Quality

The fiftieth anniversary of RCA is an appropriate time to reflect on those factors which have contributed to its success. Significant among these have been the courage to pioneer and innovate in the development of new products and new services for the nation's defense, for industry, and for the consumer. RCA's pioneering and innovating spirit, so evident throughout its operations, is particularly exemplified in its approach to quality. Quality, of course, embraces all product assurance attributes such as reliability, producibility, maintainability, value, product control, and ultimate service to the user.

Throughout our history, RCA has been in the forefront in developing and applying new quality approaches. Typical of these are the development of reliability and maintainability prediction and assessment techniques, which became the standard for the Defense Department and industry. In addition, it was RCA that initiated the first application of reliability demonstration testing under AGREE (Advisory Group on Reliability of Electronic Equipment).

The pioneering spirit is still present. Traditional techniques are being honed to improve their effectiveness. New techniques, some of which are described in this issue, are in a continual state of development. The quality cost program is worthy of special mention. This program provides management visibility of the costs involved in producing a high quality product. It includes the costs incurred in engineering and manufacturing, as well as in the quality operations. Visibility not only highlights problems requiring attention, but permits the planning necessary to shift resources from fire-fighting to fire-prevention. The net effect is to produce a higher quality product at lower cost per hour and per year of service to the user.

CO-AMP, an acronym for Cost Optimization-Analysis of Maintenance Policy, is an RCA-developed computer technique for determining the most cost effective maintenance practices for the military services. This valuable tool has potential applications in the industrial and consumer markets as well. Techniques for the prediction and assessment of safety in complex systems are currently under development.

RCA maintains a highly professional staff of product assurance personnel. Their objective is to assure customer satisfaction with RCA products and services and thereby contribute to the Corporation's future business potential. Equally important is their direct contribution to current profits by controlling defects and their associated costs. In the last analysis, however, the responsibility for achieving quality rests with each manager, supervisor, and engineer. Your personal understanding and dedication to the modern concepts of quality assurance are vital to our success.

The product assurance articles contained in this issue of the *RCA Engineer* should provide insight among engineers, designers, and managers into their roles—as well as those of the specialists — in our continuing program to keep the name RCA synonymous with quality throughout the world.

W. W. Watts
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Our cover
Many random (yet related) factors affect total product quality; eventually, each phase contributes to engineering excellence, product assurance, and high reliability in RCA products and systems. The colorful flow of square patterns on our cover symbolizes this concept of control over infinitely variable and random occurrences.

RCA Engineer

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

Contents

high-Q engineering

In engineering, Q is a familiar symbol representing performance factor of a circuit, a component, or a mechanical system. To improve Q, a designer gives painstaking attention to several interrelated characteristics. In an analogous and more encompassing way, Q can connote product quality, and it is from this aspect that this issue examines the myriad of factors contributing to a high-Q product.

Basically, a high-Q (high quality) product satisfies the customer's expectations regarding performance. But what are these expectations—and how are they best satisfied? The answer is simple, but the attainment is difficult—a high-Q product requires a thorough knowledge of the interrelationships of engineering, manufacturing, and marketing, and a healthy respect for the costs involved in changing these relationships.

First, let's look at performance. A customer usually knows exactly what he wants in this regard—and is willing to pay for it. For example, why do high-performance automobiles today sell for more money, more often, than the economy models? The customer simply wants the increased performance, and is willing to pay for it. Similarly, the high-fidelity buff is willing to double or triple his investment for another 50 cycles of response or another couple of watts of power.

A more subtle influence on performance considerations, however, comes with the customer's appreciation for a product that is "built to last." Reliable performance has been, and will continue to be, a primary factor in the marketplace. Coupled closely with reliable performance is the characteristic of maintainability, or ease of servicing. Current emphasis on long-term guarantees, warranties, and service policies support the importance of this characteristic.

Cost, naturally, is a major factor underlying all product quality considerations. But contrary to popular belief, high-quality does not necessarily mean high price. Often, a rigorous and challenging examination of the costs of achieving product quality results in increased simplicity, reliability, serviceability, and reduced cost. In general, the customer must know that he is receiving value for his money, and the seller should be satisfied that he is receiving his just profit.

The papers in this issue are written by specialists who treat the areas of product assurance, value engineering, reliability, maintainability, and cost effectiveness with a very high degree of engineering excellence. However, the papers are not written for other specialists in these fields; rather, they are written to remind every engineer of his basic involvement in producing the best possible product for the marketplace.

Hopefully, the papers in this issue will provide all of us with a new insight and appreciation of how to engineer a high-Q product.

Future Issues

The next issue, the fourteenth anniversary of the *RCA Engineer,* will contain representative papers from most areas of RCA. Some of the topics to be covered are:

Quadruplex TV tape recorders

Professional societies

Liquid crystals

Video phase equalizer

World markets

RFI and EMI

Silicon-on-sapphire devices

TV images from space

Science in the U.S.S.R.

Discussions of the following themes are planned for future issues.

Microwave devices and systems

Interdisciplinary aspects of modern engineering

RCA engineering on the West Coast

Linear integrated circuits

Consumer electronics

Computerized educational systems

Product assurance concepts

H. E. Schock, Jr.

The concepts of product assurance are applied at RCA on a Corporate-wide scale. The objectives, recommended techniques employed, and the organizing and planning for high quality are described from the consumers point of view. Systems effectiveness, reliability, maintainability, human factors, product safety, statistical assurance, baseline management and quality assurance are other areas discussed in this paper.

INTEGRITY is a key word in product quality and reliability. Developments of specialized production and control techniques aid in maintaining this integrity, optimizing production efficiency, and assuring value received by the customer.

Early quality concepts

The early Greek concept of quality was *the goodness of an object*. By 1922, this concept had changed little and quality was thought of as the characteristics distinguishing one article from another, goods of one manufacturer from those of a competitor, or one factory product from another grade turned out by the same factory.[1] Today the customer applies this same concept to quality except for a greater emphasis on economics and control.

In 1924, statistical concepts were applied to measure and control variations in quality of the manufactured product. Better coordination of the design with the process capability[2] was achieved. The techniques developed in 1924 are being used today as the basis for modern product assurance skills. The economic applications have been broadened by better data availability and accounting procedures coupled to the computer.

Modern objectives

Regardless of the modern techniques, a manufacturer's results are still measured by three essential requirements for consumer, industrial and government products: 1) satisfy the customer, 2) make a profit, and 3) increase business.

To realize these objectives and achieve optimum efficiency, management strives to take best advantage of the changing technology. In RCA there are many combinations of product and

customer requirements that must be met at various phases in the life cycle of RCA products. Some are in early growth stages, some are reaching maturity and still others are at their peak. In all stages of product growth, there is one common need: a continuing control of product assurance.

Organization

Many customers are not interested in who will do what, or in the details of management organization; they rightly look at the products and the results. When a new product is involved, the customer wants to be assured in detail that the product will meet his expectations; the customer feels entitled to special assurance.

In reviewing an organization for conformance to product assurance goals, it has been common to use a check list (Fig. 1); each block represents one element intended as a reminder or guide; and each block ties down responsibilities for the final line, staff, or program responsibilities. Many of these blocks are part of existing organizational duties; thus, no separate functions are necessary to meet the overall goals. Some blocks, such as Reliability Engineering and Quality Control are more complex and represent organizations involving many interactions between line, staff, and program activities.

There is no one best way for all products and organizations. The options change with slight variations in product conditions and manpower skills. The checklist, however, when reviewed with past experience and special future considerations, can aid in determining an optimum structure.

A product assurance program must have one integrating and control point. In this concept, RCA has provided important contributions that have been considered and adopted by other companies throughout industry. The final

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received the BS-AE-ME from Cornell University in 1942, and continued his additional training through various university courses and other educational programs. He joined RCA in 1942 as a student engineer and has been associated with various Divisions in the Corporation as: Manufacturing Engineer, Project Engineer, Product Manager, Financial Administrator, Quality Control Manager, and Customer Product Assurance Manager. In 1958, he was appointed to his present position to work with the Divisions in developing programs and controls in Product Assurance areas. His industrial activities include serving as Chairman of the Quality Reliability Engineering Committee of the Electronic Industries Association, and as a working member in activities of the USA Standards Institute and the US National Committe of the International Electrotechnical Commission. Professional activities include membership and active participation in the ASQC, the Society for Advancement of Management, the ASME, and the IEEE. He is also a member of the Engineers Club of Philadelphia and the Franklin Institute.

decision for a product assurance program requires a balance between the generalist and the specialist. The generalist assures proper overall integration and application. The specialist provides knowledge with controls and audits. The modern manager uses a PERT-Critical Path Program including product assurance requirements for cost and time in the same way as the

manager of 1940 used a Gantt chart for production requirements for time.

Systems effectiveness

To determine true customer requirements for design life and field use is an increasing challenge complicated by rapidly changing design and user conditions; thus, broad cooperation must be developed between advanced technology and marketing. Such cooperation is enhanced by the development of many specialized analytical tools for systems effectiveness and integrated logistics support. The CO-AMP II and QUEUE programs are typical examples of two of these analytical tools.

At RCA, the systems concept emphasizes "what is required by the customer" rather than "how requirements are to be met." This is necessary to provide flexibility and parallels the manner of determining organizational responsibilities (Fig. 1); as before, defining the objectives is more important than a given detailed organizational pattern.[3]

In addition to being useful in product review, some of the systems effectiveness tools are finding increasing use in measuring internal effectiveness of programs and product assurance trade-offs such as:

> Recognition of trend patterns,
> Analysis of actual experience vs theoretical forecast, and
> Logistics research

New uses for these tools are being found daily in reviewing element progress against the total product systems effectiveness potentials.

Reliability

Electronics engineers are familiar with RCA's role in using historical field data to estimate failure rates for general vintages of products under certain broad-stress exposure levels. This technique was further refined to provide the present MIL Standard 217A. As might be expected, this is not the ultimate, and RCA has proceeded with additional work to aid in the preparation of MIL Standard 883 test methods and procedures for microelectronics. This document will provide the base necessary for product stability and verification before failure rate estimates can be meaningful.

The growth of reliability techniques is not limited to U.S.A. designers and users. The International Electrotechnical Commission, of which the U.S.A. has been a member since 1904, has recognized the need for reliability guidelines for international commerce. Therefore, Technical Committee #56 prepared reliability considerations and terms for use in writing IEC recommendations for electronic components (parts) and systems. RCA has been active in this work.[4]

One of the major problems in properly defining reliability terms has been the difficulty of describing reliability at various product phases:

Reliability	Conditions
theoretical	optimum and derated
design	anticipated
achieved	production variations

To forecast and verify accurately the reliability levels for each variable, there is a growing need to integrate prediction, testing, and failure analysis for each chemical/physical interface. New techniques are resulting in better estimates and identification of the control and preventive action needed; to achieve this is the real object of the reliability exercise.

Maintainability

The science of maintainability has developed beyond the qualitative check lists for the common factors historically associated with maintenance. In 1957 RCA inaugurated quantizing techniques and verification programs for maintainability. Recognized as major elements in systems effectiveness, computer data logging and simulation techniques provide economic meaning to the maintainability terms and definitions of MIL Standard 778. Although developed for government application, these terms find increasing use in domestic and international applications for consumer and industrial products.

Former marginal testing techniques used on filament devices, are meaningless on solid-state products, until such approaches are restructured. Similar revised techniques are applied in areas where mechanical safety considerations are needed in nondestructive testing. Safety requirements may necessitate complete disassembly of equipment, and in some cases, even stripping and replating of parts, as in the case

of aeroplane landing gear inspection. Designing for maintainability to support a round-the-clock operation of equipment is a major element in systems effectiveness.

Human factors

Aided by industrial stylists and psychologists, the design of electronic equipment must consider human factors to assure customer satisfaction. Development of many product features are justified not only on the basis of appearance but for subtle user advantages for non-technical customers and technicians alike. Human engineering has received increasing attention with the use of biomechanics for reviewing industrial production and maintenance. Application of the philosophy of preventing defects demands a thorough consideration of production operator control and field maintenance in advance. Designing with these objectives in mind, reduces or eliminates the possibility of errors.

Product safety

The electronics industry has long been aware of the important area of systems and product safety. Active industry safety programs have been coordinated with new product developments and requirements are under continuing review. RCA has been a leader in the development of quantizing techniques to measure systems safety, especially for major systems. Such techniques are similar to failure analysis and prediction techniques used for reliability.

Statistical assurance

The use of statistical techniques has grown during the past ten years to become one of the main tools of product assurance. Aided by the computer and by advanced analysis techniques,[5] data analysis and accelerated life test programs are used to optimize test time and the number of test units. Good statistical programs recognize that data is only of value when used with proper analysis. Programs are constantly under development for the better use of data in product development, production and to analyze product field experience.

The economic importance of making the best use of available data has resulted in a demand for specialists having a balance of statistical skills

Fig.1—Product assurance matrix.

Product Assurance	Marketing/Sales	Product Engineering	Production & Materials	Financial	Personnel	Outside Division
Systems effectiveness	Program plan	Value engineering	Type Test	Contracts controls	Special training	Standards
Reliability assurance	Reliability requirements	Reliability engineering	Life Test	Systems cost effectiveness	Reliability training	
Maintainability assurance	Maintainability requirements	Maintainability engineering	Maintainability verification		Service training	Parts & accessories
Human factors assurance	Human factors requirements	Human factors engineering	Industrial engineering		Quality motivation	User factors
Product safety assurance	Product liability reviews	Product safety engineering	Product safety control		Product safety training	Safety committees
Statistical assurance	PERT Netting	Design statistics	Statistical quality control	PERT/cost	Employee records	
Baseline management assurance	Control document control	Configuration control	Data acceptance control	Financial reports control	Employee qualification	
Quality assurance	Proposal reviews	Qualifications	Quality control	Quality cost effectiveness	Employee training	
Supplier quality assurance		Supplier engineering capability	Supplier quality control		Supplier training	
Performance quality assurance	Competitive analysis	Service publications	Customer response control	Warranty	Sales training	Field service feedback
Advanced technology	Marketability analysis	Research applications	Methods improvements	Economic studies	Training requirements	Customer training
Product assurance audit	Audit	Audit	Audit	Audit	Audit	Audit

and practical product experience. Such specialists constantly aid in the search to recognize an assignable cause, envision the economic importance, and then take corrective action.

No discussion of statistical assurance would be complete without a brief mention of some of the available important references. Briefly, such product assurance techniques include: sampling plans for attributes[6] and variables[7], reliability tests for exponential distribution[8,9,10,11], and reliability tests for Weibull distribution[12].

Baseline management

The term "baseline management" was originated in the early 1960's as a program developed to aid in defining project objectives. Development of this concept advanced to configuration management baselines, another specialized area where RCA contributed in training personnel in industry and government. Such training considered the concepts, philosophies, and intentions of the customer.[3,13] Techniques developed for the government are equally usable for nongovernment programs and custom products.

Field use and production requirements necessitate configuration control systems for maintenance of equipment and fast analysis of possible problems. The uniformity of terminology developed in this area continues to be a stabilizing influence for the further development of international agreement on definitions and terms.

Quality assurance

The in-house production aspect of product assurance has been a classical area for quality control. Goals developed in the 1920's on economic considerations[2] continue to support reviews and controls for preventing problems; original goals include:

Optimize inspection costs
Optimize rejection costs
Attain maximum benefits from quality production
Attain optimum results from destructive tests
Optimize tolerance limits

Emphasis on planning and verifying assure management perception and re-

view through the techniques of PERT/cost, critical path, quality cost, and systems effectiveness. Developing confidence levels for product quality factors receives much attention and new management techniques aid in proper application of effort.

What is product quality assurance? The dictionary definition defines *quality control* as: "A system for verifying and maintaining a desired level of quality in a product or process by careful planning, use of proper equipment, continued inspection, and corrective action where required."[15]

The importance of the term quality assurance is readily apparent where the same dictionary defines "assurance" as: "A positive declaration intending to give confidence; full confidence; freedom from doubt; certainty."

The combination of these two definitions best expresses the meaning of the term quality assurance. The use of prevention and verification is implied and readily understandable in the context.

Techniques for quality assurance expand daily with new facilities, capabilities, and products. In microelectronics, for example, such techniques have resulted in development of new inspection standards, test methods, and new procedures for specifying quality parameters such as mean value control and distribution control.[14] Knowledge is not limited to microelectronics and has expanded to many commercial and government product areas.

The optimum use of new techniques, within the flexibility of the organization, continue to be a major objective of the quality assurance activity. The use of guidelines to establish the product assurance program includes responsibilities relating to both customer and company.

Supplier quality assurance

Surveys of supplier capabilities have increased validity of data and confidence of vendor performance. The growing use of supplier certification has aided in reducing problems and in expediting operations that produce higher quality products.

Acceptable quality goals are determined by a combination of historical data and the expected performance for each component characteristic. A general acceptable quality level is a passe approach for supplier quality programs. The *philosophy* of *specific planning with verification* has replaced the practices of screening or relying on after-the-fact reviews.

An industry-wide quality and reliability assurance procedure and questionnaire is available for electronics parts suppliers to furnish information for prospective users.[16] Such information provides more detailed data and speeds up valuable surveys.

New practices have entered into the procurement quality picture with parts distributors setting up testing, and screening and burn-in facilities for semiconductors and similar parts. Some distributors are performing the final assembly operation, especially for custom items such as connectors. These and similar practices require continued analysis for economic and product quality considerations. In laminated plastics during 1962 there were 1800 customer specifications for reliability requirements alone, despite NEMA,

ASTM, and industry attempts to standardize. Continued efforts are under way to prevent similar proliferations in integrated-circuit quality and reliability specifications. Such information is coordinated on a Division basis through product assurance committees.

Field performance

The customer's final opinion of the product is the prime consideration of the success of product assurance activities. This response affects establishment of quality standards and determines the relative competitive position of the product. Major problems are time delays and inaccurate field data that result in information of questionable value. Emphasis in solving this problem has, therefore, been directed in developing several parallel approaches:

> Product reviews before and during production;
> Product reviews before shipment (customer acceptance laboratory approach);
> Use condition simulation in addition to review to specification;
> Accelerated life testing; and
> Field experience auditing.

The product assurance activity must always be ready to expect anything when changes are needed to solve possible problems. However, the temptation to incorporate any improvement as soon as possible must be carefully weighed. Systems effectiveness evaluation techniques are especially useful in analyzing these improvements for effects on product field performance, economics and reputation.

Audits

Full evaluation of a product assurance program requires a carefully conducted audit on a continuing basis. The audit uses a good check list as a guide[17] and pays particular attention to cause-effect relationships. Actual product-use requirements and conformance to specifications receive attention. In addition to product areas, auditing programs examine procedures and instructions for conformance to the operating system.

New technologies

No discussion of product assurance would be complete without a brief mention of the important effect of new technologies. Planning for new prod-

ucts of microelectronics and hybrids requires careful review for facilities and manpower training to assure proper product assurance evaluation. Similar planning is necessary for new production techniques to develop the closest controls and appropriate failure analysis capabilities. Many committees and councils are available for dissemination of information throughout the industry. The number of new technical societies is an indication of this attempt to keep pace with new technologies.

Summary

To be the leader in designing and producing high quality products is one of RCA's most important goals. A company's reputation for high-quality products must remain a constant challenge—a demand that cannot be compromised. Product assurance skills must be applied in all areas to assure high quality, prevent problems and verify that the product conforms to demanding user requirements.

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The design engineer and the concept of value

Carlos Fallon

The design engineer is often caught among the diverse values offered by the Prophets, the Devil, and the competition. He seldom has time to plumb the depths of economics and sociology for the morsel of wisdom which applies to the value he contributes to his company's products. He works hard, practices good human relations, develops a sense of political acumen, and makes moderate progress in his career. He wonders why some engineers who work less, are mean and ornery, make appalling political blunders, and produce *less results,* nevertheless get ahead. Very often, the answer is that the little results these men produce are *the right kind of results.* Moderate effort, *in the right direction,* has greater value than back-breaking effort in the wrong direction. That is the reason successful engineers seem to sail easily and pleasantly through their work. On the other hand, much useless and frustrating activity comes from working toward the wrong goals, or from allocating effort among the right goals in the wrong proportions.

A SOUND UNDERSTANDING of the concept of value can help the engineer in industry direct his efforts toward the right kind of results; to distinguish between more or less, on the one hand; and better or worse, on the other. *More or less* are matters of fact. *Better or worse* are matters of value. More or less generally call for effort; better or worse always call for judgment.

One definition of the concept of value

> *An idea that relates goals to each other and to the cost of attaining them.*

But there is a lot more to it than that, for to understand value fully is to capture the essence of wise decisions made by successful men throughout the ages. We can hardly hope to do that, but we can approach it by striving to understand those aspects of value which are perceptible in our day-to-day work.

How value was rent asunder

When industry went from individual craftsmanship to mass production, product value was partitioned, and the product began to suffer under many masters. Making it work went to Engineering. Making it pretty went to Styling. Buying the ingredients went to Purchasing. Making it economically went to Manufacturing. Finding the money and riding herd on it went to Finance. As craftsmen were forced to

separate, their products lost value— a modern violin is inferior to a violin made by Antonio Stradivari, but abundant violins, of reasonable quality, have replaced scarce violins of superb quality—what, then, is the problem?

Competition

Japan is selling violins in the United States, Finland is selling "Spanish" guitars. Spain is selling motorcycles—competing with Japan and England for *our* motorcycle market. Yet competition is a source of strength and progress in the free world. The thing to do is not to bewail it but to beat it.

One way to beat competition is to recapture the high performance and fine quality of individual craftsmanship without losing the advantages of volume production. Striving toward this objective, industry has developed a variety of organizational and administrative approaches, all centered around the concept of industrial teamwork.

The engineer and the competition

The key player in the industrial team which contributes to product value is the design engineer. There are ugly automobiles that work and sell; there are expensive automobiles that work and sell; but there are no automobiles that do not work and still sell—be they ever so beautiful and inexpensive.

The design engineer makes the product work. Through his ingenuity—the word *engineer* comes from *ingenium—*
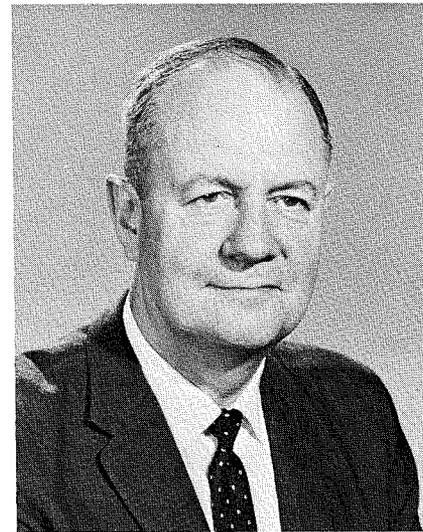
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received his education as a Colombian naval officer at the *Escuela Militar de Cadetes* and under the British and U. S. naval missions to Colombia. He served as technical advisor to the minister of war, supervisor of naval construction and repair, and finally as chief of staff of the small but relatively modern Colombian navy. In 1941 he came to the United States as a naval architect and mechanical engineer, hoping to fulfill a lifelong ambition to become a civilian. After Pearl Harbor his mother volunteered him for the Army Air Corps where he served as a combat intelligence officer. Mr. Fallon's engineering experience encompasses missile-borne and ground telemetry equipment, nucleonics instrumentation, and missile launching system design. In conjunction with Dr. G. E. Davis, Chief of the Nucleonics Section of the New York Naval Shipyard, he designed the 120 Curie, Cobalt 60, gamma ray source in use at that shipyard. He also designed an air particle sampler used in our nuclear submarines for radioactive contamination control. In addition to his work in RCA's plants throughout the world, he has lectured on value analysis in England, Norway, Sweden, and Denmark. In September 1968 Mr. Fallon gave the invited address at the international meeting of the Scandinavian Society of Value Analysis. He has published technical papers on resource allocation, decision theory, and value engineering. He is a member of the Society of American Value Engineers, American Society of Mechanical Engineers, Mathematical Association of America, and the Canadian Mathematical Congress.

7

he overcomes what John Stuart Mill called *difficulty in attainment*.[1]

> "That a thing may have any value in exchange, two conditions are necessary. It must be of some use; that is, it must conduce to some purpose, satisfy some desire. . . . But, secondly, . . . there must be also some difficulty in its attainment."

The air we breathe—useful as it is—presents no difficulty in attainment, so we do not pay for it. Flying, on the other hand, *does* present difficulties and it *is* desirable, so engineers design planes, Finance raises the money, Purchasing buys the materials, Manufacturing makes the planes, Marketing sells them, and customers buy them. They give money in exchange for the product, or more accurately, as Peter Drucker says,[2] for what the product *does* for them.

The gross income of most industrial companies, therefore, is based on the exchange value of the products or services they offer. As long as he is a prime mover in the creation of exchange value, a good design engineer is in the enviable economic position of a goose who lays golden eggs.

Nature of exchange value

Looking at exchange value as a fishing net to capture customer dollars in the stream of competition, we can see that each knot, or nodal point in the net, corresponds to one of the factors governing exchange value in a competitive industry. These factors, or nodes, are:

1) Customers with money and unsatisfied wants—a market.
2) Utility to such customers—the product must suit the market.
3) Difficulty in attainment—the product must be hard to get.
4) Total cost to the customer—an inverse component of value. Given difficulty in attainment, the customer wants to pay the least for overcoming that difficulty.
5) The customer's other options—competition.

Given customers with money and *unsatisfied wants* at node 1, the design engineer must create *utility* at node 2, overcome the *difficulty in attainment* at node 3, keep the *cost* down at node 4, and stay abreast of *competition* at node 5.

Such span of responsibility calls more for an octopus than for a goose who lays golden eggs.

With some exceptions, such as selling your soul to the Devil, exchange value involves an intricate relationship among the arts, the physical sciences, and the social sciences, all of which must contribute *jointly* to providing a product acceptable to the customer. [To simplify exposition, the word *product* will be used in this article for *both* products *and* services, and what is said of the *design engineer*, in his contribution to value, will apply to the corresponding creative function in other industries.]

Scientist, engineer, beggarman, thief . . .

. . . doctor, lawyer, Indian Chief? The engineer is a scientist-plus. The plus is economic feasibility, in exchange for which the design engineer trades off his formal contribution to pure science. The pure scientist is primarily an explorer into the unknown, a searcher for additional knowledge. His creative effort is in the field of discovery.

The engineer, although also an explorer, is primarily a pioneer and an inventor, putting exploration and discovery at the service of man. His creative talent is mainly in the field of invention.

Beggarman, thief? . . . Only in the sense of skillful scrounging, such as practiced by good sergeants in the army.

Doctor, lawyer, Indian Chief? . . . These callings represent the diversity of customers an engineer must design for, not to mention the Army, Navy, Air Force, Coast Guard, NASA, and the Marine Corps. Visualize this array of customers, and invite into the picture some of the missing ones—housewives, truck drivers, preachers, teachers, farmers, jobbers.

Would it make sense for an engineer, trained primarily in the physical sciences, to embark personally upon the sociological task of interviewing all these classes of customers? Yet, he must please them. He is expected to apply the physical sciences to the service of man, and man is a *social* animal.

The industrial team

The engineer in industry actually creates exchange value, but who defines it? Who establishes the requirements to make a product worth buying? The customer, of course. So industry has

developed activities that specialize on customer wants—Marketing, Styling, Advertising. Industry has also developed its own professional customers, its own professional buying activity—Purchasing. All these activities are studied under the social sciences.

Is the engineer caught in the middle?

Yes, in the key position which bridges the gap between the physical and the social sciences. Whether he is *caught*, like a quarterback when the line collapses, or whether he walks into the pocket to throw a pass, depends to a great degree on the performance of his blockers.

How does he communicate with them? Originally, when our football developed out of Rugby, communication took place in the heat of the play, as it does in basketball today. Later, when plays were planned beforehand, a set of elaborate signals was used to designate the play, its direction, and the players involved. It worked for a while, but not well enough. So the huddle became the rule, rather than the exception, and it proved to be a most effective means of communication, reducing the "signals" to a time delay and triggering device. The change was forced by the increased fluidity and dynamics of the game, by the need for greater flexibility and faster communication.

Industrial competition today presents the same challenge. Time—meeting and beating schedules—is as important to the design engineer as improved performance or reduced cost. He has the choice of waiting for information or going out to get it himself. He often does the latter, and often loses in accuracy and completeness what he gains in time.

Such is the information dilemma—either fly with insufficient information and risk falling on your face, or wait for all the facts and risk missing the boat. What does the customer *really* want? What new materials are available? Can the proposed design be manufactured economically? By designing it differently, can it get through the factory faster? What advances have taken place in manufacturing methods during the past year? Which suppliers can really help us?

The engineer re-reads the specs, he telephones, takes trips, scans library shelves, searches for the right people to answer his questions. All this time his sketch pad, slide rule and lab instruments are idle. Instead of doing engineering work, he has been desperately seeking information which yesterday's methods do not provide in time for today's needs.

If he is astute, if he has been around the plant long enough, and if he has friends, *he calls a huddle.* Let the formal information flow-in later; *this* time around he will meet face-to-face with specialists who have the data and skills he needs.

A committee? Hardly. The chairman of a committee is not supposed to take the initiative. A quarterback is. Committees were developed as parliamentary instruments to represent diverse *interests.* A football huddle, on the other hand, relates diverse skills to a *common interest.*

A value task group

Who should make up the huddle? It should certainly include specialists in product assurance, cost estimating, purchasing, and in manufacturing, but it should also include a couple of other engineers—say one electrical and one mechanical—to evaluate financial, purchasing and manufacturing information in engineering terms, just as the other members of the group evaluate engineering information in business terms.

The task group follows a search pattern for timely information, *jointly* putting the facts together and jointly evaluating them. The different lines of information then mesh into a network which turns out to be quite different in total effect than the arbitrary sum of independently gathered data, for "Everything which interacts must be studied together." [Professor Kenneth E. Boulding, interviewed in *Business Week,* January 4, 1969, page 82. (Professor Boulding is the retiring president of the American Economic Association.)]

Such a systems-oriented task group exchanges and digests, in a few hours, the information that normally takes weeks to circulate in written, drawn, or coded form. More important, the information itself is more useful because its interaction is detected at once instead of being discovered later when something does not work, costs too much, or is not available in time.

Output of the value task group

If the inputs of the task group are information and multidiscipline knowledge, its outputs are options, options to be compared and then adopted or rejected by the design engineer. Each of these options should hold water in the tests of procurability, technical feasibility, productibility, and customer acceptance.

Members of the task group ask each other questions that forestall time-consuming vendor inquiries, design review objections, manufacturing problems, and marketing complaints.

What does the design engineer himself contribute? First, he provides direction, briefing the group on the problem or opportunity to be tackled and on the information he needs; second, he sets bounds within which the group must work; third, he exercises judgment in using or not using the information generated by the group; and finally he contributes the invaluable industrial ingredient of cool courage —that combination of judgment and daring which leads to a good batting average in risk-taking.

As described up to this point, the design engineer and the task group have been getting along very well. Their relationship is one of trust, confidence, and mutual support. Is this a real-life situation?

Remember, we said of the design engineer, *"If* he is astute, *if* he has been around the plant long enough, *if* he has friends, he calls a huddle."

Of course these people work well together. They are friends. They know their way around, and they have helped each other in the past. We might have added—about the design engineer—"If he is politically adroit, tactful, and persuasive . . ." because it takes such skills to borrow people from other departments, take them away from their regular tasks, and get them to look at someone else's problems while their boss is fidgeting and their regular work is lagging behind.

The RCA value program

To get the information he needs, when he needs it, a good engineer should not have to be politically adroit, tactful, and persuasive. If he is talented and acts like a prima donna, the thing to remember is that prima donnas make a lot of money for opera companies, and the thing to do is to provide both prima donnas and design engineers with a supporting cast.

In an industrial plant, however, members of the supporting task group often arrive on the stage, not as a chorus but as a committee, each singing the aria of his own department.

Enter the value specialist

The value specialist may be an administrator of value analysis, of value engineering, or of value systems and controls, but an administrator he *is.* His task is not to out-design the designers, out-buy the buyers, or out-cost-reduce the cost specialists. His administrative task is to get the right people together, at the right time, in a suitable conference room, so that they can generate, search for, exchange, and evaluate information *jointly.* His motivational task is to get them to work for THE MAN RESPONSIBLE—in this case the design engineer.

Where friendship catalyzed the emergency task group described above, wholesome self-interests catalyzes the planned task groups of the value program. Each man gains advance information on what engineering is up to. This information gives his department more lead-time to prepare for what is coming. Whether he is a buyer, manufacturing engineer, or cost estimator, his suggestions reach the design engineer at the time when he can best use them. Specific purchasing, manufacturing, and financial recommendations enter the design cycle as initial inputs instead of reactions.

The greatest benefit to all participants in the value task group is in elapsed time. Today's *joint* planning, at the working level, forestalls tomorrow's panics, releasing management time to handle real uncertainty.

What to work on

Prime targets for a value task group are:

1) Jobs which have to advance the state of the art. The fiercest competition today is in the race for new products—new ways of doing things. For this leap into the unknown an engineer needs, more than ever, fresh information on new materials, new suppliers, new manufacturing methods.

2) Jobs which must be delivered ahead of schedule—getting there first. When there is no time for the step-by-step approach characteristic of yesterday's gentler competition, a value task group can do concurrently much that was done sequentially.

3) Jobs which cost more than they should, either because the price would exceed what the customer can pay, or because the gross margin does not yield enough profit. Here is an example of such a project.

An engineering-oriented value task group

What has been said above about the design engineer as quarterback would apply to the responsible buyer if the task was primarily a buying task, or to a styling specialist if the task was to improve customer acceptance by making a more beautiful TV cabinet. When the engineer is THE MAN RESPONSIBLE, as in a design task, he is of course the quarterback. The example that follows was chosen because it is a recent example—December 1968—and because it represents a typical engineering-oriented value task group.

D. Sauer, Leader, AM-FM Shortwave Transmitter Engineering at the Meadow Lands plant of our Commercial Electronic Systems Division had the task of reducing cost on the BTA-

5/10U TV Broadcast Transmitter in order to yield a profitable gross margin to us at a competitive price.

He called W. D. Boyle, purchasing manager, to arrange for a value task group. Bill Boyle gave the ball to Don Stokes, administrator of value analysis, who got together with Dave Sauer on the composition of the team. The team included three people from engineering —one a manager—two buyers, a top-notch manufacturing specialist, and a cost estimator. Don Stokes served as value administrator and Dave Sauer, THE MAN RESPONSIBLE, as quarterback.

Savings were:

Transformers	$ 45.00
Rectifiers (2)	2.00
Manometer	10.00
Timer	12.00
Capacitors & tank coils	57.00
Meters & bezels	91.00
Blower	153.00
Cabinet	445.00
Resourcing of parts	325.00
Total savings per Transmitter	$1,420.00

One of the ground rules, of course, is that the savings are never accomplished at the expense of required performance, quality, reliability, and other elements of utility. Consultants from the Marketing function attend the meetings to safeguard customer acceptance. With such Engineering and Marketing talent to guard the goodies, it would be wasteful to have them work only on such baddies as high cost, excess weight, excess volume, etc. So the team works on *both*

platters of the scales of value: increasing the goodies as well as reducing the baddies. This double-track approach is characteristic of the RCA value program.

The value analysis job plan

The multidiscipline task of analyzing value follows the general pattern of the scientific method: incorporating problem solving and innovation techniques with the teamwork characteristic of group dynamics. Meant to be a fast-moving drive by people of different skills at various levels of education, the job plan must be outlined as simply as possible. Since the task group must answer certain questions, we start with questions of the type listed in Table I.

Conclusion

Being a key contributor to exchange value—chief source of his company's income—the engineer can contribute more and can profit personally from an economic understanding of the concept of value. If the measurements of macro-economics seem astronomical, the studies in micro-economics can be said to be molecular, then the value of specific industrial products must be studied . at something resembling atomic and subatomic levels.

A few venturesome economists have each identified one or another of the "subatomic" particles such as *utility, difficulty in attainment, customer wants, customer resources, cost to the supplier, worth to the customer, price, total cost to the customers,* and *the customer's other options,* but no one yet has constructed a theoretical model which in any way approximates the relationship among these elements in real life.

The practical results of taking a close look at the structure of product value were presented in this article as bait to lure unguarded engineers into joining the author in the fascinating task of building a model that approximates the structure of product value.

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Table I--Foundations of the value analysis job plan.

Information phase: matters of fact

What is it?	Part number and description
What does it do?	Function
What does it cost?	Actual or estimated cost

Analytic phase: matters of value

What *should* it do?	Functions that will provide greater customer satisfaction or greater system effectiveness.
What *should* it cost?	Basic or lowest cost of performing the function.

Creative phase: innovation

What will do it better?	Better methods of performing the function.

Evaluation phase: comparison and choice

What will it buy us?	Gains in profit, time, or customer acceptance.
What will it cost us?	Dollars, time, disruption.
What are the risks?	Technical, economic, others.

Implementation phase: action

Who must approve it?	Authorization
Who will provide the funds?	Budget
Who will do it?	Manpower
Where?	Facilities
Who will monitor progress?	Control
Who determines priorities?	Completion date and cut-in point.

Maintainability from the servicing viewpoint

C. T. Morrell

An operation and maintenance (O&M) project has many problems as well as many little quirks that are peculiar to any operation that requires both human and equipment compatibility over long periods of time to achieve smooth operation of complex electronic, electrical, and mechanical systems. This paper outlines some management thinking that has proven successful on service programs and discusses some of the quirks that equipment designers can inadvertently build into a system.

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received the Associate Degree in Electrical Engineering from Long Beach City College in Long Beach, California and has additional credits. He joined RCA Service Company as Quality Control Engineer on the TITAN Project at Marysville, California in 1961 following associations with Hughes Tool Company, Aircraft Division (Flyng Boat Project). At the completion of the TITAN Project he was transferred to the BMEWS as the Project Quality Control Engineer. In mid-1965 he was promoted to Manager, Quality Assurance and at the same time assumed the duties of Administrator, Product Assurance for the Government Services Division of the Service Company.

A DEQUATE INSTRUCTIONS form the base upon which the O&M contractor can develop a program to keep his equipment operational and to keep the incentive contract payments coming. Thus, by starting with adequate instructions, the O&M contractor has taken the necessary first step in satisfying management objectives.

Operating schedules and instructions

Operating schedules are usually dictated by the customer, the Contract, or the Statement of Work, and the contractor may have very little flexibility. He does, however, have the responsibility for maintaining these schedules and for issuing timely and thorough instructions to support the operating personnel. Such instructions should be

1) Written to the training level or background of the personnel that are to carry out the duties;
2) Complete enough so that a new operator, trained but not familiar with

the particular equipment, can perform his duties with a minimum amount of supervision.
3) Written to a high enough level so that a technician reading them will not take them as an insult to his training and background.

There is an inclination to feel that the instructions contained in a manufacturers' operating instruction or a technical order are adequate and therefore no other preparation is necessary. In some cases, this is true; however, in others, the material may be too sketchy, too detailed, or maybe just too cumbersome to carry out and to maintain in the working areas. For knowledgeable technicians, a straightforward checklist might be more practical.

Preventive maintenance schedules and instructions

Preventive maintenance (PM) schedules are usually given, on new systems, by the manufacturer and have been established during the design and manufacture based on some combination of experience and calculations. This schedule is a good place to start but may not be the best for optimum oper-

ability and sustained actual operation. There is a difference in calculating reliability goals during the design and manufacturing period and achieving these during operation and maintenance era. This difference is treated later under the discussion of Reliability.

Preventive maintenance schedules can vary in time periods by shift, by day, by week, by month, etc., up to a year. Some electronic/electrical equipment may require no more than a tweaking of the controls to reset limits; other equipments must be completely shutdown for a period of time for cleaning, inspection, and adjustment. Mechanical or hydraulic equipment would probably require several pieces of equipment to be replaced, wear measurements to be taken, and a complete cleanup/washdown to be performed.

Preventive maintenance instructions should be complete, within the limits indicated above for operating instructions. There is, at times, a tendency to feel that all personnel are journeymen in their various field and, therefore, don't require or need detailed instruc-

Fig. 1—Sample form for reporting preventive maintenance and corrective actions.

tions. True, they may not need detailed instructions, but they do need checklists and detailed notes for tolerances, types of test equipment to be used, types and amounts of lubricants if applicable, etc. The only person that really never made a mistake or forgot an operational step wasn't doing anything to begin with. The most conscientious technician still needs the assistance of instructions or checklists to jog their memories as they go along their daily operational duties.

Reliability

As previously stated, the methods of determining reliability factors during the design and manufacturing stage and during the operation and maintenance period are, and must be, different. During design and manufacturing, reliability is calculated based on piece part and assembly reliability estimates, test data, operating ranges, temperature, etc. During the O&M period, reliability is determined by actual, meaningful, and timely reporting. This means accurate record keeping and, above all, timely feedback to operating areas. With such feedback, an unreliable item within a system or assembly can be recognized by comparing the number of failures against population and frequency.

To solve this type of reliability problem, the preventive maintenance schedules can be adjusted, or if possible, the unreliable part can be replaced with a better, more reliable component that falls within form, fit, or function. This latter is not always possible within the confines of Configuration Control and/or the criteria called for in some Specification Control Drawings. Specific problems for the O&M contractor caused by information contained in Specification Control Drawings will be discussed in more detail later. Also methods of determining and reporting reliability will be given under the discussion of Software.

Hardware

All O&M and some Service Projects have their share of hardware and it can come in all shapes and combinations whether it be electronic, electrical, mechanical, or hydraulic.

It is in all of these systems that there is constant need of Preventive Maintenance as well as Corrective Maintenance programs, history and correlation of failure causes, as well as man hour expenditures.

This, then, leads management to examine several areas to determine if they are getting the best out of their programs and what can they do to improve operations. Some of the typical areas that are examined are:

1) Manpower utilization
2) High man-hour consumer items
3) High equipment failure rates
4) High failure rate assemblies
5) Piece parts contributing to assembly failures
6) Preventive maintenance effectiveness

The necessary information covering these areas can be found in the system and equipment logs that are maintained on an action-by-action and day-by-day basis; however, this not only is a very laborious method of information retrieval but may also add to labor expenditures.

We therefore need a reporting system that will give this information on a timely basis, utilizing the minimum of manpower and reporting expense. This type of reporting then becomes the Software program of the O&M or Service Project.

It should be understood that the above thoughts regarding logs is not to imply that they are unnecessary and should not be maintained. On the contrary, they are vital for historical as well as

follow-up data—to operating as well as systems personnel—in the historical tracing of maintenance actions or the sequence of deteriorating failures of a system or component for future identification and prevention. In many cases they serve as the input to any Software program.

Software suggestions

Throughout the Government Services Division of the Corporation there are several varities of this system already in use; they range from the Government enforced systems, such as the Air Force AFM 66-1 program, to smaller more suitable project-devised programs.

A good reporting system that will answer the operating management's pertinent questions can be programmed into a computer, if available, or can be provided by an active EAM system. The basic form to be used by all maintenance personnel for reporting both preventive maintenance and corrective maintenance actions can be similar to the Service Company's Repair Report (Fig. 1) or the Air Force's AFTO forms such as the 210, 211, 212, or 349 and 350.

To provide all the data required, the equipment must be fully identified down to the lowest serialized components and piece part. This, then would include system, site (where applicable), set, group, unit (cabinet), assembly (chassis), subassembly, piece part. This can be accomplished by a coding system for the first five items and by part and serial number for the last three.

The forms may be of single or multicopy depending on how many steps of the maintenance program they are to cover; e.g., on-equipment or off-equipment fixes. They would be initiated by all maintenance personnel and the accuracy of their initiating and reporting details is most essential to the total accuracy and usefulness of the final reporting outputs.

The individual reports, to be accumulated on a daily basis and keypunched into required card format, can be used to obtain answers to all the questions previously asked of the Hardware section by selected sorting and printing

for the various reports; e.g., group, site, area, piece part, man-hour utilization.

The final runoff reports are then processed back to the O&M reliability and operating groups where they can then be applied to charts that show the mean levels for an operation as well as a standard deviation from that mean. Experience has shown that a standard or 2 (2 standard deviations) is an ideal alarm level with a standard of 3 (3 standard deviations) as an indication of immediate action. This system is applicable to the measurement of manpower utilization as well as all equipment levels and location failure ratings.

The timely machine printouts and progressive charting will assist management in adjusting preventive maintenance schedules and at the same time locate equipment problems before they can become a serious operational hazard by indicating the offensive assemblies and piece parts, or the determination of an area, location, requiring additional personnel training or increased supervision.

This information that has been programmed into the cards or computer can also be utilized to schedule and preprint all of the pertinent information onto a preprinted PM form and as such save many man hours of having to prepare forms and schedules by tedious manual methods.

Configuration control

The problem of Configuration Control for the O&M or Service Project is also quite different from those confronted by our manufacturing counterparts. In O&M it is not so much the determination and setting up of Configuration Control as it is the maintaining of the configuration over a long period of time: five, ten, or maybe fifteen years.

By now you are asking: "How can this be when the configuration is given to the Project in the form of Specification Control Drawings, etc." You are right in thinking this way; but have you considered what is to happen when time passes and some of the manufacturers named on those drawings are no longer in business, or over a period of time he has changed his designs and no longer manufactures the item, or maybe improved it so that form, fit, or

maybe function is not to the drawing. Too, sometimes a manufacturer will only maintain spare parts for a certain period of time and then dispose of the design tooling and even replacement components.

Design engineers, when they specify a manufacturer and his part number on a Specification Control Drawing, are thinking that they are helping in the procurement of an item, and they are at the time; however, let's consider this item from the O&M side several years later. The same parts may or may not be available from the same source or several sources and maybe at different prices, and there may be considerable cost savings by being able to shop around. When a particular vendor and part number is on the print, then the O&M contractor must maintain that vendor or have nonconforming materials. It would be much better to reference a vendor and part number and specify OR EQUIVALENT.

Those projects that have to do with Government contracts are held to control of nonconforming materials, and this means total compliance to the drawings. As such, materials review board action is required to permit a vendor change even though he may have gone out of business or may no longer produce the same items he did ten years ago. Therefore, the preparation of a complete Specification Control Drawing is essential but let's initiate the procedure of only referencing suggested vendors and vendor part numbers.

Conclusions

An economical O&M program can be developed for any equipment or system, and it will not vary to any great extent whehter it be electronics, electrical, or mechanical because management is looking for the same answers in all.

There are the noted differences, and they must be viewed from different angles and there are considerations that will help the O&M operators. However, the truly efficient operator will utilize a Product Assurance Program for recognition and correction of both quality and reliability riddles before they develop to the problem category.

Reliability sampling plans

E. C. Smith

In recent years, military specifications for electron tubes have called for increased reliability. Reliability has been defined in terms of failure rate or mean-time-to-failure at some specified confidence level. It is the responsibility of the electron-tube manufacturer to establish adequate testing plans that will meet these military requirements. This paper describes a proposed method for a life-test sampling plan based on the exponential failure distribution. The equation relating the cumulative Poisson distribution and confidence level was used as a basis for development of a useful set of curves for establishing meaningful sample plans.

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received the BSEE in 1949 from the Milwaukee School of Engineering. He taught radio and television courses from 1949 to 1952 at Temple University Technical Institute. He has pursued graduate study at Catholic University, Washington, D.C. From 1952 to 1954 he was a test engineer for the Engineering and Research Corporation where he performed quality checks of flight simulators. In 1954 he joined RCA as a test engineer. In 1958 he was given the responsibility of heading the Specification Engineering activity. He has also developed computer programs used in processing color picture tube life test data. At present, Mr. Smith is Acting Engineering Leader, supervising the Specification Engineering activity, which develops the electrical testing specifications for power, conversion, and color picture tubes. He is a registered professional engineer in Pennsylvania. He is a member of the IEEE since 1950.

E LECTRON TUBES exhibit an exponential failure distribution[1] during the period of life that precedes "wear out". When "wear out" occurs, another failure distribution (usually Gaussian) is observed. The exponential failure distribution can be described in terms of the number N_s of tubes surviving the test, as follows:

$$N_s = N \exp(-t/m) \qquad (1)$$

where t is the test duration, m is the mean-time-to-failure, and N is the number of tubes started on life test.

The exponential failure distribution can be derived from the Poisson distribution. First, the well known Poisson distribution $P(r)$[2,3] is described as follows:

$$P(r) = \frac{(t/m)^r \exp(-t/m)}{r!} \qquad (2)$$

where r is the number of failures and $P(r)$ is the probability of exactly r failures occurring.

If $r=0$, Eq. 2 becomes the familiar reliability expression, as follows:

$$P(0) = \exp(-t/m) \qquad (3)$$

The equation relating confidence level, CONF,[4] and cumulative Poisson distribution is as follows:

$$\text{CONF} = 1 - \sum_{r=0}^{r} \frac{(NT/m_s)^r \exp(-NT/m_s)}{r!} \qquad (4)$$

where N is the number of tubes in the sample, T is the life-test duration (time truncated), m_s is the specified mean-time-to-failure, and r is the number of failures.

This equation shows that confidence level decreases as the number of failures, r, increases. (Cumulative terms for the Poisson distribution are tabulated in the book of *Standard Mathematical Tables*).[5] Eq. 4 has been plotted for confidence levels of 90% and 70% (Figs. 1 and 2) where the ordinate is sample size N and the abscissa is life-test duration T in terms of specified mean-time-to-failure m_s. It should be noted that these curves are based on truncated life-testing (i.e., each tube in the sample is tested until failure or until T hours of life are reached). For this reason, the curves are adjusted to account for the fact that all tubes do not reach T hours without failure or do not fail at exactly T hours. In addition, it is assumed that, when failures occur within the truncated time the average time of failure is $T/2$ hours.

If a military specification calls for a specified mean-time-to-failure ($m_s = 1000$ hours at a confidence level of 90%) a sampling plan has to be established to fit the requirement. For example, if life-test sockets are available for twenty-three tube samples, the line is drawn horizontally on 90% confidence graph at a sample size of twenty-three tubes. This line intersects the failure curves as shown in Fig. 1.

For $r=0$, the life-test duration is 0.1 m_s. This duration means that each of the 23 tubes must be life-tested 0.1 x 1000, or 100 hours, with no failures permitted. If, however, one failure does occur, the life-test duration is increased so that each tube must operate for 173 hours with no additional failures. If one more failure occurs, making a total of 2 failures, a decision to continue test can be made. However, the life-test duration must again be increased to 242 hours. The life-test sampling plan is tabulated as follows:

Confidence level=90%

Sample size=23 tubes *Life-test duration (hours)*	*Number of failures*		
	Accept	*Cont. test*	*Reject*
100	0	1	2
173	1	2	3
242	2	3	4
310	3	4	5
381	4	5	6
453	5	6	7
530	6	7	8
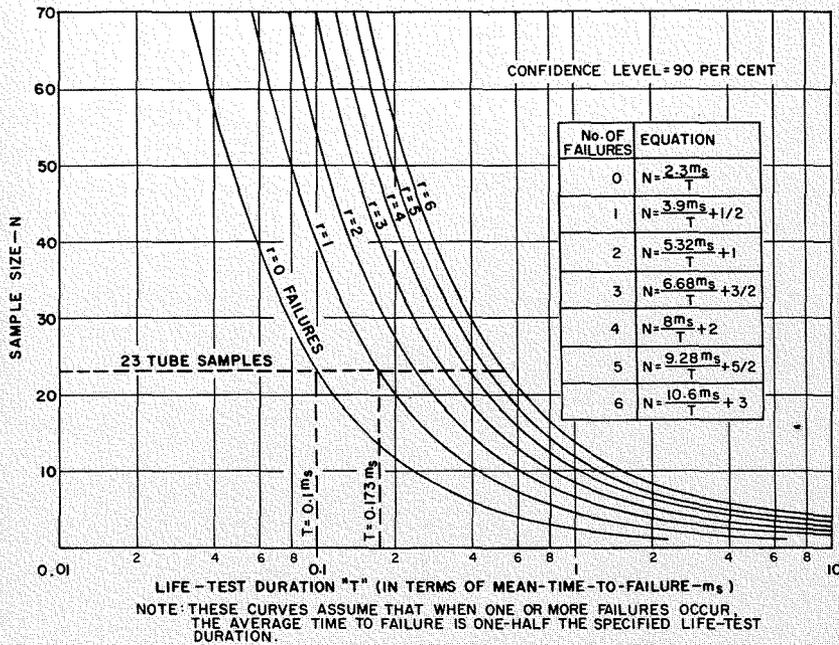
14

Fig. 1—Probability that r failures will occur based on a confidence level of 90%.

CONFIDENCE LEVEL = 90 PER CENT

No. OF FAILURES	EQUATION
0	$N = \dfrac{2.3 m_s}{T}$
1	$N = \dfrac{3.9 m_s}{T} + 1/2$
2	$N = \dfrac{5.32 m_s}{T} + 1$
3	$N = \dfrac{6.68 m_s}{T} + 3/2$
4	$N = \dfrac{8 m_s}{T} + 2$
5	$N = \dfrac{9.28 m_s}{T} + 5/2$
6	$N = \dfrac{10.6 m_s}{T} + 3$

NOTE: THESE CURVES ASSUME THAT WHEN ONE OR MORE FAILURES OCCUR, THE AVERAGE TIME TO FAILURE IS ONE-HALF THE SPECIFIED LIFE-TEST DURATION.
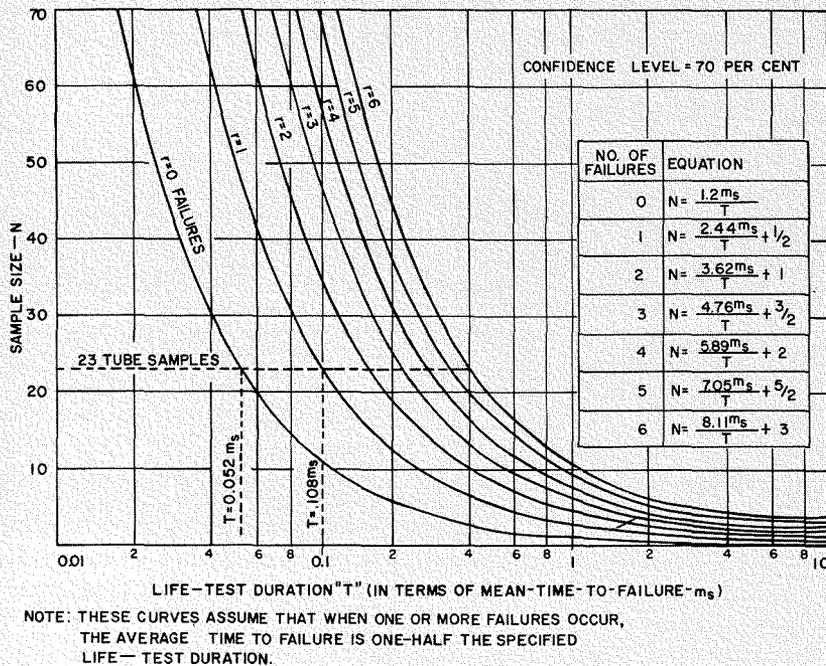
Fig. 2— Probability that r failures will occur based on a confidence level of 70%.

CONFIDENCE LEVEL = 70 PER CENT

NO. OF FAILURES	EQUATION
0	$N = \dfrac{1.2 m_s}{T}$
1	$N = \dfrac{2.44 m_s}{T} + 1/2$
2	$N = \dfrac{3.62 m_s}{T} + 1$
3	$N = \dfrac{4.76 m_s}{T} + 3/2$
4	$N = \dfrac{5.89 m_s}{T} + 2$
5	$N = \dfrac{7.05 m_s}{T} + 5/2$
6	$N = \dfrac{8.11 m_s}{T} + 3$

NOTE: THESE CURVES ASSUME THAT WHEN ONE OR MORE FAILURES OCCUR, THE AVERAGE TIME TO FAILURE IS ONE-HALF THE SPECIFIED LIFE— TEST DURATION.

Life-testing according to this plan is terminated when the number of failures in a given life-test duration does not exceed the number shown in the "accept" column. Conversely, the product fails to meet the military requirements when the number of failures equals or exceeds the corresponding number in the "reject" column.

The effect of reduced confidence level at 70% is illustrated in a similar manner. Again, a horizontal line is drawn at the sample size of twenty-three tubes. For $r = 0$, the life-test duration is 0.052 times m_s. Therefore, each of the 23 tubes must be life-tested 0.052 x 1000, or 52 hours with no failures permitted. The 20% reduction in confidence level reduces the life-test duration nearly one-half, with no failures allowed. The life-test sampling plan is tabulated as follows:

Confidence level = 70%
Sample size = 23 tubes
Life-test duration (hours)

Life-test duration (hours)	Accept	Cont. test	Reject
52	0	1	2
108	1	2	3
165	2	3	4
221	3	4	5
280	4	5	6
344	5	6	7
406	6	7	8

It is evident that reduction of confidence level reduces the testing time and, in turn, reduces the cost of the life test. In addition, the curves show that a lower number of tubes in the sample requires a longer life-test duration. The combination of sample size, N, life-test duration, T, and confidence level can be balanced to conform to the availability of life-test sockets and tubes. Failure rate plans for confidence levels of 90% and 60% are provided in MIL-STD-690A, "Failure Rate Sampling Plans and Procedures."

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Cost effectiveness in phonograph record production

J. M. Eargle

This paper treats several areas of phonograph record production with particular emphasis on the quality manager's role evaluating the tradeoffs between product quality and cost. To aid in this evaluation, the tradeoffs are discussed in a graphical (mathematical) manner which should stimulate qualitative thinking regarding cost and quality.

T O GAIN A BETTER APPRECIATION of what cost effectiveness means, we might plot product effectiveness, E, against the cost, C, required to produce that product at various quality levels. Hopefully, the curve will always be positive. The low-cost region curve may show many inflection points, but the high-cost region will tend to be asymptotic at a limiting value of quality or effectiveness. With this model, cost effectiveness at any point along the curve could be defined as $\Delta E/\Delta C$. Thus at any point on the curve, we have a measure of the effect of an incremental change in cost. In the region where $\Delta E/\Delta C$ is fairly high, obviously a small increase in cost results in a significant improvement in quality. Likewise, where $\Delta E/\Delta C$ has a fairly low value, an increase in cost would result in negligible quality improvement. This situation is depicted in Fig. 1 and 2.

Figs. 1a, 1b, and 1c represent individual cost-effectiveness curves. Fig. 1a could characterize, say, engineering cost effectiveness. Ordinarily, effectiveness would tend to level off as costs increased beyond a certain amount, but one could easily postulate a second rise and leveling off as the result of an engineering "breakthrough."

Fig. 1b could illustrate labor-cost effectiveness; this curve would increase monotonically, tending to level off without inflection points. Fig. 1c could be the cost-effectiveness curve for certain kinds of materials. The presence of a maximum indicates the existence of one, and only one, material for opti-

mizing a given operation or application. Such curves could be constructed for *all* the other areas—tangible as well as intangible—that enter into the total picture of product quality and effectiveness.

Fig. 2 represents the *sum* of all the individual cost effectiveness curves, each one weighted according to its role in determining total product effectiveness. In general, this curve will exhibit many inflection points and tend to level off as costs increase beyond a certain point.

Stated simply, the Quality Manager's job in the area of cost effectiveness is to take each of these elements, add them together with a proper weighting factor for each to produce a curve like that shown in Fig. 2; and then select an operating point along this curve. Since the elements which make up this curve will always be changing, so will the operating point, but this point will in general tend to be on a knee of the curve in a region which is concave downward—in other words, at a point where an *increase* in costs tends *not* to produce a significant increase in effectiveness.

