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TOWARDS AN IMPROVED BASIS OF ESTIMATING AND CONTROLLING R AND D TASKS

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TOWARDS AN IMPROVED BASIS OF ESTIMATING AND CONTROLLING R AND D TASKS

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As has been widely reported, total national expenditures for research and development have risen to $20 billion annually with Department of Defense outlays accounting for about $7 billion of this total. The National Industrial Conference Board has estimated that total R and D spending may increase to twice this rate within the next ten years.

This Paper is concerned with management planning and control in one major phase of the total R and D effort, technological development. In general this work is concerned with determination of feasibility and precludes activities that would progress to the development of hardware for experimental and operational testing. For example, before a microwave relay system could be designed with confidence, thousands of measurements on the characteristics of the transmission medium were made under a variety of conditions. Current studies in plasma technology will provide a basis for judging whether practical commercial use can be made of this source of power. In part, this Paper is also applicable to the basic research phase of R and D and to advanced developments not incorporating subsystem design.**

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**The advanced development category in R and D includes work that would progress to the point where experimental hardware is required. Examples are the testing of boundary layer effects on modified aircraft and the re-entry phenomena on contemporary or modified hardware. The primary aim of basic research is expansion of knowledge in a field without direct applications in mind. Current investigations of antimatter and DNA molecules are examples.

In recent years, new analytical techniques have increasingly replaced older approaches to managerial operating controls in systems development and production phases of manufacturing activities. This evolution has had relatively little impact upon the exploratory development area.

Scientists must have enough freedom to accomplish goals, but they must also have self-discipline to use this freedom effectively. A management control system for research and development should serve as a buttress for such self-discipline and lend direction to work in order to avoid needless repetition, failures, and disappointments.

An organization cannot be oblivious to the needs for adequate planning and control of research and technology programs. An internally financed project competes for funds with other programs and ideas within the firm. Also, efficient planning and control is necessary to compete with other firms for government support.

The purpose of this Paper is to outline some suggestions for improving operational cost estimating and control techniques for technological development programs. These approaches were developed as a result of study of a cross-section of on-going projects and other pertinent sources. The techniques suggested are intended to provide increased visibility for the establishment, pursuit, and accomplishment of research objectives. A control system based on objectives directs attention to results of research. This takes the emphasis off functional schedules and cost categories per se.

OBJECTIVES AS THE FRAMEWORK FOR MANAGEMENT CONTROL

Generally, one of the first procedural steps in the establishment of a management control system is to subdivide the program into successively smaller increments of work. Of basic importance, however, is the consideration that work cannot be assigned, and value of the contribution subsequently evaluated, unless performance and accomplishment are coordinated with some definable objective. In one sense, the term "objective" refers to the results to be attained by individuals and groups through work performance. In a more specific sense, objectives relate to specific tasks to be accomplished.

An initial step in the establishment of objectives for R and D is the statement of project purpose. A breakdown or fragmentation of objectives is the next procedure. The listing of such objectives then becomes the guideline for administration of the project until such time as changes occur.

There is a range of possibilities in the achievement of many research objectives. At the extremes are goals that must either be completely achieved or are totally unsuccessful. Such objectives are roughly analogous to games such as chess, where the aim is simply to win. In between are objectives that allow a whole range of degrees of partial attainment. For many objectives there are natural ways of measuring such achievement. Others do not seem to be as amenable to measurement in this way.

A control system for R and D management should recognize possibilities for the attainment of degraded objectives, either out of necessity or as a deliberately chosen course. Within the present state of the art in management control systems for R and D, completion of an objective in a program can best be recognized as the end of that phase of the project. The development of a methodological treatment for complications resulting from a deliberate lowering or raising of sights during the course of a program is dependent on time-cost-performance analytic trade-off techniques for R and D projects. A comprehensive procedure for trade-off analysis does not exist today even for design and manufacturing functions, both of which are easier to formulate conceptually than R and D activities.

Problem-solving in technological development may result in fulfilling the objectives of a plan, rejecting the plan or portions of it because of an inability to fulfill its objectives, or modifying a plan to make it conform to something the problem-solver has discovered or created by accident. Subsequent modification of a plan may be effected to make it accord with or take advantage of such a discovery.

A basic difficulty is that technological development problems are frequently ill-defined. A considerable portion of the effort involved is sometimes devoted to problems to which formal problem solving methods do not apply. A continuum that ranges from well-defined problems to such undefined problems as those illustrated by the composition of a musical score may be considered.* In purely creative effort, planning may exist only in the minds of particular problem-solvers. Furthermore, the more abstract the task, the greater will be the uncertainty that usually surrounds the forecasting of success or failure. In general, however, technological development projects are more amenable to definition. Projects that have reached the technological development stage are partially creative and partially mechanistic.

ESTIMATING UNDER UNCERTAINTY

Managerial controls for a research program usually must be established on a quicksand of uncertainty. Uncertainty, of course, involves conditions ranging from considerable confidence on the one hand, to extreme uncertainty on the other. While a complete discussion of the subject is unwarranted here, it is useful to examine a few areas along such a continuum (see Fig. 1).

Confidence in an estimating situation is based on objectivity obtained through experience, which will vary from limited to considerable. Much relevant data may be available to estimators upon which they can base cost estimates in a development program, such as a new jet fighter aircraft. There is more uncertainty about the estimate for a new type of weapon system on which only a minimal amount of data is available and for which the specifications are completely different from predecessor systems.**

Where the estimator has no objective criteria on which to rely, he acts according to his best judgment which is influenced by his own

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*But even though the composition of music appears to be an example of highly creative effort, rudimentary attempts have been made to compose music by computers, thus implying that the techniques involved can be systematized. Moreover, productive people in the arts are not necessarily considered creative by their peers but rather may owe their success to exceptional mastery of such basic techniques.

