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Technological Change Through Product Improvement in Aircraft Turbine Engines

Robert Shishko

A Report prepared for

UNITED STATES AIR FORCE PROJECT RAND

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SANTA MONICA, CA. 90406

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PREFACE

For the past two decades, Rand has been studying and analyzing R&D policies, the economics of technological change and growth, and weapon acquisition strategies. This effort has concentrated at various times on quantitative techniques to improve the predictability of R&D and acquisition programs,[1] on policy research to improve the acquisition process,[2] on institutional aspects of Air Force acquisition decision-making,[3] and on case studies of particular R&D programs.[4]

This report presents the results of a Rand-initiated effort to understand a relatively unstudied form of technological change--product improvement. The study specifically quantifies the impact of product improvement R&D for U.S. jet engines developed for military purposes over the last 30 years. One of the techniques of analysis used here derives from an earlier Rand study by A. J. Alexander and J. R. Nelson.[5] In part, this report should be viewed as a continuation of their work.[6]

Although much of this report deals with observations about product improvement as a process, some policy implications are also discussed. In an era when new systems are brought into service irregularly, product

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[1] For example, R. L. Perry, D. DiSalvo, G. R. Hall, A. J. Harman, G. S. Levenson, G. K. Smith and J. P. Stucker, *System Acquisition Experience*, RM-6072-PR, November 1969; and A. J. Harman assisted by S. Henrichsen, *A Methodology for Cost Factor Comparison and Prediction*, RM-6269-ARPA, August 1970.

[2] See R. L. Perry, G. K. Smith, A. J. Harman, and S. Henrichsen, *System Acquisition Strategies*, R-733-PR/ARPA, June 1971.

[3] See, for example, B. H. Klein, W. H. Meckling, and E. G. Mesthene, *Military Research and Development Policies*, R-333, December 1958, and most recently, see W. D. Putnam, *The Evolution of Air Force System Acquisition Management*, R-868-PR, September 1972.

[4] For example, R. L. Perry, *A Prototype Strategy for Aircraft Development*, RM-5597-1-PR, July 1972.

[5] A. J. Alexander and J. R. Nelson, *Measuring Technological Change: Aircraft Turbine Engines*, R-1017-ARPA/PR, May 1972.

[6] This study has been revised and expanded from the author's dissertation submitted to the Department of Economics, Yale University.

SUMMARY

Most of the quantitative work in the area of technological change has dealt with the process of new product innovation or of state-of-the-art-breaking R&D for military applications. However, an area of R&D activity that is often as important as new product R&D is R&D directed at improving an existing object, often called product improvement.

The validity of several hypotheses about product improvement was tested quantitatively using data from product-improvement programs involving U.S. turbine engines developed for military purposes over the past 30 years. Three directions are identified for engine product-improvement programs. The first of these is called performance improvement. Here, the objective is to increase the performance or "technological level" of the engine. The second direction is called cost-reducing product improvement. The objective here is to reduce the production cost of an engine by deliberately committing R&D funds to that effort during a product-improvement program. The third direction has as its objective improvements in maintainability and reliability levels. Beginning in 1968 work funded under Component Improvement Programs (CIPs) has been of this type.

To quantify what is meant by "technological level," multiple regression analysis was used to estimate a multidimensional technology tradeoff surface for new engine designs as a function of a set of engine performance parameters. This technology equation was then applied to subsequent product-improvement versions.[1] The results indicated that on average product-improvement engines embody a higher level of technology than their original versions but that the rate at which technology can be incorporated into product-improvement versions is significantly less than the long-run average for new designs. This was not unexpected. Some new technology can be incorporated into an

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[1] The dividing line between the initial development program and the product-improvement program was taken to be the Model Qualification Test (MQT) of the engine.

existing engine, but to take advantage of all of the available technology, one must essentially start from scratch.

On the cost side, a function was estimated representing the maximum performance growth (as measured by thrust) attainable at various expenditure levels. Each increment to thrust becomes more costly--that is, thrust growth is subject to diminishing returns with respect to dollar resources. Furthermore, for a given level of expenditure, the greater the thrust of the original version, the larger the absolute increase in thrust in the product-improvement version but the smaller the percentage increase.

The cost of physically modifying engines to increase their thrust was also studied. Using regression techniques again, it was found that the larger the percentage change in thrust, the closer the costs of modification come to the production cost of an engine with the same thrust.