This graphical description of cost effectiveness is essentially mathematical. Fortunately, none of us actually has to draw such curves, but it is quite clear that our jobs force us into an awareness of all factors which would be involved if we did have to draw them. Many of the decisions are not ours to make, specifically those quality attributes due to advertising, promotion, and the cosmetic aspects of packaging. In looking at manufacturing in general, we can visualize a continuum
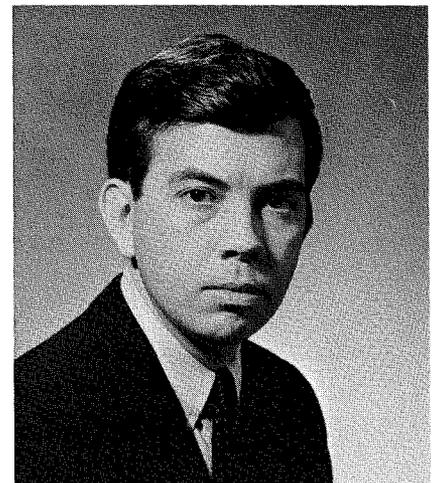
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extending from low-volume high-cost items at one extreme to high-volume low-cost at the other. Phonograph records are clearly at the high-volume low-cost end, but before we take a detailed look at records we will describe two items related to the record business: one at the middle of the continuum and the other at the opposite (high-cost low-volume) end.

High-cost low-volume production

At the high-cost low-volume end of the continuum, let us consider a manufacturer of precision tape-to-master disc transfer lathes. His engineering and design costs may well be at the top of their respective quality-versus-cost curves; considerable money may well have been spent in these areas in the manufacturer's goal to improve upon state-of-the-art performance. The same would likely be true in the manufacturer's choice of materials: he would use the best materials regardless of cost. The company is likely to be a small one with little overhead to liquidate. Also, advertising and promotion costs would be low since the manufacturer would probably know his limited market very well and even be in direct communication with it. The item would probably be sold directly to the user, and it is very likely that each lathe-transfer system would be customized to some extent for each user. Perhaps the most significant fact of all is that the manufacturing cost of the item is a very high percentage of the market price. The quality manager of this plant has relatively little freedom in the several areas of cost effectiveness since his major concern here is the engineering and reliability of the item and the meeting of rigorous performance specifications.

Medium-cost medium-volume production

A phonograph is representative of products at the middle of our continuum and, as with most durable consumer items that come out in yearly models, there is great flexibility in the choice of materials in this product. Accordingly, manufacturers become very cost conscious. The engineering and design efforts will have two goals: better performance and fewer parts. There will be considerable amounts of money spent on purely cosmetic features, such as surface finish and styling, in an effort to attract customers in a highly competitive market place. Also, there will be large amounts of money spent in advertising and promotion. Significantly, the manufacturing cost of the item may be between 50 and 60% of the sale price.

Phonograph record production

Let us now move on to phonograph records. Unlike the other two products, a record has something of a dual nature: on the one hand, it is a piece of hardware (and one that is not so easy to manufacture); on the other hand, it is a piece of software, conveying, as it does, a message or program which is entirely apart from anything having anything to do with its manufacture. To the quality manager of a record company, the various quality attributes of a record many seem clear and distinct. He can easily separate musical performance, recording technique, and manufacturing quality. The consumer, on the other hand, makes no such distinction. To him, quality is quality. If he doesn't like the performance, or if there should be wrong notes in the performance, the consumer feels the product is simply one of poor quality. Occasionally the consumer's phonograph may not be working properly and will tend to mistract on certain records. To the consumer, this again is a case of bad quality in the record when in reality it is a systems problem involving both the record and the phonograph. To a certain extent, the same kind of judgments on the part of the consumer would hold for the timeliness of a record release. In our pop musical market, where fads come and go in short order, the first record in a new Pop style may be very successful in the marketplace. A good imitation of it four months later, may find rough going and will surely be judged far more severely than the original. The quality manager must be aware of all these aspects and their interrelations, and he must be in a position to inform management of these and other aspects which may be as obvious to them as they are to him. Although his area of responsibility rarely extends outside the bounds of manufacturing and the electrical aspects of recording, he must be involved to some extent in the other areas.

Let us now examine some specific aspects of record production and look at the effect on the overall product of raising and lowering costs.

Materials

The single most important material in a phonograph record is PVC (polyvinylchloride). Each company has its own variation, and many use a copolymer resin system. Throughout the years the price of the basic resin has continued to go down, and at this point it is in the neighborhood of 15 cents/pound. The properly controlled compression molding of PVC yields records which exhibit a ground noise level sufficiently below the threshold of annoyance to the consumer. Increasing the resin cost by going to a material such as methyl methacrylate, would result in little if any improvement in the ground noise level. The expense, however, would be far greater. Alternatively, decreasing the vinyl costs by adding some type of inorganic filler to the compound would lower product quality as a result of increased surface noise in the product. Therefore, it is clear that we are working fairly high up in the cost effectiveness curve for our materials. There are times, however, when a tradeoff is made involving compound costs and quality, times when a filled compound may well be used. The decision to do this is based upon a careful study of the program material on the record
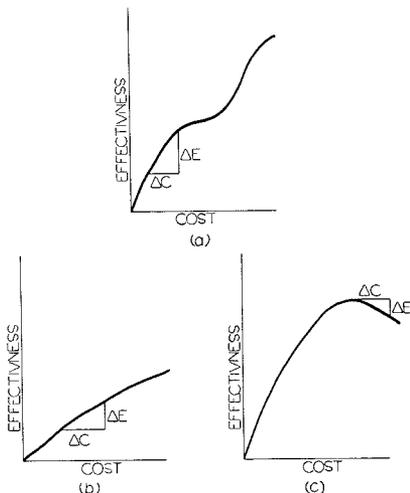

Fig. 1—Representative types of component cost-effectiveness curves.
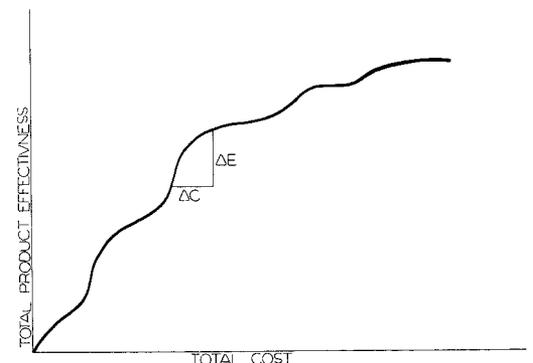
Fig. 2—Composite cost-effectiveness curve.

and how that program material may be affected by the inevitable increase in noise level.

Packaging

Another item of substantial cost in an LP record is the chipboard jacket with its four-color cover art and printed back liner—a format which is standard throughout the industry. The cost could be lowered somewhat with a thinner base material, but this would result in a flimsier package, one more susceptible to scuffing and bending. In addition to the effect on the company's quality image in the market place, the anticipated savings might be reduced to some extent by the necessary changes in warehousing and handling of the new package. Thus it would be considered a bad move. Alternatively, the cost could be increased by going to a thicker base material and perhaps coating the four-color art work with a plastic laminate—a procedure which could easily double the cost of the present jacket. It would afford no better protection for the record, but the cost could probably be justified for certain special deluxe issues. Occasionally the consumer is charged a dollar more than usual for a record. It may be a recording of a special nature, perhaps a very expensive production with high talent costs, and one that may have a printed insert with four-color pictures. In this case, Marketing chooses deluxe packaging because of its value in persuading the customer that the extra dollar that he is spending is really worth it. Ordinarily, however, it is clear that our current packaging represents operation at an optimum point on the cost effectiveness curve.
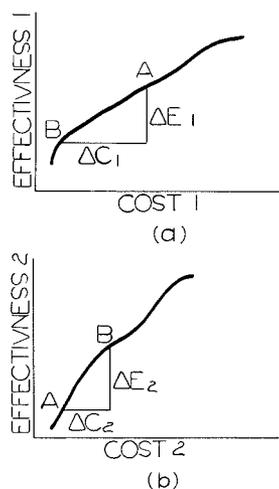
Fig. 3—The tradeoff principle ($\Delta C_1 = \Delta C_2$).

Engineering

Significantly, the LP record as we know it was engineered twenty years ago. A minor modification, the introduction of the stereo disc, was made ten years ago. This modification required very little change in the way of metal plating and pressing and involved only a moderate investment in new master-lacquer-transfer machinery in the studios. Presently, considerable engineering effort is spent in high-speed metal plating, perfection of an automatic press with a considerably reduced molding cycle, automatic audio testing facilities, and automatic sleeving and packaging of records. The aim of these engineering pursuits is to lower the unit cost of the record as well as to build into it less variability in quality.

A pilot plant incorporating these engineering developments is now operating in the Record Division Engineering Laboratory in Indianapolis. Final improvements in the automatic press are being made in readiness for installation in the new RCA Great Britain Record Plant in 1969. Those who have worked with the new machinery have been impressed with the high degree of dimensional control and molding characteristics from record to record. The consistency is truly remarkable; even when the press is adjusted for improper molding, the fault is consistent record to record! This is in clear contrast to our present record presses, where so much of the behavior is operator controlled.

While automatic tick and pop detectors can never replace a pair of trained ears as a gauge of record quality, there can be no doubt of the usefulness of these devices for many routine testing operations. Electronic tick and pop detectors can be quite sophisticated indeed. One European record company has demonstrated a "quality computer"—a detector which grades records on a quality scale from 0 to 100. Its scores are on the average within 10 points of the scores given by trained testers!

We are not by ourselves in such engineering pursuits. The major companies in this country as well as in Europe are active in designing automatic machinery. Some are ahead of us, while others are clearly behind. But there is always the rivalry between companies

which drives each to improve the product at little or no increase in cost. Therefore, it is appropriate that a major company expend engineering efforts in these directions in an attempt to secure for itself the unmistakable advantage of even a temporary gain in quality over its competitors.

Recording

One of the most interesting areas of the record business, the recording operation is where technology and musical artistry come together to create the "software" of our business. In the last two or three years, a revolution has occurred in the art and science of recording. A few years earlier it was the recording engineer's job simply to capture on magnetic tape something which was taking place acoustically in the studio or concert hall. This is still a big challenge for recording engineers whose specialty is classical music, but in the Pop area the engineer has become a participant in the performance itself. It is often the interplay of ideas between the performers in the studio, the record producer, and the engineer at the mixing console which shapes the final form and content of today's popular song. The recording engineer has recourse to about every kind of signal processing device available. Indeed, many of them design and build their own specialiezd devices—their own "bag of tricks," so to speak—to enable them to produce exotic new sounds. One result of this realignment of creative responsibility is that studios everywhere have almost over night become obsolete. Throughout the industry vast sums of money are being spent on new studios, equipping them with
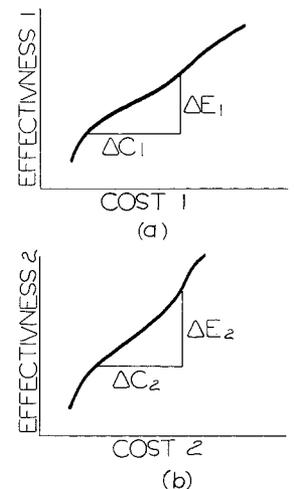

Fig. 4—Another type of tradeoff ($\Delta E_1 = \Delta E_2$).

new recording machinery and remixing equipment offering the maximum in flexibility.

Where are we with respect to cost effectiveness? At this point the question can hardly be answered because we are not sure which of many possible directions is best. We do not know, for example, that an expensive piece of recording machinery in vogue today will not be useless two years from now. The most difficult job in Recording Management, outside of the purely creative responsibility, is to distinguish between fads and significant developments. We do not know where we are on the cost effectiveness curve in the recording area, but we do know that wise purchase practices, such as investing in convertible (or modular) equipment, reduce the chance of obsolescence of capital machinery in the long run. It is perhaps comforting at this point to note that recording lathes —those work horses of the industry that are used in the transfer operation from master tape to master disc—seem never to become obsolete. Although the newer automated lathes perform certain functions more handily, the bulk of today's records were mastered on machines twenty years old!

Independent production companies

If we could summarize the state of sound recording today as a happy, somewhat excited, if not slightly confused, activity which is eager to define its new creative role, we could also point to the changes which are taking place in the artistic production area. More and more, independent production companies are assuming importance in creating products for major companies, which only a few years ago relied exclusively upon staff producers. In this development, the record industry is paralleling the motion picture and television industries, which years ago shifted the bulk of their creative activity to independent production companies. By itself, this shift does not directly influence product performance or quality on the consumer level. However, the increased production costs which result here can certainly play a role in determining tradeoffs in specific areas of product quality.

Tradeoffs

No discussion of cost effectiveness is complete without reference to the
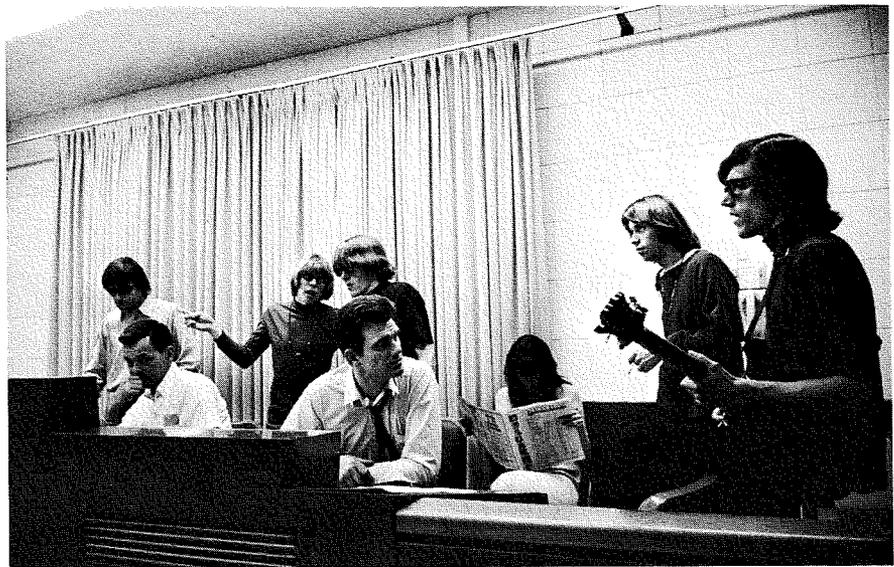
Today's recording engineer has his own bag of tricks which enables him to interact with the artist to introduce new and exotic sounds. In the photo, members of The Jefferson Airplane rock group exchange ideas with their producer and recording engineer while taking time out for the playback during a recording session.

tradeoff principle. A tradeoff occurs when a cost *decrease* in one area of product effectiveness is applied as a cost *increase* in another area with a net *improvement* in total product effectiveness. Fig. 3 shows this graphically. Before the tradeoff, operation is at point A on each curve, while point B on each curve represents the operating point after the tradeoff. The two vertical effectiveness scales are assumed to be normalized to one another by the application of appropriate weighting factors. Since $\Delta C_1 = \Delta C_2$, there is no net increase in cost. However, there is an *increase* in total product effectiveness given by $\Delta E_2 - \Delta E_1$.

Several observations can be made at this point:

1) Weighting factors for the various component cost-effectiveness curves must be assigned with great care. It invariably involves the talents of many people.
2) The tradeoff principle is an obvious way to optimize product effectiveness for a given cost.
3) The tradeoff principle can lead to a new "way of thinking" about product improvement. It has been applied for years, often unconsciously, and usually under some specific pressure. How much more effective it could be if quality managers continually sought out occasions to use it.
4) Tradeoffs need not be limited to the two-way case discusses. Three and even more areas can be involved at once.

Another kind of tradeoff, one that management is always interested in, involves a *decrease* in cost with no net

change in product effectiveness. In this case, $\Delta E_1 = \Delta E_2$ and $\Delta C_1 - \Delta C_2$ is the resultant cost saving. This is shown graphically in Fig. 4.

A specific example of a tradeoff in record manufacture might be the following: a given record release might be placed on a lower factory standard, regarding compound and controls with the resultant cost saving applied perhaps to a fancier, more attractive, package. Certainly the price would be the same, and possibly it could be demonstrated that the appeal of the packaging—the value placed on it by the customer—more than offsets the decrease in audio quality as it might be perceived by the customer.

Conclusion

The principles of cost effectiveness have been presented in a graphical-mathematical way in the belief that this approach best stimulates the quality manager's thinking in this area. Several areas of phonograph record manufacturing have been examined in detail with emphasis on cost effectiveness and the quality manager's role in evaluating *all* the facets of product effectiveness has been stressed. Finally, the concept of the tradeoff and its potential for optimizing product effectiveness has been discussed, again in a graphical manner, in the belief that this approach will help the quality manager to think *quantitatively* about the interplay between the many areas of total product effectiveness.

What does quality cost?

E. S. Shecter

A system for identifying (hence controlling) quality costs is described. This system can assist in the identification of the most fruitful areas in which to invest money to improve product quality. Specifically, this paper defines the elements that are analyzed under this system, provides some guidelines for analysis, and suggests some possible applications.

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A NY COST SYSTEM must aid management in identifying areas where cost performance can be improved. Many systems provide this information by subdividing material, labor, and overhead as separate cost elements —with control methods used for each

element. A more recent cost control system—quality costs—is being applied at several major operating activities of RCA. In this system, the cost elements are functions (e.g., test, inspection, process control, design review) and are not necessarily categorized into material, labor, or overhead. The basic premise behind collecting and analyzing costs in this manner is to identify the relative magnitude of each cost element and to determine which of these elements might be reduced or avoided. This information then enables an intelligent management decision on the potential return on an investment.

To a very great extent, the quality of the product is determined in design. The quality costs system takes this into consideration and is applicable to engineering areas as well as the manufacturing cycle. In addition to providing information to management for action, it has the advantage of becoming a system which points to needed changes. It presents change and action-oriented data which helps establish the environment needed for change.

Principal elements

The four principal elements of quality costs identified by this system are:

Prevention costs which are incurred in an attempt to keep defects from occurring in the first place;

Appraisal costs which are incurred in evaluating product conformance to requirements;

Internal failure costs which result from a failure to complete a task properly with the result that scrap, rework, and retest operations are necessary; and

External failure costs which are associated with servicing customer complaints or customer returns which must be replaced as the result of delivery of nonconforming product.

In this paper, internal and external failure costs are treated as simply failure costs.

Cost breakdown

As has been noted, quality costs are accumulated on a functional basis rather than a departmental basis and, therefore, they include direct and indirect labor changes. A typical breakdown of costs into three major categories—Prevention, Appraisal, and Failure—is given in Table I and is described in the paragraphs that follow:

Prevention costs

Quality planning costs are related to preparing a quality program plan to define all actions necessary to ensure that quality and reliability requirements and standards will be met. This is generally the cost of quality assurance engineering time for developing the program plan and for updating maintenance of this plan.

Training and motivation is the cost for preparing and implementing training programs—including the expenses of the instructor and the participants. Also included are efforts associated with employee motivation.[1]

Process control costs are associated with developing and establishing manufacturing process controls required by design. The costs include not only the quality assurance engineer's time but also the manufacturing engineer's time required to set up the program and the specification review time required to evaluate manufacturing and quality control specifications.

Vendor selection costs cover the time required by the vendor survey team to select vendors who are most likely to provide trouble-free equipment, materials, parts, and services.

Design review costs are for the time that the Design Review Team and all other participants spend reviewing a design. It also includes the preparation time required for the formal design review.

Table I—Typical quality costs.

Prevention	Appraisal	Failure
Quality planning	Incoming inspection	Rework
Training and motivation	In-process inspection	Retest
Process control	In-process test	Scrap
Vendor Selection	Final inspection	Malfunction reporting and analysis
Design review	Final test	Corrective action costs
Parts selection and qualification	Quality audit	Material review board
Other reliability activities	Calibration	Customer complaints
Specifications and procedures		Warranty service costs

Parts selection and qualification costs involve the time that the design engineers and the reliability engineers require to select and specify reliable parts required for a given program.

Other reliability activities are costs associated with such reliability activities as failure mode and effects analysis, reliability apportionment, maintainability prediction, and other reliability elements not associated with malfunction reporting or failure analysis.

Specifications and procedures costs account for the time required to prepare specifications and procedures related to quality requirements for specific programs for the division. This involves the time of quality assurance engineering and reliability personnel who review and approve specifications and procedures. It does not include engineering time for writing the specification.

Appraisal costs

Incoming inspection includes the cost of actual inspection and test on all incoming parts and components as well as time spent by engineers and others verifying this performance on purchased items. This cost also includes field inspection in vendor plants.

In-process inspection costs are associated with performing inspections by product quality assurance and manufacturing inspectors as material flows through the production line. It includes time spent in inspecting processes as well as inspecting product. Consequently, labor costs of quality investigators or quality specialists, when product appraisal is being performed, is included.

In-process test costs are associated with tests by quality assurance, manufacturing, and engineering on items as they progress in the building cycle. It also includes test monitoring. All costs associated with environmental testing are also included. Time required to prepare test or inspection procedures is included—identified as a separate element.

Final inspection costs is associated with performing final inspection and is normally a product quality assurance cost.

Final test is the cost of the final performance and environmental test on the deliverable end item regardless of the activity doing the job (including test monitoring). Qualification testing may be segregated from acceptance testing but should be included as an appraisal cost.

Quality audits are costs associated with performing audits, normally by quality assurance engineering. It does not include financial audits; however, customer audits and supplier audits should be a subdivision of this cost.

Calibration covers all costs associated with recall, calibration, repair, and redelivery of equipments or tools and gages being calibrated.

Failure costs

Rework costs are the labor costs resulting when various activities in the division (such as Manufacturing, Quality Control, Quality Engineering, Manufacturing Engineering and perhaps Engineering) rework an item to acceptable condition after it has been rejected. In addition to actual rework time, these costs may include preparation of procedures for accomplishing the rework, establishing the control procedures, performing additional reinspections, and material required. Rework that is due to Engineering Change Notice (ECN's) or customer directed changes should be calculated separately.

Retest costs are associated with all retesting resulting after initial failure of equipment. This too includes all labor categories associated with retesting the equipment until it reaches the point at which it was rejected and becomes acceptable. Retest due to ECN's which are required to meet new requirements or retest required as a result of an ECN not specifically required due to equipment failure should also be calculated separately.

Scrap costs are for material and labor associated with the fabrication of an item which is subsequently scrapped due to nonconformance to specification. In this category, all scrap should be counted, including that which is discarded by Manufacturing due to nonconformance. Scrap associated with non-usable edges of products, cuttings, and chips are not to be included. The additional scrap resulting from ECN's should be compiled separately.

Malfunction reporting and analysis costs are associated with preparing malfunction reports and the time spent in performing the analysis and writing up the failure analysis. It includes the time spent by those activities performing analyses (such as Manufacturing Engineering, Quality Assurance, Reliability, and Design) to determine the cause of the problem. It also includes analysis costs in the quality or other laboratories.

Corrective action costs are associated with performing corrective action as a result of inspection or audit. In addition to correction on hardware, corrections on documentation and procedures are also included.

Material review board costs are associated with reviewing nonconforming material and determining its disposition. The time required of the participants in the Material Review Board should be recorded.

Customer return costs are associated with receiving, evaluating, and repairing products returned by the customer. Also included are shipping charges associated with return and reshipment of the nonconforming product.

Customer complaint costs include travel and subsistence for those persons responding to a specific customer complaint as well as the time spent by Marketing, Engineering, Product Assurance and Manufacturing personnel to satisfy a customer. Frequently, a trip is made partly as a sales venture and partly to respond to customer complaints. That portion associated with customer complaints should be included.

Warranty service costs cover material, labor, and travel required to uphold our warranty obligations to the customer.

Analysis

One of the problems with such a program is that costs may not be in the needed format. It becomes difficult to identify all the elements needed to completely develop the quality costs even though the cost elements can be defined. This limitation can be overcome by starting with an approximation of actual costs. If all the costs can be identified by survey or by a review of existing cost data or can otherwise be approximated within ±20%, it usually becomes obvious where expenditures need redirection in order to achieve maximum benefit. Once this decision is made, the system to accumulate and analyze the costs may be refined. It is not uncommon, however, for rough cost estimates to provide valuable information identifying areas requiring action.

A rather common industry experience when initiating a quality cost system is to find very little money being spent in areas of prevention, very large expenditures in appraisal, and even larger expenditures in the area of failure. Management action may be taken directly from the quality cost report in the areas of prevention and appraisal, but supplementary information based on inspection, test, or field results are mandatory to take intelligent action on failure costs. This information is also desirable, but not essential, for action in some areas of prevention and appraisal. Merely increasing the expenditure in prevention is not sufficient. Knowing where to increase the expenditure is vital.

Quality cost reporting can be related to a number of different bases. There is no fixed rule that defines an acceptable or an appropriate set of relationships. It is difficult, if not unrealistic, to compare product lines or plants; however, the individual costs obtained within a plant can nevertheless provide extremely useful information. In order to do so, the bases that may be used are:

1) A labor base, such as total labor, direct labor, or applied labor.

2) A cost base, such as shop cost, manufacturing cost, or total material and labor.

3) A sales base, such as net sales billed or sales flow of finished goods transferred to inventories.

4) A unit base, such as the number of units produced.

These measurement bases are only as good as the methods used for keeping them consistent. Major changes—such as automation, changes in sales volume, procurement instead of manufacturing of certain items—may affect the base measurement.[2]

The analysis of quality costs always begins with a comparison of the total against one of the bases noted above. When the percentage is above a norm (or a goal) further analysis is then considered. Consider the following figures:

Cost Element	$
Prevention	44,500
Appraisal	150,000
Failure	80,500
Total	275,000

These figures show the appraisal cost running almost twice the failure cost, implying that an excessive amount of money is being spent for product inspection and test. It is necessary then to analyze the operation to determine in which area these costs are being expended with a view towards eliminating some of the unnecessary costs. For example, inspection efficiency can be improved through relocation of inspection or test points, retraining of personnel, or adoption of improved test methods. It also appears from this example that more attention should be given to the prevention area in order to reduce the total costs.

A second example might lie in the area where failure costs constitute a very high percentage of the total quality costs, or the highest single element of these costs. Under these circumstances, it is necessary to analyze quality, inspection, or test records (or field data) to determine the nature of the deficiencies. Since these records by themselves do not give sufficient indication of the magnitude of the dollars being expended for these failures, the quality cost system allows the analysis to be dollar oriented. Management can then determine an appropriate means for correcting the problem. This might be the assignment of individuals to a task force to get the job done. The extent of such a task force can be more readily established when it is known how many dollars could be saved as a result of an intelligent application of effort. Assignments are made based on the analysis of the major causes responsible for the bulk of the problems. It is in these areas where the work of the task force should begin.

Other applications

In addition to its analytical assistance, a quality cost system enables utilization of costs for current budgeting and estimating. An example is the adjustment in purchase quantities based on improved yields or the amount of retest included. This is often based on experience which may not be current. When a quality cost analysis is maintained, quoted costs more nearly reflect current conditions.

The system assists in the identification of the most fruitful areas in which to invest money to improve product quality. As such, its value cannot be overlooked.

Summary

A quality cost system provides valuable action-oriented data. The method allows cost analysis and identification of areas requiring management attention prior to development of major problems. Furthermore, proper implementation of the system enables economic development of product quality with optimum quality levels.

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A cost-effective look at spacecraft component testing

L. Gomberg

The trend towards fixed price programs, accompanied by stringent schedule requirements, has forced RCA to make a critical reassessment of the traditional methods for testing spacecraft and spacecraft components. The assessment consisted of a detailed review of the rationale for vacuum testing at the component level and a concomitant review of the failure history on several successful spacecraft programs. As a result, certain conclusions were drawn:

1) Vacuum testing is only required on vacuum sensitive items;
2) The sensitivity of these items could be predicted; and
3) A thermal cycle test would be more protective.

These conclusions have now been implemented successfully in a major classified spacecraft program.
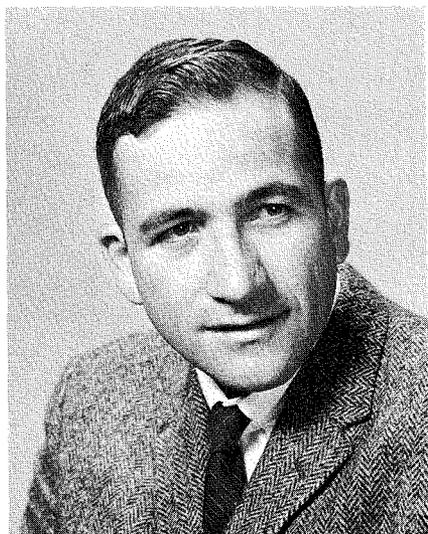
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received the BS in Mathematics and Chemistry from New York University in 1950 and the MS in Mathematical Statistics from Columbia University in 1952. From 1952 to 1954 Mr. Gomberg was a Quality Assurance Engineer with the RCA Electron Tube Division in Harrison, New Jersey, and subsequently worked as a Development Engineer with the Federal Radio and Telephone Company in Clifton, New Jersey. In 1955, he joined the Electron Tube Division of Sonotone Corporation, Elmsford, New York as a Development Engineer. In 1956, he was promoted to Chief Engineer of the Tube Division. Mr. Gomberg joined the RCA Astro-Electronics Division in January 1963. He was the Product Assurance Manager on the Lunar Orbiter Program and was previously Product Assurance Administrator on the Relay II Program. He is presently Product Assurance Manager for a classified program. He is a member of the IEEE and ASQC.

IT HAS BEEN AN ACT of faith in spacecraft testing to subject all spacecraft components to vacuum thermal testing prior to their integration on the spacecraft. With the emphasis on fixed-price contracts and stringent scheduling, a detailed reassessment was made of this philosophy. As a result, it was concluded that many components did not require vacuum testing. Additionally, the components which will require vacuum testing can be predicted in advance. The remainder of this paper delineates the rationale and analyses which resulted in this decision.

The purpose of vacuum testing at the component level is to

1) Provide confidence in its ability to perform in vacuum at the spacecraft test level and ultimately in orbit;

2) Determine the suitability of the design for vacuum operation; and

3) Detect vacuum-sensitive anomalies.

For the program under consideration, the specified components test plan was carefully analyzed. It required all components to be tested in vacuum for 12 hours at each of three temperature levels with the temperature-time rate of change (dT/dt) unspecified. This program had been in existence for several years at RCA, and the test philosophy was thoroughly embedded.

An initial review of the failure history showed that the component tests were not as effective as they should have been in protecting against system failures. It appeared that the reason for this deficiency lay in the limited number of temperature cycles and the specified dT/dt which permitted gradual temperature transitions. Based on other program experience, it appeared that a more effective test for weeding out incipient problems would consist of several thermal cycles with a dT/dt of approximately 0.5°C/minute. It also became apparent that it would be desirable for test facility, and schedule reasons, that the test be performed with a temperature box. To ascertain whether this was possible, a systematic review of the merits of vacuum testing was conducted. This took the form of an analysis of the failure history of several RCA programs (for example, Relay, Lunar Orbiter, RAE, and a classified program). A review of the effects of vacuum on the materials and parts in the articles and on the actual function of the articles was conducted.

Effects of vacuum operation

When designing for vacuum operation, consideration must be given to:

Temperature—in a vacuum, convection is no longer present as a heat transfer process.

Outgassing—materials with high vapor pressure will change state from a solid to a gas. Additionally, some gas may be absorbed or trapped in the conformal coating, etc.

Sublimation—certain metals and other materials will vaporize in vacuum and deposit on the nearest cold surface.

Breakdown—in vacuum, effects such as Paschen's law, multipactor, electrical arcing and other phenomena become a serious consideration.

Dimensional anomalies—the loss of atmospheric pressure can cause dimensional distortion in housings, boards and parts.

Migration of lubricating materials—certain lubricants tend to migrate or otherwise disappear in vacuum.

Cold Welding—rotating or sliding metal parts may stick or cold-weld in vacuum under certain conditions.

It became clear that not performing vacuum testing might permit deficiencies in the areas cited to go undetected and prevent verification at the component test level. To determine whether this was a real possibility, each component was reviewed in terms of its materials, parts, application and history for possible problems. The results are summarized in the following paragraphs.

Thermal

To compensate for the addition of convection as a thermal heat transfer process, 5°C was added to the top end of the temperature. Thus, components subjected to thermal cycling underwent temperature level tests which were 5°C higher than those required in vacuum. This was considered by the thermal group to be more than adequate compensation.

Outgassing

All parts and materials were reviewed to provide assurance that they will not outgas. For example, all RCA components utilize printed circuit board construction employing 2-ounce G-11 glass epoxy with electrolytic copper traces coated with reflowed, electrodeposited Sn-Pb (60 to 40%). These boards and the process for their fabrication have been successfully employed by RCA for the past five years on such

programs as TIROS, Lunar Orbiter, RAE-AAS, Ranger, etc.

The conformal coatings used were originally developed for TIROS and Lunar Orbiter and then used on other programs. Precautions against gas entrapment and incomplete coatings formulation are provided by de-aerating such materials (pulling a vacuum) when mixing, and a high temperature bake after application. Again these formulations have been thoroughly qualified for use in vacuum by virtue of extensive testing prior to their adoption. Verification of the success of these methods is provided by the successful performance in the cited programs.

The housings are made of 6061-T6 aluminum (0.040-inch thick typical and the tape recorders 0.100 inch; all components are painted with a polyamine epoxy paint which is space-qualified). The harness wire, internal to the components, is made of Teflon-coated copper wire; the connectors are all gold-plated brass. Thus, there is nothing employed which can outgas significantly. There still remained the possibility that improper materials might be inadvertently employed or the process might not be properly implemented. Since this possibility existed on previous programs, an extensive review of RCA malfunctions and test discrepancy history was made to determine what the frequency of occurrence of this type of problem had been. Not one vacuum malfunction in over 10,000 analyzed could be attributed to improper materials or an incorrectly implemented process in applying these materials.

Sublimation

Every part and material was and is reviewed by knowledgeable personnel prior to its acceptance for use in a spacecraft program to ensure that it does not contain material which could sublimate. For example, zinc and cadmium platings and wax-impregnated lacing are not permitted.

The effectiveness of these controls has been verified by reviewing the failure history. Again no failures were attributed to sublimation.

Breakdown effects

The factors which can initiate electrical breakdown in vacuum are well known. These are:

Voltages present in excess of 200 volts. Presence of substantial amounts of RF power.

High voltage gradients (volts/mil) resulting from sharp edges, etc.

The spacecraft components were reviewed as delineated in the attached table. The only components liable to have problems in this area are transmitters.

Momentum wheel assemblies

Despite their low voltage application, momentum wheel assemblies were tested in vacuum to provide a reference for motor current and assure adequate lubrication throughout the system.

Tape recorders

Since the recorders are hermetically sealed, pressurized and helium-leak tested after each environmental exposure, it was decided that it would be safe to forego the vacuum portion of the test.

DC-DC converters

Although there are no high voltages present, it was decided to subject the prototype units to thermal vacuum because of the newness of the design.

Dimensional stability

The design precautions required to obviate problems in this area are well known and have been taken on the program. These precautions include:

Adequate numbers of vent holes.

Structurally-sound design (that is, covers are dimpled; materials have adequate safety factors).

Assurance that these measures are more than adequate is provided by the previous performance of RCA hardware. Additionally, a series of tests was conducted on Lunar Orbiter. The rapid ascent of the launch vehicle introduced the possibility of distortions. A series of tests was conducted which required each component to be pres-

surized to two atmospheres. The chamber was then opened, resulting in a rapid decompression. There was no evidence of any distortion.

Lubrication migration

This is a significant problem, as evidenced by several shutter problems experienced on certain programs. The use of a properly qualified space grease, Versilube (G-300), obviated the condition. However, to avoid problems, all shutters and open switches were exposed to vacuum as part of the acceptance test procedure.

Cold welding

This is a recognized phenomenon in vacuum. The safest course is to pressurize and to expose all such components to vacuum testing.

Failure history

The following paragraphs summarize the RCA failure history on several recent spacecraft programs. The conclusions are that components which will be vacuum-sensitive can be successfully anticipated.

Relay I

On the Relay I program, there were a total of 141 malfunctions at the component, subsystem and spacecraft levels. Of these, 79 (56%) were associated with the wideband systems (receiver, beacon and transmitter); 25 (17.8%) occurred in thermal vacuum, and 4 of these (3% of the total number of malfunctions) required vacuum to evidence themselves. All of these were in the TWT and associated power supply. This could have been anticipated because of high voltages (E_H — 1200 V, E_{coll} — 600 V) and high RF power (10 watts at 1600 MHz).

Relay II

A total of 78 malfunctions were reported at all levels of testing, 60 in component level and 18 on the spacecraft level. Exactly 9 (11.5%) occurred in vacuum; of these, two required vacuum to occur. Not unexpectedly, these involved the TWT and associated high voltage supply.

It is also interesting to note that the percentage of thermal vacuum failures is higher at the spacecraft level than at the component level. This would seem to indicate that the spacecraft test, because of the additional handling, longer test times, and more careful data review, is more effective in detecting failures.

Lunar orbiter

There were a total of 1130 test discrepancies at all levels of test; that is, board, component, subassembly and spacecraft. These break down into:

    196 board-level malfunctions
    931 component and subassembly
      3 spacecraft
    ————
    1130 total malfunctions

Of these, 260 (23%) occurred in thermal vacuum. Four required vacuum to evidence the failure. These included:

A breakdown of the TWTA (12 watts at S-band) bandpass power monitor filter at critical pressure.

A breadown of Teflon-insulated wire in the TWT power supply. The supply was required to put out a helix voltage *(En)* of 1200 volts and a collector voltage of 600 volts. The fix was to put in silicone rubber wire.

A breakdown of a capacitor in the TWT power supply in spacecraft test. The failure was attributed to an accidental crease of an aluminum sheet in the capacitor stack causing a voltage stress. The unit had passed flight acceptance testing in vacuum at the power supply and TWTA level.

A breakdown of flex wiring in the TWTA in vacuum. Again this was corrected by using silicone-insulated wire.

All of these failures could have been anticipated in light of the criteria cited previously.

Antenna aspect subsystem of the radio astronomy explorer satellite

There were a total of 54 failures at all levels of test. Of these, four occurred in vacuum, of which two required vacuum to manifest themselves.

A failure of the DC-DC converter, which was required to produce 400 volts from

a 24 volt bus in vacuum. The problem was anticipated, tests conducted and a fix, better venting, was implemented.

A failure of a shutter blade in vacuum. In this case, the addition of Versilube G-300 eliminated the condition. Again, the problem could have been anticipated on the basis of the ground rules cited.

Classified program, phase A

On this program, there were a total of 114 malfunctions and discrepancies reported. Of these, 18 occurred in vacuum and 18 in thermal tests. One required vacuum to manifest itself; this was the magnetic stepper switch where the lubrication was found to have disappeared, and the use of Versilube G-300 corrected the problem. The transmitters were chronic problems, passing the supplier's vacuum but failing in the spacecraft vacuum. They subsequently failed in thermal testing at the supplier after extensive temperature cycling.

Classified program, phase B

As a whole, there were a total of 117 test discrepancies at the component level on this program. This broke down into 32 in thermal vacuum and 23 in thermal tests. Considering the longer exposure time in vacuum, it would appear that the thermal test is equally good at detecting problems at the article level. None of the vacuum failures would have required the vacuum test to manifest themselves.

Conclusions

The following conclusions were made as a result of this study:

RCA is convinced, based on its experience, that thermal test is equally as efficient as thermal vacuum in detecting incipient defects on certain non-vacuum-sensitive components.

The thermal cycle is more effective than temperature-vacuum storage tests in vacuum.

Certain articles are vacuum-sensitive. These can be identified in advance in terms of their performance, parameters, construction, function or parts.

Thermal vacuum, as performed on previous programs, has not been particularly protective in spacecraft tests.

Quality assurance in consumer electronics

L. M. Krugman

Like Caesar's Gaul, all Quality Assurance in the Consumer Electronics Division can be divided into three parts: 1) concept and development, 2) design and verification, 3) production and field performance. But unlike ancient Gaul, CED's quality assurance programs and controls are integrated for a Total Quality Control (TQC) System.[1] Since its adoption in 1966, the TQC concept has developed our product Quality Assurance from a control function into a division philosophy.
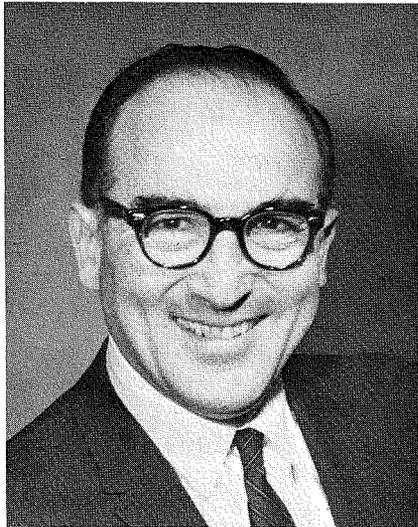
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received the BSEE from Newark College of Engineering and the MSEE from Stevens Institute of Technology. During World War II, he served with the Army Signal Corps as a Communications officer. He was an engineer with the Bell Telephone System from 1946 through 1950, and with the Signal Corps Engineering Laboratories from 1950 through 1954. He joined RCA's Home Instrument Operations in 1954 as an engineer, has served as Manager of Advanced Development, Manager of Radio and Phonograph Engineering, and was appointed to his present position in 1968. He is currently responsible for the quality, reliability and safety of RCA's Consumer Electronic Products. Mr. Krugman is a Senior Member of the IEEE, and a registered Professional Engineer in New Jersey and Indiana.

A QUALITY PRODUCT could broadly be described as one that *consistently* leads in performance and reliability for a given price. This definition implies complete and optimum coherence of all contributing activities, plans, and actions from product concept, through design, tooling, material procurement, production, sales, and customer service.

This is best illustrated by the functional organization chart, which lists just a few of the people who make TQC a go system. Notice that every major operating and planning function is represented. This permeation is basic, and we believe makes our QA activities not just symbiotic but synergetic.

Reliable, fast, and accurate communications, the *sine qua non* of any successful system, is especially critical in a heterogeneous organization. Therefore, a review of our major audits, controls, and information sources should serve as a vehicle for understanding the CED quality-assurance cybernetics.

Audits and conformance controls

Purchased material inspection

Our *Purchased Material Inspection* is conventional[2] sample inspection of incoming lots by attributes. This activity processes several millions of dollars worth of materials each day, with individual piece costs ranging from tenths of a cent for mounting screws to over $100 for cabinets.

Process inspection

A 100% inspection for specific attributes is performed at critical assembly and test points. Defects are marked for repair and recorded by failure mode. This information is used by foremen and group leaders for continuous process control. The data is also collated and reviewed by plant and division management to measure performance. The typical in-process performance goals for the color TV line are as follows:

Chassis Assembly	2.0%
Tubes	8.6%
Parts	13.0%
Test Errors	1.5%
Handling	3.5%

To appreciate what the 2% chassis line workmanship process goal means, it must be understood that a line is composed of 100 or more operators, each performing 10 to 12 operations. The goal allows 14 defects for 700,000 operations. This requires an operator reliability of 99.998%, or each operator must average less than one undetected error every 7 days.

The goal of 8.6% on tubes might seem thin, but considering the number per chassis, its attainment requires an average reliability of better than 99.6%.

A similar condition exists on parts. We often hear of an Acceptable Quality Level of 1.5% on parts. If a significant percentage did come in at that level, we could not find enough troubleshooters to keep the lines running. The handling reject goal also represents more select performance than the raw number might indicate. In addition to passing through over 150 sets of hands, each chassis is put on and pulled off a monorail at least 10 times.

Quality audits

Every major assembly and test operation is monitored by end-of-line and roving Quality Analysts. Their function is primarily problem prevention and process improvement rather than control. The sole exception to this is at the end of the instrument assembly line where every set is given a complete customer operational and visual check just before it is packed.

Life tests

These are conducted at each plant to monitor for adverse trends, and as insurance against anomalous failures. Additional long life data is also generated by the EC Tube Reliability Laboratory in Harrison and the Kinescope Life Testing facilities at Lancaster.

Laboratory measurements and tests

These are made continuously on samples of major chassis and compared to Engineering Specifications. Deviations are highlighted to effect any required corrections.

Consumer acceptance laboratory

The Consumer Acceptance Laboratory (CAL) is the auditing arm of the RCA Sales Corporation. A laboratory is lo-

cated at each assembly plant. As the name implies, it is a "customer" oriented facility. Acceptance criteria is based on critical evaluation of all appearance, assembly, alignment and operating characteristics. The laboratories are administratively separated from manufacturing operations so that their judgement will not be influenced by production schedule pressures.

The CAL checks the daily production of each line through a random sample drawn from the finished goods inventory. Each laboratory has complete authority to hold production by lot, day, week, or can cause the recall of instruments in the field.

The complete quality performance for each product line is charted and reviewed weekly by division management concurrently with production and sales figures.

Attitudinal programs

The importance of individual integrity and self-motivation to the success of a QA program has been well publicized.[3,4] In complex mass-production organizations, recognition is generally based on group, line, and even section performance. We continue to find, however, that stimulus of individual pride in workmanship produces the more consistent and lasting improvement trends.

John Rothfuss—when he was the Zero Defects Administrator at the Bloomington, Indiana, Plant—encouraged remarkable performance levels with personal letters. For example:

> ". . . your record of testing 484 consecutive chassis without a single reject is certainly an accomplishment for which you can be proud . . ."

The CED Vendor Recognition Program[5] was started in 1967 to motivate our suppliers toward higher quality-service performance.[6] Ratings are based on quality (maximum of 40 points), service (30), and price (30), and are applied for six basic categories: electrical parts, mechanical parts, cabinets, plastics, raw materials, and MRO.

Quarterly, the best performer in each category receives a plaque presented in an appropriate ceremony by division and plant management.

CED Quality Assurance Functional Organization

Manufacturing	Engineering	Sales Operations
Quality Control Bloomington—J. Freeman Indianapolis—W. Hamilton Memphis—J. Smith Monticello—W. Oakley Rockville—W. Davis	**Components Test and Approval** E. Evans **Product Safety and Engineering Standards** D. Obenland	**Product Performance** R. Shoemaker **Field Service** R. Hamilton **Technical Services** H. Horton
Materials Value Analysis and Vendor Performance J. Sourwine	**Product Planning** Consumer Acceptance Laboratories E. Campbell Vendor Recognition and Attitudinal Programs W. Shaw Quality Assurance Engineering and Administration E. Hilderbrand E. Klingeman D. Slider Competitive Analysis N. Foreman	**Commercial Services** L. Menaugh

Field quality information

Warranty returns reports are issued four times each month listing the part number, quantity, price, and total cost for the top 25 in-warranty part returns. This report gives trend information on high volume items, and serves to focus attention on troublesome components.

The *Field Service Engineers* are our most valuable source for field performance data. They supply continuous feedback ranging from general subjective Distributor and Dealer comments to specific performance problems. We frequently use the Field Service Engineers to check pilot and preproduction instruments to implement new product prove-in under a wide variety of operating environments.

The *Quality Index Dealers* program is another source of comparative field performance. These are a selected group of independent dealers scattered across the country. The criteria for their selection are they sell a major brand as well as RCA, and they maintain reliable records on both initial and 90-day service requirements.

Other useful sources include various independent national consumer surveys, Field Sales Reports, and individual customer complaints.

All of these are collated, analyzed, reviewed, and become an information reservoir to help all of the operating activities meet our primary objective: problem prevention.

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As part of the CED Vendor Recognition Program, the best performer for a quarter receives a plaque presented in an appropriate ceremony by the division and plant management.

RCA Consumer Electronics Division Vendor Award for outstanding performance

THIRD QUARTER 1968

COMPANY

Division Vice President   Manager Division Quality Control   Division Manager Materials

Storage reliability analysis

R. F. Ficchi

Using storage failure rates based on a recent study,[1] mathematical models can now be used to predict operational readiness of some systems. However, in many instances data for particular parts are not available. In addition, very little has been done to develop a more rigorous general approach to storage reliability. This paper will endeavor to develop some of these principles.
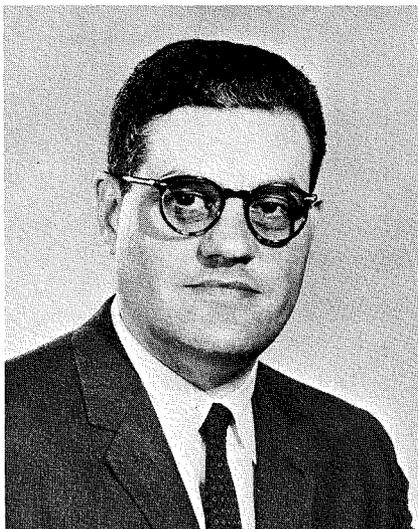
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received the BS (cum laude) from St. Joseph's College in 1941 and has completed graduate courses at the University of Pennsylvania. Prior to joining RCA in 1958 he spent 15 years with various consulting firms, specializing in electrical distribution systems for the chemical, refinery, and atomic energy industries. He has been involved in three major programs at RCA—Atlas, BMEWS, and Minuteman—and has been particularly concerned with problems associated with the performance of electronic equipment in the electro-magnetic environment. He has authored over 20 technical papers, is the author of Electrical Interference published in 1964, and is general editor and a contributing author for the forthcoming EMC Handbook. He has been active in the History of Science Society, the New Jersey Academy of Science, and the American Association for the Advancement of Science.

THE EARLIEST RECOGNITION of the problem of storage reliability came with the publication of the AGREE committee report in 1957; task 8 in that report summarized the available information. Due to the unusually high maintenance requirements for military electronic equipment during the 1960's, the need for a more concentrated study of storage conditions has become apparent. The storage problem was of particular significance because operational readiness of

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Definitions

Storage is the generic term used to define separate states: **On the shelf**—the state in which a device is not connected to a system but is packaged for preservation and is exposed to relatively benign environments. **Inert or dormant**—the state in which a device is connected to a system in the normal operations configuration and experiences below normal or periodic electrical and environmental stresses for prolonged periods up to 5 years before being used in a mission.

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systems was being affected by failures in the storage modes. As recently as 1964, a search for storage degradation data on component parts revealed that very little verified data was available. In 1965, however, the U.S. Air Force funded a program to gain a better understanding of dormant failure rates. This study[1] (published in 1967) provides information based on the collection and analysis of storage data in excess of 760 billion part-hours of experience.

Concept of strength

Ideal strength

The most general approach to the explanation of the storage problem would begin with an elementary concept that all matter possesses an inherent property called strength. Matter, in the physical world, is always in some configuration in the space-time continuum. This reality of matter can then be called a "black box" possessing strength. The strength co-exists with the physical reality of the black box; it is of fixed value and cannot be changed except by changing the nature of the black box. This strength is defined as the *ideal strength*.

The ideal strength is a function of the intended internal factors, (Fig. 1a) which are "designed-in" to give the black box the material and structural properties desired. These properties are:

Ideal material properties—the physical attributes of the materials used in their

pure states (this includes all properties of the material, e.g., chemical bonds, atomic structure).
Ideal structural properties—the exact physical configuration (e.g., length, circumference and the mechanical interdependence of the materials which are required to construct the black box).

The ideal strength, S_I, for a particular black box is constant with respect to time. This may be expressed quantitatively as follows:

$$S_I = f(P_M, P_S) \qquad (1)$$

where P_M are the ideal material properties, and P_S are the ideal structural properties.

The ideal strength is actually made up of many different strengths ($S_{I(1)}, S_{I(2)}, \cdots, S_{I()n}$ all of which represent the ideal intrinsic properties of the black box that allow it to withstand a certain stress.

For example, any black box can be said to intrinsically possess the following strengths:

> Ideal dielectric strength.
> Ideal current carrying capacity.
> Ideal ability to withstand a given temperature.
> Ideal ability to withstand a given shock.

Actual strength

The actual strength of a black box is described by the relationship:

> *ideal strength − anti-strength = actual strength*

or

$$S_{I(i)} - S_{AN(i)} = S_{A(i)} \qquad (2)$$

The anti-strength is defined as the unintended internal factors which contribute negatively to the determination of the actual strength (Fig. 1a). The concept of anti-strength was contrived due to the analogous relationship between strength and its "opposite," and the implications of "negative energy" and anti-matter as postulated by Dirac.[2] The factors that determine the anti-strength are of three types. Two of these factors—a) and b) below—are
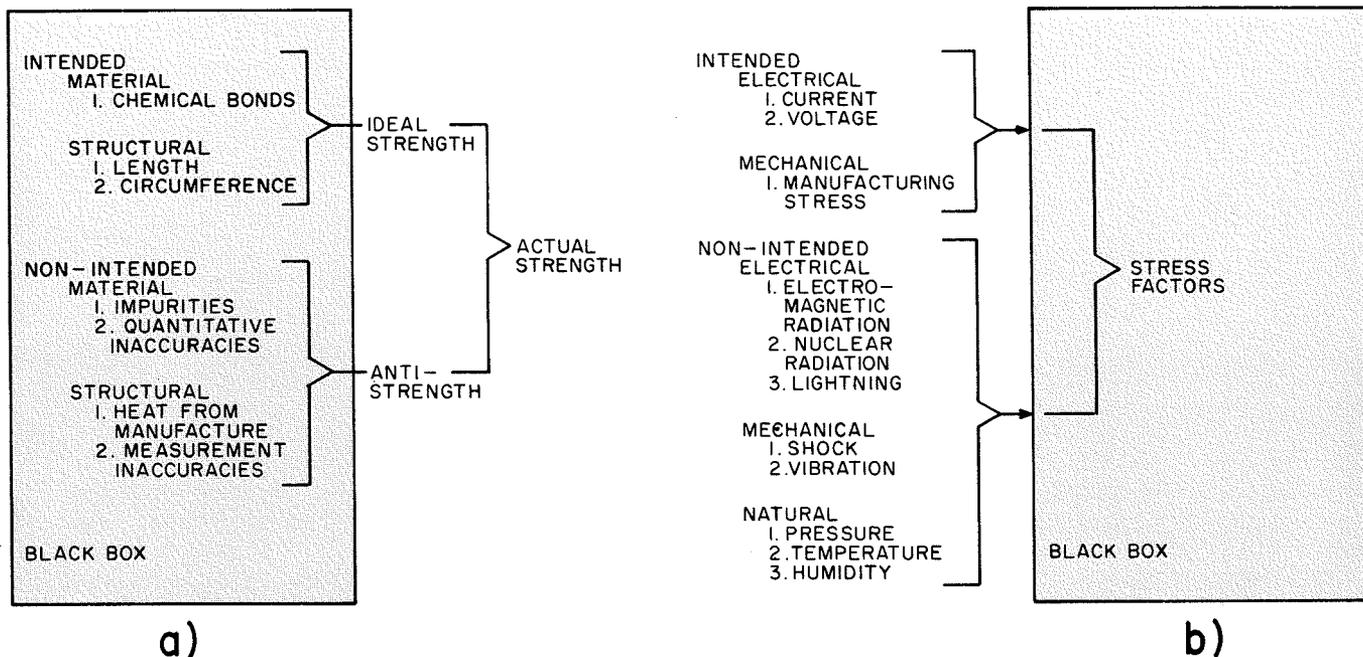
Fig. 1—Strength- and stress-determining factors: a) internal factors that produce actual strength; b) external factors that produce stress.

independent of time and are established at time, t_o, which corresponds to the time the box is fabricated. The third type—c) below—is time dependent. All are described as follows:

a) Material anti-strength — caused by unwanted impurities present in the materials used and by quantitative inaccuracies in the amounts.[2]
b) Structural anti-strength — the unavoidable degradation resulting from manufacturing stresses (e.g., heat from soldering); and the limitations of measurement which prevent the attainment of the exact physical configuration required and the ensuing effects on the mechanical interrelationship of the materials used.[3]
c) Transient anti-strength—degradation due to intended and/or unintended environment effects. The stress is thus defined as the external factors that affect the transient anti-strength.

Expressing the above definition quantitatively:

$$S_{AN}(t) = K_f + A_T(t) \qquad (3)$$

where $S_{AN}(t)$ is anti-strength (time dependent), and $A_T(t)$ is the transient anti-strength. K is evaluated at time t_o as follows:

$$K = f(A_M(t_o), A_S(t_o)) \qquad (4)$$

where $A_M(t_o)$ is the material anti-strength and $A_S(t_o)$ is the structural anti-strength.

Transient anti-strength is defined as:
$$A_T(t) = f(SS_1(t), SS_2(t), \cdots, SS_n(t)) \qquad (5)$$
where each $SS_i(t)$ is the ith time-dependent stress.

The anti-strength (Eq. 3) is also a function of many different anti-strengths, and each of these anti-strengths correspond to the reduction of a specific actual strength. Examples of these different anti-strengths are:

1) The anti-strength which degrades dielectric strength.
2) The anti-strength which degrades current carrying capacity.
3) The anti-strength which reduces the ability to withstand a given temperature.
4) The anti-strength which reduces the ability to withstand a given shock.

Therefore, the actual strength of a component is not simply a single quantity (S_A) but is actually made up of various strengths $(S_{A(1)}, S_{A(2)}, \cdots, S_{A(n)})$ all of which represent intrinsic properties of the black box which allow it to withstand a certain stress.

Concept of stress

A black box must exist in the real world of its environment. This environment is everything that is external to the black box and is synonymous to the sum-total of all the conditions existing outside of it (as affected by the presence of the black box). These

individual conditions or stresses will, in general, produce deterioration of strength by increasing the anti-strength of the black box. However, some stresses may also cause the anti-strength to decrease or not increase with time.

The external factors or stresses can be classified as intended or non-intended (Fig. 1b). Intended factors are all external factors purposely applied to cause the black box to perform its function as designed. These factors fall into two general categories:

1) Electrical (e.g., voltage applied);
2) Mechanical (e.g., the physical connection of the black box to the system).

Non-intended factors are those external factors which can never be fully controlled or eliminated. These factors can likewise be classified as:

1) Electrical (e.g., spurious electromagnetic radiation);
2) Mechanical (e.g., unwanted shock and vibration);
3) Other "natural" conditions (e.g., temperature, humidity, atmospheric pressure, contamination).

The external factors that cause the deterioration of a black box are generally the result of the interdependence of several processes acting simultaneously. These processes, such as
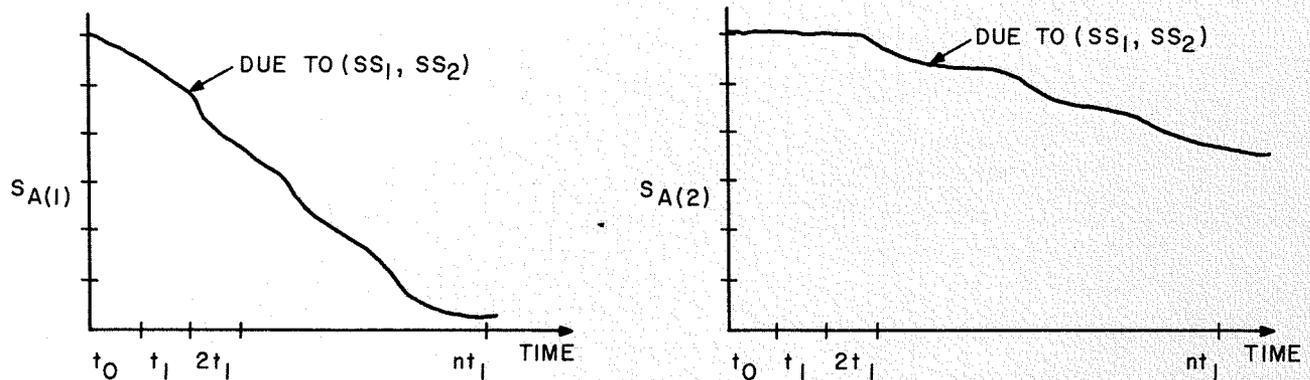
Fig. 2—A component subjected to two fixed stresses.

chemical or electrochemical, create a stress that can have a much more severe effect than the sum of the effects of each stress acting independently. For example, the effects of high humidity and certain contamination acting independently may have little effect on a part, but the two factors acting simultaneously could cause severe chemical reaction.

