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Measuring Technological Change: Aircraft Turbine Engines

Arthur J. Alexander and J. R. Nelson

A Report prepared for

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UNITED STATES AIR FORCE PROJECT RAND

Rand
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10. ABSTRACT

Estimates turbine engine parameter tradeoffs over time, using multiple regression analysis. Movement of the parameter tradeoff curve is defined as technological advance. The data base includes the first model of a given turbine engine to pass the Model Qualification Test. The history of turbine engines strongly suggests that single parameter analysis cannot capture the richness of the development process. The rate of technological advance seems fairly constant over time. However, two major manufacturers have been ahead of the others in the level of technology. Turboprops did exhibit a different technology from turbofans and turbojets. In 9 out of 10 cases, the rate of increase of technology of growth versions of engines was less than the average trend of technology for new engines, indicating that when design features become hardware, technology growth cannot take full advantage of new techniques. Comparison of Soviet and American equations revealed an early Soviet lead, reversed since the 1950s.

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PREFACE

Rand's research program on the R&D process in the context of system acquisition has extended over more than a decade. Recent Rand research indicates that improved estimates of costs and schedules might be obtainable for the development and procurement phases of the system acquisition cycle if techniques were available to assess the technological advance being sought. This report describes the development and testing of such a technique using the technology of aircraft turbine engines as an example. Plans for continuing research provide for expansion of the turbine engine findings to relate technology to the costs associated with the development, production, post-development, and operational phases of turbine engines and other products.

The measure of technological advance developed in this study is intended to capture mainstream trends. It is not able to identify fine differences among turbine engines or to distinguish small differences in contractor proposals. It is intended to provide a broader understanding of the technological advance being sought in an engine development program and to provide information for use in making decisions concerning development policy.

Some of the data used in this study were obtained from the engine manufacturers on a confidential basis and from other restricted sources. These restrictions require that the results be presented in a suitably aggregated form that does not permit identification of individual engine parameters. However, much of the data are available in standard sources such as *Jane's All the World's Aircraft*.

Initial efforts to develop an objectively obtained assessment of technical advance factors for new systems and subsystems were sponsored by the Advanced Research Projects Agency (ARPA) for the Director of Defense Research and Engineering (DDR&E). Further and more specialized research was performed under Project Rand for the United States Air Force.

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SUMMARY

Multiple regression analysis is used to estimate a multidimensional tradeoff surface of the parameters characterizing engine technology and to trace out the movement of the tradeoff surface over time. The equation with the best statistical properties contained parameters thought to be important in turbine engine development and had coefficients consistent with *a priori* notions of technological change. This equation is

$$\begin{aligned} \text{Tech} = -1187.5 &+ \underset{(9.3)}{156}\ ln\ \text{Temp} + \underset{(3.5)}{18.8}\ ln\ \text{Thrust} - \underset{(5.8)}{26.5}\ ln \\ &\text{Weight} - \underset{(3.03)}{20.6}\ ln\ \text{SFC} + \underset{(2.66)}{11.7}\ ln\ Q + \underset{(2.12)}{13.0}\ \text{Prop}; \\ &R^2 = .903 \end{aligned}$$

where Tech is the technology index (date of Model Qualification Test measured in quarters of a year from fourth quarter of 1942), Temp is turbine inlet temperature (degrees Rankine), Thrust is military sea level static thrust (lb), Weight is engine weight (lb), SFC is specific fuel consumption at military sea level static thrust (lb/hr/lb), Q is maximum dynamic pressure (lb/ft^2), and Prop is a dummy variable equaling one if the engine is a turboshaft or turboprop and zero otherwise. Numbers in parentheses are t statistics of coefficients.

The data base included the first model of a given turbine engine to pass the Model Qualification Test required of all American production engine types of the past 30 years. A technological resumé of American turbine engine experience places the statistical analysis in proper context. Examination of the history of turbine engine progress suggests very strongly that single parameter analysis cannot capture the richness of the development process.

The data were divided into a number of subsamples covering various time periods to test whether the shape of the tradeoff surface changed over time. When divided into equal halves, the subsamples were indistinguishable. Divided by thirds, the most recent period showed a slight

increase in the rate of technological advance, but the increase was barely significant statistically. Equations of the two major manufacturers (General Electric and Pratt & Whitney) showed that the shape of their technological tradeoff surface proved no different from that of the other manufacturers but that the major companies were approximately two years ahead of the others in the level of technology. Turboprops did exhibit a different technology from turbofans and turbojets; it is partly for this reason that a turboprop dummy variable is included in the above equation.

In nine out of ten cases, the rate of increase of technology of growth versions of engines was less than the average trend of technology for new engines. This result indicates that when design features are frozen in hardware, technology growth cannot take full advantage of newly developed techniques.

A sample of Soviet engines was analyzed to determine whether their technology surface and growth rates differed from those of the United States. Comparison of the Soviet and American equations revealed an early Soviet lead in technology. This lead was overcome sometime in the early 1950s, and since then American technology has moved ahead. There is some indication of a weakening in this divergent trend in recent years.

Plans for the future include the estimation of a technology production function that relates development expenditures to technology improvement and cost reduction. The models and techniques developed in this study will also be applied to other systems.

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I. INTRODUCTION

> We must attend to the quantitative aspect of a situation or problem and make a basic quantitative analysis....To this day many of our comrades still do not understand that they must attend to the quantitative aspect of things--the basic statistics, the main percentages and the quantitative limits that determine the qualities of things. They have no "figures" in their heads and as a result cannot help making mistakes.
>
> Mao Tse-tung[1]

In a recent study, Rand examined the weapon system acquisition experience of the 1950s and 1960s and compared performance, cost, and schedule predictions with the actual outcomes of major programs of all three services.[2] Evidence indicated that the precision of cost and schedule estimates made at the beginning of a development program depended in part on the extent of technical advance being sought in that program.

Initial attempts to rank technical advance were qualitative in nature, being based on the opinions of individuals who had experience in various aspects of the systems under study. This qualitative advance factor (the A Factor) was then related to schedule slippage and cost growth.[3] Some method of providing a quantitative, objective assessment of the technology advance would have been preferable. The question addressed in the present study is: Can a technique be developed for objectively quantifying the technological state of the art of a particular type of system? Such a technique would have broad implications for improving high-level strategy and decisionmaking for the entire development and procurement process and would serve as an important input in further studies on the R&D process. The present study proposes and

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[1]*Quotations from Chairman Mao Tse-tung*, Foreign Languages Press, Peking, 1966, pp. 111-112.

[2]Perry *et al.* (1969, 1971).

[3]Harman (1970).

reports tests of such a technique, measuring technological change in aircraft turbine engines. Section II considers the basic rationale and the analytical method. Section III discusses aircraft turbine engine technology trends during the past 30 years and the available hardware data base used in this study. Section IV presents the statistical results of the application of a multiple regression analysis using the turbine engine data. Finally, in Section V, plans for future work in this area are discussed.

II. MEASURING TECHNOLOGICAL CHANGE

Certain phrases are often heard with respect to technology: a device is ahead of its time; a field is technologically stagnant; a breakthrough occurs; the goals of a development project are technologically ambitious. The measure of technological change proposed in this study addresses the problem of quantifying these qualitative statements in a manner that attempts to satisfy our intuitive understanding of the language while imposing a discipline on subjective evaluations.

In addition to being intuitively satisfying, a measure of technological change ought to be derived in the context of a model or theory of the R&D process. Since we have no general theory of R&D at this point, we shall support the analysis by fragments of a theory that will later be confronted by independently generated data on aircraft turbine engines.

The analysis is confined to the development process. It proceeds on the assumption that two attributes are present in a development project. First, the object or device under development can be adequately characterized by a limited number of parameters. The development process acts on this set of parameters in such a way that the value of the set is increased. The increase in value of the parameter set is what we shall call technological advance. And second, historical continuity prevails. Continuity exists if two devices that appear at different times can be characterized by the same set of parameters. Continuity also requires that subsequent development can begin where prior development ended. That is, a given state of technology, once achieved, does not have to be reachieved.[1]

The requirements that projects be describable by a parameter set and that continuity exist define both the phenomena to which the analysis applies and the class that is excluded. Basic research and invention are excluded from our purview; on the basis of our present

[1]This requirement can be relaxed by allowing "forgetting" to take place in some specified way. We assume here that the rate of forgetting is small relative to the rate of learning.

knowledge, the output of such activity is unique, unpredictable, and unspecifiable.

The parameters that characterize a given technology can be divided into two subsets: performance parameters give the device value to the user (thrust or weight, for example), and technical parameters make the performance parameters possible (turbine inlet temperature or overall pressure ratio).[1] These two subsets are not independent and they may overlap to some extent. Specification of the technical parameters will determine the level of performance that may be achieved and vice versa. Because of the dependent relationship between the sets of parameters, it is possible to focus on just one of the subsets.

