IRE Transactions

ON MILITARY ELECTRONICS

Volume MIL-3 | 1959 | Numbers 1-4

IRE Transactions on Military Electronics

Index to Volume MIL-3, 1959

Contents

Index to Authors

G. E. Valley, Jr.

George E. Valley, Jr. (SM'55) was born in New York, N.Y., September 5, 1913. He graduated from the Massachusetts Institute of Technology, Cambridge, Mass., in 1935, and received the Ph.D. degree in physics from the University of Rochester, N.Y., in 1939. Following two years of post graduate research at Harvard University, Cambridge, he returned to M.I.T. in 1941.

During the war he was project engineer for the H_2X radar bombing system, the first American development of this type, which was used extensively by the U.S. Eighth Air Force over Europe and later by other heavy bomber units. In 1945 he served on the editorial board for the M.I.T. Radiation Laboratory Technical Series. Returning to M.I.T. in 1946, he has been successively assistant, associate, and full professor of physics, and has conducted research in the fields of nuclear physics and cosmic radiation.

A member of the Air Force's Scientific Advisory Board since its inception, Dr. Valley was asked in 1949, by the Chief of Staff, to undertake a special study of U.S. Air Defense. The *ad hoc* Air Defense Systems Engineering Committee, which he led as a result of this request, conceived the basic ideas of the SAGE System and was directly instrumental in the founding of the M.I.T. Lincoln Laboratory. Dr. Valley served as division head, assistant, and associate director of the Lincoln Laboratory and was in charge of the SAGE System. In 1957 he went on leave from M.I.T. to become Chief Scientist of the U.S. Air Force.

He is a Fellow of the American Physical Society, and holds a Certificate of Appreciation from the U.S. Army, the President's Certificate of Merit, the Air Force Association Science Award, and the Air Force Exceptional Civilian Service Award (twice).

Guest Editorial

SOME of the earliest proposals for the development of engines of war, complicated enough to be called "weapons systems," were made during the Renaissance by the great Italian painter, Leonardo da Vinci. Many people have looked at his drawings of tanks, airplanes, and other devices with amazement, not only that these should have been conceived so many years ago, but also that they should have been conceived by an artist.

The writer has shared this feeling, but the more he has tried to understand what it is that systems engineers do, the less surprised he has become that Leonardo was an inventor, and the more he wondered why other systems engineers besides Robert Fulton and Samuel F. B. Morse have not also been artists by profession.

For when a painter takes up his palette and brushes, he can create either a masterpiece or a daub; and so it is with the systems engineer. Each of these men must be able to synthesize a satisfactory pattern to be constructed largely from the components at hand—in the one case, canvas and paints, in the other, copper and cores and bits of crystal. Although the systems engineer is the captain of a team, whereas the artist works alone, he must nevertheless make the final decisions; there are relatively few successful systems which were synthesized entirely according to the majority vote in a committee. Nor will anyone who has managed the development of a system readily admit that the systems engineer requires less of that blind persistence in the face of seemingly endless frustration than does the artist starving in the proverbial garret.

It may appear, then, that the quality of the painting depends more upon its creator's vision and courage than upon his ability to run a paint factory. But history contradicts: for although we cannot say with certainty that any great number of masterpieces has been denied us because the paint was of poor quality, we do know that almost without exception the great masters engaged themselves in the development of paint and other components of their art.

And so it is with systems; the system which works and gives years of reliable service is scarcely ever the one which was engineered by a man so ignorant of components that he could not see to it that reliable, tested ones were used nor so optimistic that he allowed all of them to be specially invented for the immediate purpose.

The above is by way of asserting that systems engineering is an art; this statement cannot be proven. What can easily be demonstrated, however, is that the subject of systems engineering is notably lacking in one of the principal characteristics of a science. There is no general agreement on the definition of the words "system" and "systems engineering," for one man's "system" is another man's "component." It depends upon who you are and what

Fig. 1—This photograph of the first U.S. bomber to carry an American-made radar bomb-sight may be of historical interest to readers.

you're doing. There are, for instance, the solar system, the banking system, and the nervous system. The writer's conclusion from reading a good many of the attempted definitions is that all of them can be logically extended to cover devices which are clearly not "systems" and clearly have not been "systems engineered." From this, one can only conclude that practically anything which can conceivably be taken apart and put back together again can be regarded as a system, and that some place there exists someone who regards himself as competent to engineer the procedure.

This reasoning shaped the make-up of the present issue of these TRANSACTIONS. Systems engineering was regarded as a skill to be learned from practice and from coaching by more experienced persons, like learning to play a game—or to paint a picture.

One could not in consequence separate the issue into logical subdivisions of the over-all subject like an arithmetic book. Instead, here is presented the experience of several systems engineers. What these men have acquired is not so much knowledge which can be dissected and set down piecemeal, but an entirely different mental attribute: the one we call wisdom. All the following papers, therefore, bear essentially the same title. They are written by men of the highest stature and achievement in the field, men who have generously given their time to prepare these articles in the hope of passing on to the rest of us a little of what they have learned.

The editor felt no obligation to delete repetitions of the same idea as expressed by the different authors, for if several men independently express the same opinion, it is probably truer than if only one does so; and certainly it is the more easily understood. For the opposite reason, there was no attempt to make the papers consistent with one another, or with this editorial.

George E. Valley, Jr.

Systems Engineering and Weapon System Management*

L. I. DAVIS†

Summary—**Weapon System Management is a term in common use. The author describes some of the problems encountered in developing complete air weapons for combat use. The design problems caused by introduction of jet engines, missiles, and complex electronic systems, in the post-World War II period engendered a developmental pattern which emphasized the need for integration of all components. System engineering, in the control engineering connotation, and operations analyses are necessary parts of the management of modern military weapons.**

A NEW GADGET was added to the Norden bombsight in 1943. It was a "good gadget"—it performed well in engineering tests and was extensively tested by stateside crews before release for combat use. Group commanders in England claimed improved scores when training new crews. But, over Germany, it was another story! Lead bombardiers, old hands, tried it a few times, then adopted the practice of turning it off on the final bombing run.

This device was the automatic gyro leveling attachment, consisting of mercury switches which closed circuits when the gyro gimbals were not level, sending current through torquing solenoids which caused the gyro to precess to correct the condition sensed by the mercury switches. It was a substitute for the visual bubble levels used by the bombardier to erect the bombsight gyro to the apparent vertical. The operation of this gadget is a good example of the need for system engineering. Why lead crews turned it off during the bombing runs over Germany will be explained later in this article.

The lack of success of the automatic gyro leveling device illustrates the many lessons learned during World War II. The period immediately after the end of the war was a time of adjustment and appraisal. Military men shifted from the problems of demobilization to the job of analyzing the lessons of the conflict and the significance of air power on strategy and force composition.