Grouping available information

The above approach to the understanding of the performance of a black box is summarized by first giving consideration to the strength or stress-determining factors which are not dependent on time. These factors are intimately related to the physical and chemical properties of all material. The following are the time-independent factors which affect the actual strength of a black box:

a) The intrinsic physical and chemical properties of the materials used in the fabrication of the black box.
b) The intrinsic structural properties of the black box as a result of fabrication.
c) The effect of impurities on the chemical and/or physical properties of the material used.
d) The effects of fabrication on the structural properties of the material used.

The second consideration given to the strength or stress determining factors is that of the time-dependent factors:

e) The degradation produced by the electrical stresses applied to the black box.
f) The degradation produced by mechanical stresses applied to the black box.
g) The effects of unwanted electrical stresses developed by some outside source.
h) The effects of unwanted mechanical stresses developed by an outside source.
i) The effects of "natural" conditions on the black box.

The time-independent factors mentioned above are basic to the actual strength of the black box and the time-dependent factors are basic to the stress applied after fabrication. The factors that affect the on-the-shelf storage are time-dependent factors g), h), and i); while those that affect the inert storage are time-independent factor b) and time-dependent factors g), h), and i).

Mathematical interpretation

For any given component, each strength corresponds to a particular stress which, although intrinsic to the component and always in existence, can only be defined or make itself evident in terms of the corresponding strength, e.g.:

Strength	Stress
Current carrying capacity	Current
Dielectric strength	Voltage
Ability to withstand temperature	Temperature
Ability to withstand shock	Shock

Obviously, a component which must perform a function in the presence of one or more stresses must possess the strengths which corresponds to each of these stresses, and more specifically, must be able to withstand those stresses. In other words, assuming that an individual strength ($S_{A(i)}$) and stress (SS_i) can be expressed in the same units, the magnitude of the actual strength ($S_{A(i)}$) required to withstand a given corresponding stress (SS_i) must be at least equal to, or greater than, that stress; or, if the component is to perform its function, then:

$$S_{A(i)} \geq SS_i, \tag{6}$$

By definition, if

$$SS_i > S_{A(i)}, \tag{7}$$

then the component would be unable to perform its function, and a "failure" has occurred. Since the objective of this study is to provide a method for obtaining failure-rate data, the problem must be interpreted by a time-based model.

Time-based model

The actual strengths of a given component in the performance of given function can be considered as monotonically decreasing functions of time, with a few possible exceptions where usage will produce a temporary increase in strength. This decrease in actual strengths with time is a direct consequence of the increase in anti-strength with use. Analysis of the manner in which these actual strength(s) decrease is essential in generating time-based information for storage reliability predictions.

To clarify the relationship between stress and strength, state that the decrease in strength with use can be of two types:

1) The strength decrease which is a result of subjecting the component to a single stress, SS_i (i.e., to the corresponding stress); and

2) The decrease in a given strength, $\Delta S_{A(m)}$, which results from subjecting the component to not only the corresponding stress, SS_m, but to other stresses as well.

Thus for $t_1 > t_o$,

$$\Delta S_{A(i)} \Big|_{t_o}^{t_1} = f(SS_i) \tag{8}$$

$$S_{A(m)} \Big|_{t_o}^{t_1} = f(SS_i, SS_j, \cdots, SS_m) \tag{9}$$

in which Eq. 8 is a special case of Eq. 9 (i.e., only one stress is present). The individual strengths, $S_{A(m;i)}$ will each depend on the same factors SS_i and hence will be dependent on each other.

It would now be desirable to introduce an operator which would permit the combination of each $\Delta S_{A(i)}$ of a component and yield a "grouped" or representative picture of the manner in which the total strength of the component decreases when it is subjected to stresses $(SS_i, SS_j, \cdots, SS_m)$. This could be expressed as:

$$\Delta S_{A(total)} = f[\Delta S_{A(1)}, \Delta S_{A(2)}, \cdots, \Delta S_{A(m)}] \tag{10}$$

where each $(S_{A(i)})$ depends on the n stresses applied. However, the generation of such method is superfluous since the interdependence of the different strengths are taken into consideration in Eq. 9. Hence, it will be sufficient to determine each $(\Delta S_{A(i)})$ for the number of stresses in question on a particular application, beginning with time t_o when operation begins and continuing without interruption. Fig. 2
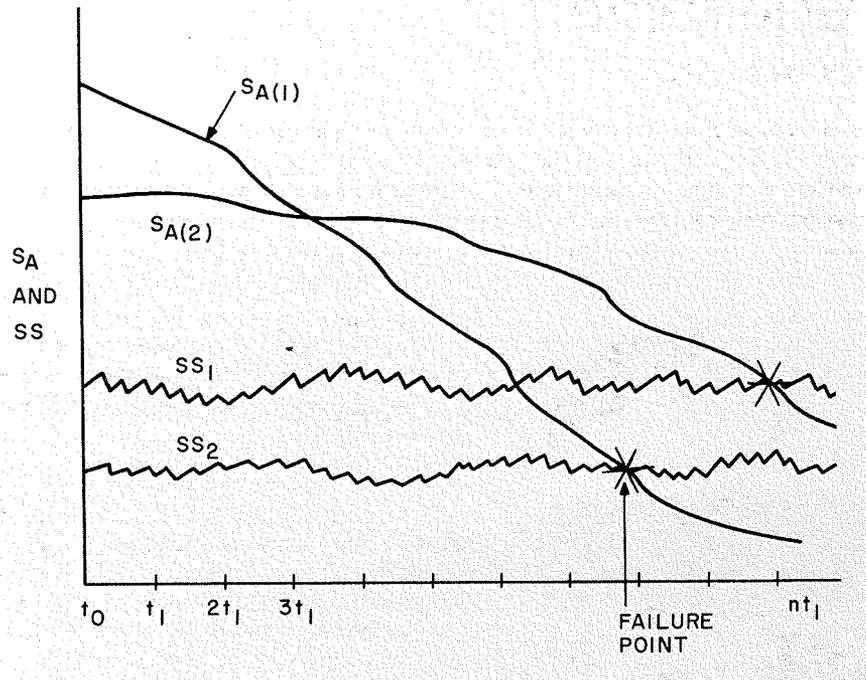
Fig. 3—The smallest t which satisfies the inequality $SS_i > S_{A(i)}$ results in a failure.

considers the limited case in which a component is performing a function which subjects it to two fixed stresses (SS_1) and (SS_2). If Eq. 4 has been evaluated at various times $t_o, t_1, 2t_1, \cdots, nt_1$, for these two stresses, then we can predict the behavior of each $(S_{A(i)})$ in similar applications of the same component.

From this point, we can use Eq. 2 (remembering that the quantities (S_A) and (SS) carrying the same subscripts are expressed in the same units) to determine the points at which:

$$S_{A(1)}(t) = f(SS_1, SS_2) < SS_1 \tag{11}$$

$$S_{A(2)}(t) = f(SS_1, SS_2) < SS_2 \tag{12}$$

Since all solutions for t are defined as failures (Eq. 2), then the smallest t which satisfies inequality 7 is the point in time at which a failure will occur under the given application. A graphic representation of this is given in Fig. 3.

Conclusions

Based on the nature of the particular black box, it is possible to set up an analysis which will enable one to develop time-based data. If the black box under study is a resistor, for example, the strength and stress factors (Fig. 1)

can be set down. Then these factors will have to be related to real-time by setting up control experiments to ascertain how long it will take for specific stress factors to reach a level that will satisfy the conditions of Eq. 7. Then, one will have established that one (1) failure will have occurred in this interval of time. At this point, by the application of statistics, a failure rate with a specified level of confidence can be set down.

It must be recognized that there is considerable area of differences of opinion in the approach that has been described. However, it is offered as a particular approach that shows considerable potential for coming to grips with the problem of establishing storage failure rates, where verifiable data does not exist.

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31

Queue II: A tool for determining system support requirements

H. R. Barton, Jr.

Determination of operational readiness and the comparison of design or support alternatives is accomplished by using a mathematical model, Queue II. In this paper, practical examples are given with supporting formulas to develop the best system behavior with respect to operational readiness, reliability, and downtime.

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QUEUE II is a mathematical model for analysis of queues inherent in various aspects of support systems. Queues or waiting lines result from randomly varying demand rates, or randomly varying servicing rates, or both. Queues can be equipments waiting for repairmen, or repairmen waiting for spares or test equipment.[1] Repair delays involving queues can be introduced at every level of maintenance or supply support, from the operating equipment back to the factory and its vendors.

The operational availability (or operational readiness) of the prime equipment is predictably affected by all of the queues in the support system. The use of Queue II enables rapid computation of the repair delays resulting from such queues, and the affect upon operational availability.

The primary objective of queue II is the evaluation of operational availability or readiness of equipments supported by maintenance and spares at multiple locations and/or levels.[2,3,4] Operational readiness/availability is defined as availability time per calendar period, or

$$R = A_o = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR} + \text{MLDT}}$$

where R = operational readiness; A_o = operational availability; MTBF = mean time between failures; and MTTR + MLDT = all downtime elements, including active repair time, logistic delays, batching, queuing delays, etc.

Queue II evaluates operational readiness by measuring the downtime contribution at each repair level or location and summing commensurably.

Typical queuing problems

Traffic control

A typical problem involving waiting lines, and one of the first applications of queuing theory to solution of practical problems, is exhibited in the analysis of traffic control problems. When the traffic light is green, traffic passes unimpeded. When the light turns red, a waiting line develops. The following green sequence must be set so that sufficient time is allowed to clear the waiting line; otherwise, the remaining automobiles join the waiting line of the next red sequence, resulting in a queue which grows with time.

Gas station

Another interesting queuing problem is the one occurring at gas stations. Queues can develop for gasoline services in one of two ways. An insufficient number of pumps can cause waiting for pump availability, and an insufficient number of pump attendants can result in waiting lines. An insufficient number of pump positions can readily deter potential customers. For this reason, it is quite usual to find more pumps at a station than are normally in use. Assignment of attendants presents opportunities for controlling both the waiting lines at the pumps and the amount of auxiliary workload accomplished, since the attendants can be utilized for numerous jobs when they are not pumping gas. Because of this arrangement, it is often found that the cost of minor repairs at a gas station is less than that involved at a repair garage.

Aircraft squadron

Next is a queuing problem which differs in significant aspects from those previously cited. The subject is a squadron of aircraft whose equipment is maintained at the associated hangar and shops. Failed equipment is transported to the shop, where it joins a waiting line for repair. In many cases, it is replaced before repair by a standby spare. When the failed equipment is repaired, it joins the supply of standby spares. This queuing problem forms a closed loop from failure to repair to standby to replacement. The population of serviced aircraft is usually limited to a small enough number so that the existence of a failure reduces the frequency of demands for service.

Because the population is so limited, it can be seen that the queue waiting for service has the population size as an upper limit rather than the 'infinite limit' for the problems previously described.

This problem has been simplified by avoiding mention of additional queues

involved. Besides the waiting line for shop repair channels and spares, connecting lines can develop for flightline tasks to isolate, remove and replace equipment in the aircraft, and for detail repair, overhaul and parts requisitioning at a depot.

Common characteristics of queuing problems

The foregoing examples have certain characteristics common to queuing problems. All have been characterized by demand rates, λ, for services and all have involved service rates, μ, the rate at which service is accomplished, or the reciprocal of service time. All of the problems have involved populations, N. For each problem, the population is considered, whether infinite or of explicit finite number. All problems involve some number, C, of service channels, described as the number of active checkout counters in a supermarket, for instance. Essential to their definition as queuing problems has been the existence in each case of a waiting line, W.

The randomness of demand and/or service rates dictates that waiting lines will vary in length, even in stable operation, about some mean value.

Each of the problems has included a customer objective which could be described as the requirement for mean waiting time. Each of the problems also has an operator objective which conflicts with the customer objective. The operator objective in each case can be described by the requirement for maximum service channel utilization. The existence of these conflicting objectives imposes the requirement for tradeoff of the cost of lost sales versus the cost of an added service channel.

Queue characteristics and relationships

As described in the previous section, queuing problems may conveniently be separated into finite and infinite queues.

Finite queue

The finite queue (Fig. 1) is described as having finite population, N, each unit of which creates demands for services, λ. Items requiring services join a waiting line, W, before entering service channels, C, where they are serviced at a rate per channel μ.

After service, these items either join a supply of spares or return to the ready population. As the waiting line for service grows in length, the ready population decreases and the aggregate demand rate for service decreases. This characteristic guarantees stable queue length for any combination of demand and service characteristics.

Infinite queue

The infinite queue consists of some population large enough to be considered infinite from the standpoint of queue effects on the aggregate demand.

A population of approximately 100 is sufficient to provide adequate accuracy in treatment as in an infinite queue. The population generates an aggregate demand rate, λ, and items join waiting lines, W for service before entering service channels, C, where they are serviced at a rate μ per channel. After service, they are discharged to the ready population. Since the population is considered large, the size of the waiting line has no significant effect on the aggregate rate of the demands for service. Theoretically, therefore, a waiting line could grow infinitely with no reduction in demand. In the real problems we have looked at, customers become discouraged by long waiting lines; however, in practical problems this factor does not caused difficulty of analysis because of the convergence to infinite queue characteristics at reasonable populations.

Analyzing the infinite queue

Note the following characteristics for a stable queue. Input of demands to the queue must be equal to the output from the service channels. That is

$$\lambda = \mu C_b$$

where C_b represents the mean number of busy service channels for the infinite queue in a stable situation. The mean number of busy service channels, C_b, is equal to the arrival rate divided by the service rate,

$$C_b = \lambda / \mu$$

This ratio (λ/μ) is designated as P, the utility factor. Note that the λ described for the infinite queue is an aggregate demand rate, whereas in the finite queue the demand rate is on a "per unit" basis. This must be kept in mind in considering the number value of P,
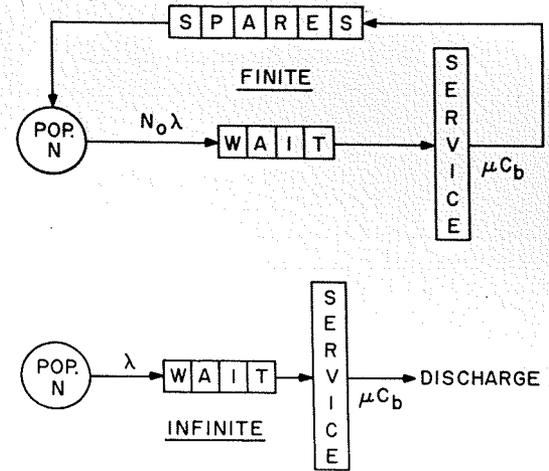
Fig. 1—Queue characteristics.

	N = 5	P = 0.8	
C	4	5	
S			
O	0.447	0.444	d
	0.447	0.444	n_d

Fig. 2—Table format.

LET N = 100

$\lambda = \lambda_u = 6/100 \quad 0.06$

$\mu = 10, \quad \rho = 0.06/10 = 0.006$

	C	1	2
N = 100	S		
$\rho = 0.006$	O	0.014	0.007 d
		0.014	0.007 n_d

$N_d = n_d (N+S) = 100 n_d = 1.4 \quad 0.7$ UNITS

$N_o = N(1-d) = 100(1-d) = 98.6 \quad 99.3$ UNITS

$C_b = N_o \rho = 0.006 N_o = 0.592 \; 0.596$ UNITS

$W_o = N_d - C_b = 0.8 \quad 0.1$ UNITS

$t_w = W_o / \mu C_b = 0.135 \; 0.017$ DAY

$t_{ws} = t_w + 1/\mu = 0.235 \; 0.117$ DAY

Fig. 3—Tabular analysis of infinite queus.
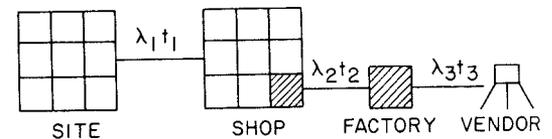
DOWNTIME $= \Sigma \lambda_i t_i = \lambda t$

UNREADINESS $= \dfrac{\lambda t}{1 + \lambda t}$

READINESS $= 1 - \left(\dfrac{\lambda t}{1 + \lambda t} \right)$

Fig. 4—Typical repair sequence.
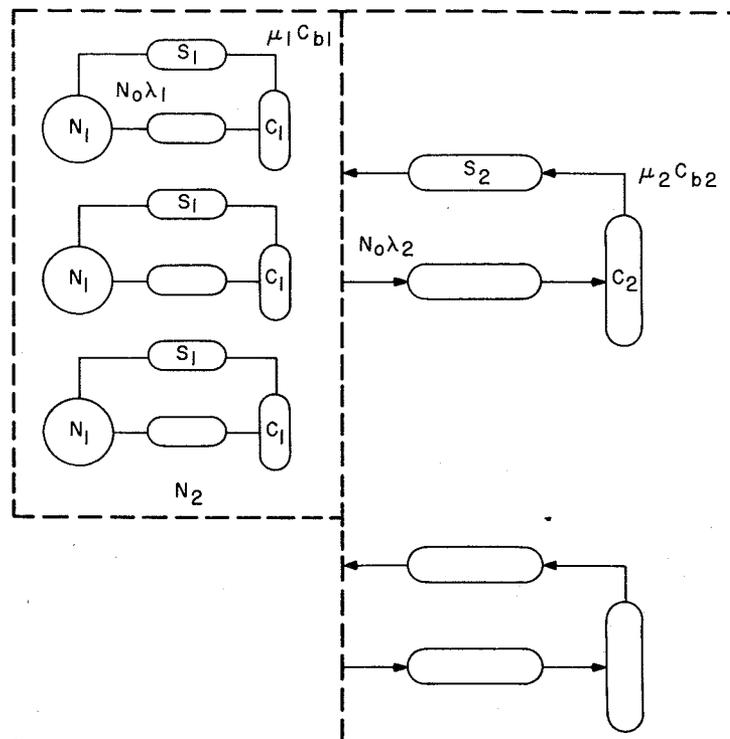
Fig. 5—Sequential queue.

the utility factor. The mean number of items in queue[5] is equal to

$$W_o = P^2/(1-P)$$

The mean waiting time is

$$t_w = W_o/\lambda$$

and the mean time in queue and service equals

$$t_{ws} = t_w + 1/\mu$$

Example

Manning for inspection of a product is a problem readily represented by the infinite queue. The infinite queue relationships follow. C equals one channel, represented by a single inspector or inspection team. The arrival rate of items of the product requiring inspection, λ, is six units/day. The rate at which products can be inspected by a single inspection team, μ, is 10 units/day. The computations we require for solution are as follows:

$$P = \lambda/\mu = 0.6 = C_b$$

The number of units waiting equals

$$W_o = P^2/(1-P) = 0.9 \text{ units}$$

The time in queue is equal to the number in queue divided by the arrival rate

$$W_o/\lambda = 0.15 \text{ day}$$

Time in waiting and service is

$$t_{ws} = t_w + 1/\mu = 0.25 \text{ day}$$

Analyzing the finite queue

Referring to Fig. 1, the closed loop configuration of the finite queue is evident. Again, the mean arrival rate into queue is equal to the mean discharge rate or

$$N_o\lambda = \mu C_b$$

where N_o is the mean operating population, λ is the demand rate per unit of operating population, μ equals the service rate per channel, and C_b equals the mean number of busy service channels. The mean number of units inoperational N_d equals the mean number waiting for service plus the mean number of busy service channels

$$N_d = W_o + C_b$$

The computations required are as follows: The number of units awaiting or undergoing service equals the fraction awaiting or undergoing service times the total of population and spares.

$$N_d = n_d(N+S)$$

The mean number of operational units in the population equals

$$N_o = N(1-d)$$

where d represents the fraction inoperable in excess of spares. Now C_b, the number of busy service channels, can be derived as

$$C_b = N_o P$$

where P of course equals

$$\lambda/\mu$$

The mean number in queue

$$W_o = N_d - C_b$$

The time in queue

$$t_w = W_o/\mu C_b$$

and the time in waiting and service is

$$t_{ws} = t_w + 1/\mu$$

Example

Let us consider a finite queue example as follows: resident inspectors are provided to inspect facilities at five locations on call, as required. The mean number of calls per day, λ, is one per location. The service rate, μ, is 1.25 calls per day per inspector. The utilization factor, P, is

$$P = \lambda/\mu = 0.8.$$

The easiest way to solve a problem of this type is by utilizing one of the sets of queuing tables available. One such set, which was applied to the solution of this problem, has a format as shown in Fig. 2.[6,7] For this format a separate page is used for each value of population and for each value of P. Separate columns are assigned for various numbers of service channels. Separate rows designate different numbers of spares assigned to the system. For each combination of service channels and number of spares, two entries are tabulated. The second entry n_d indicates the fraction of population and spares awaiting or undergoing service. For the example chosen, n_d and d have the same value since no spares are involved. For $C=4$ service channels, $n_d=d=0.447$. Where $C=5$ service channels, $n_d=d=0.444$.

The necessary computations follow:

$$N_d = n_d(N+S)$$

Notice that for four service channels, $N_d=2.24$, and for five service channels, $N_d=2.22$.

Little difference is indicated. The mean number of units operating

$$N_o = N(1-d) = 2.76, 2.78$$

for four and five channels.

$$C_b = N_o P = 2.21$$

for four service channels. The number of units waiting equals

$$W_o = N_d - C_b = 0.03$$

and the time in queue is

$$t_w = W_o/\mu C_b = 0.011,$$

for four channels. The time in queue and service equals

$$t_{ws} = t_w + 1/\mu = 0.811.$$

Note that with four service channels, the amount of time in queue is a very small part of the time in queue and service, and that no significant improvement could be derived by adding a fifth channel. An advantage of this tabular analysis is the capability for visual tradeoff and the determination of limiting utility of additional resources.

Tabular solution of the infinite queue

When the population approaches 100 units, the behavior of a system approaches that of the infinite queue. This fact makes it convenient to use tables of finite queues of 100 or more units for solution of infinite queue problems, since existing finite queuing tables provide convenient and versatile solutions. An analysis of the infinite queue is given above. Consider a tabular analysis using tables of the same format as those used for the finite queue. Arrival rate or demand rate must be defined as the aggregate demand rate divided by an arbitrary population. For the case in point (Fig. 3.)

$$\lambda_u = \lambda/100 = 0.06,$$

The service rate, u, equals 10, as before. The utility factor is now

$$P = \lambda_u/\mu = 0.006.$$

Enter the tables for $N = 100$, $P = 0.006$. For a single channel, $n_d = d = 0.014$. For two channels, $n_d = d = 0.007$.

From Fig. 3, notice that significant differences arise in waiting time and time in queue and service. As a result of adding a second channel, the total delay to shipment of the product is noted to be halved. If the cost of the additional channel and the cost of delay are known, the optimum number of channels can be established.

Queue II

Queue II was developed to enable solution of multi-echelon support problems. Its unique relationship with operational readiness permits assessment of the effects upon readiness of logistics downtime and other repair delays at all support levels and locations.

For explanation of queue II, a new queuing parameter t_{wd} must be defined: t_{wd} = waiting time for units in excess of spares.

This factor, t_{wd}, is the contribution of a particular queue to the downtime of a given equipment failure. It is derived as

$$t_{wd} = D/\mu C_b$$

Where D = mean number of units down; μ = mean servicing rate; and C_b = mean number of busy repair channels.

Also, $t_{wd} = d/[\lambda(1-d)]$

Where d = mean fraction of units down and λ = mean failure rate.

In a real operating system, there are multiple repair loops, so that all repair locations are not subjected to a common demand rate. The simplest example of a source of differing demands is that of centralization of higher repair levels. Since these support larger populations of equipment than the forward repair shops, the number of demands tends to be larger, for repair of the same equipment type. To compound the problem, some failures require corrective action at only some of the repair locations. Other locations receive fewer demands as a result.

As a consequence of the differing demands seen by different repair locations, it is convenient to convert the downtime parameter (t_{wd}) from a failure basis to a common time basis. Once this is accomplished, downtime contributions of all repair locations can be summed up to evaluate overall equipment operational readiness.

N = 9:   P = .18000

S	1	2	3	4	5	6	7
0 (D)	.4179	.1967	.1594	.1535	.1526	.1525	
0 (DT)	.7178	.2448	.1897	.1813	.1801	.1800	
1 (D)	.4037	.1374	.0883	.0795	.0781	.0780	
1 (DT)	.6769	.1593	.0968	.0864	.0848	.0846	
2 (D)	.3954	.1002	.0455	.0350	.0331	.0328	
2 (DT)	.6540	.1113	.0477	.0363	.0342	.0339	
3 (D)	.3904	.0750	.0240	.0140	.0119	.0115	.0114
3 (DT)	.6405	.0811	.0246	.0142	.0120	.0116	.0116
4 (D)	.3874	.0573	.0128	.0056	.0038	.0034	.0034
4 (DT)	.6325	.0608	.0130	.0057	.0038	.0034	.0034
5 (D)	.3856	.0444	.0069	.0023	.0012	.0009	.0009
5 (DT)	.6277	.0464	.0069	.0023	.0012	.0009	.0009
6 (D)	.3845	.0347	.0037	.0009	.0004	.0002	.0002
6 (DT)	.6247	.0359	.0037	.0009	.0004	.0002	.0002
7 (D)	.3838	.0273	.0020	.0004	.0001		
7 (DT)	.6229	.0281	.0020	.0004	.0001		

D(N+S) = .000036
DT(N+S) = .000036

S	1	2	3	4
8 (D)	.3834	.0217	.0011	.0002
8 (DT)	.6218	.0221	.0011	.0002

D(N+S) = .000006
DT(N+S) = .000006

S	1	2	3
9 (D)	.3831	.0172	.0006
9 (DT)	.6211	.0175	.0006
10 (D)	.3830	.0138	.0003
10 (DT)	.6207	.0140	.0003
11 (D)	.3829	.0110	.0002
11 (DT)	.6204	.0112	.0002
12 (D)	.3827	.0089	
12 (DT)	.6203	.0089	
13 (D)	.3827	.0071	
13 (DT)	.6203	.0072	
14 (D)	.3827	.0057	
14 (DT)	.6203	.0058	

Fig. 6—Queue II example.

The conversion is effected simply by weighing the downtime factor (t_{wd}) with the demand rate causing it. For each queue, failure rate weighted downtime,

$$\lambda \cdot t_{wd} = d/(1-d)$$

where λ = the demand rate experienced at the particular queue. It can be seen that if all repair levels are analyzed on a common time basis which compensates for differences in repair schedule from the schedule of equipment operations and demand generation, the total downtime contribution is

$$\sum_i \lambda_i t_i = \lambda t$$

where λ_i = demand rate at the ith repair location and t_i = downtime contribution per failure at the ith repair location (t_{wd})

Operational readiness = $R = A(O) = $ MTBF$/$(MTBF+MTTR)

Unreadiness
$$
\begin{aligned}
&= d = 1 - R \\
&= 1 - \text{MTBF}/(\text{MTBF}+\text{MTTR}) \\
&= \text{MTTR}/(\text{MTBF}+\text{MTTR}) \\
&= t/[(1/\lambda)+t] \\
&= \lambda t/(1+\lambda t)
\end{aligned}
$$

where λ and t are as defined above. Fig. 4 illustrates a typical repair sequence from equipment site to shop, factory and parts vendor. Fig. 5 illustrates partial queuing representation of such a system.

Queue II provides a tabular solution to each queue, permitting visual trade-off of repair channels and spares to achieve the desired downtime limit. Operational readiness resulting from a number of queues is then computed as above. Fig. 5 shows an example of a queuing table produced by application of queue II. The following definitions apply:

N = number of items supported
P = ratio of demand rate and service rate = λ/μ
D = unreadiness (d)
DT = downtime contribution $[=d/(1-d)]$
C = number of repair channels
S = number of spares

The tabular entries are of unreadiness and downtime. Note that the two quantities converge for small values. This fact is useful in analysis of real systems. Where the contributions of individual queues are small, a satisfactory approximation to Operational Readiness can be achieved simply by adding

values of unreadiness and subtracting the sum from one.

Queue II application

Nine radar sites are supported by a field repair shop, and three mobile maintenance vans attached to three radar companies. The following maintenance policies apply:

a) Failure at a radar site is localized to the degree possible by operator personnel.
b) If a spare is stored on-site, operator personnel correct the failure and request a replacement by radio. The replacement will be delivered from the squadron maintenance van by small vehicle. When the replacement is delivered the failed item will be picked up for detail repair.
c) If a spare is not stored on-site, operator personnel call squadron maintenance, and transmit localization data to the degree available. Squadron maintenance personnel proceed to site in an available squadron vehicle, with anticipated test equipment and spares requirements.
d) Field shop is responsible for all field shop repair, so every failure generates a field shop repair demand.

The operational readiness requirement for each site is

$$R = 0.93.$$

The mean demand rate, λ, for radar assembly, XYZ, is 0.016/hour. Mean service times are 4 hours for field shop repair, 16 hours travel delay from field shop to squadron; and 10 hours at site including delay for squadron maintenance assistance.

Utilization factors, P, are
$$
\begin{aligned}
P = \ & 0.06 \text{ at field shop} = 0.016 \times 4 \\
& 0.3 \text{ for travel from field shop} = \\
& 0.016 \times 16 \\
& 0.16 \text{ at site} = 0.016 \times 10
\end{aligned}
$$

Using queue II, tables are produced for

$$
\begin{aligned}
N_3 &= 9, P_3 = 0.06 \\
N_2 &= 3, P_2 = 0.3 \\
N_1 &= 1, P_1 = 0.16
\end{aligned}
$$

One feasible configuration which satisfies the operational readiness requirement is shown.

$$
\begin{aligned}
N_3 &= 9, P_3 = 0.06 \\
C_3 &= 1, S_3 = 3 \\
\lambda t_{wd}(3) &= 0.012
\end{aligned}
$$

$$
\begin{aligned}
N_2 &= 3, P_2 = 0.3 \\
C_2 &= 4, S_2 = 2 \\
\lambda t_{wd}(2) &= 0.022
\end{aligned}
$$

$$
\begin{aligned}
N_1 &= 1, P_1 = 0.16 \\
C_1 &= 1, S_1 = 2 \\
\lambda t_{wd}(1) &= 0.036
\end{aligned}
$$

This arrangement is described more clearly by considering the meanings of

the numbers. The field shop has one repair team, and three spares are assigned to the system to control the weighted repair delay to (0.012).

Four vehicles are assigned to transport replacement items from the field shop to the squadron van, to assure sufficient vehicle availability to limit unreadiness. Two additional spares are assigned to the system for the same reason. Assignment of four vehicles implies significant probability that two will be enroute to the same squadron in the same time period. One squadron maintenance team is required to service the three sites, and two spares are assigned for delays by site repair and travel by squadron maintenance. The total downtime contribution is

$$\lambda t_1 + \lambda t_2 + \lambda t_3 = \lambda t$$

where λ = common demand rate, t_i = downtime contribution per failure at the ith repair location (t_{wd}); and $\lambda t = 0.036 + 0.022 + 0.012 = 0.070$

Unreadiness is

$$
\begin{aligned}
d = 1 - R &= \lambda t/(1+\lambda t) \\
&= 0.071/1.071 = 0.066
\end{aligned}
$$

Operational readiness is then

$$R = 1 - d = 1 - 0.066 = 0.934$$

The requirement of 0.93 is met.

Summary

Queue II has been used to make support trades necessary to evaluating life cycle cost of systems. It is unique in its capability to determine operational readiness directly, and to permit comparison of design or support alternatives achieving a given level of operational readiness including the effects of queuing and logistic unreadiness.

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Support system cost effectiveness

W. A. Triplett

Integrated Logistic Support is a planned systematic approach to the problem of providing support for complex operational systems. This paper describes the basic rationale of Integrated Logistics Support; shows how this approach can be applied in a cost effectiveness study; and presents an example of how this approach was used to study support costs for a ground communications system.

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THE INCREASED COMPLEXITY of current military systems and the operational concepts that support these systems have caused the military to develop a systems-management discipline called "Integrated Logistics Support" (ILS). This discipline does not treat a system as simply a prime equipment; rather, ILS relates to the analysis and implementation of the many systems elements including computer programs, training, maintenance, facilities, procedures, instrumentation, data reduction, and transportation—in addition to the prime mission equipment factors. The greatest significance of ILS may well be its influence on the effectiveness of the U.S. military forces. This is measured in terms of economics and performance. Moreover, through ILS, the Defense Department is constantly made aware of the consequences if the question of maintenance and logistics support is ignored in the early stages of system design.

To this end, formulas, approaches, and specific computer programs have been developed which consider sensitivity and influence of multiple factors in the total cost-of-ownership in terms of the life-cycle spans involved. Through applications of an existing mathematical model, it is possible to explore a matrix involving many different maintenance policy approaches versus four levels of support:

Installation
Organization
Intermediate
Depot

Included is the capability to insert into the basic formulae all significant logistics support factors and obtain computer printouts of life-cycle cost under many combinations of the maintenance and support philosophies involved. This printout directly shows the lowest cost approach. Factors can be further refined and adjusted to show the sensitivity of costs to significant parameters, thereby providing quantitative data for optimum planning.

Perhaps of equal significance is the influence of ILS systems engineering trade-offs on equipment design. The greater resource utilization can also results of any studies that highlight potential operational benefits and highlight the related equipment design features. These may include the type and capability of test equipment and certain prime systems design features related to the economics of support, including the interface between the test equipment and the prime equipment.

What is integrated logistic support

Integrated Logistic Support (ILS) is, in effect, the formulation and implementation of a systems engineering plan for the support of prime systems. Emphasis is placed on early integration of the support aspects when systems are in their conceptual phase and when systems engineering tradeoffs can affect designs before making hardware commitments. The ILS elements related to support have recently been summarized by the Office of the Secretary of Defense as:

Maintainability and Reliability (M&R),
Maintenance Planning (MP),
Support and Test Equipment (SE),
Supply Support (SS),
Personnel and Training (P&T),
Transportation and Handling (T&H),
Technical Data (TD),
Facilities (FA),
Management Data (MD), and
Funding (F).

The objective of the ILS is to emphasize these elements in the decision making process and, at the same time, to provide economically a high or specified degree of readiness.

Design engineers will find that they are called upon more frequently to incorporate into system designs those techniques which permit the system to meet all design requirements yet reduce the ownership cost during the life of the system. The trend in the military is to consider total package (or life cycle) costs in many future procurements. A demand, therefore, exists for key management and design personnel who are knowledgeable of, and sympathetic with, the associated systems engineering disciplines.

Table I summarizes many of the effects of maintenance and logistics factors on design. Since over 25% of the defense budget is spent on supporting systems in the field, consideration of these factors is a justifiable ILS objective.

PRODUCE BASE-LINE CONFIGURATION
IDENTIFIES THE WEAPON-EQUIPMENT
DESIGN CHOSEN TO MEET SPECIFICATIONS
FOR OPERATIONAL AND READINESS
PERFORMANCE GOALS

COSTLY CHANGES
MODIFYING HARDWARE

INEXPENSIVE CHANGES
TO DRAWINGS AND
SUPPORT CONCEPTS

Performance/readiness specifications establish measurable "design-to" objectives in quantified terms. Hardware design configuration range narrows through successive readiness performance trade-offs.

HARDWARE UNDEFINED   EQUIPMENT MODES SELECTED

LIFE CYCLE PHASES

Concept Formulation	Contract Definition	Development	Production	Operational

Fig. 1—Support impact on system design.

Table I—Maintenance and logistic effects on design

Design or logistic factor	ILS requirement or significance
Built-in checkout or monitoring equipment	Inadequacy may cause mission failure due to undetected equipment faults
On-line fault isolation level	Affects the cost of replacement assemblies
Maintenance personnel training	Consider simplification of support tasks in equipment design
Technical data & documentation	Complexity of design increases operations and maintenance documentation costs
Reliability & maintainability	Perform design tradeoffs on a life-cycle cost basis to set the proper balance
Repair level decisions	Consider effect of maintenance hierarchy and repair level on life cycle costs
Test equipment (manual, special purpose, or general purpose automatic)	Consider effect of maintenance workload on choice and location of test equipment
Management data	Organize management data to simplify incorporation of modifications to fielded equipment
Funding	Consider support aspects in funding for design engineering
Equipment packaging	Consider support aspects in addition to reliability, accessibility, heat transfer, etc. in packaging design

In line with the objectives of future logistic support, DoD has prepared the Integrated *Logistics Support Planning Guide*[1] which outlines concepts and objectives which call for management actions integrating all support elements in order to maximize the availability of equipment and minimize support costs. Intended for use in ILS planning, the procedures of the *Guide* are designed to reduce costly changes to production hardware or expensive modification of operational equipment. This is illustrated in Fig. 1 (an excerpt from the *Guide*) which represents ILS as the early integration of system support aspects with the prime system and equipment design. This is followed by a continuing planned support program effectively interfacing with the prime equipment throughout the life cycle.

Ideally, the logistics support effort is initiated in the concept phase and a controlled program is carried out for the concept, definition, development, production, and operational phases. The ultimate objective is to provide a high degree of readiness at reasonable cost.

The aspects of considering logistics along with operational performance early in the design process were emphasized in an address by Dr. Finn J. Larsen[2] where he cites the importance of attaining operational performance, but also comments that, in the past, this was often done at the expense of the logistics aspects of the equipment. The present emphasis is, therefore, placed on achieving the proper balance between logistics and performance by considering the factors which establish the performance and logistics standards early in the design process, and, through judgment and trade-off analyses, to set the proper balance. One of the principal trade-off methods which can contribute significantly to achieving this goal of integrated logistics support is support-system cost-effectiveness modeling. And it will be shown that the integration of the various elements of support can be accounted for in suitable mathematical models for the prediction of support policies and practices which are optimized in a cost sense.

Support system cost effectiveness model

The cost model most recently used to characterize and analyze the logistics

support requirements of large-scale military systems has been designated CO-AMP II. CO-AMP II, developed at RCA, evolved from earlier modeling work which was based on the techniques given in Goldman and Slattery's book on maintainability.[*] CO-AMP, in this context, stands for Cost Optimization and Analysis of Maintenance Policies. Although extensive in its treatment of support heirarchy, pipeline considerations, equipment configuration breakdown, test and fault isolation factors, etc., the CO-AMP II model basically relates the demand for support to the supply of support.

Demand is treated as a linear expression involving attrition, failure, false-report-of-failure and utilization rates of operating equipments. The demand is moderated by the effects of outage. Support is characterized in terms of finite numbers of spare items, finite numbers of repair channels comprising maintenance men and test equipment and the interconnecting network between users and support activities. These latter "pipelines" provide the routes for material and requisitions and consider reprocurement paths as well as repair paths.

As its principal outputs, the analysis produces comparative estimates of total life-cycle cost and equipment operational availability between alternate support policies. These alternates involve the levels of support characteristic of military operations. Maintenance capability ranges from unit checkout—through repair by removal and replacement of a module—to module repair by removal and replacement of a part. The capabilities for test and fault isolation are stated as built-in or separate from the operating equipment. Also, the test equipment can be examined as manual or automatic. Consideration can be given to cost data in the time phases leading to and including development, acquisition, and operation. The elements of cost include prime equipment, test equipment, facilities, manpower, material, reorder costs, storage cost, supply administration, shipping and handling, and salvage credits. In addition, the model provides the capability to examine physical factors such as the number of spare items of each type at each location.

The capacity of the CO-AMP to evaluate many support alternatives is illustrated by the deployment matrix shown in Table II. This matrix includes twenty different arrangements of support over four distinct support levels, three levels of hardware logistics discard policy, and three levels of support test capability. For each policy there are four options for stating the location of spare sets. Thus, the program contains 80 different basic configurations. One or more, up to the entire 80, can be accompanied by a single computer run.

The checkout and fault isolation capabilities are designated as:

COU (checkout the entire unit)
FIM (fault isolate the unit to the module level)
FIP (fault isolate the module to the defective-part level)

These designations are listed in the right-hand column of Table II and are basic to the definition of a maintenance policy. For example, under Maintenance Policy No. 12, the unit is checked out either by the operator or some form of built-in test at the equipment. The units are then sent to a maintenance unit of the user organization where the units are again checked for false no-go indications. Faulty units are then checked to the module level and faulty modules are fault-isolated to the part level and repaired.

The basic equations used in the formulation of the CO-AMP II model are written to respond to demand for support due to scheduled maintenance, failures, attrition, theft, loss, and false no-go indications on the part of the operator. The equations also recognize each type of routing to establish pipeline quantities and transportation charges. They compute the number of service channels (men, equipment, etc.) and the required inventories of sets, assembles, and parts to provide support. Support demand is moderated by operating time fraction (utilization rate) and by availability. Float stock for repair, consumption, and service queues is computed, along with back up spares or safety stock. Fractions are assigned to specify the branching processes possible at each support level: repair fraction, not repairable this station (send to higher level) fraction, and scrap fraction. Cost input factors are completely separable between ini-
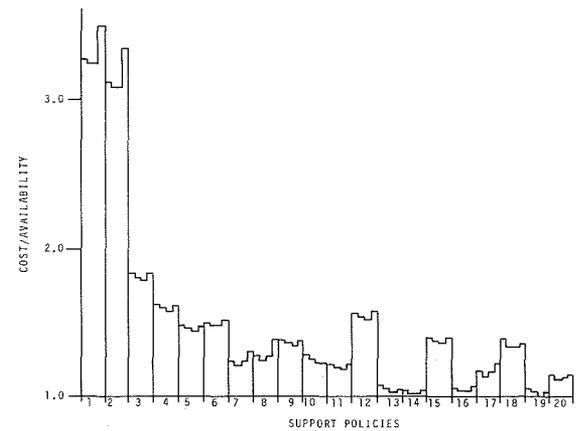
Fig. 2—Relative cost effectiveness of 80 alternate support policies.

tial production and subsequent replenishment and can be tempered by suitable learning factors.

The designations for the major cost factors which can be considered are given in Table III. This table represents a matrix of the costs during equipment acquisition and on-going support cost. The time frames are shown as development, production, replenishment, and end of program salvage. Typical examples of the definitions of some of the designated cost elements are as follows:

Cost of prime equipment (CED, CEP)— Development cost (CED) is treated as a non-recurring cost and can include fixed cost factors to account for concept and definition phases, leading to development. The cost for production of prime equipment (CEP) is formulated as the sum of a non-recurring cost term plus a recurring cost term which is dependent on the quantity purchased (learning is treated in the model). The cost of built-in test equipment (BITE) is treated separately in the CO-AMP model to facilitate support system trade-offs.

Cost of test equipment (CTSD, CTSP, CTSR)—The cost matrix contains three elements for this cost, namely development, production and replenishment. Development costs (CTSD) are included for both built-in and separate test equipment. Production (CTSP) test equipment includes both non-recurring and
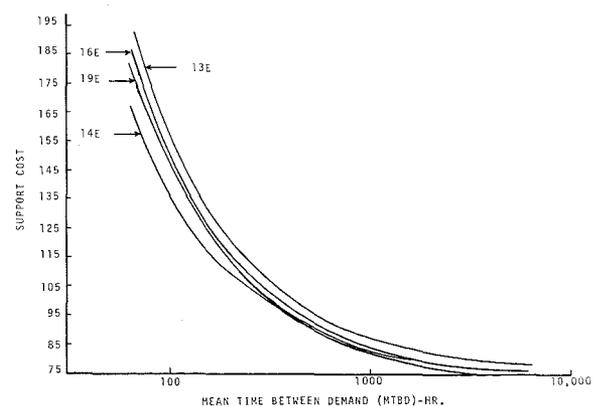
Fig. 3—Support cost versus mean-time-between-demand.

recurring costs, and for the case of the latter, learning factors are used. Replenishment (support) cost for test equipment (CTSR) is formulated as proportional to CTSP. When this formulation is considered inadequate, then better estimates can be made by treating the test equipment as prime equipment in order to compute its support costs.

Cost of maintenance manpower (CMPP, CMPR)—Provision is made via CMPP to recognize the cost of special training of maintenance manpower associated with test equipment, prime equipment, etc. formulated in the model. The replenishment cost (CMPR) is formulated to compute the cost of maintenance manpower. At the equipment level, cost is computed for scheduled and unscheduled maintenance. At the higher support levels (organization, intermediate, and depot) manpower is charged in proportion to the number of channels and the scheduled work week. In addition, labor rates are set in accordance with skill level required.

Cost of shipping and handling (CSHD, CSHP, CSHR)—The costs of shipping and handling (CSHD and CSHP) are used to formulate the development and acquisition cost of reusable shipping containers and packing design. The terminology "reusable shipping container" is an abstraction and can be applied to include the acquisition of dedicated transportation equipment, etc. The CSHR term accounts for shipping and packing charges and it distinguishes between units, modules, and parts. Further, it recognizes the routes used and permits different costs to be entered for different routes.

The method has been formulated as a computer program which provides for efficient data read-in, short running times and fully formatted output sheets. Provision is made to perform sixty-two iterations of the program for each set of input data and for each support policy examined. This set of computations consists of one computation using the input data parameters and sixty-one sets of computations in which certain of the input parameters are systematically varied.

The results thus obtained are used to construct graphs which display the behavior of the maintenance concept over ranges of the input parameters.

In summary, application of the CO-AMP II model has the capability to:

1) Investigate discard-versus-repair policies at the set and subassembly levels.
2) Consider test equipment as manual or automatic.
3) Consider equipment-level test equip-

Table II—CO-AMP II test equipment deployment matrix

Support level	Test equipment function	Maintenance policy number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Built-in test (E)	COU	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	FIM		X								X	X	X								
Organization (o)	COU		X		X		X		X	X				X	X	X	X	X	X		
	FIM		X							X				X	X	X					
	FIP									X				X							
Intermediate (I)	COU							X	X			X			X		X	X		X	X
	FIM							X	X			X			X		X	X		X	X
	FIP											X			X		X			X	
Depot (D)	COU								X	X			X			X		X	X		X	X
	FIM								X	X			X			X		X	X		X	X
	FIP												X			X		X	X		X	X

Unit   Module   Part
Logistic discard level

Legend: COU—Checkout unit
        FIM—Fault isolate to module
        FIP—Fault isolate to part

Table III—CO-AMP II cost matrix

Cost element	Time Phase Acquisition Development	Production	Replenishment support for N years	End of program salvage value	Sub-total by element of cost
Prime equipment	CED	CEP	(per other entries)	CEV	CET
Test equipment	CTSD	CTSP	CTSR	CTSV	CTST
Facilities	CFD	CFP	CFR	CFV	CFT
Manpower	—	CMPP	CMPR	—	CMPT
Material	—	CIVP	CIVR	CVV	CIVT
Reorder cost	—	—	CROR	—	CROT
Storage cost	CWHD	CWHP	CWHR	CWHV	CWHT
Supply administration	—	CSAP	CSAR	—	CSAT
Shipping and handling	CSHD	CSHP	CSHR	—	—
Salvage credit	—	—	CSVR	CSVE	CSVT
Cost totals	CD	CP	CR	CS	GCT
Present value at FOC	PVCD	PVCP	PVCR	PVCS	PVGCT

ment as separate or built-in.
4) Compute operational availability for each policy recognizing the ability to borrow from another stock location when a given stock pile is vacant. (Safety stocks and risk of logistic shortage can be input based on any level of optimism or pessimism.)
5) Investigate the hybrid support policies which assign various classes of failures to different support levels.
6) Recognize non-recurring as well as recurring cost factors.
7) Vary discretionary procurement holding times to seek optimum reorder buy quantities including consideration of total package procurement.
8) Vary packaging factors to seek optimum total life cost.
9) Investigate the sensitivity of support costs to any significant logistic support parameter.

Input data

Depending on the complexity of the system to be analyzed and the number of alternate approaches to be considered, the cost analysis requires specification of the following general types of information:

1) *Deployment factors* — number of systems, organizational structure, relation of groups, mobility, heirarchy and number of support installations, utilization rate of equipment, attrition rate.
2) *Prime equipment factors* — equip-

ment breakdown, failure rates, physical characteristics, construction (LRU's, modules, subassemblies, circuits), cost per equipment/LRU/ module, required availabilities.
3) *Logistics factors*—sparing policies (initial safety stock) supply times, production lead time, stockpile facilities, transportation factors.
4) *Maintenance support factors*—test equipment characteristics/costs (manual, automatic, hybrid, built-in), repair times, checkout times, manpower requirements/utilization/cost, test program cost, support equipment/built-in maintenance, mobility.
5) *General factors*—time period for cost analysis, escalation of manpower/ equipment costs, anticipated growth, economic basis for analysis.

Typical results of cost model applications

The following are typical of the types of equipment and systems for which RCA has used the ILS cost models:

Army Ground Communications System
Airborne Avionics System
Aircraft Electronics Subsystem
Floating Maintenance Facility
Missile and Space Systems

The results of one of these applications are discussed in the following paragraphs.

Ground communications system

As stated previously, the CO-AMP II model includes the calculation of prime equipment availability for each support policy under consideration. Therefore, the determination of the cost/availability ratio (normalized to the policy with the lowest value) can be used as an index of cost effectiveness. Recently, this index was used as one of the figures of merit for evaluating alternate means for supporting a field Army communications set. A field Army deployment of 256 sets of equipment was assumed, and the full capability of the CO-AMP II model to evaluate 80 alternate support policies was employed in the analysis. The sensitivity of support costs to certain selected logistics parameters was also determined by programming the computer to provide the desired output quantities.

The histogram shown in Fig. 2 summarizes the results. The 20 support policies numbered along the base of the histogram represent the 20 basic test equipment deployments as defined by the CO-AMP II deployment matrix (Table II). It will also be recalled that the model can accommodate four options for the location of safety stock. This accounts for the variations shown within each of the basic support policies. The ordinate used in this presentation is the normalized cost/availability ratio (C/A) previously introduced as a possible measure to support system cost effectiveness. Based on this index of system worth, Policy 19-I (the I signifying a safety stock location at the intermediate support level) is shown to be the most cost effective of the 80 possible variations. It is noted that, with the possible exception of Policies 1 and 2, the C/A ratio is relatively insensitive to safety stock location. Although not shown by this presentation, the availabilities are highest with the safety stock located at the equipment (E)—support level, and are successively lower the further the spares are from the user organization. In instances where the specified availability is the governing criteria, CO-AMP II provides the capability for independent examination of this factor.

In general, the higher numbered policies show the lowest C/A ratios, indicating the value of piece-part repair in this particular instance. The Support

Policies 13, 14, 16 and 19 (Fig. 2) are shown to be relatively close in their rating on the basis of C/A ratio. These policies were, therefore, selected for cost sensitivity comparisons.

Fig. 3 shows typical results of a cost sensitivity investigation. It contains plots of support cost as a function of mean-time-between-demand (MTBD) — a composite factor reflecting the effects of equipment failures, attrition, and false-no-go's. Below an MTBD of about 500 hrs, Policy 14-E exhibits a cost advantage. Above this point, the curves tend to level off, indicating little advantage above an MTBD of 1000 hrs.

In addition to quantitative tradeoffs, as previously discussed, it is important to examine the elements contributing to the life cycle costs of military equipment. The example shown in Fig. 4 clearly shows that support cost during the life cycle can sometimes dwarf the prime equipment or initial system investment costs in prime equipment. It also illustrates the high costs of manpower over the life cycle.

Conclusions

Following the DoD guidelines and directives governing the interface between support and prime systems, the many factors contributing to support costs and operational availability can be evaluated by deterministic modeling techniques. Applications have been made of these models to demonstrate their value in the formulation of logistic support plans and achieving the proper balance between logistics and performance early in the design process. The deterministic approach augmented by sensitivity testing provides the means for examining the factors contributing to support costs and to the balance between logistics and system performance.

The results of applications to individual equipment or composite support complexes comprising many equipments and systems demonstrate the versatility of the analytical approach. Many alternate deployments of equipment and manpower and the cost factors related to integrated logistics support can be examined. And the results can be displayed in various ways to judge the cost effectiveness or systems worth as a basic input to logistics planning.
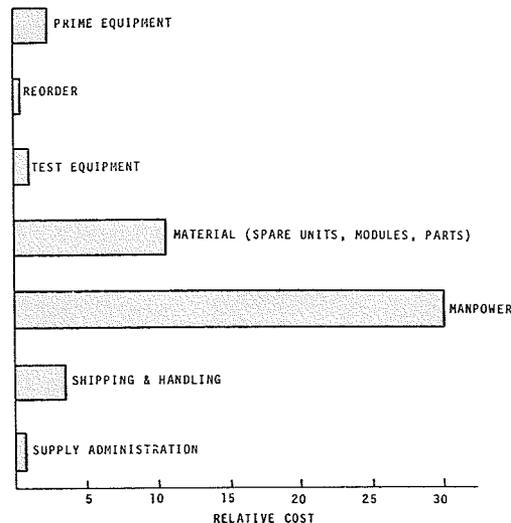
Fig. 4—Comparison of ILS life-cycle cost elements.

And ILS tradeoffs can significantly influence support equipment design, including the effects of operational constraints and considerations of commonality and integration of test functions which avoid duplication of equipment and the other factors involving development, mobility, availability, test system support and those which are or are soon to be classically considered in the Integrated Logistics Support approach.

Acknowledgment

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41

Materials characterization at RCA laboratories

Dr. R. E. Honig

The importance of the materials characterization activity has grown enormously during the past two decades, closely following developments in electronically active materials. Because of this substantial growth, materials characterization now includes several new areas. This paper acquaints engineers in the product divisions, as well as a whole new generation of technical staff members at RCA Laboratories, with the facilities available in this field at RCA Laboratories. Specifically, the methods and major instrumentation available for solving problems concerning structure, defects, and composition of materials are covered. This paper answers many of the questions most frequently asked; however, many specific problems could, and should, be discussed, in person, with any of the members of the group.
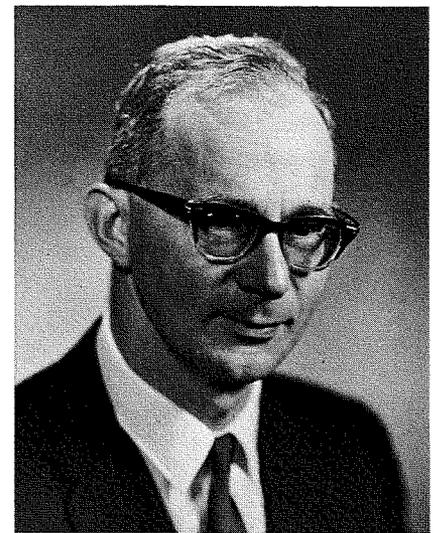
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A S RECENTLY DEFINED by the Materials Advisory Board[1], any material is fully characterized in terms of its structure, defects, and composition. We shall not attempt to improve on this definition, which doubtless reflects a great deal of soul-searching on the part of many people. On the contrary, we feel that the major areas of materials characterization to be discussed below are indeed appropriately classified under either structure and defects, or composition.

Table I summarizes present activities in materials characterization, arranged according to area and function, and listing the workers engaged in each major function. Where a name is listed twice, the percentage figures indicate roughly the time distribution between the two projects. The first two areas—microscopy and x-rays—pertain to structure and defects, except for x-ray fluorescence. The next four areas—mass spectrometry, optical spectroscopy, chemical analysis, and nuclear radiation—deal essentially with composition, while the last two entries are general in nature.

Before discussing in more detail the activities in individual areas, it will be instructive to consider a hypothetical solid sample. Fig. 1 depicts such a sample and suggests how it may be characterized by the major methods available. In clockwise order from the upper left corner of Fig. 1, we have four methods to determine surface

structures: optical microscopy (OM), scanning electron microscopy (SEM), transmission electron microscopy (EM)—with and without replica. Continuing in clockwise order, we have two methods to measure lattice constants: electron diffraction and x-ray diffraction, and finally, one example for the determination of composition: mass spectrometry (MS).

Structure and defects

Microscopy

The major activities in microscopy are summarized in Table II. Each entry is characterized in terms of sample requirements, magnification, resolution, depth of field, and major applications. It is evident from this table that the magnification and resolution gap existing between the electron microscope and the optical microscope is filled by the recently perfected scanning electron microscope (SEM) which has an unusually wide magnification range, good resolution, and a remarkably large depth of field. Because the SEM is such a recent development, a brief description is appropriate. It consists of a primary electron beam of up to 20 keV energy which scans the specimen surface. Information concerning the surface structure is derived from one of three operational modes:

1) *Emissive* mode: secondary and/or reflected primary electrons;

2) *Conductive* mode: induced electric currents flowing through the sample (e.g., charge collection by P-N junctions,

and "specimen-absorbed" currents); and

3) *Luminescent* mode: visible and IR light emission.

The signal resulting from the interaction of the beam with the sample modulates the brightness of a CRT to produce a picture of the surface. Figs. 2, 3, and 4 show pictures of an MOS device taken at three different magnifications. Fig. 2 (300×) is a general view of the surface, showing source, gate, and drain. From Fig. 3 (3000×) it is apparent that the gold overlay is not continuous, while Fig. 4 (7000×) shows in detail the polished sapphire

substrate, an epitaxial silicon layer, and a projecting ledge of silicon oxide doped with phosphorus. It is this projection which caused cracks in the insulating and conducting overlays and was responsible for the malfunctioning of the device. The enormous depth of field of the SEM is demonstrated in Fig. 5 which shows vinyl record grooves after 10 plays with a ceramic pickup weighing 5 grams. The wear caused by the stylus is clearly seen on the side of the grooves.

The equipment available for microscopic studies includes the following major items: one Leitz "Panphot" Metallographic Microscope for transmission, dark-field, and phase-contrast work; one Leitz "Metallograph"; and one "Stereoscan" Scanning Electron Microscope (Cambridge Instrument Co.) installed in March 1967; two RCA Electron Microscopes, Types EMU 3B and 3G, for transmission and diffraction studies; and one "ALBA" Ion Thinning Machine to thin samples down for transmission work.

X-rays

The major x-ray methods in use at RCA Laboratories are listed in Table III in terms of the type of recording employed, the most suitable type of materials to be characterized, and specific applications. While these methods primarily provide answers concerning structure and defects, it should be noted that minor phases present at the percent level can be identified in this fashion, and that x-ray fluorescence is suitable for determining composition down to the 1000 parts per million (ppm) level.

Of special interest is x-ray topography —a method which has become commercially available in recent years for the study and characterization of nearly perfect single crystals (containing less than 10^5 defect lines/cm²). It consists of a Jarrell-Ash Microfocus X-Ray Generator, a Lang Camera, and a scintillation counter for orienting the crystal. Fig. 6 is a schematic outline showing the three major arrangements used:

1) *Berg-Barrett surface reflection* topography reveals surface irregularities, such as misfit dislocations;

2) *Lang transmission* is used for crystals that are relatively transparent to x-rays

Fig. 1—The major methods employed to characterize a solid sample.

Table I—Materials characterization: areas, major functions, and manpower (March 1969)

Area	Major function	Manpower	
Microscopy	Scanning electron miscroscope	M. D. Coutts	(50%)
	Analysis & development	E. R. Levin	
	Electron microscope problems	M. D. Coutts	(50%)
	Electron microscope analysis	W. C. Roth	
	Microscope instrumentation	B. J. Seabury	
X-rays	Topography	S. H. McFarlane	
	Single crystal diffraction	R. T. Smith	(75%)
	Powder diffraction, fluorescence	R. J. Paff	
	General consulting	J. G. White (2 days/month)	
Mass spectrometry	Solids analysis	W. L. Harrington	
	Instrumentation	J. R. Woolston	(50%)
	Solids MS operation	E. M. Botnick	
	Gas analysis	D. A. Kramer	(50%)
Optical spectroscopy	Emission spectroscopy	P. J. Zanzucchi	
	Atomic-absorption development		
	ES & AA analysis	H. H. Whitaker	
Chemical analysis	Special problems	S. J. Adler	(25%)
		B. L. Goydish	
	Wet chemical analysis	A. Murray	
Nuclear radiation	Activation analysis, tracers	S. J. Adler	(75%)
	Radiation damage	R. F. Bailey	
Data processing	MS, X-rays, etc.	J. R. Woolston	(50%)
	X-rays	R. T. Smith	(25%)
General	Administration, general research	R. E. Honig	
	General research	D. A. Kramer	(50%)

(absorption coefficient (μ) x thickness (τ) <1), imperfections appearing as enhanced intensity; and

3) *Borrmann anomalous transmission* is used for relatively opaque crystals ($\mu\tau \approx 10$ to 20), imperfections appearing as reduced intensity.