For the sake of illustration, consider two dimensions of performance: the technology of the time will permit some minimum weight for a given level of thrust. These feasible values of thrust and weight describe a tradeoff curve as shown in Fig. 1. The curve labeled t_0 represents the state of technology during the first time period. As technology progresses, the curve shifts and the minimum weight falls for an engine of given thrust. Different users at any given time (say, t_1) may select engines that emphasize different characteristics and there would be a scatter of points as shown by A, B, and C.

Most outcomes of the development process represent compromises among many interrelated parameters, and any analysis that relies on only one or two parameters (as in the above example) would have serious limitations. Figure 2 presents the trends of selected parameters that are important in the design of a new turbine engine. In a single variable fashion, these parameters show certain improvements in the state of the art of turbine engines over the past 30 years. The figure illustrates the method that has been used extensively in the past by others to assess the technology of a new engine with respect to previous engines and the current state of the art. A particular variable was selected and compared with the same variable in previous engines. For instance, shown at the top of Fig. 2 is pressure ratio

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[1]Some characteristics are undesirable — weight, for example. Therefore, reduction in the level of such characteristics would increase the value of the device to the user.

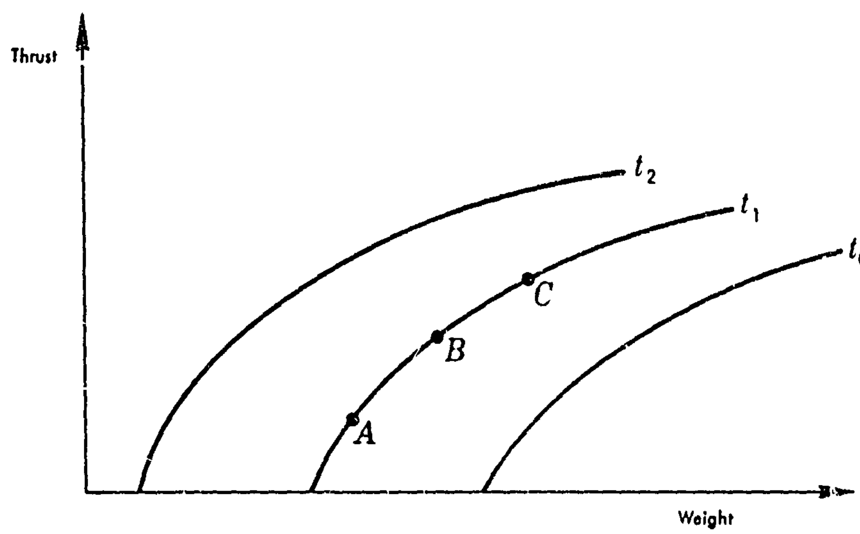
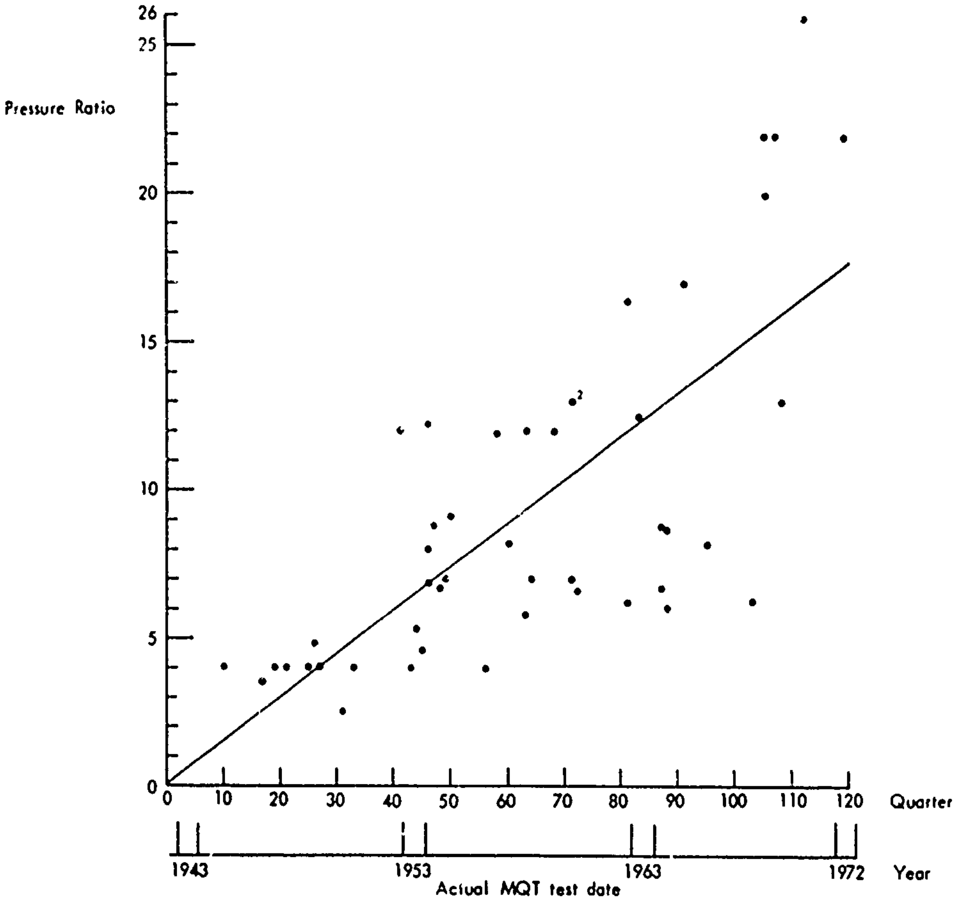


Fig. 1 — Technical Possibilities Curve or Tradeoff Surface: Movement over Time



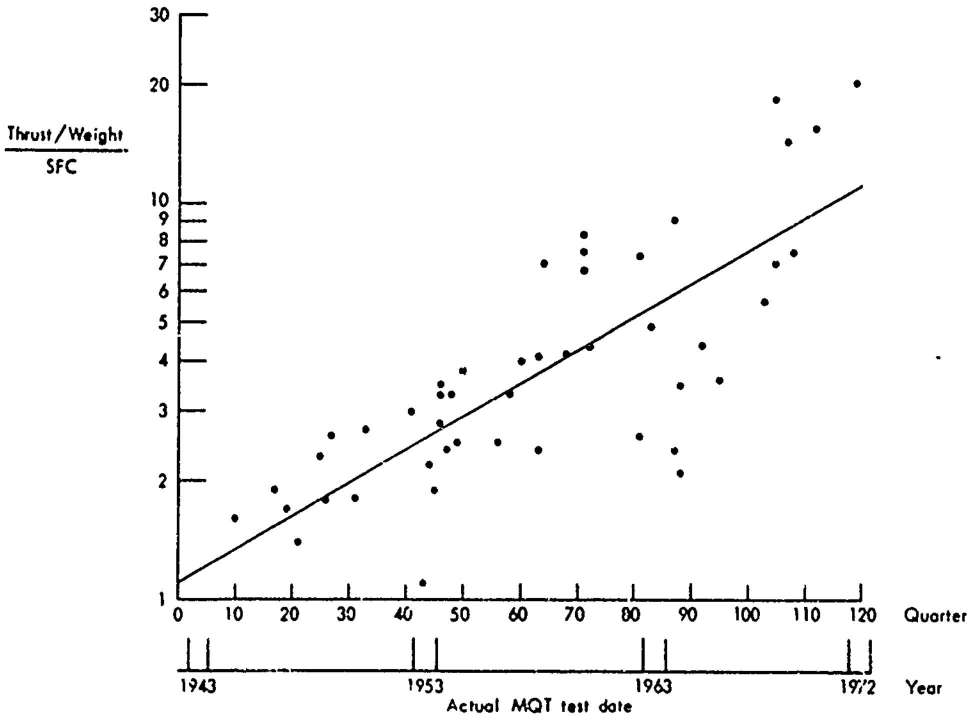


Fig. 2 — Single Variable Technology Trends

versus time. The time trend of pressure ratios for all the engines in our data sample are represented by the straight line. However, engine pressure ratio depends on the application of the engine, and in the data base there is a wide dispersion of pressure ratios. A somewhat more complex technique is used by one of the engine manufacturers, who defines an "effectiveness index" as the logarithm of the ratio of thrust to weight to specific fuel consumption (SFC) (Fig. 2, bottom). A further refinement classifies the engines into various types (augmented, unaugmented, turboprop, and so on), but the analysis still remains essentially one of a single complex parameter. Some understanding can be gained of how an engine ranks with respect to other engines for this complex variable, but no independently generated measure is obtained for tradeoffs among many variables. We therefore wish to deal with a multi-parameter surface as a measure of the level of technology. If the shape of the surface does not change over time, and if its movement is regular,[1] both the surface and its movement can be estimated by multiple regression.[2] We define this movement of the tradeoff surface as technological change. The function to be estimated has the form:

$$t = F(P_1, \ldots, P_n)$$

where t is the point in time that a particular engine first appeared, and P_i denotes the performance parameters of the engine.[3] Specification of the functional form and determination of the coefficients of the equation provide a measure of the average technological trend over time. Inserting the parameter values of a given engine into the equation yields the predicted date of appearance of that engine if it

---

[1] By "regular" we mean that the movement of the curve through time is describable by a smooth, monotonic function.

