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Technological Forecasting And its Application to Engineering Materials

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| | ROLE | WT | ROLE | WT | ROLE | WT |
| Consensus (Committee of Experts) | | | | | | |
| Correlation Techniques | | | | | | |
| Decisionmaking | | | | | | |
| Delphi | | | | | | |
| Exploratory Forecast | | | | | | |
| Extrapolative Methods | | | | | | |
| Growth Analogy | | | | | | |
| Planning | | | | | | |
| Speculative (Intuitive) Methods | | | | | | |
| Substitution | | | | | | |
| Technological Forecast | | | | | | |
| Trend Extrapolation | | | | | | |

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**TECHNOLOGICAL FORECASTING
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Report of

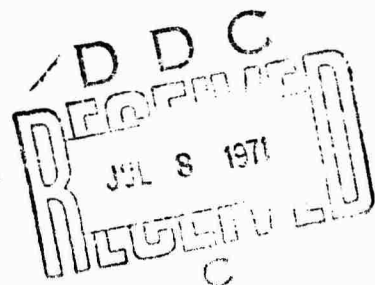
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PREFACE

Ours is a highly technological age whose chief characteristic is rapid change. Deliberate policies support research for new scientific knowledge. Massive, organized, innovative approaches to the development of new technology to meet human needs have accelerated changes in our communications, transportation, manufacture, agricultural production, data processing, recreation, space exploration, education--in fact, most aspects of life. On a continuing basis, large resources of our universities and research laboratories, government agencies, and industry are being allocated to maintaining and building the scientific and technological base of our civilization. On the other hand, our material wealth, in terms of unspoiled lands, wildlife, and clean air and water, is being seriously threatened, thus demanding additional scientific and technological effort for its conservation. As new knowledge continues to accumulate, and as human aspirations and social needs change, the policy issues involved in support of research and development increase in complexity.

Efficient and effective utilization of U.S. scientific, engineering, and technological resources is a crucial factor in meeting the changing needs of our society. To provide this efficiency and effectiveness, it is necessary to clearly understand existing technological needs and operations and the possible barriers, problems, and options to be faced. In fact, a suspicious public and government, demanding that technological developments meet their needs and desires without undesirable side effects, seek means for positive assessment, choice, and control of the utilization of technological developments.

Since the Stone Age, materials have been fundamental to the technology serving man and have enabled him to do the things he desired. In areas of need, such as food, clothing, shelter, defense, communications, and transportation, man's purpose is accomplished with devices or structures which must be made from materials. In recent times, achievements in high-technology, high-performance hardware for defense and space have depended critically on advanced materials concepts developed from new knowledge in areas such as solid-state physics and organic polymer chemistry. Equally, our capacity to satisfy the growing needs of the new area of critical domestic problems will depend on progress in materials.

Using present technology, it is estimated that the costs of housing and of health care will be approximately a trillion dollars each over the decade of the '70's. To this must be added the costs for cleaning up our environment and providing improved transportation. Clearly, our ability to meet these needs depends on correctly assessing and selecting, years in advance, preferred directions for the development and strengthening of our domestic technology.

Often in the development and application of technology, particularly in the materials area, the future is the child of the past. Future developments in materials will be based on (a) the present momentum of research and engineering developments, organizations, and concepts, (b) emerging needs, (c) new opportunities stemming from major advances in science, and (d) availability of personnel and financial resources. Unless adequate technological forecasting studies are undertaken to enable us to relate development options to resources and requirements, our achievements may fall short of our needs, and a degrading environment and quality of life may force us into costly crash programs.

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ABSTRACT

The major value of technological forecasting is in its contribution to planning and decisionmaking. Among the benefits possible from engaging in a forecast of technical opportunities in materials are: use of advanced materials technology, simplifying the selection of appropriate materials areas, identifying areas of most productive interdisciplinary activity, expanding the horizons of involved individuals, identifying roadblocks and new approaches to provide a better basis for decisionmaking, and reducing the possibility of surprise. Table 1 summarizes four considerations involved in undertaking a technological forecast, with their relationship to eight methods for exploratory forecasting.

For the second phase of the study relating to planning for future forecasting, it was considered necessary to have some specific need-orientation in mind prior to undertaking a forecast. These forecasts should be conducted by, or with the guidance of, a group whose mission includes defining desirable goals or working within specific objective guidelines.

I. CONCLUSIONS AND RECOMMENDATIONS

General Remarks

The following benefits could be derived from engaging in a forecast of technical opportunities in materials:

1. Stimulating engineers to use advancing materials technology.
2. Clarifying the needs, opportunities, problems, and goals of materials science and technology in the light of advances in other technologies, thus facilitating the selection of appropriate materials areas for increased effort and emphasis.
3. Identifying those areas where interdisciplinary activity would be most productive.
4. Expanding the horizons of the individuals involved and increasing their awareness of the relationship of the research to the institution's mission.
5. Providing an improved basis for decisionmaking, including resource allocation, by identifying roadblocks and new approaches.
6. Reducing the exposure to surprise.

It was the Committee's opinion that a major shortcoming of current formal technological forecasting of materials lies in the unfamiliarity of the materials technologist with the many methods available and their application to the planning process, rather than in a lack of adequate methodology.

In undertaking an exercise in technological forecasting, the choice of method or combination of methods to be used depends on a number of considerations, of which the following five are principal: (1) the status of the science or technology, (2) the existence and availability of pertinent data, (3) the effort required, (4) the time period covered by the forecast, and (5) the intended use and user. The first four of these considerations, with their relationship to the eight methods for exploratory forecasting, are given in Table 1, on page 22.

Specific Findings and Recommendations

1. The Committee's investigation of the practicability of using various forecasting methods found that reliable time-series data are frequently not available--even for technologies that are stable or maturing. Although the desirability of using methods of trend analysis is apparent, the practicability of doing so is often dictated by the time and effort that can be devoted to collecting data from widely scattered sources.

IT IS RECOMMENDED THAT THE DEPARTMENT OF DEFENSE SUPPORT A STUDY TO DEFINE THE MECHANISMS AND EFFORT REQUIRED TO SYSTEMATICALLY COLLECT, RETAIN, AND MAKE AVAILABLE FOR THE PURPOSE OF TECHNOLOGICAL FORECASTING, ACCURATE TIME-RELATED DATA ON MATERIALS (THEIR PERFORMANCE, PROCESSING, USE, AND PRODUCTION QUANTITIES).

2. During the consideration that this Committee gave to the problem of materials, the need for better forecasting was apparent, particularly in the areas of processing, fabrication, and manufacturing.

IT IS RECOMMENDED THAT THE ARMED SERVICES AND OTHER GOVERNMENT AGENCIES CONCERNED WITH DEVELOPING TECHNOLOGY FOR THE PROCESSING AND FABRICATION OF MATERIALS GIVE FURTHER STUDY AND EMPHASIS TO TECHNOLOGICAL FORECASTING. (Here, fabrication and processing mean the total effort expended on the material in producing the item provided to the ultimate consumer.)

3. The problems and challenges facing engineers and scientists today and in the foreseeable future require an appreciation of (a) relationships between their areas of endeavors and those of specialists in other fields, and (b) planning and decision functions in the organization with which they become involved. An understanding of the methodology of technological forecasting and of its uses would help to satisfy these needs.

Few university curricula offer adequate training in this area to the student, in either engineering or the sciences. Currently, only a relatively small number of universities offer a course in technological forecasting, and most of these courses are usually found in the business school curriculum. A small but growing number of courses in the "Impact of Technology," being sponsored by a number of schools in the Humanities, do not offer adequate exploration of the quantitative approaches being developed in the area of technological forecasting.

IT IS RECOMMENDED THAT THE GOVERNMENT URGE AND COOPERATE WITH THE UNIVERSITIES TO INITIATE AND EXTEND COURSES IN TECHNOLOGICAL FORECASTING FOR THEIR STUDENTS IN ENGINEERING AND SCIENCES.