It has been observed that there are decreases in the costs of manufacturing as the cumulative quantity of engines produced increases. This is the "learning curve" phenomenon. Yet there is a substantial variability in the observed rate of learning for different engines. One explanation is that in some engine programs there is a deliberate effort in the product-improvement phase to reduce production costs. This effect should be observable directly in reduced manufacturing cost. It was hypothesized that cost-reducing product improvement acts to shift the whole cost-quantity relationship. To test this, a cost-estimating relationship (CER) encompassing thrust, cumulative quantity, technological class, and cumulative cost-reducing product-improvement dollars was estimated. This exercise resulted in modest evidence supporting the hypothesis. But problems in estimating the CER suggested that the magnitude (and statistical significance) of the effect have been understated; more research is needed on this question. Using the CER as estimated, a hypothetical investment of $20 million in cost-reducing product improvement would be recouped only after a production run of between 500 and 600 moderately large engines (for example, $500,000 at the 100th unit).

New product innovation and product improvement are both subject to varying degrees of uncertainty, as is the case for any form of R&D. To test if either is inherently less uncertain, two equations were estimated to predict R&D costs for the development of jet engines--one equation by new development programs and one by product-improvement programs. The standard errors of the estimates of these two equations, which measure the *percentage* uncertainty in these R&D costs, were found to be statistically the same. Product improvement, one must conclude, is not inherently less uncertain with respect to cost. But since product-improvement programs generally involve substantially fewer resources per unit of time, the *dollar* risk of product-improvement R&D is several times smaller, even though the percentage risk is the same.

Thus, product improvement seems to be a way of acquiring modest technological advances at modest cost (with a resultant decrease in the total risk) as well as a technique for reducing unit costs of production hardware.

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CONTENTS

I. INTRODUCTION

For some time now there has been considerable interest in the economics of technological change and, in particular, the role of research and development in bringing about such change. Virtually all of the quantitative work in this area has dealt with the process of new product innovation or of military R&D leading to a new and advanced weapon system.[1]

However, an area of R&D activity, largely ignored, that is often as important as new product R&D is R&D directed at improving an existing object, often known as product-improvement R&D. This study focuses on the process of product improvement as an integral phase of technological change and the implications of doing product improvement for weapon acquisition strategies.

Procurement in this study refers to the acquisition of a new weapon system designed to perform a given mission. Prior to procurement, the ambiguous activity called development often must take place.

Development is conceptually difficult to define, but the National Science Foundation describes it as "the systematic use of the knowledge and understanding gained from research, directed toward the production of useful materials, devices, systems, or methods, including design and development of prototypes and processes."[2]

Military product improvement refers to the process of modifying existing weapon systems to meet a newly defined mission, or to extend a mission envelope or system capability. In the private sector, product

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[1] See, for example, A. W. Marshall and W. H. Meckling, "The Predictability of Costs, Time, and Success of Development," in *The Rate and Direction of Inventive Activity*, NBER Report, Princeton University Press, 1962: also M. J. Peck and F. Scherer, *The Weapons Acquisition Process*, Harvard University Press, 1961; or more recently, J. Rapoport, "Product Innovation: Time, Cost, and Time-Cost Tradeoffs," Ph.D. Dissertation, University of Pennsylvania, 1970; and Samuel Wagner, "An Empirical Study of Cost, Time, Outcome, and Predictability of Industrial R&D," Ph.D. Dissertation, University of Pennsylvania, 1971.

[2] National Science Foundation, *Federal Funds for Research, Development and Other Scientific Activities, Fiscal Years 1965, 1966, and 1967*, Volume XV, Washington, D.C., 1966.

improvement refers to the process of modifying an existing good or service to increase its usefulness (shift the demand curve up). On the production side, the modification of existing equipment or techniques to lower the cost of a good or service (shift the supply curve down) is also product improvement, although this activity is often referred to in the literature as "process improvement."

Both product and process improvement are forms of technological change. Such changes are not costless shifts from one state of knowledge to another, as neoclassical economic theory sometimes seems to suggest; resources must be devoted to research and development to achieve product improvement in the form of, say, greater performance.

The validity of several conjectures about product improvement that have been at least alluded to in the R&D literature are tested quantitatively using data from product-improvement programs involving U.S. turbine engines developed for military purposes over the past 30 years. These product-improvement programs usually begin after an engine has already qualified for use in manned systems;[1] in the case of jet engines, between one-half and three-fourths of all development money is spent after the engine exists in the form of usable hardware. That as much or more is often spent during the product-improvement phase as during the initial R&D phase suggests that product improvement could profitably be the subject of more empirical work than has been done.