There is no magnification inherent in any of these three methods since the x-ray picture corresponds to the physical size of the sample. However, details can be brought out by enlarging the prints 20×. Fig. 7 compares a Berg-Barrett topograph a) of a *Ga(As,P)* alloy epitaxial layer on a *GaAs* substrate with the corresponding optical micrograph b), at the same magnification. Observe that the trapezoidal arrangement of large white spots corresponds to a set of dark spots in the micrograph, and thus must represent growth pits in the epitaxial layer. On the other hand, the crossed grid of white lines, believed to be misfit dislocations, is seen only in the topograph and must be crystallographic in origin.

Fig. 2—SEM picture of an MOS device (low magnification).

An example of a Lang transmission topograph is shown in Fig. 8. It represents a magnesium aluminate spinel whose triangular center portion (appearing light-colored) is of high quality, except for the stacking fault; the
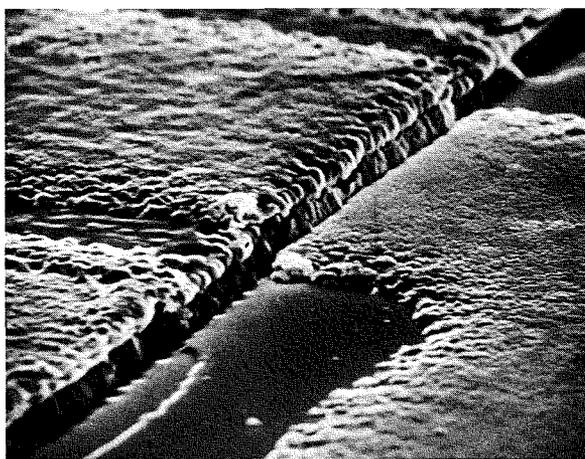
Fig. 3—SEM picture of the same MOS device (medium magnification), showing break in gold overlay.

Fig. 4—SEM picture of the same MOS device (high magnification), showing projection of silicon oxide top layer.

Fig. 5—SEM picture of vinyl record grooves after 10 plays; note the stylus wear.

Table II—Microscopy.

METHOD	SAMPLE SIZE (cm²)	SAMPLE LIMITATION	MAGNIFICATION RANGE	RESOLUTION Å	DEPTH OF FIELD (ARB. UNITS)	APPLICATION
ELECTRON MICROSCOPY	0.1	< 2000 Å OR REPLICA	$300 - 3 \times 10^5$	5 30		PARTICLE SIZE & SHAPE, CRYSTALLINITY, CRYSTAL GROWTH, SURFACE STRUCTURE DEFECTS, MAGNETIC DOMAINS, PHASE TRANSFORMATIONS
EL. DIFFRACTION TRANSMISSION REFLECTION	0.1 1	< 2000 Å				UNIT CELL DETERMINATION, CRYSTAL MORPHOLOGY, DEFECTS
SCANNING ELECTRON MICROSCOPY	1		$10 - 5 \times 10^4$	200	300	PARTICLE SIZE & SHAPE, SURFACE AND INTERFACE PHENOMENA
OPTICAL MICROSCOPY	1		$10 - 10^3$	2000	1	SURFACE MORPHOLOGY

Table III—X-rays: major areas.

METHOD	RECORDING	MATERIAL	APPLICATION
POWDER	PHOTOGRAPHIC	POLYCRYSTALS (POWDERED) EPITAXIAL LAYERS (SMALL SAMPLES)	DESTRUCTIVE: PHASE IDENTIFICATION DOWN TO 5% LATTICE PARAMETERS [f(TEMP.)] TO ± 1/10 000
DIFFRACTOMETRY	COUNTING	POLY- & MONOCRYSTALS EPITAXIAL LAYERS (LARGE SAMPLES)	NONDESTR.: PHASE IDENTIFICATION DOWN TO 5% LATTICE PARAMETERS[f(TEMP.)] TO ± 1/10 000 PREFERRED ORIENTATION
LAUE	PHOTOGRAPHIC	MONOCRYSTALS (BULK, THIN FILMS)	ORIENTATION TO ± 0.5° CRYSTALLINITY
"SINGLE CRYSTAL"	COUNTING PHOTOGRAPHIC	MONOCRYSTAL (e.g.: SPHERE)	DIFFICULT ORIENTATION CRYSTAL SYSTEM IDENT. LATTICE PARAMETERS
FLUORESCENCE	COUNTING	SOLIDS, POWDERS, LIQUIDS (Z > 22)	QUAL. & SEMI-QUANT. IDENT. DOWN TO 100 ppma
TOPOGRAPHY	PHOTOGRAPHIC	MONOCRYSTAL, NEARLY PERFECT (< 10⁵ LINES/cm²)	DEFECTS, STRAINS

Table IV—Comparison of analytical methods.

METHOD	COVERAGE	OPTIMUM SENSITIVITY (ppma)	TYPICAL SAMPLE WEIGHT (mg)	BULK	SURFACE	DESTRUCTIVE	CHEMICAL HANDLING	STANDARD USED	ACCURACY (ERROR FACTOR)	TIME REQ'D (HOURS)
MASS SPECTROMETRY	NEARLY COMPLETE, SIMULTANEOUS	0.001 – 1	100	YES	YES	YES	NO	NO YES	3 1.2	2 10
EMISSION SPECTROGRAPHY	70 ELEMENTS, SIMULTANEOUS	0.01 – 100	10	YES YES	YES	YES YES	NO SPECIAL	NO YES	3 1.1	1 10
ATOMIC ABSORPTION	70 ELEMENTS, ONE AT A TIME	0.01 – 100	10	YES YES	YES	YES YES	YES SPECIAL	YES	1.02	0.5
WET CHEMISTRY	COMPLETE, ONE AT A TIME	1 – 1000	100	YES YES	YES	YES YES	YES SPECIAL	YES	1.001	5
ACTIVATION ANALYSIS	75 ELEMENTS, ONE AT A TIME, IN CERTAIN MATRICES	0.001 – 100	1000	YES YES	YES	NO YES	NO SPECIAL	NO YES	1.2 1.05	> 10 > 10
X-RAY FLUORESCENCE	ALL ELEMENTS WITH Z > 22	10 – 100	100	YES	NO	NO	YES		1.1	0.5

Table V—Analysis of high-purity Zn bars (National Bureau of Standards Lot 1A-2)—in ppm, atomic.

IMPURITY	CONCENTRATION	REMARKS
F	0.03	NU
Na	0.02	
Mg	0.08	NU
Al	1.5	NU
Si	2	NU
Cl	0.4	NU
K	0.05	
Co	0.08	
Ti	0.15	
Fe	0.3	
Ni	0.04	
Cu	0.15	
Ag	2	M NU
Cd	0.3	
In	0.1	M
Au	0.5	M
Tl	0.4	
Pb	3	NU
Bi	0.3	NU

NU – NON-UNIFORM
M – MEMORY

surrounding dark portions are due to growth striations. The Borrmann anomalous transmission topograph of Fig. 9 shows, in reverse contrast, dislocations present in germanium.

The equipment available for x-ray work includes the following major items: one Siemens "Crystalloflex 4" three-tube stand for diffraction, fluorescence, and Berg-Barrett topography with associated electronic equipment; one Siemens "Crystalloflex 2" and camera; one GE "XRD 1" unit (1938 vintage, now practically a museum piece) for Laue orientation work; two Norelco basic diffraction units with one supply panel for single crystal, Weisenberg, high temperature, and powder ("Unicam" S150) work; one cryostat attachment for diffraction work at liquid N_2 temperature; one liquid He cryostat under construction; and the Jarrell-Ash Microfocus X-Ray Generator and Lang Camera.

Composition

The next four areas to be discussed are mainly concerned with the determination of composition. The major parameters to be considered in selecting the most appropriate analytical method may be listed, roughly in the order of importance, as follows: sensitivity, accuracy and/or precision, speed, coverage, standards available, sample size, destructive or non-destructive, bulk or surface impurities, homogeneity, and prerequisite chemical handling. Of all these entries, the first two are clearly of overriding importance, and it is a well-known axiom that they are mutually exclusive. In fact, one may safely postulate that the product of sensitivity times accuracy can only attain a certain maximum value. Speed is an important consideration if there are many samples to be analyzed and manpower

Table VI—MS analyses: sample costs and delays.

ANALYSIS	ACCURACY ERROR FACTOR	PRECISION ERROR FACTOR	PUNCH CARDS		TELETYPE	COMMENTS
			"601"	"SPECTRA 70"		
1. VISUAL	3	3				*WITHOUT PUNCH CARDS
COST, $			50*	50*		
DELAY, DAYS			NONE	NONE		
2. SEMI-QUANTITATIVE, NO LINE WIDTH CORRECTIONS	3	1.2–1.5				
COST, $			90	120	75	
DELAY, DAYS			2d	2d	NONE	
3. SEMI-QUANTITATIVE, LINE WIDTH CORRECTIONS	3	1.1–1.2				REQUIRES ANALOG-DIGITAL CONVERTER
COST, $			150	210	75	
DELAY, DAYS			4d	2d	NONE	
4. QUANTITATIVE, STANDARD AVAILABLE	1.1–1.2	1.1–1.2				
COST, $			290	380	150	
DELAY, DAYS			4d	2d	NONE	

is limited. Thus, an analysis should preferably be done in a few hours, but must not exceed a few days if the method is to be of practical value. The term coverage indicates what fraction of the impurities present can be detected by the method; the most desirable method obviously covers all elements in the periodic table with high, uniform sensitivity. To obtain absolute rather than relative values, standard samples of known composition are required. Sample size is sometimes of importance, but for most applications adequate quantities of material are usually available. Most methods will analyze for bulk impurities, some can be modified to apply to surface studies, while only a few are specifically for surfaces. The determination of homogeneity, or the lack thereof, requires the analysis of microvolumes and has become of great practical importance. Wherever possible, chemical preconcentration or handling is avoided since it is likely to introduce impurities into the sample.

Table IV presents, in concise fashion, a comparison of the major methods available at RCA Laboratories to determine composition. The first two techniques—mass spectrometry and emission spectrography—are broad survey methods of high sensitivity, permit all impurities to be detected simultaneously, and are reasonably fast, but semi-quantitative in character. Where better accuracy is required, atomic absorption and wet chemistry are indicated; however, the trace impurities must be known *a priori* and can be determined only one at a time. Activation analysis can, for certain applications, have extremely high sensitivity, but is a time-consuming and difficult technique. The major attributes of x-ray fluorescence are its speed and the fact that it is non-destructive.

It is apparent that the choice of a method depends on a detailed evaluation of the problem at hand. In the following, novel developments and equipment available in these different areas are discussed.

Mass spectrometry

An AEI "MS7" solids mass spectrograph has been in operation since 1961 and is employed for the determination of trace impurities in a wide range of matrices. The instrument consists of a source which vaporizes and ionizes a small portion of the sample. The ions produced are accelerated, energy-selected, and mass-separated in the electrostatic and magnetic analyzers, and recorded on an ion-sensitive plate. A typical set of mass spectra for a high-purity Zn sample is presented in Fig. 10 which shows rows of increasing "exposure" (total collected charge) vs. the mass scale in atomic mass units. The major ionic species are identified on the bottom line. The blackening values of the mass lines are transformed via a computer program into relative concentrations which are listed, for the same Zn sample, in Table V. The mass spectra recorded on the ion-sensitive plates are evaluated on a Jarrell-Ash Type 23-1000 Recording Microdensitometer.

For the analysis of gases, there is presently under construction a fully bakable system, consisting of an AEI "MS10" mass spectrometer and a multi-purpose all-metal vacuum system, which is to be used for a wide range of gas-analytical problems.

Emission spectrography

This method has been routinely applied to qualitative and semi-quantitative problems for many years. The equipment in use is a Jarrell-Ash 3.4 meter Ebert Spectrograph, and the plates obtained are evaluated on the microdensitometer previously listed. Studies are underway to develop novel sources of excitation.
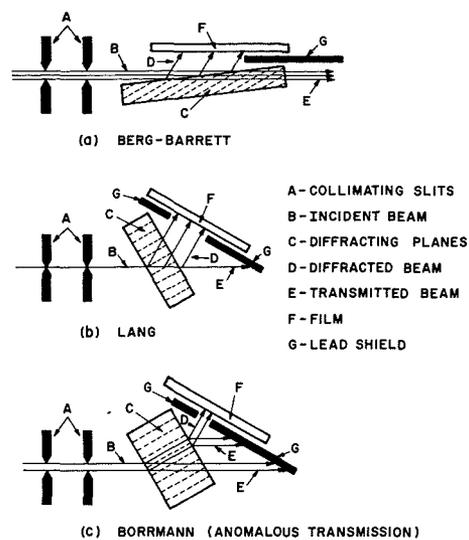
Fig. 6—The three major geometries used in x-ray topography.

A – COLLIMATING SLITS
B – INCIDENT BEAM
C – DIFFRACTING PLANES
D – DIFFRACTED BEAM
E – TRANSMITTED BEAM
F – FILM
G – LEAD SHIELD

(a) BERG-BARRETT
(b) LANG
(c) BORRMANN (ANOMALOUS TRANSMISSION)
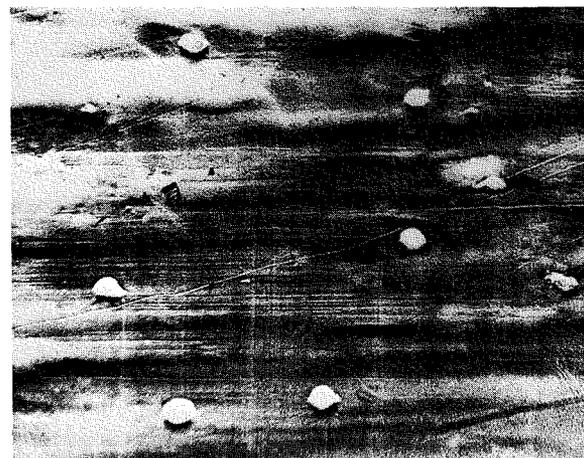
Fig. 7a—Berg-Barrett topograph of Ga(As,P) epitaxial layer on GaAs.
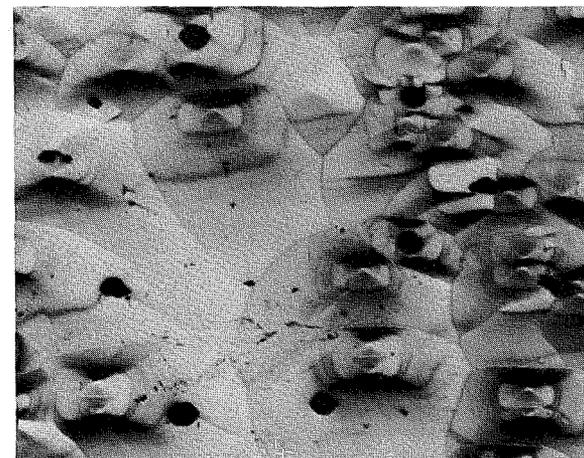
Fig. 7b—Optical micrograph of the same sample.

Atomic absorption

This is a recently developed method that has been in use at RCA Laboratories since early 1967. Fig. 11 shows in diagrammatic form the major components of atomic absorption equipment. A hollow-cathode lamp emits radiation characteristic of the cathode material chosen so as to correspond
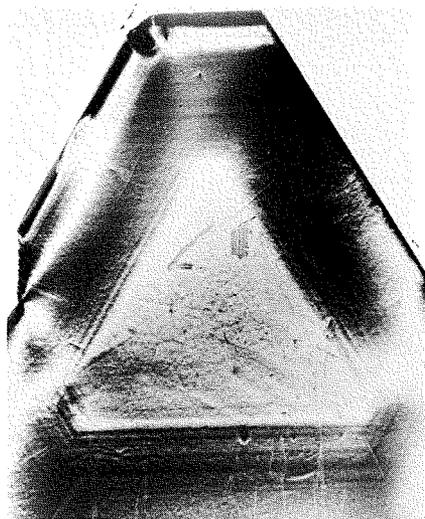
Fig. 8—Lang transmission topograph of magnesium aluminate spinel.
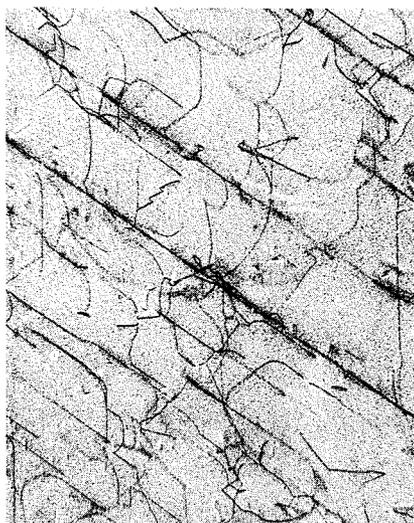
Fig. 9—Borrmann anomalous transmission topograph of Ge sample.
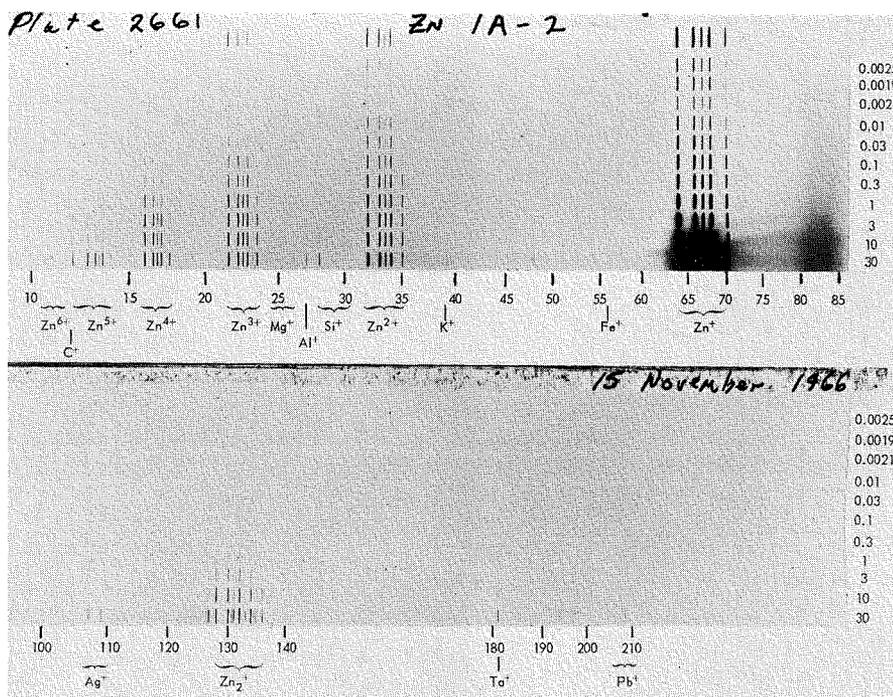
Fig. 10—Mass Spectrum of high-purity Zn sample.
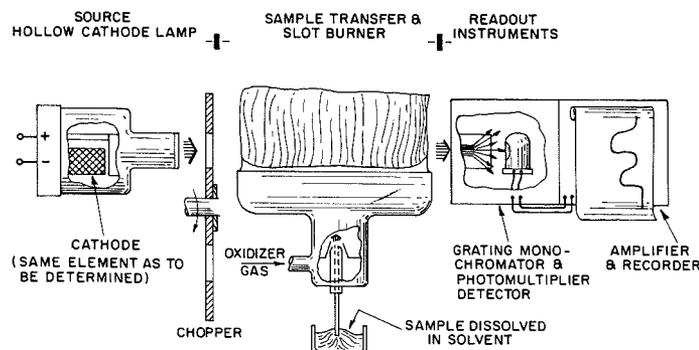
Fig. 11—Schematic view of major components of atomic absorption equipment.

to the impurity to be determined. The light emitted passes first through a chopping wheel, then through a flame produced by an oxidizer gas containing some of the sample dissolved in an appropriate solvent. A suitable line is selected in a grating monochromator, detected by a photomultiplier and phase-sensitive amplifier, and recorded. The absorption of the line intensity is proportional to the concentration of the impurity element in the sample.

Absolute concentration values are determined to ±2% or better with the help of readily made standard solutions. There are many problems formerly done by *wet chemistry* that can be handled much more quickly by this method, provided the accuracy obtainable is adequate. The equipment used in this work is a Jarrell-Ash "Model 82 500" Atomic Absorption-Flame Emission Spectrophotometer.

Wet chemistry

Major equipment available for solving wet chemical problems includes: one F&M "Model 185" CHN Analyzer, applied mainly to organic problems; one Beckman type DU Spectrophotometer for colorimetry; one Fisher Photometric Titrator; and one Micro- and one Semimicro-Balance (Mettler) located in the constant temperature/ humidity room.

Activation analysis

RCA Laboratories has facilities at the Industrial Reactor Laboratory (IRL) in Plainsboro, N.J., that make it possible to carry out studies in radiation damage, tracers, and neutron activation. The flux of *thermal* neutrons ranges from 1.5×10^{13} n/cm^2/sec at the core face to 10^{11} to 10^7 n/cm^2/sec in the thermal column. The density of *fast* neutrons at the core face is 1×10^{13} n/cm^2/sec, but drops substantially below that of the thermals in the thermal column. Activation analyses are most conveniently carried out in the thermal column. Higher detection sensivities are obtainable by irradiations at the core face, but in this case radio-chemical separations are required; there are advantages to either system. Activation analysis can be a method of unusually high sensitivity for certain selected impurities whose presence, however, must be known or suspected in advance.

X-ray fluorescence

Work in x-ray fluorescence, already mentioned in the discussion of structures and defects, is done with one of the three tubes on the Siemens Crystalloflex 4.

Automated data collection and processing

For the past four years, mass spectrographic and some x-ray calculations have been carried out via RCA-601

computer programs which were constantly improved and expanded. At present, automated data handling and processing systems based on the RCA Spectra 70 Time Sharing System, are under development which will substantially increase analytical accuracy and precision and, at the same time, reduce delays and sample cost. The reduction in delays and cost is clearly brought out in Table VI. It is clear that in the future such computer-based methods will be applied to the solution of many more analytical problems of a complex nature.

Interaction with laboratory staff and operating divisions

The effectiveness of a Materials Characterization Group is limited by its ability to communicate with the rest of the world. To select, for a given problem, the most appropriate technique and then to apply it so that optimum results are obtained in minimum time requires a full understanding of the submitted problem. To this end, a new detailed "Request for Characterization" form has been drawn up (Fig. 12) which attempts to obtain all essential information from the originator of the problem. The heading "Object of Experiment", when properly filled in, supplies the analyst with the background necessary to form an independent opinion concerning the methods best suited for the problem, and enables him to assist in the selection of the most suitable samples and parameters to be studied.

The need for "Complete Description of Sample" and "Specific Information Requested" is self-evident. After the characterization has been carried out, the analyst will fill in all pertinent results in the bottom third of the form. To encourage further inquiries and exchange of information, the name of the person to be contacted, if different from that of the analyst, is given at the bottom.

Because the volume of samples submitted always exceeds the work capacity of the Materials Characterization Group, a sample backlog builds up which is kept under constant scrutiny. To keep the backlog in any one area from growing beyond 2 to 3 weeks, the analyst must be sure that each sample submitted is significant and essential.

Fig. 12—Request form for materials characterization.

The upper right-hand corner of the Request Form is for internal use. It lists the area(s) applicable to the problem posed. and there is space to fill in estimated and actual man-hours and cost required to fully characterize the sample if this is desired by the originator.

Future developments

Which areas in materials characterization are most likely to be emphasized in the future? In part, this question can be answered by observing the trends in the types of samples submitted and of the information .requested. Thus it is quite clear that interest has shifted from bulk to surfaces and thin films, and from average composition to inhomogeneous distribution of impurities. For this reason, we are seriously considering the addition of an electron microprobe to the roster of major equipment. To check on the purity of gaseous materials used in the fabrication of thin films, a gas mass spectrometer is under construction and will soon be put in use.

Among types of materials, emphasis has shifted from elements to compounds and alloys, requiring a more accurate knowledge of stoichiometry. To this end, attention should and will be paid to improving accuracy and precision of the analytical methods employed to determine the concentration of major constituents, in particular atomic absorption and mass spectrometry.

Because there is a steady increase in sample load whereas manpower is limited, the need for automated data collection and handling via the most recent computer techniques becomes of paramount importance. The punched card system used in conjunction with the RCA-601 computer during the past five years is now being replaced by the RCA-Spectra 70 Time Sharing System which permits instant interaction between analyst and computer. This most recent system which increases accuracy and precision and, at the same time greatly reduces delays and sample costs, will be applied to many more analytical areas.

Reference

1. Materials Advisory Board Publication MAB-229-M, *Characterization of Materials* (Washington, D.C., 1967).

AWARDED TO BY THE RADIO CORPORATION OF AMERICA IN RECOGNITION OF OUTSTANDING ACHIEVEMENT IN SCIENCE

The 1968 Individual Awards for Science and Engineering

Dr. Zoltan J. Kiss, of the Materials Research Laboratory, RCA Laboratories, Princeton, N.J., recipient of the 1969 David Sarnoff Outstanding Achievement Award in Science . . . "for contributions to photochromic and laser materials."

Dr. Kiss has made important contributions to the understanding and development of new laser and photochromic materials. When he joined RCA Laboratories in 1960, he began work on lasers with emphasis on the study of new materials of potential use in such devices. Specific results of his research include three new laser materials, a sun-pumped laser, and a very efficient laser pumped by cross-relaxation—the first device of its kind. Another result of this research was a new insight into the behavior of rare-earth ions in solids, including phosphors. Recently this understanding has led Dr. Kiss to a quite different field of study, that of the photochromic properties of single crystal, inorganic materials. He discovered several new photochromic materials with greatly improved characteristics and also found a photochromic material—the first with such a property—whose state can be detected without the use of radiation. His personal studies and discoveries have led the way for the very large number of engineers and scientists at RCA Laboratories and elsewhere in RCA who are now studying photochromics and their potential for a variety of applications including data storage and display.

Dr. Zoltan J. Kiss

The 1968 Team Awards for Science and Engineering

L. A. Barton

J. A. Castellano

Dr. J. Goldmacher

Dr. G. H. Heilmeier

Dr. R. Williams

L. A. Zanoni

Lucian A. Barton, Joseph A. Castellano, Dr. Joel Goldmacher, Dr. George H. Heilmeier, and **Louis A. Zanoni,** Consumer Electronics Research Laboratory, and **Dr. Richard Williams,** Materials Research Laboratory, all of RCA Laboratories, Princeton, N.J., recipients of a 1969 David Sarnoff Outstanding Team Award in Science . . . "for basic studies of liquid crystals with imaginative ideas for their application to practical displays."

Drs. Goldmacher, Heilmeier, and **Williams** and **Messrs. Barton, Castellano,** and **Zanoni** developed a means of exploiting the electro-optic effect in liquid crystals so that for the first time the electronic control of the reflection of light is possible. In their research on the utilization of the light-modifying aspects of liquid crystals, they discovered new optical effects of particular interest for display purposes. They also synthesized the first liquid crystals to have the desired properties at room temperature. Emphasis was placed on developing materials and structures suitable for television. Applications which may be exploited more immediately are under joint development with Electronic Components, Somerville. Because of this team's work, RCA has been established as a leading center of work in the liquid crystal field, an area with great potential commercial value.

L. J. Berton

H. A. Freedman

J. A. Goodman

N. L. Gordon

J. T. O'Neil

Dr. B. H. Sams

A. H. Simon

T. M. Stiller

48

Outstanding Achievement Awards

RCA's highest technical honors, the four annual David Sarnoff Outstanding Achievement Awards, have been announced for 1969. The awards consist of a gold medal, a bronze replica citation, and a cash prize for each.

The Awards for individual accomplishment in science and in engineering were established in 1956 to commemorate the fiftieth anniversary in radio, television and electronics of David Sarnoff. The two awards for team performance were initiated in 1961. All engineering activities of RCA divisions and subsidiary companies are eligible for the Engineering Awards; the Chief Engineers in each location present nominations annually. Members of both the RCA engineering and research staffs are eligible for the Science Awards. Final selections are made by a committee of RCA executives, of which the Executive Vice President, Research and Engineering, serves as Chairman.

Edward J. Nossen, of the Defense Communications Systems Division, Camden, N.J., recipient of the 1969 David Sarnoff Outstanding Achievement Award in Engineering . . . "for outstanding individual contribution through the recognition of an unfilled need in the Apollo mission, and the invention of a novel ranging system to fulfill that need."

Mr. Nossen has made several outstanding technical contributions to radar and communications technology. Mr. Nossen was given the difficult problem of providing a backup system for crew safety, in the event of failure of the Apollo rendezvous radar—but with no room or weight available for additional equipment in the space craft. He proposed that the VHF voice radio be used also for range measurement during lunar maneuvers. Mr. Nossen invented a ranging technique based on a 3-tone ranging system capable of measuring range with accuracies to 100 feet while simultaneously achieving the required voice communications. He personally made numerous presentations to NASA, prime contractors, and astronauts, resulting in award of a non-competitive contract to RCA by NASA in October 1967. This VHF ranging system, which has since been described by the astronauts as an operational necessity, was developed and delivered to NASA far ahead of the most optimistic estimates. Mr. Nossen's efforts resulted not only in a brilliant technical success for RCA, and an important contribution to the safety of the Apollo mission, but also in the development of a very profitable area of business for RCA.

Edward J. Nossen

Leonard J. Berton, Harry A. Freedman, James A. Goodman, Nathan L. Gordon, John T. O'Neil, Dr. Burnett H. Sams, Allen H. Simon, and **Thomas M. Stiller,** all of the Data Processing Applied Research Laboratory, RCA Laboratories, Princeton, N.J., recipients of a 1969 David Sarnoff Outstanding Team Award in Science . . . "for the creation of a versatile, advanced, time-sharing system for the Spectra 70/45."

Messrs. Berton, Freedman, Goodman, Gordon, O'Neil, Simon, and **Stiller** and **Dr. Sams** have developed a computer time-sharing system which surpasses competitive systems in performance, sophistication and versatility. The team distinguished itself by its accurate assessment of the most desirable features comprising computer time-sharing systems; by its rapid response in the successful creation and implementation of the system; by its creativity in the incorporation of novel features which greatly enhanced the utility and versatility of the time-sharing system; and by the significant value the system has added and is continuing to add to RCA electronic data processing systems. The system that was created has a number of sophistications not available in other time-shared systems. These have made it possible to provide a time-shared system to potential RCA customers at a cost not achievable with other systems. Most importantly, the system is designed so that the user cannot interfere with the operation of the system or destroy other users' programs or data. The strongest testimonial to the quality of the RCA system is its acceptance by computer users. It has turned out to be an excellent sales tool for the Information Systems Division and has played a direct role in the number of Spectra 70 sales.

H. Ball

F. B. Lang

C. D. Boltz, Jr.

R. K. Lockhart

L. A. Briel

T. Wagner

J. Hugh Wharton

Messrs. Henry Ball, Lewis A. Briel, and **Theodore Wagner,** of the Commercial Electronic Systems Division, Burbank, Cal. **Messrs. Charles D. Boltz, Jr., R. Kennon Lockhart,** and **J. Hugh Wharton,** of the Consumer Electronics Division, Indianapolis, Ind., and **Mr. Frank B. Lang,** of the Astro-Electronics Division, Hightstown, N.J., recipients of the 1969 David Sarnoff Outstanding Team Award in Engineering . . . "for excellence of team effort and interdivisional cooperation leading to the rapid development of a low-cost, single-tube, color television camera."

Messrs. Ball, Boltz, Briel, Lang, Lockhart, Wagner and **Wharton** have made an outstanding new contribution to the development of color camera technology. Specifically, they carried out the engineering work on an important technical breakthrough and its subsequent exploitation via the design, development and public demonstration of a major new product in less than one year. While most commercial television cameras require at least three tubes, this new camera requires only one tube and utilizes an entirely new technology. It employs a stripe filter technique—fundamentally, an 'area sharing' system—to encode the color information in the form of alternating brightness values. The major significance of this development is that it literally cuts in half the cost of any existing color television camera, thus opening up hitherto unreachable opportunities in the educational, industrial and cable television markets. The greatly lower costs of the new RCA camera should thus have far reaching effects on color television's growth, as well as enhancing RCA's competitive position.

49

Reliability incentive contracts: cost effectiveness tradeoff analysis

E. J. Westcott

This paper reviews a typical military procurement containing performance incentive-fee provisions. Customer requirements are evaluated and transformed into suitable quantitative indices to permit a detailed analysis of alternatives; thus a basis is provided for selecting the best alternatives to achieve maximum results in accordance with customer's desires and, secondarily, maximum incentive fees. The techniques utilized in the development of the cost alternatives are described to provide an insight into influences on product behavior.

E. J. Westcott, Mgr.
Systems Assurance
Defense Communications Systems Division
Camden, N.J.
received the BS in Engineering from the American Institute of Engineering and Technology in 1949 and the MS in Electrical Engineering from Drexel Institute of Technology in 1963. He joined RCA in 1952 as a Field Engineer and was assigned as a Technical Representative with the Strategic Air Command. From 1956 to 1960 he performed Reliability and Maintainability Analyses on the Talos Land Based Weapon System and the Atlas Missile System. In 1961 he was transferred to the Surface Communications Division where he was promoted to Engineering Leader. He was responsible for all RCA Minuteman Systems Testing and Evaluation. He directed the Environmental, Reliability and Electromagnetic Qualification Test Programs for the Minuteman System. He was made Manager of Systems Assurance Activity in 1966 and was responsible for Defense Communications System Division Reliability, Maintainability, Human Factors and Systems Testing Programs. He is currently on special assignment as Manager of the Integrated Logistic Support System for the Advanced Surface Missile Ship Program. He is a memer of the IEEE and is active with the group on Reliability.

R ECENT GOVERNMENT PROCURE-MENTS have contained incentive fee provisions based on contractor performance within stated cost, schedule and reliability objectives. Since customer objectives are not always stated in a form which permits rapid assessment by management personnel, treatment of the requirements is necessary to provide sufficient visibility to enable decision making.

Typical requirements

A typical set of customer cost, schedule, reliability incentive fee requirements for large-scale production of a previously designed digital equipment (box A and box B) are summarized as follows:

Fixed price incentive fee contract
Fee maximum +20%: Overrun/underrun cost-sharing (customer 70%/contractor 30% up to maximum of 12% of contract value for the difference when contractor bears 100% burden).
Reliability incentive: plus $600K to minus $236K (Scale adjusted by number of relevant failures occurring on test samples during qualification and production testing.
Schedule incentive: Implicitly related to reliability incentive cumulative test time for fixed number of units to be placed on test each month and the number of failures permitted are based on rate of production delivery.

The problem confronting industry on such a procurement is to determine the degree of reliability achievable within the confines of the cost of enhancement vs. the economic return (increased fee).

Analysis of the reliability incentive parameters enable the proposing contractor to measure and respond to the real desire on the part of the customer to have the product improved.

These data can be interpreted in the following manner. If the initial equipment design is sound (i.e., electrical performance is achievable; parts selection and application is within good electrical, thermal and environmental design practice; and if the same degree of quality workmanship is expended in the fabrication and manufacture processes), then, the equipment can be reasonably expected to exhibit the same degree of reliability as that previously demonstrated by the developmental units. Since it is hypothesized that the foregoing is a reasonable conclusion, we can infer that the rewards (incentive fee for reliability) are being furnished by the customer for a definite improvement. It follows that a zero incentive reward is to be furnished to the contractor who produces the equipment as prescribed by the customer's specification. It also follows that a negative reward (penalty) is to be imposed on the contractor who tries to improve his profit by cutting corners in the procurement of parts and materials and who does not maintain adequate quality control over manufacturing processes and workmanship.

Reliability fee incentives

The customer-established, qualification-fee incentives (Fig. 1) are applicable during initial qualification testing of nine equipments (box A and box B) for a cumulative test time of 17,000 hours. The fee is greatest for the small-est number of failures and decreases in an exponential manner as the number of failures increases.

A similar set of customer established fee incentives applicable during production testing are presented in Figs. 2 and 3.

Analysis of the reliability incentive fee schedule (Figs. 1, 2, and 3) at the breakeven point (zero fee) provides confirmation of the belief that the customer is providing some latitude in the behavior of equipment being produced as prescribed by his specification. In Fig. 2 it is apparent from the band of acceptable number of failures (box A from 31 to 41) that the customer will not penalize a 14% degradation and will not reward a 14% improvement. This is consistent with the fact that we are dealing with a random process and some variation in observed reliability is expected even though materials and workmanship remain constant. This wide band of no-change in reward/
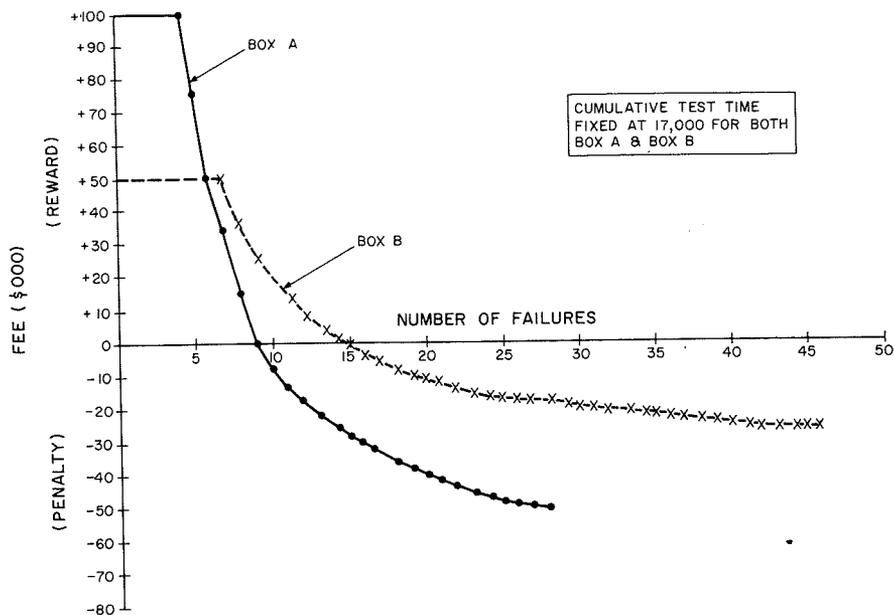
Fig. 1—Fee vs. failures (qualification tests).

penalty acts to desensitize the payment of fee as a function of good fortune and extraction of penalty as a function of bad fortune.

Since we are concerned with the ability of an equipment to meet the customer objectives, the data in Figs. 1, 2, and 3 must be converted into design parameters with associated risk. Referring to Fig. 1, we must ask ourselves what incentive fee we can expect from any change in equipment MTBF. The least fee that can be expected is related to the maximum expected number of failures for the MTBF. The maximum expected number of failures is that number for which there is a 50% probability of achieving that number or fewer.

Since we are dealing with a Poisson process this type of problem is similar to that of determining the probability of x or more defects occurring in n trials. The Poisson summation is

$$P(c,a) = \sum_{x=c}^{\infty} \frac{a^x e^{-a}}{x!} \qquad (1)$$

where: x=number of defects; $a=np$; c=number of times event occurs; b= fraction defective; and n=random sample size.

This summation is the limit of the Binomial Summation

$$P(c,n,p) = \sum_{x=c}^{n} C_{n}^{x} p^x (1-p)^{n-x} \qquad (2)$$

Eq. 2 yields the probability of the event happening at least c times in n trials. Eq. 1 tabulated by E. C. Molina, was

utilized to transform the customer requirements (fee vs. number of failures) into a series of graphs depicting the risks of alternatives (expected least fee vs. MTBF). We proceed as follows:

Given a fixed test time of 17,000 hours; $P=0.5$, at breakeven (zero fee); and c=nine (9) failures.
To solve for a, using Molina's[1] tabulation (Table II), we find that the breakeven (zero fee) can now be calculated by dividing the fixed test time by the value of a. The MTBF for Box A is determined to be 1750 hours. Proceeding in a like manner points may be found for various MTBF values and with other selected probabilities. A family of these curves are generated (Figs. 4 and 5) to provide visibility in establishing the bounds for design analyses.

Methodology

A study was conducted, including an analysis of the previously designed equipment: parts lists, failures rate predictions, estimated parts stress levels, estimated parts costs, the prototype Equipment reliability demonstration test results and equipment failure history during the R&D Program. In addition to the foregoing, analysis was performed on the failure trends being encountered in existing programs for parts identical and/or similar to those utilized in previously designed equipment.

During the course of the study it became necessary to analyze additional data such as: parts screening techniques, parts burn-in techniques, board burn-in techniques and manufacturing practices employed in existing pro-

grams in order to evaluate results and develop recommendations for employment of additional (expanded) techniques and improved practices and controls to: yield greater reliability, reduce the number of defects encountered during board- and end-item testing, and reduce failures due to workmanship during the fabrication process.

Ground rules

During the study the following ground rules were employed: The equipment parts lists and part specifications were evaluated and candidate parts were selected which had corresponding form, fit and function and had previously exhibited lower failure rates and/or were undergoing reliability improvement programs to enhance their reliability.

The following features of the prototype (previously designed) equipment reliability predictions were used as baseline for improvement: The parts count used in the prediction was used as the basis for analysis. The prototype equipment predictions were used as baseline for reliability improvement.

The relative improvement shown for prediction was used as the expected improvement factor for production equipment demonstration, as related to the prototype equipment demonstration results. The cost effectiveness criterion for evaluation of part types was to maximize reliability improvement per dollar.

Analysis and tradeoffs

To establish the cost effectiveness of enhancing the reliability of the baseline design an analysis of the qualification and production program reliability cost incentives was performed. The reliability cost incentive data were converted (Figs. 4, 5, 6, and 7) into a form which provides visibility for decision making. The plotted curves present the probability of attaining fee for an equipment with an inherent design MTBF.

In establishing the breakeven point for fee (zero fee) in terms of the number of failures permitted, the customer has established an MTBF requirement of 1750 hours (box A) and 1080 hours (box B). In other words, if the box A design is capable of meeting a 1750 hour MTBF then nine such equipments

51

Fig. 2—Fees vs. failures (box A production test).

Fig. 3—Fee vs. failures (box B production test).

Prototype equipment test results showed that the box A configuration had accumulated 10,095 total test hours and experienced six relevant failures while the box B configuration accumulated 10,055 total test hours and experienced ten relevant failures. The MTBF calculated for box A was 1685 hours and 1,005 for box B. Projections were made for comparison of the box A and box B MTBF's at the 50% confidence level (break-even) and these were calculated to be approximately 1750 hours and 1080 respectively. It should be noted that a total of 16 relevant failures occurred during the prototype reliability demonstration test program.

Analysis of prototype equipment reliability prediction

The prototype equipment design and reliability predictions were reviewed to determine the relative failure contribution of the various part types. The high failure rate contributors were resistors, diodes, integrated circuits, capacitors and transistors for both configuration box A and box B. Each of the foregoing part types was analyzed in detail in order to develop a list of part type candidates which have similar form factors and improved reliability characteristics. Effort was concentrated upon capacitors and resistors in view of their considerable contribution to equipment reliability, and the relatively low cost of parts having considerably better reliability than those used in the prototype equipment. Of the known possible replacements, those for resistors and capacitors appeared to be most cost effective. Cost estimates were obtained for the initial part type and the recommended part candidate and the information was utilized to determine the total cost impact for reliability improvement.

subjected to a 17,000 hour test have a 50-50 chance of meeting the reliability objective and the contractor, would, in turn, receive a zero fee (no penalty/no gain). This incentive feature is more readily observed by entering Fig. 4 at an MTBF value of 1750 hours and zero fee and noting that the point of intersection meets the 50% probability curve. Fig. 5 indicates the expected incentive fee for box B versus demonstrated MTBF. Proceeding in this manner we can now establish the increased amount of fee attainable for various improved design (MTBF enhancement).

Figs. 6 and 7 illustrate expected incentive fees versus demonstrated MTBF for box A and box B during production.

It should be noted that while the actual fee schedules for qualification and production incorporate discrete fee-failure relationships, investigation of reliability improvement requires probability analysis, since no guarantee can be given of the number of failures occurring in tests for any given MTBF. For this reason, it was decided to use "expected fee" in making decisions whose value may fall between actual fee increments. Although a specific margin of reliability improvement may not be sufficient to increase "expected fee" by a full increment, it still is favorable in that it provides greater surety of any increments.

Table I contains a summary of fee attainable vs. MTBF achieved for boxes A and B. With this information we are now in a position to examine the maximum amount of investment consistent with maximizing attainable fee.
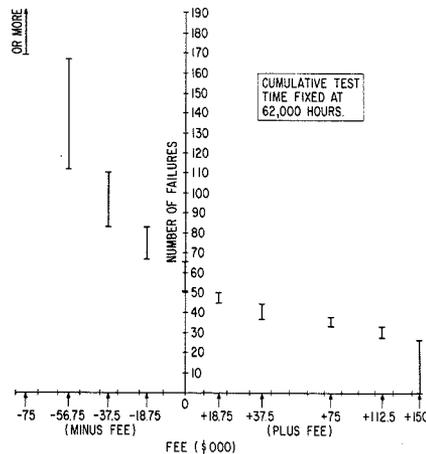
Table I — Attainable fee versus achieved MTBF.

			Box A			
MTBF	1750	2100	2250	2800	3250	3700
Qualification fee (K$)	0	22.5	33	65	85	100
Production fee (K$)	0	37.5	75	150	225	300
Total fee (K$)	0	60	108	215	310	400
			Box B			
MTBF	1080	1310	1500	1750	2050	2500
Qualification fee (K$)	0	8	15	26	40	50
Production fee (K$)	0	18.75	37.5	75	112.5	150
Total fee (K$)	0	26.75	52.5	101	152.5	200

The prototype equipment reliability predictions, reliability demonstration, parts lists, part costs and available parts stress design constraints were analyzed and a list of candidate parts with more desirable reliability characteristics was developed. After screening this candidate list with the design group the list was submitted to purchasing to obtain a cost differential between the baseline parts and the candidate parts. A reliability prediction was made for these part types and, in turn, scaled to the reliability demonstration data to determine the degree of reliability improvement attainable.

Prototype equipment reliability demonstration test results

An analysis was performed of the prototype equipment reliability demonstration test results for the purpose of establishing the box A and box B demonstrated MTBF numerics at 50% confidence for comparison to the production program reliability incentives. The types of failures which occurred during the demonstration tests were also reviewed to ensure against recurring during the production Program.

Reliability improvement analysis

The cost effectiveness of reliability improvement was evaluated by estimating the improvement in mean-time-between failures and the cost of the high-reliability parts to achieve it, then this additional cost was compared with the expected increase in reliability incentive. The cost incentive provisions of the anticipated contract were not initially considered. Intentionally exceeding contract cost targets was not
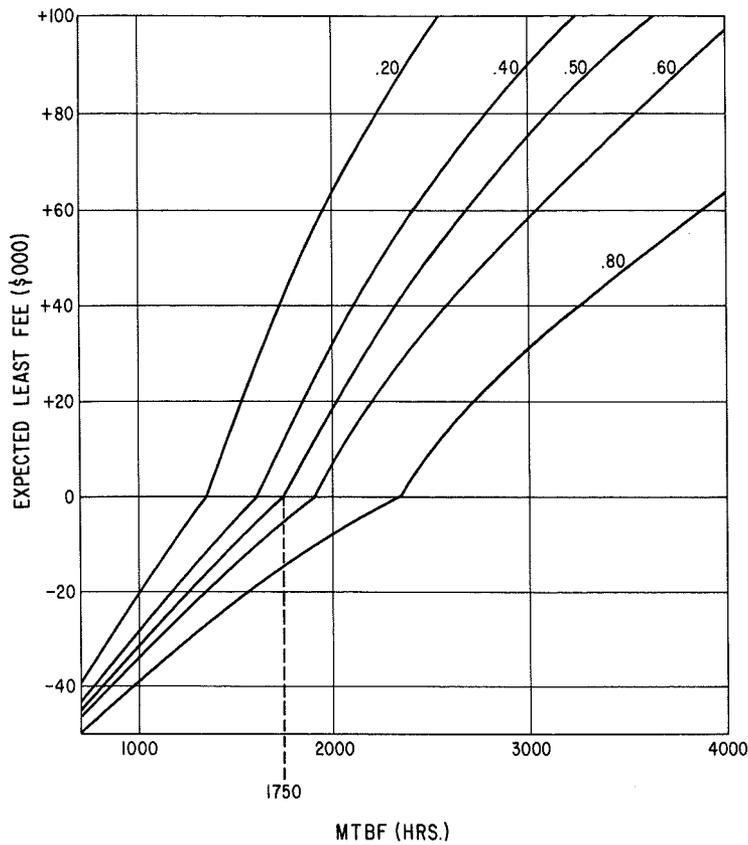
Fig. 4—Expected least fee vs. MTBF for various levels of confidence.
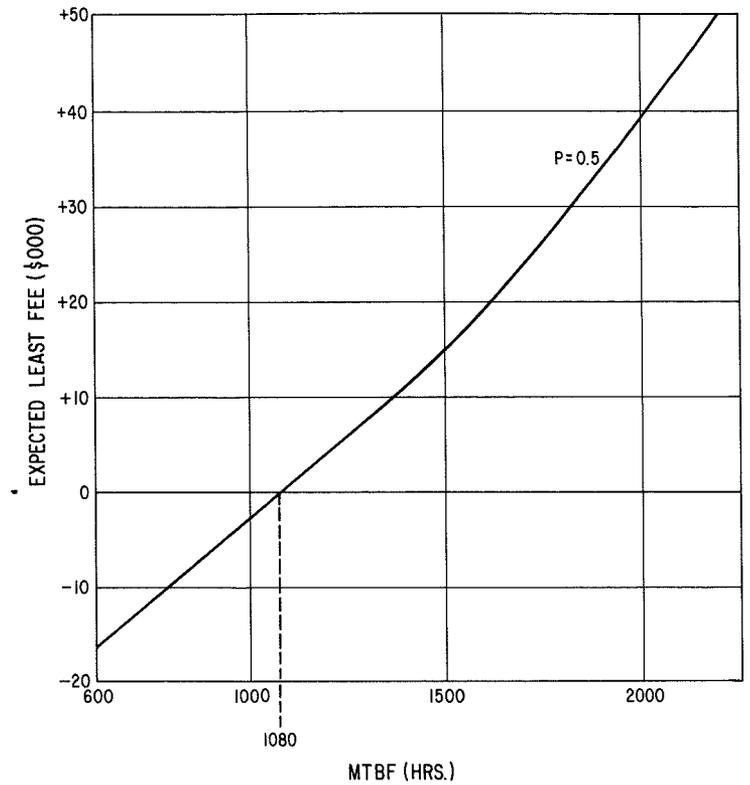
Fig. 5—Expected least fee vs. MTBF at 50% probability.
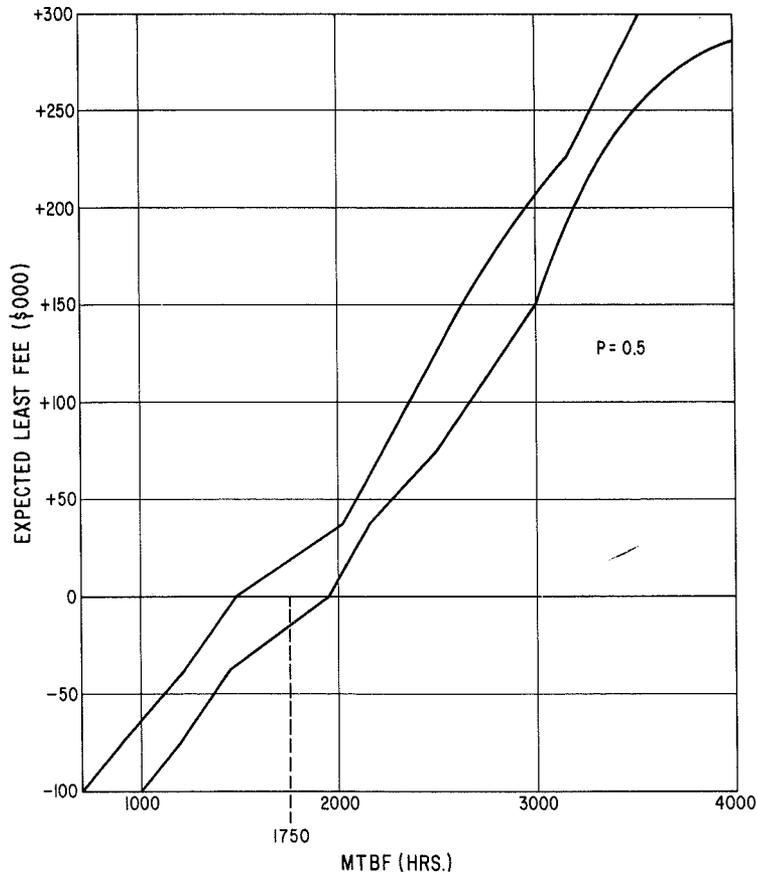
Fig. 6—Expected least fee vs. MTBF for various levels of confidence.
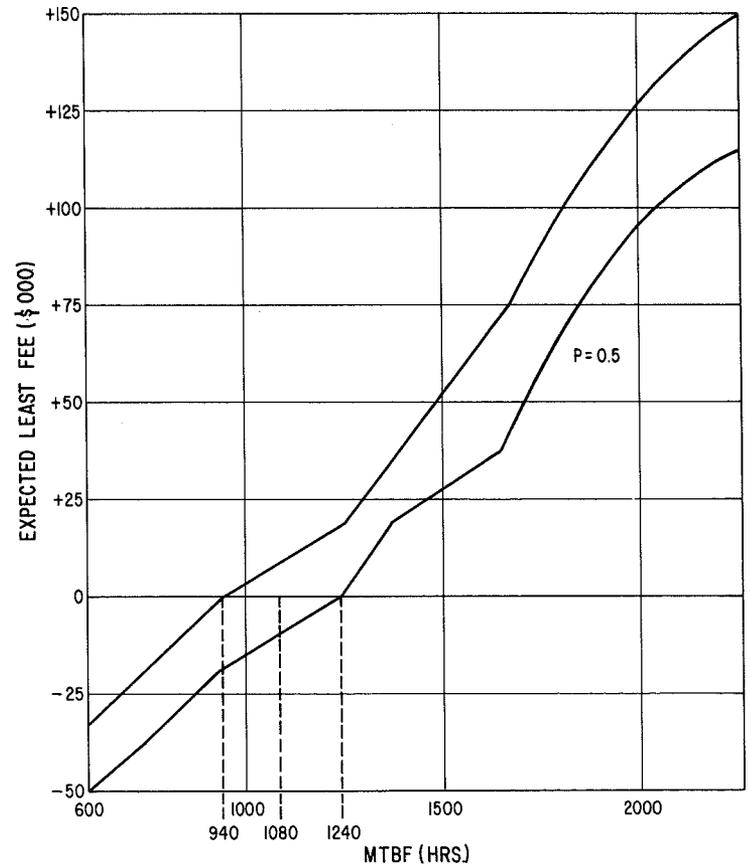
Fig. 7—Expected least fee vs. MTBF for various levels of confidence.

considered an acceptable approach to recommend to management, except where the overrun could be well-defined, and where high confidence is held that favorable results would occur from planned cost overrun. Additionally, if improvement were shown cost effective against only the reliability incentive, the advantage would appear to be clear.

Each high population part type was investigated to determine whether a more reliable alternative part might be available. This investigation involved only five integrated circuit types, but nearly all capacitors and resistors. The reason for this disparity lay in the cost of reliability improvement, smallest for capacitors and resistors, primarily due to initially lower costs per unit, and comparable failure rates. Each proposed alternative was investigated to eliminate those obviously incompatible with physical or electrical requirements of the prototype design. Remaining parts were evaluated for relative reliability improvement, and cost impact on the production program for all applications of the parts in box A and box B. Reliability improvement was estimated by comparing failure rates of original parts from prototype equipment reliability predictions with failure rates of the alternative parts under the same stress conditions. The expected change in equipment failure rate was compared with the prototype equipment prediction, to develop a *relative* improvement. This relative improvement was compared with the prototype equipment reliability demonstration results, to estimate expected production equipment demonstration results, and the concomitant reliability incentive. This incentive is compared with the total program cost of all alternative parts, less the cost of their original counterparts.

It may be possible that maximum short-term gain would accrue through equipment cost reduction, resulting in expected cost underrun and less reliability than demonstrated by the prototype equipment. This approach was not pursued.

Since the impact of reduced reliability could be expected to impair the contractor's image with the customer which could result in poor prospects for future contracts from the same customer.

Table II—Incentive fee improvement vs. reliability improvement.

	Box A				Box B			
MTBF	1750	2200	2300	3300	1080	1400	1450	2000
Qualification fee (K$)	0	44	56	88	0	11	13	39
Production fee (K$)	0	75	115	235	0	27	32	110
Total fee (K$)	0	119	171	323	0	38	45	149
Hi-rel resistors	0	95	—	95	0	—	45	45
Hi-rel capacitors	0	—	168	168	0	61	—	61
Total (K$)	0	95	168	263	0	61	45	106
Net fee gain (K$)	0	24	3	60	0	23	0	43

Conclusion and recommendations

As a consequence of this analysis it was found that the use of Hi-Reliability capacitors and resistors for reliability improvement is cost effective and results in higher fee return (Table II).

It is evident from the Table III that the fee return for reliability improvement can be sufficient to offset the cost of improvement, even when this cost is subtracted directly from the incentive fee. Table III clearly shows that maximum net fee gain is attained when the MTBF's of boxes A and B are 3300 and 2000 hours, respectively. This arrangement would in turn yield a net fee gain of $60,000 plus $43,000 for a net total of $103,000.

There is an additional source of cost available in compensated cost overrun less the penalty in cost incentive. The real cost of reliability improvement is not an equal reduction in fee.

The proposed contract has implicit provisions for cost-sharing the improvement program. If the reliability improvement program should result in a cost overrun, the reduction in fee as a result is only 30% of such overrun, even without a scope change which may be justified by the improvement program. With the improvement tabulated in Table II, the net fee gains would be as shown in Table III.

Table III—Net fee gains for alternate designs.

	Box A			Box B		
MTBF	2200	2300	3300	1400	1450	2000
Program cost increase (K$)	95	168	263	61	45	106
RCA cost share (K$)	29	50	79	18	14	32
Reliability incentive fee (K$)	119	171	323	38	45	149
Net fee gain* (K$)	90	121	244	20	31	117

*12% overrun not exceeded

Management should review the cost incentive schedule to determine whether total fee can be maximized by planned cost increase. Another alternative to be reviewed by management is to increase baseline proposal cost to accommodate the cost of some degree of reliability improvement. If an affirmative decision is reached, a further decision is necessary regarding the degree of reliability improvement to be incorporated, and the consequent addition to baseline cost. The risk of this action is the possibility of not being as cost competitive as with the original baseline cost.

In addition to the above there are cost savings which can be achieved during contract performance by having more reliable devices which result in fewer trouble-shooting actions and fewer production interruptions and result in greater fee returns and greater customer confidence and satisfaction.

It is further recommended that the following tasks be implemented after such a production contract acquisition.

Proposed tasks

1) Perform detail stress analysis in order to detect unusual parts applications and recommend design changes to enhance reliability through parts application techniques.
2) Establish board repair and rework criteria and develop procedures which protect the inherent reliability of the board and assembled piece parts.
3) Establish touch-up criteria and develop procedures which protect the inherent reliability of the board and assembled piece parts.
4) Establish parts handling controls and develop procedures to protect the inherent reliability of the piece parts.
5) Establish procedures which delineate inspection methods and analysis requirements for all discrepant, rejected, dropped, reworked, repaired, touched-up materials and parts.
6) Perform detail worst case circuit analysis in order to recommend design changes which would improve reliability by enabling circuit performance with greater part parameter variation or enabling the selection of parts with less parameter variation.