[2] Multiple regression determines the curve or surface that best fits a sample of observations.

[3] We recognize that cost is an important parameter to both the supplier and user of a product. At this point, however, we shall concentrate on technology and defer discussions on costs to the final section.

followed the general technological trend. An engine that appeared earlier than predicted would be "ahead of its time." A "breakthrough" would be represented by a sharp shift in the equation at some point in time.[1]

Both scientific and institutional reasons support the assumptions of regularity in technical change. The underlying scientific and technical relationships are slow to change. New relationships are discovered, of course, but rarely is an entire corpus of scientific thought and engineering accomplishment completely displaced. Discovery is marginal and piecemeal. But even if a major scientific breakthrough should occur, embodied experience and organizational structure provide a conservative counterforce. People with specialized experience will solve problems in proved ways; they will recast new problems to look like old problems, and they will modify old solutions to fit new conditions.

One feature of the analytical technique also favors the assumption of continuity. By emphasizing performance rather than technical parameters, we give greater weight to outputs than to inputs. In many cases, the user does not care how a product is produced, so long as it has value in use. Breakthroughs affecting the technical parameters may not be reflected as such in the set of performance parameters. This is especially true if a new technology becomes more efficient over time and if there are diminishing returns to the old technology. At some point, the new technology becomes marginally better than the old and is used subsequently. However, analysis of the output parameters would show a smoothness over time despite the incorporation of the new technology.

Much of the process described above can be reformulated as a simple model of the development process. The model described below is intended to aid interpretation of the discussion. It serves to organize perceptions rather than to yield testable predictions.

---

[1]The function describing the movement of the tradeoff curve would show a discontinuity. Whether there are such jumps can be determined statistically.

We assume that, at a given point in time, the technology can be described by a set of k implicit technical relationships among n performance parameters (P) and m technical parameters (T).[1]

$$
\begin{aligned}
&f_1\ (P_1, \ldots, P_n; T_1, \ldots, T_m) = 0 \\
&\cdot \\
&\cdot \\
&\cdot \\
&f_k\ (P_1, \ldots, P_n; T_1, \ldots, T_m) = 0
\end{aligned}
\qquad (1)
$$

These technical relationships include standard engineering equations, scientific "laws," empirical observations, and other constraints on the values of parameters. The difference between the total number of variables and the number of equations determines the dimensionality of the tradeoff surface. For example, if $k = m + 1$, the system can be "solved" in the following interesting way:

$$
\begin{aligned}
&T_1 = h_1\ (P_1, \ldots, P_n) \\
&\cdot \\
&\cdot \\
&\cdot \\
&T_m = h_m\ (P_1, \ldots, P_n)
\end{aligned}
\qquad (2)
$$

and

$$0 = F\ (P_1, \ldots, P_n) \qquad (3)$$

Equation (3) represents the tradeoff surface among the performance parameters. Choosing the values of the Ps determines the required values of the Ts.[2] If the user of the technology has a utility function (U) with the performance parameters as arguments, he can maximize $U = U\ (P_1, \ldots, P_n)$ subject to $F\ (P_1, \ldots, P_n) = 0$.

---

[1]The designation of what is a performance parameter and what is a technical parameter may be rather arbitrary. Basically, performance parameters are arguments in a user's utility function.

[2]Of course, any k variables can be solved for explicitly in terms of the remaining $(m + n - k)$ variables if the appropriate conditions for the existence of a solution are satisfied. In real situations, however, it is improbable that this symmetry exists.

If k is greater than m, the dimensionality of the tradeoff surface is reduced, and if k is equal to m + n the surface is reduced to one feasible point. In actual engineering practice it is likely that k is somewhat greater than m. This means that only a subset of the performance parameters will appear on the tradeoff surface.

Technological *change* is introduced by adding a time variable, t, to the technological constraint Eq. (1). Equations (2) and (3) will then include the time variables also.

$$T_i = h_i\ (P_1, \ldots, P_n, t) \qquad (2')$$

$$h(t) = F\ (P_1, \ldots, P_n) \qquad (3')$$

The equation that is estimated empirically in Section IV is (3').[1] The function h(t) incorporates the assumption of regularity discussed above.

---

[1]In order to be assured that Eq. (3') can be written as an explicit function of t, it is sufficient that t enter into the constraints in a certain way: either $f_i\ (P_1, \ldots, P_n;\ T_1, \ldots, T_m) + g_i(t) = 0$ or $f_i\ (P_1, \ldots, P_n;\ T_1, \ldots, T_m)\ g_i(t) =$ constant.

III. TURBINE ENGINE TECHNOLOGY AND DATA BASE

We selected American aircraft turbine engines as the initial subject for testing the technique of measuring technological change for three reasons: (1) qualitatively, a strong technological trend was evident over a 30-year period, (2) an adequate data base was available for analysis, and (3) turbine engines are important products incorporating billions of dollars of development and procurement resources.

The design, development, and production of U.S. aircraft turbine engines can be said to have started in earnest with the introduction of the British-designed Whittle engine at the General Electric Company in Lynn, Massachusetts in September 1941. From that modest beginning, the turbine engine has advanced to complete domination of the entire military and commercial aircraft powerplant market. It is also making inroads in ground and water transportation and commercial power generation.

Table 1 categorizes turbine engine technology trends since 1940 and indicates the companies involved. A qualitative assessment of advancing technology is indicated by such improvements as replacing centrifugal compressors with axial flow compressors, the transition from uncooled to cooled turbines, the advance from single-design-point engines to multi-design-point engines, the replacement of aluminum and conventional steel by titanium and superalloys, the increase in aircraft speed from subsonic ranges through Mach 3, and the progression of engine type from turbojet to turboprop to turbofan.

Table 2 lists the engines considered in this study and their manufacturers. The data points from the early 1940s to the late 1960s comprise 47 different turbojet, turboprop/turboshaft, and turbofan engines. All are primary engine data points in the sense that we use each engine only once in the data. If the engine appeared in several versions, for example, with and without afterburner, we include only the first engine model to pass a Model Qualification Test (MQT) in the data base. However, ten growth engines used in a separate post-development analysis are also listed. These engines incorporate thrust or horsepower growth on the order of 30 to 50 percent.

Table 1

TURBINE ENGINE TECHNOLOGY HISTORY

	Early 1940s (WW II)	Late 1940s	Early 1950s (Korean War)	Late 1950s	Early 1960s	Late 1960s (Vietnam)	Early 1970s
Types of Engines in Production	J	J	J, T	J, T	J, T, TF	J, T, TF	J, T, TF
Technological Events	Increased thrust Centrifugal to axial compressor Single design point mission Limited use of high temperature steels; primarily conventional steels	Augmentation Two position nozzle Stainless steel, aluminum, conventional steel Higher pressure ratio -- dual rotor	High pressure ratio -- variable stators Titanium begins to replace aluminum Sustained supersonic flight Small helicopter engines Reliability/durability Moderately higher turbine temperature	Cooled turbine Mach 3 Small light weight engines Commercial J Subsonic TF Titanium and superalloy material improvements Transonic compressor	Supersonic TF Multi-design point mission Superalloy materials Light weight design Component improvements Commercial TF	High bypass TF (military and commercial) High temperature turbine Cooling techniques 3-spool rotor Compatibility/integration Increasing sophistication of development Commercial technology and requirements becoming as advanced as military	High thrust/weight High component performance High temperature materials Cooling techniques Composite materials
Companies	General Electric Westinghouse	Allison Boeing Curtiss-Wright Fairchild General Electric Pratt & Whitney Westinghouse	Allison Boeing Continental Curtiss-Wright Fairchild General Electric Lycoming Pratt & Whitney Westinghouse	Allison Boeing Continental Curtiss-Wright Fairchild General Electric Lycoming Pratt & Whitney	Allison Boeing Continental Curtiss-Wright Garrett General Electric Lycoming Pratt & Whitney	Allison Continental Garrett General Electric Lycoming Pratt & Whitney	Allison Continental Garrett General Electric Lycoming Pratt & Whitney