Aeronautical engineers learned a lot from the headaches of trying to make a combat weapon out of an assembly of airframe, engine, and equipment. One difficulty arose from the fact that airplanes are designed with the expectation that a certain thrust will be available at a specified altitude. If the engine propeller combination fails to deliver the expected thrust, the airplane operates off the design point, with serious loss in aerodynamic efficiency.

Another headache might be called "May and December" marriages; for example, airframe and engine combinations each representing the most advanced design practice in its field, and compatible with each other, were loaded down with equipment and armament that was of World War I design.

Turning from engineering to administrative matters, scheduling problems were always plaguing the assembly plants. Long lead time items such as fire control systems, bombing systems, and engines were never delivered on schedule. This was inevitable because the airframe could be built and wrapped around the assembly almost as quickly as the salesman promised. The fact that the airplane builder had no contractual control over the G.F.E. (government furnished equipment) added to the confusion.

Ancillary equipment—ground support items such as tractors for towing, fuel servicing trucks, test instruments, and crew training devices were overlooked in provisioning the combat commands—or were not funded because their priority was not associated with the combat weapon itself.

Turning from some of the lessons learned in World War II to the problems posed by an advancing technology in the immediate postwar years, aeronautical engineers found 1) new propulsive devices—jet engines, ramjets, and rockets; 2) new and demanding military requirements; 3) complex communications, radar, navigation, fire control, and bombing equipment; and 4) missiles and all the design problems of complete automatic control.

The new power plants were voracious in their consumption of fuel, and the thrust-speed-altitude relationships made possible a new regime of operation. These considerations led to many design studies, which surprised military planners, especially when they produced fighter designs that were heavier than the "heavy" bombers of World War II. As a consequence, designers questioned the practice of issuing "Military Characteristics" that specified range, altitude, minimum acceptable top speed, takeoff and landing roll, equipment to be carried, and engine to be used. They rightly claimed that such a rigorous description constrained the design to a single end—and if the product was not what the military expected, the military should blame itself because industry could not change the laws of thermodynamics nor the laws of motion as set forth by Newton.

The military "requirement" to carry 10,000 pounds 10,000 miles brought Breguet's equation[1] out of the dust of the textbooks. As a result, design studies emphasized weight reduction, and every pound of equipment weight was questioned. Aeronautical design has always placed a

* Manuscript received by the PGMIL, October 14, 1958.

† Major General, Office of Information Services, ARDC, Andrews Air Force Base, Md.

[1] $$\text{Range in miles} = \text{constant} \times \frac{\text{propulsive efficiency}}{\text{specific fuel consumption}} \times \frac{\text{lift}}{\text{drag}} \times \log \frac{\text{initial gross wt.}}{\text{weight less fuel}}.$$

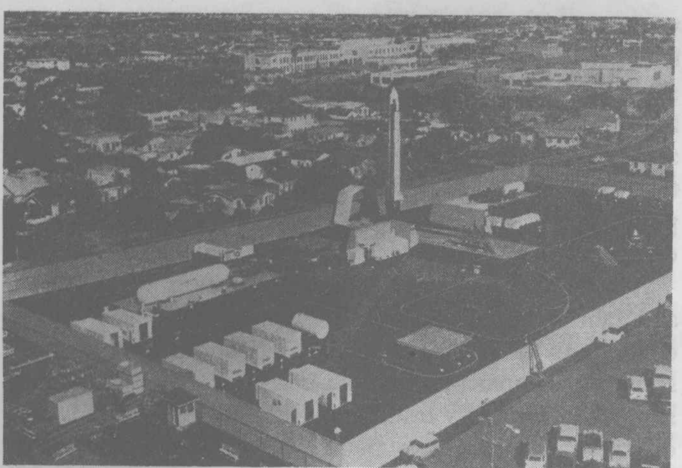

Fig. 1—Thor missile operational launching complex.

premium on efficiency because each pound must carry much more than its own weight. An airplane built to the safety factors used in bridge design will not get off the ground. In addition, the loss in the propulsion efficiency term, because of the new jet engine, brought more pressure to reduce weight. Equipment designers were warned daily that each pound of extra weight carried to the target meant sixteen or twenty pounds more in takeoff gross weight. The problem is the same in missiles. An additional pound accelerated to warhead velocity means fifty pounds additional in the lift-off weight of a ballistic missile.

About this time (1948) the term Weapon System Management began to be used in the Engineering Division of the Air Materiel Command of the USAF as a result of the lessons learned in World War II and the problems posed by the new jet engine, missile, A-bomb technology.

This term was the outgrowth of discussions held among the engineering laboratories, the aircraft and missile project offices, and engineering management in the persons of Generals Chidlaw, Craigie, Crawford, and Putt. The laboratories, conscious of the critical nature of system designs in which coupling and feedback caused dynamical problems, pressed for the establishment of an agency responsible for "systems" engineering. The aircraft and missile project offices recognized this need and, in addition, the administrative problems of scheduling long lead time items, ancillary equipment, and training devices. Engineering management recognized these problems and also the problems of system optimization in a combat as well as in an aerodynamic sense.

The word "Weapon" emphasizes efficiency in combat as the goal. The word "System" emphasizes the desire to integrate all elements—to have a complete package to deliver to the using combat command. The term "Management" implies the sound administrative practices required to plan all elements and to schedule components, testing, ancillary equipment, and training.

Consideration of the tremendous job of integrating into one complete design the characteristics of tens of thousands of components, the procurement of parts on subcontracts, the scheduling of long lead time articles, the parallel development of ground handling and test equipment, plus the very specialized talent required for operational and systems engineering studies, lead to only one solution: develop weapon systems by a prime contract with one agency, with a "weapon system manager."

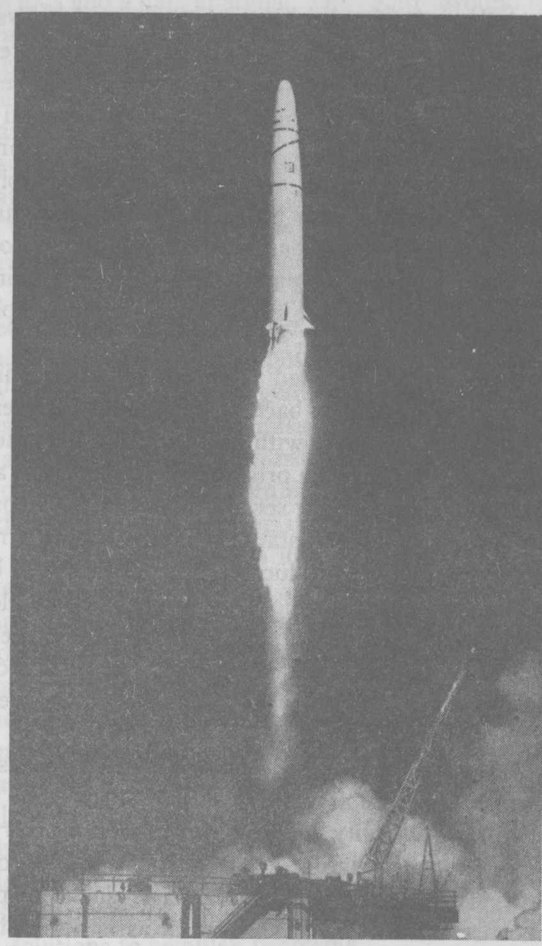

Fig. 2—Thor missile shortly after launching.