4. In the course of the Committee's brief examination of technical progress in plastics, it became apparent that two of the significant limitations to the advance of this important technical area are the lack of a recognized engineering discipline and the inadequate supply of trained manpower devoted to the tailoring of plastics to specific needs. These limitations suggest a disciplinary area for careful consideration by university and government groups, and an additional use to which intelligent forecasting in engineering materials should be put, that is, ascertaining not only future materials needs but also the future need for trained manpower to provide the necessary advance in that materials field.

IT IS RECOMMENDED THAT TECHNOLOGICAL FORECASTING BE USED BY GOVERNMENT AND UNIVERSITIES TO IDENTIFY NEEDS FOR CURRICULUM DEVELOPMENT AND FUTURE TRAINED MANPOWER IN TECHNICAL AREAS OF OPPORTUNITY.

5. In considering the second phase of the study relating to planning for future forecasting, the Committee felt that it was necessary to have some specific need-orientation in mind prior to undertaking a forecast. It was considered imperative that forecasts be conducted by, or with the guidance of, a group whose mission includes defining desirable goals or working within specific objective

guidelines--a group whose responsibility is planning for a desired future, assessing opportunities for the future, and making specific recommendations for action. The following recommendation is therefore made:

IT IS RECOMMENDED THAT TECHNOLOGICAL FORECASTING, TAKING INTO ACCOUNT THE TECHNIQUES DISCUSSED IN THIS REPORT, BE INCLUDED IN ARMED SERVICES STUDIES PERTAINING TO THE LONG-RANGE PLANNING AND ALLOCATION OF RESOURCES IN AREAS PERTAINING TO, OR UTILIZING, FUTURE MATERIALS TECHNOLOGY. EXISTING GOVERNMENT AND INDUSTRY TECHNOLOGICAL FORECASTS SHOULD BE EXAMINED BY A MULTI-SERVICE GROUP OR NON-GOVERNMENT GROUP.

II. INTRODUCTION

A. The Need for the Study

Technological forecasting, as an aid to the visualization of possible or likely future technological trends, has developed rapidly within the last decade. This growth is due primarily to two basic causes. First, better allocation of human and capital resources is more urgently needed because society's goals and expectations are more demanding, seriously straining our capabilities. Second, technology assessment is becoming a more prevalent part of the management process. Indeed, it is becoming imperative that more carefully thought out choices be made for the directions of future technological advances prior to the large-scale commitment of scarce resources. Thus, a greater planning effort is required at all levels of our social, political, and economic enterprises.

Because rational planning on a national scale must involve forecasting the outlines of future technology, the methods of technological forecasting are becoming more important in the planning process. Since in many ways new and improved materials and processes form the foundation for general technological advance, it is important to understand objective forecasting methods in the area of materials. The principal early applications of technological forecasting in materials have been made for highly technical organizations, such as the Department of Defense (DoD) and the aerospace industry, by highly technical specialists, in highly technical areas. Various techniques have been applied with variable success.

The general field of technological forecasting has developed some of the normal attributes of an emerging discipline. Enthusiastic advocates tend to use a special language that must be understood before the uninitiated can converse with the practitioner. Often, articles and talks are liberally sprinkled with words and phrases, such as PERT/CPM, normative, Delphi, SOON, morphological

analysis. scenario, BRAILLE, and relevance trees. This vocabulary, no doubt, allows a few experts to communicate rapidly with each other. However, the harassed and uninitiated manager who has to decide (1) whether to undertake an exercise in technology forecasting, (2) what kind of forecasting to do, and (3) how best to plan his programs, is sometimes confused by the broad sweep of words, the dearth of data, and the choice of specific pertinent examples of forecasts upon which to lean.

B. Objective of the Study

This study, for the Department of Defense, was initiated as a consequence of (1) the increasing complexity of our technology, including the side effects of rapid technological change, (2) the growing recognition of limitations in resources to support development of the new materials technology required for advanced weapons systems, and (3) uncertainties regarding the status of the relatively new discipline of technological forecasting and the possible contribution it might make to technical planning and resource allocation.

The objectives of this study of technological forecasting in engineering materials were (1) to examine the mechanisms for improving materials technology forecasting and for defining goals, and (2) to define a plan for forecasting future advances, opportunities, and problems in materials science and technology, including interactions with other technologies. This committee has been concerned principally with the first of these objectives.

The committee evaluated various techniques for exploratory technological forecasting with special reference to the materials field. It characterized techniques, determined their relation to each other, and indicated some of the factors that determine their applicability to a specific use. Only exploratory forecasting methods were covered in this study. Combining normative with exploratory forecasting (as the experts in the field tend to do) is confusing to the uninitiated.

Hopefully, this report will be of use to individuals who may prepare or utilize technological forecasts in the materials field to define alternatives and identify possible opportunities or roadblocks.

III. THE UTILITY OF TECHNOLOGICAL FORECASTING

The major value of technological forecasting is in its contribution to planning and decisionmaking. An important precept of technological forecasting is that the course and, particularly, the timing of research and development activities and future technological achievements need not be viewed passively as being beyond influence. Forecasting can provide an image of what is possible and/or likely and, starting from this vantage point, the evaluation of alternatives, selection of options, positive technical planning, allocation of resources, and implementation of the technical program can be focused to increase the probability that a possible desired event will occur. As an example, in the late 1940's Dr. Theodore Von Karman headed a study group to forecast technical progress and opportunities for the U. S. Army Air Force. With faith in this forecast, the Air Force proceeded to plan and fund the research and development leading to the achievements of the forecasted progress. This action helped to assure success and shorten the time to realization.

The purposes of forecasting are related to the needs and objectives of the organizations that will use them. The potential users are: the national government, for national policy and for allocation of resources (men, facilities, money); industry, for assistance in deciding on its own investment and in selecting paths and areas of research and development; the universities, for planning future academic roles and curricula; and the individual scientist and engineer, for selection of a fertile, promising, or challenging area of effort, within the limits of their freedom of choice.

More specifically, a thorough forecast in the field of materials can yield benefits such as the following:

A. A forecast of technical opportunities in materials can stimulate engineers in other technologies to approach their problems in such a way as to

take advantage of advancing materials development. Engineers often incline toward accepting the present state of the art, rather than utilizing the predictable advances in materials.

B. Conversely, forecasting can help to clarify needs, opportunities, and problems and goals of materials science and technology in the light of predicted advances in other technologies, thus facilitating the selection of materials areas for increased effort and emphasis.

C. Closely related to the above considerations is the probability that forecasting will help to identify those areas where interdisciplinary activity would be most productive.

D. Exercises in forecasting can expand the horizons of the researcher and the research manager and can foster a heightened awareness of the relation of the research to the institution's mission.

E. By identifying roadblocks and new avenues to national progress and economic development, forecasting would provide an improved basis for decision-making by those concerned with broad policy for science and technology.

The forecast is less useful as an assertion regarding the future than as a guide in making choices in the present. A forecast can be successful if it only stimulates the asking of important questions and provokes clear, consistent, creative thought. Its value should be judged not only by hindsight--was it right or wrong--but by how much it contributes toward effective progress. A credible technological forecast is a necessary part of any logical process of resource allocation, whether by government in trying to shape the future or by industry and universities in trying to react effectively to the inevitability of the future.

IV. TECHNOLOGICAL FORECASTING METHODS

A. General Structure

Technological forecasting in engineering materials is the act of describing an image of what is possible and/or likely in materials technology at some future time. It involves consideration of such factors as (1) the properties and performance of materials as they exist today, (2) known physical limitations, (3) anticipation of possible future needs and related developments, (4) the technical and economic factors influencing materials fabrication and usage, (5) the beneficial and adverse effects of materials processing and usage, and (6) the effects on our society caused by and influencing the use of materials. The evidence we have indicates that the forecast is a projection of the most likely future materials developments, in terms of performance, usage, and attendant consequences.