J = Turbojet
T = Turboprop/Turboshaft
TF = Turbofan

Table 2

TURBINE ENGINE DATA BASE

Period	Early 1940s	Late 1940s	Early 1950s	Late 1950s	Early 1960s	Late 1960s
Engines started and companies	J30 W J31 GE J33 GE-A J34 W J35 GE-A	J40 W J42 PW J44 F J46 W J47 GE J48 PW J57 PW J71 A J73 GE T34 PW T40 A T50 B	J52 PW J65 CW J69 C J75 PW J79 GE T53 L T55 L T56 A T57 PW T58 GE	J58 PW J60 PW J85 GE J93 GE T63 A T64 GE TF30 PW TF33 PW TF35 GE JT8D PW	J97 GE J100 C T65 C T76 G TF37 GE	TF34 GE TF39 GE TF41 A JT9D PW CF6 GE
Number of engines started in period	5	12	10	10	5	5
Growth derivatives			J33 A J35 A		T56 A T58 GE	J52 PW J69 C T53 L T55 L T64 GE TF30 PW
Number of engines in period			2		2	6

General Electric early made a number of changes to the original Whittle design, which utilized a single centrifugal-stage compressor, to create the 1-A turbojet that first flew on October 2, 1942 in a Bell P-59A. During the period (1941-1942) that GE started work for the Army Air Corps, the Navy began working with Westinghouse to build a different kind of turbojet using a multistage, axial-flow compressor. That engine, which later became the J30, was the first Navy engine to be produced in quantity.

Both companies had previous experience in the design and manufacture of large steam turbines and GE was dominant in the design, development, and manufacture of superchargers for aircraft reciprocating engines. At the time, the principal manufacturers of aircraft reciprocating engines were Curtiss-Wright and Pratt & Whitney. Neither of these companies was asked by the U.S. military to undertake turbine engine development, presumably because the military did not want to interfere with essential war production.

The military desire for more powerful engines quickly led GE from the 1-A to the J31 to the J33 (all centrifugal-flow engines), each having increasingly higher thrust, while Westinghouse went from the J30 and J32 to the J34 axial flow turbojet. The J33 and J34 were the first American aircraft turbine engines to be produced in large quantities.

GE also began the development of axial-flow compressors with the T31 turboprop (which was never successful) and the J35 turbojet engine. The axial-flow compressor permitted a much smaller diameter engine, and thus less frontal area, than the centrifugal compressor design for comparable pressure ratio and thrust -- a highly desirable feature for engines installed in high-speed jet fighter aircraft. Although the axial-flow compressor was at that time inferior in fuel consumption and weight, it offered potentially higher compressor pressure ratios through the addition of compressor stages and thus promised ultimately greater fuel economy in a more compact envelope than the centrifugal compressor. One stage of a centrifugal compressor appeared to have a pressure ratio limit of 4:1 or 5:1, and it was not then considered feasible to stack centrifugal stages. Development emphasis rapidly shifted to engines using axial-flow compressors.

The development of the original turboprop engine, the T31, encountered considerably more difficulty than expected. A reliable gear box and propeller combination was slow to emerge. Thus the turbojet tended to dominate operational applications in the early 1940s. The primary use was for single-design-point missions for subsonic fighter aircraft.

Toward the end of World War II, Allison took over production and further development of the J33 and J35 from GE. General Electric concentrated on a growth version of the J35 (later the J47). Pratt & Whitney began turbine engine development and production by buying licenses to produce versions of two Rolls-Royce centrifugal-flow turbojets (the J42 and J48). But P&W felt the need to overcome the technological lead built up by GE and Westinghouse; and while producing the British power plants under license, they also designed entirely new engines, one of which was the axial-flow, dual-rotor prototype of the J57. The dual-rotor compressor, incorporating concentric shafts, each carrying a number of compressor stages, and each revolving at different speeds (thus improving stage-matching characteristics throughout the compressor), was a novel solution to the problem of achieving higher pressure ratios.

Curtiss-Wright subsequently entered the field with the T35 design and purchased licenses for the production of the British Armstrong-Siddley Sapphire, later the J65. Two other companies also participated, Fairchild with a drone engine design designated J44, and Boeing with a small turboprop, the T50. (A possible reason for Boeing's entering the field was to learn about the application of turbine engines to the aircraft Boeing was interested in building.)

During the late 1940s, Westinghouse began to work on engines more advanced than the J34, eventually developing the J40 and J46, while Curtiss-Wright attempted to develop turboprop variants of the British engines for which they had secured licenses, thus starting the T47 and T49 programs. The two most successful engines of those that entered development late in the 1940s were the J47 (GE) and the J57 (P&W). The dual-rotor of the J57 allowed a compressor pressure ratio in excess of 10:1, resulting in a lower specific fuel consumption than had yet been achieved. Pratt & Whitney also began work on the turboprops, principally the T34. General Electric began development of an advanced version of the J47, later designated the J73. Allison, apart from proceeding toward an improved version of the J35 (later designated J71), also attempted turboprop designs, notably the T38 and T40. From that experience came the very successful T56. In those early days of engine development, new engines were essentially larger versions, incorporating up-rated technology, of engines already in production. Most new engine programs started from a base of development money added to a production engine contract.

The turbojet still dominated the late 1940s. Because higher thrust was the primary performance requirement of the era, augmentation was introduced, first by the injection of water and alcohol into combustors, later through afterburning. Additional multistaging of the axial-flow compressor allowed higher pressure ratios, again reducing specific fuel consumption. Many designs of the period moved to production status because of the demands imposed by the Korean War and the challenge of surprisingly good Russian engines.

In the early 1950s the roster of active companies included Allison, Continental (which started with a French license for the Marbore engine that later became the J69), Fairchild, Lycoming (which began developing the T53 and T55), GE, P&W, and Westinghouse. Westinghouse had considerable difficulty with the Navy J40 engine program, and toward the latter part of the decade discontinued aircraft development and production -- the first major firm to do so.

The early 1950s saw the beginning of engines designed to sustain flight at speeds through Mach 2. The GE J79 incorporated an axial-flow compressor with variable stators which allowed high-pressure ratios to be obtained with a single multistage rotor and which was an alternative solution to the problem of obtaining high-pressure-ratio compressors. (P&W's solution was the dual rotor.) The axial-flow turbojet continued to dominate fighter, bomber, and unmanned vehicle applications; turboprop and turboshaft applications were limited to helicopters and transports. Relatively moderate uncooled turbine temperatures still were customary, although materials had improved enough since the previous decade to allow an increase of as much as 200°(F) in compressor and uncooled turbine temperatures. Thrust-to-weight ratios improved from values of about 2:1 in the early 1940s to around 4:1 in the early 1950s. Considerable effort went into improving the life and reliability of engines.

The late 1950s saw the advent of the air-cooled turbine, allowing turbine inlet temperatures in excess of 2000°(F), and substantially aiding the development of engines designed for Mach 3 flight -- the P&W J58 and the GE J93. The turbofan appeared, providing a new technique for increasing engine efficiency in subsonic flight. The TF33 was the first. Several small engines with high thrust-to-weight ratios were developed for unmanned applications and smaller aircraft.

Like Westinghouse, Fairchild (after losing the J83 competition to GE's J85), and Boeing (never seriously in the field) essentially dropped out of the turbine engine business leaving Allison, Continental, Curtiss-Wright, Lycoming, GE, and P&W. Commercial aircraft powered by turbojet engines began to enter service during the late 1950s, the most notable being the JT3 derivative of the P&W J57. The turbofan was rapidly becoming the most favored engine for flight speeds of Mach 2.0 and less. Turboshaft engines (for the helicopter and small transport applications) and turbojets for specialized applications (Mach 3 or more) or for smaller aircraft and drones were the principal competitors. Titanium began to replace aluminum for use in the cooler parts of an engine, superalloys being developed for the hot sections. Design and manufacturing techniques for producing cooled turbine stator and rotor parts received increasing attention. The transonic compressor began to show its potential.

Substantial improvements in materials and cooled turbine technology made it possible by the early 1960s to obtain turbojet thrust-to-weight ratios in excess of 6:1, appreciably better than the 4:1 of the 1950s and the 2:1 of the early 1940s. Design practices were introduced to take advantage of the improved structural and heat properties of new materials. Pressure ratios of 15:1 or 20:1 were achieved. The use of turbofan engines permitted specification of multi-design-point missions involving wide ranges of flight speeds. Of engine programs begun in the early 1960s, the TF30 was the only military engine built in substantial numbers (and it actually started development in the late 1950s). The P&W JT3D and JT8D turbofans were the most successful commercial engines.