**For a detailed analysis, see G. H. Fisher, A Discussion of Uncertainty in Cost Analysis, The RAND Corporation, RM-3071-PR (DDC No. AD 279936), April 1962.

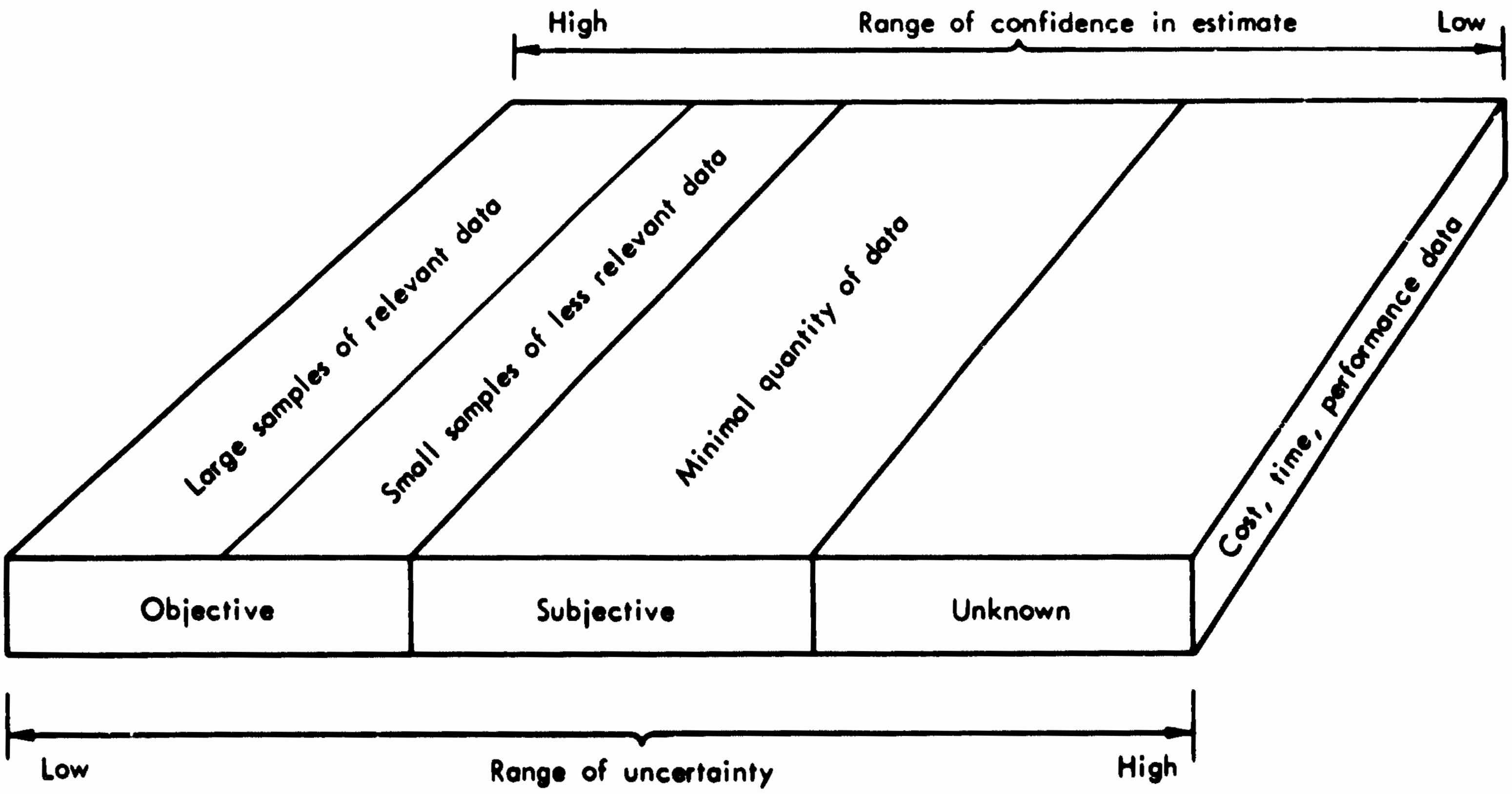

Fig. 1 -- Uncertainty in an estimating situation

background and sometimes personal viewpoints. Accordingly, the basis for subjective estimates cannot be as readily identified as in objective estimates.* The subjective approach, however, must be used extensively in the absence of an accumulation of past data or when the estimator is unable to conduct a current investigation using sampling techniques. In highly subjective cases, the estimator may not even have intuitive feelings about the outcome of a problem, since little or no information exists on which to base a prediction.**

As in development programs, the term "estimate-to-complete" is commonly used as a measure of resources required to complete work in process in R and D. While there is nothing wrong with the notion of

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*One of the more serious shortcomings of the subjective approach to estimating is that it is influenced by psychological considerations. This introduces subtle and hidden cause-and-effect relationships, which cannot be readily evaluated by others.

**See S. H. Archer, "The Structure of Management Decision Theory," Academy of Management Journal, Vol. 7, No. 4, December 1964, pp. 269-287.

estimating resources remaining to carry a program to conclusion, implementation is obviously more difficult in technological development projects. In the past, all too often such estimates have been based not on careful analysis, but rather by merely listing dollars remaining in an initial budget. Techniques are needed that will provide more analytical bases for preparation of estimates-to-complete. At the same time, there is a necessity for increased emphasis on keeping the plans upon which estimates-to-complete are based up to date. Means for accomplishing both of these requirements will now be discussed, together with a suggestion for an improved indicator of program status.