The option to do product-improvement R&D and modification has far ranging implications for the weapon aquisition process, particularly since the armed services will be faced with severely constrained budgets in the 1970s. At the same time, it seems likely that the costs of *new* weapon systems will be rising as weapon planners seek to take advantage of state-of-the-art technology. It is improbable that current weapon procurement procedures can be made compatible with austere budgets; alternative procedures, strategies, and philosophies will have to be adopted.

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[1] This benchmark is called the Model Qualification Test (MQT) and is also known as the 150 hr. test.

One alternative to the acquisition of wholly new systems is to design systems to accept product-improvement modifications and to make those modifications as various threats materialize. By doing so, one may hope to slow down the rate of military obsolescence. Abstracting from the institutional complexities that affect defense decisionmaking, a decision on product improvement versus new development and procurement ought to come from an analysis based on the same economic criterion, the minimization of cost for a given level of effectiveness (or any equivalent formulation).

Despite this, new R&D (and procurement) and product improvement are typically treated as separate and unrelated activities. Among the several reasons for this are the separation of the relevant decisionmaking agencies and separation of the events in time.

Often the decisions in these two areas are the responsibility of different authorities. For example, in the Air Force, the Air Force Systems Command is usually responsible for the development and initial procurement of a new weapon system, but the product-improvement phase is sometimes the responsibility of the Air Force Logistics Command. Such a separation can result in participants acting as if the life-cycle of a weapon system begins and ends with that command, causing, among other things, a non-optimal allocation of overall defense resources. Part of the responsibility lies with civilian agencies: for example, components of the Office of the Secretary of Defense (OSD) are active participants in the R&D and procurement process.

Separation of the two decisions in time also contributes to the idea of independence. In many cases, short-sightedness on the part of weapon system designers with respect to possible technological advances and enemy countermeasures has led to more new procurements than might have been necessary if product improvement were viewed as an integral part of the acquisitions process.

In discussing product improvement for jet engines, we need a benchmark event to serve to distinguish between the initial development and the product-improvement program. The benchmark event we shall take is that of the MQT, which is probably the single most important event in an engine development program. The MQT is a test in which an engine must run continuously for 150 hours, although current practices make it imperative that an engine undergo between 10 and 12 thousand hours of testing before attempting the MQT.

The MQT is not the only benchmark event in an engine development program. The date of first flight marks the first time the engine is actually operated in an aircraft. The Preliminary Flight Rating Test (PFRT) is a *50 hour* endurance test and generally demonstrates technical feasibility of the design. The MQT, however, is the final test before installation in production aircraft for operational use; usually an engine goes into significant practical use within months of its MQT.

Most engines that pass the MQT and have moderate production runs usually undergo some form of post-MQT development, also known as the product-improvement program. Typically a product-improvement program has as its objective the development of an improved version with a specific application in mind. This new version is usually designated by a new dash number, for example, the J79-15. Under current conventions, even dash numbers are reserved for the Navy and odd dash numbers are reserved for the Air Force.

The term "product-improvement" is unfortunate since it implies that only the performance side of the engine is given attention. My contention is that the activities that go on during the product-improvement program can be put into *three* categories. The first of these I have called *performance improvement*. Here the bundle of parameters or attributes that contribute to the overall performance of a mission is improved. For example, since maneuverability is highly valued in fighters, and thrust and maneuverability are highly related, more thrust from a fighter engine is often sought in a product-improvement program emphasizing performance advances. Some engines have undergone substantial "thrust growth," such as the J52's nearly 50 percent increase in thrust, or the J79's 36 percent.

The second area of interest in an engine product-improvement program I have called the "cost-reducing development" or, in a word, *producibility*. Here development funds are spent in order to lower the cost of manufacturing. There is an obvious tradeoff between the pre-MQT development effort and the post-MQT program. Money can be spent in the initial development program to achieve a lower production cost, but if the maintenance of a development schedule is important, often the production cost implication of a particular design will be relegated to the background and the problem of reducing costs left to the product-improvement program.

The third category is *maintainability and reliability* and the correction of Flight Revealed Deficiencies (FRD). Again there is a tradeoff between pre- and post-MQT development efforts. Often initial development contracts are weak in their specification of field maintainability and reliability levels. Corrections of the problem areas are consequently left to the product-improvement program. This fact has been recognized, and since 1968 separate funding by the Navy and Air Force for work on engine maintainability and reliability problems has been set up under the title Component Improvement Programs (CIP). Usually the objective of work done under the CIP is to increase the time between overhauls, and this is accomplished by engineering longer lasting parts for the engine. This aspect of product improvement is cost reducing also, but it is directed at operating costs, not production costs.