Reference

1. Molina, E. C., *Poisson's Exponential Binomial Limit* (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1942).

Failure-mode analysis

F. E. Oliveto

Failure-mode evaluation techniques may be applied effectively in system design and product assurance activities. Examples and descriptions are given in this paper, with companion tables, of the analysis of components, circuits, and systems.
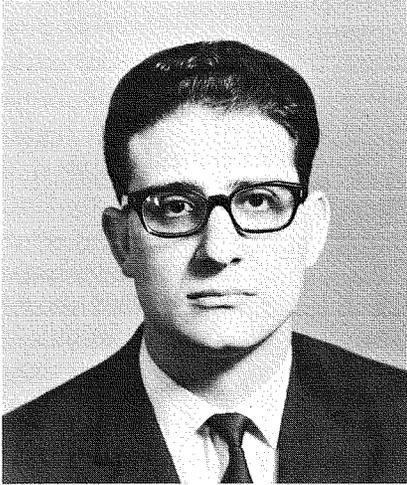
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received the BS in Electronic Physics from St. Joseph's College in 1958 and the MS in Probability and Statistics from Villanova in 1968. From 1956 to 1958 he was a cooperative student at the Burroughs Research Center. In 1958 he joined the Advanced Development Department in the Electronics Division of the Westinghouse Electric Corporation as a Design Engineer, working on the development of new applications of transistorized circuitry in adverse and exotic environments. In 1960 he joined RCA Communications Systems Division, and was assigned to the Minuteman Program as a Project Engineer. In this capacity, he participated in the reliability predictions, failure mode analysis, statistical and probability techniques, chaired the design review program, and was especially concerned with problems of circuit stability over long intervals of time. Also, he was responsible for the development of techniques that made possible prediction of circuit operations over three-year intervals, taking into consideration parameter drift and degradation. He is presently working on a systems reliability analysis research program. The program consists of determining the utmost equation or methods for reliability systems. After establishing the best equations or methods, the above is programmed into a computer in order to afford better accuracy, speed, and availability for future utilization. As a result of this research, the reliability department is now able to perform the specific tasks more quickly and accurately. The ultimate goal, is to further improve the reliability department through the use of state-of-the-art techniques. Mr. Oliveto has presented technical papers both nationally and internationally. Mr. Oliveto is a member of IEEE and a group member on Reliability, Circuit, and Component Parts. He is also a member of the International Platform Association and is listed in Who's Who in the East and the Community Leaders of America.

FAILURE-MODE ANALYSIS can be used to determine the manner in which a device fails; such analysis may be performed at various levels in a system, subsystem, or individual circuit. Whatever level one chooses for evaluation, the functional failure-mode characteristics are determined by utilizing the output states of each *element* in accordance with the failure mode of the element either *open* or *short*.

The failure effect of each component upon the element output is determined by assuming a single failure of components in either the open or short modes; *catastrophic failures* which tend to make the component either fail in the open or in the short mode. *Parameter drift failures* are not considered since their random nature involves a radical drift of one or more parameters of the part; when this drift is an increase, it is assumed that the effect will be toward an open mode, while a decrease assumes that the effects will be toward the short mode. Based on these criteria, the percentage parameter drift is distributed proportionally to the open and short modes. Since drift is more noticeable in linear than in digital circuits, it is recommended that drift be considered in a failure-mode analysis to provide a more realistic condition. Combined (multiple) component part failures are not covered in this paper, because of the small probability of occurrence compared to single failures.

In addition to analyzing the element of a catastrophic failure for each component part, the failure-mode study technique evaluates the part or element from the following aspects:

1) Proper usage, necessity, and criticalness of operation
2) Optimum circuit performance and criticalness to the entire system.
3 Total system performance . . . any malfunctions, misuse, and safety which would affect performance of intended functions.

Failure-mode evaluation

The failure-mode evaluation technique analyzes and evaluates the circuit, subsystem, or system for each correct input

to determine the output. The failure-mode technique can be used as follows:

1) Evaluate performance of any element: system, subsystem, individual circuit or part.
2) Determine probability of success or failure of a particular element.
3) Plan safety precautions.
4) Perform realistic reliability predictions.
5) Perform maintainability evaluation.
6) Do logistics planning.

To utilize the failure-mode technique, the specified correct input must be applied to the element. A true output is defined as a concurrent correct output for a specific input while a false output is defined as a concurrent incorrect output for a specific input. Thus, an incorrect output indication means that the element is not functioning as expected for a given input. Conversely, a correct output indication means that the element is apparently functioning as expected for a given input. Obviously, either of these circuit outputs may constitute logical 1, logical 0, or any possible voltage state depending upon the input and the expected output.

Typical example

The technique described here is applicable to either a circuit or a system. A two-input gate circuit is used as an example (Fig. 1). The basis for success is that a circuit operates properly when the correct design circuit is given, while a system operates properly when the intended function is performed.

The two-input gate (Fig. 1) provides either of two outputs; binary 0 (-6 volts) or binary 1 (0 volts). The two states of the transistors, i.e., non-conducting (binary 0) and conducting (binary 1) are investigated.

For binary 0 output, the following conditions must exist:

1) V_{in} (input voltage) is zero.
2) Transistor Q_1 is not conducting, therefore, output is -6V.

For binary 1 output, the following conditions must exist:

1) V_{in} is -6 volts.
2) Transistor Q_1 is conducting, therefore output voltage is zero.

Tables I and II are a general format utilized in the derivations of the various aspects of the failure-mode evaluations; columns 1, 2, and 4 are self
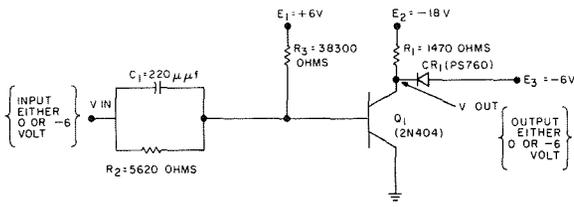
Fig. 1—Two-input gate.

explanatory. [*Editor's note:* As a supplement to Tables I and II, the failure modes and their associated probability of occurrence are available from the author and are listed for nearly forty difference components grouped in convenient categories. Values are based on nominal application and are convenient references for both circuit and system analysis; this information was originally included as Appendix A of this paper.]

The percentage allocations for the open and the short modes given in column 3 of Tables I and II are obtained from various sources such as field data, laboratory test data, results of surveys of available data from technical publications, and user references. In the absence of such data, the engineering experience and judgment of parts specialists helped to establish the percentage probability allocated to open or short modes.

Since each component part has at least two connections to its respective board, a solder joint adjustment is given in column 5. Such connections have a known probability of breakage that disconnects the part from the cir-

cuitry and represents a part failure in the open mode.

The output of the element (column 6) is indicated with correct and incorrect statements. When the output is proper for a specified input, an "X" is placed in the correct statement and in the same manner, when an output is not proper for a specified input, an "X" is placed in the incorrect statement.

Each column of correct and incorrect statements is added to determine the sum of probabilities of failure according to the expected failure behavior (open or short) of each component part in the circuit. The total of these two columns in column 7 is equal to the failure probability of the circuit. Now, examine the application of each of the uses of the failure-mode technique to specific problems in system analysis.

Performance evaluation of any element

Self-testing: The most desirable circuit procedure incorporates 100% self-test circuit features; usually, this does not occur because of cost, weight, and schedule considerations. Therefore, one must determine which circuits and how many should be tested in a system.

Considerations of cost, weight, and schedules usually impose a ground rule that perhaps 80% of the circuits can be tested within system constraints; from this, one must determine which circuits should be tested and included in the 80% category. By using failure-mode analysis, the circuits for system self-testing can be chosen by two criteria: criticalness, and high probability of failure.

Criticalness means the relative importance of a circuit to the intended function of the system. Suppose that a specific circuit fails and thus, the system cannot accomplish its intended mission. Such a circuit is considered critical and the self-test system features should include the circuit.

An example of criticalness would be represented by a power supply failure; the system would have no power to operate.

High probability of failure is defined as the probability of system failure caused by the failure of each individual part in any of its possible modes of failure. When the probability is

known for every system circuit, the figure can be used as a guide to determine which circuits should be included for the objective self-testing procedure. For example, assume that a choice must be made between equally important circuits to be self-tested; the failure-mode analysis determines, the relative probability of each circuit. Suppose one circuit has the probability of failure of 95% (if any of its parts fail catastrophically either in the open or short mode) but the second circuit fails only 80% of the time (if any of its parts fail catastrophically either in the open or short mode); thus, it is evident that the circuit with the higher probability of failure should be chosen for self-testing. How this relative probability of the circuit failure is obtained will be explained later.

Fail-safe is a condition where part of a system fails catastrophically in the open or short mode, yet the intended function of the system is maintained so that no inadvertent operation of the system occurs. Failure-mode evaluation determines whether the system fails safe if one of the components fails catastrophically in the open or short mode. One can also determine the components whose catastrophic failures contributed to inadvertent operation such as inadvertent launch of a missile.

Circuit evaluation

Failure-mode evaluation techniques can also be applied to individual circuits or parts; for circuit evaluation, this technique can indicate:

1) Any errors in the circuit overlooked by the designer.
2) Excess parts not necessary to perform the intended function properly (such parts can be eliminated).
3) Circuit simplification by using fewer parts or by some other arrangements.
4) Need for compensatory provisions to overcome difficulties caused by a part failure where the probable part failure mode is uncovered. This might be compensated through redundance of parts, minimization or reduction of harmful destructive effects and extreme environmental conditions, reselections of parts, alteration in design to eliminate a mode of failure, or the installation of warning devices, circuit breakers, fail-safe mechanisms, interlocks, or failure isolation mechanisms.

Failure-mode techniques applied to individual circuit parts can indicate: 1) where better quality parts should be

Glossary of terms

Failure-mode analysis is a determination of the manner in which a device fails.

An *element* is a component part, circuit or subsystem.

Open or *fail open:* a discontinuity or a break that occurs from external or internal causes in the continuity of a component part, and causes an incomplete path for current flow.

Short or *fail short:* an abnormal connection (internal or external) of relatively low resistance, whether made accidentally or intentionally, between two points of different potential in a component part or a circuit.

A *parameter drift failure* is of a random nature and involves a radical drift of one or more parmeters of a part.

Catastrophic failure is characterized by sudden and drastic occurrences. Included in this category are opens, shorts, or other radical departures from initial characteristics. Failures occur in an unpredictable manner, and in too short a period of time to permit detection through normal preventive maintenance practices. The catastrophic failure can be the result of an accidentally inflicted damage or some hidden defect. It is complete, usually obvious, and unpredictable with respect to the time of its occurrence.

A *critical failure* results when the intended function can no longer be accomplished, e.g. a missile launch or a satellite in orbit.

A *major failure* results when the primary function is accomplished, but some of the major capabilities essential to the system overall performance are impaired.

A *minor failure* results when the intended function or major capabilities are not impaired by some minor malfunction. Without them only a slight degradation of performance would be noticed, and the primary operation or major capabilities would not be lost.

The addition theorem

1) If two events can occur simultaneously, the probability that either A or B or both A and B will occur is

$$P(A \vee B) = P(A) + P(B) - P(A) \cdot P(B)$$

2) If the two events are mutually exclusive so that when one occurs the other cannot occur, equation (1) simplifies to:

$$P(A \vee B) = P(A) + P(B)$$
Since $= P(A) \cdot P(B) = 0$

For the purpose of the failure-mode analysis, the second equation was chosen, since multiple failure will not be considered. The probability of both A and B occurring is equal to zero, thus the events to be considered are mutually exclusive and equation number 2 is used:

$$P(A \vee B) = P(A) + P(B) \text{ or}$$
$$P(A \vee B \vee Cv \ldots Vn) =$$
$$P(A) + P(B) + P(C) + \cdots + P(N).$$

Table I—Input (V_{in})=0; output (V_{out})=−6; and Q_1 not conducting.

Column 1 Component parts (number & type)	Column 2 Component parts failure rate (λ in part per million MIL-HDBK-217A used)	Column 3 Component parts failure modes and associated probability of a occurrence of each mode	Column 4 Component parts failure probability due to failure mode product of cols. 2 & 3	Column 5 Solder joint adjustment factor	Column 6 Output description Correct	Incorrect	Column 7 Failure rate according to output description Correct	Incorrect
R_1 (MIL-R-22684) Fixed Film	0.125	Open (0.98)	0.122500	0.122501		x		0.122501
		Short (0.02)	0.002500	0.002500		x		0.002500
R_2 (MIL-R-11) Composition	0.0035	Open (0.93)	0.003255	0.003256	x		0.003256	
		Short (0.07)	0.000245	0.000245	x		0.000245	
R_3 (MIL-R-22684)	0.125	Open (0.98)	0.122500	0.122501	x		0.122501	
		Short (0.02)	0.002500	0.002500	x		0.002500	
C_1 (MIL-C-11015) Ceramic	0.0050	Open (0.05)	0.000250	0.000251	x		0.000251	
		Short (0.95)	0.004750	0.004750	x		0.004750	
CR_1 (MIL-S-19500) Silicon	0.140	Open (0.05)	0.007000	0.007010		x		0.007010
		Short (0.95)	0.133000	0.133000	x		0.133000	
Q_1 (MIL-S-19500) PNP Ge≤1W	0.550	B-Open (0)	0.0000000	0.0000005	x		0.0000005	
		E-Open (0)	0.0000000	0.0000005	x		0.0000005	
		C-Open (0)	0.0000000	0.0000005	x		0.0000005	
		C-E-Short (63)	0.3465000	0.3465000		x		0.3465
		C-B Short (37)	0.2035000	0.2035000		x		0.2035
TOTAL				0.9485155			0.2665045	0.682011

used to improve the circuit probability of success, and 2) the quantity and quality of spare parts required to assure proper performance of the intended function.

Probability of element success of failure

To estimate the relative probability that a given circuit will fail in the output-correct or in the output-incorrect modes, upon the occurrence of failure, it is necessary to add all of the failure rates for the mode considered for a given input. (In system reliability calculations, the basic *addition theorem* rules of probability are used). The ratio of this sum to the total failure rate is the relative probability of failure (upon failure occurrence) in the mode considered. The probability of failure, in itself, in a given mode for any period of time, is assumed to be an exponential function of λt, where λ is the total failure rate in the mode considered and $P_f \approx 1 - \exp(-\lambda t)$ when the linear approximation is used, we have P_f (probability of failure) in a practical approximation to be:

$$Q = 1 - \exp(-\lambda t) \approx \lambda t$$

From the two-input gate example, relative probabilities of correct and incorrect outputs of the two states can be calculated. From Table I (when $V_{in}=$ 0, and $V_{out}=-6$V), the number of incorrect outputs due to component failures either open or short=5 failures. Five failures=0.682011 failures/million; therefore, the relative probability of the output failing in the incorrect mode is:

$$\frac{Failure\ rate\ due\ to\ five\ failures}{Total\ circuit\ failure\ rate}$$
$$= \frac{0.682011}{0.9485155} = 0.72\ or\ 72\%$$

The number of correct outputs due to component failures either open or short is equal to 10 and, likewise, the relative probability of the output failing in the correct mode is equal to:

$$\frac{Failure\ rate\ due\ to\ ten\ failures}{Total\ circuit\ failure\ rate}$$
$$= \frac{0.2665045}{0.9485155} = 0.28\ or\ 28\%$$

From Table II, $V_{in}=-6$V and $V_{out}=0$. The number of incorrect outputs due to component failures open or short is equal to 11. Eleven failures=0.4722535

failures/million, and relative probability of the output failures due to the incorrect mode is equal to:

$$\frac{Failure\ rate\ due\ to\ 11\ failures}{Total\ circuit\ failure\ rate}$$
$$= \frac{0.4722635}{0.9485155} = 0.50 = 50\%$$

The number of correct outputs due to component failures either open or short is equal to 4. Four failures= 0.476262 failures/million and relative probability of the output failures due to the correct mode is equal to:

$$\frac{Failure\ rate\ due\ to\ 4\ failures}{Total\ circuit\ failures\ rate}$$
$$= \frac{0.476262}{0.9485155} = 0.50 = 50\%$$

Table III shows the relative probabilities of both states calculated from the two-input gate example. [*Editor's note:* Failure modes of integrated circuits were covered by the author in a separate appendix B which was not included because of space limitations. Modes of failure for nine different types of circuits are analyzed. Such data is useful in circuit, system, or module analysis.]

Table II—Input (V_{in})=0; output (V_{out})=−6; and Q_1 conducting.

Column 1 Component parts (number & type)	Column 2 Component parts failure rate (λ in part per million MIL-HDBK-217A used)	Column 3 Component parts failure modes and associated probability of a occurrence of each mode	Column 4 Component parts failure probability due to failure mode product of cols. 2 & 3	Column 5 Solder joint adjustment factor	Column 6 Output description Correct	Incorrect	Column 7 Failure rate according to output description Correct	Incorrect
R_1 (MIL-R-22684) Fixed Film	0.125	Open (0.98)	0.122500	0.122501		x		0.122501
		Short (0.02)	0.002500	0.002500		x		0.002500
R_2 (MIL-R-11) Composition	0.0035	Open (0.93)	0.003255	0.003256		x		0.003256
		Short (0.07)	0.000245	0.000245		x		0.000245
R_3 (MIL-R-22684)	0.125	Open (0.98)	0.122500	0.122501	x		0.122501	
		Short (0.02)	0.002500	0.002500		x		0.002500
C_1 (MIL-C-11015) Ceramic	0.0050	Open (0.05)	0.000250	0.000251	x		0.000251	
		Short (0.95)	0.004750	0.004750				0.00475
					x		0.007010	
CR_1 (MIL-S-19500) Silicon	0.140	Open (0.05)	0.007000	0.007010		x		
		Short (0.95)	0.133000	0.133000		x		0.133000
Q_1 (MIL-S-19500) PNP Ge≤1W	0.550	B-Open (0)	0.0000000	0.0000005	x		0.3465000	
		E-Open (0)	0.0000000	0.0000005		x		0.0000005
		C-Open (0)	0.0000000	0.0000005		x		0.0000005
		C-E-Short (63)	0.3465000	0.3465000		x		0.0000005
		C-B Short (37)	0.2035000	0.2035000		x		0.20350000
TOTAL				0.9485155			0.476262	0.4722535

Table III—Relative probabilities for two-input-gate example.

V_{in} (volts)	V_{out} (volts)	Relative probability of incorrect output due to either open or short components	Relative probability of correct output due to either open or short components
0	−6	72%	28%
−6	0	50%	50%

Safety precautions

Safety is defined as freedom from potential or actual occurrence of undesired, unscheduled, or out-of-sequence events that jeopardize life, health or property.

The objective of the failure-mode evaluation technique is to provide direction for achieving safety from the research and development phase through the operational phase without compromising essential characteristics of the system. Some objectives are as follows:

1) Design safety into the system and therefore avoid retrofitting.
2) Optimize the safety level of the system to protect personnel and equipment from potential hazards.
3) Prevent accidents which would damage or destroy system elements.

Failure-mode analysis points out potential hazards due to the component parts catastrophic failures early in the design phase so that potential hazards can be eliminated.

By conducting a failure-mode analysis the designer can determine which component parts (when failing catastrophically) would place the circuit and system in hazardous state. Results of the failure-mode analysis provide an evaluation of safety of the element with respect to component parts catastrophic failures.

By performing the failure-mode analysis study, tables can be generated and maintained as functional safety input data; such a functional analysis tool used in the entire system assures compliance with specific system criteria pertaining to hazardous conditions.

Such tables can be described as road maps illustrating the relation of all of the element functional outputs to the component parts or the circuits. Fault and failure occurrences of the element due to catastrophic failure are described in functional terms, in terms of the circuit or the component part failure modes.

Realistic reliability predictions

When component failure has no effect on the ability of the system to meet its main function, the component part failure rate can be eliminated to give a realistic (true) failure rate of the system operation. For example, when total system failure rate is equal to $100^f/10^6$ and when some of the failures analyzed in the failure-mode evaluation technique (either catastrophic or degradation) have no effect on the system operation, then the realistic system failure rate is determined as follows:

$$\lambda_R = \lambda_T - \Sigma\lambda_C$$

Where λ_R = realistic system failure rate; λ_T = total system failure rate before failure mode evaluation study; and $\Sigma\lambda_C$ = the sum of the component parts which have no effect on the proper system operation.

Using the number in the example just mentioned:

$$\lambda_T = 100^f/10^6$$

Assume that $\Sigma\lambda_C = 10^6$
Then $\lambda_R = 100^f/10^6 - 10^6 = 90^f/10^6$
   $\lambda_R = 90^f/10^6$

The failure rate of component part failure modes not impairing system operation in any manner whatsoever would be eliminated as a possible catastrophic failure. Even if they should fail, the system would still complete its intended primary function. It would be unrealistic to penalize the system with a lower probability of success because of component part failure modes that do not contribute to proper system operation. Otherwise, this penalty would have to be offset in various ways to increase the probability of the system success. For example, extra redundance, circuit redesign, or better parts might be used; all this would increase cost, weight, and time.

Maintainability evaluation

Maintainability is concerned with the probability that a failed item of equipment will be restored to operability in not more than a specific interval of down time when maintenance and administration conditions are stated. Failure-mode analysis is useful for evaluating maintainability because it provides insight into:

1) Repair of circuit or equipment after a failure has occurred.
2) Maintenance of the circuit or equipment in operating condition, or the proper corrective action during preventive maintenance operations.

Such information can be obtained by using the following trouble-shooting methods based on the results of the failure-mode evaluation technique:

1) The relative probability of failure of the component parts or modules can be used to diagnose a circuit. Assume that an equipment failure has to be diagnosed to the module level; on this basis, it is best to start to troubleshoot the module having the highest relative probability of failure, and then take the next highest and so on.
2) By utilizing Tables I and II, it is possible to determine what effect various component parts have on a specific circuit or equipment or, in case of the modules, which ones affect equipment functions. These tables point to the relationship existing between an output and the individual component part or modules. From the tables, the output can be designated as either correct or incorrect. The actual description of the output condition should be stated exactly when known, for each individual component part. For example, when a component part or module fails catastrophically either open or short, the actual output condition, such as shift in frequency, a rise in voltage, or too much gain, should be stated. By doing this for each individual component part, a complete view of the cause of the circuit or equipment malfunction is obtained.

Another designation for the output condition is to categorize catastrophic failure (open or short) of the component part or module as critical, major and minor effect.

Logistics planning

Logistics not only encompasses spare parts, overhaul facilities and power needs, but such support considerations as installation and checkout procedures, technical manuals and training . . . all aspects of equipment utilization except those of operation.

The failure-mode analysis technique effectively analyzes and determines spare parts requirements and total provisioning requirements; this is done by using results of relative probabilities of failure, the criticality analysis, and the overall use of the tables given in the example.

By performing the failure mode analysis, *the items critical to the equipment operation* can be determined and decision criteria can be developed for spare provisioning. The relative probability of failure of the component parts or modules are employed strictly to compare one item against another or the

relative importance of having item A as a spare instead of having item B or C. After the failure-mode analysis is completed, all of the relative probabilities of module failures are known. By using these relative probabilities, the spares provision can be determined to accomplish the intended function. Assume that spares are to be determined between two equally important modules, but only one of these modules is to be considered for spares. The following factors should be considered to decide the best possible choice of module: 1) relative probability of each module, and 2) the number of modules used in the equipment.

Assume that a relative probability of failure of .05 for module A was calculated from the failure mode evaluation, and B was calculated to be .10; also, there are 10 modules of type A of equal importance in the equipment and 3 modules of type B also of equal importance. By using the binomial distribution, the new relative probability of failure of 10 modules for A and 3 modules for B will be determined:

$$P_f = \sum_{x=1}^{n} C_x^n \, P^x (1-P)^{n-x}$$

where P_f = relative probability that at least one out of n modules will fail; P = relative probability of one module; n = number of modules used in the equipment; and x = number of modules which are predicted to fail.

Therefore, let us calculate the relative probability that at least 1 out of 10 type A modules will fail.

$P = 0.05$, $1 - P = 0.95$, $n = 10$, and $X = 1$

$$P_{f_A} = \sum_{x=1}^{10} C_x^{10} \, (0.05)^x (0.95)^{n-x} = 0.3151$$

The above equation states that the probability is 0.3151 that at least one out of the ten type A modules will fail, when the failure probability of one is equal to 0.05.

Similarly, for type B modules, we have:

$P = 0.10$, $1 - P = 0.90$, $n = 3$, and $x = 1$

$$P_{f_B} = \sum_{x=1}^{3} C_x^3 \, |0)^x (0.90)^{n-x} = 0.2430$$

Therefore, it is observed that, even though the type B module has the higher probability of failure, the type A module will be chosen for spare provisions, since, from the equipment point of view, there is a higher probability that at least one out of the 10 type A modules will fail rather than one out of 3 type B modules.

Having chosen type A module for spare provision and knowing that relative probability of at least one of the 10 modules of type A to be 0.3151, how many of the type A modules need spares?

Assume that time of operation and cost are not involved; also assume that a probability level of total modules of the particular type used in the system is required (type A modules).

Therefore, the number of type A modules to require spares would be:

$P_f = 0.3151$ — Failure probability of having one unit of the 10 modules in fail state.

$P_{s_1} = 0.6849$ — Probability of success of having 10 modules of type A in the success state.

$P_{s_{10}} = 0.95$ — Probability of success of one module of Type A.

$P_d = 0.98$ — Desired probability of success of the 10 modules of type A used in the equipment.

$n = ?$ — Desired number of type A modules in order to bring the probability of success to 0.98.

$n-x = ?$ — The spares that would be required of type A modules.

Using the binominal distribution, we have:

$$P_d = \sum_{x=10}^{r} C_x^n \, (.95)^x (.05)^{n-x} = 0.98$$

By using the accumulative binominal distribution, it is found that in order to have a probability of success of 0.98 an $n = 12$ is needed, that is:

$$P_d = 0.98 = \sum_{x-10}^{12} C_x^{12} (0.95)^x (0.05)^{12-x} = 0.98$$

therefore, $n - x = 12 - 10 = 2$

The above equation states two spares are necessary for at least 10 modules to operate with a probability of success of .98. It was assumed for the example that time was not involved, since it was only a comparison between two modules; but suppose time is involved, then the new probability of failure or success for each individual module must be calculated. Using the formula $e^{-\lambda t}$, which assumes constant failure rate, the probability that no failure will occur in a given time interval of operation is given by:

$R(t) = \exp(-\lambda t) = \exp(-t/\mathrm{MTBF}) =$
$P =$ probability of success

where λ = failure rate of the component parts (or module) = $1/\mathrm{MTBF}$; MTBF = mean time between failures of the module; and t = mission or operating time;

If $PS = \exp(-\lambda t)$, then $1 - PS = 1 - \exp(-\lambda t)$.

We have:

$$P_d = \sum_{x}^{n} C_x^n \, (\exp(-\lambda t)) (1 - \exp(-\lambda t))^{n-x}$$

If the linear approximation is used, as described before, we have:

$$P_s = 1 - \lambda t$$
$$1 - P_s = \lambda t$$
$$P_d = \sum C_x^n \, (1 - \lambda t)^x (\lambda t)^{n-x}$$

Therefore, the above formula states that if at least x modules are required and given a P_s with a certain failure rate (λ) and operating time (t), then the number (n) can be computed by using ($n-x$) and the number of spares can be determined.

Summary and conclusion

The failure-mode analysis technique is of great value to the design engineer and the product assurance activity. Failure mode analysis can be utilized for:

1) An evaluation technique for any element.
2) A determination of the probability of success or failure of a particular element.
3) A realistic reliability prediction.
4) Eliminating potential hazards for safety purpose.
5) Determining maintainability evaluation.
6) Logistics planning.

The charts or tables generated as a result of the failure-mode evaluation serve as a checkout of most failures encountered. Therefore, this technique properly used, can save equipment failures, time, and cost in the overall system operation.

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Computer processing of records for measuring and test equipment

L. E. Cyr

Thousands of pieces of measuring and test equipment (MTE) at the Astro-Electronics Division now provide better accuracy and are controlled for optimum utilization. In addition, data reports on MTE items cost less to prepare, and timely special reports can be produced with greater ease. This improvement was brought about by using a computer to generate management and logistics information from the massive files of descriptive and historical data associated with large quantities of MTE. This paper describes the types of data collected, the method of presenting it to the Spectra 70 computer, and the selected-information reports that can be obtained by means of the present computer program.

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received the BS in Mathematics from the University of New Hampshire School of Technology in 1963. He joined Vitro Laboratories and developed on-board maintenance schedule programs for nuclear submarines. In 1964, he became associated with Link Computation Center of General Precision as a Scientific Computer Programmer and programmed guidance and navigation systems for the Apollo mission simulator. In October of 1965, he joined RCA Management Information Systems of the Astro-Electronics Division where his primary responsibilities have been the development, implementation and enhancements of computer based systems, including control of measuring and testing equipment, materials inventory control, and accounting projects.

THE AUTOMATED MTE (MEASURING AND TEST EQUIPMENT) CONTROL PROGRAM at AED was developed by Management Information Systems for the Test Equipment Maintenance and Calibration Activity to enable the timely and effective maintenance of the thousands of electronic measuring and test equipments, and critical tools, used to design and construct components and systems for aerospace applications at AED. The program recently was transferred from an RCA 301 computer to its replacement, a Spectra 70, which increased the speed of processing data and further reduced operating costs. Full use is made of the Spectra 70 capabilities for high-reliability record storage, data processing, and reporting. At present the master file is updated weekly and the average maintenance cost of an inventory record is 60 cents/year.

This MTE control program ensures that:

Equipment inventory records are current and accurate.
Equipment will be available for planned demands.
Equipment is calibrated at optimum intervals.
Equipment is serviced at routine intervals, and replaced when maintenance becomes inefficient.
Equipment spare-parts stocks are efficiently related to requirements.
Maintenance workloads are planned for most efficient use of manpower.

Master record

All information on a specific equip-

ment is maintained on a measuring and test equipment history card (Fig. 1). Three types of information are carried on this card: the top section contains "current" information; the lower two sections record the calibration and repair history, and the movement and inventory history. Handwritten information entered initially or as corrections on one of these cards is key-punched and used as input data for the computer. An updated printout then is produced by the computer.

Current information

Current information includes four categories:

1) An equipment's unique identification,
2) Its present assignment and location,
3) The incorporating MTE system (if applicable), and
4) Its calibration status.

The unique identification includes not only the manufacturer, model and serial numbers, and functional description, but also information such as the date received, cost, owner, warranty expiration date, property tag, purchase-contract number, purchase order or IDT concerned, appropriation number, and a calibration-instruction reference.

The assignment and location identifies the custodian, plant (or other) location, shipping memo, related contract, facility forecast, and the scheduled date of return.

The system information includes the system inventory number, model, serial number, and general description.

With this data, units may be reported by systems so that the calibration times for all equipments may be shifted to equivalent periods or multiples of the shortest period.

Calibration information comprises two groups. The first is substantially unchanging and consists of the calibration-interval (or cycle) code letter and time period, the average time for calibration and repair for the type of equipment (given in hours and tenths), and the inventory code, which is the last digit of the last year the equipment was inventoried. The second group consists of the date of the last calibration or repair, date of the last scheduled calibration, and due date for the next calibration. This information is automatically updated as each request for service is issued.

Calibration and repair history

A maximum of 15 repairs or calibrations can be shown on an MTE history card. As more entries are needed, the earliest entry is dropped from the card (but is retained in the computer file). The information listed in this section of the card includes:

RCA   Measuring and Testing Equipment History

Fig. 1—Typical measuring and test equipment history card.

The scheduled date for calibration,
The date of receipt of the equipment for calibration or repair,
The actual calibration or repair date,
The current calibration-cycle code and period,
The time elapsed since the last work done,
The number of hours required for current maintenance,
Work and malfunction codes,
Inventory numbers of equipment (up to six) utilized in maintenance operations,
Circuit symbols of parts repaired or replaced (up to three can be listed on the card, but 12 may be entered into the computer file), and the initials or code identifying the individual performing the service operations.

Movement and inventory history

Fifteen entries showing equipment relocations or inventory events can be accommodated on this part of the card. When a sixteenth (or succeeding) takes place, the earliest card entry is dropped. The "movement" information is received on a Location Notification form and is used to automatically update the entries (as specified) for dates of possession, custodian, shipping memo, physical location, contract subtitle, and facility forecast number. Inventory information is recorded at the time of annual inventory and updates the inventory code entry.

Computer processing

Input data

Logically selective and properly organized input data to a computer can be of great help in minimizing processing costs. The MTE program provides for seven input formats, of which three (number 1, 3 and 4 of the next listing) provide 90% of the input data. These inputs are entered into the computer on the following forms:

1) Master record (MTE history)
2) Master record deletion
3) Service request
4) Arrival notification
5) Location notification
6) Calibration and movement activity deletion
7) Special data request

Routine reports

For the purpose of this paper, "routine" reports are considered to be those produced on a periodic basis to ensure that calibration and maintenance for each equipment are performed and recorded in accordance with the established requirements, as distinguished from "special" reports, which are essentially statistical data required to properly maintain and control the record-keeping system, and to permit comparisons, conclusions, and prediction to be made on the basis of total performance.

Data must be submitted to the computer in pre-established codes and formats. Deviations from these result in a supplementary error report after each printout, listing items which cannot be processed or cannot be located in the computer stores due to erroneous input.

To produce the first MTE history card for the maintenance activity file, all available information is written on a blank MTE history card. The informa-

SERVICE REQUEST - MEASURING AND TESTING EQUIPMENT

CALIBRATION FILE

INVENTORY NUMBER (CC 3-10)	DATE ISSUED	MANUFACTURER	MODEL	SERIAL NUMBER	SHOP ORDER NUMBER

| DESCRIPTION | RANGE | OWNER | BUILDING | FLOOR | BAY | CALIBRATION CYCLE CODE | PERIOD | CALIBRATION DUE DATE |

PROPERTY TAG/CONTRACT PURCHASED ON — PURCHASE ORDER NUMBER OR I P T ACQUIRED ON — CUSTODIAN — FROM (GROUP)

SYSTEM INVENTORY NUMBER — SYSTEM MODEL (HTX) — SYSTEM SERIAL NUMBER — SYSTEM DESCRIPTION

CHECK WORK REQUESTED
- ☐ CALIBRATION
- ☐ REPAIR
- ☐ PI/PM
- ☐ NEW EQUIPMENT
- ☐ OPERATIONAL CHECK
- ☐ PURCHASED SERVICE

CALIBRATION INSTRUCTION — WARRANTY EXPIRATION DATE — UNDER WARRANTY — DATE OF NEXT CALIBRATION

SPECIAL INSTRUCTIONS OR MALFUNCTIONS:

KEY PUNCH (CC 11-12) CARD 1 / CARD 2	DATE IN (CC 13-16) YEAR / WEEK	CHANGE CC DUE DATE (17)	NEXT DUE DATE (CC 18-21) YEAR / WEEK	RETAIN CC SERV REQ (22)	AMBIENT TEMPERATURE °C	HUMIDITY %	PROBLEM NUMBER
30 / 40							

WORK CODES (CC 23-24)
- ☐ C   IN TOL
- ☐ R   IN TOL
- ☐ CA   OUT TOL
- ☐ CR   OUT TOL
- ☐ PI   PERIODIC INSPECTION
- ☐ PM   PREVENTIVE MAINTENANCE
- ☐ OC   OP CHECK
- ☐ PS   PURCHASED SERVICE
- ☐ AC   NEW EQUIPMENT-ACCEPTED
- ☐ RJ   NEW EQUIPMENT-REJECTED
- ☐ D   DAMAGE, REPAIR

MALFUNCTION CODES

(CC-25-27)	(CC-28-30)
(CC-31-33)	(CC-34-36)

AUTHORIZED BY

LABOR		TRACEABLE INVENTORY NUMBERS	MATERIAL DESCRIPTION	CIRCUIT SYMBOLS	CHARACTERISTIC MEASURED	READINGS			MEAS RATIO
DATE	HOURS					BEFORE	AFTER	DIFF.	

DATE CAL/REP (CC 37-40) YEAR / WEEK — TOTAL HOURS (CC 41-43)

PERFORMED BY (INITIALS) (CC 44-46)

ACCESSORIES

REMARKS/WORK SUMMARY

AED 376 (R-3-66)

Fig. 2—MTE service request form.

tion then is fed through the medium of a key-punched standard computer-input card, into the computer, which stores the information and also prints out a verifying MTE history card. The print-out is filed until the equipment's status changes at which time the new information is written in, and the card is submitted as new input for the computer. Additional and corrected information is added to the store, and a new MTE history card is printed out.

When an equipment is permanently removed from AED inventory, a master record deletion form is initiated; a final MTE history card then is printed, at which time all information is automatically removed from the computer stores. The deleted inventory number may be used again, if so desired.

The service request from (Fig. 2) is produced by the computer when maintenance scheduled for an equipment is due, or it is issued by the equipment custodian for unscheduled maintenance. It uniquely identifies the equipment concerned, includes pertinent related information, and the reason for issuance of the request. When a service request, issued through the maintenance activity, is received by the equipment custodian, he either releases the equipment to them, or sends a "non-releasable" notification, giving the earliest feasible release date. When the equipment is received, maintenance forwards a copy of the service request and an arrival notification to the computer. Entry of the content data informs the computer that inventory No. X has been received, thus inhibiting the issuance of new service requests for that item and preventing its inventory number from appearing on a past-due calibration list. When a "non-releasable" notification is received, it also is fed into the computer, which then issues a new service request at the release or "slippage" date given in the notification.

In both of the preceding two cases, a new MTE history card is printed out with an additional history line recording the new information. Upon completion of calibration or repair, a description of the action taken is filled in on the service request for submission to the computer, which completes the history line on the MTE history card.

Upon the transfer of measuring or test equipment to another location, a location notification form is initiated. This information is submitted to the computer, which prints out an MTE history card, recording the event as a new line in the "movement" section of the card and updating the pertinent information (for example, custodian, related contract number) in the "current information" section.

The six types of inputs just described are entered into the computer on a weekly schedule. All input information to the system is checked by the computer for consistency and accuracy before its entry into the master file. (Erroneous data is rejected and appears later in an error report.) Five output lists are produced:

1) A list of inventory numbers of equipment having a "date of next calibration" earlier than those on the service requests,
2) A list of equipment for which calibration is overdue,
3) A list of loaned equipment which is due or overdue,

Table I—Special reports

Report	Description
Calibration workload schedule	Provides maintenance personnel with 1-year projection of workload for equipment on periodic maintenance (starting one week following issuance of last service request). Specifies number of equipments due each week and predicts total manhours required for calibration. Equipments with due dates for calibration earlier than those included in the main report are listed separately, to permit verification of the immediate workload. (Equipment not scheduled for periodic maintenance is not shown.)
Analysis	Reported by manufacturer and model number. Computes figure of merit which can be used as a basis for establishing a change in the frequency of calibration for a particular model, based on an analysis of the calibration and repair history of the equipment (see Appendix A for the analysis method). The necessary transactions to update the average hours by manufacturer and model are generated. A listing of all inventory numbers (with keypunching instructions) is supplied to assist in changing the calibration period. If the total number of malfunctions encountered during this analysis is greater than 50, a *Malfunction Code Action Summary Report* is supplied. Analysis feedback input data cards are generated.
Analysis feedback	When a calibration period is changed, a compilation of the total man hours of maintenance time for the former and the present periods for all equipment involved is generated by the computer. A total of $70,000 reduction in cost for calibration and maintenance was shown for the years 1967 and 1968.
Facilities forecast	Future needs for measuring and test equipment by programs (contracts and contract subtitles) are projected. This report is useful for program activities as an accountable equipment listing.
Manufacturer and model	An inventory of all equipment registered in the computer stores. Provides data required for budget analysis. Provides status of present and future availability (useful for proposals).
Systems	Lists special test-equipment systems; all items associated with each system. Shows individual equipment and total system costs.
Property tag	Lists fixed-assets type of information. Separates capital and leased equipment, thus giving government-contract accountability.
Calibration cycle	Groups, by manufacturer and model number, all equipment having the same calibration period and code. Uses special inventory-number ranges for 1) government-owned end items, 2) government-owned special test equipment, 3) leased equipment, and 4) tagged and non-tagged capital equipment. Totals in these ranges are supplied for each manufacturer and model and for each special range. First-cost totals by groups and for the entire file are given. Useful as a master listing for new entries.
First cost	Supplies first-cost, date acquired, purchase-order number, etc. to support financial accounting in the preparation of proposals.
Descriptions	Associates manufacturer and model number with equipment description and categorized specifications.
Inventory summary	A complete listing of inventory in more readily useable form than the MTE history card files.
Circuit symbol	A list of circuit items repaired or replaced, by manufacturer and model of equipment. This guides the maintenance technician in his approach to trouble diagnosis.
Parts usage	A listing of total parts usage (during the year) in maintenance of all equipment. A useful guide to inventory stocking.
Missing inventory	Each physical inventory list is compared with that stored in the computer. A list of any equipment not accounted for then is generated.
Generalized extracts	Individual lists of an infinite variety are available from the computer stores. The present program permits extraction of equipment lists by custodian, using group, location (building, floor, and bay), contract, contract subtitle, calibration instruction, property tag, loan due date, and calibration period.

4) Service request forms for items due for calibration within the next 2 weeks, and

5) MTE history cards, to reflect any updated information submitted to the computer.

Special reports

The special request form contains a list of the additional reports which are available. These may be restricted to only electronic test and measuring equipment (or only tool and gage equipment) when interest is concentrated only on one group—thus minimizing computer-time costs. The reports presently available are shown in Table I.

Future developments

Looking to the future, a study is being performed to identify those items which differ widely from the maintenance "mean" for each type, with a view to removing from use equipments which require excessive unscheduled repair. Information for studies of this type is readily available from data stored in the computer system.

Conclusion

A computer system alone cannot provide effective management; judgement still must be exercised by men. But a well designed system can be the means of ensuring that the men who make the decisions have the information they need to be most effective. The measuring and test equipment control system is based on a set of computer routines designed to meet the requirements for accuracy, flexibility, and efficiency demanded by the AED managers who rely on it for information guidance. By ensuring that the men and women who build and test the products of the Astro-Electronics Division are continuously equipped with functioning, calibrated test equipment and tools, the measuring and test equipment control system—as the other systems of the AED Management Information System —plays an important part in the efficient production of reliable, high-quality products for space.

Acknowledgements

Appendix A—Calibration period analysis

The calibration period for a particular type or model of test equipment is constantly reviewed to determine the optimum length of time it can be expected to operate without recalibration or repair. A figure of merit (FM) is established (from historical data supplied by the computer) in accordance with the following expression:

$$FM = \frac{C_{nc} + R_{nc}}{C + R} \times 100$$

where

C is the total number of pieces of equipment received for recalibration.
R is the total number of pieces of equipment received for repair.
C_{nc} is the number of pieces of equipment received not requiring recalibration.
R_{nc} is the number of pieces of equipment not requiring recalibration after repairs.

For an FM between 50 and 79, no change in the interval between calibrations is recommended. Outside of this range, the recommended changes run as follows:

FM	Interval change
29 or less	− 12 weeks*
30 to 39	− 8 weeks
40 to 49	− 4 weeks
80 to 89	+ 4 weeks
90 to 99	+ 9 weeks
100	+ 12 weeks

* This performance is considered suspicious and would be investigated further.

63

Multilayer printed-wiring board analysis

N. B. Shain

As process controls and product-inspection techniques progress, the performance and dependability of multilayer boards continue to improve. In this paper, the author describes the analyses, the elusive problems, and the prescribed corrective measures resulting from investigations into processing, assembly, testing and inspection of multilayer boards.

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received the BA in General Science from Pennsylvania State Univ. in 1948 and has done graduate work for the MS in Mechanical Engineering at Southern Methodist University (1954-55). He was a design engineer for Chance-Vought Aircraft until 1956. He joined the technical staff of the Burroughs Corporation Research Center in 1956 as a Development Engineer. His major duties included component evaluation, reliability, system and failure analysis and the initiation of non-destructve test techniques related to the ATLAS Program. In 1960 he joined RCA as a consulant on Electrical Connection Techniques. He participated in the design of data link, Minuteman, Dyna-soar, Apollo and many other high reliability programs. In his present assignment he has made contributions in the area of improved mechanical packaging and interconnections for micro electronic components for several RCA programs. Mr. Shain is a member of the IEEE, he has represented RCA on various ASTM, SAE, and EIA committees. He has authored many papers in his speciality area and has participated in several technical seminars.

RAPID CHANGES in technology and the manufacturing of multilayer printed-wiring boards restricts the accumulation of useful life test information necessary to make reliability predictions. Radical and continuous changes in process controls are needed to solve specific production problems. Consequently, new process controls are never tightened to the point where all quality defects can be screened out. Thus, the problems of the long-term failure mechanisms are always just a little beyond immediate solution. In this paper, printed-wiring board materials, processes and characterizations are studied and corrective measures described for the problems analyzed.

Printed-wiring boards

Dissimilar materials that comprise multilayer printed-wiring boards cause many manufacturing and testing problems. A multilayer printed-wiring board is physically small, relatively light in weight, and can accommodate many microelectronic components. Boards consist of combinations of single- or double-sided printed-wiring wafers which are stacked, laminated and drilled into an integrated three-dimensional wiring plane. The multilayer board serves a dual function; it provides structural support for the surface mounted electronic components; and includes several layers of etched wiring paths for the various components mounted on the board surface.

Multilayer board failures examined

An initial examination of a series of multilayer board failures revealed that unstable or high-resistance connections resulted in total open connections after exposure to the thermal shock and vibration environments. Although it

was not possible to identify any one failure mechanism, the source of the failure mechanism could be ascribed to the following:

1) Some failures occurred at the butt joint interface of the pad and the plated-through hole.
2) Other failures occurred at the interface between the pad and the mounting insulation.

In both cases, an applied force caused adjoining members to separate (Fig. 1) resulting in electrical open connections. This was induced by one or more violent thermal or mechanical stresses which occurred during the flow-soldering operation, the subsequent cleaning operation, or during an environmental reliability screening test. Three significant changes to the multilayer-board fabrication process, corrected the failure mechanism previously described:

1) Copper plating materials and processing was changed from an acid copper to a more ductile copper material.
2) The drill tip configuration and speed of drill operation was changed to minimize the heat of friction.
3) All holes were cleaned before the through-hole plating process with an acid type chemical cleaner. This eliminated most of the contamination from the metallic surfaces and improved the metal-to-metal contact (Fig. 2).

The investigation showed that none of the basic process steps in fabricating multilayer boards stands out as the most troublesome. The process itself apparently has no latent effect on any specific cause for failure. Failures observed in assembled multilayer boards are easier to identify and isolate because of the effectiveness of in-process testing; these include:

1) Human-induced problems incurred during assembly and maintenance reflected as catastrophic electrical opens or intermittent performance at room ambient conditions.

2) In-process failures introduced during screening or acceptance tests observed as a failure to function or intermittent performance during exposure to high-or-low temperature environments.

Open traces examined

Examination of open traces under magnification showed two distinct patterns: 1) those attributable to mechanical over stressing, and 2) those attributable to some form of chemical reaction (Fig. 6). Evident in trace 1) of reduced "cross section", chipping, or cracking in the area of the broken trace may have been human-induced during the processing of the board. The examination of trace 2) produced additional information of failure modes, but, the failure mechanisms could not be readily determined. Further studies provided no conclusive evidence of the cause of the failure. A judgement was made that such conditions could be remedied through the use of suitable fabrication instructions and close surveillance of the fabrication. This close surveillance in-process inspection was immediately imple-

mented in the multilayer-board fabrication areas to detect the possible source of differences during the manufacturing operation.

Since almost all trace failures were of the same type, a series of traces that had not failed were inspected; none of these showed any evidence of failure or degradation. This is considered significant since all boards had been exposed to the same thermal conditioning and process variations during laminating and soldering. The possibility that mechanical stresses resulting from differences in the thermal expansion was practically eliminated, and it was concluded that normal temperature cycling of multilayer printed-wiring boards does not destroy basically good traces or connections.

Etched-board traces

A further inspection of etched-board trace failures and comparison with acceptable traces produced information of significant process difference. Under a given magnification some traces indicated smooth homogeneous copper-grain surface structure while others indicated a rougher surface condition. It was concluded that the surface roughness was caused by overexposure to the etching solution. Inspection of other traces revealed conditions where rough handling of a board contributed to its failure. These included cut throughs in an attempt to remove excess materials (solder shorts) and cracked joints which could have been caused by excessive stressing of the laminated structure.

Failure analysis

A detailed failure analysis was performed on multilayer boards and modules having electrically open and short characteristics. The failed multilayer printed-wiring boards were found to be more valuable for an improved product than acceptable boards. Failures of a mechanical nature were monitored and tabulated; however, no attempt was made to investigate the problems of delamination, raised pads or broken exterior copper paths, drilled hole problems or cosmetic (measles, crazing, weave texture) defects at this time. Failures of an electrical nature were investigated to identify specific failure modes and mechanisms and to verify that the re-

vised in-process controls for both fabrication and module assembly areas had eliminated the major causes for defective material.

Failure analysis procedure

To provide maximum information with the least destructive testing to the sample board, a procedure was evolved to locate and identify the cause of failure. Since multilayer-board-module failures are classified as either electrical "opens" or "shorts", the following procedure was implemented:

1) Verify module failure by either a functional test or milliohm meter test to establish continuity.
2) Remove components within suspect area from board and verify electrically.
3) Check the continuity of each through-hole connection (top to bottom continuity) and each trace (to and from points).
4) Check board drawings to identify trace routes, layers and "via" points in the circuit.
5) Perform radiographic inspection along the logical electrical paths to localize fault to a particular area.
6) As a result of steps 1 to 5, the failure could not be isolated to a particular area.
7) Details of the failure area can now be exposed by etching, optical defraction, or micrographic inspection.
8) The failure mechanism can now be pinpointed from the preceding observations.
9) The deatils of steps 1 to 8 were carefully documented.

During the foregoing procedure, great care was exercised in the handling of the small parts particularly during unsoldering of the component parts, etching of epoxy material to expose interlayer surfaces, and during the preparation of micro-sectioned samples. All suspect samples were visually examined at various magnifications up to "500X" to determine the factors causing the electrical open failure. Emphasis was placed on these electrical open failures because they occurred so frequently during the initial production program that they were relatively easy to isolate. Analysis of electrical shorts was withheld for later investigation.

The classification of electrical open-circuit failures within multilayer boards was divided into two categories: connection failures (within holes) and board failures (in traces). The classification of electrical short-circuit failures were identified as interlayer or intralayer defects.
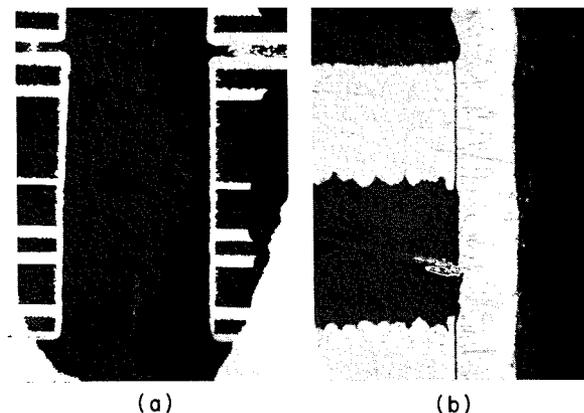
Fig. 1—Plated-through hole, conventional: a) 25X, b) 500X.
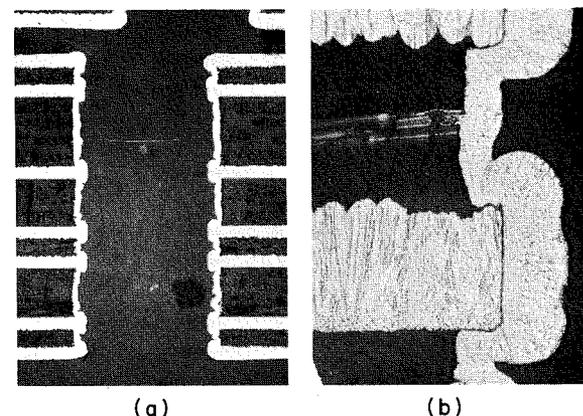
Fig. 2—Plated-through hole, chemically cleaned: a) 25X, b) 500X.
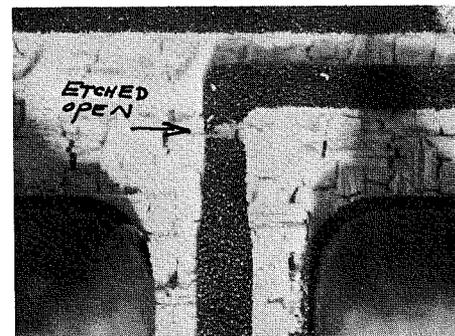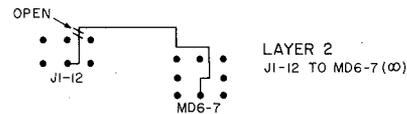
Fig. 3—Macrophotograph of etched trace connecting J1-12 and MD6-7.
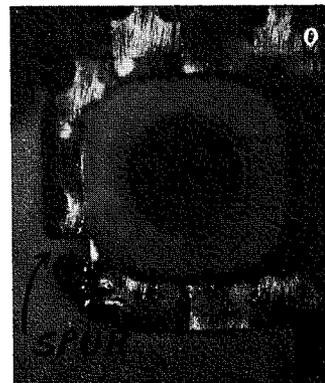
Fig. 4—Macrophotograph of the defect area of the board showing the portion of the copper that was not etched.

LAYER 2
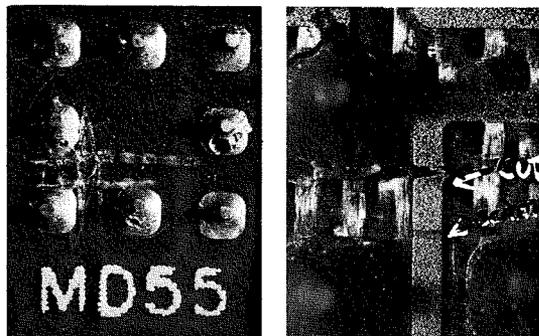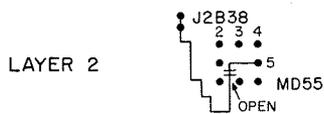
(a)   (b)

Fig. 5—Macrophotograph showing a) the cut epoxy which results from the removal of a short from MD55-1 to 8 and b) the same sample with the epoxy chemically dissolved. This shows the cut and scratch which resulted from the repair.

MD73-1   MD84-3   LAYER 2   MD28-5   OPEN

MDI3-7 TO MD28-5 = 30MΩ
MD73-1 TO MD84-3 = IOMΩ
MD28-5 TO MD84-3 = ∞
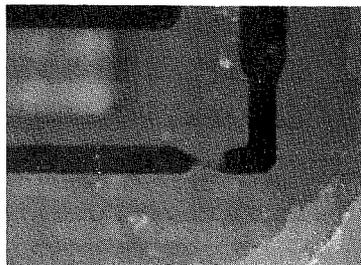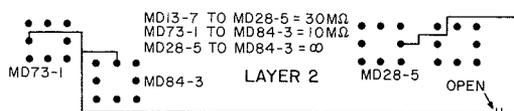
Fig. 6—Macrophotograph of etched open between MD28-5 and MD84-3.

Failure analysis results

Failures responsible for defective multilayer printed-wiring boards are only partially understood; in most cases of board failure, the fundamental physical and chemical process causing the failure could not be readily identified. The results of the failure analysis performed on 48 electrically open defective multilayer boards. (Fig. 3) revealed the following information:

Total inspected	48	
Connection failure		
Induced by repair	5	10%
Process problem		
(no plating)	1	2%
Board failures		
Unsuccessful repairs		
to trace	5	10%
Unrepaired traces	37	78%

Three additional "electrical-short" multilayer boards (different types) were subjected to analysis: all showed evidence of an unwanted intralayer connection (Fig. 4):

1) Only one case of insufficient plating thickness was considered to have caused a board failure.

Table I—The nature of failures and corrective action.

Failure mode	Failure mechanism	Failure effect	Corrective action
Electrical open	Insulated interface (epoxy smear)	No electrical output	1. Control drill configuration and Operational speed. 2. Chemical cleaning.
Either open, intermittent or high resistance	Overetched or missing trace	No output, on and off output, or high resistance output	If trace is visually open establish cause as mechanical or chemical in nature. If mechanical: 1. Inspect for scratches on board. 2. Scratches in glass master. If cracked: 1. Suspect handling abuse. If chemical: 1. Inspect for unneutralized etchants within board. 2. Pinholes or scratches in the glass master or on photoresist.
Electrical open	Inadequate through-hole plating	No electrical output	Check plating process: Bath constituents Current density Immersion time Physical location in bath
Electrical open	Lifted pad	No electrical output or intermittent output	Usually caused by abuse during maintenance, or part removal. Review repair procedure.
Electrical open or short	Misregistration of innerlayers	Either missing or unwanted connections	Check artwork Check laminating tooling Check drill templets or N/C tapes Check photoresist application
Electrical short	Underetched or spur in trace	Additional connection	Check artwork Check etcher Check etching solution
Insulation resistance breakdown	Resin starvation or exposed laminate fiber	Water absorption or reduced creepage path	Check raw material Check laminating temperature Check solder process

Table III—Multilayer board process changes.

Operation or material characteristic	Original configuration	New configuration	Justification
1. Copper plating for through-hole connections	Acid copper plating bath	Pyrophosphate copper plating bath	To increase ductility of deposited copper and minimize impact of thermal shock.
2. Through-hole drilling a. drilling operation		New drill tip configuration and reduced drill operational speed	To minimize heat (frictional) and reduce "epoxy smear" problem.
b. hole cleaning	No operation specified	Chemical hole cleaning	To remove epoxy material from interface connection area. Reduce potential "epoxy smear" problem, and increase interconnection contact area.
3. End product electrical test	Hand continuity test and capacitive check	"DITMCO" continuity checker	New automatic (DITMCO) test machine eliminates human inspection factors.
4. Laminating materials	No resin content specified for base laminate, 50% resin content specified for pre-preg material	Increased resin content in base laminate and pre-preg materials	Reduced blistering, delamination problems and minimize measle or crazing conditions.

2) There was some evidence of poor quality drilling (rough holes) in several (2) failed boards, but neither were considered to be the prime cause of failure.
3) There was one case of misregistration of the interlayers which resulted in an open failure (caused by mishandling during fabrication).
4) The use of silver filled epoxy to repair an innerlayer open trace resulted in five failures.
5) A majority of all connection defects were mechanically induced and resulted in either hole plating errosion or displaced adjacent copper traces.
6) The most critical condition noted, was the presence of electrical opens and shorts in boards during advanced stages of the module assembly.

Failure analysis conclusions

A preliminary conclusion drawn from the results of this investigation indicates that multilayer printed-wiring boards will have built-in electrical deficiencies which are functions of 1)

variations in the fabrication processes; 2) improper inspection and/or testing; and 3) the physical handling that the board encounters during assembly into a functional electronic module.

Almost all of the failures are attributed to the human variables associated with faulty or improper handling (Fig. 5), processing of the board during its fabrication, or abuse of the board during normal maintenance and testing of production assemblies. A majority of the failures reported in module assembly could be traced to problems in the board fabrication area that should be identified by continuity testing and thus should not be submitted in that condition for module assembly. Problems associated with fabrication (Table I) are often complex and difficult to identify prior to the completion of an unassembled multilayer printed-wiring board.

Table II—Assembled quality control data on multilayer boards.