Industry, at least those firms which had the breadth and depth to compete, welcomed this procedure. They had a sincere desire to do a good job by furnishing to the military a really integrated weapon. In addition, the aircraft industry noted the growth of expensive "equipment." The airframe of the B-17 accounted for 78 per cent of the cost of the combat weapon; however, the airframe of the B-47 cost less than 50 per cent of the weapon delivered by AMC to the Strategic Air Command. So the profit motive entered the picture.

Industry gladly accepted weapon system management. It joined its voice with that of the military (which was patting itself on the back for putting the monkey on someone else's back). The chorus of mutual congratulations swelled so high that the idea acquired the dubious label of "Weapon System *Concept*."

So many articles have been written and speeches delivered about the "Weapon System Concept" that the need and the origin have almost been forgotten. The need arose from vital systems engineering problems, and the origin of the term came from a desire to manage the planning and scheduling of a combat weapon as a complete system.

Today, ten years after the origin of the term, we can assess the value of the practice with knowledge based on experience, not theory. In those cases where weapon systems management has been successful, we see a proper balance of emphasis on all aspects of the total problem.

Before "cutting tin," four types of studies are required. "Operations analysis" studies analyze the military problem and attempt to express in quantitative terms the gains or losses in over-all mission preformance effected by emphasis on this or that element of performance.

An example might be cited from our experience in the Korean War. We can look back on the battles between the F-86s and MIG 15s and, with the exquisite accuracy of hindsight, point out that the probability of success in aerial combat is the product of four serial probabilities. The probability of success of a combatant, after the enemy aircraft has been sighted, is the product of the probability of being able to maneuver into position, the probability of closing to effective range, the probability of hitting the target and the probability that those hits are lethal. The final product, the probability of success, is very sensitive to the weakest link in the chain $P_K = P_M \times P_R \times P_H \times P_L$. The MIG 15 had better altitude, acceleration and turning radius than the F-86 plus a cannon with explosive shells. The weak link was the probability of hit term. Under the very dynamic conditions of high-speed jet combat, a good operations analysis study would show emphasis should be placed upon the fire control equipment which assists the pilot in aiming his guns. The F-86 was equipped with automatic radar ranging and a gyro gunsight designed by C. S. Draper of M.I.T. Automatic range finding relieved the pilot of estimating or visually measuring range by stadiametric means, and the gyro computing gunsight computed the correct lead in inertial space coordinates with minimum dynamic error. The final box score on F-86 vs MIG engagements shows a ratio of about 15 to 1 in favor of the fighter with the more sophisticated fire control equipment.

The second type of preliminary study is the classical performance study on range, altitude, speed and payload with the propulsion units available.

The third type of study concerns itself with system dynamics—commmunications, computation, data processing and control. Accuracy studies lie in this class because of their dependence on the analysis of dynamic error introduced in data handling, computation and control. If system dynamics are ignored, the kind of trouble is experienced that was encountered when the automatic gyro leveling device was introduced into combat.

The fourth type of study before engineering models are constructed deals with research on the state of development of component parts. The decision to start a full fledged weapon system project should be made on the basis that the probability of successful solution of unknown features of the design is reasonably high. If management chooses "off the shelf" "proven" components, or waits till all components are thoroughly tested, the final product will be obsolete when it reaches the field. If, on the other hand, management elects to introduce too many new design features, the probability of success is rather low, and the probability of meeting operational dates approaches zero. It has been said that we cannot schedule invention, that some things require a fixed gestation time, and the period is not shortened by putting more people and money on the problem.

After the design of the weapon has been agreed upon, and fabrication has begun, "weapon system" management can look to the details of ground handling equipment, fuel servicing equipment, checkout consoles and other logistic support items. Crew training must be scheduled in advance of equipment, of course, but the actual training must wait until prototypes are available, and until experience with developmental testing reveals the methods and skills required.

Developmental testing is more than "proof testing" of a model. Modern high-performance missiles are much more sophisticated than a mere assembly of tested parts. Each part is designed to carry its load and perform its function with minimum weight and power. If the original design does not fail when first subjected to full-scale load tests, it was probably overdesigned. Developmental testing is a process of probing for weaknesses, redesign, refabrication and retesting, first of prototypes, then of articles made by production tooling.

Good system management plans for thorough testing for fabrication of sufficient articles so that the testing can be done in parallel; it recognizes that performance is affected by production methods, tooling, and quality control as well as engineering design. Therefore, the testing phase is not complete until the product of the production line has been handled by combat troops in an operational environment.

In this connection it is appropriate to emphasize that a proper balance between component and complete system testing is necessary. If system testing is delayed until elaborate component testing is complete, the over-all cycle is unnecessarily extended. Although system testing is more expensive, there are a great many component as well as system weaknesses that will not be found until complete systems are tested on the ground and in flight.

On the other hand, in those cases where systems produced by "weapon system" management have failed, we see attempts to short-cut the foregoing studies and steps. In most cases the attempt to buy time with money produces unreliable systems much later than the operational dates promised. Management, unskilled in system engineering, attempts to break down the design in many components, to be produced in parallel. Many times it is "easy to do it the hard way" producing overly complex solutions to problems that are relatively simple when reviewed from a total system viewpoint. On the other hand, a really sophisticated design cannot be achieved without extensive system engineering studies to determine the required performance of each component, plus the nature of the interaction of components upon the performance of the whole.

The interaction of the performance of components when assembled into a system and operated in the geometry of the combat situation brings us back to the example used in the introduction of this article.

Why did the automatic gyro leveling attachment fail to perform satisfactorily over Germany?

The system, consisting of the gyro (which stabilized the bombsight optics), the bombardier, the auto pilot, the airplane and the gyro leveling attachment, had a definite feedback path. The bombardier, in keeping the crosshairs of the optics on the target, sent signals through the auto pilot to correct the heading of the airplane. The acceleration of the plane as it changed its heading was sensed by the mercury switches of the leveling device and interpreted as a change in the apparent vertical. This in turn caused the gyros to precess—moving the optics. The sense of the correction appeared to be degenerative or stable if one ignored phase shifts, and certainly there was nothing that looked like tight coupling or high gain in the system.