A complementary approach to the problem of obtaining status estimates of R and D work in progress might be the use of an estimate of possible success in meeting sub-objectives within a program. The estimate would be a numerical value in a scale from 0 to 100* developed in answer to the following question from the researcher:

What is the possibility that the sub-objective will be met (assuming authorized time and cost are unchanged)?**

The concept of estimates of possible success is not really new, but it has had little effect on managerial control techniques, especially those for R and D management, where it is most vitally needed. Both the estimate-to-complete and the estimate of success may generally be elicited and recorded as a range rather than a single value.

Formal identification of uncertainty during the progress of a program is important, since in the final analysis record-keeping is the sum and substance of effective management control. A highly abridged statement of some of the more useful approaches to the identification and integration of uncertainty into the control system follows.

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*But division into increments of less than 10 probably would imply spurious accuracy -- it should be noted that both the estimate-to-complete and the estimate of possible success are essentially subjective in nature.

**Such estimates of uncertainty should prove especially useful to program planners and administrators in government and industry. The need is recognized, for example, in Department of Defense Directive 3200.9 which, in describing the concept of technology "in hand" states that "the key criterion is its level of confidence in the probability of successful development." (Underlining added.)

CHECKLISTS FOR UNCERTAINTY

As a fundamental step in the suggested approach for obtaining estimates of possible success and corresponding estimates-to-complete, each researcher should be provided with a checklist on which to record the bases of estimates for a segment of work definable by a specific sub-objective. A completed checklist would be submitted by the estimator at the time of the first estimate and resubmitted monthly or quarterly. Figure 2 is a partial listing of illustrative considerations to be included on such a checklist. An estimator would indicate the relative degree of certainty for each factor by checking the appropriate column opposite each factor.

The purpose of the checklist is to provide estimators with a systematic technique upon which to base the subjective estimates. In some instances, it could also be used as a reporting device, analysis of which would help reveal potential deviations from planned objectives through identification of areas where high uncertainty exists.

TRACKING OF SUBJECTIVE ESTIMATES

On a periodic basis, perhaps monthly, or less frequently depending on the degree of activity in a program, status estimates could be obtained for each unit of work or sub-objective. In addition, a summary chart would be prepared for the total program. As indicated above, each estimate is to be predicated on the latest approved planning for the project. The values would be posted to the chart when obtained. An example of this approach using ranges is presented in Fig. 3.

When confronted with continuous record-keeping of this type, the researcher would be more inclined to take the progress-estimating responsibility seriously. The completed charts should also be of considerable historical value.

The chart should always be based on the latest planning data, which would be inserted in a format beneath the chart. The planning information should be brief but still convey the basic plan. The resource categories shown are illustrative and are intended only to suggest important considerations. Space would also be provided for

Factors Contributing to Uncertainty	Degree of Certainty			
	High	Moderate	Low	Unknown
STATE OF THE ART Consider the difficulty of the program vis-à-vis the state of the art in the fields involved.				
CAPABILITY Consider number and caliber of specialists needed with respect to organizational manpower resources or available consultants.				
AVAILABILITY OF MANPOWER Consider time-phased availability of qualified personnel in view of program objectives and other organizational demands.				
TEST RESULTS Examine importance of test results to favorable attainment of program objectives, especially within time and cost constraints.				
AVAILABILITY OF HARDWARE Consider significance of availability of any necessary hardware on dates required.				
RELIABILITY OF SYSTEMS Take into account possible impacts imposed by system reliability considerations.				
INTERFACING WITH OTHER PROGRAMS Consider possible delays caused by slippages in awaiting contingent results from programs either within the organization or external, if applicable.				
IMPASSES/BREAKTHROUGHS Consider possible impasses in all elements of the program that would affect planning and, conversely, possible breakthroughs.				