Cumulative total chem clean boards	37,000
Cumulative total electrical rejects	754
Cumulative percent defective	2.03%
No. of open connections (all boards)	332
% defective	0.93%
No. of electrical shorts (all boards)	422
% defective	1.10%
No. of defective high density boards (30% boards used)	422
% defective of total rejects	53.2%
Opens (155 of 333) 46.5%	
Shorts (247 of 421) 59.5%	
*(1) No. of rejects identified during bench test	705
*(2) No. of rejects identified after bench test	49
Open 37	
Short 12	

Notes:

*(1) Indicative of boards containing inherent trace defects, not identified prior to assembly.

*(2) Indicative of failures introduced during module assembly.

Summary of failure information

Based on failure data acquired from quality control records (Tables I and II) in the various multilayer-board fabrication and assembly areas, the following information was tabulated:

1) A 20 to 25% reject rate was noted in the fabrication area, primarily due to unrepairable mechanical and electrical trace defects. This rate could be reduced if visual and mechanical inspections of "interlayers" were replaced with an automatic electrical test.

2) A reject rate of 2 to 3% was experienced on boards in the module assembly area. This was primarily due to the use of hand-tested (electrical) boards containing inherent trace defects that adversely affected reliable performance. Failures induced by repair contributed an additional .5% defects to the reject rate. This condition has been significantly reduced to less than 1% defects after implementation of automated continuity testing of unassembled boards on a 100% basis in the board fabrication area.

3) Boards removed from equipment during system screening tests contributed approximately 0.3% to the reject rate. All failures were associated with unsuccessful multi-lead component replacement; the plated-through hole was destroyed.

Economic considerations

Because of the growing competition in the electronics industry, multilayer-board production yields have been achieved that were considered impossible to obtain a year ago. This higher yield has resulted in reduced production costs and has provided the basis for optimism when considering the production feasibility of more complex or sophisticated printed-wiring board assemblies. The results achieved in this program indicate that properly designed, applied, inspected and tested multilayer boards containing many circuit paths or functions could have substantially the same failure rate regardless of the number and complexity of circuit paths, laminated layers and number of plated-through hole connections. This observation is based on the extrapolation and interpretation of the results of failure analyses performed on electrically defective multilayer boards; the major failure mechanisms were associated with the circuit integrity within the board structure, rather than at the junction of the individual layers to the plated-through hole interconnection.

Training

The most significant aspect of multilayer printed-wiring board production relating to reliability noted was that major failure modes could be corrected by more stringent inspection and quality-control practices. During the past 12 months, a significant attempt has been made to train and motivate printed-wiring board production personnel, and to provide more effective test intrumentation and inspection procedures. This was especially important during the initial production phase because the incoming multilayer board was only visually inspected prior to being committed to module assembly; no electrical test was performed on the product until after the components were assembled into a functional unit. This condition increased the possible cost for defective boards approximately 10 times and made it mandatory to identify defective material at the earliest possible time.

Inspection and testing

Current inspection procedures have practically eliminated defective boards from entering our normal module-assembly cycle. This improvement does not imply a reduction in process or workmanship defects during board fabrication, for a check of reject records shows that the problem still exists. Improved testing has shifted the impact of the problem back toward the originating source. This indicates that it is possible to achieve product maturity during the early-learning phase of a new process or technique. Also, visual, metallurgical and radiographic inspections augmented by electrical testing is required after specified printed-circuit board manufacturing operations. In the present processes each interlayer is visually inspected prior to lamination by a comparison check to an established master overlay. This operation has been shown to be only partially effective in screening out printed-wiring board defects. Inspection of statistical data shows that visual inspection dependent upon human variability can only identify 20-25% of the electrical defects that are found by an automatic circuit test machine. This statement must be qualified to explain that the visual inspection did not screen every possible contact trace while the automatic machine tested all connections and traces on a 100% basis. From this information, a conclusion can be formulated whereby an electrical continuity test for all individual layers should be required prior to lamination. This could significantly reduce the rejection rate for boards at advanced stages of board fabrication, and reflect a major reduction in board costs.

Conclusions

The preceding discussion summarizes our observations of the problems encountered during the mass production of multilayer printed-wiring boards. This information provides a base for comparison that is important to future programs that intend to use this type of board. The reliability data presented is important to the establishment of failure rate and economic cost information and can provide insight into anticipating problems in the selection and evaluation of various processes involved in the fabrication of boards. Table III lists examples of product and process changes that were necessary to provide an acceptable product. A continuing program of monitoring failure causes and effects of other configurations of printed-wiring boards (in other applications) will be necessary until complete product maturity is achieved. A large fund of valuable information has been acquired and relates to the longevity and expected causes of failures in multilayer printed-wiring boards. This recognition of reliability problems through the analysis of board failures, initiation and monitoring of corrective action and the documentation of program results has resulted in increased dependability.

Diagnostic programs for Videocomp phototypesetters

G. W. Maymon

Diagnostic and maintenance programs are primarily troubleshooting tools for the field maintenance engineer. The design philosophy for such programs is to provide the capability for locating any machine malfunction in the minimum time. Reliability evaluation is implicit in these programs since they are categorically designed to function under worst-case conditions. Additionally, since these programs are designed at the lowest logic level (rather than on a higher functional level), they are valuable as factory checkout programs. This paper describes the test and maintenance techniques for the analog and digital circuitry in the RCA 70/832 Videocomp system.

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received the BSEE from Newark College of Engineering. From 1955 to 1966, he participated in the development of a large scale electronic telephone switching system (No. 1 ESS) at Bell Telephone Laboratories. He joined the Graphic Systems Division in 1966 as a Senior Member, Technical Staff, assigned to develop test and maintenance (T/M) programs for the 70/822 Videocomp System. Since 1967 he has been leader of a group responsible for T/M and special programming projects. He is a member of the IEEE.

VIDEOCOMP SYSTEMS are inherently hybrid systems. They are high-speed phototypesetters controlled by a programmed digital control unit and capable of producing a wide variety of typefaces on the screen of a high-resolution cathode ray tube (CRT)[1]. The CRT images are reproduced on phototypesetting film or paper by means of the photorecording technique shown in Fig. 1.

System description

The configuration of the 70/832 system is shown in Fig. 2. The system input is a magnetic tape containing composed text[2], operational commands, and typographical font data. The heart of the system is the RCA series 1600 control processor[3]—a programmable digital control unit containing control software and memory storage for digitized font data. The software decodes input commands and supervises the transfer of text data to the photocopy unit via the photocopy control electronics.

The input/output facilities available to the maintenance engineer in the field are as follows:

Inputs
1) Program input to the series 1600 processor from a 9-level magnetic tape station.
2) Hexadecimal input data switches located on the system control panel (Fig. 3). This is the means by which the maintenance engineer selects diagnostic program blocks from the input tape and enters test data into the system.
3) A portable maintenance console which provides direct control of various series 1600 functions.
4) A built-in test panel which provides

a limited substitute for the series 1600 processor.

Outputs
1) Photocopy output from images written on the face of the cathode ray tube.
2) Decimal lamp display on the system control panel. This is the means by which fault indication numbers are obtained from the digital diagnostic programs by the maintenance engineer.
3) Lamp displays on the portable maintenance console.
4) Memory dump facility to a 9-level magnetic tape.

Photocopy unit

A block diagram of the photocopy unit (PCU) is shown in Fig. 4. It consists basically of a high resolution cathode ray tube (CRT), analog driving and compensation circuitry, an optical system, and a camera system. The individual character images are formed on the CRT face as a series of variable length vertical strokes. The spacing between adjacent strokes is a function of the point size of the character being formed and the writing granularity mode.

The point is the unit upon which the system of measuring type is based. A point is 0.01384 inch, or nearly 1/72 inch; one pica = 12 points.

PCU maintenance facilities

There is no direct feedback mechanism between the PCU and the series 1600 processor. Analysis of test patterns applied to the analog circuitry of the PCU is made in two basic ways:

1) Visual examination of the several test patterns produced on the CRT and reproduced on output film.
2) Looping test patterns in television fashion to allow dynamic adjustments (focus, etc.) and to provide dynamic

test conditions in the analog circuitry for oscilloscope troubleshooting techniques.

Photocopy control electronics unit

The photocopy control electronics unit (PHYCE) is the input/output (I/O) interface between the series 1600 processor and the photocopy unit (PCU). It contains the necessary control logic and buffering to interface font stroking data transfer from the series 1600 processor memory to the higher-speed analog stroke-writing circuitry in the PCU.[4]

PHYCE digital diagnostic facilities

Implementation of a high fault-resolution program for any control electronics interface involves a hardware/software design tradeoff to enable design of test routines at the lowest possible logic level. A relatively small amount of powerful maintenance logic was incorporated into the PHYCE to feed back into the series 1600 processor several critical test points scattered throughout the PHYCE logic (Fig. 5). Also, a special step-by-step (S×S) maintenance mode was incorporated
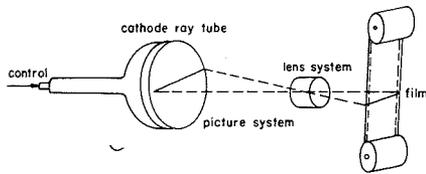
Fig. 1—Videocomp recording principle.

MTCE = MAGNETIC TAPE CONTROL ELECTRONICS
CPCS = CONTROL PANEL CONTROL ELECTRONICS
PHYCE = PHOTOCOPY CONTROL ELECTRONICS
PCU = PHOTOCOPY UNIT

Fig. 2—70/832 Videocomp system.

into the logic to allow substitution of the processor's input/output transfer pulse (strobe) for the selected videoring counter oscillator, providing "snap-shot" samples of test points within normally autonomous sequential logic chains. The additional maintenance hardware comprises approximately 6% of the total PHYCE logic and permits the design of a diagnostic software package capable of making rigorous analyses of component failures within the PHYCE.

Maintenance plan

The basic objective of the 70/832 test and maintenance programs (T/M) is to provide a means of quickly isolating the cause of hardware malfunctions and thereby minimize machine down time due to troubleshooting. The design of the diagnostic programs is based on the assumption that only one hardware fault will occur at any one time. Although the programs are inherently helpful in locating multiple faults, explicit fault resolution is necessarily reduced.

The programs are contained on a single magnetic tape consisting of several functional blocks. The first block is a 256-byte bootstrap loader which executes the loading of a T/M control program into upper memory of the series 1600 memory. The control program resides in memory throughout the testing period and supervises the loading and execution of each individual diagnostic program block. There are several program blocks on the tape, providing test and maintenance facilities for all component units of the 70/832 system. For the purpose of this paper, the three program blocks listed in Table I will be considered in some detail:

Table I—Diagnostic program blocks.

1) PHYCE digital diagnostic program,
2) Standard PCU pattern generator, and
3) Special PCU pattern generator.
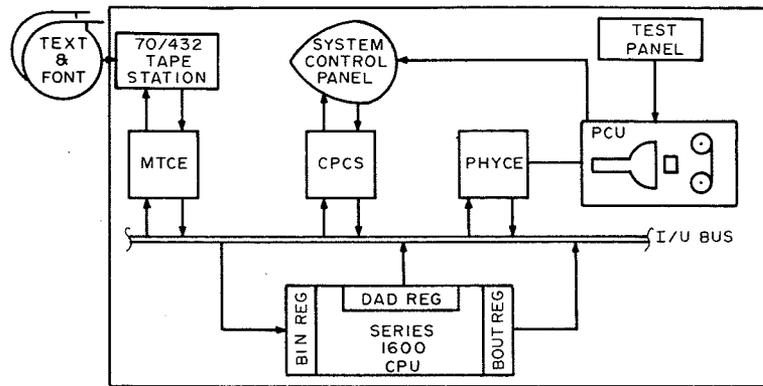
Digital diagnostic programs

A typical diagnostic program flow is shown in Fig. 6. The program establishes test conditions in the PHYCE logic by transmitting a functional command and a byte of test data to the PHYCE while it is in the special $S \times S$ maintenance mode. The program then selects and reads the appropriate PHYCE test point, bringing a byte of data containing the logic conditions at the selected test point back into the series 1600 processor. The *received* test result is then compared in the processor against the *expected* test result stored as constant in the processor memory. A mismatch will result in a program branch to a failure routine; a match will allow the program to continue to the next test in sequence. The individual tests are structured as "building blocks" in which each successive test in the program builds upon preceding tests, making use of previously verified logic. Accordingly, testing begins on directly accessible and common logic circuitry; logic acces-

sible only through verified logic chains follows, until the entire fabric of the PHYCE has been rigorously examined.

The several selectable test points are effectively "handles" on the logic, each consisting of eight data bits assembled in the PHYCE and transferred back into the input register (BIN) of the series 1600 processor. Some of the test points are homogeneous groups of flip-flops such as the horizontal register. Others are a conglomeration of separate functions scattered throughout the PHYCE logic and assembled into a composite test byte. An example of such an assembly is shown in Fig. 7.

The applied tests are designed to exercise the PHYCE logic test points in as many ways as possible. For example, to verify that each flip-flop of a homogeneous register can be independently set to 1 and reset to 0, the following test byte sequence is used. The effect is to "walk" a 1 through a field of 0, followed by a 0 through a field of 1.
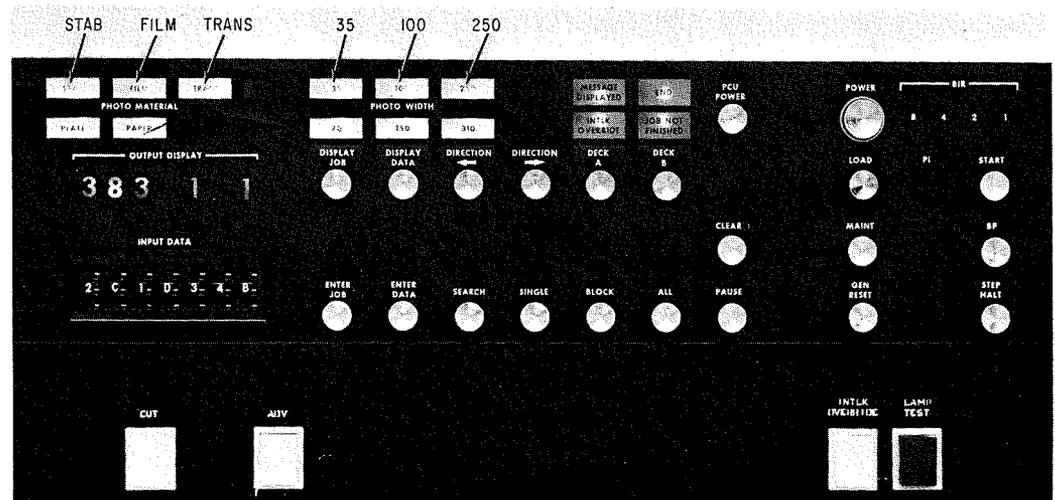
Fig. 3—System control panel.

69
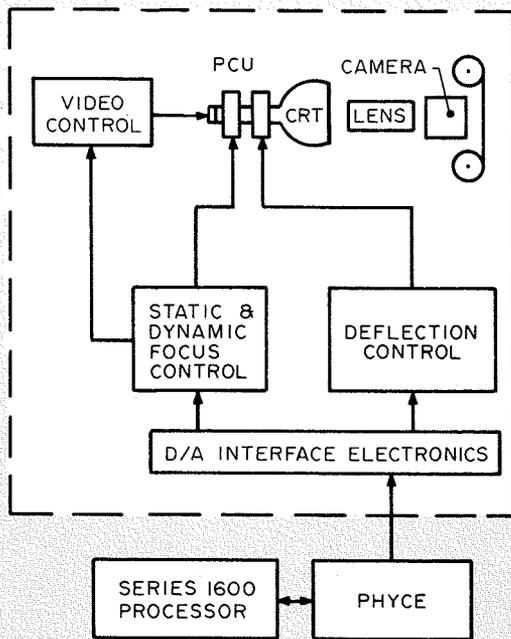
Fig. 4—Photocopy unit.
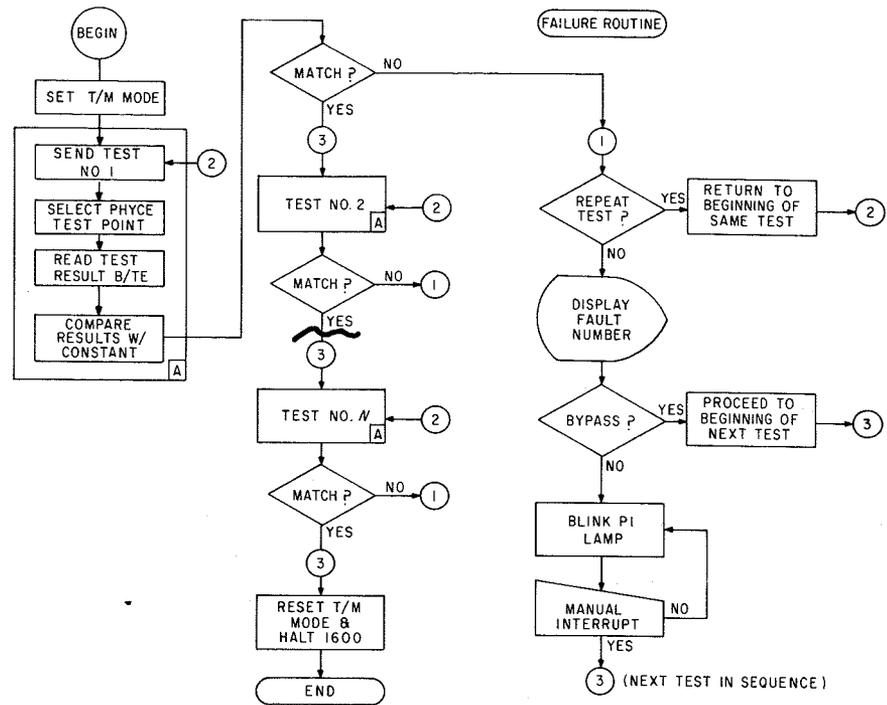
Fig. 6—General flow of the PHYCE diagnostics.
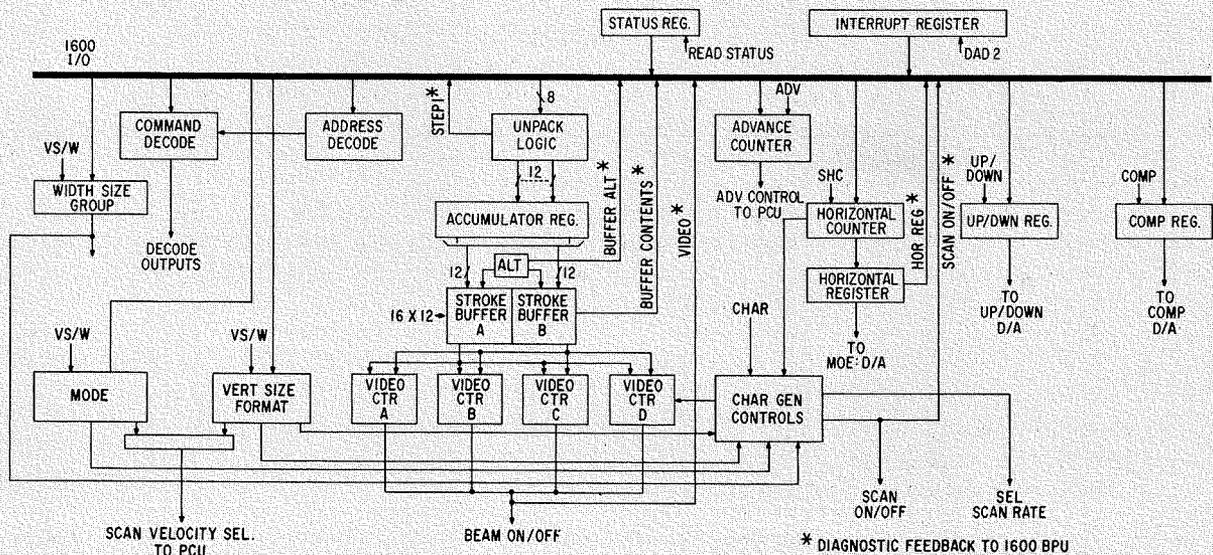
Fig. 5—70/832 PHYCE block diagram.
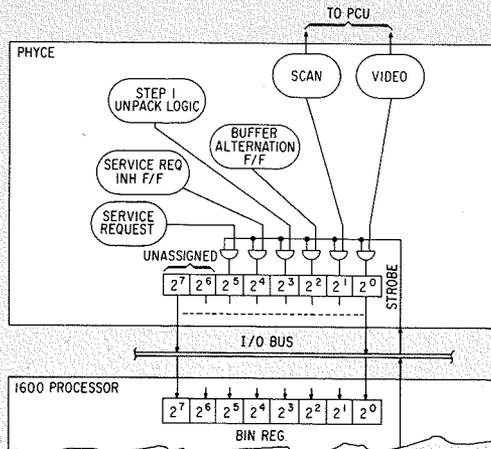
Fig. 7—Test bit assembly in PHYCE.

Typical register test sequence

Byte 1	00000000	all bits reset.
Byte 2	00000001	only 2^0 bit set.
Byte 3	00000010	only 2^1 bit set.
Byte 4	00000100	only 2^2 bit set.
Byte 5	00001000	only 2^3 bit set.
.	.	.
.	.	.
.	.	.
Byte 9	10000000	only 2^7 bit set.
Byte 10	00000000	all bits reset.
Byte 11	11111111	all bits set.
Byte 12	11111110	only 2^0 bit reset.
Byte 13	11111101	only 2^1 bit reset.
Byte 14	11111011	only 2^2 bit reset.
Byte 15	11110111	only 2^3 bit reset.
.	.	.
.	.	.
.	.	.
Byte 19	01111111	only 2^7 bit reset.
Byte 20	11111111	all bits set.

The fault-numbering scheme consists of assigning a unique five-digit number to each individual bit of every test-result byte in the program. This allows possible fault indications from 00001 to 99999 (see Table II).

Table II—Diagnostic fault-numbering plan.

Test-result byte No.	0	1	2	3	4	5	6	7
1	00001	00002	00003	00004	00005	00006	00007	00008
2	00009	00010	00011	00012	00013	00014	00015	00016
3	00017	00018	00019	00020	00021	00022	00023	00024
.		.		.		.		.
.		.		.		.		.
.		.		.		.		.
n	62960	62961	62962	62963	62964	62965	62966	62967
.				.		.		.
.		.		.		.		.
.		.		.		.		.

A bit analysis is made of each test-result byte. The technique (Fig. 8) consists of an "exclusive-OR" compare in which all mismatching bits are flagged:

Received test byte	11110011
Expected test byte	11111011
Exclusive-OR result	00001000

i.e., the 2^3-bit (fault No. xxxxx) was received back in the wrong state.

The flagged bits are indentified and their respective fault numbers displayed by shifting the exclusive-OR result successively to the left into the "carry" position and testing for a 1 in that position.

The maintenance engineer identifies the physical fault by looking up the fault number in a fault dictionary.

Sequential PHYCE logic, such as the clocked gating which controls the beam settling delay counter, is also diagnosed by use of the test result byte and the special $S \times S$ maintenance mode. The function of the counter is to inhibit video during the first four microseconds of a CRT sweep. The test is to verify correct counter loading and decrementing for each of eight possible crystal-controlled counting rates. In the $S \times S$ mode, the several oscillators are inhibited and replaced by a strobe-pulse under control of the series 1600 processor. The mechanism of the test is to count the number of strobes necessary to raise the video toggle function for each oscillator selection. The video signal is fed back to the processor as the 2^0 bit in one of the conglomerate test result bytes (Fig. 7). Each reading of the video signal is considered a possible fault number:

Selected crystal	Substitute strobes required	Fault Nos.
5.4 MHz	22	10013 to 10045
4.8 MHz	20	10047 to 10079
.	.	.
.	.	.
.	.	.

If the video bit is 1 at any point during the countdown, the fault number will indicate the point; numbers 10012 and 10046 indicate the video signal is on before the first clock pulse.

Under normal test conditions, the failure routine displays the fault number on the decimal display lamps of the system control panel and goes into a short wait loop which repeatedly blinks a program indication (PI) lamp on the panel. Escape from the wait loop is obtained by a manually generated processor interrupt which returns the program to the next test in sequence. There are several alternate test options available to the maintenance engineer:

1) *Test repeat*—A dynamic loop of the failing test may be established by setting a breakpoint switch so that a test result mismatch will cause a branch to the beginning of the failing test routine instead of to the wait-loop routine. The loop will continue as long as the fault remains, providing a facility for oscilloscope examination of the failing circuit under dynamic conditions.

2) *Bypass feature* — Since each fault number represents a bit that was read back in the wrong state, it may be necessary to examine associated failures that are occurring at the same time and study the logic to determine the most probable cause. To simplify the collection of all fault numbers, the wait-loop can be bypassed for each test result mismatch. With this option in force, the fault numbers are sequentially displayed long enough to be viewed and recorded and the program automatically continues to the remaining tests in the program.

3) *Program loop*—The entire program can be indefinitely repeated until manually terminated. This option is useful for repeatability tests. The normal wait-loop or the bypass feature can be set up for this option.

The current PHYCE diagnostic program for the 70/832 is capable in most single fault instances of localizing the problem to one or a small number of integrated circuit module boards. In some cases, fault resolution down to a circuit chip can be obtained.

Analog diagnostic programs

The test and maintenance programs for the photocopy unit (PCU) provide three basic types of diagnostic facilities:
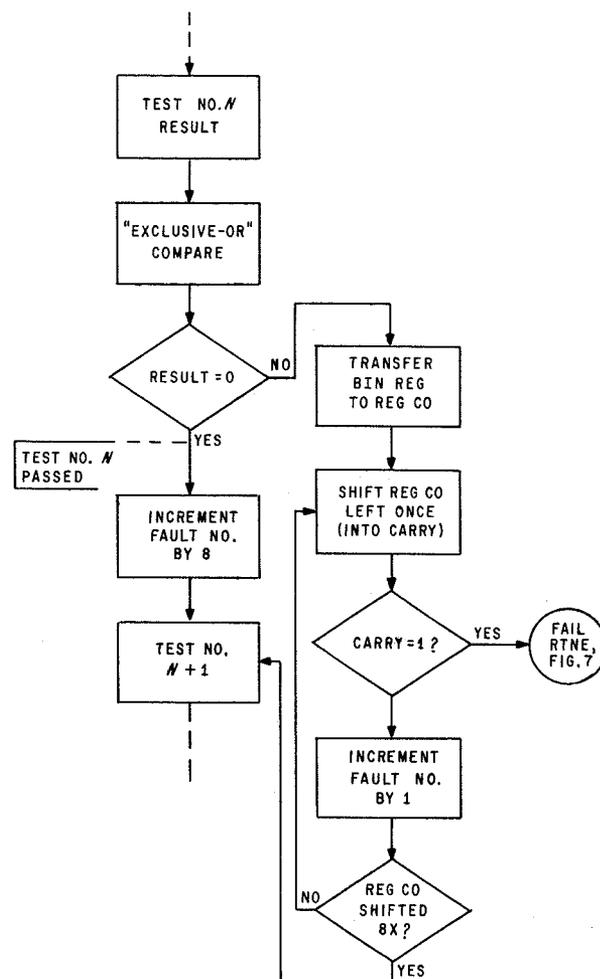
Fig. 8—Bit analysis technique on failure.

1) Prescribed test pattern generation;
2) "On-site" pattern design and generation; and
3) Program loops for circuit examination under dynamic conditions.

With reference to Table I, two analog program blocks are listed. Each of these blocks consists of a control program loaded into the series 1600 processor memory which generates test patterns to be written on the face of the CRT. Each program contains the options of either reproducing the CRT image on film or dynamically looping the pattern to produce a television-type CRT display. The *Standard PCU Pattern Generator Program* contains a library of prescribed patterns designed to provide information for evaluation and analysis of the various PCU parameters. The maintenance engineer has the facility to individually select the patterns in any order and to specify any of four possible writing modes in addition to the "film or loop" option previously mentioned. The grid pattern shown in Fig. 9 is a typical test pattern

71
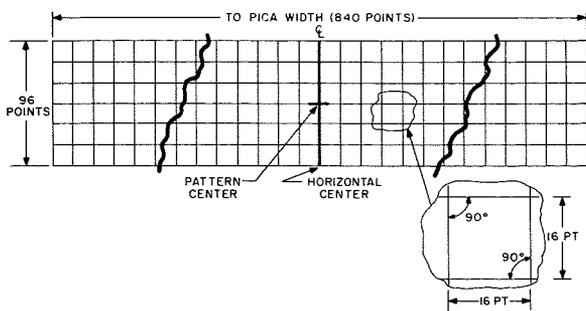
Fig. 9—Grid test pattern.
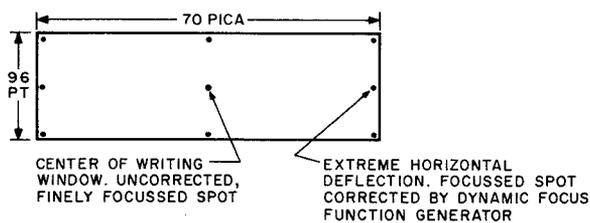
Fig. 10—Focus test pattern.
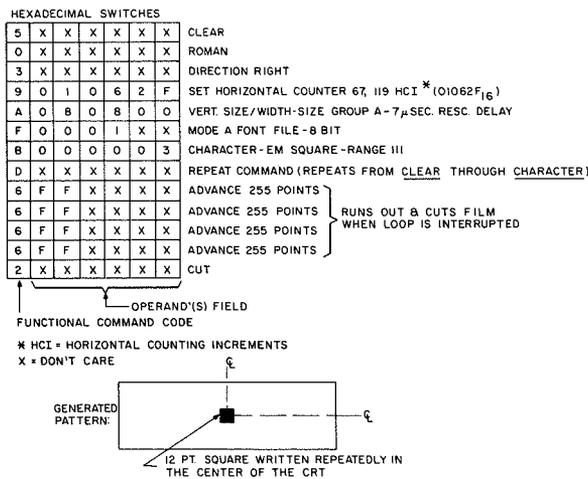
Fig. 11—Special pattern generation routine.

designed to qualitatively evaluate the following adjustable PCU parameters:

1) Uniform perpendicularity over the entire writing window;
2) Horizontal linearity across the entire window;
3) Pattern centering; and
4) Overall horizontal and vertical size.

The mechanism for generating the pattern is two overwriting sub-patterns. The first sub-pattern consists of writing a single vertical stroke, 96-point "character" across the width of the window—spaced at 16-point intervals. The center "character" is a two stroke, 96-point vertical line to produce a darker center line in the final pattern. The second sub-pattern is a set of horizontal lines, written across the width of the window at several vertical positions spaced 16 points apart. Each horizontal line is formed by contiguously writing a series of single vertical increment, 32-point-wide "characters" across the window.

Uniform perpendicularity is verified by all angles of each square in the grid measuring 90°.

Horizontal linearity is verified by each horizontal spacing interval being 16 points wide. A growth of reduction of the individual spacings indicate a non-linearity in the horizontal deflection. Vertical deflection non-linearity is of much less concern in the 70/832 because of the limited vertical deflection. The center of the pattern is identified by the intersection of the heavy vertical rule and the middle horizontal line.

Size adjustments can be made so that horizontal and vertical size as produced on the film is 70 pica (840 points) and 96 points, respectively.

Although the looping option is available for this pattern, its generation mechanism is too complex to be of any real value as a TV-type display because of the short persistency of the CRT phosphor. A simpler one-pass pattern, such as the 3 x 5 dot pattern in Fig. 10, can be very useful in loop mode. This pattern cycle is rapid enough to produce a non-flickering pattern on the CRT, allowing dynamic examination of spot focus at various points on the CRT face with a microscope.

The *Special Pattern Generation Program* is functionally similar to the Standard Generator except that the maintenance engineer "programs" his own pattern designs "on-site", thereby tailoring a pattern to fit his specific diagnostic needs. This program allows the user to dial a string of input instructions into a buffer area in the series 1600 processor memory via the hexadecimal input switches on the system control panel. When the user has completed loading his routine into the buffer, he pushes a button to generate the pattern defined by his routine. The "film or loop" option is also available to him in this program.

A typcal string of commands and the resulting pattern is illustrated in Fig. 11.

The user can also use the Special Pattern Generator to produce short dynamic test loops for oscilloscope examination of circuit points in both the PHYCE and the PCU. In such cases, the entire loop can be a string of functional commands with no pattern being produced on the CRT face.

Future possibilities

At the present, the lack of direct feedback of PCU test points into the series 1600 processor precludes programmed analysis of PCU hardware failures. As the VIDEOCOMP systems evolve to serve other typesetting applications, new diagnostic techniques may become possible. For example, a high speed microfilm reading capability is being studied. Such a system would use the CRT as a flying-spot scanner with a photomultiplier being used to sense the "black" and "white" transitions of the information on the microfilm. A digital control interface unit would encode the scanned information into digital data and transfer it into the series 1600 memory. The information could then be retrieved and reproduced at a later time. Such a system inherently provides a diagnostic loop for on-line fault detection and analog adjustment of several PCU parameters. The basis for this new technique would be a precise reference pattern on a glass plate located at the normal microfilm position in the flying spot scanner optical plane. The standard reference plate, the photomultiplier, the PCU analog circuitry, the CRT, and the microfilm optical systems, and the processor are considered as a closed loop in which the analog function generators are the loop variables. Adjustment of the analog function generators will, in effect, correct the horizontal and vertical parameters as they appear on the CRT face. Software in the series 1600 processor will then be able to detect and numerically evaluate deviations from the nominal values, stored as constants in the processor memory, and produce a quantitative display of the error.

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2. Greenberg, J. S., Schubert, R. E., "Electronic Composition System," RCA ENGINEER, Vol. 13, No. 6 (Apr-May, 1968).
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Evaluation of missile miss distance

W. J. O'Leary

For obvious reasons, missiles cannot be tested under all conditions and over all ranges. The model described in this paper can be used to extrapolate the results of a few tests under certain conditions to a wide range of conditions. This model also facilitates diagnosis of system problems and analysis of system characteristics.
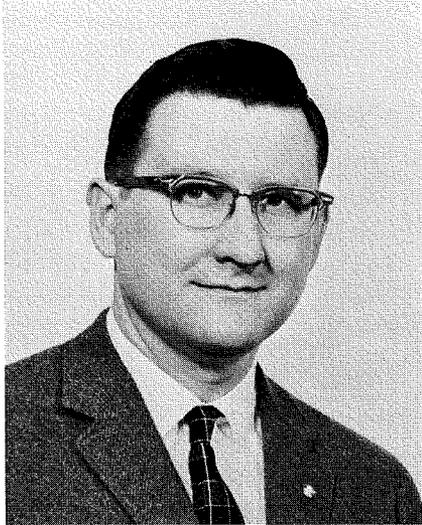
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FIRING MISSILES as a performance demonstration of the miss distance presents a number of problems in the design of the test and the analysis of results. Among the problems of particular concern are

1) The high cost of each observation limits the number of tests;
2) Every set of conditions (e.g., range, altitude) has a distinct miss distance distribution which presents a potential difficulty of relating observations under varying conditions; and
3) Restricting the test to one or two conditions limits test conclusions to those conditions.

Each of these problems appears to work in the direction of very limited information for a reasonable test size. An approach is developed for the design and analysis of missile miss distance tests which permits great flexibility in the design of the test in addition to providing a high utilization of the data for analysis. The result is a possibility for significant reduction in test costs while retaining the same level of risks in the test decisions.

The approach to test design is based on a framework of design verification. This means that the test serves the function of validating the theoretical basis of the missile system design. The distinct advantage to be gained here is that a favorable test result will not only indicate the achievement of requirements but will also provide the required confidence in applying the design relationships for

1) Estimating expected results over a wide range of conditions,
2) Redesign to meet other requirements, and
3) Allocation of requirements within the system.

These design relationships are usually in the form of a quantitative mathematical model. Such a model would combine all significant system and external variables that have an affect on missile miss distance. It is not the purpose of this paper to elaborate on the characteristics of such a model but rather to make use of the model to indicate expected results for a given set of conditions. Thus, through the use of the miss distance model, all significant system errors can be combined for a specific set of target conditions to obtain an estimate of miss distance. This estimate is then used as a reference standard of comparison against observed miss distance and as a link to relate the several observations made under widely varying target conditions.

Another key element in the development of the approach is the statistical nature of the variable—miss distance. In target problems, reasonable first order assumptions for the distribution of hits around the target include

1) No net bias.
2) A gaussian distribution of hits around the target center.

Miss distance estimate

The average location of the hits is at the origin, and the standard deviation in this case is a function of the significant errors defined in the miss distance model. Under these conditions, the magnitude of the miss distance is distributed in accordance with a Rayleigh distribution given by

$$p(r) = (r/\sigma^2) \exp(-r^2/2\sigma^2)$$

where r is the magnitude of the miss distance, and σ is the standard deviation of the gaussian distribution previously defined.

The mean and standard deviation of this Rayleigh distribution can then be expressed in terms of the standard deviation of the gaussian distribution of hits around the target as $r' = 1.25\sigma$ and $\sigma_r = 0.655\sigma$. Thus, for a Rayleigh distribution there is a fixed ratio between the mean and standard deviation:

$$\sigma_{r/r'} = \frac{0.655\sigma}{1.25\sigma} = 0.523$$

These results can now be related to the miss distance measurements. Assume that there are n measurements of miss distance made for a variety of target conditions and given by X_i, $i = 1, 2, \cdots, n$. Also, assume that the expected miss distance from the design model for each set of target conditions is given by $r'_i, i = 1, 2, \cdots, n$.

If the hypothesis is true, that the observations are from populations with
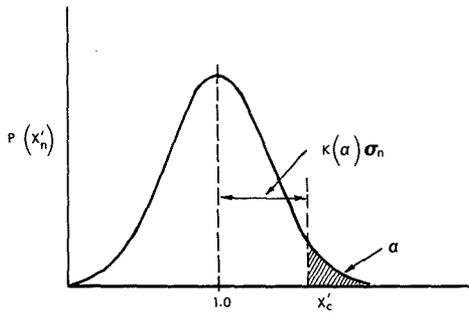
Fig. 1—Test criteria for acceptance of the null hypothesis that the model is correct.
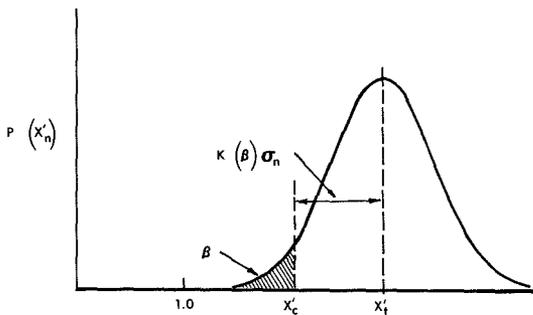
Fig. 2—Acceptance criteria assuming the model is not a true representation.

means estimated by the model, then the ratio X_k/r'_k for all values of k will have an expected value of 1.0. In addition, as shown above, there is a fixed relationship between the mean and standard deviation of the Rayleigh distribution. For this normalized scale, the standard deviation of the Rayleigh distribution is 0.523. Thus, with an assumption that the model is a true representation of real life, a very convenient normalization procedure can be used to relate all observations—regardless of the variety of target conditions. The normalized parameter can then be analyzed as if all observations were from the same population.

With this property of the normalized scaling of miss distance, a set of normalized operating characteristic curves can be calculated and used for test design.

By the central limit theorem, the mean of a sample of n observation would be distributed as a gaussian distribution with a standard deviation of

$$\sigma_n = 0.523/n^{1/2}$$

Based on a mean of 1.0 and a standard deviation of $0.523/n^{1/2}$ the normal form of the gaussian distribution of this sample mean is given by

$$P(x'_n) = [(n/2\pi)^{1/2}/0.523]$$
$$\exp[-(x'-1)^2 n/0.523^2]$$
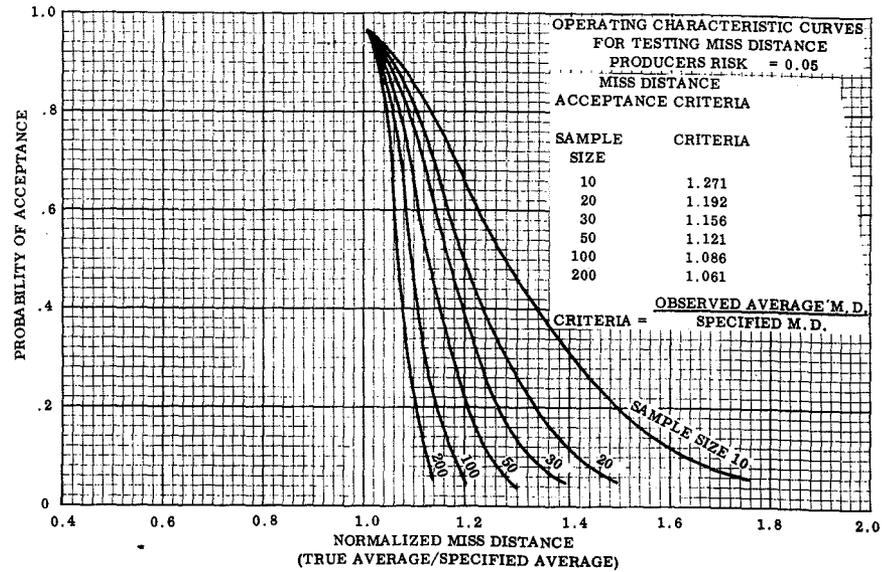
Fig. 3—Operating characteristic curves for testing miss distance; producer's risk $\alpha=0.005$.
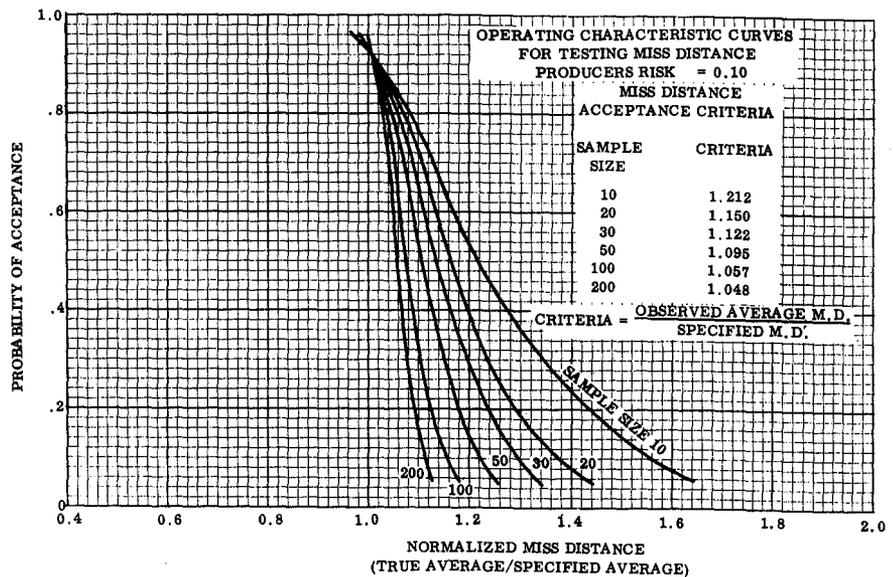
Fig. 4—Operating characteristic curves for testing miss distance; producer's risk $\alpha=0.1$.
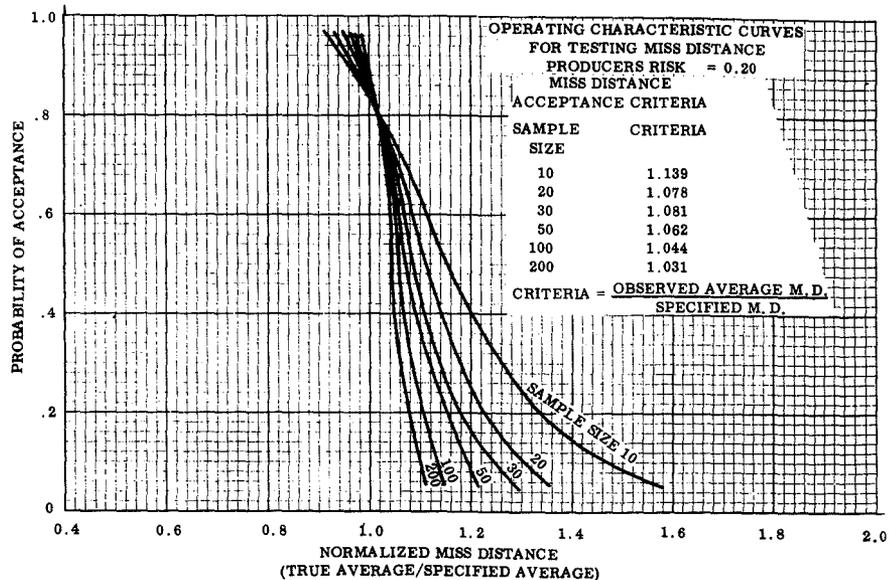
Fig. 5—Operating characteristic curves for testing miss distance; producer's risk $\alpha=0.2$.
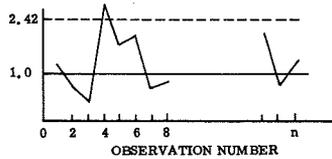
Fig. 6—Control limits of the model.

It is now possible to establish the test criteria for acceptance of the null hypothesis that the model is correct (Fig. 1). If the acceptance criteria on the sample mean is set at x'_c, any test mean above this value will lead to a rejection of the null hypothesis. The risk of this result (considering the model is correct) is equal to the area α as shown. If $K(\alpha)$ is the number of standard deviations above the mean, 1.0, to limit the risk to α, the acceptance criteria may be expressed as

$$x'_c = 1.0 + K(\alpha)\sigma_n$$

or

$$x'_c = 1.0 + K(\alpha)0.523/n^{1/2}$$

Example

Suppose the sample size is $n = 30$ and α is to be limited to 0.05. From a table of the normal distribution, a risk of $\alpha = 0.05$ corresponds to a $K(\alpha) = +1.64$. The acceptance criteria which limits the risk to 5% that an acceptable model will be rejected is given by

$$x'_c = 1.0 + 1.64(0.523/30^{1/2})$$
$$x'_c = 1.156$$

The next step in the derivation of the operating characteristic curve is the determination of the probability of acceptance when the hypothesis is that the model is a true representation is false. If the actual average miss distance is higher than predicted, the true average may be stated as x_t' where $x_t' > 1.0$. Based on a mean of x_t' and a standard deviation of $0.523\, x_t'/n^{1/2}$, the gaussian distribution is given by

$$P(x'_n) = [(n/2\pi)^{1/2}/0.523x'_t]$$
$$\exp[-(x'-x'_t)^2 n/(0.523x'_t)^2]$$

This situation is shown graphically in Fig. 2. In this case, a test average below the acceptance criteria, x_c', will lead to an acceptance decision when the model is not true. The probability of acceptance is equal to the area β as indicated and is the risk of acceptance when the hypothesis is false. To determine the

value x_t' for a given risk, β, the relationship can be written

$$x'_c = x'_t + K(\beta)\sigma_n$$
$$x'_c = x'_t + x'_t K(\beta)0.523/n^{1/2}$$

or

$$x'_t = \frac{x'_c}{1 + K(\beta)0.523/n^{1/2}}$$

substituting for x_c'

$$x'_t = \frac{1.0 + K(\alpha)0.523/n^{1/2}}{1.0 + K(\beta)0.523/n^{1/2}}$$

To continue the example for the sample size of 30, the value of x_t' will be calculated at which the risk of acceptance is limited to $\beta = 0.10$. From the table of the normal distribution $K(\beta) = K(0.10) = -1.28$.

Thus

$$x'_t = \frac{1.156}{1.0 - 1.28(0.523/30^{1/2})}$$

$$x'_t = 1.32$$

This means that with a sample of 30 missiles with a normalized acceptance criteria of 1.156 there is a 10% chance of an acceptance decision when the true average miss distance is 32% higher than predicted by the simulation model.

Figs. 3, 4 and 5 show families of operating characteristics curves for producers risks (α-risks) of 0.05, 0.10 and 0.20.

Curves are shown for sample sizes of 10, 20, 30, 50, 100 and 200. Also shown in these Figures are the acceptance criteria for each sample size. In the curves as presented, specified miss distance is synonomous with the miss distance predicted for a given set of conditions with the system design model. If the specified miss distance is somewhat larger than that predicted by the model (i.e. equivalent to a safety factor in system design) it is possible to make constant scale adjustments in all model estimates so that all observations are scaled to the required miss distance rather than the model prediction. This is equivalent to the hypothesis that the true miss distance is a fixed proportion higher (i.e. the safety factor) than would be predicted by the simulation model.

Advantages of this technique

A very definite advantage of this technique is that the test designer is free to select a representative set of tests and

be limited only by sample size. The test designer is not forced to limit his attention to only 1 or 2 test conditions to obtain reasonable test results. Other advantages derive from the conveniece of diagnostic data analysis.

One convenient diagnostic data analysis technique is the control chart. Missile tests are run in time sequence and it is desirable to assess progress during this sequence, as well as detecting potential problems. To be useful, the control chart must take into consideration the normal variation of the process and only direct attention to an apparent unusual condition. This can be done by setting an upper control limit such that there is only a 1% chance that this limit would be exceeded by any one observation of miss distance. An observed miss distance falling above this limit miss distance is then interpreted as a potential problem. To calculate this control limit, it is necessary to return to the Rayleigh distribution

$$P(r) = (r/\sigma^2)\exp(-r^2/\sigma^2)$$

Integration of this expression from 0 to R gives the cumulative probability that this miss distance $r \leq R$:

$$P(R) = 1 - \exp(-R^2/2\sigma^2)$$

If $P(R)$ is selected to be 0.99, then

$$\frac{R^2}{2\sigma^2} = 4.6$$

$$R = 3.03\sigma$$

But the mean of the Rayleigh is 1.25σ; thus the normalized control limit is

$$R_n = \frac{3.03\sigma}{1.25\sigma} = 2.42$$

A typical control chart is shown in Fig. 6. By the criteria previously stated, observation number 4 is suspect.

Another diagnostic technique that may be applied to the test is a comparison of the average for n samples to the standard deviation of the n samples. This provides a convenient test for the presence of bias in the system (e.g. a tendency to aim consistently to the right of the target). The expected value of this ratio is

$$\frac{1.25\sigma}{0.655\sigma/n^{1/2}} = 1.91n^{1/2}$$

A ratio of mean-to-sample standard deviation significantly higher than this value would indicate system bias.

Technical excellence

B. D. Smith

The Zero Defects program was very successful in Manufacturing activities at RCA because quality workmanship could be directly related to a quality product. However, no such direct relationship existed in Engineering. This paper describes a motivational program that was designed specifically for engineers and scientists at the Aerospace Systems Division as part of the Zero Defects program.

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received the BSEE from the Georgia Institute of Technology in 1951; the MSEE from Drexel Institute of Technology in 1960; and has graduate credits toward the MBA. From 1951 to 1956, he worked for the Philco Corporation on the development and test of airborne speech scrambling equipment, UHF receiver-transmitter modifications, and advanced development of color television. He joined RCA in 1956 initially working on the design and development of airborn fire control radar, missile auxiliaries, and countermeasure equipment. In 1959, as Manager of Product Design Assurance, Mr. Smith was responsible to the chief engineer for the design assurance aspects of all Airborn Systems Division Projects. In 1961, Mr. Smith transferred to Burlington to assume Product Assurance responsibility for the Air Force Satellite Inspector Program and in 1962 he was made Product Assurance Manager for all Airborn Systems Division Programs. In 1965 he also assumed responsibility for the division Zero Defects and Personal Excellence Programs for which the division received the Air Force Craftsmanship Award in 1967. Mr. Smith is a senior member of IEEE and ASQC, and is a registered professional engineer in Massachusetts.

I N PHASE I of our Zero Defects Program, RCA was able to report the usual success story of reduction of Manufacturing defects. However, in technical areas (such as Engineering) after the initial surge of interest died down, it was difficult to sustain the motivation. In manufacturing, workmanship quality can be measured because defects lead to rejected units, rework, and lost time and materials. Likewise, the effect of various incentive programs can be measured, and the results used to reward outstanding performance. However, it is not easy to measure the performance of scientifically oriented people because their mistakes do not appear as a readily measurable workmanship item.

As a result, Phase II of Zero Defects at RCA contained a program specifically tailored for the scientific and creative people — the engineers. The problem of decreasing defects in engineering was extremely difficult to define because no one was sure exactly what constituted an engineering defect. Consequently there were no clear solutions developed which would enable us to show our performance improvement through "defect" reductions.

Rather than measure defect reductions in Engineering, a motivation program was established to improve performance in general. The purpose of this program—Technical Excellence—was to cause the Engineering department as an entity to function more effectively by encouraging engineers to be more professionally oriented, more active in their professional societies, better educated, and have better communications with management.

Technical excellence organization

Figure 1 shows the Technical Excellence organization. The program is headed by the Chief Engineer, who takes an active interest in the program.

An Advisory Board, with representatives from Product Assurance, Personnel, and Engineering Administration, is available for coordination with other division motivation programs. However, the key point of the organization is the Technical Excellence Committee. Representatives from each engineering section are carefully selected to plan and implement the program. Their selection required careful consideration of both technical and professional competence. The direct participation of the engineers, through their Technical Excellence Committee, significantly enhanced the success of the program.

Recognition levels

The Technical Excellence Committee decided that three types of recognition would be appropriate:

1) An engineering section would be recognized quarterly for best performance in predetermined professional areas.
2) A team award would be given when appropriate for meritorious performance.
3) An individual would be selected monthly for an Engineer of the Month Award.

Selection criteria

Section awards

Figure 2 lists typical elements which were included for measurement for the engineering section awards. In area I, professional societies, the first objective was to increase total engineering membership in appropriate professional societies. A second objective was to get more active attendance at society meetings. Finally, additional participation in the activities of the societies was encouraged through appropriate committee memberships. Just the act of belonging to a professional society provides an engineer with state-of-the-art technical dialog and progress in his (and related) fields which helps keep him updated on new developments. Active participation in

society meetings and activities is an important form of continuing education, and also provides peer contacts with engineering communities outside of the RCA organization.

Continuing education (II of Fig. 2) is self explanatory. Emphasis is on both graduate and college level courses outside of RCA and on participation in internal special education programs. (These latter programs are often designed to cover state-of-the-art courses not yet available in the universities.)

An engineer gets considerable ego satisfaction and personal recognition when he is able to formally write or present his engineering accomplishments. He also goes through a self-discipline and education exercise in the process of preparing his presentation. To encourage this type effort editorial and graphic assistance was provided as well as assistance in getting papers approved and published. Participation in our internal design reviews was also encouraged and recognized as a form of personal Technical
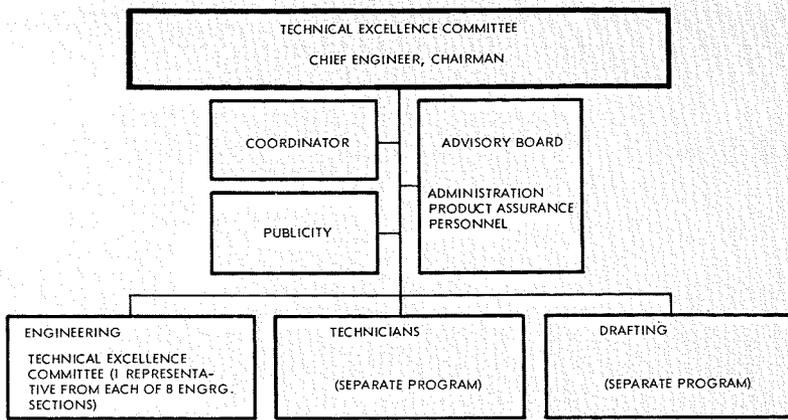
Fig. 1—Technical excellence organization chart.

TECHNICAL EXCELLENCE COMMITTEE
CHIEF ENGINEER, CHAIRMAN

COORDINATOR — ADVISORY BOARD

ADMINISTRATION
PRODUCT ASSURANCE
PERSONNEL

PUBLICITY

ENGINEERING
TECHNICAL EXCELLENCE COMMITTEE (1 REPRESENTATIVE FROM EACH OF 8 ENGRG. SECTIONS)

TECHNICIANS
(SEPARATE PROGRAM)

DRAFTING
(SEPARATE PROGRAM)

Fig. 2—Technical excellence section scoring.

I. PROFESSIONAL SOCIETY MEMBERSHIP
PROFESSIONAL SOCIETY COMMITTEE MEMBERSHIP
PROFESSIONAL MEETINGS ATTENDED

II. CONTINUING EDUCATION

III. COMPANY REPORTS
PAPERS PUBLISHED OR PRESENTED
ENGINEERING NOTEBOOKS
DESIGN REVIEW REPORTS
ENGINEERING AND IR&D HIGHLIGHTS

IV. PATENT DISCLOSURES
PATENT FILINGS

Excellence. Areas III and IV of Fig. 2 also illustrate the kinds of things which, if improved, tend to make the engineering group more effective, more efficient, and more able to find answers to questions which arise in solving their daily engineering problems.

Team awards

The criteria for Team Awards are dependent on particular circumstances, but the objective is to recognize outstanding performance or professional excellence of two or more individuals on a common project. An outstanding technical breakthrough or performance of a key assignment on schedule are typical of criteria used.

Engineer of the month awards

Selection of the Engineer of the Month involves the following considerations:

Creativity: How has the award candidate applied his imagination to this assignment? Has he developed any ingenious approaches?

Technical accomplishment: What did he accomplish technically? Did he develop a unique approach?

Acceptance and discharge of responsibilities: Did he accept the responsibility assigned and follow through? Did he deliver on schedule?

Technical papers and presentations: Has he made any presentations within or outside of RCA in his field of interest? Is his research notebook kept current, including proper witnessing of the work being done and witnessed?

Professional society activities: Is he a member of one or more professional societies? Does he attend their meetings? Does he participate in their activities? Is he on any committee or is he an officer in any professional group?

Patent disclosure: Has he filed any disclosures on his most recent work?

New areas of business: Has he made outstanding efforts in planning, fostering, and influencing the direction of technical effort in new areas of company business?

Recognition

Section of the month

Recognition of the Section of the Month is accomplished through suitable publicity and by presentation of a handsomely engraved walnut plaque. Special section recognition events are also scheduled as appropriate. For example, an annual banquet is held with all engineers (and their wives) who have had papers published during the year. This tangible recognition has been well received by both engineers and their wives.

Team citations

Team awards include a framed certificate, a pocket slide rule, and recognition at the Engineer of the Month luncheon which is hosted by the Chief Engineer and Division Vice President.

Engineer of the month

The Engineer of the Month is also recognized, with his wife, at the Engineer of the Month luncheon; he also is given a professional textbook of his choice. A handsome engraved medallion is presented to the Engineer of the Month as lasting recognition of his achievement.

Communication

Part of the Technical Excellence Program included a program to improve communication from management to the engineers. The *Technical Excellence Newsletter* was established to fulfill this objective.

Results

Obviously, quantitative results are not easily obtained in a broadly based Technical Excellence Program. We do, however, have enough statistics to indicate that the original assumptions on improving performance were funda-

mentally sound. For example, 43% of the RCA Aerospace Systems Division engineering staff are attending either local colleges or universities or are taking after-hours courses. We have seen nearly a 100% improvement in our publications performance. Our patent submissions have increased, and communications have notably improved. Membership in professional societies has increased to 70% of the engineering staff.

Some basic but realistic assumptions enable some of this performance to be converted to dollars. For example:

1) If Technical Excellence increased motivation and morale in engineering so as to cause efficiency to increase by 1%, this would result in over $100,000 cost avoidance in a year with our engineering payroll.

2) If membership in professional societies saves the average engineer 15 minutes per week, it would represent potential savings of over $10,000 per year. It seems reasonable that the kinds of information made available by professional societies could give an engineer insights to see alternate solutions to problems. Advertisements in the professional society magazines also gives him additional insight into new products and processes which might improve his work. Thus, the concept of saving time through professional society membership seems reasonable.

3) If the benefits of continuing education allow the average engineer to save 15 minutes per week, potential savings are again over $10,000 per year. Again, it seems reasonable that the broader perspective afforded by continuing education can be responsible for quicker or alternate solutions to problems or could enable the engineer to be more effective in his engineering approach.