When the phenomenon of hunting or oscillating on high altitude bombing runs was reported to the Armament Laboratory in 1944, a stability analysis was made. The methods used were those set forth in den Hartog's text, "Mechanical Vibrations." When the geometry of the problem, the phase shift in gyro precession, erection rates and reasonable assumptions about response times were cranked into Routh's stability criteria, it was apparent that stability was a function of altitude. To the electrical engineer the 90° phase shift in the gyro part of the loop would be obvious and a danger signal. The "gain" around the loop does not become apparent until a study of the geometry of the action shows the airplane pivoting about a radius that is the projection on the vertical of the line of sight to the target. The greater the altitude, the greater the radius and acceleraion. Thus, the "gain" increases with altitude—and at the extreme altitudes of the combat bombing runs over Germany a low-frequency hunt or oscillation was experienced. Experienced bombardiers broke the feedback loop by turning off the automatic device. They leveled the bombsight by visual reference to the bubbles when the plane was in straight and level flight.

"Weapon System" management has been outstandingly successful in the ballistic missile program. This has not been achieved by a single prime contract, nor by "concepts" or programs or printed schedules. The success is due to the fact that systems engineering is done under a separate contract. General Schriever has in effect raised it to top management status, and objective studies and research can be conducted unbiased by sales and production pressures. Schedules on subcontracted items and comprehensive testing can be established in that same atmosphere.

The bright and shining label "Weapon System Concept" will not solve our system engineering problems, nor will it change the fact that it takes twice as long to develop a missile propulsion plant as it does to wrap the tin around it. The work that needs to be done still has to be done by people who deal in facts, not labels and who have the training and experience and patience to find simple but sophisticated solutions to complex problems.

Systems Engineering for Usefulness and Reliability*

W. C. TINUS† AND H. G. OCH†

Summary—**With the increasing complexity and cost of weapon systems, it is becoming ever more important to provide a product that will be useful to the customer, that will provide reliable service, and that will have growth capabilities so that its useful life can be prolonged to meet the ever increasing enemy threat. The management of the research and development program for such large projects must provide detailed and careful planning and control in order to produce an integrated system on a minimum schedule.**

System approach, now the byword of the electronic industry, means many things to many people. To the authors of this paper, it is the orderly arrangement of many details that are necessary to the sound planning of a large development effort.

IDEALLY, a development program results in equipment which comes into operational use at the time it is needed and performs its intended functions well, serves its user with a practical maximum of reliability and has a long operational life due to adequate foresight in its concept and inherent growth capability in its design. Additionally, the ideal development is carried out at reasonable cost and the design lends itself to economical manufacture and maintenance.

It is hardly necessary to say that if all development projects could come closer to this ideal, much faster technical progress could be made and much less development effort would be wasted.

It has become more and more apparent in recent years that better over-all planning before large development effort is expended and better checking of plans throughout the development interval, are the only ways to make the results of large development efforts more nearly approach the ideal.

The basic prior planning of developments and the continuing detailed adjustments of these plans during development to insure a well-balanced outcome are the heart and soul of systems engineering. In this paper, the authors have undertaken to discuss in some detail the course of a large development in an effort to illustrate the controlling effect on the outcome of good planning at every step along the way.

A well-planned system development program can be divided into six major phases as follows:

1) Study phase
2) Proposal evaluation
3) System design
4) Equipment design
5) Model construction and test
6) Completion of manufacturing information.

* Manuscript received by the PGMIL, October, 1958.
† Bell Telephone Labs., Whippany, N.J.

Generally, these steps follow in chronological order. However, many of the detailed steps actually overlap and even recur during the development program.

STUDYING THE PROBLEM

Let us begin by examining the first step of our program—the study phase, in which the problem which the customer wants solved is considered. It may be a very concrete problem, and he may have a proposed solution to it which he wants carried out. On the other hand, it may be a very vague problem which has yet to be explicitly stated. The systems study engineers must first attempt to understand the problem thoroughly and to state it explicitly. It must be defined clearly in relation to other surrounding problems, and solutions should be proposed which are compatible with the surrounding problems. The comparison of different possible solutions must be made on the basis of both technical and economic analyses. A proposed solution must be subjected to such broad questions as "Is it timely to undertake any solution to this problem?" and "Who is best qualified to undertake it?"

In the case of defensive military systems, an evaluation must be made of the expected threat in the time period when the equipment will be deployed. Similarly, in the case of offensive weapons, the probable defense posture of the enemy must be examined again as of the time period when the equipment will be operational. Only through careful and objective comparison of the opposing capabilities, at a future realistically estimated time, can reasonable assurance be had that the equipment to be designed will not be obsolete before it finds usefulness. Added insurance can be obtained, of course, by providing, wherever possible in the design, the potential for growth and extension of the design to keep up with the ever-advancing military technology.

In the study phase, it is of extreme importance to evaluate objectively the state of the art available for the project. If a major advance in technology is undertaken, it is necessary that the state of the art be pushed with attendant extra risks. On the other hand, if a completely reliable system is the objective, techniques and devices which are completely proven and are in the state-of-the-art stockpile must generally be used. The first approach, if carried to extremes, would move technology forward with giant strides without ever producing reliable equipment which could be depended upon to function when it is most needed. The second approach, if carried to extremes, would eventually result in being far behind in the technological race. Obviously, a compromise is needed, using as many of the techniques and devices "off the shelf" as possible, while pushing the state of the art forward in a relatively small number of areas where such advances are most urgently needed. In making the choice of these areas, it is important that concentrated effort be available and applied from the very outset to the major unknowns of the project in order to insure the proper meshing of the development schedule.

The study phase is for gathering ideas. One approach for getting all the hopefully bright ideas on the table is to rule out all evaluation whatever until *all* the ideas, preposterous or not, are on display. This technique is most useful in cases where there is a shortage of ideas for consideration. As all available ideas are boiled down and interrelated, it becomes possible to define the kind of subsystems that are needed and to determine tentative requirements for these subsystems. The backbone of this skeleton of ideas is the plan for time sequential or tactical operation of the system. The mission for the system must be outlined in a step-by-step fashion starting from turn-on of the equipment to "mission accomplished." Without such correlation, the equipment units in a system degenerate into a group of interconnected "black boxes" which are separate entities and do not comprise a system.

When the system skeleton begins to take form, it is time to make a preliminary analysis of system capability. This consists of rough estimates of accuracy, fire power, and such other parameters as are necessary to assure that the conception of the system will be satisfactory. If these estimates show adequate performance capability, and it is reasonably certain that a better approach has not been overlooked, it is timely to proceed with more detailed considerations.

Evaluating the Proposed Solution

The second phase of development may be called a complete evaluation of the recommended system. This evaluation is essential and must be carefully conducted to furnish an enduring foundation for the large development effort to follow. It must be made with the advice and assistance of the equipment design engineers, who will later do the detailed design work, and must go into considerable depth of analysis of the subsystems in order to insure feasibility of the system plan. Over-all system performance requirements must be continually reviewed in the light of these more detailed analyses of the subsystems and components in an attempt to uncover basic technical or economic conflicts. When such conflicts are revealed it is necessary to propose means for designing around them, or to revise requirements to maintain an economic balance.