During the early 1960s there was continued emphasis on the development of new materials and on improvements in component performance and design. Exploratory and advanced development programs and demonstrator engines began to receive more emphasis. Curtiss-Wright essentially discontinued engine development and a new company, Garrett-AiResearch (which had considerable experience as a designer of auxiliary power units for aircraft), moved into the market, specializing in small turboprop and turbofan engines. The only company to enter the field since the early 1950s, Garrett had experience analogous to GE's pre-1940 experience in superchargers. But unlike GE, Garrett was attempting to enter a highly competitive market.

The high-bypass turbofan that appeared late in the 1960s was made possible by improvements in materials and components earlier in the decade. The TF39 high-bypass turbofan used in military transports and the commercial JT9D and CF6 permitted flight performance advances as large as those arising in the transition from the turbojet to the turbofan a decade earlier. Pressure ratios in excess of 20:1 and turbine inlet temperatures in excess of 2000°(F) became operational realities in commercial as well as military applications. Bypass ratios exceeded 5:1 for several engines. Garrett introduced a three-spool rotor (as did Rolls Royce in the RB-211). Composite materials, used sparingly at first in the new engines, promised substantial weight reduction over the next decade. Increasingly, engine-airframe compatibility problems demanded more attention than at any earlier time.

As the 1970s began, three large companies (Allison, GE, and P&W), and three small companies (Continental, Garrett, and Lycoming) remained in the turbine engine field. All six were active in both the commercial and military markets. But stationary electrical power and maritime applications were also becoming important markets for turbine engine manufacturers.

The design goals of engines slated to be produced in the early 1970s were higher thrust-to-weight ratios, higher cycle efficiency (through improved component performance), and higher turbine inlet temperatures (through reliance on advanced materials and advanced turbine-cooling technology). Generally, it seems very probable that the well established trend toward constantly advancing technology and constantly increasing engine performance will continue throughout the 1970s.

IV. STATISTICAL RESULTS

We performed a statistical analysis of the data sample on turbine engines with several objectives in mind. Our primary objective was to determine the shape and movement of the tradeoff surface of performance parameters (as described in Section II). We made statistical tests of the assumptions that the shape of the surface did not change over time and that movement was regular. In addition, we wanted to determine how post-development rates of technological change differ from the average rate of new developments, and whether there is a difference between the technologies of different companies or countries.

Linear, semi-logarithm, and full logarithm forms were tested, as well as quadratics and polynomials. Often, we examined several alternative measures of the same basic variable. Finally, we looked at several different combinations of variables, each corresponding to a particular version of the basic hypothesis. All of these equations were estimated from the same data base to see which yielded the most satisfactory results.

Table 3 shows a representative summary of the results. The first equation is the one that satisfied the criterion of reasonableness and produced the highest degree of statistical correlation.[1] We shall discuss that equation after an examination of the more important alternatives.

Of the functional forms tested, the semi-logarithm form was clearly superior. Equation (2) in Table 3 is the best of the alternative forms examined; it fitted the data much less well than Equation (1).

Several opportunities were present for using alternative measures of a particular parameter. For example, thrust may be measured at its maximum value at sea level, maximum value at altitude, cruise value, or with afterburner. Statistical results were very much stronger when the variables were chosen at the maximum (non-afterburning), sea level,

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[1] Continuous data revision and updating will alter the values of the coefficients in the equations. On the basis of a similar process that took place while the research was being done, we expect such revisions to be quite minor and not to effect the qualitative conclusions.

Table 3

SELECTED REGRESSION EQUATIONS, TECHNOLOGICAL TREND

1.	Best equation (semi-logarithm)	$R^2 = .903$ SE = 9.6	$\text{Tech} = -1187.5 + \underset{(9.3)}{156}\ ln\ \text{Temp} + \underset{(3.5)}{18.8}\ ln\ \text{Thrust} - \underset{(5.8)}{26.5}\ ln\ \text{Weight}$ $- \underset{(3.03)}{20.6}\ ln\ \text{SFC} + \underset{(2.66)}{11.7}\ ln\ Q + \underset{(2.12)}{13.0}\ \text{Prop}$
2.	Linear	$R^2 = .832$ SE = 12.6	$\text{Tech} = -77.1 + \underset{(6.95)}{.077}\ \text{Temp} + \underset{(.92)}{.00066}\ \text{Thrust} - \underset{(2.33)}{.006}\ \text{Weight} - \underset{(3.42)}{34.4}\ \text{SFC}$ $+ \underset{(1.65)}{.0094}\ Q + \underset{(.23)}{1.77}\ \text{Prop}$
3.	Cruise variables	$R^2 = .835$ SE = 12.5	$\text{Tech} = -1501.8 + \underset{(12.2)}{213}\ ln\ \text{Temp} + \underset{(1.08)}{.86}\ ln\ \text{Thrust}^* - \underset{(3.54)}{8.4}\ ln\ \text{Weight}$ $- \underset{(3.85)}{27.6}\ ln\ \text{SFC}^* - \underset{(.8)}{3.10}\ ln\ Q^* - \underset{(2.75)}{24.3}\ \text{Prop}$
4.	Date of first flight	$R^2 = .891$ SE = 10.7	$\text{Flight} = -1245.6 + \underset{(8.8)}{163.7}\ ln\ \text{Temp} + \underset{(3.46)}{20.7}\ ln\ \text{Thrust} - \underset{(5.72)}{29.2}\ ln\ \text{Weight}$ $- \underset{(2.68)}{20.3}\ ln\ \text{SFC} + \underset{(2.38)}{11.7}\ ln\ Q + \underset{(1.7)}{11.8}\ \text{Prop}$
5.	Pure performance	$R^2 = .691$ SE = 16.9	$\text{Tech} = -38.9 + \underset{(3.7)}{33.4}\ ln\ \text{Thrust} - \underset{(5.02)}{39.0}\ ln\ \text{Weight} - \underset{(3.35)}{38.9}\ ln\ \text{SFC}$ $+ \underset{(1.79)}{13.9}\ ln\ Q + \underset{(1.54)}{16.5}\ \text{Prop}$
6.	Technical	$R^2 = .831$ SE = 12.4	$\text{Tech} = -1121.9 + \underset{(6.2)}{152.9}\ ln\ \text{Temp} + \underset{(3.12)}{18.6}\ ln\ \text{Pressure} - \underset{(4.21)}{7.17}\ ln\ \text{Airflow}$ $+ \underset{(2.49)}{16.0}\ \text{Fan}$

Figures in parentheses are t statistics of coefficients. SE = Standard error: R^2 uncorrected for degrees of freedom; n = 47.

Table 3, continued

Definition of Variables

Airflow	=	Total airflow through the engine; lb/sec.
Fan	=	Dummy variable; one if turbofan, zero otherwise.
Flight	=	Date of first flight; quarters, 4th quarter 1942 equals one.
Pressure	=	Overall pressure ratio.
Prop	=	Dummy variable; one if turboprop, zero otherwise.
Q	=	Maximum dynamic pressure; lb/ft^2.
Q^*	=	Cruise dynamic pressure; lb/ft^2.
SFC	=	Specific fuel consumption at military sea level static thrust; (lb/hr)/lb thrust
SFC^*	=	Specific fuel consumption at cruise.
Tech	=	Technology index; model qualification test date; quarters, 4th quarter 1942 equals one.
Temp	=	Turbine inlet temperature; Degrees Rankine.
Thrust	=	Military sea level static thrust; lb. or ESHP (equivalent static horsepower) if turboprop.
$Thrust^*$	=	Cruise thrust.
Weight	=	Engine weight; lb.

static condition, as reflected in Eq. (1). For comparison, Eq. (3) shows the results obtained when the variables are measured at the cruise condition.

The choice of a dependent variable presented a problem. We had to know the date that a particular level of technology has been achieved. Three milestones are available for most of the jet engines. The date of first flight marks the time that the engine is actually operated in an aircraft. The Preliminary Flight Rating Test (PFRT) is usually a 50-hour endurance test leading toward fully rated flight testing of a new engine. The Model Qualification Test (MQT), normally a 150-hour endurance test, must be passed before installation in production aircraft for operational use. Use of first flight date (Eq. (4)) resulted in a statistical fit almost as good as in the best equation. However, since first flight and subsequent flight testing often was made with a relatively unproved engine at an early stage of final development, we decided to use the date of MQT as best representing the point in time that a level of technology was demonstrably available for production.[1]

We attempted to estimate separate tradeoff surfaces for the technical parameters as well as for the performance parameters. The estimation of a technical parameter surface was not wholly successful (Eq. (6)). A partial explanation may be that the parameters that are available to characterize the input technology are not detailed enough to do the job. The parameters were airflow, turbine inlet temperature, pressure ratio, bypass ratio, compressor stages, and physical dimensions. Insufficient information was available to test the influence of many other technical parameters that might be of interest (component efficiencies, stage loadings, and so on). The use of *only* performance parameters (Eq. (5)) produced still poorer results.