In Section II certain conjectures about the performance and technological aspects of product improvement are tested using multiple regression techniques and data from U.S. aircraft turbine engines. In Section III I attempt to identify another direction for product improvement, production cost reduction. In a departure from traditional learning curve theory, I attempted to distinguish between inadvertent learning (which is essentially costless) and a deliberate attempt to reduce costs by committing R&D funds toward that goal.

In Section IV, the uncertainty of production-improvement R&D is compared with new product R&D, and the relative costs explored of making product-improvement modifications. Section V is a discussion of the policy implications for weapon acquisition strategies.

Examples and insights into the product-improvement process in related private sector industries (petroleum refining and civil aviation) are presented in Appendix A for the interested reader.

II. PRODUCT-IMPROVEMENT ACTIVITY IN U.S. JET ENGINES--TECHNOLOGY AND PERFORMANCE IMPROVEMENT

Little is really known about the product-improvement process. How is product-improvement R&D different from new product R&D? How is the "object" changed during product improvement? What does product-improvement R&D cost and how does this compare with new product R&D? Is product-improvement R&D really less uncertain than new product R&D?

Several conjectures about product improvement are tested empirically with reference to U.S. jet engines: First, I seek to show how product improvement alters the "level of technology" of a jet engine, and this change characterizes product-improvement R&D as opposed to new product R&D. Second, to attack the same problem from the cost side, the indirect production function, ϕ (X),[1] is estimated for performance improvement (in particular thrust growth) in jet engines and then the hypothesis is tested that this function is concave. Concavity of this function satisfies one intuition about product improvement--namely, that product-improvement activity is subject to diminishing returns. Concavity also guarantees that an optimal program of R&D spending exists.[2]

U.S. jet engines were selected for this study of product improvement for three reasons. First, there has been a strong technological trend in evidence over the past 30 years. This means that a sample taken from different time periods would contain engines embodying rather different "levels of technology," and results would be strengthened by not being confined to any one "technological level." Second, there has been a tradition of doing product-improvement R&D on jet

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[1] ϕ (X) is really an abbreviation for ϕ $(p_1,\ldots,p_n,X)$ where p_i is the price of the ith factor of production in the product-improvement process. ϕ (X) is the maximum output achievable with expenditure X and factor prices $p_1,\ldots,p_n$ and hence is just an indirect production function with constant factor prices implicit.

[2] For more detail, see Robert Shishko, "An Optimal Control Model of Product-Improvement R&D," P-4668, The Rand Corporation, July 1971.

engines. Numerous engines have been improved and re-improved. Third, there appears to be an adequate data base. Jet engines can be characterized on the basis of measurable technical and performance parameters, and these parameters are available for almost all engines, whether new or product-improved versions. Costs of initial and product-improvement R&D are also available (though not necessarily readily); and there is a common benchmark event for all initial and product-improvement R&D programs. That benchmark event, already noted, is the Model Qualification Test.

That there has been steady, and, qualitatively speaking, strong technological progress since the first use of a jet (turbine engine) to power an aircraft can be seen in Table 1. This table summarizes the major technological advances since the early 1940s as well as the U.S. companies that have been in the jet engine field in each period.

A HISTORY OF TECHNOLOGICAL ADVANCES IN U.S. JET ENGINES[1]

Frank Whittle, an RAF officer who had advocated the use of turbojets in aircraft as early as 1929, succeeded in developing a turbojet engine and conducting a bench test in 1937. The American aircraft turbine engine industry got its start when General Electric made a number of changes in the original Whittle design. The General Electric design, the 1-A, first flew in a P-59A on October 2, 1942. This engine featured a single centrifugal-stage compressor.

Almost concurrently the Navy began working with Westinghouse to develop a greatly improved and quite different turbojet. This engine utilized a multi-stage, axial-flow compressor, and as the J30 it was the first Navy jet engine to be built in quantity. The advantage of axial-flow compressors over centrifugal for aircraft was that additional stages could be added to the axial to increase the compressor pressure ratio and achieve better fuel consumption. However, the stacking of

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[1] This section is an abbreviated version of a history of turbine engine technology appearing in Arthur J. Alexander and J. R. Nelson, *Measuring Technological Change: Aircraft Turbine Engines*, R-1017-ARPA/PR, The Rand Corporation, May 1972.

Table 1

TURBINE ENGINE TECHNOLOGY HISTORY

Period	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
Trends in engineering development	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 and 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 and integration Increasing sophistication of development Commercial technology and requirements becoming as advanced as military	High thrust to 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

Source: A. J. Alexander and J. R. Nelson, *Measuring Technological Change: Aircraft Turbine Engines*, R-1017-ARPA/PR, The Rand Corporation, Santa Monica, May 1972, p. 12.

centrifugal stages was not considered practical.[1] The demand for engines of higher thrust led to the development of the J33, a centrifugal-flow engine from G.E., and the J34, an axial-flow engine from Westinghouse. These were the first large-scale production engines.