In this re-examination, a great deal of detailed attention must be given to the human engineering aspects of the system, from the standpoint of fitting the machine to the operators. A careful look must be taken at the proposed division between automaticity and human decision. Time analyses must be made to interleave the operations accomplished by the human operators and the machine. The proposed tactical operation of the system may have to be rearranged in order to minimize total time needed for the mission or to prevent even momentary overloading of a human operator. Displays and controls must be worked out in principle if not in detail to study the probable reaction of human operators to the stimuli of the indicators. Much thought must be given to accomplishing the mission with a minimum of operational controls.

At this point in a development project, it is important to undertake a preliminary assessment of the reliability of the recommended system. The reliability of the system, of course, depends primarily on the reliability of the component parts, all of which can only approach but never achieve 100 per cent reliability. It must be remembered that new ideas for components, or new design techniques, while providing greater technical capabilities, will generally not provide an immediate improvement in reliability. As a matter of fact, new components and design concepts usually introduce new problems and reduce reliability for some time. The eventual reliability of new components is generally better than the reliability of those they replace. However, this results only after experience is accumulated—experience in methods of manufacture, experience in proper design use of the unit, and experience with the unit in an operating system under actual field environmental conditions.

Of critical importance in estimating reliability is a knowledge of environment. Temperature, humidity, shock, vibration, pressure, and other elements of environment during shipment, storage, and use must be estimated so that realistic evaluations of component reliability can be made. Estimates of mean time to failure for the system are essential for comparison with the total mission elapsed time. Inherent potential weak points in the system must be examined and a start made in the planning for maintenance procedures and maintenance test equipment.

The recommended system must also be critically examined in this period to determine if it can be adequately maintained as it will be deployed in the field. Will it be practical to bring test equipment to the system when needed? How much built-in test facilities should be provided? Do the size and weight and operating requirements permit intricate built-in test equipment? Should only "Go-No Go" test facilities be provided? What are the expected technical qualifications of the operators? of the maintenance crew? These and many other questions have to be satisfactorily answered before it is reasonably certain that the recommended system will be an effective one for the customer's use.

Based on this more detailed study of the proposed system, it is important to re-examine the tentative schedules for the project with respect to its prospects for meeting the expected enemy capability at time of deployment. One of the most critical scheduling problems has to do with the technical advances required in the state of the art for completion of the project. A careful assessment must be made of the probability that the necessary technical breakthroughs will be accomplished in time for use in the project. Obviously, this is an area of calculated risk and the project can rise or fall if judgment on this is wrong. This is generally the only area where any consideration should be given to parallel developments for insurance of success, and the less desirable alternates carried along in development must also be capable of meeting the system requirements or the project is in grave jeopardy.

Outlining the System

Having accomplished this close scrutiny of the recommended system plan and having found all factors favorable, it is now possible to prepare a complete specification of performance requirements. This is the first major step in the establishment of a firm development plan for system design. If the project has been properly handled, this document has already been in process from the very beginning. During the study and evaluation stages, it has become more elaborate and now attains its full maturity in the project as the project "Bible." When reproduced for each group of subsystem designers, it will become the designer's guide and will furnish the basis for detailed compatibility at the interface between subsystems.

During the development processes just described, it is important that all important changes in system objectives be cleared with the customer. Weapon systems usually start with a set of objectives which are highly desirable but probably not completely attainable. It is often necessary that the objectives be modified to a level attainable in the program time scale. This frequently requires the deletion of superfluous emergency modes and operational frills in order to make the design simpler and more practical from a reliability and maintenance standpoint.

The development plan must include a system philosophy to be followed regarding reliability of components. The development organization may already have established reliability standards; however, these are generally broad in nature and it is necessary that the project spell out standards which are tailored to its specific environmental conditions. These will include guides for choosing components of known reliability and the derating factors that are to be used throughout the design. When components must be used whose performance and reliability are unknown, suitable environmental tests must be made and changes in component designs undertaken to insure the consistency of these elements with the rest of the system.

The ever increasing complexity of our military systems has emphasized the importance of minimizing the number and type of manual operations. The development plan for a system must, therefore, include firm requirements on the types and numbers of controls so as to leave the human operators as free as possible to make their major decisions. A system that has too many maintenance adjustments is apt never to be ready when needed. It is important that the maintenance philosophy and planning for test circuitry be available at the beginning of the design period so as to produce a uniformity and optimization of the field maintenance procedures.

It will be obvious that in setting up the philosophies for reliability and maintenance, a number of system performance compromises will have to be made. These may, of course, be reflected by minor changes in the project "Bible" and modifying what was a too optimistic performance to a more practical and reliable level.

On any large job, a system generation breakdown chart is required. This is a chart naming the subsystems and their further subunits so that the assignment of tasks to various development groups can be made. The division into subunits must be made in a way which will produce a separately manufacturable and testable unit for which an individual test specification can be written. A set of requirements for each unit can be made available for all groups working on the project, showing what each unit is expected to do and insuring compatibility at the interfaces between units. As the designers proceed and find that changes need to be made, these specifications must be kept up to date. It is always possible then for the system coordinating group to evaluate the current expected performance of the system.

It is essential that complete schedules for the project be provided and maintained, highlighting all significant mileposts for the basic development, prototype, and production phases of the project. Each identifiable unit on the generation breakdown chart must be scheduled for electrical design, brassboard, laboratory test, mechanical design, model test, subsystem test, and any other significant program check points.

Since the project organization is usually not equipped to design all subsystems, units, or components required in the system, a plan for subcontracting design effort and model production is necessary. It is essential that all schedules and specifications be completely agreed upon with properly qualified subcontracting groups in the same or other companies.

Designing the Equipment

Now an all-out effort is applied to the actual detailed electrical and mechanical design of the system components. Prior to this phase, there has been a concerted attack on the most difficult problems—those requiring major technical advances in the art. Also, prior to this point there may have been several areas where parallel approaches were being studied so as to insure the most effective solution. These by now must be resolved to a single approach, with enough emphasis to insure success in the time period.

Throughout the design phase, there must be a more or less continual re-evaluation of system performance and subsystem specifications to maintain compatibility of design and effect necessary compromises. The amount of this, of course, will depend primarily on the difficulty of the job and the degree of success the individual designers attain on each subunit of the system. A program of periodic meetings of all supervisory personnel on the project is helpful in accomplishing this aim. These meetings may be held on a bi-weekly basis and should be limited to about a two-hour period. Each is led by the project group, and the technical material covered in each meeting is specific to a single area or subsystem. A brief discussion of the objectives and attainments usually uncovers minor incompatibilities and misunderstandings which can then be worked out in detail by the particular engineers concerned, without appreciable wasted effort. These meetings are helpful in maintaining fluidity of thinking in the project and permit even major modifications if and when unexpected technical break-throughs do occur. These meetings also serve to keep the project manager and his system-design group completely informed on progress in each area. These meetings should not, however, take the place of the day-by-day discussions that are necessary between the designers of subsystems which are interrelated or have common interfaces.