One rational approach to planning for the future involves a series of steps:

1. Perform an exploratory forecast that indicates where the technology could be at some future time. There are several procedures available for making these forecasts; eight are described later.
2. Choose one or more possible goals from the exploratory forecasts.
3. Outline and evaluate alternate possible approaches to each goal.

The evaluation includes such factors as:

- (a) Potential rate of progress toward the goal.
 - (b) Cost of achieving the goal.
 - (c) Probability of success.
4. Decide on the specific goals to be reached and which of the suggested paths will be pursued toward those goals. These decisions

may be aided by correlating the alternate goals and paths with the resources available.

5. Allocate and program the available resources (dollars and manpower) against the decisions made in Item 4.

In the language of the professional "forecaster," the term "forecast" includes steps one through three. Step one is often called "exploratory forecasting." Steps two and three, if limited to the selection of possible goals followed by the development and evaluation of alternate approaches or paths to each goal, usually are called "normative forecasting."

Often, it is desirable (and even necessary) to enlarge this latter concept by evaluating alternative goals as well as alternative paths. For example, in the development of advanced turbojet engines, one has the long-standing goals to increase thrust per unit weight and to increase efficiency. More recently, the goals to reduce noise pollution and air pollution have been added. It is imperative that the "decisionmaker" have an analysis and display of the interaction of these goals as well as the effects of alternative paths to those goals. A large body of methodology is evolving for analysis and display of interacting goals and approaches using various correlative procedures. The following list of articles exemplifies the methods used:

Scenarios

Carson, Rachel L., Silent Spring, The Riverside Press, Cambridge, Mass., 1962.

Linstone, H. A., "MIRAGE, Military Requirements Analysis Generation, 1970-1975," Report LAC/592371, January 1965.

Stanford Research Institute, The World of 1975, (Composite of Reports 232-236 of Long-Range Planning Reports), 1965.

Cross-Support Matrices

Gordon, T. J., and H. Hayward, "Initial Experiments with the Cross Impact Matrix Method of Forecasting," Futures, Vol. 1, No. 2, Dec. 1968, pp. 100-116.

Ralph, Christine, "The Application of Decision Impact Analysis to the Solution of Multi-Variable Problems," NATO Defense Research Group Seminar on Technological Forecasting and its Application to Defense Research, National Physical Laboratory, Teddington, England, 12-14 November 1968, pp. 57-68.

Relevance Trees

Cheaney, E. S., "Technological Forecasting as a Basis for Planning," ASME, May 12, 1966.

Jestice, A. L., "Project Pattern, Planning Assistance Through Evaluation of Relevance Numbers," Paper presented to the Operations Research Society of America, October 7-9, 1964. (Minneapolis-Honeywell, Inc.)

Other Logic Networks such as PERT and CPM

Woodgate, H. W., Planning By Networks, Brandon Systems Press, New York, 1964.

Input-Output Models

Fontela, Emilio, and A. Duval, "Changes in Relative Prices and Technical Coefficients," The Fourth International Conference on Input-Output Techniques, Geneva, Switzerland, January 8-12, 1968.

Marginal Utility Models

Cetron, M. J., and Harold F. Davidson, "Methodology for Allocating Corporate Resources to Objectives for R&D (MACRO R&D)," Industrial Management Review, Massachusetts Institute of Technology, Cambridge, Massachusetts, Winter 1969.

The main thrust of this study has been to describe and evaluate the methods for "exploratory forecasting." These techniques provide methods for

determining what the future could be and represent the first step toward development of meaningful plans and programs. Section B describes eight approaches to exploratory forecasting.

As stated earlier, the total field of technological forecasting embraces the activities involved in the display and evaluation of alternate goals and alternate paths to those goals. Detailed descriptions of these normative forecasting methods are included in the references cited above but were not evaluated extensively by this committee.

B. Types of Exploratory Forecasts

1. Speculative or Intuitive Methods

a. Personal Judgment. In some cases, forecasts are made by the decisionmaker and range between:

- (1) A careful and thoughtful reflection concerning anticipated changes (technological, social, economic, etc.).
- (2) A subconscious, visceral feel concerning the future.

b. Expert Opinion. When the decisionmaker's background does not include the technologies relevant to a decision with long-range impact, it is customary to consult an expert in the critical areas involved.

c. Consensus of a Committee of Experts. Many of the disadvantages associated with consultation with a single expert are ameliorated by the use of a carefully chosen committee. Here, the ideas of each expert are displayed and discussed among his peers until a consensus forecast evolves.

d. Delphi Method.* The Delphi method attempts to arrive at a consensus with regard to the future by soliciting opinions from several individual

*A comprehensive bibliography on the Delphi method may be found in "The Design of a Policy Delphi" by Murray Turoff, Journal of Technological Forecasting, Vol. 2, Nov. 2, 1970.

experts, through a succession of questions or rounds, and returning these opinions to the members of the group. The technique is akin to the committee of experts' approach, with some important differences. At no time during a Delphi experiment are the members of the panel in direct, face-to-face contact with one another. All communication and polling are accomplished through a central "clearinghouse" that limits the impact of psychological influences on the results. Thus, a particularly influential, persuasive, respected, or overpowering panel member does not affect the results, and the likelihood of a bandwagon effect based on majority opinion is minimized. The experts remain anonymous, and concern for reputation does not bias the final results.

For example, in a typical Delphi experiment, a panel of 50 to 60 experts might be asked during the first round merely to list the most important developments that they foresee. The resulting list of events is returned to the panel members who are asked for their judgment concerning certain factors related to each event, when they expect each event to occur, the probability of occurrence, and perhaps some indication of the desirability or feasibility of the event. In further rounds, members are asked to provide reasons for their opinions, especially when those opinions differ widely from an apparent consensus. This feedback system is designed to stimulate thinking and to call the attention of the individual panel members to factors and developments which they might otherwise have overlooked or dismissed as insignificant. Through successive rounds of questioning and reassessment of opinions, the answers usually converge toward a consensus or, in some cases, a polarization of views. The final result is a list of possible future occurrences and the judgments concerning the factors investigated, such as probability and time of occurrence. When polarization does develop, the Delphi mechanisms themselves tend to provide, concomitantly, a reasonably clear record of the assumptions that led to the differing views.

One of the drawbacks of this method is that it is rather cumbersome and time-consuming, especially when run through several rounds. Other limitations to the value of the Delphi exercise are: (1) the ability of the Delphi operator to bias the result by his choice of questions, and (2) the selection of the participants, with their special backgrounds and attitudes.

2. Extrapolative Methods. The first three of the several methods described below are probably the most widely used, and sometimes the most abused. Their success is critically dependent on data that are adequate, reliable, and historically accurate. Often, the data do not meet these requirements, and forecasts must be attempted utilizing data that may represent an indirect measure of the effect sought or that have large uncertainties because of incomplete reporting procedures. When this occurs, the assumptions and uncertainties must be clearly stated, and the physical model (which generally rationalizes the use of the particular data points for extrapolating certain effects) must be available for review.

a. Simple Trend Extrapolation. Extrapolation of single trends of technological performance is based on the assumption that those forces that have produced given rates of technological advance in the past will continue to produce the same rates of advance in the future.

Simple trend extrapolation is initiated by selection of the performance characteristic of a given technology that appears most important or valuable in the use of that technology. More than one characteristic may be identified, but the method is considered simple trend extrapolation unless cross-correlation between trends is attempted.

Time-series data for the selected performance characteristic are collected and plotted with time as the abscissa. The quantitative measure of performance is plotted on the ordinate scale, which is preferably

logarithmic, since most performance characteristics increase exponentially within a restricted time span. A straight line or curve is fitted to the time-series data either by mathematical or "eyeball" methods. The forecast is made simply by extension of this historical trend into the future.

