

# Reliability from a System Point of View

ALEXANDER W. BOLDYREFF†

THE DEVELOPMENT of complex electronic and electromechanical systems during the past fifteen years has been guided primarily by considerations of improved performance.

In this development, perhaps the most outstanding factor has been a systematic effort to minimize human error by a maximum utilization of automatic or semi-automatic devices.

While the progress in this direction has been truly remarkable, it has been achieved at the expense of ever increasing complexity and cost.

A few examples will illustrate this point:

- 1) Number of vacuum tubes on one destroyer:<sup>1</sup>

| Year | Number of Tubes |
|------|-----------------|
| 1937 | 60              |
| 1944 | 850             |
| 1952 | 3200            |

- 2) A modern mobile search radar for ground defense is composed of:

|      |              |
|------|--------------|
| 500  | vacuum tubes |
| 2000 | resistors    |
| 1500 | capacitors   |
| 300  | transformers |

as a part of a complete itemization of more than 20,000 replacement parts.

- 3) The Norden bombsight of World War II could be carried by one man and cost 2500 dollars. The computing bombsights of today weigh between one and two thousand pounds and cost more than a quarter million dollars.

It is not surprising to find associated with this growth in complexity an alarming rate of failure of equipment, and an ever increasing requirement for inspection and maintenance.

Thus, during World War II more aircraft were lost due to deterioration than were lost in combat.<sup>2</sup> Again, quoting from World War II experience:<sup>3</sup>

- 1) Sixty per cent of the British radars shipped to the Far East were found defective on arrival. Of the

remaining 40 per cent, arriving in operating condition, half deteriorated on the shelf.

- 2) For a set of U. S. bombsights, 60 per cent failed as a result of poor packaging and rough handling, 15 per cent failed due to improper maintenance and overhaul, another 10 per cent of the failures were attributed to poor design.

The situation is no better today, and acceptable performance standards for complex electronic equipment are possible only at the cost of extensive repair and maintenance facilities. For military electronics, an estimate of the maintenance bill is from ten to one hundred times the cost of original equipment. Considering the number and the caliber of technicians required to service adequately existing electronic equipment, it does not seem possible that, if the present trends continue, the training of technicians can keep in step with the demands for their services, particularly in the event of total mobilization.<sup>4</sup>

The seriousness of the reliability problem has been thoroughly recognized now for a number of years. A great deal of work has been done to acquire a better understanding of this problem. Various methods of improving reliability have been advocated during the past nine or ten years.

It has been pointed out<sup>5</sup> that in the case of aircraft, after nearly half a century of experience, suitable reliability was attained only through redundant design; so that in case of failure of one component, another could be substituted in its place. In this way, even though some kind of failure (requiring emergency service outside the normal maintenance routine) may occur in aircraft every seven and a half hours of flying, the ratio of failure to disaster is ten thousand to one. This ratio is one to one for the systems which are serial in nature, such that the failure of any one component leads to system failure, as, for example, in the case of guided missiles.

Considering the complexity of many systems in use today or in the process of development, it is not surprising that a great deal of emphasis has been placed on the importance of component reliability.<sup>6-8</sup>

<sup>4</sup> G. B. Devey, "Reliability in electronic equipment," *PROC. IRE*, vol. 38, pp. 344-345; April, 1950.

<sup>5</sup> L. N. Ridenour, "The Philosophy of Guided Missile Design," Res. and Dev. Board, Shock and Vibration Bull. No. 18; August, 1951.

<sup>6</sup> R. Lusser, "A Study of Methods for Achieving Reliability of Guided Missiles," USNAMTC Tech. Rep. 75; July 10, 1950.

<sup>7</sup> R. Lusser, "General Specifications for the Safety Margins Required for Guided Missile Components," USNAMTC Tech. Rep. 84; July 10, 1951.

<sup>8</sup> R. Lusser, "The Statistical Aspects of Reliability," *Electronic Applications Reliability Rev.* RETMA, no. 2; 1953.

† The RAND Corp., Santa Monica, Calif., and Univ. of Calif., Los Angeles, Calif.

<sup>1</sup> Prog. Rep. on "Reliability of Electronic Equipment," by the Ad Hoc Group on Reliability of Electronic Equipment for the Committee on Electronics of the Research and Development Board, EL 200/17, vol. 1 and 2; February 18, 1952.