The problem of achieving higher compressor pressure ratios was tackled by Pratt & Whitney in the late 1940s in a novel and radical way. One of their designs, later incorporated into the very successful J57, involved an axial-flow dual-rotor compressor. This compressor consisted of concentric shafts, with a number of compressor stages on each revolving at different speeds to improve the stage matching characteristics throughout the compressor. This system allowed a compressor pressure ratio in excess of 10, resulting in a lower specific fuel consumption (SFC).

During this same period, higher thrust was still the predominating requirement. Consequently, augmentation was introduced, first with water and alcohol and later with an afterburner.

Early attempts to harness turbopower to a propeller were more difficult than anticipated, primarily because of the problems encountered in finding a reliable gear box and propeller combination. Some early successes included Allison's T38 and T40, from which valuable experience was gained and later applied to the very successful T56.

The early 1950s saw the beginning of engine designs that are still in use today. G.E.'s J79 was capable of sustained supersonic flight up through Mach 2. The J79 contained a variable stator (vanes), axial-flow compressor, which allowed high pressure ratios to be obtained using a single, multi-stage rotor. During this period, the axial-flow turbojet prevailed as the best choice for fighters, bombers, and unmanned applications, while turboprop or turboshaft engines were used for transports and helicopters.

Turbines were still uncooled, but advances in materials allowed temperatures in the compressor and turbine to increase about 200 degrees. Thrust-to-weight ratios improved from values around two in the early 1940s to around four in the early 1950s.

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[1] The centrifugal compressor appeared to have a limit on the pressure ratios of about four to five for a single stage.

The late 1950s saw two major innovations. First, air-cooled turbines allowed temperatures in excess of 2000° F and substantially improved engines designed for Mach 3, such as Pratt & Whitney's J58 and G.E.'s J93. Second, the highly efficient turbofan engine, such as the TF33, was introduced for subsonic flight.

By the early 1960s, the turbofan began to emerge as the preferred engine for subsonic and supersonic flight through Mach 2.[1] Substantial improvements had been made in materials and cooled turbine technology. Titanium was replacing aluminum in the cooler parts of the engine, while even higher strength superalloys were being developed for the "hot" sections. Design and manufacturing techniques for producing cooled turbine stator and rotor parts were improved. The transonic compressor began to show considerable promise during this time. Thrust-to-weight ratios on the order of six and pressure ratios in the range of 15 to 20 were possible.

In the late 1960s, the high-bypass turbofan made its appearance. The TF39 high-bypass turbofan allowed improvements in military airlift technology (the C-5), while Pratt & Whitney's JT9D (Boeing 747) and G.E.'s CF6 (Douglas DC-10) allowed corresponding improvements in the commercial field. By this period, turbine inlet temperatures in excess of 2300° F and pressure ratios exceeding 20 were achieved. These advances were made possible by the advent of new composite materials and improved component performance, and these trends are continuing into the early 1970s.

TECHNOLOGICAL PROGRESS IN MILITARY JET ENGINES-- A MULTIPLE REGRESSION ANALYSIS

The methodology of multiple regression analysis will allow comparison of the "technological level" embodied in the earliest operational version of a jet engine with its most recent product-improved version. Clearly, the qualitative impressions about technological advance that were conveyed in the last section and that formed the basis of Table 1 are insufficient.

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[1] See Appendix A for a brief history of the adoption of turbofans in commercial jets.

What *is* needed is a way of indexing engines in a consistent fashion over a continuous indexing set representing different *vintages*. Using such a technique, a later vintage is deemed to embody a greater "technological level." In other words, a real number, v, is assigned to each possible position of a technological possibilities frontier (t.p.f.), representing the combination of engine parameters achievable at a point in time.