Any of the standard mathematical techniques for curve-fitting and extrapolation may be used, including procedures for probability of variation and establishment of confidence limits, based on scatter in the historical data. Values or ranges of performance at specific future times may be forecast from the plotted data.

b. Growth Analogy. Most biological growth proceeds exponentially until some natural limit is approached, whereupon the growth rate diminishes in an asymptotic approach to the limit. Apparently, many technological fields "grow" in the same manner from conception of a new idea, followed by exponential growth until "maturity" is approached.

The above analogy forms a basis for forecasting technological improvement. The process of forecasting is identical with simple trend extrapolation described previously, up to the point of fitting a curve to the time-series data of performance. At that point, some limit that will eventually prevent any further progress must be identified. Ordinarily, this limit will be a physical constraint, although legal or economic limits may apply. Curve-fitting is then accomplished by using a formula in which performance at any point in time is a function of the beginning performance level, the initial exponential rate of progress, the limit established, and time. Formulas for this function may be found in any of several texts on technological forecasting.

This technique of forecasting helps to prevent forecasting absurdities, which often result from mindless extension of exponential trends in simple trend extrapolation. However, care must be taken in the determination

and use of limits to prevent errors arising from imposition of artificial, transient, or imagined constraints.

c. Substitution. The substitution forecast is a form of trend extrapolation that is based on an approach quite different from that used for simple trend extrapolation or growth analogy, as defined above. In the substitution forecast, instead of measuring the increase in performance occurring in technology, the measurement is of the rate at which one technology is substituting for another in general usage. The method is useful for forecasting only the use of materials and not the improvement in materials properties or performance. For example, one may measure the rate of substitution, with time, of diesel engines versus steam for railroad locomotion. The relative increase in performance of the two technologies is the principal factor in the substitution process. Performance increments are not measured directly but are reflected only in the rate of substitution.

The basic assumption in substitution forecasting is that substitution, once started, will proceed inexorably to conclusion.

The forecast starts with the determination that a new technology is in fact starting to displace an older technology. After selection of the measurement term that best defines the fraction of total usage of each technology, time-series data of the fraction of usage are gathered for both technologies. The time-series data are used to establish the initial takeover rate and to predict the year in which takeover will reach 50 percent. Then, a formula is used to forecast the dates when various percentages of takeover will occur. The formula produces the characteristic "S" curve in forecasting the rate of takeover.

d. Correlation Analysis. Technological forecasting by correlation analysis is based on established or assumed interrelationships among various measures of performance within and among various technologies. Simple

trend extrapolation applied to these interrelated measures of performance may lead to contradictory forecasts or to the forecast of physically impossible situations.

Correlation-analysis forecasting utilizes trends in as many performance characteristics of the technology as possible in terms of time and resources available for the forecast. Then, physical laws, natural relationships, and design considerations, which may govern the relationships between or among the performance characteristics, are determined. Historical performance for each characteristic is determined using the methods described for simple trend extrapolation. These trend data should be checked for conformance to the relationships established.

Trial forecasts of each performance parameter are made, using the techniques of simple trend extrapolation or growth analogy. For various time intervals of the forecast, the predicted separate performances are tested against the assumed relationship among the various parameters. Where this test indicates a discrepancy, an adjustment in the forecast is necessary to establish consistency. Generally, the adjustment is made on the basis of the forecaster's knowledge of the relative dependency, or independency, of the various characteristics.

One or two interactions using this method ordinarily will produce a set of forecasts that is internally consistent and that provides a reasonable view of the future for a given technology. With considerably greater effort, forecasts for several related technologies may be developed which would take cognizance of the more complex relationships between technologies and even include social, political, and economic relationships. Obviously, a major limitation on correlation analysis is the degree of confidence that can be placed on the correlation function.

C. Perspective

Technological advances occur principally as foreseeable extensions of current art, using current state of knowledge, although major technological changes occasionally stem from unexpected discoveries, and while, conceivably, the possibility of such discoveries could be anticipated by an expert or experts given the proper challenge, the main thrust of the technological forecasting methodology, as reviewed here, is based primarily upon an orderly progression of advances.

All methodologies developed to date for forecasting future events contain inherent weaknesses in regard to accuracy or objectivity. Some of the weaknesses in the current methods of exploratory technological forecasting are the following:

1. Speculative (or Intuitive) Techniques. The major weakness in this area is related to its reliance on the personal judgments of individuals, albeit experts. These judgments are inevitably subject to the biases of the individual. Although the "committee of experts" may minimize the impact of personal bias, concern for reputation encourages conservatism and restraint in interaction with peers. Thus, imaginative and creative results are rare. In addition, committee discussions are subject to undue influence by persuasive, overbearing, or otherwise influential individuals. Although the Delphi technique overcomes most of the disadvantages of the committee approach, it takes more time and effort. In recent years, a number of experimental techniques that are mixtures of Delphi, brain storming, committee processes, role playing, etc., have been used to try to stimulate new ideas, new approaches, and creativity. The review of those efforts is beyond the scope of this study and, probably, it is too soon to comment on their utility. All of the speculative techniques may suffer from failure of the participants to obtain and utilize data relevant to the forecast.

2. Extrapolative (or Trend) Techniques. Although large amounts of historical data may be available, the plotting of trends can be extremely misleading. Reliance on simple trend extrapolation is based on the assumption that all influences operative in the past will continue to operate in the same proportion in the future. A critical analysis of this assumption is essential to more effective trend analysis. Although analyses relying on the same data base and using similar techniques are likely to produce the same results, the objectivity and reproducibility of these analyses are not necessarily a measure of their validity. For example, had the trend of the mid-60's in expenditures for research and development continued its exponential rate of growth, these expenditures would have surpassed the gross national product long before the turn of the century. Of course, such obviously absurd conclusions should lead the forecaster to use the more credible extrapolative techniques, such as growth analogy, substitution forecast, and correlation analysis described earlier. Another difficulty relates to the selection of the "pacing parameter." For example, if one looks at the emerging generation of transport aircraft in terms of trends in speed, the air buses should all be Mach 2 aircraft. However, cost per ton mile, rather than speed, is obviously the principal concern of the purchasers of these aircraft and, accordingly, the new air buses conform to the trend of ton miles per hour as a function of time. A third difficulty lies in the establishment of limits, particularly in the use of growth analysis trends. Care must be taken to insure that limits imposed are indeed real and not imagined. For example, early investigators erred in assuming the speed of sound as the upper limit for the speed of aircraft.

V. THE SELECTION OF FORECASTING METHODS

The exploratory forecasting methods described in the previous section were grouped into two general approaches--speculative (intuitive) and extrapolative (trend). Each of these approaches includes four methods from which the forecaster may select the method(s) best suited for his subject.

In undertaking an exercise in technological forecasting, the choice of method, or combination of methods to be used, depends on a number of considerations, of which the following five are principal: (1) the status of the science or technology, (2) the amount of pertinent data required (its existence and availability), (3) the effort required, (4) the time period covered by the forecast, and (5) the intended use and user.