<sup>2</sup> D. C. Kennard, discussion of paper by J. M. Frankland on "Criteria for Specifications," Res. and Dev. Board, Shock and Vibration Bull. No. 17, March, 1951.

<sup>3</sup> R. R. Carhart, "The General Problem of Reliability in Missile Systems," The RAND Corp., paper S-4; July 9, 1951.

Particularly noteworthy in this connection are the ARINC Study, the Signal Corps-Cornell University Program, the Vitro Study, the Bell Laboratories Studies, the RETMA, the JETEC, the AGREE, etc.<sup>9</sup>

At the same time, a great deal of effort has been and is being expended on component testing and inspection before they are employed in complex systems. But while all this is highly necessary, it may be far from sufficient to insure sufficiently high reliability of a complex high-performance system.

Let us define reliability as the probability of failure-free operation, for a specified length of time, in a specified environment.

For a serial system of  $n$  components, such that the failure of any one component causes system failure, it is possible to estimate the system reliability in terms of the (geometric) mean component reliability.

Consider a system of 500 components. For systems with reliabilities of 0.70 and 0.95, the mean component reliabilities are 0.99929 and 0.99995, respectively. Thus, it may be argued that the reliability of a system can be increased from 0.70 to 0.95 by an improvement in mean component reliability of only 0.07 per cent. But, of course, this reasoning is misleading. Component improvement means decreasing the probability of failure. In the example under discussion, to improve system reliability from 0.70 to 0.95, we would have to decrease the probability of component failure from 0.00071 to 0.00005, and this means that we must eliminate more than 90 per cent of failures for components which are already highly reliable. To do this for each of the very many different components of many complex systems now in the process of design is patently impossible, even at a prohibitive cost in time and money.

Let us return to the definition of reliability. To be operationally significant, this definition must be quantitative; *i.e.*, the reliability of various components, or systems, must be represented by a number. For vacuum tubes, this is frequently expressed in terms of mean life to failure. Unfortunately, this quantity is not a characteristic constant. Thus, a vacuum tube may have a mean life of 10,000 hours in ground equipment, 2500 hours in aircraft, and 13 minutes in a missile.

It is, therefore, impossible to speak of the component reliability without specifying the particular system in which it is employed, as well as the way in which the system is going to be used. And this includes the handling, packing, transportation, and storage, as well as the operational use. Certainly the rest of the system constitutes an important, sometimes the most important, part of the environment in which a given component must operate.

This brings us to the question of compatibility of various components and subsystems. To use an example, are the electromechanical, electronic, and optical

components of the guidance system in a guided missile compatible with the ram jets or rocket engines of the propulsion system?

Such questions cannot be answered except by a comprehensive systems approach; I believe that the problem of reliability cannot be solved satisfactorily without the use of systems approach, and this means both system analysis and system synthesis.

Reliability, after all, is merely one of the parameters of a given system, the other parameters being performance, complexity, cost, logistic requirements, etc. These parameters are interdependent. Thus, improved performance generally implies greater complexity, lower reliability, and higher cost.

Let us consider the various steps in a system development program. These are five in number:

- 1) Definition of system objectives in terms of performance requirements.
- 2) Research, or investigation of alternate reasonable means of achieving system objectives.
- 3) Development, or selection and perfection of the best means.
- 4) Prototype test, or verification of performance, and determination of causes of failures.
- 5) Design and production, or final choice and manufacture of well engineered, reliable systems, capable of reliably meeting performance requirements.

Note that the degree of success in any step depends on the preceding steps.

Thus, the choice of performance requirements will usually dictate the complexity of the system and the tolerances of all the components. Yet this is often done in the absence of sufficient factual data or rational analysis and most often done by administrators or executives, who technically are the least competent to make these decisions. It is my opinion that here is the greatest source of low reliability, dooming many projects to ultimate failure. Certainly the most crucial question is whether the required performance is either actually necessary, or even technically attainable at a reasonable cost and in a reasonable length of time. Frequently, this question cannot be accurately answered without considerable research, development, and test, the feedback from which should dictate necessary changes, although in many cases substantial increase in reliability can be bought by relaxing unnecessarily stringent performance requirements. However, it is very difficult to point this out to the project engineers. Altogether too many of them treat the initial system objectives and exact performance requirements as sacred, and insist on freezing component and system design before there is a chance to subject system objectives to a critical analysis or to obtain feedback from actual performance tests.