The equation actually chosen as best representing the trend of the technological tradeoff surface is similar to a pure performance

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[1] Several data points are for engines that did not pass the 150-hour Model Qualification Test, either because they were being utilized in non-manned applic tions (in which the MQT is not a full 150-hour test), or because they had not passed the test when the development program was canceled. In these cases, the date of the downgraded MQT or date of cancellation as used.

equation, except that turbine inlet temperature -- a technical parameter -- appears as an important variable. One obvious explanation for the statistical power of turbine inlet temperature, even after the major performance parameters have been included in the equation, is that since temperature plays a dominant role in the thermodynamics of engines, a major development goal has been ever higher temperatures. These higher temperatures have been one of the chief sources of improved performance as measured by the major performance parameters. But in addition to the major parameters, many less important engine characteristics have been left out of the equation. Turbine inlet temperature may be a proxy for these parameters. In this case we considered temperature as a technical budget from which expenditures are made. The major expenditures are accounted for by the major parameters, but they do not exhaust the budget. The residual explanatory effect of temperature measures its contribution to the excluded variables. In addition, the advanced materials and production techniques used to achieve high temperatures were also available for secondary uses throughout the engine.

The equation best representing the tradeoff surface (Eq. (1)) includes variables that one would expect to be important, with the parameter coefficients having the correct signs with respect to technological advance. Thrust, weight, SFC, and dynamic pressure are the performance parameters. Turbine inlet temperature, as discussed above, is a technical parameter that may be acting as a proxy for excluded performance parameters. Weight and SFC, being more highly valued as they get smaller, have negative coefficients. That is, holding other variables constant, SFC and weight have fallen over time. Thrust, temperature, and dynamic pressure have positive coefficients indicating growth over time, as one might expect. A dummy variable is also included that takes on the value of 0 if the engine is a pure jet or a turbofan, and 1 if it is a turboprop. This dummy variable automatically incorporates certain adjustments required for differences in turboprops. For example, the power of turboprops was measured in horsepower rather than in pounds of thrust and the dummy variable will reflect this difference.[1]

A graphical representation of the technological trend equation is plotted in Fig. 3. On the vertical axis is plotted the calculated date[2] of appearance (date of MQT) of an engine of specified characteristics. This date, which may be thought of as an index of technology, is determined by inserting the engine's parameters into Eq. 1. The horizontal axis represents the actual date the engine's technology was demonstrated. The 45° line is therefore defined as the average trend or expected date of technology over the period. Points plotted above the 45° line represent engines "ahead of their time": that is, their parameters, taken as a whole, appeared earlier than predicted by the equation. Likewise, points below the line are "late" or "conservative" developments. The average deviation from the line (the standard error of the equation) is 9.6 quarters.[3] This means that approximately two-thirds of the observations could be expected to fall within plus and minus 9.6 quarters of the 45° line. This rather wide spread of almost five years around the trend line illustrates one of the problems of interpreting the results. There is a broad range of deviations because of random disturbances. The equation therefore cannot be used for making fine distinctions, but if certain points or trends deviate sharply from the average, we should be able to distinguish them from the ambient noise.

In an attempt to determine whether the equation changed significantly over time, we split the sample into subsamples covering various time periods. Dividing the sample into equal halves yielded the surprising result that there was little statistically discernible difference

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[1]If the conversion factors between the parameters of turboprops and turbojets are multiplicative (for example, if thrust = k · horsepower), then the dummy variable in the logarithmic equation incorporates all of these conversion factors. However, unless one knows all of these conversion factors from independent sources, it is not possible to say whether the dummy variable measures the conversion factors or a difference in the timing of the technology.

[2]The dates on both axes are measured in quarters of a year beginning with zero as the third quarter of 1942.

[3]The standard error is actually the square root of the average squared deviation.

$$TECH = -1187.5 + 156.2 \log_e TEMP + 18.8 \log_e THRUST - 26.5 \log_e WEIGHT - 20.6 \log_e SFC + 11.7 \log_e Q + 13.0\ PROP; \quad R^2 = .903$$

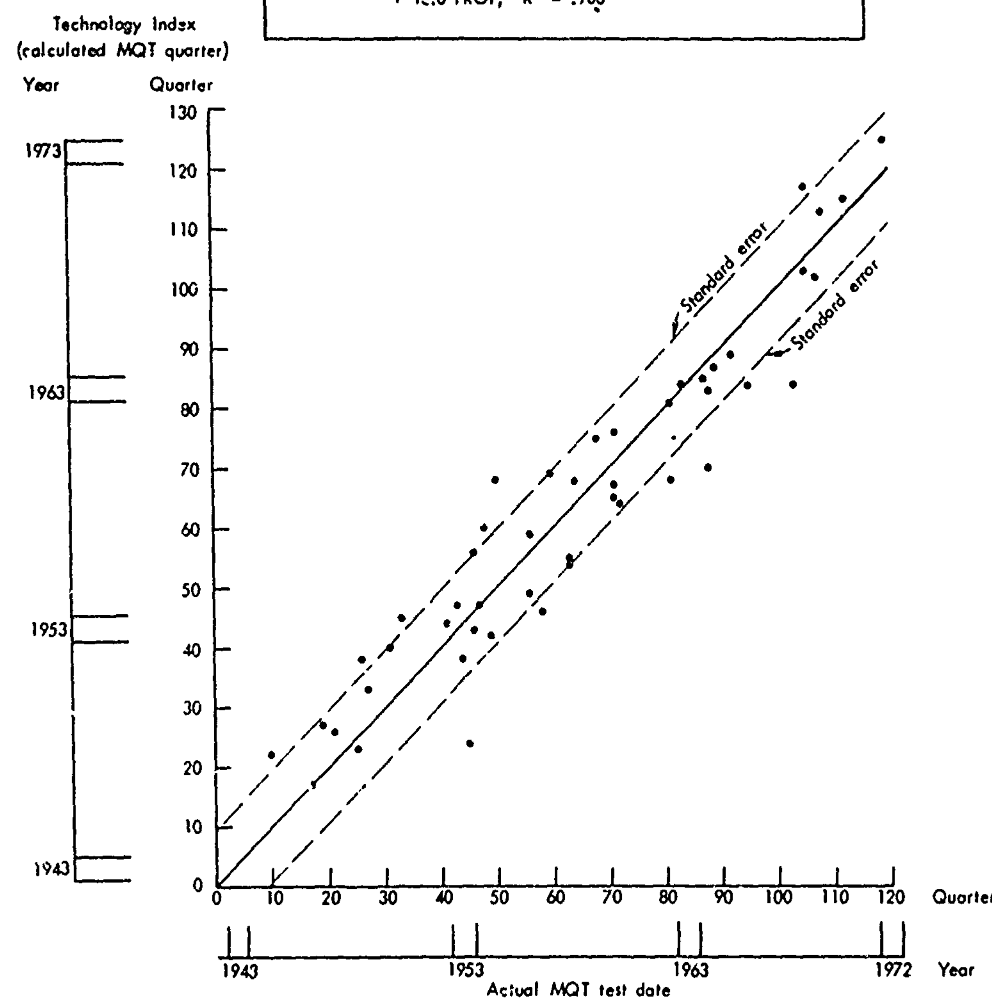

Fig. 3 — Turbine Engine Multi-Variable Technology Trend

between the technology trends for earlier and later engines.[1] (See Table 4 for statistical tests of differences in subsamples.) When we divided the sample into thirds, we found weak evidence for somewhat more rapid technological advance in the latest period. This result can also be shown in a plot of the residuals of the technology equation versus time. The plot is U-shaped with positive residuals predominating in the first and last thirds, and negative residuals in the middle third. A final test of possible curvature of the points about the 45° line was made by raising the dependent variable to a power. Highest R^2 was obtained when an exponent of 1.8 was used, but the increase in R^2 was so small as to be insignificant. Interpretation of these results as signifying an acceleration in technology should be made with caution. First, the statistics are very weak. Second, the interpretation must be made with respect to a specific equation that has been *defined* as best representing the average technological trend. For example, redefining the dependent variable to be $MQT^{1.8}$ would eliminate the apparent acceleration. Since we have no independent information as to the "correct" functional form of the technology equation, almost any monotonic transformation (which preserves ordering) is acceptable.

We selected other subsamples by engine type. Pure turbojets and turbofans were statistically indistinguishable from one another in terms of the equation, whereas turboprops did differ. It is partly for this reason that the dummy variable for turboprops is included in the equation. A division by major manufacturer (GE and P&W) in one subsample and the other manufacturers in a second subsample showed that the technological tradeoff surface was similar for the two subsamples but that the major companies were approximately two years ahead of the others in the level of technology.[2]

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[1] The Chow test for significance was used. See Chow (1960).