The first four of these considerations are presented in Table 1 and are related to the eight methods for exploratory forecasting. Although the specific characteristics of intended use and user further influence the choice of methods in any particular case, they could not be displayed on the table. The committee's conclusions concerning objectivity, reproducibility, and accuracy are indicated under Confidence Index in the lower section of Table 1. The checked blocks in Table 1 indicate where methods are generally applicable. For example, when forecasting an emerging technology, if required data are not available for other methods, speculative methods are the only alternative. However, in an established or maturing technology, indeed wherever historical data are available, extrapolative methods can provide a higher confidence index over a longer time period. Methods of trend analysis are considered highly objective because they make use of moderate-to-large amounts of historical data. They also provide reproducible forecasts for long forecast periods. For example, Table 1 indicates that forecasts from correlation analyses are moderately reproducible for forecast periods of greater than ten years and highly reproducible for forecast periods of one to ten

TABLE 1. Considerations for Selecting Exploratory Forecasting Methods

| METHOD CONSIDERATIONS | | SPECULATIVE (Intuitive) | | | | EXTRAPOLATIVE (Trend) | | | |
|---------------------------------|--------------------------|----------------------------|-----------------------------|--|-----------|--------------------------|-------------------|-----------------|----------------|
| | | 1. PERSONAL JUDGMENT | 2. GENIUS (Known Expert) | 3. CONSENSUS (Committee of Experts) | 4. DELPHI | 5. SINGLE TREND | 6. GROWTH ANALOGY | 7. SUBSTITUTION | 8. CORRELATION |
| STATUS | STATUS OF TECHNOLOGY | | | | | | | | |
| | Emerging | X | X | X | X | | | | |
| | Established | | | | X | X | X | X | X |
| | Mature | | | | | | X | X | X |
| DATA | DATA AVAILABILITY | | | | | | | | |
| | Little | X | X | X | X | X | | | |
| | Moderate | | | | | X | X | X | |
| | Much | | | | | | | | X |
| EFFORT | WORK REQUIRED | | | | | | | | |
| | Little | X | X | | | X | | | |
| | Moderate | | | X | X | X | X | X | X |
| | Much | | | | X | | | | X |
| TIME | TIME COVERED BY FORECAST | | | | | | | | |
| | Short | X | X | X | X | X | | | |
| | Moderate | | | X | X | X | X | X | X |
| | Long | | | | X | | | | X |
| CONFIDENCE INDEX TIME PERIOD | OBJECTIVITY | | | | | | | | |
| | Low | X | X | | | | | | |
| | Moderate | | | X | X | | | | X |
| | High | | | | X | X | X | X | X |
| | REPRODUCIBILITY | | | | | | | | |
| | Little | * >4 | >10 | >10 | | | | | |
| | Moderate | 1-3 | 1-10 | 4-10 | >4 | | | | >10 |
| | High | | | 1-3 | 1-3 | 1>10 | 1>10 | 1>10 | 1-10 |
| | CONFIDENCE IN ACCURACY | | | | | | | | |
| | Little | >4 | >10 | >10 | >10 | >10 | | | |
| | Moderate | 1-3 | 4-10 | 4-10 | 4-10 | 4-10 | >10 | >10 | >10 |
| | High | | 1-3 | 1-3 | 1-3 | 1-3 | 1-10 | 1-10 | 1-10 |

* Note: Numbers used refer to the period, in years, for which the forecast applies.

years. Nevertheless, history is replete with broken trends, and the mere existence of data (which enables objectivity) and the ability to draw a straight line (which should be quite reproducible) do not ensure validity.

This Committee's investigation of the practicability of using various forecasting methods found that reliable time-series data are frequently unavailable, even for stable or maturing technologies. Although the desirability of using methods of trend analysis is apparent, the practicability of doing so is often limited by the time and effort that can be devoted to collecting data from widely scattered sources.

As part of this study, exploratory attempts were made to forecast advances in two areas--powder-metal technology and plastics. In both cases, the paucity of organized data on the development of material properties, uses, and production--all as a function of time--was a major or prohibitive limit to the analysis of trends. Although data exist on all these topics somewhere--scattered in some form in government reports, industrial files, journals, and books--they are so dispersed that the forecaster is forced to make assumptions, or to undertake a monumental task of data gathering as a basis for his analysis. Clearly, this scarcity of available, accurate data applies to most materials.

The situation is similar to the early days of economic forecasting when, for lack of reliable data, readily available in libraries, great dependence was placed on the memory and intuition of experts. Obviously, improvement is needed in gathering, cataloging, and disseminating information with which the techniques of forecasting operate.

Some illustrative examples of method selection follow.

In many important areas of materials technology, the choice of forecast techniques may be simple. Short-term forecasts of commodity-metal production provide an example wherein the availability of pertinent data and the recognition

of existing trends make the choice of trend-extrapolation methodology clear. Beyond this, if one is interested in medium- to long-term forecasts in areas which involve new scientific facts or discoveries in existence but which are not yet widely recognized or available in the form of technological data, then in addition to trend-extrapolation, a speculative method using a variety of experts should be employed.

When materials forecasting is undertaken as an adjunct to R&D planning, the choice of method is rarely simple. One is likely to be dealing with a relatively new area of technology where there exists an abundance of recent unorganized data. Although the data are collected and organized, definite trends may not be discernible. Even for relatively mature technologies where organized data exist, with meaningful trends, there may be large social, economic, or political pressures for change with no clear alternatives yet identified. In these cases, consideration of the results of more than one method or using a combination of methods will enhance perspective and produce a more credible forecast of the range of feasible alternatives.

Consider, for example, the development of high-temperature, load-bearing plastics. If one plots maximum use temperature as a function of the year of development, a possible extrapolation, as shown in Figure 1, would indicate that maximum use temperature would not exceed 672°K (750°F) before the year 2000. Yet in a Delphi exercise conducted at TRW, Inc., it was anticipated that 672°K (750°F) plastics could be available in 1975 and 811°K (1000°F) plastics could be available in 1980. See ▽ values in Figure 1. One reason for the apparent discrepancy between this result and the trend extrapolation could be the fact that plastics have already been made in the laboratory (e.g., polybenzimidazole and polybenzothiazole) that are stable to temperatures well in excess of 655°K (700°F) but because of expense have not yet found their way to market. Knowledgeable