In equation (1), the function f represents the t.p.f. at time t.

$$f(P_1(t), P_2(t),\ldots,P_n(t)) = v \qquad (1)$$

where $P_1(t),\ldots,P_n(t)$ is a set of performance parameters of an engine developed at time t.[1]

Consider two points in time, t_1 and t_2. At time t_1, performance parameters $P_1(t_1)$ $P_2(t_1),\ldots,P_n(t_1)$ are observed. The function f evaluated at $P_1(t_1)$, $P_2(t_1),\ldots,P_n(t_1)$ is v_1. Suppose at time t_2, $P_1(t_2),\ldots,P_n(t_2)$ is observed, and the function f evaluated at $P_1(t_2),\ldots,P_n(t_2)$ is v_2. Then an engine with performance characteristics $P_1(t_2),\ldots,P_n(t_2)$ can be said to have a greater technological level or to be of a later vintage than an engine with performance characteristics $P_1(t_1),\ldots,P_n(t_1)$, if and only if $v_2 > v_1$. It follows that two engines satisfying equation (1) with v held constant are deemed to be of the same vintage and consequently embody the same technological level. Equation (1) thus presents an *ordinal* index of technology. This means that although one engine is more technically advanced than another, by how much is unknown. For example, an engine with an index of 100 is not necessarily twice as advanced as an engine with an index of 50. The ordinality property also means that any statement made to the effect that one engine is more advanced than another based on one index will also be true for any other index that is a monotonic transformation of the first index. In mathematical terms, $f(P_1,\ldots,P_n) > f(P_1',\ldots,P_n')$ implies $\Psi(f(P_1,\ldots,P_n)) > \Psi(f(P_1',\ldots,P_n'))$ for any Ψ such that $\Psi' > 0$.

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[1] By defining the technological level in terms of performance parameters, more weight is put on outputs than inputs. Implicitly users are assumed to be more interested in thrust, fuel consumption, and so on than how the performance is achieved.

Data collected on U.S. jet engine performance levels and knowledge of the date on which the performance levels were achieved permitted estimation of a function, f, using multiple regression techniques. Each observation consisted of a vector of performance variables of a military jet engine developed in the last 30 years and the dates of various benchmark events in the engine's development history. The choice of the dependent variable presented a problem. It was assumed that each engine developed for military purposes was at or near the "state of the art"--that is, the technological possibilities frontier--and that this state of the art was advancing monotonically. Another way of expressing this last assumption is to say that development funds at least sufficient to preserve R&D results are being spent in the turbine engine area. These assumptions then allowed the value of the dependent variable to be assigned based on the calendar time of a particular event in the engine's development history.

It was felt that the dependent variable should be tied to the date of the Model Qualification Test, because (1) the MQT, an endurance test of 150 hours, more truly represented technology than a more dramatic but less reliable test of an engine's ability to perform, and (2) the MQT is a common and specific benchmark event for all engines that go into production aircraft. The dependent variable that was chosen was the quarter in which the MQT was passed, with one being the fourth quarter of 1942 when the first U.S. jet engine was flown. Because it was felt that the coefficients of $P_1,\ldots,P_n$ should not be affected by the choice of origin, a restriction was imposed on the form of f, namely that shifting the starting point of the dependent variable n quarters shifted the function $f(P_1,P_2,\ldots,P_n)$ n quarters for all values of $P_1,P_2,\ldots,P_n$.

Two forms for the function f satisfying this restriction were estimated. These were the linear form and semi-logarithmic form:

$$v = \alpha_0 + \sum_i \alpha_i P_i(t) \qquad (1a)$$

and

$$v = \beta_0 + \sum_i \beta_i \ln P_i(t) \qquad (1b)$$

respectively.

Both of these forms have the property that along a ray from the origin the marginal rate of transformation remains constant. To prove this, we first note that equations (1a) and (1b) both satisfy a generalized homothecity property:

$$v(\lambda P) = \xi(\lambda)\, v(P) + \delta(\lambda) \tag{2}$$

where $P = (P_1, P_2, \ldots, P_n)$. From this it follows that

$$\frac{\partial v(\lambda P)}{\partial P_i} = \xi(\lambda)\, \frac{\partial v(P)}{\partial P_i} \tag{3}$$

and hence

$$\frac{\dfrac{\partial v(\lambda P)}{\partial P_i}}{\dfrac{\partial v(\lambda P)}{\partial P_j}} = \frac{\dfrac{\partial v(P)}{\partial P_i}}{\dfrac{\partial v(P)}{\partial P_j}} \tag{4}$$

This property implies that technological change is neutral with respect to equal percentage changes in two performance variables.

A further restriction was imposed in regard to the suitability of the estimated function f; the signs of the estimated coefficients, either $\hat{\alpha}_i$ or $\hat{\beta}_i$ should be in accordance with *a priori* notions. Why this restriction is reasonable can be seen by differentiating equation (1a) or (1b) with respect to time. For example, differentiating (1b) yields

$$1 = \sum_i \beta_i \frac{1}{P_i} \frac{dP_i}{dt} \tag{5}$$

or

$$\frac{1}{\beta_i} = \frac{1}{P_i} \frac{\partial P_i}{\partial t} \Big|_{\substack{P_j \text{ constant} \\ i \neq j}} = \frac{\dot{P}_i}{P_i} \Big| \text{cet. par.} \tag{6}$$

Thus if we have an *a priori* notion as to the sign of $\dot{P}_i/P_i\,|$cet. par., the sign of β_i must be the same.