During the design phase, as brassboard models are created and tested, it is important that the results of these tests be fed back to the system planning group so that they can perform their function of re-evaluation. As the tests progress, individual designs should be frozen as soon as adequate performance is in sight, so that the final drafting can get under way. No project can afford time to comb out all of the minor bugs from subunit design before starting the drawings for a true prototype model. Good judgment has to be exercised and calculated risks taken in deciding when a design is adequate. The detail frills can be ironed out during the time that the design is on the drafting board, or even while the prototype models are under construction.

Models and Manufacturing Information

Most military jobs are rush jobs and the last two phases in the development program generally occur more or less simultaneously. These involve the construction and testing of the models of the system and the completion of manufacturing information. If everything were ideal, the drawings provided for building of these models could be used directly as a major part of the manufacturing information. However, problems are always uncovered in the fabrication of the models, and operational difficulties are bound to occur during the test of these models. It is necessary to feed back information quickly and accurately to the drafting groups so that manufacturing information can be completed.

A well-developed plan of test is needed proceeding through unit tests and subsystem tests to system tests. In each case, there will be the usual de-bugging stage, followed by tests which will completely cover the performance of the unit with respect to its electronic, mechanical, environmental, and human engineering requirements. The planning for the model program should have provided enough models of each unit, subassembly, subsystem, or system, to allow for shock, vibration, temperature, and humidity testing, as well as life testing of critical units. Past experience has generally shown that most types of equipment should be thoroughly life tested as early as possible in the model program. Short life of components discovered too late can produce an insurmountable logistics problem for the customer during early deployment and can result in a serious tactical situation.

Development Manpower

So far, the stages of development have been discussed with little reference to the organization of manpower required for such development. Some comment is in order on the organizational structure of the project and the kinds of people that are needed. It goes almost without saying that the kinds and number of people needed will vary throughout the project.

The success of a project depends very heavily on the choice of and the responsibilities invested in the project engineer. The size of the project should have an important bearing on the level of management vested with this responsibility. Placing the responsibility too low in an organization can be a limitation on the project engineer with respect to the delegations of authority he needs to conduct the job effectively. Placing the responsibility too high in an organization relegates the project to a position of sharing with many other duties the attention of the project manager.

It is not necessary here to dwell on the particular capabilities of the project manager. He must deal with many people including customer representatives, engineers, and subcontractors and obviously must have a background of training and experience to enable him to understand their language and their problems.

In a project of any substantial size, the project engineer needs a system design group to assist him in coordinating the efforts of all other groups and subcontractors. This group will ordinarily constitute about 5 to 10 per cent of the total personnel on the project and will vary in size and in composition with elapsed time. For example, in the study phase this group needs people of high analytical ability and keen insight into the customer's problem, mixed with a smaller number of experienced development engineers. Some members of the team may necessarily have their heads in the clouds since they may be working on the forefront of knowledge, while others in the group must keep their feet firmly on the ground if a practical recommendation is to ensue.

As the project progresses to the proposal evaluation stage, the bright ideas must be subjected to a searing examination by dedicated critics whose purpose is to determine objectively if the bright ideas are really bright when examined from all pertinent angles. The systems group must thus include one or more pessimists who must be well informed in the applicable scientific fields and perhaps be even better informed about the practical problems involved in reducing ideas to practice. The critic may be an old timer who has learned by long experience how to take a constructive negative attitude toward a proposed idea, or he may be a youngster with a special talent for asking embarrassing questions. Mutual respect can be maintained between proposer and critic by having them change roles on different jobs or even on different aspects of the same job.

The characteristics of the systems group will continually change and eventually, at the field test phase of the program, it will be made up of people having particular capabilities in field testing operations and who are experienced in dealing with the customer at military proving grounds, firing ranges, or military test sites. The specific assignments and responsibilities of the group as the development job progresses may be listed as follows:

1) System performance requirements
2) Maintenance capability
3) Economic balance
4) Continual evaluation and analysis of system performance
5) System test specifications
6) Conduct of field test and analysis of results.

This emphasis has been put on the systems design group because of its importance in the processes of planing and in directly assisting the project engineer. However, as previously indicated, it ordinarily constitutes only a small portion of the people required for the enterprise as a whole.

As the project gets into the detailed equipment design phase, the effort rapidly mushrooms to include many people new to the project. Assuming that planning has been good up to this point, there is still a very great need for good management from here on out if the development is to proceed with efficiency and on schedule. Only a few of the points involved will be discussed here.

First, responsibility for every unit and subunit in the whole system must be assigned to a specific individual. He must understand that he is undertaking to meet the technical requirements and to meet them on the assigned schedule. It is clearly his duty to sound the alarm to the project leader as soon as he suspects that a precarious situation is arising.

Second, the best qualified available talent should be assigned to the various portions of the job. This frequently means getting outside help by subcontract and resisting the urge to do everything within the organization.

Third, the easy parts of the job must be held in step with the hard parts. To let the easy parts proceed at maximum rate may look like fast progress on the job as a whole, but usually results in inefficiency when the problems on the hard tasks demand changes.

Good fiscal management and planning is just as essential to the success of a development as good technical planning, but cannot be discussed further in this brief paper.

Conclusion

This paper has discussed some of the many facets of good project management, an important contribution in the development of useful and reliable equipment. Systems engineering, which many have found so difficult to define, may really have no better definition than simply all the things one has to do to insure a sound plan for carrying out a large development effort.

Systems Engineering*

R. H. JEWETT† AND R. A. MONTGOMERY†

***Summary*—A description is given of practical systems engineering methods as applied to large military systems in an industrial environment. Particular emphasis is placed on a design approach which stresses minimum interconnections between subsystems and on system testing methods. Also discussed are system evaluation, management, and costs.**

Introduction

A "SYSTEM," for the purposes of this article, may be defined as an assembly of equipments or components chosen, arranged, and operating together so as to accomplish a certain defined task. This task is the "mission" by the military definition, or simply the "job" in a business sense. A system may contain other systems, which are then called subsystems. For example, a telephone network is a system insofar as it meets communication requirements; however, it is a subsystem when considered as part of an air defense system.

The nation's railroads are good examples of early large-scale systems. Such systems included rights of ways, tracks, rolling stock, fuel, stations, trainmen and other personnel, personnel housing, tunnels, bridges, and many other constituents. Railroad promoters who were poor system designers, either in choice of market or ability to meet competition, failed. This element of competition provides the only real criterion of successful system design and will be discussed in this paper.