The last and the most important point is that engineering is an art that can be practiced successfully only on a firm base of scientific fact. Reliable design is impossible for an unknown environment.

<sup>9</sup> "Reliability Factors for Ground Electronic Equipment," ed. by Keith Henney, McGraw-Hill Book Co., Inc., New York, N. Y.; 1956.

How much effort is expended on basic research? Let us take as an example the annual budget of our Federal government: of the seventy billions, forty-five billions, or about sixty per cent, is spent on defense. Of this sum about two and a half billions are earmarked for research and development, and only six per cent of this figure is to be devoted to basic research.<sup>10</sup>

This was emphasized in a recent report to the Congress by the Commission on Organization of the Execu-

<sup>10</sup> "Federal Funds for Science" (The Federal Research and Development Budget, Fiscal Years 1953, 1954, and 1955), Natl. Science Found., U. S. Government Printing Office, Washington, D. C.

tive Branch of the Government: "Among the Federal Agencies devoted to research and development there is but a minor amount of basic research into the laws of nature and the nature of materials. Yet the safety, the increase of productivity and the advancement of health in our Nation must come from constantly increasing knowledge through fundamental research. From these explorations come knowledge, discoveries, invention, and progress."<sup>11</sup>

<sup>11</sup> "Research and Development in the Government," a report to the Congress by the Commission on Organization of the Executive Branch of the Government; May, 1955.

## Design of Experiments for Evaluating Reliability

JOHN HOFMANN†

### THE NATURE OF EXPERIMENTATION

#### Introduction

THE consulting statistician is frequently charged with the analysis of large masses of data, and with drawing conclusions and making recommendations from the results. The data are usually collected according to the time-honored techniques peculiar to the field of endeavor represented. This often means that there have been collected, without control, observations on many variables. Some are related and others unrelated to the problem at hand.

The statistician has techniques for the analysis of such data, which sometimes are applicable after a few assumptions are made. However, often the only recourse is to curve fitting, or regression, *i.e.*, an attempt to fit a surface to the data taken, assigning one variable as dependent and the others as independent according to some rationalization. The problem in such analyses is usually the magnitude of the computations. Surface fitting with statistical methods usually involves matrix inversion, and it appears sometimes as though the matrix associated with any worthwhile undertaking is invariably large.

The design of experiments, with "design" used in the statistical sense, can be considered a means of reducing the computational problems by controlling the independent variables. However, before we pursue this point, it seems worthwhile to turn philosophic and to probe the meaning of the word "experiment."

Certainly, we are all familiar with experimentation. We do it every day without philosophical probing.

† Systems Labs. Corp., Sherman Oaks, Calif.

Asked to define an "experiment," however, those who are trained in physics or chemistry will give a far different answer than will an engineer or a microbiologist. The meteorologists, astronomers, and biologists who must deal with available data may be completely lacking in ideas on the subject.

Webster defines an experiment as "a trial or special observation made to confirm or disprove something doubtful, especially one under conditions determined by the experimenter; an act or operation undertaken in order to discover some unknown principle or effect or to test, establish or illustrate some suggested or known truth." From this definition, certainly an acceptable one, we can note at least two kinds of experiment: the absolute experiment, exploratory in nature, planned to add to our fund of knowledge some new facts; and comparative experiments, designed to compare two or more theories, processes, or products and yield data on which to base an administrative decision.

The distinction seems, at first glance, to hold up. Millikan, measuring the charge on the electron, or Joule, measuring the mechanical equivalent of heat, are adding to our knowledge of nature. On the other hand, a production engineer, comparing the yield and precision of two machines, or an electronic engineer, comparing the output or service life of a black box to corresponding specifications, is seeking data, by means of a comparative experiment, on which he may base a decision—usually one with important economic consequences to him.

Actually, there are many in-between types of experiment. For example, the determination of atomic weights, apparently an absolute, knowledge-contributing experiment, is in reality a comparative experiment since it