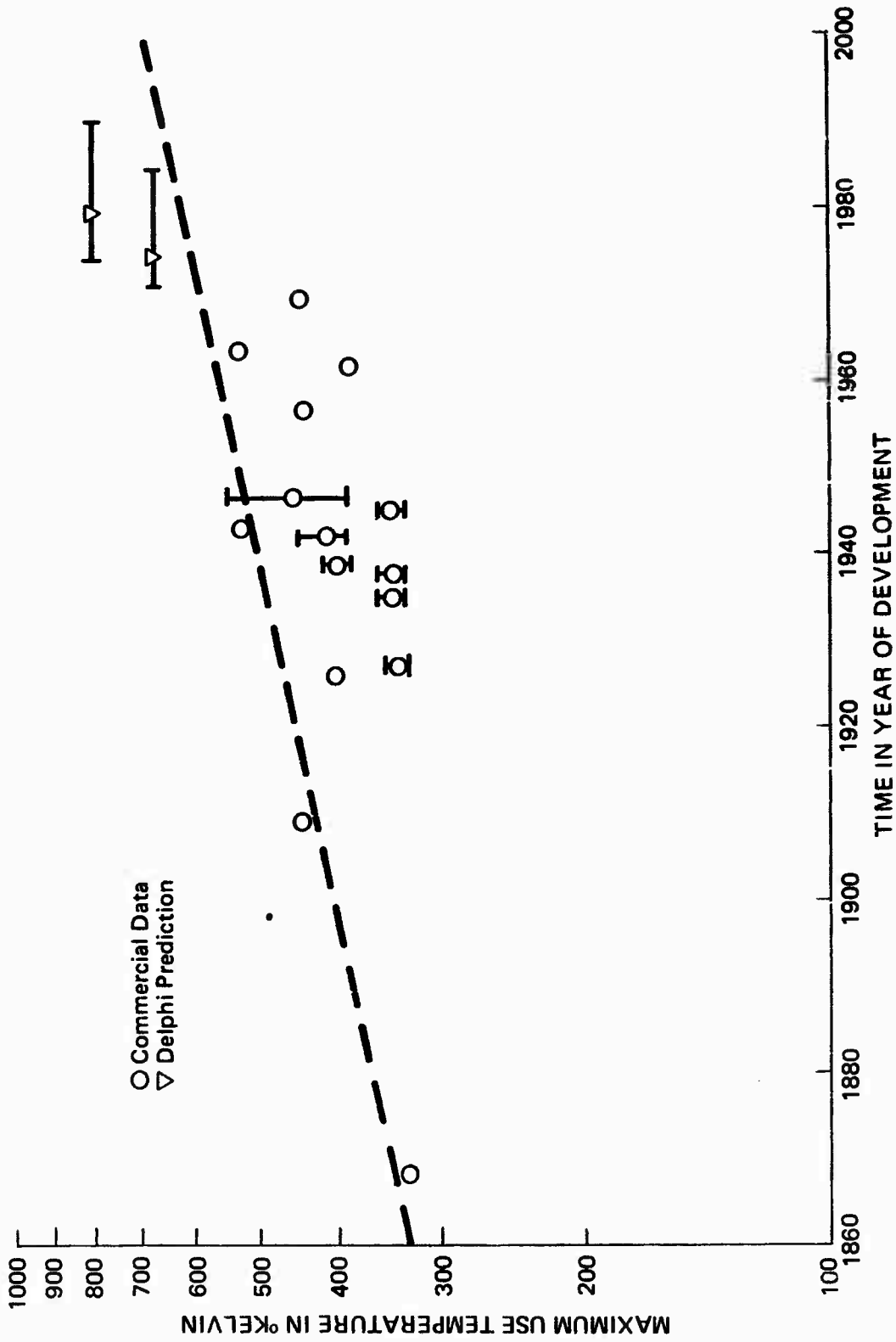


Figure 1 Development of Commercial High Temperature Load-Bearing Plastics

Delphi panelists tend to integrate such laboratory information into their estimates, resulting in an indication that there may be a significant deviation from the trend line possible in the next ten years.

More importantly, although trend data exist over a 100-year period, the parameter (maximum use temperature) being examined has not been a pacing parameter in polymer development until quite recently. Oxidation, photostability, crazing, and other physical characteristics have been much more important in the history of polymer development. Furthermore, there have not been many good scientific leads to greatly increased thermal stability of polymers until relatively recent times. Thus, the trend data may be highly misleading and one is well advised to accept the reasoned judgment of experts.

In many cases, to lend credibility to the forecast, the comparison of results from two methods can be useful. Consider the example of the forecast use of plastics in car bodies as shown in Figure 2. In this case, a substitution analysis was made to determine the rate at which metal in car bodies was being displaced by plastics. The Delphi forecast made by TRW and used in the previous example also contained questions concerning the use of plastic in cars. The two forecasts tend to reinforce each other. In this instance, the important point is that neither of these two analyses was very convincing alone. (The substitution analysis is based upon very limited data early in a substitution where the forecast is uncertain at best.) The combination of the two methods does tend to lend credibility to the forecast.

The point illustrated by these last two examples is that in areas of technical uncertainty, a combination of methods is helpful in assessing the range of feasible alternatives which constitute the forecast. On the other hand, there is a limit to the amount of resources and time available to make any given technological forecast. Therefore, it is helpful to have a relatively clear idea of the strong and weak points

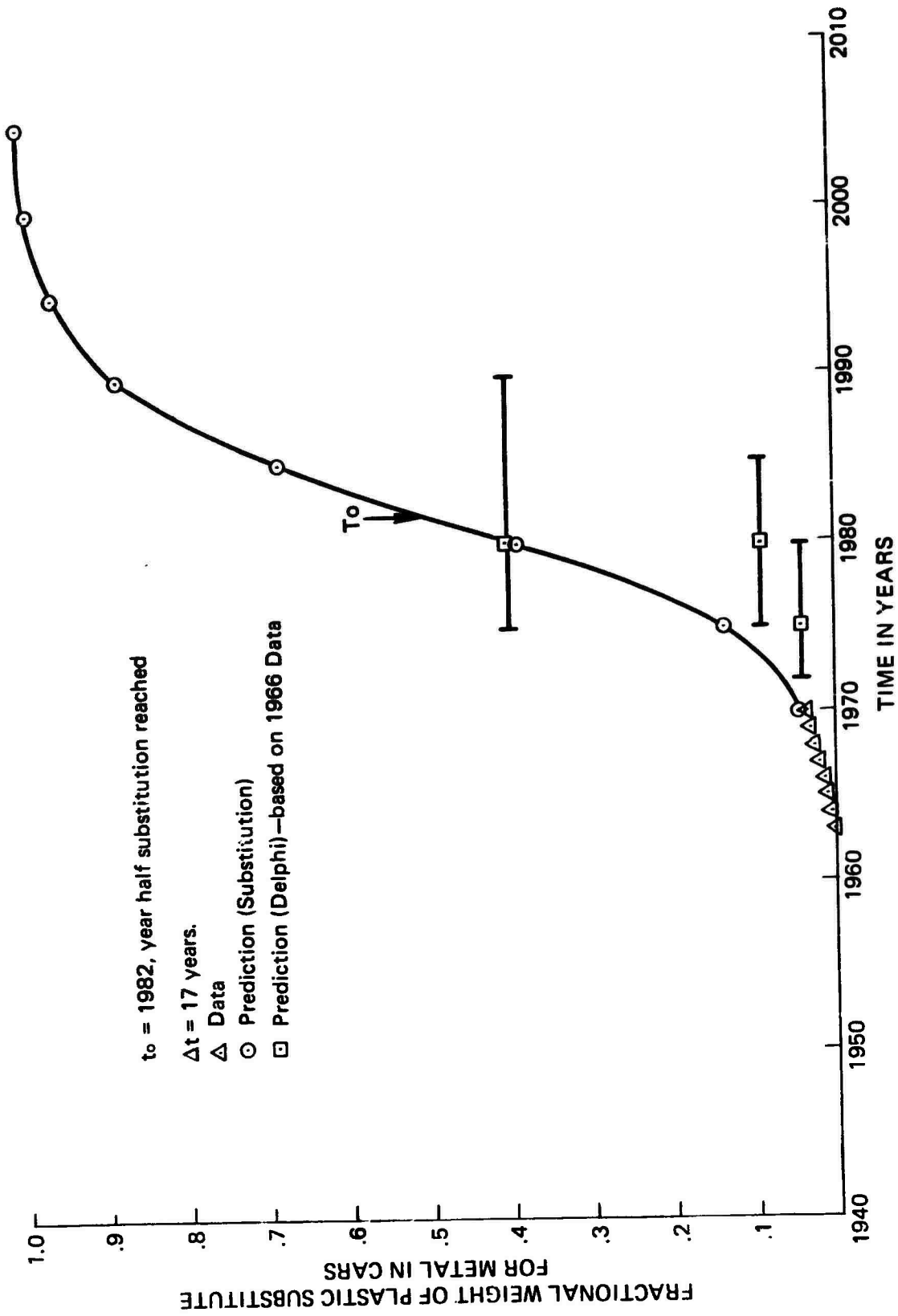


Figure 2 Substitution of Plastic for Metals in Car Bodies

of each method with respect to the areas of consideration mentioned earlier; namely, the status of the science or technology area under investigation, the amount of data, and the amount of work required for the forecast. Such comparisons are presented in Table 1.

In summary, if one will be satisfied with the cheapest, most subjective, nonreproducible forecast requiring no data and very little effort, and with little confidence in its accuracy, one can simply guess at the future. On the other hand, good forecasting tools are available for the eight- to ten-year period provided the existing data are available. Such forecasting methods should be used to produce a more credible forecast when the penalty for "surprise" may be great. Today, the principal problem with the application of forecasting techniques using trend analysis is the unavailability of an adequate data base in a useful form, particularly in regard to materials properties as a function of time.

APPENDIX A
CASE HISTORY
ON
THE USE OF TECHNOLOGICAL FORECASTING

**CASE HISTORY
ON
THE USE OF TECHNOLOGICAL FORECASTING**

**Choice of Approaches to Permit Higher
Inlet Temperatures of Turbine Engines**

The primary objectives in development of aircraft turbine engines are (1) to increase thrust per pound of engine weight, (2) to reduce fuel consumption, and (3) to increase life. The first two of these are generally aided by an increase in maximum cycle temperature, i. e., increased turbine-inlet temperature. The component of the engine that has always limited turbine-inlet temperature is the rotating turbine blade operating at relatively high stresses in the hot gas stream. The first U. S. turbojet engines developed for World War II used blades made from cobalt-base alloys because these alloys had the highest temperature capability at the stress levels of interest. For some years, every subsequent increase in turbine-inlet temperature was preceded by the development of an improved superalloy (cobalt- or nickel-base) that would operate at higher temperature levels.