In industry, teams of engineers are required for each of the principal systems engineering functions, *viz;* design, management, evaluation, and testing. Members of each of these teams must all approach their jobs with a healthy respect for, and understanding of, the other facets of systems engineering.

* Manuscript received by the PGMIL, November, 1958.
† Pilotless Aircraft Div., Boeing Airplane Co., Seattle, Wash.

Systems engineering, in particular, is evolving as a distinct branch of engineering practice. The systems engineer bases a new system design on known fundamental physical capabilities—future inventions cannot be scheduled for inclusion. The systems engineer must also leave the detail design of subsystems to others. Constrained from specializing, he must be skillful in interpreting the potentials and limitations of alternate system configurations.

The experience of the authors has been primarily with large-scale military systems for air defense purposes. Their work has been carried out in an industrial environment under continuous competitive pressure. It is hoped that this paper will convey some of the lessons learned.

Problem Formulation

Successful systems result from applications of technology at a specific time to a "mission" of current and continuing importance. An organization, in order to compete, must have internal or external access to the technological possibilities in each of many scientific and engineering fields and must also provide the special skills in synthesis required to select critical elements. The synthesis work is generally done under competitive pressure: either direct competition for a contract, or indirect competition for the same available funds.

A system is engineered with in certain limitations. Fig. 1 diagrams the constant pressure upon these boundaries.

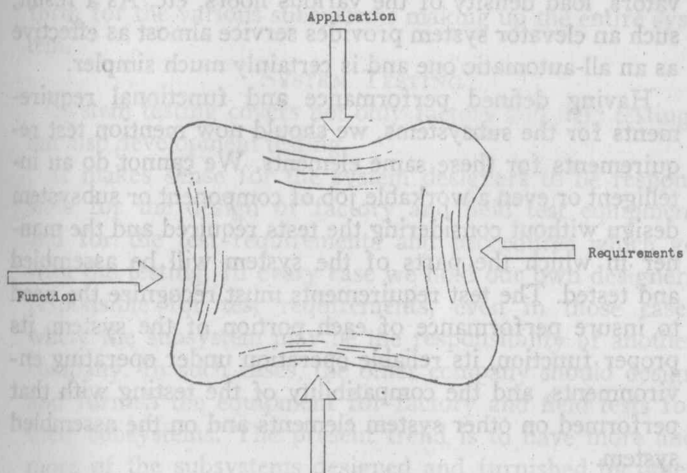

Fig. 1—Forces affecting system design.

Principal pressures are:

1) Function—what the system has to be designed to accomplish.
2) Application—the environment in which the system must function.
3) Requirements—the special features which the system must contain to satisfy the customer. These may include compatibility with other systems, use of other systems as subsystems, use of standard parts, and maintainability by unskilled technicians.
4) Constraints—the limitations imposed by specific circumstances under which the system design job is to be executed. Typically these are economy, time, manpower, size, weight, etc.

System Synthesis

Assuming a thorough understanding of the system requirements has been reached, system synthesis begins. Initially the search is for even *one* technically palatable solution to the problem. Frequently this is a long and sometimes unsuccessful venture. After a single technically satisfactory approach has been determined, variants and alternatives usually immediately suggest themselves.

From this point a parallel program evolves. On the one hand a simple mathematical model of the system is constructed, and preliminary system evaluation begins. At this time the evaluation consists of parameter studies directed towards obtaining a relative picture of the effects on system performance of varying critical parameters. The evaluation will use both the tools of simulation and game theory. However, in some cases the game theory analysis is replaced by competitive gaming. This gaming in some respects is the equivalent of the child's game of "Battleship, Cruiser or Destroyer." The essentials are to determine the outcome of a contest between two teams. One team is provided with the assumed characteristics of the system being tested. The other team is also granted a finite set of assumed capabilities. The ensuing game is arbitrated by an umpire whose evaluation provides the desired data.

In the other, or parallel, approach, the system configuration is established by the initial design team. Many of the critical system design choices are made during this period. It is important that this work be done soundly and carried far enough so that the subsequent step of system design execution does not bring too many unpleasant surprises. If the initial design is soundly carried out, then the remainder of the task will flow more smoothly.

The composition of the initial design team is important. The team itself must be fairly small and coherent, and must be able to draw on the organization's technical resources for technical inputs and recommendations. The output of the team is a system design document and configuration for the over-all system, including requirements and performance estimates for all subsystems.

System Design

Having established the preliminary system design to the point where it has passed the test of technical feasibility, and where it has been reasonably optimized by the evaluation team with respect to such factors as effectiveness, cost, reliability, etc., we come next to the problem of subdividing this rather broadly defined package into smaller packages called subsystems, sub-subsystems, and components, which can be worked upon by a large body of designers of the actual hardware. The package in each case must be discretely defined, such that minimum coordination between design groups is required. In other words, each package must not have too many strings sticking out that have to be knotted jointly with other groups.

Each subsystem definition must spell out:

1) The performance required.
2) The functional relationships to other subsystems and to the over-all system.
3) The test requirements.

In approaching this problem we must first be sure that the over-all system performance requirements as established by the preliminary design group are thoroughly documented. This document is the base line from which all work stems, and it must be maintained in a current—therefore dynamic—state throughout the life of the design activity. Next, we must make our initial definition of the performance requirements of the major subsystems, their sub-subsystems and finally, component performances, as required to provide the over-all system performance. At this point it should be emphasized that these requirements must remain flexible during the course of design progress, in order that performance deficiencies which are bound to show up in design and test of some subsystems and components can be accommodated by the extra performance achieved in other areas.

In addition to the performance requirements of the subsystem and components, we require definitions of the functional relationships between the various subsystems, again on a flexible basis which can adapt to new knowledge as the design progresses. These relationships between subsystems are variously called interties or interfaces. In general, the more sophisticated the system, the more interties it requires. When we ask that a system respond to a given situation with great rapidity and, in addition, in a manner which varies with small differences in a large number of factors, we are increasing the subsystem interties required. To illustrate, consider a passenger elevator. If we assume that it operates only between the first and second floor and that it has light traffic, it can respond more slowly to a simple pushbutton switch and use a simple off-on electric motor. If it must operate between several floors with high traffic, we want it to operate much faster to provide adequate service. No longer can we use a simple off-on motor, so we must provide control circuits which assure smooth acceleration up to high speed and smooth deceleration. Also, the control system must sort out the floor from which the signal comes. Now we're getting a number of interties between various parts of the system. The size of any system design job is a function of the number of interties between the parts of the system which in turn are governed by performance requirements (as in the elevator example). It is also a function of the size (number of subsystems) of the system. If, for example, we take a battery of our high-speed elevators in an office building and ask the control system to dispatch the elevators automatically, taking into consideration the number of people ringing at different floors, the time of day as to whether people are coming to work or going home, how full each elevator is in picking up passengers during descent, etc., we have a much larger and more complex system.