[2] When we examined the deviations from the trend line for each engine, we found that GE had a positive average deviation (technologically progressive), P&W had a zero average deviation, and the other companies' deviations were negative. These findings correspond to the industry's evaluations of the different companies during the period under review.

Table 4

TESTS OF DIFFERENCES BETWEEN EQUATIONS OF VARIOUS SUBSAMPLES

Subsample I	Subsample II	F Statistic	Degrees of Freedom	Significance[a] (percent)
First half of time period	Second half of time period	1.76	7/33	10-20
First two thirds of time period	Last third of time period	2.80	7/33	~2.5
Turbojets[b]	Remaining sample	2.21	6/35	5-10
Turbojets	Turbofans	.79	6/23	>25
Turbojets[b]	Turboprop	1.79	6/25	10-20
Turbofans[b]	Remaining sample	1.55	6/35	20-25
Turbofans[b]	Turboprops	1.41	6/10	>25
Turboprops[b]	Remaining sample	3.06	6/35	1-2½
Turboprops	Remaining sample	1.85	7/35	~10
GE and P&W	Remaining sample	1.03	7/33	>25
U.S.	USSR	3.92	7/61	.1-.5

[a]Pr[illegible]lity that two subsamples are randomly drawn from the same parent po[illegible]ation -- that is, that they possess similar characteristics. The lower the probability, the more clearly distinct the subsamples.

[b]These equations did not include the dummy variable for turboprops.

The development of engines beyond the MQT is often more costly than the entire development program up to the MQT. We therefore performed an analysis on 10 growth engines. We expected that since the design of a growth version of an engine has many of its features frozen in hardware, the technology would grow at a slower rate than demonstrated by new engines. This expectation was strongly borne out, as shown in Fig. 4, where post-MQT technological growth is plotted for the 10 engines. The left-hand point of each pair of points represents the technology at MQT. The right-hand point is a measure of technology of a later model of the engine. The connecting line indicates the rate of growth of technology for each engine. Nine out of the 10 engines showed growth curves of less than 45°. The one exception represented a major, troublesome, and costly redesign.

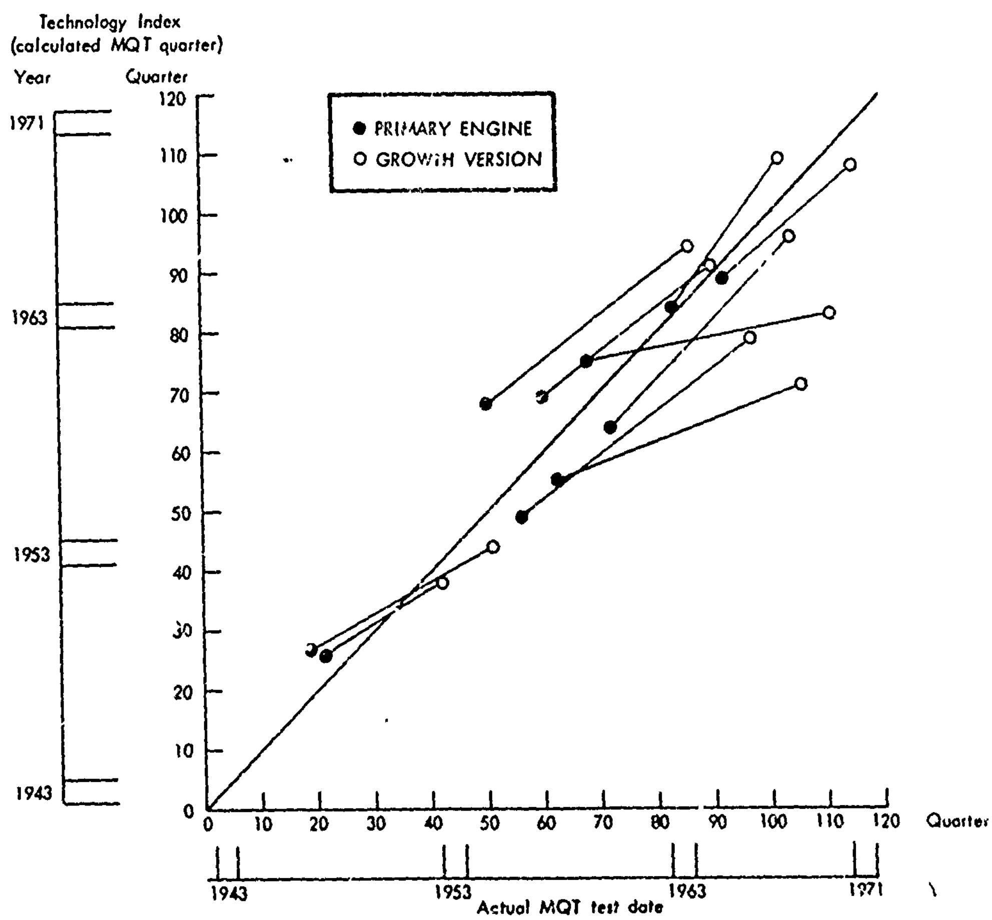

Fig.4 — Post-Development Technology Growth

The technology equation, as discussed earlier, can be interpreted in two ways. First, it shows how a tradeoff surface of engine characteristics has advanced over time. And second, it defines an index of the level of technology, which enables one to make an ordinal comparison of the technological level of two engines, as was done above in the comparisons of the growth versions of engines with their first MQT models. One can compare the technology levels of engines of different countries using the same technique. However, two countries with very different histories of industrial and technological development may exhibit quite different patterns of technological progress. In such a case, an index of technology based on the experience of one country may rank two engines differently from a similar index developed according to the experience of another country. This possibility of ambiguous or conflicting results has been called "the index number problem" in economics. We wanted to compare the technological level of American engines with engines of the Soviet Union. To investigate the seriousness of the index number problem for such a comparison, we estimated a technology equation from available Soviet data consisting of 28 engines:

$$\begin{aligned} \text{Tech} = -2061 &+ \underset{(5.0)}{273}\, \ln \text{Temp} + \underset{(1.5)}{33.6}\, \ln \text{Thrust} - \underset{(2.3)}{46.01}\, \ln \text{Weight} \\ &- \underset{(.9)}{19.9}\, \ln \text{SFC} + \underset{(1.02)}{11.9}\, \ln Q + \underset{(1.6)}{31.0}\, \text{Prop} \end{aligned}$$

$$R^2 = .79$$
$$SE = 14.8$$

The results of comparing the engines according to indexes based on each country's equation indicate a general consistency in the rankings. In Fig. 5a we plot the technology index obtained by placing the characteristics of the Soviet engines in the U.S. equation.[1] A simple least-squares regression line is drawn through these points. The same technique was followed in Fig. 5b with the U.S. engines indexed according

[1] A plot of the U.S. engines' characteristics in the same U.S. equation yields the scatter around the 45 degree line shown in Fig. 3; only the 45 degree line is shown here.