Early in the 1950's, it became clear that the temperature capability of the superalloys was advancing rather slowly, about 20°F per year. If more rapid advances in turbine-inlet temperatures were to be achieved, alternative approaches would be needed. Some materials groups believed that there was an opportunity in alternative materials systems, such as cermets or molybdenum. For example, the refractory metal molybdenum has a melting point about 2000°F higher than nickel or cobalt and certain materials groups initiated large development programs to solve the major problem with molybdenum, namely, its oxidation resistance. Other groups more correctly judged that the greatest opportunity lay in cooling the turbine blade. They first looked at the cooling of blades fabricated from sheet steels. Finally, the industry evolved the present approach, the cooling of the most advanced cast superalloys.

With hindsight, we cannot say with certainty what kind of technological forecast was used. It was not a detailed formal technological forecast that outlined specific alternatives. In part, it was the usual informal normative forecasting. The advantages of high turbine-inlet temperatures were defined from an engine cycle analysis by experts in such analyses. The advantages of these high turbine-inlet temperatures were made known widely, and large advances in turbine temperatures became an objective or goal. Recognizing this need, various groups pursued various routes to that goal, depending on their assessment of the potential of the route and on their own capabilities. Individuals, trained in the materials discipline, pursued new routes to high temperature materials arguing that the air used for cooling would result in a performance penalty that might be avoided if cooling were not necessary. Those who pursued cooling felt that a price would have to be paid for cooling (the benefits were only partially offset by the cost) and that the dramatic new materials might not be successful.

In assessing the growth potential in superalloys, we are not sure that formal time extrapolations were made, but clearly the slow potential growth was recognized and stated by knowledgeable persons, ("Genius" and forecasting). One example of extrapolation is shown in Figure A-1 from an Aerospace Industries Association Forecast entitled, "Aerospace Technical Forecast, 1962-1972," published in 1962.* This trend extrapolation suggested a continued growth of 25°F per year, reaching a probable limit of about 2000°F near the year 1966. They emphasized that further improvements in turbine-inlet temperatures would result principally from cooling but with some modest material improvements.

Only a few examples of the increases in turbine-inlet temperatures resulting from material and cooling improvements are available in the open literature.

* "Aerospace Technical Forecast, 1962-1972," Aerospace Industries Association of America, 1725 DeSales Street, N.W., Washington, D.C.

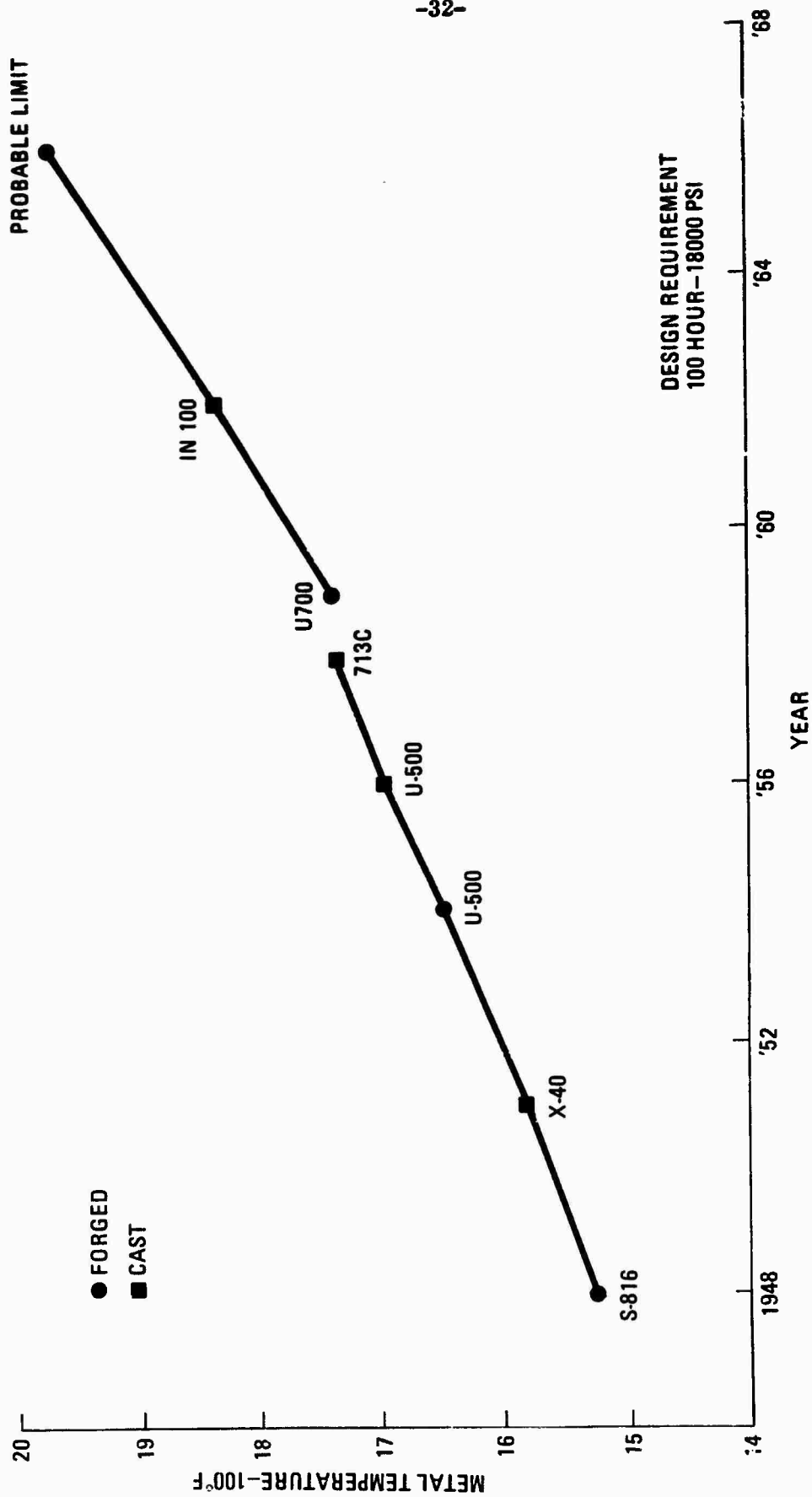


Figure A-1 Turbine Bucket Requirements
(Non-Refractory Alloys)

Source: "Aerospace Technical Forecast, 1962-1972." Aerospace Industries Association of America, 1725 DeSales Street, N.W., Washington, D. C.

Figure A-2* shows the growth in temperature capability of materials from 1958 to 1970, and superimposed upon that is shown the amount of cooling achieved by improvements in design and manufacture of cooled blades. The associated growth in turbine-inlet temperature for both uncooled and cooled engines is shown in Figure A-3.* The introduction of turbine cooling permitted a sudden significant increase in turbine-inlet temperature and a continued growth that would not have been possible through improvements in materials, thus verifying the intuitive forecasts of some years ago.

New concepts in blade materials not considered 15 years ago offer promise today and, for the future, continued improvements in materials are sought for this application. For convection-cooled blades, shown in Figure A-2, a 100°F improvement in material capability will permit a greater increase in turbine-inlet temperature than all the possible improvements in bucket design configuration. Film and transpiration-cooled blades offer further opportunities.

*Gresham, H. E., "Materials Aspects of Advanced Jet Engines," Metals and Materials, Vol. 3, No. 11, Nov. 1969.