Fig. 2 -- Sample Checklist for Estimating Uncertainty

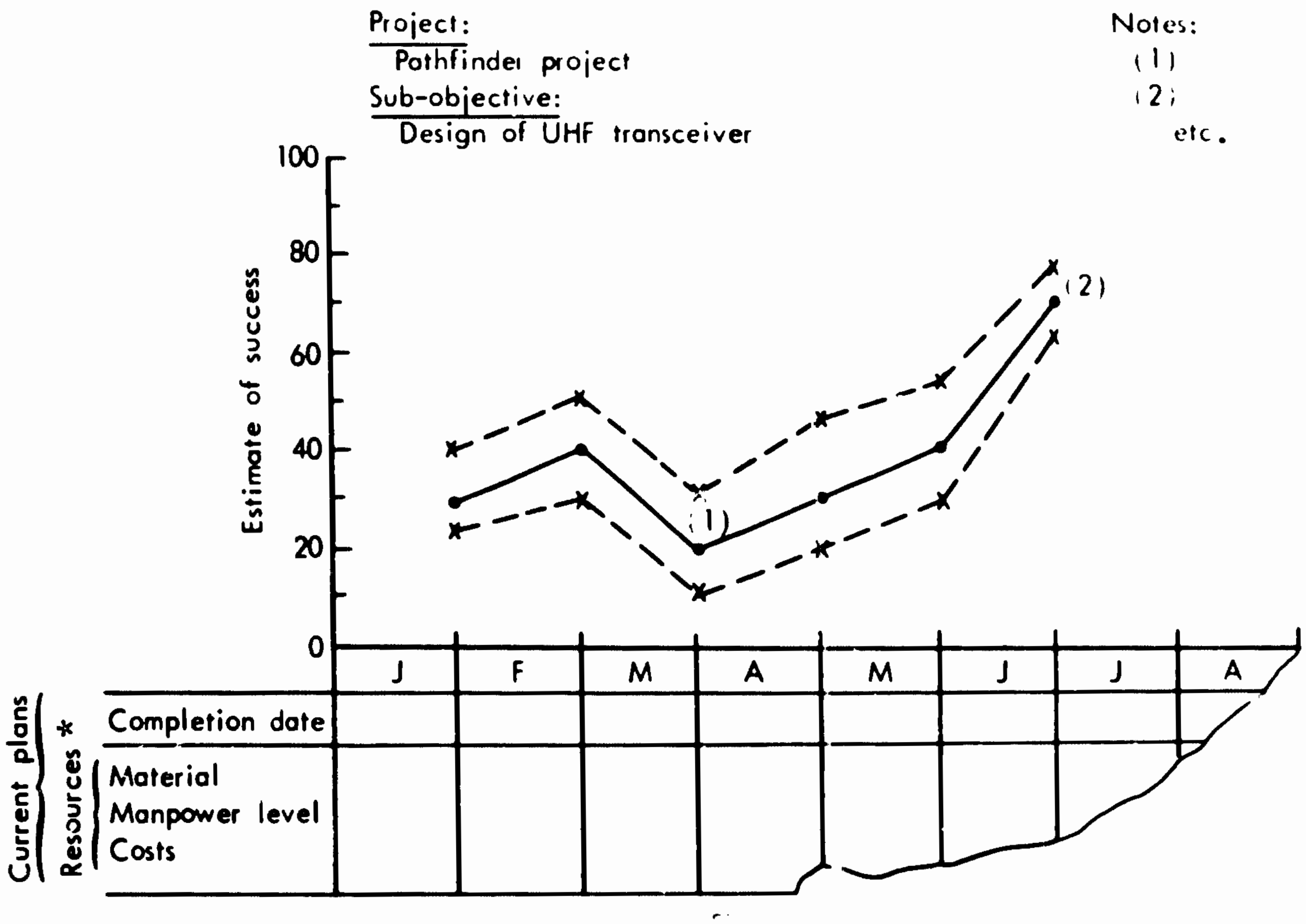

Fig. 3 -- Tracking of estimates of success (shown with ranges)

the recording of notes relative to significant changes made during the conduct of the task. Thus, any marked changes in the estimates would be keyed to changes in basic plans without necessity for referral to other sheets or sources except for extensive technical detail. Reasons for anticipation of any unusually high degree of uncertainty -- for example, an estimate of 50 $\pm$ 20 -- should also be noted on the graph.

Another control technique for continuous monitoring of uncertainty is illustrated in Fig. 4. The horizontal scale represents the cumulative expenditure of funds and may be posted monthly or at an alternate appropriate interval.

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*Latest estimates of <u>total</u> resources to be required, including those already consumed, except in the case of manpower, where the average monthly level-of-effort might be more meaningful.