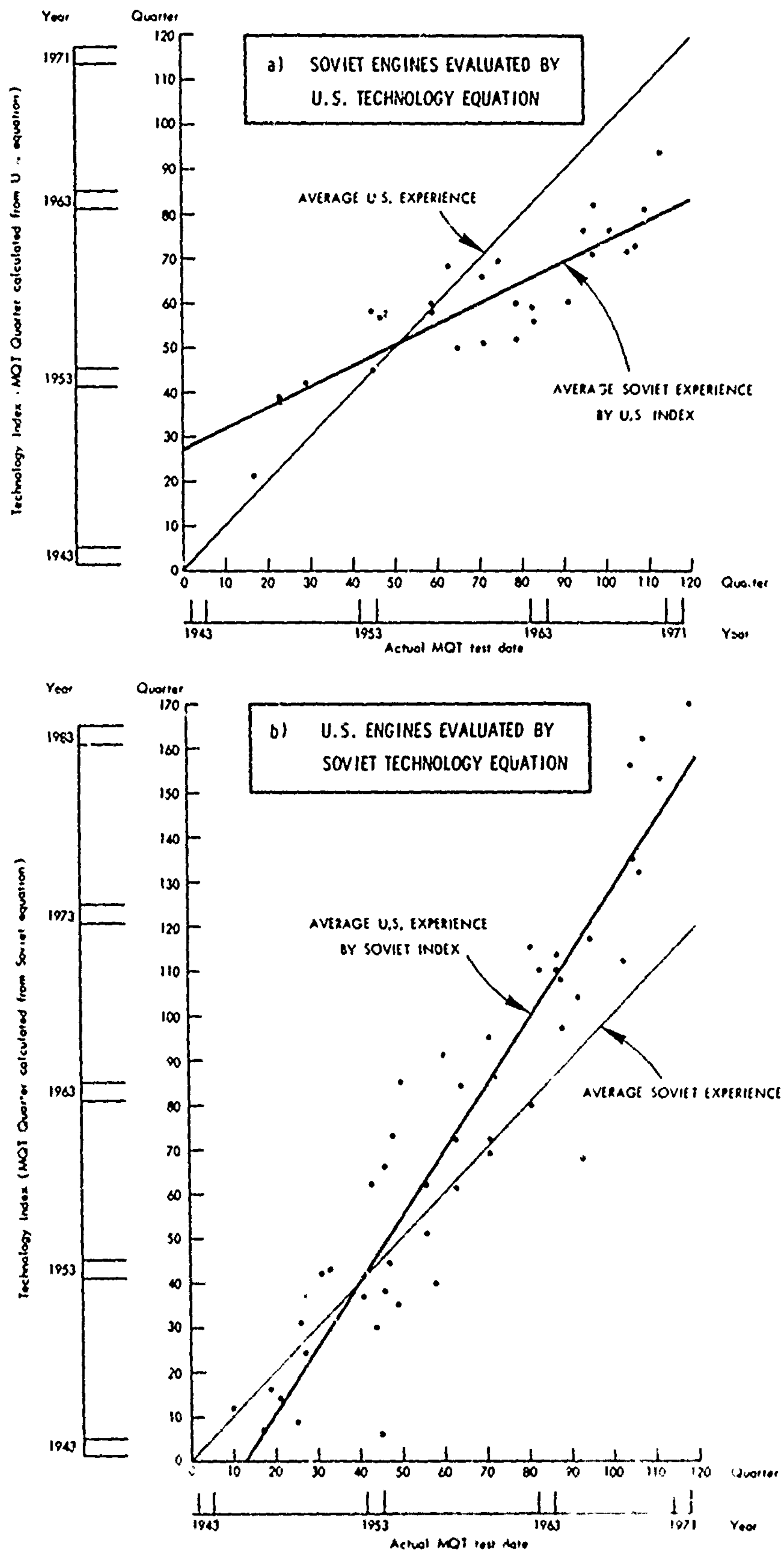

Fig.5 — U.S.- USSR Turbine Engine Technology Comparisons

to the Soviet equation.[1] Both plots indicate an early Soviet lead that disappeared in the early 1950s. Since that time the gap between the two technologies appears to have widened. It must be emphasized that these results are accompanied by considerable statistical uncertainty. Although general trends seem to be discernible over the long run, precise short-term predictions are clearly not warranted.

Why might these trends differ? The same engine parameters appeared in the Soviet technology equation as in the U.S. equation, and they were changing in the same direction over time. The major statistically significant difference between the Soviet and the U.S. equations is in the value of the coefficients for turbine inlet temperature, implying, not implausibly, that U.S. and Soviet designers were emphasizing different aspects of technology. The Soviets seem to have been concentrating more on the front of the engine, increasing thrust-per-pound of air flow and putting into production a transonic compressor before the United States, whereas the United States moved toward the back of the engine with high turbine inlet temperatures and the requisite advanced metallurgy.

The apparent difference between the technologies of the United States and the Soviet Union is also probably due in part to differences in military requirements. Furthermore, the growth of technology is, to some degree, dependent on the resources devoted to R&D. Since both military requirements and R&D investments are outputs of a more general decisionmaking process, they are subject to change. Any extrapolations of the lines of Fig. 5 must take these things into account, especially since the analysis on which the lines are based is derived from a linear model, which does not allow for slope changes over time.[2]

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[1] The 45 degree line in this case represents the best line drawn through the Soviet data.

[2] When quadratic functions were fit to the points in Fig. 5, they could not be distinguished either visually or statistically from the linear functions that are shown.

V. EXTENSIONS AND APPLICATIONS

The analysis of technological change has proceeded thus far with no mention of costs. The focus has been on pure technology, even though it is clear that a full treatment of technological change must recognize the intimate connection between technology and costs. In this section we extend the model of technological change introduced in Section II and relate future empirical investigations to the extended model.

We first define a technological production function. Production functions relate the outputs of an activity to the inputs. In this case, the output is technology and production costs, and the inputs are the resources or costs of development. This function can be written as:

$$D = F(T,S)$$

where D is the cost of development, T is the level of technology, and S is a shift factor that operates on the average cost curve. The function is valid for only one time period. As knowledge accumulates and development takes place, the surface of feasible alternatives shifts out over time. We assume that there is some separability in the allocation of development resources; that is, a given input can be directed in varying proportions toward increasing technology or decreasing costs. The level of technology (T) is an index number given to a performance tradeoff surface as described in Section II. There is a question as to whether the individual parameters should enter into the technology production function or whether a summary figure such as T is sufficient. If the composition of technology affects development costs, the individual parameters should appear explicitly. This is an empirical question; for analytical convenience we shall treat technology as a scalar.

The technological production function provides only part of the information required to determine the amount and allocation of development resources. The net benefits derived from development must be known in order to determine an appropriate development strategy. We can make the discussion more concrete by specifying demand and cost functions for the product, and by specifying the incentives and institutional matrix under which the developer operates. Demand for the product can be written as $p = f(Q,T)$ where p is price per unit and Q is quantity. Price would be expected to fall with increased quantity and rise with higher levels of technology. The average cost function is $C = C(Q,S,T)$ where C is average cost per unit. We thus have a simple three equation model.

$$\begin{cases} D = F(T,S) \\ p = f(Q,T) \\ C = C(Q,S,T) \end{cases}$$

A description of the behavior of the decisionmaker depends on the particular case; consider first a profit-maximizing monopolist selling the product in a market described by the demand equation. He must determine the optimum R&D budget, the allocation of that budget, and the quantity he should produce. Profits, or net returns (R), can be written as:

$$R = pQ - CQ - D = Qf(Q,T,) - QC(Q,S,T) - F(T,S);$$

net returns are maximized by maximizing the value of this equation.

We re-emphasize that the analyst must know the institutional setting of the developer as well as his goals to perform the analysis. If the institutional setting were changed, one would observe different outcomes. For example, consider another producer who develops a product for *his own use*; the output is not for sale on an open market, but rather the single organization develops, produces, and consumes it. If only the institutional setting is changed, the gross benefits to the developer can be found by integrating under the demand curve.[1] In this case, the net returns equation becomes

[1] In economic terms, integrating the demand curve yields the sum of benefits over each unit of consumption.

$$R = \int_0^Q f(Q,T)dQ - QC(Q,S,T) - F(T,S).$$

All variables will, in general, have different optimal values in this case than in the first case.

Often, a development organization -- a business firm, government agency, military service -- will have a number of variables specified in advance by other organizations. Using an Air Force example, we can list a number of likely constraints: the number of squadrons of an aircraft type set by the political leadership; the development budget authorized by Congress; the total development plus procurement budget established by the Defense Department; the level of technology required by the user. Each combination of constraints yields an outcome that in general is unique. Coupling the constraints with the organizational incentives produces a rich mix of possible results. It is therefore not surprising that one finds in fact a wide variety of development styles. Patterns of aircraft R&D in the United States, Europe, and the Soviet Union are strikingly different. Even within the United States, one notes great dissimilarities among the military, air line, and utility markets. The model described above should permit a fuller understanding of such differences.

The movement of the technological production function over time depends on past development decisions. An emphasis on either technology advancement or cost reduction will tend to persist because the individuals and organizations, having become experienced at and accustomed to solving one class of problems, will find it easier to continue solving the same problems. Thus we find that military products incorporate ever higher levels of technology, not only because military preferences lie in that direction but also because the R&D organizations are set up to turn out that kind of product. It would be costly, at least in the short run, to alter the existing resources and organizations.

Additional research and empirical validation are needed to work out the details and implications of the models sketched out above. Data are being collected on turbine engine development and production costs. With these data, it will be possible to estimate the technological production function. Development and production cost equations would be the output of this analysis. Other research will investigate the underlying mechanisms that shift the technological production function. In this respect, we plan to examine the use in the 1960s of demonstrators and engine prototypes.

The models of technology described here are quite general. They are not intended to be applicable to turbine engines only. We are analyzing other products, including aircraft, to help determine their range of applicability. For example, objectively determined technological advance factors (A factors) have been substituted for qualitative A factors in estimating cost and schedule relationships in development projects.[1] The post-development phase of product improvement is also being analyzed with the aid of the technology concepts developed in this report.[2]

The concept of a technological production function embedded in an explicit institutional matrix with specified goal-oriented behavior should provide the framework for a broader understanding of the R&D process.

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[1] Harman (1972).

[2] Shishko (1972).

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