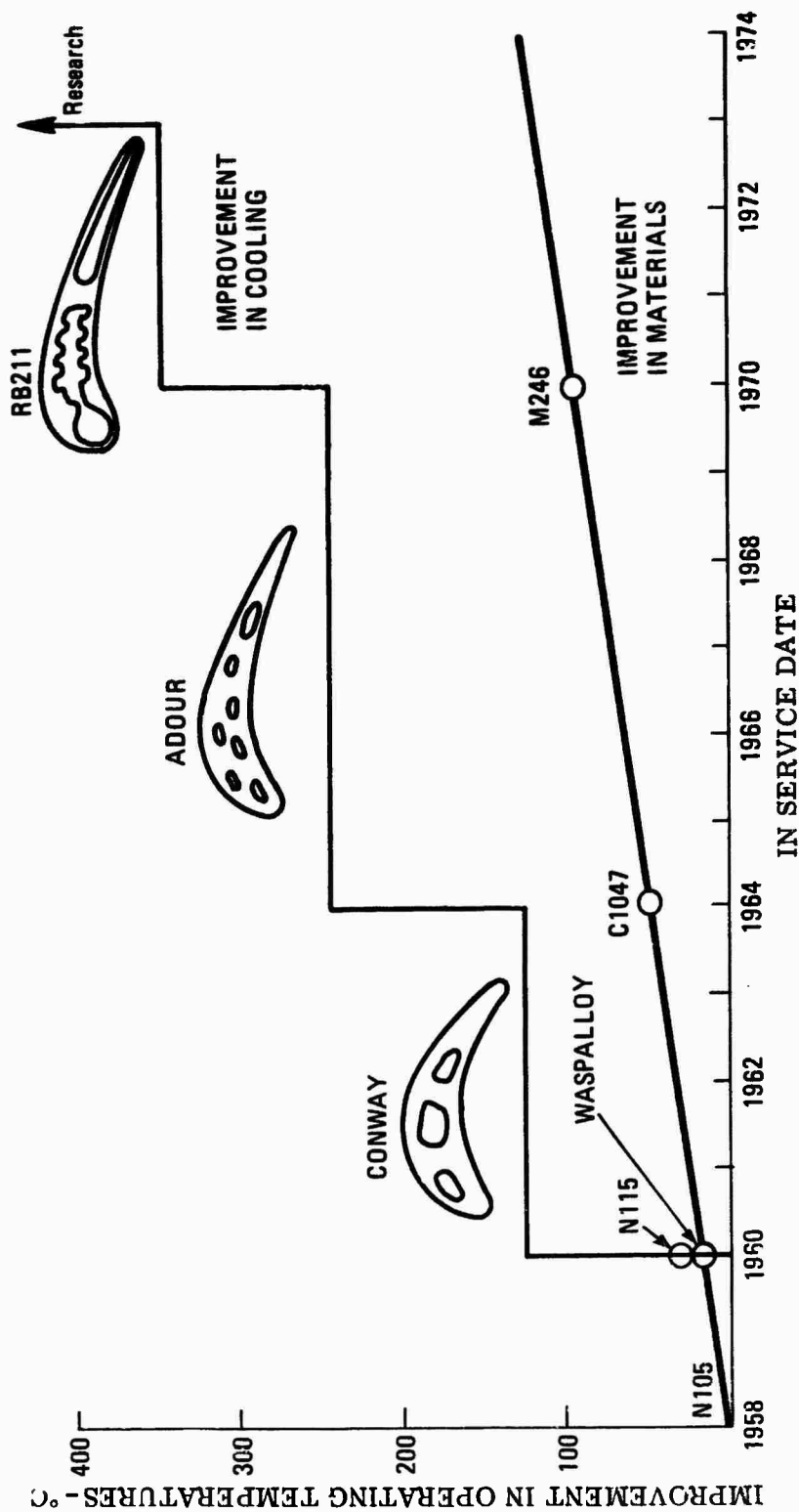


Figure A-2 Effect of Materials and Cooling Design on Engine Operating Temperatures

Source: "Gresham, H.E., "Materials Aspects of Advanced Jwt Engines," Metals and Materials, Vol. 3, No. 11, Nov. 1969.

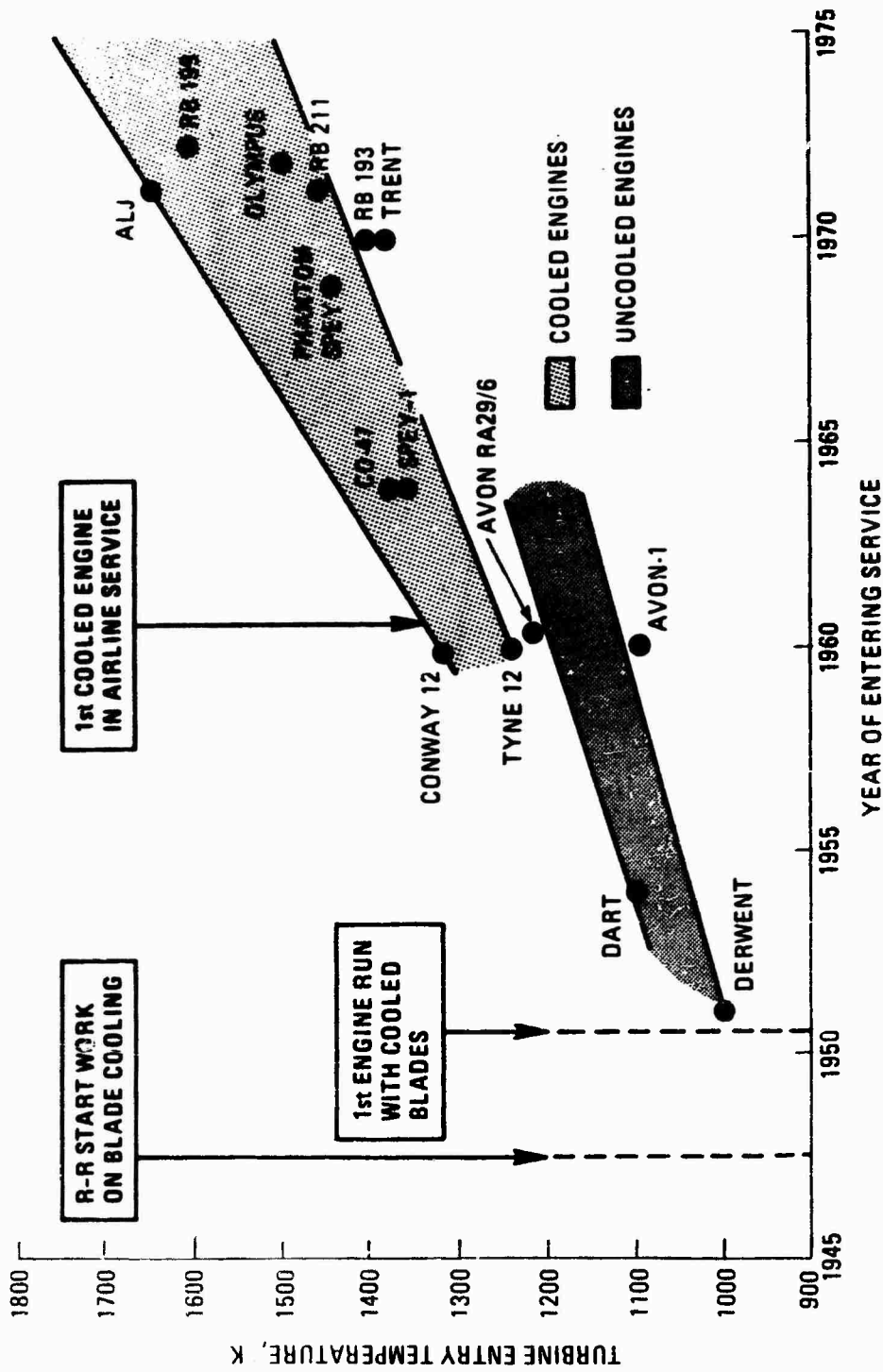


Figure A-3 Growth in Turbine-Inlet Temperatures for Cooled and Uncooled Engines

Source: Gresham, H.E., "Materials Aspects of Advanced Jet Engines," Metals and Materials, Vol. 3, No. 11, Nov. 1969.

APPENDIX B

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