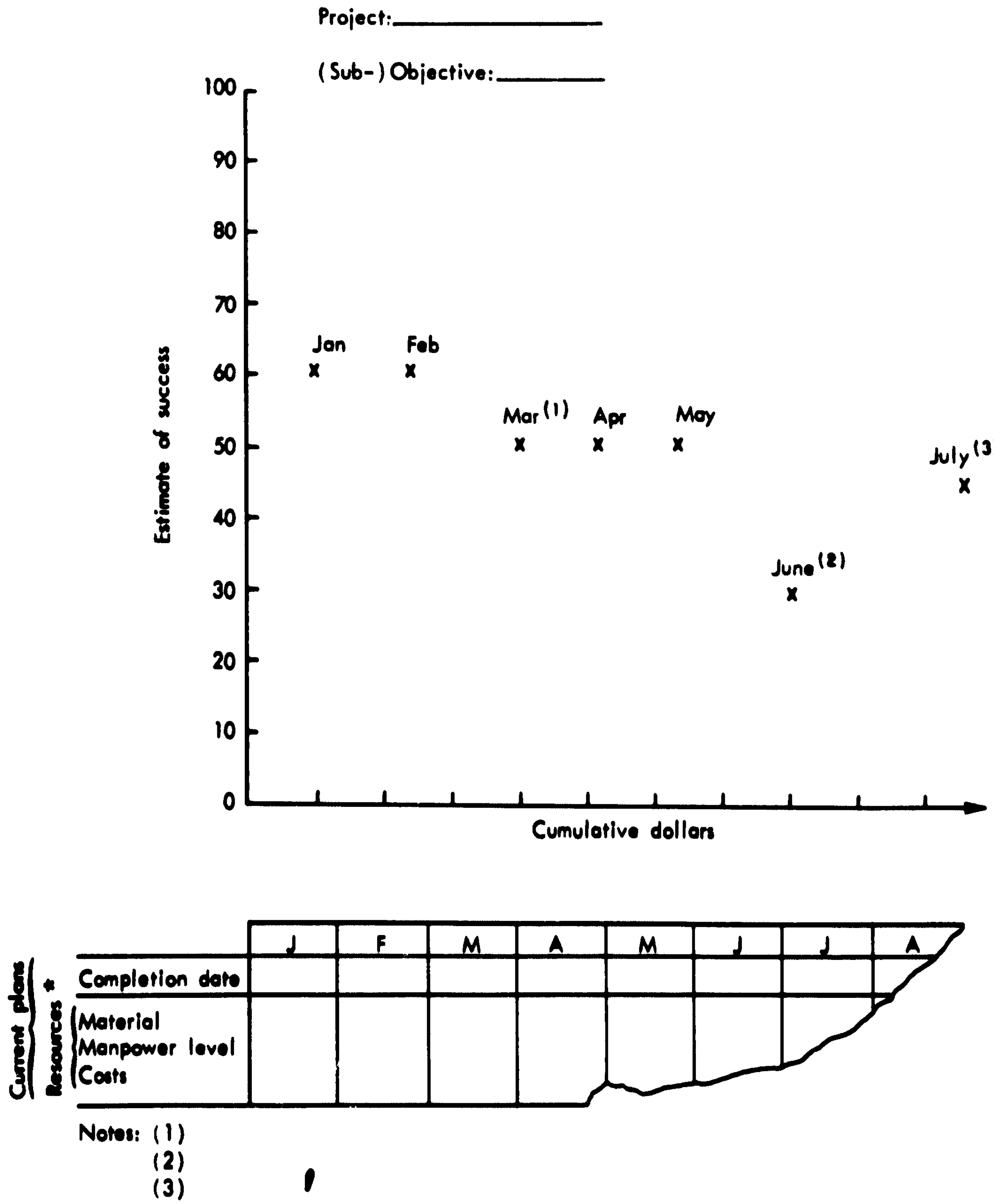

Fig. 4 -- Profile of uncertainty versus expenditure of funds

*See footnote on page 9.

The rationale for this chart is that some progress toward resolution of total uncertainties would be achieved as funding increases on exploratory and advanced development programs, although this, of course, is not always the case. Certainly when the profile indicates a decided diminution in estimate of probable success, this should trigger inquiry by an analyst. Under present practices, there are undoubtedly many instances when management becomes aware of only marginally satisfactory progress toward meeting the program objective too late to bring effective remedial actions to bear. Any inquiry should at minimum uncover difficulties that should be brought to the research chief's attention. Likewise breakthroughs which denote a marked increase in possibility of success should be similarly evident.

USE OF TREE DIAGRAMS FOR VISIBILITY AND CONTROL

The process of solving technological development problems may be viewed as branches in a tree-diagram, with each node a possible sub-objective and each branch the activity necessary to complete the objective.* The tree-diagram can provide insight for both managerial and staff use into the status of programs and expenditures of resources. The technique can also aid in the prognostication of potential problem areas. Although sometimes used for initial planning purposes, it appears that application of the concept of the tree diagram for control of on-going technological development programs is practically nil.

A simple tree for a sub-objective of a technological development project showing funding information is portrayed in Fig. 5. Costs are posted monthly or at other appropriate intervals, and branches are drawn to scale. In the illustration, three variants of A occurred and two have been terminated. As of the status date, two courses of investigation were being pursued actively -- A_3 and C.

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*Recall that this study has dealt with R and D projects not involving extensive hardware design. For efforts where large-scale design and attendant interdependencies are involved, network approaches (PERT, CPM et al) may be more appropriate.