4) If improved communication saves each engineer 5 minutes per week, potential savings are again over $10,000 per year.

Qualitative assessments of results since Technical Excellence began indicate that these kinds of improvements are reasonable and, if anything, conservative, even though we are unable to accurately pinpoint absolute values.

Reliability-cost tradeoff study for electronic equipment

J. S. Korda

This paper prescribes the economical limits of the employment of high-reliability high priced parts to achieve high system reliability. The mathematical formulae derived from the basic cost function are valid in all cases whether the "system" is a cordwood module or a complex computer.

STUDIES of the cost of maintenance of military electronic equipment show these costs to be as much as 60 to 1000 times the original procurement cost. To avoid such expenditure, higher requirements are being imposed on manufacturers to achieve greater inherent reliability.

Reliability can be designed into an equipment in many different ways:

1) Derating components,
2) Employing redundancy, or
3) Selecting components.

Component derating

Derating is one of the most powerful reliability tools available to the designer. The principle to keep in mind is that the life of most parts increases as the stress level is decreased below the rated value. In general, the more a part is derated the longer it will last. Practically, however, there is a minimum stress level below which increased circuit complexity required to step up performance will offset the gain in reliability.

Redundancy

Redundancy can be defined as the provision of more than one means for accomplishing a given function. The designer may often find that redundancy is the quickest and easiest solution if the circuit function is already designed. On the other hand, redundancy may exceed the limitations on size, weight, and power; furthermore, the required sensing and switching circuits often are so complex as to offset the advantage of redundancy.

Component selection

Space age electronic systems are becoming increasingly complex requiring

extremely high reliability while at the same time they must occupy less volume and weigh less. Because of these seemingly contradictory requirements and the above mentioned limitations of component derating and redundancy techniques the component selection becomes the last effective tool to achieve high reliability. In this paper an attempt will be made to discuss the economical limits of component selection.

Mathematical model

The mathematical model of any electronic equipment with no built-in redundancy is:

$$R(t) = \exp(-\lambda t) \qquad (1)$$

where $R(t)$ is the reliability of the system; λ is the failure rate of the system; and t is the mission time.

Generally, the failure rate of a system of m components can be expressed as:

$$\lambda = \sum_{i=1}^{m} c_i \lambda_i, \qquad (2)$$

were c_i is a constant dependent on the quantity and duty cycle of the ith component; and λ_i is the failure rate of the ith component

Substituting Eq. 2 into Eq. 1:

$$R(t) = \exp(-\sum_{i=1}^{m} c_i \lambda_i t) \qquad (3)$$

Reliability requirements

For easier pictorial presentation, assume that $m=2$. Therefore, to satisfy (or exceed) a system reliability requirement, R', for a mission of T hours, it can be written:

$$R' \leq \exp[-(c_1\lambda_1 + c_2\lambda_2)T];$$

For $R' > 0.90$, this can be approximated by

$$R' \leq 1 - (c_1\lambda_1 + c_2\lambda_2)T.$$

Therefore,

$$c_1\lambda_1 + c_2\lambda_2 \leq \frac{1-R'}{T}. \qquad (4)$$
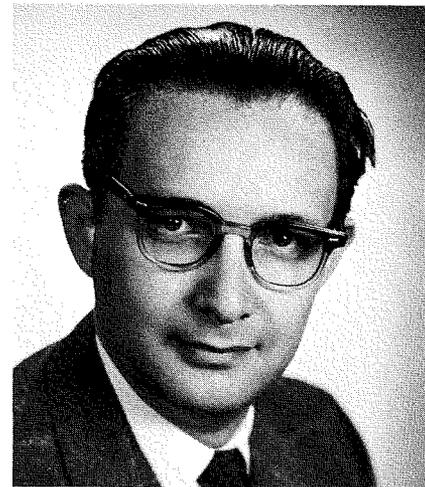
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started his university education at the Technical University of Budapest and graduated in Mechanical Engineering from the University of British Columbia, Vancouver. Prior to graduation, he worked fifteen years in telecommunication with Standard Telephone and Cables, Budapest and with British Columbia Telephone Company, Vancouver. After graduation he took up positions with Computing Devices of Canada Ltd. in Ottawa as Reliability Engineer. In 1965 he joined RCA Limited, Montreal as Administrator of the Aeorspace Reliability Engineering Group. Mr. Korda is a member of CASI, APEO and CEQ and is a registered professional engineer.

Considering the present state-of-art, it can be assumed that:

$$\lambda_1 \geq \lambda_1^*$$

and

$$\lambda_2 \geq \lambda_2^*$$

where λ^* designates state-of-art failure rates.

It can be seen that there are numerous solutions to this problem. In Fig. 1, any point in the solution space bounded by the straight lines joining points A, B, C satisfies Eq. 4.

Obviously, the values at point A give the highest reliability result. However, the cost of parts increases sharply as the failure rate decreases. Therefore, the question is what higher price is reasonable for higher reliability?

Cost function

The cost of maintenance is a function of the replacement cost and manpower cost modified by the failure rate. Thus the cost difference, δ, between a pres-
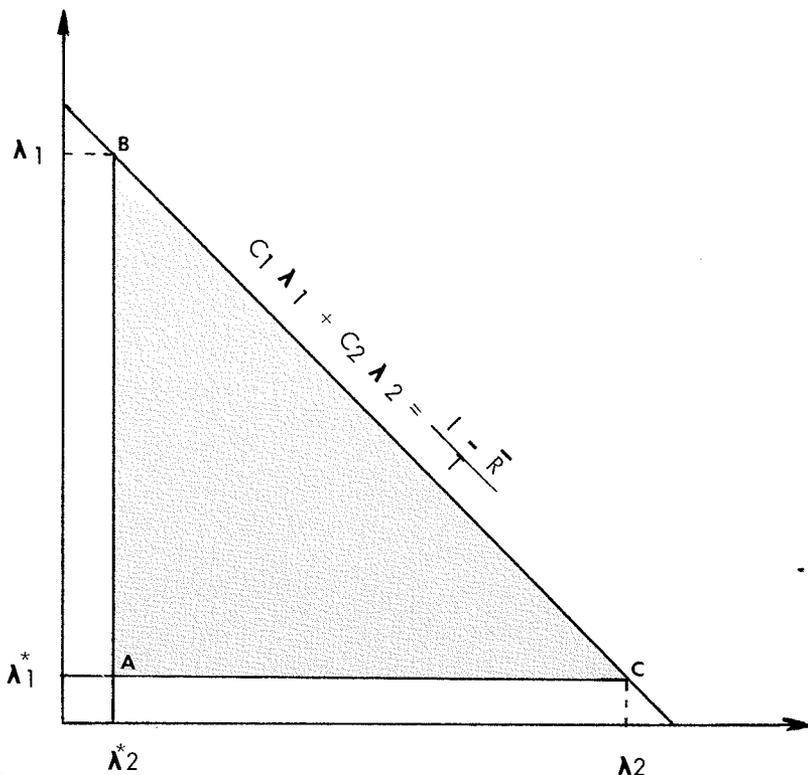
Fig. 1—Solution space boundaries for Eq. 4.
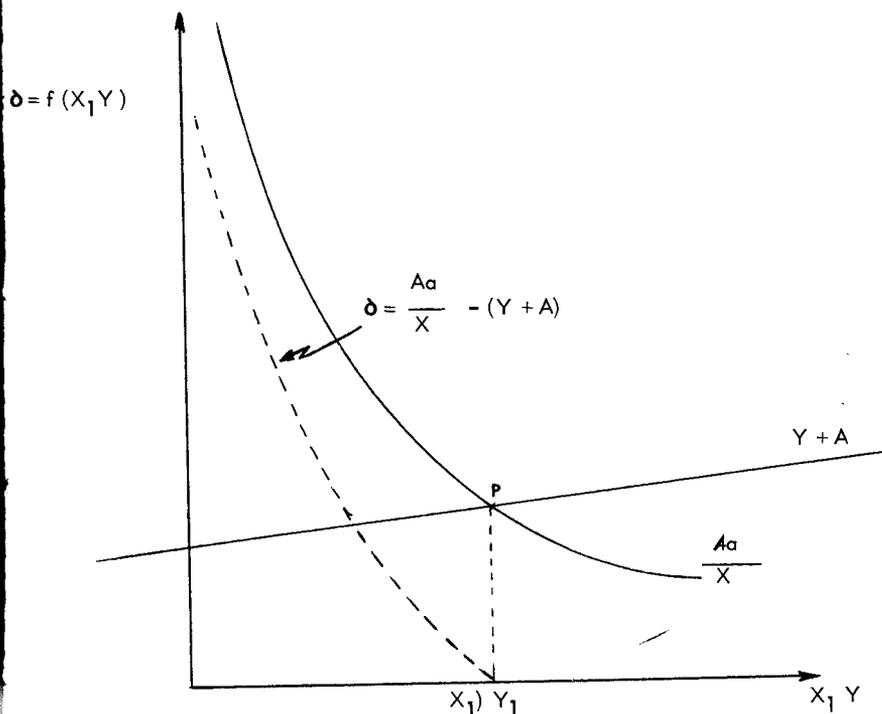
Fig. 2—Cost differential, δ, caused by going to a higher reliability component.

ently used and a new, improved equipment may be expressed as:

$$\delta = \sum_{i=1}^{m} [(M_{oi} + S_{oi}) \lambda_{oi} - (M_{ni} + S_{ni}) \lambda_{ni}] \quad (5)$$

where M_{oi} is the manpower cost of the ith old part; M_{ni} is the manpower cost

of the ith new part; S_{oi} is the cost to procure the ith old part; S_{ni} is the cost to procure the ith new part; λ_{oi} is the failure rate of the ith old part; and λ_{ni} is the failure rate of the ith new part.

It can be seen, as long as the difference in maintenance cost is positive ($\delta > 0$),

the new equipment will cost less than the old one.

At this point, the following assumptions are made:

1) Since the new parts are the same type as the old ones, the manpower requirements are the same, i.e.

$$M_{oi} = M_{ni} = M_i$$

2) Equipments having exponential failure patterns are maintained as failure occurs, i.e. no preventive maintenance.
3) The expected design life of the equipment is much larger than the MTBF of the equipment.

Therefore Eq. 5 becomes:

$$\delta = \sum_{i=1}^{m} [M_i (\lambda_{oi} - \lambda_{ni}) + S_{oi} \lambda_{oi} - S_{ni} \lambda_{ni}] \quad (6)$$

It can be recognized that:

$$S_{ni} = S_{oi} + \Delta S_i$$

where ΔS_i is the increase in procurement cost:

$$\delta = \sum_{i=1}^{m} [M_i + S_{oi}) (\lambda_{oi} - {ni}) - \Delta S_i \lambda_{ni}] \quad (7)$$

If it is recognized that

$$M_i + S_{oi} = A_i \text{ (a constant)}$$
$$\lambda_{oi} = a_i \text{ (a constant)}$$

And the following notations are introduced:

$$\lambda_{ni} = x_i$$
$$\Delta S_i = y_1$$

Then Eq. 7 becomes:

$$\delta = \sum_{i=1}^{m} A_i (a_i - x_i) - y_i x_i \quad (8)$$

Breakeven point (P) is when $\delta = 0$:

$$\delta = \sum_{i=1}^{m} A_i (a_i - x_i) - y_i x_i = 0 \quad (9)$$

For simplicity, assume that $m = 1$, and after little manipulation Eq. 9 becomes:

$$\delta = \frac{Aa}{x} - (y + A) = 0 \quad (10)$$

It can be seen from Fig. 2 that the cost difference (δ) will always be positive if

$$0 < x < x_1 \text{ and } y < y_1$$

Conclusion

The mathematical formulae derived are valid regardless of the system complexity. Using computers to solve Eq. 7 for any number of "components" (parts, modules, stages, etc.) raises no problem, and at the same time the procuring agency and the manufacturer can easily recognize what amount may be invested to purchase an equipment to save on maintenance cost.

Human performance and equipment reliability

Dr. H. B. Matty

The terms *reliability* and *human performance*, when mentioned together, usually elicit the concept of the reliability of human performance. While this is an important relationship, there is also another interface which exists between reliability and human performance. This is the use of equipment reliability data in analytic techniques used to predict human requirements in maintenance. This paper will discuss an hypothetical space system, using in-space maintenance as a frame of reference. However, the techniques are applicable to all electronic systems of any appreciable size.

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is a graduate of the University of Arizona, and holds the PhD in Psychology from Florida State University. From 1941 to 1947, he was employed by the New York Telephone Company, working mostly on tests and measurements of toll systems. He was on military leave to the US Army during WW II. Recalled to active duty with the USAF in 1948, he worked two years with airborne radar and two years in electronic countermeasures. During 1952 and 1953, while employed by Bell Aircraft Corporation, he participated in R&D testing of the RASCAL missile's guidance system. While a Graduate Assistant at Florida State University from 1954 to 1957, he taught Psychology and conducted behavioral research. In 1957, he joined the Coral Gables VA Hospital, where he established the Psychology Laboratory in the Research Department. He joined RCA in January 1960, as Systems Engineer, and was promoted to Group Leader in 1961. Currently, his group is responsible for all human factors engineering within his division. He also consults throughout the company on man-machine problems, and is the RCA representative to the Electronics Industries Association committee on Human Factors in Electronics. Dr. Matty is a Senior Member of the IEEE, a member of the Eastern Psychological Association, and of the American Psychological Association (Society of Engineering Psychologists). The author of numerous technical papers, he is listed in *American Men of Science* and in *Who's Who in the East*.

CONSIDERING THE COMPLEXITY of modern electronic systems, it is axiomatic that there will be a clear relationship between human performance and system reliability. A careful study[1] of nine missile systems revealed that about 30% of the failures and 20% of the unscheduled holds resulted from human performance failures. These data have been widely circulated and as far as can be determined, they have not been seriously disputed. From these data, it follows that about 25% of the reliability effort on electronic systems should be devoted to human performance in reliability. However, experience has shown that in reality the figure is much smaller.

Analysis of maintenance systems

The first consideration is to look at the procedure which is customarily employed to analyze maintenance systems. Fig. 1 shows information usually provided to systems engineering, how it is used, and what data results. The dashed boxes represent information ordinarily available at the start of the analysis, the solid boxes represent analytic steps to be accomplished, and the circles represent results.

The maintenance functions analysis is a study of what failures can occur and what maintenance will be needed.

Since both men and machines are involved in maintenance, alternative combinations of these are examined systematically to see which combination best meets system requirements. Once the optimal combination is determined for each equipment item to be maintained, the various maintenance functions (such as preventive maintenance, checkout, fault detection, fault location, replacement, repair, and calibration) are allocated, equipment by equipment, to both man and machine. The functions allocated to man are then classified and grouped, and a statement of the expected human performance is written out step-by-step. This task synthesis, as it is called, is complete when all the maintenance functions allocated to man are accounted for in one synthetic task or another.

Sequence analysis is the fitting of these maintenance tasks into an acceptable temporal relationship with mission events, with those operating tasks which may be scheduled precisely by requirements of the mission, and with crew duty cycles. Sometimes sequence analysis reveals a conflict in a man's time or in the use of an equipment. The dashed line represents the procedure of reallocating functions, changing the task, and then re-examining the newly resulting sequences. This method of successive approximations is an iterative procedure which usually converges to a solution quickly.

If these steps are documented adequately, maintenance task analysis can
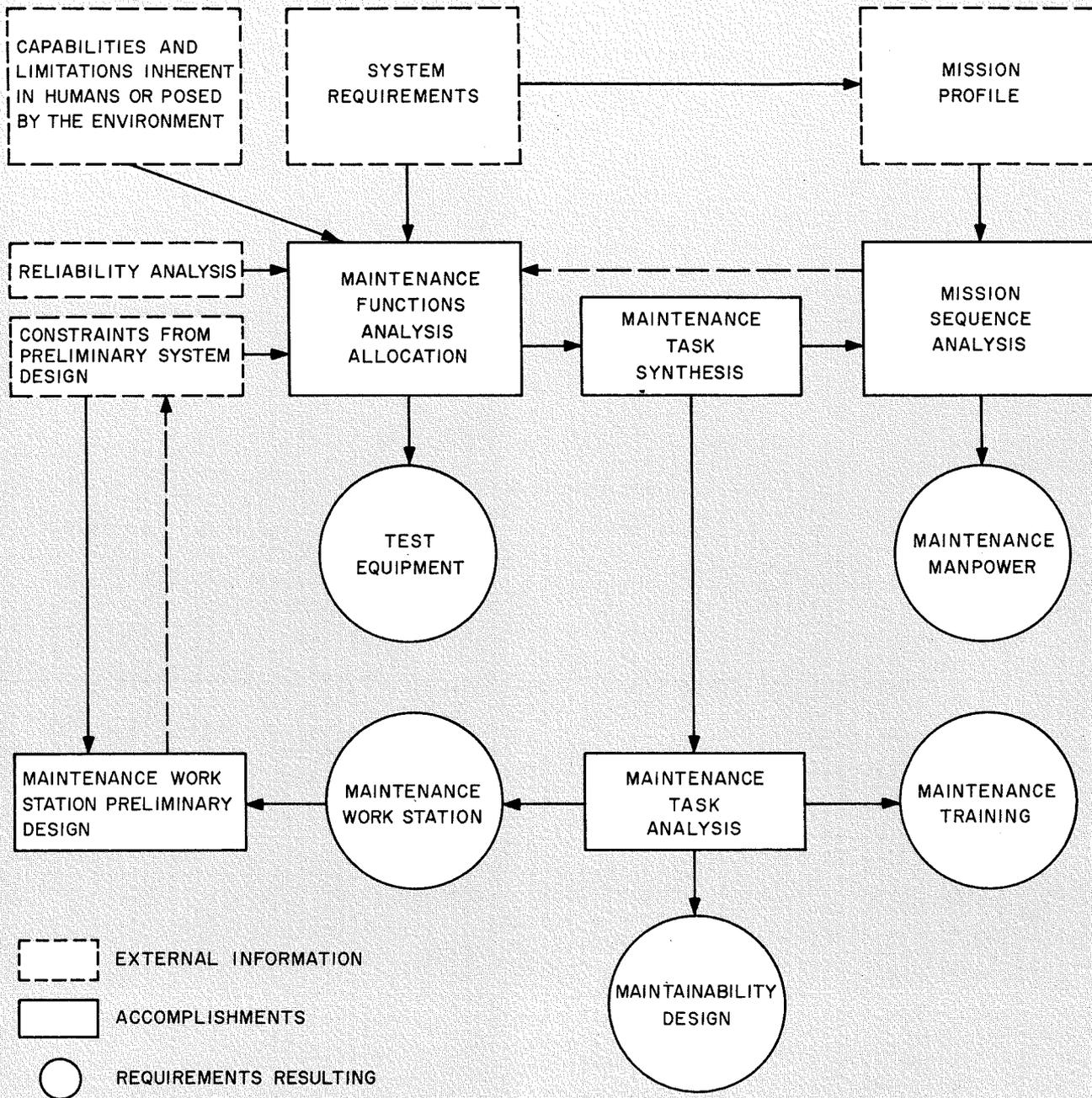
Fig. 1—Customary procedure for analyzing a maintenance system.

EXTERNAL INFORMATION

ACCOMPLISHMENTS

REQUIREMENTS RESULTING

be reduced to a straightforward consideration of the tasks. Each step is examined for the implications it has for required information display, required operating controls, required tools, required maintainability design features of the unit to be maintained, required training, and for a long list of human factors related to environmental control and the layout of workspaces.

Maintenance workload prediction

The next consideration is to show how equipment reliability data can be utilized in such procedures. Consider an hypothetical space mission in which a four-man crew is operating an orbiting space vehicle on a 1000-hour mission. An analysis of the requirements for in-space maintenance of the reconnaissance equipments which might be

expected to be on board must be made. Suppose an earlier analysis of system requirements has resulted in selection of reconnaissance equipments. These might be a high resolution radar; several optical systems, each with a different resolution; an IR camera, the airborne portion of a telemetry data link; a computer; and a display/control panel for operation and maintenance. Let us say a system performance

requirement is, that whenever the vehicle is within range of any one of a selected set of reconnaissance targets, the probability of successful operation of the equipment must be at least 0.99.

From this requirement, a maintenance workload can be predicted. In general, maintenance workload increases directly with the number of equipments to be maintained, with mission duration, and with the required probability of successful operation. On the other hand, maintenance workload varies inversely with reliability of the equipment to be maintained. The first step in predicting this workload in checkout is to determine how often these equipments must be checked out in order to maintain the required probability of success.

It is a common practice in reliability engineering to estimate this probability by $P(s) = \exp(-t/m)$, where t is a number of hours, m is the mean time between failures, and exp is the Napierian exponential function. Since, in the given case, $P(s)$ is fixed, the task is to find m and to compute t. The reliability data most likely to be available are component failure rates. Since system failure rates of non-redundant components are the reciprocal of the sum of the reciprocal of the failure rates of the individual items, the notion of the *failure bit* will be introduced. A *bit* is 10^8 divided by the mean-time-between-failure, where 10^8 is included solely to avoid the use of decimal places. If component failure rates are expressed in bits, it is simple to estimate mean-time-between-failure for the system by merely adding up all the bits and dividing 10^8 by the sum. In the given case, one would add all the bits associated with the radar components to all the bits associated with the computer, all the bits that are associated with the IR camera, and so forth.

These calculations are well known, so therefore, assume that m has been found, and that the t which maintains the probability of success at 0.99 has been calculated. By simple algebra, it can be seen that t is the product of m and the natural log of the reciprocal of $P(s)$. Let us say that t turns out to be 3 hours (after the calculations have been adjusted to take account of the fact that the equipments are operating for only a portion of the total time in space).

The meaning of "$t = 3$ hours" must now be considered. At the time of successful checkout, the $P(s) = 1.00$ for that instant. Since $P(s)$ is an exponential function of time, the values of $P(s)$ will decrease exponentially thereafter About *three hours* later, it will have fallen to 0.99. If the equipment is then checked out again, and no faults are indicated, the $P(s)$ is again 1.00 and so forth. Thus, the probability of successful operation of the reconnaissance equipment at times when it is needed, can be maintained above 0.99 by running a checkout every three hours.

The workload which this imposes on the crew can be synthesized in the usual fashion. By plotting crew duty cycles against mission profiles, one can then determine how many of the crew needs to be trained to perform the checkout and the associated functions allocated to man, such as simple plug-in replacement. An important factor in this determination is, of course, how the rest periods and the remaining workload—i.e., operating tasks—are distributed among the crew members.

Repair Requirements

So far, it has been determined how equipment reliability data can be operated upon to help determine the workload in checkout. The next question is how the workload in repair, at the level of component replacement, can be determined. The computation discussed previously gave no indication of how often tasks which require manual fault location and component replacement will occur. Therefore, it is necessary to operate on equipment reliability data to yield predictions about this kind of maintenance workload.

It was noted from the previous calculation that three hours after checkout, one would be 99% confident that there is no malfunction. After another checkout, one is about certain (100% confidence) and so on. This procedure does not account for wear or aging because they are too slight in three hours to have any computational significance. Actually, a certain number of failures per mission may be anticipated regardless of the state of confidence maintained throughout the mission. This seems contradictory at first glance, but we will see that it is not. In the example given, the probability of success varied from about 1.00 to about 0.99, and the average during any 3-hour period would be about 0.995. Since a 1000-hour mission would include about 333 such intervals, the probability of experiencing at least one failure would be equal to 1 minus 0.995 raised to the 333rd power $(P(f) = 1 - (0.995)^{333})$. This is such a very high probability that one can almost be certain at least one failure will occur. A reasonable estimate of the anticipated number of failures may be obtained simply by dividing the anticipated total operating time by the mean-time-between-failures.

How many of the crewmen should be trained further than just to operate checkout equipment and make plug-in replacements? The crew duty cycle (hours on duty divided by total hours) can be multiplied by the best anticipated number of failures. This product tells how many failures could be expected to occur while any single crewman is on duty. If that product is then subtracted from the total anticipated failures, decision can be made about whether a second man should be trained to make component repairs and manual fault locations to the component level. A simple guideline would be: if the product is 2½ times the remainder, one man will suffice; if twice the product is 2½ times the remainder, two men are required, and so forth.

Conclusion

No attempt has been made to present a discussion of all the possible uses of equipment reliability data for prediction of human requirements in maintenance. The examples given merely emphasize the intimate relationship which exists between reliability data and human requirements. The human performance role is of such importance to the meeting of system requirements that every consideration must be taken into account to strengthen the accuracy of its prediction. Consideration of the effect of equipment reliability on human performance will strengthen such predictions.

Reference

[1] Shapero, A., et al. *Human Engineering Testing and Malfunction Data Collection in Weapon System Test Programs*, WADD TR 60-36 (Wright Air Development Division, 1960).

Engineering and Research Notes
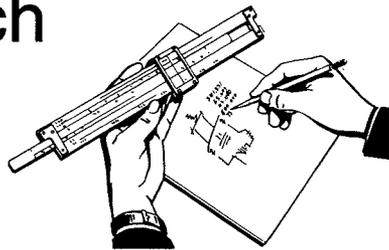
Fast-Fourier-transform correlation vs. direct-discrete-time correlation

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Fast-Fourier-transform (FFT) correlation is compared to direct-discrete-time (DDT) correlation of complex signals in terms of number of operations and memory requirements. The results establish criteria for evaluating which of the two techniques is the more economical in a real time application involving an indefinitely long input data sequence.

Direct discrete time correlation

The cross correlation of a sequence of complex data samples with a reference sequence containing N complex samples is defined in direct discrete time (DDT) by

$$\rho_{12}(\lambda) = \frac{1}{N} \sum_{n=0}^{N-1} f_1(n) f_2(n+\lambda) \tag{1}$$

where $f_1(n)$ is the complex conjugate of the reference signal and $f_2(n)$ is the complex input sequence, with λ denoting the number of shifts of the input into the reference. Each correlated output is thus a sum of complex products at given values of time shift.

The number of arithmetic operations, O, required per ouput is, at most, proportional to N:

$$O(DDT) = k_o N \tag{2}$$

where k_o is a constant of proportionality.

In the implementation of the DDT correlator, N complex input samples as well as the N complex reference samples must be stored. The storage requirement, S, in terms of number of complex words is, therefore

$$S(DDT) = 2N \tag{3}$$

Fast-Fourier-transform correlation

The fast-Fourier-transform (FFT)[1,2,3] applies to the discrete Fourier transform of a time-sampled sequence. The technique requires a number of operations which are proportional to $N \log_2 N$ rather than N^2 when the length of the sequence, N, is a power of 2. Similar savings are obtainable when N is highly composite.

In the application of the FFT to correlation, the time sequences are transformed into the frequency domain, multiplied, and inversely transformed to produce a periodic correlated output. The computation is defined by

$$\rho_{12}(\lambda) = \frac{1}{N} \sum_{k=0}^{N-1} F_1(k) F_2(k) \exp(j 2\pi \lambda k / N). \tag{4}$$

where $F_1(k)$ and $F_2(k)$ are the transforms of $f_1(n)$ and $f_2(n)$. Eq. 4 is a cyclic version of Eq. 1 having period N.

For the case of an indefinitely long input-data sequence, Stockham[4] and Helms[5] discuss procedures for sectioning the input pieces containing L complex samples. The relation for L is

$$L = P + N - 1 \tag{5}$$

where L is a power of 2 for optimum use of the FFT; N is the length of the reference sequence; and P is the resulting number of useful outputs produced by each section.

Assuming the reference sequence is originally stored in terms of its frequency components, the comparable upper bound of required operations, O, per output is

$$O(FFT) = \frac{2 k_F L \log_2 L + k_M L}{P} \tag{6}$$

where k_F is a constant associated with the operations involved in computing each Fourier component and k_M is associated with the multiplication of each pair of input and reference function frequency components.

For a real-time input, the FFT correlator requires a buffer stage to collect and transfer the continuous flow of input data samples to batch form. Employing in-place processing in the forward and inverse FFT operations and an output buffer to collect the useful outputs, the total amount of storage, S, required (neglecting storage of control parameters) is

$$S(FFT) = 3L + P \tag{7}$$

Criteria for comparing DDT and FFT correlation

The DDT and FFT correlation realizations are shown in Fig. 1 together with the number of operations and memory requirements. A comparison between the number of operations required per output for the two methods is made for the condition in which the constants of proportionality are equal. The result may be expressed as

$$R_o = \frac{O(FFT)}{O(DDT)} = \frac{L[2 \log_2(L+1)]}{NP} = \frac{L[2 \log_2(L+1)]}{N(L-N+1)} \tag{8}$$

When $R_o < 1$ a reduction in the number of operations is provided by the FFT method.

A comparison in terms of memory is made by expressing the ratio of Eq. 7 to Eq. 3 as

$$R_S = \frac{S(FFT)}{S(DDT)} = \frac{3L+P}{2N} = \frac{4L-N+1}{2N} \tag{9}$$

More memory is always required by the FFT method as indicated by R_S which is always $> 3/2$ since $L \geq N$.
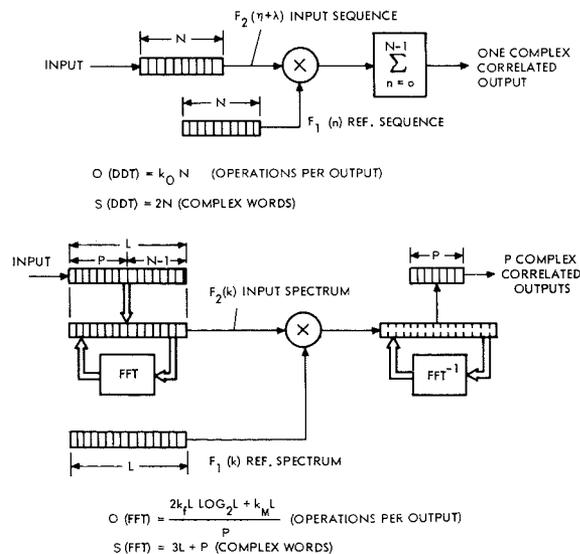
Fig. 1—Correlation realizations for DDT and FFT.

Fig. 2 illustrates the tradeoff between operations saved and increased memory required by the FFT correlation technique. Note that maximum reductions in required operations are achieved when the input section length, L, is in the region of twice the number of reference function samples, N, to be correlated. Also, the resultant savings provided by the FFT method are more important in applications requiring large values of N.
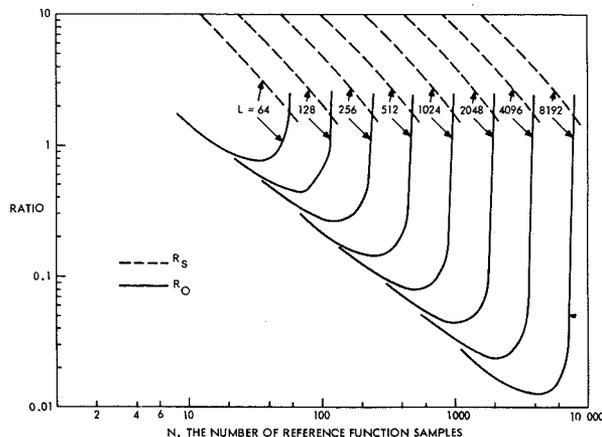
Fig. 2—Tradeoff between operations required and memory requirements.

Conclusions

The savings in the number of operations provided by the FFT correlation technique must be weighed against the required increase in memory over that of the DDT method. With a knowledge of the dollar savings provided by a decrease in the number of required operations together with a knowledge of the cost of additional memory, the relative economics of the two correlation methods for real time applications can be evaluated by means of the criteria presented here.

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Voltage-transfer test probe measures up to 50 kVDC with digital voltmeter accuracy

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Measurements of high voltages (~50 kV) often have to be made with extreme precision, where loading of the source cannot be tolerated. For instance, the focus and cathode electrode voltages of an image intensifier may be at potentials of −30 kV and at high impedance; yet their relative magnitudes should be known within several volts.

It is usually more convenient to measure these voltages with respect to ground using one digital voltmeter, rather than to measure their relative values using several floating voltmeters. Conventional techniques and instruments are unsatisfactory because of loading errors and personnel hazard. The system described in this paper uses a capacitive voltage divider, consisting of two capacitors and a surge-limiting resistor.

Two-step method

A small capacitor and surge limiting resistor are mounted in a grounded test probe, which is first touched to the voltage to be measured (Fig. 1). The probe is then touched to the input of the digital voltmeter, which has a large capacitance connected between its input terminal and ground. When the division ratio is large, the voltage measured on the digital voltmeter, which is reduced by this division ratio, will be small compared to the voltage to be measured. The input impedance of the voltmeter is usually 10 megohms, so that the decay time constant may readily be made large enough to permit accurate reading of the initial voltage, before it has time to decay. The low-level circuit may be reset to zero by shorting the input to ground.

If decay is considered objectionable, an operational amplifier, with the large capacitor in the feedback loop (i.e., an operational integrator), will provide an output that is effectively drift-free for long periods of time (Fig. 2). The formula for the voltage measured (before decay occurs) is

$$E_{HV} = E_{DVM}\left[\frac{C_2 + C_1}{C_1}\right] \approx E_{DVM}\left[\frac{C_2}{C_1}\right]$$

The absolute calibration of the measurement will, of course, depend upon the values of the two capacitors chosen, but it can easily be trimmed to a convenient factor by adding capacitors in parallel with C_2. The construction of the probe is extremely simple, as one side of the capacitor-resistor string is grounded. The problem of high-voltage switching (when measuring high voltages at various points) is avoided by using the concept of the transfer probe; moreover, safety and convenience are increased.

Fig. 1—Two-step measurement procedure using voltage-transfer probe.

Fig. 2—Digital voltmeter with impedance buffer.
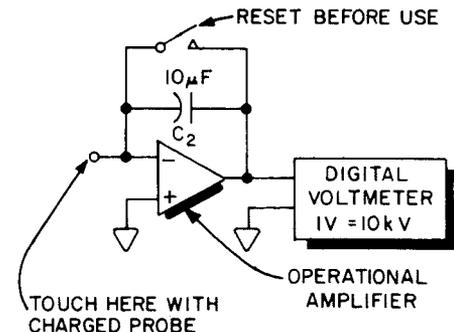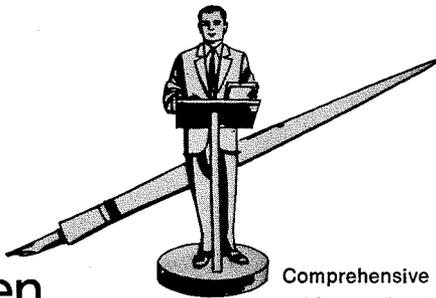
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ACOUSTICS

ACOUSTOELECTRIC STEADY STATE, Current Fluctuations in the—L. Friedman (Labs. Pr) *The Physical Review,* Vol. 174, No. 3; 10/15/68

ELECTROACOUSTIC EFFECT in III-V Compound Semiconductors—J. Dienst (Labs., Pr) Conf. on Wave Interactions in Solids, City College of New York; 2/6-7/69

AMPLIFICATION

TRANSFERRED-ELECTRON AMPLIFIERS and Oscillators—F. Sterzer (EC, Pr) International Solid-State Circuits Conf., Phila., Pa.; 2/19-21/69; *ISSCC Digests;* 2/69

TRANSFERRED-ELECTRON AMPLIFIERS, Stabilized Supercritical—B. S. Perlman, T. E. Walsh (EC, Pr) International, Solid-state Circuits Conf., Phila., Pa.; 2/19-21/69

ANTENNAS

ANTENNA PATTERN DISTORTION by an Iotropic Plasma Slab—M. P. Bachynski, B. W. Gibbs (LTD, Montreal) *IEEE Trans. on Antennas & Propagation,* Vol. 16, No. 5; 9/68

CIRCUIT ANALYSIS

LINEAR IC ARRAYS, Designing Communications Circuits with—H. A. Wittlinger (EC, Som) EDN Seminars on Integrated Circuits, Los Angeles, Calif.; 2/11/69, Boston, Mass.; 3/4/69, New York City; 3/5/69 and in *EDN Seminar Proceedings;* 2/69

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CIRCUITS, INTEGRATED

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LINEAR IC ARRAYS, Designing Communications Circuits with—H. A. Wittlinger (EC, Som) EDN Seminars on Integrated Circuits, Los Angeles, Calif.; 2/11/69, Boston, Mass.; 3/4/69, New York City; 3/5/69 and in *EDN Seminar Proceedings;* 2/69

MONOLITHIC INTEGRATED CIRCUITS, The ABC's of—M. V. Hoover (EC, Som) International Automotive Engineering Congress, Detroit, Mich.; 1/13-17/69 and IEEE Southeastern Michigan Section, Southfield, Mich.; 2/19/69; *SAE Preprint;* 1/69

MOS ANALOG DELAY LINE, Integrated—R. Mao, K. Keller, R. W. Ahrons (EC, Som) International Solid-State Circuits Conf., Phila., Pa.; 2/19-21/69; *ISSCC Digests;* 2/69

MOS CIRCUITS, Computer Analysis and Simulation of—A. Feller (AT, Cam) IEEE International Solid-State Circuits Conf., Digest of Technical Papers, Vol. XII; 2/20/69

MULTI-LAYER PRINTED CIRCUITS fabrication control—H. F. Shellack (DCSD, Cam) National Engineering Packaging Conf. (NEPCON), Anaheim, Calif.; 2/11/69

RCA LINEAR ARRAYS, Design Ideas for—H. M. Kleinman (EC, Som) *RCA Reprint;* 12/68

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THICK FILM Hybrid Technology—M. L. Topfer (DME, Som) NEP/CON West, Anaheim, Calif.; 2/12/69

TRANSFER BONDING System for Integrated Circuits—K. C. Hu (Labs., Pr) IEEE International Solid-State Circuits Conf., Phila., Pa.; 2/19-21/69

UHF INTEGRATED POWER AMPLIFIERS—W. E. Poole (EC, Som) International Solid-State Circuits Conf., Phila., Pa.; 2/19-21/69; *ISSCC Digest;* 2/69

COMMUNICATIONS COMPONENTS

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POWER AMPLIFIER, Thermal Design of an Airborne, 1 KW High Frequency—E. M. Morse (DCSD, Cam) NEPCON National Engineering Packaging Conference, Anaheim, Calif.; 2/11/69

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COMMUNICATIONS SYSTEMS

EFFICIENT COMMUNICATION with Adaptive Diversity—J. Wilder (Labs., Pr) *IEEE National Telemetering Conf. Record;* 1968

FILTERED-Biphase Channels, Signal-To-Noise Ratio Requirements for—C. Devieux (AED, Pr) *IEEE Aerospace and Electronic Systems;* 3/69

INFRARED MODULATION Techniques—T. E. Walsh (EC, Pr) *Electro-Technology;* 2/69

COMPUTER APPLICATIONS

COMPUTER-AIDED TRANSISTOR DESIGN—R. B. Schilling (EC, Som) IEEE Electron Devices Group, Pittsburgh, Pa.; 2/13/69

MOS CIRCUITS, Computer Analysis and Simulation of—A. Feller (AT, Cam) IEEE International Solid-State Circuits Conf., *Digest of Technical Papers,* Vol. XII; 2/20/69

COMPUTER COMPONENTS

PHOTODETECTING ARRAY, A High Speed, Word-Organized—J. M. Assour, R. S. Mezrich, D. H. R. Vilkomerson (Labs., Pr) IEEE International Solid-State Circuits Conf., Phila., Pa.; 2/19-21/69

COMPUTERS, PROGRAMMING

META PI—An on-line interactive compiler-compiler—J. T. O'Neill, Jr. (Labs., Pr) *AFIPS*—Volume 33; 1968

SOFTWARE SIDE of ATE, The—R. E. Turkington (ASD, Burl) talk, NSIA-MAC, Los Angeles, Calif.; 1/14/69

COMPUTER STORAGE

HOLOGRAPHIC COMPUTER MEMORIES—R. D. Lohman (Labs., Pr) Canadian Institute of Management, Data Processing Inst., Ottawa, Canada; 2/19/69

CONTROL SYSTEMS

AUTOMATION—Phase Two Refinements—N. R. Amberg (CESD, Plymouth) American Society of Tool and Manufacturing Engineering Systems Approach to Automation Seminar, Boston, Mass.; 2/15/69; *Proceedings* of ASTME

DISPLAYS

ELIMINATION OF SPECKLE NOISE in Holograms with Redundancy—H. J. Gerritsen, W. J. Hannan, E. G. Ramberg (Labs., Pr) *Applied Optics,* Vol. 7, No. 11; 11/68

REFLECTIVE LIQUID Crystal Television Display—J. A. VanRaalte (Labs., Pr) *Proceedings of the IEEE,* Vol. 56, No. 12; 12/68

REFLECTIVE OPTICAL STORAGE EFFECT in Mixed Liquid Crystal Systems, A New Electric Field Controlled—G. H. Heilmeier, J. E. Goldmacher (Labs., Pr) *Applied Physics Letters,* Vol. 13, No. 4; 8/15/68

ELECTROMAGNETIC WAVES

BAND EDGE SHIFT of $CdCr_2SE_4$ Near Curie Temperature—C. P. Wen, B. Hershenov, H. von Philipsborn, H. Pinch (Labs., Pr) *Applied Physics Letters,* Vol. 13, No. 5; 9/1/68

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INTERACTION OF MICROWAVES with Superconducting Thin Films—R. V. D'Aiello, S. J. Freedman (Labs., Pr) Conf. on Wave Interactions in Solids, City College of New York; 2/6-7/69

RADIO SCATTERING by an Extended Rough Surface—H. Staras (Labs., Pr) Electrical Engineering Department Seminar, U. of Penn.; 2/11/69

RF SPUTTERING PROCESSES—J. L. Vossen (Labs., Pr) Colloquium at Xerox Research Labs., Webster, N.Y.; 2/27/69

ELECTRO-OPTICS

ELECTRO-OPTIC MODULATION Methods, Comparison of—W. J. Hannan, J. Bordogna (Labs., Pr) *IEEE Transactions on Aerospace and Electronic Systems,* Vol. AES-4, No. 6; 11/68

ENERGY CONVERSION

FUEL ECONOMY of an Internal Combustion Engine, An Index to Characterize the Overall—T. Szirtes (LTD, Montreal) ASME Winter Annual Meeting & Energy System Exposition, New York; 12/68

TEN-WATT CW BROADBAND POWER SOURCE at S-Band, Hybrid Integrated—E. Belohoubek, D. Stevenson, A. Rosen (EC, Pr) International Solid-State Circuits Conf., Phila., Pa.; 2/19-21/69; *ISSCC Digests;* 2/69

ENVIRONMENTAL ENGINEERING

LOW VOLTAGE BREAKDOWN in Electronic Equipment when exposed to a Partial Pressure Nitrogen Environment Containing Water Vapor—R. F. Sharp, E. Meyers, D. Collins (AED, Pr) 2nd NASA Workshop on Voltage Breakdown in Electronic Equipment at Low Air Pressure, Jet Propulsion Lab., Pasadena, Calif.; 3/5-7/69

THERMAL DESIGN of an Airborne, 1 KW High Frequency Power Amplifier—E. M. Morse (DCSD, Cam) NEPCON (National Engineering Packaging Conf.), Anaheim, Calif.; 2/11/69

LABORATORY TECHNIQUES

ALBA MACHINE for Thinning Specimens for Electron Microscopy, Improvements to the—M. S. Abrahams, C. J. Buiocchi, M. D. Coutts (Labs., Pr) *The Review of Scientific Instruments*, Vol. 39, No. 12; 12/68

DEEP CENTERS IN SEMICONDUCTORS, Determination and Properties of—H. Schade (Labs., Pr) Solid State Seminar at Swiss Federal Institute of Technology, Zurich, Switzerland; 2/69

DETECTION OF OXYGEN in Laboratory Furnaces, Simple Technique for—A. E. Widmer (Labs., Pr) *The Review of Scientific Instruments*, Vol. 39, No. 12; 12/68

EPR AND RESISTIVITY MEASUREMENTS of Lithium-Defect Interactions in Electron Irradiated Silicon—B. Goldstein (Labs., Pr) Annual Conf. on Solid State Physics, U. of Manchester, England; 1/7-9/69

INFRARED LINE VIEWER—T. R. Schein (ASD, Burl) *RCA Technical Note #819;* 2/18/69

MEASURE MOSFET PARAMETERS with Ease—F. M. Carlson (EC, Som) *Electronic Design;* 2/15/69

MICROWAVE SUSCEPTIBILITY MEASUREMENTS, Voltage Induction Method for—M. Toda (Labs., Pr) *IEEE Transactions on Microwave Theory and Techniques*, Vol. MIT-16, No. 10; 10/68

SCANNING ELECTRON MICROSCOPY of Film Surfaces—M. D. Coutts (Labs., Pr) RESA Meeting, Hopewell Junction, N.Y.; 2/6/69

SCANNING ELECTRON MICROSCOPY in the Life and Physical Sciences, Applications of—M. D. Coutts (Labs., Pr) New York Society of Electron Microscopists, N.Y.; 1/22/69

TRAP DETERMINATIONS in Low-Resistivity Semiconductors, A Technique for—L. R. Weisberg, H. Schade (Labs., Pr) *J. of Applied Physics*, Vol. 39, No. 11; 10/68

LASERS

LASERS—G. Y. Eastman (EC, Lanc) Rotary Club, East Petersburg, Pa.; 1/30/69

LASER ENERGY, Characteristics of—R. J. Pressley (Labs., Pr) Lecture series at LaSalle College, Phila., Pa.; 2/6/69

POWER EFFICIENCY of a Pulsed Injection Laser with a Fabry-Perot Cavity, Theoretical Maximum of the—H. S. Sommers, Jr. (Labs., Pr) *Solid State Electronics*, Vol. 11; 1968

THREE-TERMINAL GaAs LIGHT EMITTER-MODULATOR Device—F. P. Califano, M. C. Steele (Labs., Pr) *Electronics Letters*, Vol. 14, No. 19; 9/20/68

LOGIC THEORY

THRESHOLD LOGIC, Fundamentals of—R. O. Winder (Labs., Pr) *Applied Automata Theory*, pp. 235-318; 1968

MANAGEMENT

COST EFFECTIVENESS via Weighted Factor Analysis—N. Salatino, M. Feistman, P. Neyhart (DCSD, Cam) 1969 Annual Symp. on Reliability, Chicago, Ill.; 1/21-23/69

RESEARCH-ON-RESEARCH, Some Thoughts on—J. Hillier (Labs., Pr) *Research Management*, Vol. XI, No. 6; 1968

WHAT EMPLOYERS EXPECT OF New Engineers—D. R. Musson (CESD, MdwLds) panel discussion, IEEE, Pittsburgh Section; 2/10/69

MATHEMATICS

ANALYZING MARKOV CHAINS, The Delay Method of—J. Sklansky, K. R. Kaplan (Labs., Pr) *SIAM Journal of Applied Mathematics*, Vol. 16, No. 6; 11/68

A Note on Integral Equations and Parseval's Theorem—A. A. Clark, R. F. Barry (ASD, Burl) *IEEE Trans. AES*, Vol. AED 5, No. 1; 1/69

PROBLEM SOLVING SYSTEMS, Problem of Representation for—S. Amarel (Labs., Pr) Machine Intelligence Workshop, Stanford University, Palo Alto, Calif.; 2/19/69

MECHANICAL DEVICES

ELECTROLESS PLATING, Influence of Agitation on—N. Feldstein, P. R. Amodio (Labs., Pr) 2nd Symposium on Plating in the Electronics Industry, Boston, Mass.; 2/6-7/69

THERMOCOMPRESSION BONDING of Beam Leads—W. Greig, A. Z. Miller (EC, Som) Drexel Institute, Phila., Pa.; 2/17/69

MEDICAL ELECTRONICS

INTRA-VENOUS PROCESSING of Doppler Ultrasonic Signals—Indirect Blood Pressure by Ultrasonic Detection of Arterial Wall Motion—G. W. Gray, F. L. Hatke (CESD, Cam) Conf. on Engineering in Medicine and Biology, 21st Annual Mtg., Houston, Texas; 11/18/68

INTRA-VENOUS ULTRASONIC TRANSDUCER DESIGN—Indirect Blood Pressure by Ultrasonic Detection of Arterial Wall Motion—J. G. Ziedonis (CESD, Cam) B. Mount (Hoffman-LaRoche) Conf. on Engineering in Medicine and Biology, 21st Annual Mtg., Houston, Texas; 11/18/68

OPTICS

ELECTRON OPTICS of Vidicons—J. R. Leaman (EC, Lanc) *Orbit;* 2/69

PLASMA PHYSICS

ELECTRON-HOLE PLASMAS, Instabilities in—B. Robinson (Labs., Pr) Conf. of Wave Interactions in Solids, City College of New York; 2/6-7/69

PROPERTIES, MOLECULAR

MOLECULAR STRUCTURE AND PROPERTIES of Liquid Crystals—J. Goldmacher (Labs., Pr) J. T. Baker Chemical Company, Phillipsburg, N.J.; 2/19/69

NEMATIC LIQUID CRYSTALS in the Presence of a Magnetic Field, Alignment-Inversion Walls in—W. Helfrich (Labs., Pr) *Physical Review Letters*, Vol. 21, No. 22; 11/25/68

PROPERTIES, SURFACE

HYBRID SOURCES for Diffusion of Dopants into Silicon-on-Sapphire Films—D. J. Dumin (Labs., Pr) *J. of Electrochemical Society*, Vol. 116, No. 1; 1/69

INTERACTION OF MICROWAVES with Superconducting Thin Films—R. V. D'Aiello, S. J. Freedman (Labs., Pr) Conf. on Wave Interactions in Solids, City College of New York; 2/6-7/69

IONIC SURFACE STATES from a Band-Edge Method—J. D. Levine, S. G. Davison (Labs., Pr) *The Physical Review*, Vol. 174, No. 3; 10/15/68

LIQUID CRYSTALS, Molecular Structure and Properties of—J. Goldmacher (Labs., Pr) Texaco Research Center of RSEA, Beacon, N.Y.; 1/14/69

THIN-FILM Microwave Components—M. Caulton (Labs., Pr) *NEREM Record;* 1968

TUNABLE ACOUSTICAL PHONON DETECTOR Using Tm^{2+} in CaF_2—E. S. Sabisky, C. H. Anderson (Labs., Pr) *Applied Physics Letters*, Vol. 13, No. 6; 9/15/68

PROPERTIES, ACOUSTIC

ELECTROACOUSTIC EFFECT in III-V Compound Semicondcutros—J. Dienst (Labs., Pr) Conf. on Wave Interactions in Solid, City College of New York: 2/6-7/69

PROPERTIES, CHEMICAL

CHEMICAL VAPOR DEPOSITION of Materials Using in Electronics—J. J. Hanak (Labs., Pr) Lecture at Notre Dame, Indiana; 1/15/69

PHOTOLYSIS of Pyracyloquinone in Methanol. An Example of Benzenoid-Quinoid Valence Tautomerism—J. Castellano (Labs., Pr) *Tetrahedron Letters*, No. 59; 1968

ZINC SULFIDE—II. Thermal Recrystallization Effects, Particle Size and Morphology of—R. A. Brown (EC, Lanc) *J. of Electrochemical Society;* 2/69

PROPERTIES, ELECTRICAL

DIELECTRIC PROPERTIES of Nb_3O_7Cl—M. L. A. Robinson (Labs., Pr) *J. of the Physics and Chemistry of Solids*, Vol. 29, No. 11; 1968

ELECTRON EMISSION from the Schottky Barrier Structure ZnS:Pt:Cs—R. Williams, C. R. Wronski (Labs., Pr) *Applied Physics Letters;* Vol. 13, No. 7; 10/68

ELECTRON PARAMAGNETIC RESONANCE, Investigation of the $Si-SiO_2$ Interface—A. G. Revesz, B. Goldstein (Labs., Pr) American Physical Society, New York; 2/3-6/69

GENERATION AND RECOMBINATION of Free Carriers in $SrTiO_3$, Study of—J. J. Amodei, W. R. Roach (Labs., Pr) *Physical Review Letters*, Vol. 21, No. 24; 12/9/68

PHOTOEMISSION of Electrons and Holes into Silicon Nitride—A. M. Goodman (Labs., Pr) *Applied Physics Letters*, Vol. 13, No. 8; 10/15/68

TRANSIENT DOUBLE INJECTION in Germanium—R. H. Dean (Labs., Pr) *Applied Physics Letters*, Vol. 13, No. 5; 9/1/68

PROPERTIES, MECHANICAL

PHOTORESIST FILMS, The Effect of Whirler Acceleration on the Properties of—G. F. Damon (EC, Som) *Photo/Chemical Fabrication;* 2/69

PROPERTIES, OPTICAL

AMBIENT-SENSITIVE PHOTOELECTRONIC Behavior of CdS Sintered Layers—F. B. Micheletti, P. Mark (Labs., Pr) *J. of Applied Physics*, Vol. 39, No. 11; 10/68

CATHODOLUMINESCENCE OF N-Type GaAs—J. I. Pankove (Labs., Pr) *J. of Applied Physics*, Vol. 39, No. 12; 11/68

DYNAMIC SCATTERING in Liquid Crystals—G. H. Heilmeier (Labs., Pr) *Appliance Engineer*, Vol. 2, No. 4; 1968

ELECTROLUMINESCENCE in $Al_xGa_{1-x}P$ Diodes Prepared by Liquid-Phase Epitaxy—H. Kressel, I. Ladany (Labs., Pr) *J. of Applied Physics*, Vol. 39, No. 11; 10/68

NEW DEEP-LEVEL LUMINESCENCE in GaAs:Sn—H. Kressel, H. Nelson, F. Z. Hawrylo (Labs., Pr) *J. of Applied Physics*, Vol. 39, No. 12; 11/68

PHOTOCHROMIC Change in Refractive Index—J. M. Hammer (Labs., Pr) *Applied Physics Letters*, Vol. 13, No. 9; 11/1/68

PHOTORESIST FILMS, The Effect of Whirler Acceleration on the Properties of—G. F. Damon (EC, Som) *Photo/Chemical Fabrication;* 2/69

RADIATIVE EFFICIENCY and Deep-Level Luminescence in n-Type GaAs Prepared by Liquid-Phase Epitaxy, Observations Concerning

RADIATIVE EFFICIENCY and Deep-Level Luminescence in n-Type GaAs Prepared by Liquid-Phase Epitaxy, Observations Concerning—H. Kressel, F. Z. Hawrylo, M. S. Abrahams, C. J. Buiocchi (Labs., Pr) *J. of Applied Physics*, Vol. 39, No. 11; 10/68

RADAR

HANDHELD TACTICAL RADAR—R. Van Olst (MSR, Mrstn) Boy Scouts of America, Troop 44, at the Methodist Church; 2/12/69

THREE-BEAM MONOPULSE TRACKING RADAR, Signal Processors and Accuracy of—P. Z. Peebles (MSR, Mrstn) *IEEE Trans. on Aeropsace & Electr. Systems*, Vol. AES-5, #1, pg. 52; 1/69

RADIATION EFFECTS

RF SPUTTERING PROCESSES—J. L. Vossen (Labs., Pr) Colloquium at Xerox Research Labs., Webster, N.Y.; 2/27/69

RECORDING

QUADRUPLEX RECORDING, Velocity Errors in—Part II—R. N. Hurst (CESD, Cam) SMPTE, Toronto, Canada; 1/18/69

RELIABILITY

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RELIABILITY TASKS vs. Product Reliability—D. I. Troxel (DCSD, Cam) 1969 Annual Symp. on Reliability, Chicago, Ill.; 1/21-23/69

SOLID-STATE DEVICES

AVALANCHE AND TRANSFERRED-ELECTRON DEVICES, Recent Advances in—F. Sterzer (EC, Pr) IEEE Electron Devices Group Chapter Mtg., Nutley, N.J.; 2/27/69

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TRANSFERRED-ELECTRON AMPLIFIERS and Oscillators—F. Sterzer (EC, Pr) International Solid-State Circuits Conf., Phila., Pa.; 2/19-21/69; ISSCC Digest; 2/69

TRANSFERRED-ELECTRON AMPLIFIERS, Stabilized Supercritical—B. S. Perlman, T. E. Walsh (EC, Pr) International Solid-State Circuits Conf., Phila., Pa.; 2/19-21/69

SPACE COMMUNICATION

SPACECRAFT DATA STORAGE in the 1970's — R. J. Treadwell (AED, Pr) 6th Space Congress, Univ. of Florida, Cocoa Beach, Fla.; 3/17-19/69

SPACECRAFT

STEREOSCOPIC PICTURES from the Earth Resources Satellite—P. J. Alley

(AED, Pr) 1969 ASP-ASCM Convention, Washington, D.C.; 3/10/69

TIROS and ESSA SATELLITE DESIGN and Test for Mission Success — A. Schnapf (AED, Pr) MSFC/ASQC Convention, Huntsville, Ala.; 3/17-19/69

SPACECRAFT INSTRUMENTATION

PHOTOGRAMMETRY AND TELEVISION from Space—P. Wood (AED, Pr) ASP-ACSM Convention, Washington, D.C.; 3/12/69

SUPERCONDUCTIVITY

INTERACTION OF MICROWAVES with Superconducting Thin Films — R. V. D'Aiello, S. J. Freedman (Labs., Pr) Conf. on Wave Interactions in Solids, City College of New York; 2/6-7/69

ISOTOPE EFFECT in Superconductors— Rothwarf (Labs., Pr) The American Physical Society, New York; 2/3-6/69

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TELEVISION BROADCASTING

COLOR CAMERA, RCA TK-44A Live — R. C. Parkhill (CESD, Cam) Society of Broadcast Engineers, Phila., Pa.; 1/20/69

MULTIPLE TV PROGRAMMING, A Computer Controlled System for — R. Post (NBC, N.Y.) 104th SMPTE Technical Conference; 11/10-15/68, Washington, D.C.

ZERO DELAY VIDEO SYSTEMS—R. J. Butler (NBC, N.Y.) 104th SMPTE Technical Conf., Washington, D.C.; 11/10-15/68

TELEVISION EQUIPMENT

PHOTO DIELECTRIC TAPE CAMERA SYSTEMS—J. A. D'Arcy (AED, Pr) NRR Company, Naval Air Development Center, Johnsville, Pa.; 3/25/69

REFLECTIVE LIQUID Crystal Television Display—J. A. Van Raalte (Labs., Pr) Proceedings of the IEEE, Vol. 56, No. 12; 12/68

TRANSMISSION LINES

DIELECTRIC SUPPORTED STRIP TRANSMISSION LINE, Characteristic Impedance of—M. A. Earle, P. Benedek (LTD, Monreal) IEEE Trans. M.T.T., Vol. 16, No. 10; 10/68

TUBES, ELECTRON

ELECTRON OPTICS of Vidicons—J. R. Leaman (EC, Lanc) Orbit; 2/69

PHOTO ERASABLE DARK TRACE Cathode-Ray Storage Tube—W. Phillips, Z. J. Kiss (Labs., Pr) Proceedings of the IEEE, Vol. 56, No. 11; 11/68

PHOTOMULTIPLIER TUBES, New Gallium Phosphide—T. T. Lewis (EC, Lanc) Argonne National Laboratory, Chicago, Ill.; 1/16/69

Author Index

Subject listed opposite each author's name indicates where complete citation to his paper may be found in the subject index.