Compare this with the single-parameter equation involving P_i:

$$v = b_0 + b_i \ln P_i$$

$$\frac{1}{b_i} = \frac{1}{P_i} \frac{dP_i}{dt} = \frac{\dot{P}_i}{P_i} \Big| \text{mut. mutandis} \tag{7}$$

The sign of $\dot{P}_i/P_i|$mut. mutandis may be ambiguous. Indeed, in order to place a meaningful restriction on the sign of an estimated coefficient, that sign must remain stable. In particular, the sign of a coefficient must be independent of the choice of origin of the equation, which again leads to the choice of the semi-logarithmic or linear forms for estimating equation (1).

The sample from which equation (1) was estimated comprised 35 U.S. turbojet and turbofan engines from the early 1940s to the late 1960s. Table 2 shows which engines were included in the sample. These engines represented primary data points in that if an engine had several models, for example, with or without afterburner, only the first version to pass the MQT was used as the representative technological level.[1] The performance data used in estimating equation (1) appear in Appendix B.

Table 3 shows the variables considered in estimating equation (1). Often alternative measures of the same basic variable were available. For example, thrust might have been measured at its maximum value at sea level, at its maximum value at altitude, at its cruise value, or with augmentation (that is, afterburner). Generally, statistical results were strongest when maximum thrust, dynamic pressure, and total pressure were chosen. The criterion for choosing among the equations satisfying the two previously mentioned restrictions was to select the equation(s) having the lowest standard error.

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[1] Certain engines in the technology data base (Table 2) have not technically speaking passed a man-rated 150-hr MQT. The J44, J97, and J100 fall into this category. In addition, the J52 and J85 MQT dates in the sample of original engines (though not in the product-improvement engine data base) correspond to the less stringent non-man-rated 150-hr MQT.

The MQT "date" for the J93 is the first flight of the B-70, which is about three years after the J93's PFRT. At the time of this study, the TF34 was on the verge of passing its MQT. I therefore included the TF34 and used the expected MQT quarter and performance characteristics.

The JT8D, JT9D, and CF6 are of course commercial derivatives of military engines. They were included in the sample in the belief that they were roughly state-of-the-art engines at the time of their appearance. Statistical tests confirmed this view. The MQT "date" for these engines was actually the date of the FAA certification, which is similar to a 150-hr MQT.

Table 2

TURBOJET AND TURBOFAN ENGINE DATA BASE

	Early 1940s	Late 1940s	Early 1950s	Late 1950s	Early 1960s	Late 1960s
Engine started and company	J30 W J31 GE J33 GE J34 W J35 GE	J40 W J42 P&W J44 F J46 W J47 GE J48 P&W J57 P&W J71 A J73 GE	J52 P&W J65 CW J69 C J75 P&W J79 GE	J58 P&W J60 P&W J85 GE J93 GE TF30 P&W TF33 P&W TF35 GE JT8D P&W	J97 GE J100 C TF37 GE TF41 A	TF34 GE TF39 GE JT9D P&W CF6 GE

A = Allison
C = Continental
CW = Curtiss Wright
F = Fairchild
GE = General Electric
P&W = Pratt & Whitney
W = Westinghouse

Table 3

VARIABLES CONSIDERED IN ESTIMATING TECHNOLOGICAL LEVEL

AIRFLOW = Total airflow through the engine; lbs/sec.

PRESSURE = Total pressure = QMAX x PR; lbs/ft^2.

QMAX = Maximum dynamic pressure; lbs/ft^2.

QCR = Cruise dynamic pressure; lbs/ft^2.

SFCMIL = Specific fuel consumption at military thrust, sea level static; (lb/hr)/lb thrust.

SFCCR = Specific fuel consumption at cruise.

TEMP = Turbine inlet temperature at maximum thrust, sea level static; degrees Rankine.

THRUSTMIL = Military thrust at sea level static; lbs.

THRUSTMAX = Maximum thrust at sea level static; lbs.

THRUSTCR = Cruise thrust; lbs.

WEIGHT = Engine weight; lbs.

PR = Engine pressure ratio.

LENGTH = Engine length; ft.

DENSITY = Engine weight/engine volume; lbs/ft^3.

T/A = Thrust/airflow; lbs/(lb/sec).

T/V = Thrust/engine volume; lbs/ft^3.