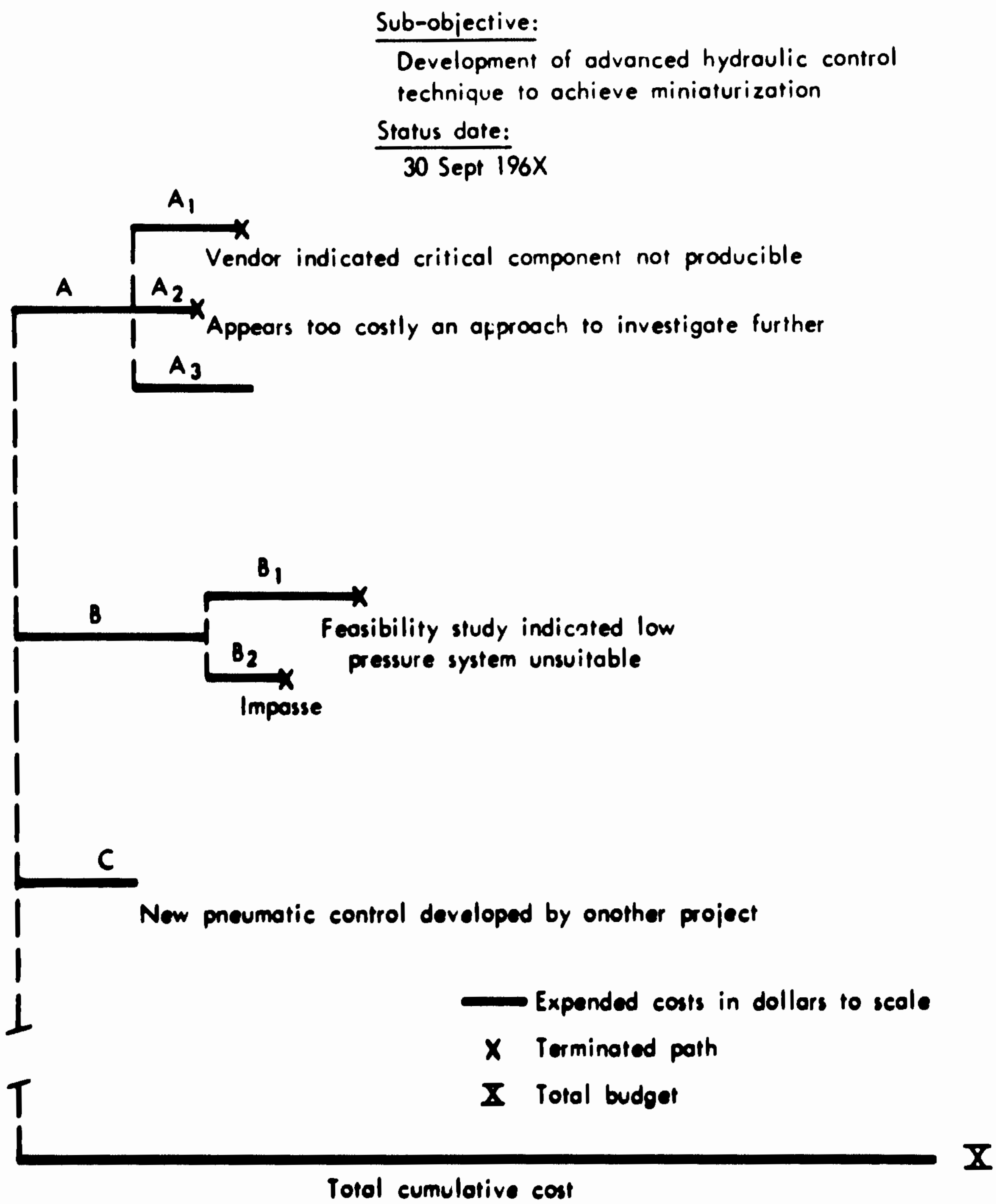

Fig. 5 -- Cost expenditure tree diagram

When a new path is taken, and indicated by a new branch on the tree, brief explanatory notation should be made. Explanations of terminations and other significant factors should be recorded similarly. Since the branches are drawn to scale, relative costs expended on each path of study can be readily seen, as well as compared with total cumulative expenditures.

Although separate tree charts may be used for presenting individual types of information--for example, schedule, cost, estimate of success, et cetera--it may be preferable to incorporate much of this data on one chart as illustrated in Fig. 6.* An inspection of the graph would indicate how funds have been apportioned and subsequently expended as well as performance against schedule. For comparison with the financial and schedule performance, stages of completion of the tasks and estimates of success would be visible.

This chart reveals that three major courses of action have been undertaken with A_2, B_1, B_2, and C still active. The subtask indicating the most promise in meeting the objective or sub-objective, as of the latest status date, is B_2.

The most appropriate level for application of this latter more comprehensive chart would vary. In some cases, a summary version showing status against overall project objectives may be sufficient. In other circumstances, a full set of separate charts may be maintained on each sub-objective. A third possibility is a summary chart plus detailed charts for critical sub-objectives only.**

NARRATIVE REPORTS OF TECHNICAL PROGRESS

In addition to the graphic suggestions described above, reporting of progress in narrative form should not, of course, be completely

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*Whether separate charts should be used to control each attribute -- i.e., cost, manpower, time, etc., -- depends, of course, on the specifics of the project being managed and the organizational functions involved.

**This control chart can probably be most expediently maintained through use of a board incorporating pocket strips or grooved metal label holders across its length. Tickets or cards would be inserted in the slots. It might logically be located in the office of the research chief or his assistant.