Our experience shows that good systems engineering requires a strong effort to keep the number of interties to a minimum in the interest of compressing development time, maintaining system reliability and achieving flexibility together with minimum development cost. It is most important to analyze these intersystem relationships and systematically reduce them until it can be shown that further reduction will have an unacceptable system performance degradation. There is a definite limit to the total complexity of a system which can be developed on a reasonable time scale, regardless of the man-power applied. The total complexity is directly related to the number of interacting functions or interties between various parts of the system. A very large system employing large numbers of designers can be effectively managed only if the number of interactions between its parts are kept down.

At this point it is interesting to consider how man affects the problem of functional relationship between subsystems. Man is a flexible, if somewhat performance-limited, machine. He is especially useful in minimizing system complexity if his performance limits are not exceeded. Let's go back to our elevator illustration. An elevator starter with average intelligence and limited training does a highly satisfactory job of elevator dispatching when he mentally juggles the factors of time of day, present positions of elevators, load density of the various floors, etc. As a result, such an elevator system provides service almost as effective as an all-automatic one and is certainly much simpler.

Having defined performance and functional requirements for the subsystems, we should now mention test requirements for these same elements. We cannot do an intelligent or even a workable job of component or subsystem design without considering the tests required and the manner in which the parts of the system will be assembled and tested. The test requirements must recognize the need to insure performance of each portion of the system, its proper function, its reliable operation under operating environments, and the compatibility of the testing with that performed on other system elements and on the assembled system.

We have discussed the requirements for organizing a system design job in terms of packaging the parts of the system for the design groups to go to work on. This has required a definition of performance and functional and test requirements. There is, however, one more aspect of work organization which should be considered, which is the scheduling. In order to keep control, the scheduling must be given top billing. To do this, we start with the over-all schedule indicating final system test dates required and work back to establish the dates for subsystem and even component testing. It is obvious that all the dates may have to be juggled several times in order for a compatible set to emerge. This process forces close attention to be paid to the realistic availabilities of components. The resulting schedule, when approved by top management, is called the "master" schedule and can be modified only by top management. Equivalent schedule control is required in production.

The importance of scheduling is generally well recognized, but there are two facets frequently overlooked. The first is to make sure that all items of the system are included. Those most frequently missed are the support and test equipment in final product form. Support and test equipment as required for the development program is usually provided for, but the design of the production version is frequently missed in the initial scheduling. Consequently, it becomes the bottleneck in production and in effective use of the system in the field. The second item often neglected is flexibility in the schedule. Things never go as planned, and the schedules must take into account alternate ways of proceeding without affecting the final dates when one or more delays are encountered in some of the component or subsystems development.

The designers, in proceeding, must tackle the toughest and least certain parts of the problem first. Analysis and test should be programmed to yield critical answers at the earliest possible dates. As the design proceeds and provides answers on the performance realized by the various components and subsystems, these answers (both better and poorer than expected need to be coordinated with other subsystem design groups to rebalance the performance of the entire system. This in turn will cause a readjustment of the performance and intertie relationships originally set forth for the various subsystems making up the entire system.

System Testing

System testing covers not only factory and field testing, but also development testing.

It makes sense for the system designers to be responsible for the design of factory and field test equipment and for the test requirements and procedures which go with the testing. In every case we hold our own designers responsible for test requirements, even in those cases where the subsystem may be the responsibility of another company. In such cases, the other company should design and furnish the equipment for factory and field tests for their subsystems. The present trend is to have more and more of the subsystems designed and furnished by other companies, either as government-furnished subsystems or by subcontract. In either case, the prime contractor's role is becoming one of the assembling and testing the system, while manufacturing very little of it. Largely as a consequence of this, our factory layout is governed by the requirement of orderly assembly and test sequences.

We use a method in our operation which has several levels of test, in which the component tests may be level 6 and the smallest assembly of components may be level 5, building up larger subsystems at lower test level numbers until the final system test may be level 0.

It is obvious that with this kind of assembly and test procedure there is a problem of performance tolerances which is analogous to the tolerance problem on mechanical parts. The total system tolerance on performance is broken down in a systematic manner to the successively lower test levels. The tolerance on the small assemblies must be narrow enough so that when they combine with the tolerance of other subassemblies at a higher level they do not finally exceed the acceptable deviation for the entire system.

Fig. 2 shows percentages of floor area devoted to assembling and testing in a typical case. In choosing the number of test levels during the assembly process, we attempt to minimize the total time and cost of testing. If no tests are performed until final assembly there are bound to be many faults which are difficult to isolate and the assembly line gets clogged. On the other hand, the subsystem tests are also time consuming and costly, so there is an optimum number of test levels.

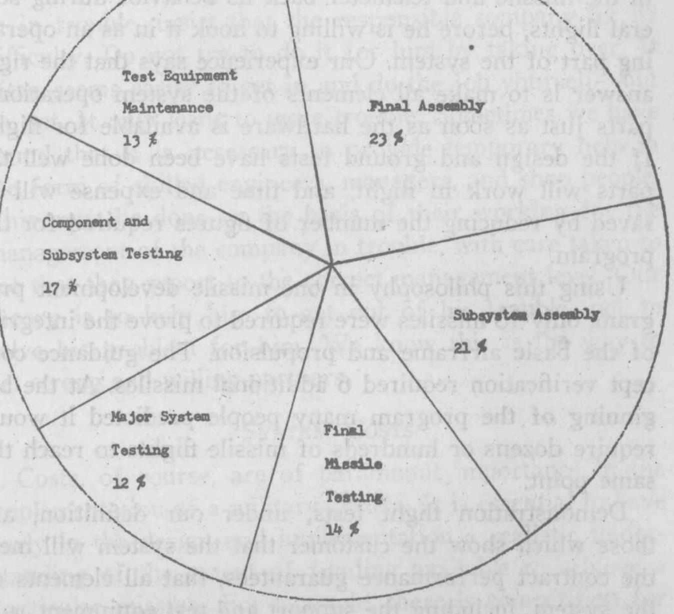

Fig. 2—Typical factory floor area requirements—for assembling and testing—excluding office space.

Regardless of what other test equipment may be used in the factory during the assembly process, the last checkout is performed on system test equipment which is identical to that furnished the customer for his use in the field. It is also wise to test in the factory to a tighter set of tolerances than is allowed for use in the field. This will provide some compensations for the degradation which occurs due to drifts with time, or less skill in field testing.

While there are many facets to development testing, such as component tests, breadboard tests, subsystem laboratory tests, etc., it is the flight test programs which are most interesting, meaningful, and visible, at least in missile development programs. We are able to identify three types of testing in missile flight test programs, namely, evaluation, demonstration, and exploration. This does not mean,