Other sections identify each frequency and wavelength band, provide the title for each FCC Rule Part, explain the new emission designations, and list all U.S. TV broadcast channel frequencies, standard frequencies, and special industrial, scientific and medical frequency bands.

For the system design engineer and engineering manager, this reference may be invaluable. It is the only publication we have seen that contains such often needed information. Its small size and new flexible binding are perfect for carrying in a jacket pocket or tucking away in a briefcase.

RCA employees may purchase a copy of *Frequency Allocations* for $4.00 (regular price is $5.00) through **Mrs. Dora Mineo, RCA Frequency Bureau, One Independence Way, Princeton, N.J.** Make checks payable to RCA Corporation. Non-RCA purchasers should address Mrs. Mineo at P.O. Box 2023, Princeton, N.J. 08540. For further information about placing company orders or quantity orders (10 or more), please call Mrs. Mineo at **Tacnet 254-9566 or (609) 734-9566.**

Guide to the 215-page frequency allocation table.



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