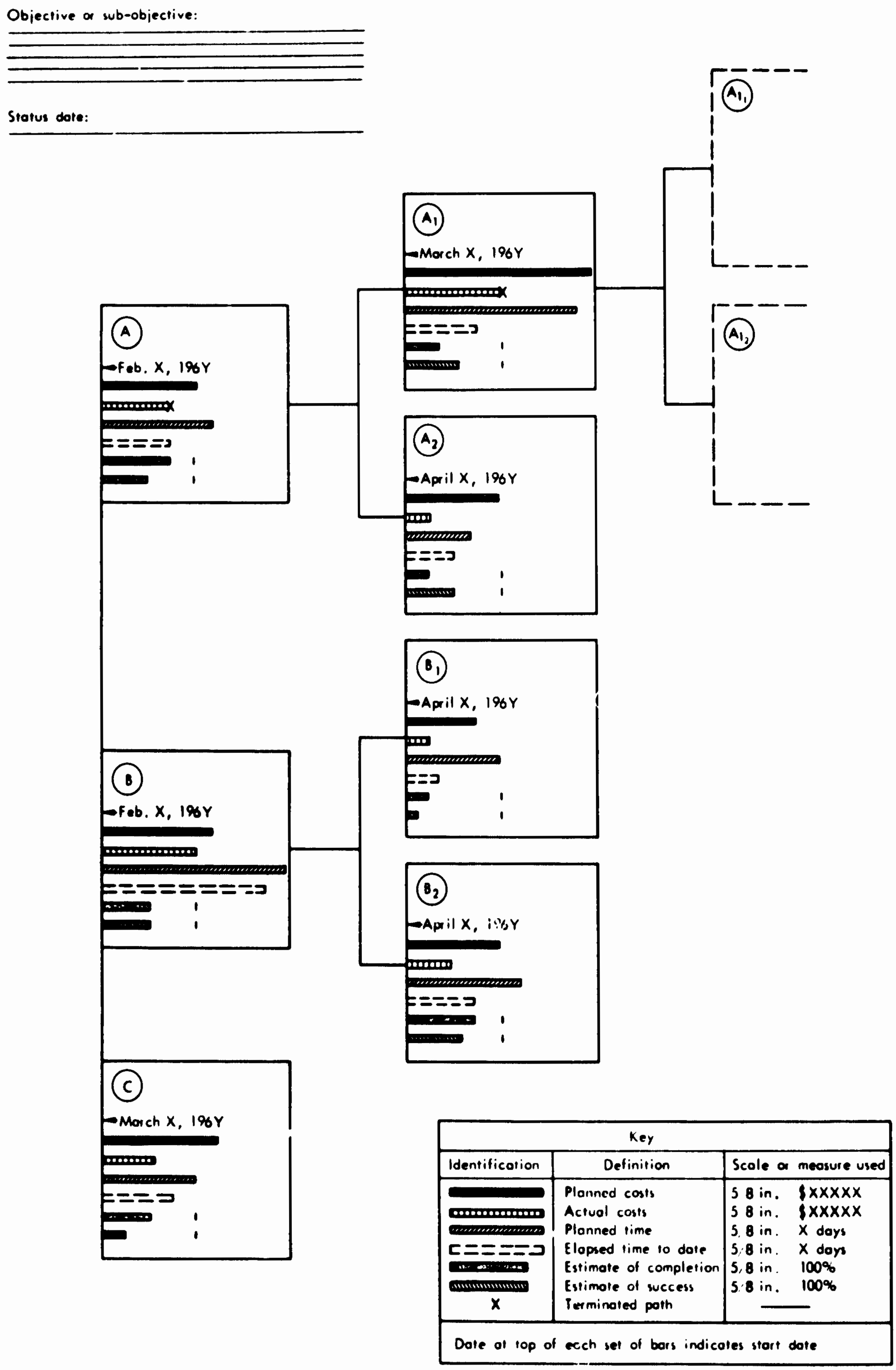

Fig. 6 -- Sample status chart for R and D programs

supplanted. However, it is important that descriptive information be reported in as efficient and effective a form as possible. Basically, narrative reports of technical progress should provide comprehensive information on status compared with prescribed objectives and sub-objectives.

A checklist should be used including detailed and explicit questions. Several suggestions are as follows: What new principles have been evolved? What hypotheses have been tested? How do possible advances relate to future applications? What further research might be required to achieve results? Checklists of this type enable management to elicit and receive information of the type needed for control purposes and to evaluate progress against estimates.

One of the difficulties bearing directly on results of research work is the quality of work performed. Obviously a fundamental aim of research should be to produce as high quality work as possible within resource, schedule and technical constraints. It is important that the narrative report attempt to deal with aspects of quality in the performance of research work so that necessary corrections may be instituted. Again checklists may be utilized to aid an analyst in bringing potential deficiencies to supervisory attention. Several questions which might be asked in assessing the quality of research methodology are: Have the validity and reliability of evidence gathered been established? Were appropriate methods selected to analyze the data? Were adequate provisions made for control over important variables? Were test results properly conducted, interpreted, and applied?*

While the term "quality" as applied to all research work is perhaps not subject to rigorous definition, questions such as the above provide a means for allowing persons not directly involved in the work to offer constructive suggestions on conduct of the work. It is widely felt the quality of research work cannot be judged by those not expert

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*For a description of a somewhat analogous approach intended for evaluation of educational research reports, see Edwin Wandt. A Cross-Section of Educational Research, David McKay Company, Inc., New York, 1965, pp. 1-13.

in the given field. While in the final analysis this is probably true, many characteristics of experimental design and related methodologies are common among diverse programs. These common features provide a vehicle for use in constructing guidelines for commenting on aspects of quality of the work.*

UTILITY OF SUGGESTIONS

Figure 7 shows the relationship of the procedures suggested in this Paper. The question may arise as to whether all the suggestions noted are applicable to all technological development projects. In a general sense they are more or less universally applicable. However, some procedures would be less adaptable to small programs than large, while others would be relatively immune to size, type, and importance of the project. Also, a program extending over a considerable time span would be likely to benefit more from the techniques than one completed in a brief period. In addition, where geographic dispersion is a factor -- and certainly contracted work is such an example -- generally more controls acknowledging conditions of uncertainty would be indicated than the case in which research is performed at the headquarters.

The feasibility of objectives and sub-objectives as a framework for management controls is nearly universal. However, it is true that characteristics of objectives vary widely among projects. The measurement of thrust-to-weight objectives in a propulsion program may be more tangibly stated than the more nebulous determination of possible psychological effects of extended inter-planetary travel. Goals for the latter project can nonetheless be derived and documented explicitly. Checklists for estimating uncertainty associated with objectives and sub-objectives then can be implemented and utilized. Estimates of success can be tracked even on extremely small projects.

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*Caution should be exercised in judging quality of research by the reputation of the researcher alone. Investigators with admirable reputations have been known to produce products that could not stand up under critical evaluation.