ASTRO-ELECTRONICS DIVISION

Alley, P. J. spacecraft
Collins, D. environmental engineering
D'Arcy, J. A. television equipment
Devieux, C. communications systems
Gomberg, L. reliability
Meyers, E. environmental engineering
Schnapf, A. spacecraft
Sharp, R. F. environmental engineering
Treadwell, R. J. space communication
Wood, P. spacecraft instrumentation

AEROSPACE SYSTEMS DIVISION

Barry, R. F. mathematics
Clark, A. A. mathematics
Schein, T. R. laboratory techniques
Turkington, R. E. computers, programming

ADVANCED TECHNOLOGY

Feller, A. circuits, integrated
Feller, A. computer applications

COMMERCIAL ELECTRONIC SYSTEMS DIVISION

Amberg, N. R. control systems
Gray, G. W. medical electronics
Hatke, F. L. medical electronics
Hurst, R. N. recording
Musson, D. R. management
Parkhill, R. C. television broadcasting
Ziedonis, J. G. medical electronics

DEFENSE COMMUNICATION SYSTEMS DIVISION

Feistman, M. management
Feistman, M. reliability
Neyhart, P. management
Neyhart, P. reliability
Morse, E. M. communications components
Morse, E. M. environmental engineering
Ray, R. H. communications components
Salatino, N. management
Salatino, N. reliability
Shellack, H. F. circuits, integrated

Tiger, B. reliability
Troxel, D. I. reliability

DEFENSE MICROELECTRONICS

Topfer, M. L. circuits, integrated

ELECTRONIC COMPONENTS

Ahrons, R. W. circuits, integrated
Ahrons, R. W. circuits, integrated
Belohoubek, E. energy conversion
Brown, R. A. properties, chemical
Carlson, F. M. laboratory techniques
D'Agostino, M. V. circuits, integrated
Damon, G. F. properties, mechanical
Damon, G. F. properties, optical
Eastman, G. Y. lasers
Feller, A. circuits, integrated
Feryszka, R. circuit analysis
Feryszka, R. circuits, integrated
Gardner, P. D. circuits, integrated
Greig, W. mechanical devices
Hanchett, G. D. solid-state devices
Hoover, M. V. circuits, integrated
Keller, K. circuits, integrated
Kleinman, H. M. circuits, integrated
Leaman, J. R. optics
Leaman, J. R. tubes, electron
Lee, H. C. solid-state devices
Lewis, T. T. tubes, electron
Mao, R. circuits, integrated
Miller, A. Z. mechanical devices
Perlman, B. S. amplification
Perlman, B. S. solid-state devices
Poole, W. E. circuits, integrated
Poole, W. E. communication components
Preisig, J. O. circuit analysis
Preisig, J. O. circuits, integrated
Rashid, A. circuits, integrated
Rosen, A. energy conversion
Schilling, R. B. computer applications
Sterzer, F. amplification
Sterzer, F. solid-state devices
Sterzer, F. solid-state devices
Stevenson, D. energy conversion
Walsh, T. E. amplification
Walsh, T. E. solid-state devices
Walsh, T. E. communications systems
Wittlinger, H. A. circuit analysis
Wittlinger, H. A. circuits, integrated

LABORATORIES

Abrahams, M. S. laboratory techniques
Abrahams, M. S. properties, optical
Amarel, S. mathematics
Amodei, J. J. properties, electrical
Amodio, P. R. mechanical devices
Anderson, C. H. properties, surface
Assour, J. M. computer components
Assour, J. M. solid-state devices
Bordogna, J. electro-optics

Buiocchi, C. J. laboratory techniques
Buiocchi, C. J. properties, optical
Califano, F. P. solid-state devices
Califano, F. P. lasers
Castellano, J. properties, chemical
Caulton, M. communications components
Caulton, M. properties, surface
Coutts, M. D. laboratory techniques
Coutts, M. D. laboratory techniques
Coutts, M. D. laboratory techniques
D'Aiello, R. V. electromagnetic waves
D'Aiello, R. V. properties, surface
D'Aiello, R. V. superconductivity
Davison, S. G. properties, surface
Dean, R H. properties, electrical
Dienst, J. acoustics
Dienst, J. properties, acoustic
Dumin, D. J. properties, surface
Feldstein, N. mechanical devices
Freedman, S. J. electromagnetic waves
Freedman, S. J. properties, surface
Freedman, S. J. superconductivity
Friedman, L. acoustics
Gandolfo, D. A. superconductivity
Gerritsen, H. J. displays
Goldmacher, J. properties, surface
Goldmacher, J. properties, molecular
Goldmacher, J. displays
Goldstein, B. laboratory techniques
Goldstein, B. properties, electrical
Goodman, A. M. properties, electrical
Hammer, J. M. properties, optical
Hanak, J. J. properties, chemical
Hannan, W. J. electro-optics
Hannan, W. J. displays
Hawrylo, F. Z. properties, optical
Hawrylo, F. Z. properties, optical
Heilmeier, G. H. properties, optical
Heilmeier, G. H. displays
Helfrich, W. properties, molecular
Hershenov, B. electromagnetic waves
Hicinbothem, W. A. solid-state devices
Hillier, J. management
Hu, K. C. circuits, integrated
Kaplan, K. R. mathematics
Kiss, Z. J. tubes, electron
Kressel, H. properties, optical
Kressel, H. properties, optical
Kressel, H. properties, optical
Ladany, I. properties, optical
Larrabee, R. D. solid-state devices
Larrabee, R. D. solid-state devices
Levine, P. A. communications components
Levine, P. A. solid-state devices
Levine, J. D. properties, surface
Liu, S. G. communication components
Liu, S. G. solid-state devices
Liu, S. G. communication components
Liu, S. G. solid-state devices
Lohman, R. D. computer storage
Mark, P. properties, optical
Mezrich, R. S. computer components
Mezrich, R. S. solid-state devices
Micheletti, F. B. properties, optical

Nelson, H. properties, optical
O'Neill, J. T. computers, programming
Pankove, J. I. properties, optical
Phillips, W. tubes, electron
Pinch, H. electromagnetic waves
Pressley, R. J. lasers
Pruss, T. V. superconductivity
Ramberg, E. G. displays
Revesz, A. G. properties, electrical
Roach, W. R. properties, electrical
Robinson, B. plasma physics
Robinson, M. L. A. properties, electrical
Rothwarf, A. superconductivity
Sabisky, E. S. properties, surface
Sahm, P. R. superconductivity
Schade, H. laboratory techniques
Schade, H. laboratory techniques
Sklansky, J. mathematics
Sommers, H. S. lasers
Staras, H. electromagnetic waves
Steele, M. C. lasers
Toda, M. laboratory techniques
VanRaalte, J. A. displays
VanRaalte, J. A. television equipment
Vilkomerson, D. H. R. computer components
Vilkomerson, D. H. R. solid-state devices
VonPhilipsborn, H. electromagnetic waves
Vossen, J. L. electromagnetic waves
Vossen, J. L. radiation effects
Weisberg, L. R. laboratory techniques
Wen, C. P. electromagnetic waves
Widmer, A. E. laboratory techniques
Wilder, J. communications systems
Williams, R. properties, electrical
Winder, R. O. logic theory
Wronski, C. R. properties, electrical

RCA LIMITED, MONTREAL

Bachynski, M. P. antennas
Benedek, P. transmission lines
Earle, M. A. transmission lines
Gibbs, B. W. antennas
Shkarofsky, I. P. electromagnetic waves
Szirtes, T. energy conversion

MISSILE AND SURFACE RADAR DIVISION

Peebles, P. Z. radar
VanOlst, R. radar

NATIONAL BROADCASTING COMPANY

Butler, R. J. television broadcasting
Post, R. television broadcasting

Patents Granted

to RCA Engineers
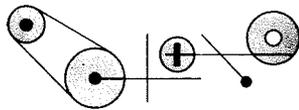
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Method of fabricating improved solderable lands—G. W. Leck (Labs., Pr) U.S. Pat. 3,421,938; January 14, 1969

Deposition of Niobium Stannide—J. J. Hanak (Labs., Pr) U.S. Pat. 3,420,707; January 7, 1969

Bistable ferroelectric field effect device—G. H. Heilmeier, P. M. Heyman (Labs., Pr) U.S. Pat. 3,424,654; January 21, 1969

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Photoconductive compositions and electrophotographic recording elements made therefrom—E. C. Giaimo (Labs., Pr) U.S. Pat. 3,428,452; February 18, 1969

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ELECTRONIC COMPONENTS

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MOS Tetrode—J. Olmstead, L. A. Jacobus, E. G. Athanassiadis (EC, Som) U.S. Pat. 3,427,514; February 11, 1969

High Voltage semiconductor transistor—A. Blicher, B. R. Czorny (EC, Som) U.S. Pat. 3,427,515; February 11, 1969

Microwave Oven — W. N. Parker (EC, Lanc) U.S. Pat. 3,422,240; January 14, 1969

Method of Making a vapor device—W. B. Hall (EC, Lanc) U.S. Pat. 3,419,950; January 7, 1969

Signal Translating System—M. S. Fisher (EC, Som) U.S. Pat. 3,421,098; January 7, 1969

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Monolithic semiconductor microcircuits with improved means for connecting points of common potential—G. Cohen (EC, Som) U.S. Pat. 3,423,650; January 21, 1969

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Pickup device—O. H. Schade (EC, Hr) U.S. Pat. 3,426,235; February 4, 1969

Method of fabricating semiconductor devices—M. M. Bell (EC, Hr) U.S. Pat. 3,429,030; February 25, 1969

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Monolithic integrated circuits with a plurality of isolation zones—H. Goshgarian (EC, Som) U.S. Pat. 3,430,110; February 25, 1969

Thermionic converter—W. E. Harbaugh (EC, Lanc) U.S. Pat. 3,426,221; February 4, 1969; Assigned to U.S. Government.

INFORMATION SYSTEMS DIVISION

Document handling apparatus — R. L. Adams (ISD, Cam) U.S. Pat. 3,432,035; March 11, 1969

Conversion from NRZ code to self-clocking code—J. A. Vollee (ISD, W. Palm) U.S. Pat. 3,422,425; January 14, 1969

Error Detection System—A. T. Ling (ISD, Cam) U.S. Pat. 3,420,991; January 7, 1969

Method and apparatus for connecting leads to a printed circuit board—R. S. Fow, J. R. Oberman (ISD, Cam) U.S. Pat. 3,425,021; January 28, 1969

Control circuit for automatically quantizing signals at desired levels—J. Agin (ISD, Cam) U.S. Pat. 3,426,210; February 4, 1969

Voltage regulated power supply including a breakdown device and means tending to keep the current flow therethrough constant—D. W. Hall (ISD, W, Palm) U.S. Pat. 3,428,885; February 18, 1969

Logic circuits—A. S. Sheng (ISD, Cam) U.S. Pat. 3,430,071; February 25, 1969

HOME INSTRUMENTS

Television focus voltage supply—J. O. Preisig (HI, Pr) U.S. Pat. 3,432,718; March 11, 1969

Coil form—G. R. Solmos (HI, Indpls) U.S. Pat. 3,432,785; March 11, 1969

Oscillator using a transistor as voltage controlled capacitance—T. J. Campbell (HI, Indpls) U.S. Pat. 3,422,369; January 14, 1969

Phonograph Pickup — M. E. Miller (HI, Indpls) U.S. Pat. 3,420,534; January 7, 1969

Automatic stereo switching and indicating circuit—D. J. Snyder (HI, Indpls) U.S. Pat. 3,423,536; January 21, 1969

Retrace driven deflection circuit with SCR switch—J. B. Beck (HI, Indpls) U.S. Pat. 3,423,630; January 21, 1969

Remote control system—L. A. Harwood (HI, Som) U.S. Pat. 3,423,725; January 21, 1969

Transistor deflection circuit with clamper means—J. A. McDonald, J. B. Beck (HI, Indpls) U.S. Pat. 3,424,941; January 28, 1969

Auxiliary beam deflection yoke—R. L. Barbin (HI, Indpls) U.S. Pat. 3,424,942; January 28, 1969

Temperature compensation of deflection circuits—J. A. McDonald (HI, Indpls) U.S. Pat. 3,428,854; February 18, 1969

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Step recovery damper diode for retrace driven horizontal deflection circuits — R. C. Lemmon (HI, Indpls) U.S. Pat. 3,428,857; February 18, 1969

Circuit for stabilizing the DC output voltage of a gain controlled amplifier stage in a direct coupled integrated circuit signal translating system—L. A. Harwood (HI, Indpls) U.S. Pat. 3,430,154; February 26, 1969

Integrated circuit biasing arrangement for supplying V_{be} bias voltages—L. A. Harwood (HI, Indpls) U.S. Pat. 3,430,155; February 25, 1969

ASTRO-ELECTRONICS DIVISION

System for switching the attitude reference of a satellite from a first celestial body to a second celestial body—W. L. Gill, H. Perkel (AED, Pr) U.S. Pat. 3,427,453; February 11, 1969

MISSILE AND SURFACE RADAR DIVISION

Light beam recorder using vibrated lens system—P. J. Donald (MSR, Mrstn) U.S. Pat. 3,427,631; February 11, 1969

Variable Amplitude drive—R. W. Chambers (MSR, Mrstn) U.S. Pat. 3,415,133; December 10, 1968; Assigned to U.S. Government.

RCA VICTOR, LTD

Display systems—R. J. Clark (LTD, Montreal) U.S. Pat. 3,422,420; January 14, 1969

Scanning antenna feed—P. Foldes (LTD, Montreal) U.S. Pat. 3,423,756; January 21, 1969

Character generator for simultaneous display of separate character patterns on a plurality of display devices—R. J. Clark (LTD, Montreal) U.S. Pat. 3,426,344; February 4, 1969

DEFENSE MICROELECTRONICS

Emitter follower circuit having substantially constant current emitter supply—M. V. D'Agostino (DME, Som) U.S. Pat. 3,431,505; March 4, 1969

Direct coupled amplifier including two-stage automatic gain control—K. Giontzeneli (DME, Som) U.S. Pat. 3,421,100; January 7, 1969

COMMERCIAL ELECTRONIC SYSTEMS DIVISION

Non-random field shift apparatus for a television waveform monitor—L. J. Baun (CESD, Cam) U.S. Pat. 3,420,952; January 7, 1969

Line-select apparatus for a television waveform monitor—L. J. Baun (CESD, Cam) U.S. Pat. 3,423,525

PATENTS AND LICENSING

Signal Translating system—H. M. Bach (P&L, Pr) U.S. Pat. 3,420,954; January 7, 1969

AEROSPACE SYSTEMS DIVISION

Broad Band High Gain Video Amplifier—L. C. Drew, H. F. King (ASD, Burl) U.S. Pat. 3,421,101; January 7, 1969

Electrical spatial discimination technique for image scannng sensors—M. J. Cantella (ASD, Burl) U.S. Pat. 3,409,789; November 5, 1968; Assigned to U.S. Government

ELECTROMAGNETIC AND AVIATION SYSTEM DIVISION

Method of radar return integration using a dual-gun, write-read, recording-storage tube—R. C. Wilcox (EASD, Van Nuys) U.S. Pat. 3,417,335; December 17, 1968; Assigned to U.S. Government

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NATIONAL BROADCASTING COMPANY

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PARTS & ACCESSORIES

Method of securing a rod to a supporting structure—J. D. Callaghan, (P&A, Dpt) U.S. Pat. 3,429,033; February 25, 1969

DEFENSE COMMUNICATION SYSTEMS DIVISION

Continuous burning high-intensity ARC lamp — C. Lauxen, J. B. Long (DCSD, Cam) U.S. Pat. 3,409,795; November 5, 1968; Assigned to U.S. Government

Distributed feedback frequency compression in frequency modulation reception—A. Newton (DCSD, N.Y.) U.S. Pat. 3,428,900; February 18, 1969

Professional Meetings

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AUG. 19-22, 1969: **Western Electronic Show & Convention (WESCON),** Cow Palace & San Francisco Hilton Hotel, San Francisco, Calif. **Deadline info:** 3/15/69 (abst) 6/25/69 (papers) to: WESCON, 3600 Wilshire Blvd., Los Angeles, Calif. 90005.

SEPT. 8-12, 1969: ***Int'l Man-Machine Systems Symposium,** St. John's College, Cambridge, England. **Deadline info:** 6/15/69 (papers) to: W. T. Singleton, Applied Psychology Dept., Univ. of Aston in Birmingham, Birmingham 4, England.

SEPT. 16-19, 1969: **Solid State Devices Conf.,** Univ. of Exeter, Exeter, Devon, England. **Deadline info:** 6/27/69 (syn) to: P. C. Newman, Allen Clark Res. Ctr., Caswell, Towcester, Northamptonshire, England.

SEPT. 21-26, 1969. ***Intersociety Energy Conversion Engrg Conf.,** Statler Hilton Hotel, Washington, D.C. **Deadline info:** 1/15/69 (abst) to: T. G. Kirkland, U.S. Army R & D Ctr., Fort Belvoir, Va.

OCT. 15-17, 1969: ***Symposium on Switching & Automata Theory,** Univ. of Waterloo, Waterloo, Ontario, Canada. **Deadline info:** 5/16/69 (abst) to: John Hopcroft, Computer Science Dept., Upson Hall, Cornell Univ., Ithaca, N.Y.

OCT. 27-29, 1969: ***Electronic & Aerospace Systems Conv. (EASCON),** Sheraton Park Hotel, Washington, D.C. **Deadline info:** 6/2/69 (abst), 6/30/69 (papers) to: H. P. Gates, Jr., P.O. 2347, Falls Church, Va. 22042

OCT. 29-31, 1969: **Nuclear Science Symposium,** Sheraton Palace Hotel, San Francisco, Calif. **Deadline info:** 6/15/69 (A & S) to: J. F. Osborn, G. E. Co., 175 Curtner Ave., M/C 650, San Jose, Calif. 95125.

OCT. 29-31, 1969: ***Photographic Processing,** Society of Photographic Scientists and Engineers, Twin Bridges Marriott Motel in Washington, D.C. **Deadline info:** 7/1/69 (abst), 8/15/69 (sum) to: Clifford B. Krumm, Photographic Processing Branch, Wright Patterson AFB, 1975 Shaftesbury Road, Dayton, Ohio 45406.

NOV. 5-7, 1969: **Northeast Electronics Research & Engineering Mtg (NEREM),** Sheraton Boston Hotel, War Mem. Aud., Boston, Mass. **Deadline info:** 5/31/69 (abst) to: C. J. Peters, Sylvania Elec. Pdts., 40 Sylvan Rd., Waltham, Mass. 02154.

NOV. 18-21, 1969: **Conf on Magnetism and Magnetic Materials,** Benjamin Franklin Hotel, Phila., Penna. **Deadline info:** 8/11/69 (abst) to: J. D. Blades, Franklin Inst. Res. Labs., Phila., Penna. 19103.

DEC. 8-10, 1969: **Int'l Symposium on Circuit Theory,** Mark Hopkins Hotel, San Francisco, Calif. **Deadline info:** 7/1/69 (papers) to: R. A. Rohrer, Fairchild Semiconductors, 4001 Junipero Serra Blvd., Palo Alto, Calif. 94304.

JAN. 25-30, 1970: **Winter Power Mtg.,** Statler Hilton Hotel, New York, N.Y. **Deadline info:** 9/15/69 (papers) to: IEEE Hdqs., Tech. Conf. Svcs., 345 E. 47th St., New York, N.Y. 10017.

MARCH 17-20, 1970: ***Symposium on Management & Economics in the Electronics Industry,** Univ. of Edinburgh, Edinburgh, Scotland. **Deadline info:** 5/1/69 (syn) to: IEE, Savoy Place, London W.C. 2 England.

May 19-21, 1970: ***Signal Processing Methods for Radio Telephony,** London, England. **Deadline info:** 8/25/69 (syn); 12/29/69 (ms) to: IEE, Savoy Place, London, W. C. 2 England.

Meetings

APRIL 23-25, 1969: ***Southwestern IEEE Conf. & Exh.,** San Antonio Conv. Ctr., & Palacio Del Rio Hotel, San Antonio, Texas. **Prog info:** W. H. Hartwig, Univ. of Texas, EE Dept., Austin, Texas 78712.

APRIL 30-MAY 2, 1969: ***Electronic Components Conf.,** Shoreham Hotel, Washington, D.C. **Prog info:** James O'Connell, ITT Hdqs., 320 Park Ave., New York, N.Y. 10022.

MAY 5-7, 1969: **Electrical & Electronic Measurement & Test Inst. Conf.—Instrument and Measurement Symp. (EEMTIC & IM),** Skyline Hotel, Ottawa, Ontario, Canada. **Prog info:** G. E. Schafer, National Bureau of Standards, Boulder, Colorado 80302.

MAY 5-7, 1969: **International Microwave Symp.,** Marriott Motor Hotel, Dallas, Texas. **Prog Info:** J. B. Horton, POB 5012, Texas Instr. Inc., Dallas, Texas 75222.

MAY 5-8, 1969: ***Int'l Congress on Instrumentation in Aerospace Simulation Facilities,** Polytechnic Inst. of Bklyn. Grad. Ctr., Farmingdale, New York. **Prog info:** C. R. Spitzer, MS-236, NASA Langley Res. Ctr., Hampton, Va. 23365.

MAY 5-8, 1969: ***1969 Design Engineering Conf.,** The Waldorf-Astoria, New York. **Prog info:** Clapp & Poliak, Inc., Show Management, 245 Park Ave., New York, N.Y. 10017.

MAY 6-8, 1969: **Conf. on Power Thyristors and their Applications,** London, England. **Prog info:** IEE, Savoy Place, London, W.C. 2 England.

MAY 6-8, 1969: **Congress on Nuclear Electronics,** EURATOM Lab., Palazzo Dei Congressi at Stresa, Stresa, Italy. **Prog info:** Luciano Stanchi, C.C.R., EURATOM, 21020 Ispra, Italy.

MAY 7-9, 1969: **Int'l Joint Conf. on Artificial Intelligence,** Statler Hilton Hotel, Washington, D.C. **Prog info:** D. E. Walker, Mitre Corp., Bedford, Mass. 01730.

MAY 12-16, 1969: **Underground Distribution Conf.,** Anaheim Conv. Ctr., Anaheim, Calif. **Prog info:** W. A. Thue, Florida Pwr. & Light Co., POB 3316, Miami, Fla. 33101

MAY 13-15, 1969: **Ind. & Comm. Power Sys. & Elec. Space Heating & Air Conditioning Jt. Technical Conf.,** Statler Hilton Hotel, Baltimore, Maryland. **Prog info:** D. T. Michael, 3917 Millsbrae, Cincinnati, Ohio 45209.

MAY 14-16, 1969: **Spring Joint Computer Conf.,** Sherton Boston Hotel, War Mem. Audit., Boston, Mass. **Prog info:** T. D. Bonn, Honeywell EDP, 200 Smith St., Waltham, Mass. 02154.

MAY 18-21, 1969: **Power Industry Computer Application Conf.,** Brown Palace Hotel, Denver, Colorado. **Prog info:** W. D. Trudgen, G. E. Co., 2255 W. Desert Cove, Phoenix, Ariz. 85029.

MAY 19-21, 1969: ***Off-Shore Technology Conf.,** Albert Thomas Conv. Ctr., Houston, Texas. **Prog info:** R. F. Nelson, Shell Oil Co., P.O. Box 60193, New Orleans, Louisiana.

MAY 19-21, 1969: **Aerospace Electronics Conf. (NAECON),** Sheraton Dayton Hotel, Dayton, Ohio. **Prog info:** J. E. Singer, 5705 Coach Four Dr., East Kettering, Ohio 45440.

MAY 21-23, 1969: **Electron, Ion and Laser Beam Technology Symposium,** Green Audit., NBS, Gaithersburg, Maryland. **Prog info:** B. W. Schumacher, West. Elec. Corp., R & D Ctr., Churchill Boro, Pittsburgh, Penna. 15235.

MAY 22-23, 1969: **Workshop on Applied Magnetics,** Sheraton Park Hotel, Washington, D.C. **Prog info:** O. Kiltie, Ballastran Corp., Fort Wayne, Ind. 46808.

MAY 26-28, 1969: **Laser Engineering and Applications Conf.,** Washington Hilton Hotel, Washington, D.C. **Prog info:** W. B. Bridges, Hughes Res. Lab., 3011 Malibu Canyon Rd., Malibu, Calif.

JUNE 3-5, 1969: **Conf. on Microelectronics,** Congress Theater, Eastbourne, Sussex, England. **Prog info:** IEE, Savoy Place, London W.C. 2 England.

JUNE 6-7, 1969: ***Product Assurance Conference and Technical Exhibit,** IEEE, Hofstra College, Hempstead, Long Island, New York. **Prog info:** B. Held, Grumman Aircraft Engineering Corp., Bethpage, Long Island, New York 11714.

JUNE 8-12, 1969: ***The Sixth Annual Design Automation Workshop,** SHARE (DA), ACM (SICDA), IEEE (Computer Group). **Prog info:** N. Garaffa, Jr., RCA ISD, Building 13-2-8, Camden, N.J. 08101.

JUNE 9-10, 1969: **Chicago Spring Conf. on Broadcast & Television Receivers,** Marriott Motor Hotel, Des Plaines, Illinois. **Prog info:** N. T. Watters, Zenith Radio Corp., 6001 W. Dickens Ave., Chicago, Illinois 60606.

JUNE 9-11, 1969: **Int'l Comm. Conf.,** Univ. of Colorado, Boulder, Colorado. **Prog. info:** Martin Nesenbergs, Inst. for Telecommunication Sci., R-614, Boulder, Colorado 80302.

JUNE 17-19, 1969: **Electromagnetic Compatibility Symposium,** Berkeley Cartaret Hotel, Asbury Park, N.J. **Prog info:** Charles Joly, Honeywell, Inc., POB 54, Eatontown, N.J. 07724.

JUNE 17-19, 1969: **Computer Conf.,** Leamington Hotel, Minneapolis, Minn. **Prog info:** D. L. Epley, Dept. of EE, Univ. of Iowa, Iowa City, Iowa 52240.

JUNE 22-27, 1969: **Summer Power Mtg.,** Sheraton Dallas Hotel, Dallas, Texas. **Prog info:** IEEE Hdqs., Tech. Conf. Svcs., 345 E. 47th St., New York, N.Y. 10017.

JULY 7-11, 1969: ***Conf. on Nuclear & Space Radiation Effects,** Penn State Univ., J. Orvis Conf. Bldg., Univ. Pk., Penna. **Prog info:** E. A. Burke, Air Force Cambridge Res. Lab., Hanscom Field, Bedford, Mass.

JULY 20-25, 1969: **Engrg. in Medicine & Biology & Int'l Fed. for Medical & Biological Engrg Conf.,** Palmer House, Chicago, Illinois. **Prog info:** Lawrence Stark, Univ. of Illinois, Chicago, Illinois.

AUG. 5-7, 1969: **Joint Automatic Control Conf.,** Univ. of Colorado, Boulder, Colo. **Prog info:** W. E. Schiesser, Dept. of Chem. Engrg., Lehigh Univ., Bethlehem, Pa. 18015.

SEPT. 2-6, 1969: ***Int'l Conv. on Educational and Training Technology,** Grosvenor House, London, England. **Prog info:** A. V. Phelps, ETTIC 69, Savoy Place, London, W.C. 2 England.

SEPT. 7-11, 1969: **Electrical Insulation Conf.,** Sheraton-Boston Hotel & War Mem. Aud., Boston, Mass. **Prog info:** H. P. Walker, NAVSEC, Code 6156D, Washington, D.C. 20360.

SEPT. 8-12, 1969: **European Microwave Conf.,** London, England. **Prog info:** IEE, Savoy Place, London, W.C. 2 England.

Engineering
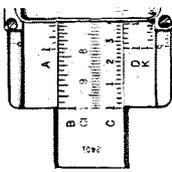
News and Highlights

SEER holds "ILS tradeoff and life-cycle-cost tools" course

Systems Engineering, Evaluation, and Research (SEER) held a quantitative ILS (integrated logistics support) tradeoff course at Cherry Hill Inn the week of February 3 through February 7. The course emphasized the methodology contained in the series of CO-AMP (computer analysis of maintenance policies) computer programs which have been under development and use by SEER over the past three years (see the papers by W. Triplett, p. 37, and E. J. Westcott, p. 50, in this issue). Representatives from each branch of the military and engineers from the five DEP divisions attended the one week session.

The main purpose of the course was to instruct RCA engineers from the operating divisions how to use the programs so that more emphasis can be placed on the quantitative aspects of ILS in the divisions.

The course was conceived by E. Leshner, Manager of Value Systems and Control, Defense Engineering and organized by M. Keller, W. Triplett, and W. Rapp of SEER. Course instructors from SEER were R. Howe, K. Hicks, A. Messey, and W. Rapp.

Value Engineering in the Government Services Division

Mr. W. J. Zaun, Vice President, Operational Controls, RCA Service Company, launched the Government Services Value Engineering Department with the first annual Value Engineering seminar at the Rickshaw Inn on February 10. Mr. J. F. Murray, Staff Vice President, Government Services, gave the opening address.

Mr. Carlos Fallon, Manager, Value Analysis and Purchasing Research, Corporate Staff followed Mr. Murray and described the history of Value Analysis, its advantages, the importance of the customer's wants, and what value really means (see p. 7 of this issue). Mr. K. Stoll, Administrator, Value Systems and Controls, Hightstown, discussed effective approaches to Value Engineering (see RCA ENGINEER, Vol. 13, No. 5, Feb-Mar. 1968). Mr. G. B. Finigan, Manager, Special and Project Contracts, then spoke of the contractual aspects of Value Engineering Change Proposals.

The Value Engineering Department is currently concentrating on those Government contracts which include Value Engineering clauses. At present, there are nine such contracts.

The managers of each of these contracts have assigned a Value Engineering Coordinator to develop Value Engineering Change Proposals. They submit these proposals to Mr. F. G. Healy, Manager, Value Engineering, for review, revision and coordination with Government Services Contracting prior to submission to the Government Contracting Officer.

H. M. Gurin retires

Hank Gurin, Staff Engineer at AED retired recently after completing more than 34 years with RCA. As Staff Engineer, he handled special assignments for the Chief Engineer and also served as the Technical Publications Administrator. Prior to joining AED in 1958, Mr. Gurin was on loan to Radio Free Europe in Munich, Germany, for one year as Chief Engineer. Mr. Gurin was active in television and broadcasting for more than 25 years at NBC. During World War II, Mr. Gurin was a Laboratory Officer at the Material and Science Laboratory for the U.S. Navy. Mr. Gurin received the BSME with honors from New York University in 1936 and took advanced courses at Columbia University. He is a Fellow of the SMPTE; an Associate Fellow of the AIAA. He served as a member of the AIAA Executive Council and as Chairman of its Princeton Section. He was also Associate Editor of the AIAA *Journal of Spacecraft and Rockets*. Mr. Gurin is an active member of the American Association for the Advancement of Science and the Acoustical Society of America.

Dr. G. H. Heilmeier honored by Eta Kappa Nu as outstanding young electrical engineer of 1968

Dr. George H. Heilmeier of the RCA Laboratories was honored as the Outstanding Young Electrical Engineer of 1968 by Eta Kappa Nu, national electrical engineering honor society. Dr. Heilmeier received his award at the Eta Kappa Nu Annual Award Dinner on March 24 at the New York Hilton Hotel. The presentation was made by Dr. George H. Brown, an Eminent Member of Eta Kappa Nu and Executive Vice President, Patents and Licensing, for RCA.

Winners of the Eta Kappa Nu award and honorable mentions are selected for outstanding professional achievements, civic and social activities, and cultural pursuits. They must be no more than 35 years old, with a BSEE, or equivalent, degree held no more than 10 years.

Dr. Heilmeier, 32, was honored for his outstanding work in the application of new effects in solids and liquids and his many contributions to community and church affairs.

At RCA Laboratories, Dr. Heilmeier is Head, Solid State Devices Research. He has received international recognition as leader of the RCA research team that discovered an electro-optic effect in liquid crystals that makes possible for the first time the electronic control of the reflection of light.

Dr. Heilmeier received his BS degree from the University of Pennsylvania in 1958, and his MS, AM, and PhD, from Princeton University in 1960, 1961, and 1962, respectively.

Dr. George Heilmeier (center) holding his Eta Kappa Nu award is flanked by (from left to right) Dr. Webster, Staff Vice President, RCA Laboratories; Dr. Hillier, Executive Vice President, Research and Engineering; Mrs. Heilmeier; and Dr. Brown, Executive Vice President, Patents and Licensing.
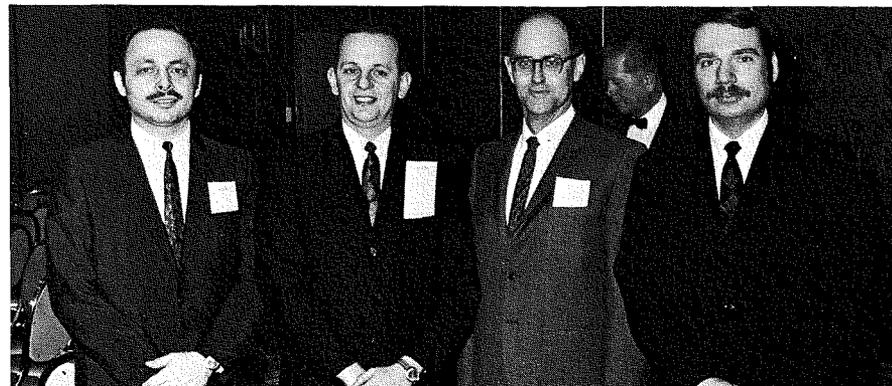
Past RCA men who have won the Eta Kappa Nu award with Dr. Heilmeier. From left to right, Dr. Lewin, Dr. Heilmeier, Mr. Wentworth, and Dr. Hofstein (who left RCA after he was nominated.)

Staff announcements

Consumer Electronics Division

B. S. Durant, Division Vice President and General Manager, Consumer Electronics Division has appointed **J. S. Peters** as Division Vice President, Consumer Electronics International Operations.

Information Systems Division

J. R. Bradburn, Executive Vice President, Information Systems has appointed **J. J. Worthington,** as Manager, Product Assurance, Information Systems Division.

J. R. Lenox, Division Vice President, Manufacturing and Engineering has announced the organization of Manufacturing and Engineer as follows: **A. D. Beard,** Chief Engineer, Engineering; **H. Kleinberg,** Manager, Engineering—Camden; **W. R. Maclay,** Manager Engineering—Marlboro; **J. N. Marshall,** Manager, New Product Line; **H. N. Morris,** Manager, Engineering, Palm Beach; **R. E. Wilson,** Staff Engineer; **H. J. Martell,** Manager, Manufacturing Operations—Marlboro; **B. W. Pollard,** Manager, Operations Programs—New Product Line; **K. L. Snover,** Manager, Manufacturing Operations—Palm Beach; **R. L. Weaver,** Manager Facilities and Plant Engineering.

J. R. Bradburn, Executive Vice President, Information Systems announced the appointment of **J. T. Cimorelli** as Division Vice President and General Manager, Memory Products Division; and **J. Stefan,** Division Vice President and General Manager, Magnetic Products Division.

H. P. Lemaire, Manager, Memory Products, Engineering has announced the organization of the Memory Products Engineering Activity as follows: **B. P. Kane** continues as Manager, Memory Systems Engineering; **A. C. Knowles,** Manager, Application and Design Engineering

—Devices; **P. D. Lawrence,** Manager, Device Test Engineering; **C. H. McCarthy** continues as Administrator, Engineering Administration; **E. A. Schwabe,** Manager, New Products and Core Engineering; **L. A. Wood** continues as Manager, Engineering Services.

Defense Electronic Products

I. K. Kessler, Vice President, Defense Electronic Products has appointed **G. D. Prestwich** as Division Vice President, Defense Marketing.

S. Sternberg, Division Vice President and General Manager, Electromagnetic and Aviation Systems Division, has appointed **N. A. Montone** as Manager, Marketing—Van Nuys Operations.

RCA Laboratories

H. R. Lewis, Director, Materials Research Laboratory, has appointed **J. J. Tietjen** as Head, Semiconductor and Luminescence Research.

F. D. Rosi, Staff Vice President, Materials and Device Research has appointed **L. R. Weisberg** as Director, Semiconductor Device Research Laboratory.

W. M. Webster, Staff Vice President, Laboratories, has appointed **T. O. Stanley** as Staff Vice President, Systems Research.

Electronic Components

C. P. Smith, Manager, Conversion Tube Operations, Industrial Tube Division has announced the appointment of **R. E. Simon** as Manager, Advanced Technology.

L. W. Grove, Manager, Camera and Display Tube Operation, has announced the organization of the Camera and Display Tube Operation as follows: **J. K. Johnson,** Manager, Camera Tube Manufacturing; **J. G. Kindbom,** Manager, Display Tube Manufacturing; **M. Petrisek,** Manager,

Camera Tube Product Development Engineering and Applications; **P. H. Vokrot,** Administrator, Camera and Display Tube Administration.

R. C. Pontz, Manager, Photo and Image Tube Operation has announced the organization of the Photo and Image Tube Operation as follows: **W. W. Bucher,** Administrator, Photo and Image Tube Administration; **H. R. Krall,** Engineering Leader, Product Development; **M. K. Massey,** Manager, Image Tube Manufacturing; **R. G. Stoudenheimer,** Engineering Leader, Applications Engineering Image Tubes; **K. A. Thomas,** Manager, Photo Tube Manufacturing.

R. E. Simon, Manager, Advanced Technology, has announced the organization of the Advanced Technology—Conversion Tube Operations as follows: **R. W. Engstrom,** Manager, Advanced Optics and Systems; **J. L. King,** Manager, Development Shop; **E. D. Savoye,** Manager, Conversion Devices Laboratory.

C. E. Burnett, Division Vice President and General Manager, Solid State and Receiving Tube Division has appointed **N. S. Freedman** as Manager, Liquid Crystal Program.

Instructional Systems

M. H. Glauberman, Director, Instructional Systems has appointed **N. N. Alperin** as Manager, Software Development.

Finance

K. Kozarsky, Director, Computers and Telecommunications has appointed **J. R. Sandlin** as Manager, Computer Systems.

Operations Staff

Dr. J. Hillier, Executive Vice President, Research Engineering has appointed **A. R. Trudel** as Staff Engineer, Product Engineering.

A. Sternberg wins national award

Alexander Sternberg, senior engineer in Quality and Reliability Assurance in RCA's Microwave Devices Operations Department in Harrison, New Jersey has won the 1968-69 national award of the Electronics Division of the American Society for Quality Control. The Award was presented to Sternberg by Division Chairman P. R. Krauss at the 15th Annual Symposium on Reliability. The award is given "for outstanding service to the division and to the society over a sustained period of 15 years." Mr. Sternberg has the A.B. degree from Washington University, St. Louis and the M.A. and M.S. degrees from Rutgers University. He joined RCA in 1962 as a member of the Reliability and Quality Assurance group of the Astro-Electronics Division. Prior to that, he worked for the U.S. Army Ordnance and other electronics companies in establishing reliability programs. Mr. Sternberg has held many important posts in the American Society for Quality Control including that of Chairman of the Electronics Division. He is now a Director at Large. Mr. Sternberg is a Fellow of the ASQC and a Senior Member of the IEEE.
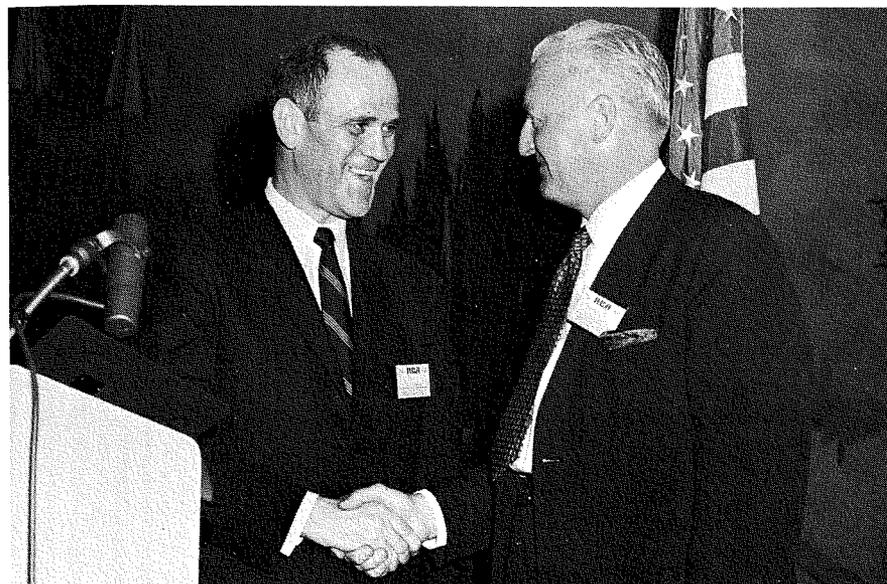
Alexander Sternberg (left) senior engineer in Quality and Reliability Assurance in RCA's Microwave devices Operations Department, Harrison, New Jersey, being congratulated by C. H. Lane, Division Vice-President and General Manager of the Industrial Tube Division on his winning the 1968-69 annual national award of the Electronics Division of the American Society for Quality Control. Sternberg received the award at the Annual Symposium on Reliability at the Palmer House, Chicago on January 22.

Professional activities

RCA Engineers instrumental in award to Philadelphia Chapter of the IEEE Reliability Group

The IEEE Philadelphia Reliability Chapter received the 1968 award for being the "Outstanding Chapter of the Year". This award was presented during the 1969 Reliability Symposium by the IEEE National Reliability Administrative Committee. **Max Tall,** Chapter Chairman for the year beginning July 1968 and Manager, RCA Defense Product Assurance, received the award on behalf of the chapter.

The chapter earned the award because of its outstanding program of activtities in 1968. **Mr. Bernard Tiger,** Systems Assurance Consultant in DCSD and Chapter Chairman for the year ending June 1968, was instrumental in organizing much of the chapter's activities. This included its first all-day seminar on failure analysis of microcircuitry, equipments, and systems. In addition, the chapter members (many of whom are RCA engineers) were extremely active in presenting technical papers and participating in chapter as well as other IEEE activities.

A highlight of the 1969 year is the Second Annual Seminar on Failure Analysis on May 22, 1969 at the University of Pennsylvania.

Defense Communications Systems Division

J. H. Goodman has been elected to serve as Vice Chairman for the Philadelphia Section of the IEEE Group on Reliability effective June 1, 1969.

Aerospace Systems Division

P. M. Toscano has successfully completed a course in Fallout Shelter Analysis sponsored by the Department of Army.

Defense Microelectronics

M. L. Topfer was Program Chairman of Greater N.Y. Section of International Society of Hybrid Microelectronics.

Systems Engineering, Evaluation, and Research

B. Stockwell recently addressed the Polytechnic Institute of Brooklyn's student chapter of the American Institute of Aeronautics and Astronautics. The one hour lecture on Space Systems Design followed a curriculum in Aerospace Engineering.

Astro-Electronics Division

J. Fagan was named Chairman, Mid Atlantic Chapter, Institute of Environmental Sciences Nominating Committee.

Licensed engineers

Frank W. Dickel, Corporate Standardizing, Cherry Hill; Penna. PE-002868E; 3/24/69.

James T. Shields, M&SR, Mrstn; New Jersey, PE-16545; 11/22/68.

John Stevens, ISD, Palm Beach, Fla.; Penna. PE-014151-E; June, 1968.

Promotions
to engineering leader and manager

Defense Electronic Products

C. A. Oattes: from "A" Engineer to Leader, Design & Development Engrg. (S. Schach, Parts Applications)

F. C. Shashoua: from Manager, Advanced Recording and Display to Manager, Advanced Technology Burlington Laboratory. (Camden)

D. Woywood: from Leader to Manager, Electro-Optic Techniques. (Camden)

A. Feller: from AA Engineer to Leader, Advanced Circuit Techonology. (Camden)

Missile and Surface Radar Division

W. S. Sepich: from AA Engineer to Mgr., Equip. D&D (P. Levi, Mech. Engrg. & Radiation Equipment)

P. Levi: from Mgr., Equip D&D to Mgr., Radiation Equipment (D. M. Cottler, Radiation Equipment Engineering)

Electromagnetic and Aviation Systems Division

R. P. Egermeier: from Mgr., Elect D&D to Staff Engineer (J. L. Parsons, D&D, Van Nuys)

R. Landau: from Prin. Mbr., Engrg. Staff, to Leader, D&D Engrg. Staff (J. L. Parsons, D&D, Van Nuys)

J. G. MacKinney: from Staff Engrg. Scientist to Leader, D&D Engrg. Staff (J. L. Parsons, D&D, Van Nuys)

Astro-Electronics Division

T. R. Wylie: from Ldr. Engr. to Manager, Specialty Engrg. (R. Packer, Princeton)

R. D. Wilkes: from Ldr. Engr. to Manager, Specialty Engrg. (R. Packer, Princeton)

R. H. Goerss: from Ldr. Engr. to Manager, Specialty Engrg. (A. Garman, Princeton)

R. R. Scott: from Ldr. Engr. to Manager, Specialty Engrg. (R. Packer, Princeton)

P. B. Lazovick: from Ldr. Engrg. to Manager, Specialty Engrg. (G. Barna, Princeton)

G. G. Frippel: from Ldr. Engrg. to Manager, Specialty Engrg. (A. Garman, Princeton)

J. C. Blair: from Ldr. Engrg. to Manager, Specialty Engrg. (G. Barna, Princeton)

R. C. Greene: from Ldr. Engrg. to Manager, Specialty Engrg. (G. Barna, Princeton)

L. Berko: from Ldr. Engrg. to Manager, Specialty Engrg. (R. Packer, Princeton)

E. W. Dusio: from Ldr. Engrg. to Manager, Specialty Engrg. (E. Goldberg, Princeton)

S. M. Ravner: from Ldr. Engrg. to Manager, Specialty Engrg. (A. Garman, Princeton)

C. Staloff: from Ldr. Engrg. to Manager, Specialty Engrg. (A. Garman, Princeton)

F. J. Bingley: from Ldr. Engrg. to Manager, Specialty Engrg. (G. Barna, Princeton)

R. F. Sharp: from Ldr. Engrg. to Manager, Specialty Engrg. (E. Goldberg, Princeton)

B. M. Soltoff: from Ldr. Engrg. to Manager, Specialty Engrg. (G. Barna, Princeton)

J. R. Engel: from Ldr. Engr. to Manager, Specialty Engrg. (R. Packer, Princeton)

A. Sherman: from Ldr. Engr. to Manager, Specialty Engrg. (G. Barna, Princeton)

R. J. Treadwell: from Ldr. Engr. to Manager, Specialty Engrg. (G. Barna, Princeton)

R. G. Horner: from Admin. Equip. Eng. to Manager, Specialty Engrg. (J. Kiegler, Pr.)

L. E. Golden: from Ldr. Eng. to Adm. Syst. Engrg. (J. Kiegler, Princeton)

J. J. Corr: from Sr. Engr. to Manager, Specialty Engrg. (R. Hogan, Princeton)

J. W. Jones: from Ldr. Engr. Syst. Proj. to Manager, Specialty Engrg. (R. Hogan, Pr.)

C. T. Cole: from Adm. Spec. Test Equip. & Age to Manager, Specialty Engrg. (R. Hogan, Pr.)

J. R. Staniszewski: from Adm. Equip. Eng. to Manager, Specialty Engrg. (R. Hogan, Pr.)

F. T. Scearce: from Ldr. Engr. to Manager Specialty Engrg. (R. Hogan, Princeton)

E. W. Mowle: from Adm. Equip. Engrg. to Manager, Specialty Engrg. (R. Hogan, Princeton)

L. Gomberg: from Adm. Proj. Prod. Assur. to Manager, Specialty Engrg. (R. Hogan, Princeton)

Information Systems Division

C. E. Reeder: from "AA" Engr. to Leader, D&D Engrg. (J. J. O'Donnell, Electrical Standards, Camden)

Electronic Components

J. H. Barrett: from Superintendent, Tube Manufacturing to Manager, Production Engrg. (A. M. Trax, Mgr., Process & Production Engrg., Marion)

RCA Global Communications

F. X. Meyer: from Design Engr. to Group Ldr. (E. Williamson, Mgr., Svcs., N.Y.)

A. J. Falco: from Design Engr. to Group Ldr. (J. A. Goldberg, Mgr. External Telex Engrg., N.Y.)

M. Fruchter: from Design Engr. to Group Ldr. (E. J. Williamson, Mgr. Engrg. Svcs., N.Y.)

E. T. Murphy: to Group Ldr. (D. Mandato, Mgr. Special Systems Design, N.Y.)

G. A. Long: from Mgr. Thailand Operations to Group Leader (J. M. Walsh, Mgr. Satellite & Radio Engrg.)

W. Schulhafer: from Design Engr. to Group Leader (I. A. Cohen, Mgr., Leased Channel Engrg., N.Y.)

New TPA and six new Ed Reps appointed

Mr. Irving M. Seideman has been appointed Technical Publications Administrator for the Astro-Electronics Division of RCA. In this capacity, Mr. Seideman is responsible for the review and approval of technical papers; for coordinating the technical reporting program; and for promoting the preparation of papers for the RCA ENGINEER and other journals, both internal and external. Mr. Seideman had previously been the Editorial Representative for AED.

The new Editorial Representatives are:
  Mr. Donovan M. Hall, Government Service Department, RCA Service Co., will work with M. Gander, TPA for the Service Company;
  Mr. Sidney Weisberger, Astro-Electronics Division, will work with I. M. Seideman, TPA for AED;
  Mr. A. G. Evans, Magnetic Products Division, will work with M. F. Kaminsky, TPA for Information Systems Division.
  Messrs. M. R. Sherman of Defense Microelectronics, **E. J. Podell** of Systems Engineering, Evaluation, and Research, and **J. L. Krager** of Central Engineering will work with M. G. Pietz, TPA for Defense Engineering.

These new Editorial Representatives will be responsible for planning and processing articles for the RCA ENGINEER, and will support the TPA's in their respective divisions as required.

Hall   Podell

Mr. Hall is presently Manager of Field Support Engineering and Quality Assurance reporting to the Vice President of Operational Controls, RCA Government Services. He received training in electronics at U.S. Navy electronic schools in 1949 and attended courses in television engineering and mathematics at Compton Jr. College, Compton, California and the University of Minnesota from 1952 thru 1954. He was employed in power transistor research at Minneapolis-Honeywell, General Research Laboratories in 1953 and 1954. In 1955 Mr. Hall joined RCA Government Services as a Field Engineer. In 1961 he became Field Contracts Manager for RCA Government Services, managing contracts with Central GEEIA Region, Air Force Security Services and Air Defense Command of the U.S. Air Forces at Oklahoma City. In 1963 he was appointed Manager of Installation Services for Field Engineering Operations at Cherry Hill, New Jersey where he managed the planning and installation of radar systems, communications systems, and radio and television broadcast facilities for US Government and commercial cus-

tomers in South East Asia, South America, Europe, Africa and Continental US.

Mr. Edwin J. Podell received the BA in Physics from Temple University in 1950. Before joining RCA in 1958, he managed technical publications groups at Philco and at American Electronics Labs. On his first assignment with the Missile and Surface Radar Division, he participated in the BMEWS program.

After five years his efforts were devoted to various technical proposals issued by M&SR. Since October 1966, Mr. Podell has been assigned to publications and support engineering as a member of SEER's Technical Operations group; he is responsible for all technical reports and proposals issued by SEER.

[*Editor's note:* the biography and photograph of Mr. Weisberger were published in Vol. 13, No. 2 of the RCA ENGINEER; the photos and biographies of Messrs. Evans, Krager, and Sherman will be included in future issues.]

Burlington Laboratory established

A satellite of DEP Advanced Technology Laboratories has been established at ASD in Burlington, Mass. **Fred Shashoua** who will manage it will report directly to **Dr. James Vollmer,** Manager, Advanced Technology Laboratories. **Gardner Burton** and **Larry O'Hara** will join the Burlington Laboratory as Leader and Member of Technical Staff, respectively. This group will work on injection laser technology. It is planned to add two additional leader groups by the end of June.

Awards

Astro-Electronics Division

C. Devieux has been named Engineer of the Month of January for his work on high density magnetic tape recorders and for the analytical design of the communication system to support the Satellite Data Collection System for the Earth Resources Satellite. **Dr. P. C. Murray** was cited as the Engineer of the Month for February for his work in the conception of a system for the registration of high-resolution multispectral TV pictures from space.

Aerospace Systems Division

Terry J. Donofrio, Member, Radar Engineering, was selected as the Engineer of the Month for November for his work on the High Power Microelectronic Noise Jammer Program. **Paul F. Minghella,** Senior Member, Automatic Test Equipment Engineering was selected as the Engineer of the Month for December for his contribution to the LCSS Program.

The team of **L. E. Alston, W. C. Bradley, D. F. Dion, S. H. Drucker, J. R. Garvey, R. Nohelty,** and **G. J. Sandorfi** from Advanced Systems and Technology was selected for a team award for the month of November. The team was selected for its oustanding work on the High Resolution Scan Converter Program.

The team of **Burton R. Clay** and **Nunzio A. Luce** from Advanced Systems and Technology was selected for a team award for the month of December. The team was selected for its outstanding performance on the Laser Obstacle Detector for the High-Speed Railway program.

Aviation Equipment Department expands

The Aviation Equipment Department of EASD recently completed the expansion of their engineering facilities. These expanded facilities, located at 2037 Granville St., West Los Angeles, Calif., provide additional laboratory and drafting areas as well as space necessary for the planned increase in engineering personnel. Approximately 12,000 sq. ft. were added to the existing 13,000 sq. ft. to accommodate 50 additional personnel.

The need for new avionic equipment development for the general-aviation and commercial airline markets is expected to continue at an increasing rate, and the Aviation Equipment Department has been preparing to meet that demand. Scheduled releases for 1969 include new radars, transponders, distance-measuring equipments, and navigation-communication systems.

An organization chart of the present engineering department under **G. A. Lucchi** is given below:

Aviation Equipment Department, Engineering
G .A. Lucchi, Mgr.

Systems Engineering R. W. McKelvy, Mgr.	Radar Engineering C. J. Monroe, Mgr.	NAV/COM Engineering R. P. Crow, Mgr.	DME Engineering L. M. Johnson	Transponder Engineering G. A. Lucchi, Acting Mgr.	Laboratory A. DeMicco, Ldr.
Advanced Development G. J. Giel	Research J. H. Pratt A. Vose	Engineering Budgets E. H. Kimball, Adm.	Publications Engineering J. J. McDonough, Ldr.	Drafting L. B. Parker, Ldr.	Model Shop S. Norstroni

Index to RCA Engineer
volume 14

This index covers Vol. 14-1 (June-July 1968), 14-2 (Aug.-Sept. 1968), 14-3 (Oct.-Nov. 1968), 14-4 (Dec. 1968-Jan. 1969), 14-5 (Feb.-Mar. 1969), and the present issue, 14-6 (April-May 1969). Since *RCA Engineer* articles are also available as reprints, the reprint number (PE-000) is noted throughout. *RCA Engineer* papers are also indexed along with all other papers written by the RCA technical staff in the annual *Index to RCA Technical Papers*.

95

SOLID-STATE DEVICES

L-BAND TRF AMPLIFIER, An integral-cavity—A new concept—K. W. Uhler (EC, Som) **14-3** (reprint PE-405)

SOLID-STATE POWER SOURCES, Microwave—Dr. F. Sterzer (ISD, C.H.) **14-3** (reprint booklet, RCA Computer Applications, PE-412)

TRANSISTOR DESIGN, A self-consistent regional approach to computer-aided—Dr. R. B. Schilling (EC, Som) **14-3** (reprint RE-14-3-16)

SPACE COMMUNICATION

RETRODIRECTIVE ANTENNA SYSTEMS to spacecraft, Application of—W. Garner, D. McGiffney (AED, Pr) **14-5** (reprint RE-14-5-16)

SPACE ENVIRONMENT

POINTING REQUIREMENTS for Satellite Tracking from Earth—H. Harmening (MSR, Mrstn) **14-1** (reprint booklet, RCA Engineering, PE-408)

RUGGEDIZATION of camera tubes for space applications—J. G. Ziedonis (EC, Lanc) **14-4** (reprint RE-14-4-12)

SPACECRAFT

EARTH RESOURCES SATELLITE—Dr. H. M. Gurk, B. P. Miller (AED, Pr) **14-4** (reprint RE-14-4-5)

SPACE ENGINEERING, Digital Computers in—R. Goerss (AED, Pr) **14-5** (reprint RE-14-5-17)

TIROS DECADE—A. Schnapf (AED, Pr) **14-3** (reprint PE-411; reprint booklet, RCA Computer Applications, PE-412)

TELEVISION BROADCASTING

COLOR VIDEO SWITCHING SYSTEMS—R. J. Butler (NBC, N.Y.) **14-1** (reprint RE-14-1-8)

TV TRANSMITTER MONITORING Problems—W. L. Behrend (CESD, Mdw. Lds.) **14-1** (reprint RE-14-1-10)

ZERO-DELAY video systems—R. J. Butler (NBC, N.Y.) **14-5** (reprint RE-14-5-13)

TELEVISION EQUIPMENT

PHOTO-DIELECTRIC TAPE CAMERA SYSTEMS—J. A. D'Arcy (AED, Pr) **14-4** (reprint RE-14-4-22)

TUBES, ELECTRON

CATHODOLUMINESCENT PHOSPHORS, Development of—A. L. Smith (EC, Lanc) **14-4** (reprint RE-14-4-9)

CERAMIC-METAL TETRODES for distributed amplifier service—C. E. Doner, W. R. Weyant (EC, Lanc) **14-4** (reprint RE-14-4-1)

CERMOLOX TUBES for single-sideband, Design of—A. Bazarian (EC, Lanc) **14-4** (reprint RE-14-4-2)

COAXITRAN—J. A. Eshelman, B. B. Adams (EC, Lanc) **14-4** (reprint RE-14-4-11)

COLORIMETRY AND CONTRAST PERFORMANCE of color picture tubes—G. M. Ehemann, W. G. Rudy (EC, Lanc) **14-4** (reprint RE-14-4-8)

COLOR-PICTURE-TUBE DEVELOPMENT, Milestones in—H. R. Seelen (EC, Hr) **14-4** (reprint RE-14-4-23)

ELECTRON OPTICS of Vidicons—J. R. Leaman (EC, Lanc) **14-1** (reprint booklet, RCA Engineering, PE-408)

GASES AND GETTERS in color picture tubes—Dr. J. C. Turnbull, Dr. J. J. Moscony, A. Month, J. R. Hale (EC, Lanc) **14-4** (reprint RE-14-4-20)

IMAGE ISOCON—an improved image orthicon—E. M. Musselman, R. L. VanAsselt (EC, Lanc) **14-4** (reprint RE-14-4-7)

KLYSTRON for the Stanford two-mile linear accelerator—A. C. Grimm, F. G. Hammersand (EC, Lanc) **14-4** (reprint RE-14-4-10)

PHOTOMULTIPLIER-TUBE OPERATION, Computer Simulation of—D. E. Persyk (EC, Hr) **14-3** (reprint booklet, RCA Computer Applications, PE-412)

POWER TRIODE for microwave cooking, Design of a 915-MHz—W. P. Bennett, D. R. Carter, I. E. Martin, F. W. Peterson, J. D. Stabley, D. R. Trout (EC, Lanc) **14-4** (reprint RE-14-4-4)

RUGGEDIZATION of camera tubes for space applications—J. G. Ziedonis (EC, Lanc) **14-4** (reprint RE-14-4-12)

VIDICON, A sterilizable and ruggedized—Dr. S. A. Ochs, F. D. Marschka (EC, Lanc) **14-4** (reprint RE-14-4-13)

VIDICONS in Modern TV Systems, The Application of—R. E. Johnson (EC, Lanc) **14-1** (reprint booklet, RCA Engineering, PE-408)

VIDICON PHOTOCONDUCTORS—J. F. Heagy (EC, Lanc) **14-4** (reprint RE-14-4-6)

TUBE COMPONENTS

GASES AND GETTERS in color picture tubes—Dr. J. C. Turnbull, Dr. J. J. Moscony, A. Month, J. R. Hale (EC, Lanc) **14-4** (reprint RE-14-4-20)

VIDICON PHOTOCONDUCTORS—J. F. Heagy (EC, Lanc) **14-4** (reprint RE-14-4-6)

Author Index

Subject listed opposite each author's name indicates where complete citation to his paper may be found in the subject index. An author may have more than one paper for each subject category.

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