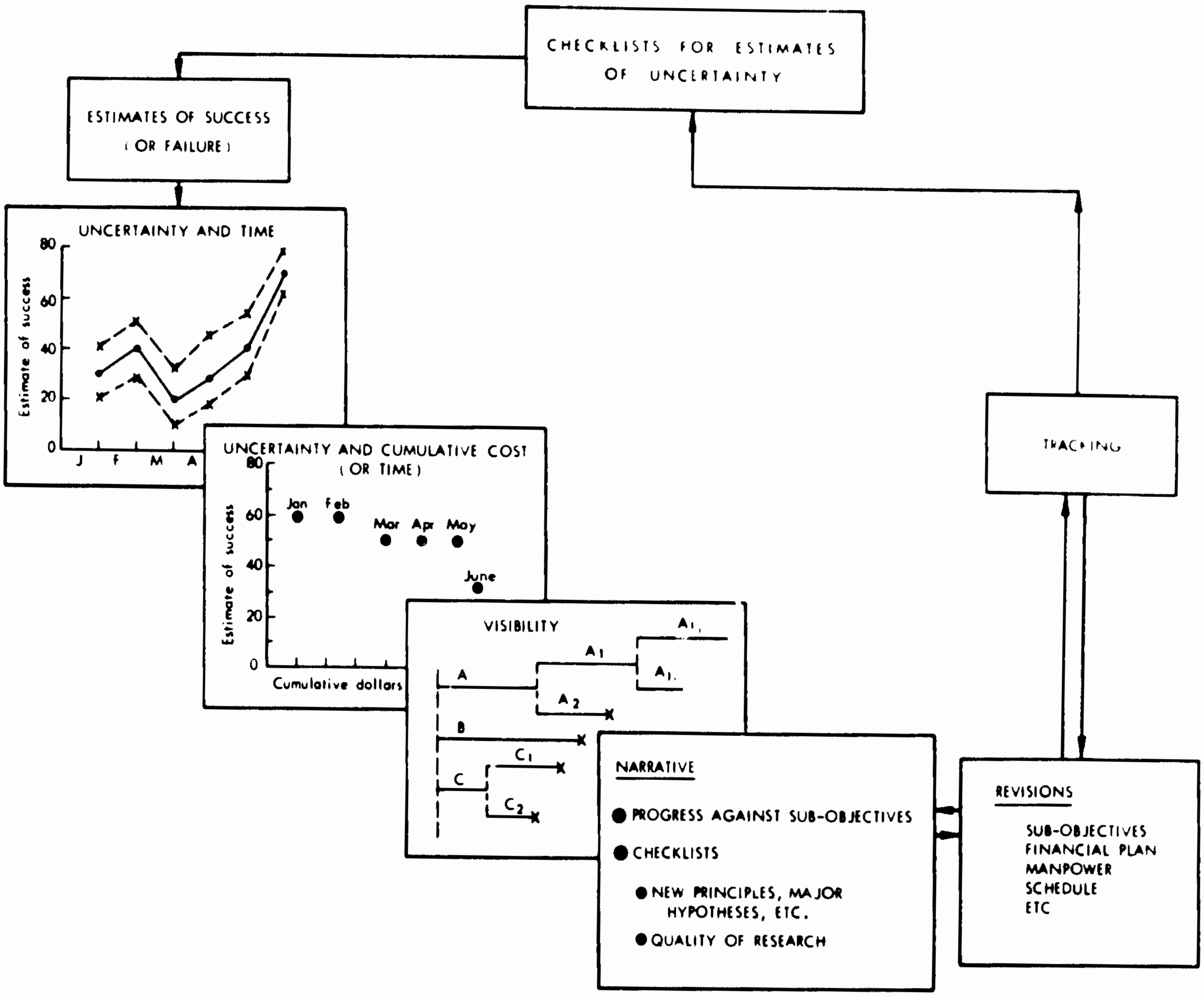

Fig. 7 -- Abridged chart of uncertainty techniques

On the other hand, utilization of detailed tree diagrams for managerial control may not always be worthwhile on very small projects. Such diagrams may be most appropriate on programs where significant amounts of physical testing are involved. They also may be useful to a more limited degree in projects -- in either the physical or soft sciences -- where several alternative approaches need to be laid out and then analyzed.

Most programs today -- and this is also true in the production and system development phases -- can benefit from attempts to integrate time, cost, and technical performance considerations. Many of the procedures outlined above contribute to such an effort. Additionally, utilization of the managerial control techniques noted here would contribute to an improvement in record-keeping, which often has not been performed in too comprehensive and efficient a manner in research administration.

In all cases, of course, the work devoted to development and monitoring of management controls must be kept in reasonable ratio to the cost and importance of the program being controlled. However, a well-considered management control system for technological development projects can actually result in a decrease in the time that project management must devote to administrative matters by indicating only those areas requiring attention.

COMMENTARY

Effective managerial control requires that planning at all stages be accepted by both researchers and management. If a laissez-faire attitude exists within the research organization, even a properly conceived control system can hardly be expected to function correctly. Certain of the traditional approaches to recording and analysis of technological development programs are satisfactory when used, although indications are that in many cases they are not too effectively applied. However, complementary techniques are needed to accommodate the unique characteristics of research activities. In the technological development area, it is especially important for control purposes that the complex of program objectives and sub-objectives be clearly identified and that uncertainty be dealt with in an explicit fashion.

As conceived, the techniques for management control suggested in this Paper should not interfere with creative activity but, on the contrary, might actually lend direction to the researcher in the conduct of his work. Proper implementation of such procedures by project administrators would help encourage system and order in projects designed to achieve technological development objectives which, in turn, could have far-reaching and beneficial results.

BIBLIOGRAPHY

Anthony, Robert N. and J. S. Day, Management Controls in Industrial Research, Harvard University, Boston, Massachusetts, 1952.

Archer, S. H., "The Structure of Management Decision Theory," Academy of Management Journal, Vol. 7, No. 4, December 1964, pp. 269-287.

Eyring, H. B., Some Sources of Uncertainty in Engineering Design Projects, The RAND Corporation, RM-4503-PR, Santa Monica, California, February 1965.

Fisher, G. H., A Discussion of Uncertainty in Cost Analysis, The RAND Corporation, RM-3071-PR (DDC No. AD 279936), April 1962.

Gutenberg, A. W. and L. S. Hill, Paper and Discussion on Managerial Control Theory for the Twenty-fourth Annual Meeting of the Academy of Management, The RAND Corporation, P-3048, January 1965.

Hill, L. S., "Communications, Semantics, and Information Systems," The Journal of Industrial Engineering, Vol. 16, No. 2, March-April, 1965, pp. 131-135.

Pardee, F. S., State-of-the-Art Projection and Long-Range Planning of Applied Research, The RAND Corporation, P-3181, July 1965.

Reitman, W. R., "Heuristic Decision Procedures, Open Constraints, and The Structure of Ill-defined Problems," in M. W. Shelly and G. L. Bryan (eds.), Human Judgments and Optimality, John Wiley & Sons, Inc., New York, 1964.

Wandt, Edwin, A Cross-Section of Educational Research, David McKay Company Inc., New York, 1965, pp. 1-13.