The "best" estimate of equation (1) was:[1]

$$\hat{v}_{MQT} = -872.36 + \underset{(16.96)}{113.85}\ \ell n\ \mathrm{TEMP} - \underset{(4.77)}{13.97}\ \ell n\ \mathrm{SFCMIL} - \underset{(4.39)}{32.19}\ \ell n\ \mathrm{WEIGHT}$$

$$+ \underset{(5.77)}{26.88}\ \ell n\ \mathrm{THRUSTMAX} + \underset{(3.31)}{6.89}\ \ell n\ \mathrm{PRESSURE} \qquad (8)$$

$$R^2 = .95 \qquad F(5,29) = 109.74 \qquad S.E. = 7.72$$

An alternative equation in semi-logarithmic form nearly as good as the above expression was

$$\hat{v}_{MQT} = -942.90 + \underset{(17.15)}{122.54}\ \ell n\ \mathrm{TEMP} - \underset{(5.58)}{20.17}\ \ell n\ \mathrm{SFCMIL} - \underset{(4.32)}{33.02}\ \ell n\ \mathrm{WEIGHT}$$

$$+ \underset{(5.55)}{28.34}\ \ell n\ \mathrm{THRUSTMAX} + \underset{(4.33)}{8.37}\ \ell n\ \mathrm{QMAX} \qquad (9)$$

$$R^2 = .95 \qquad F(5,29) = 107.67 \qquad S.E. = 7.79$$

Any conclusion based on this methodology of indexing technological levels (vintages) should be the same whether one specification of equation (1) or another (nearly as good) was used. Therefore, equations (8) and (9) were both carried through the analysis.

The "best" linear estimate of equation (1) was

$$\hat{v}_{MQT} = -48.15 + \underset{(.0119)}{.0666}\ \mathrm{TEMP} - \underset{(8.76)}{37.73}\ \mathrm{SFCMIL} - \underset{(.0031)}{.0105}\ \mathrm{WEIGHT}$$

$$+ \underset{(.0007)}{.0015}\ \mathrm{THRUSTMAX} + \underset{(.0045)}{.0091}\ \mathrm{QMAX} \qquad (10)$$

$$R^2 = .88 \qquad F(5,29) = 41.85 \qquad S.E. = 12.03$$

---

[1] Numbers in parentheses indicate standard errors of the coefficients. Let v_{MQT} be used to symbolize that the MQT date was chosen to determine vintage.

Technology trend equations (8)-(10) differ from those in Alexander and Nelson, R-1017, because of different sample coverage. The main difference is that here turboprop and turboshaft engines have been excluded since a sample containing only turbojets and turbofans was thought to be more appropriate for a study of product improvement.

Any differences in the predicted MQT date for an engine arising from the use of a technology trend equation in this study versus the analogous equations in R-1017 are statistically insignificant.

All three equations indexing the position of the t.p.f. were not pure performance equations. Turbine inlet temperature, a technical parameter, always appeared as a very significant explanatory variable, even after the major performance variables included were already in the estimated equation.[1] Temperature plays the key role in the thermodynamics of jet engines. Consequently, the attainment of higher temperatures has been a long-term goal of jet engine development programs. These higher temperatures have been one of the chief sources of improved performance as measured by the major performance parameters. However, a host of less important engine characteristics have not been taken into account in equations (8) through (10). Turbine inlet temperature may then serve as a proxy for these omitted variables. In other words, temperature acts as a "technical budget" from which expenditures can be made. The major expenditures go toward the major parameters, thrust, SFC, and so on, but they do not exhaust the budget. The residual explanatory power of temperature derives from its ability to act in place of the omitted parameters.

In all three equations the coefficients have the expected signs. Thrust, turbine inlet temperature, and total or maximum dynamic pressure have positive coefficients indicating growth over time holding other variables constant. Weight and SFC, being more highly valued as they get smaller, have negative coefficients indicating that they have fallen over time, other things being equal.

Figure 1 is a plot of the actual versus calculated values of v_{MQT} for the "best" semi-logarithmic equation, and Figure 2 is a plot of the "best" linear equation. The outer lines indicate the one standard error interval.

In an attempt to determine whether these equations changed significantly over time, the sample was split into equal halves and

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[1] The "best" pure performance equation was

$$\hat{v}_{MQT} = -79.84 - \underset{(7.40)}{19.26}\ \ell n\ \text{SFCMIL} - \underset{(6.27)}{44.44}\ \ell n\ \text{WEIGHT}$$

$$+ \underset{(8.15)}{43.83}\ \ell n\ \text{THRUSTMAX} + \underset{(5.16)}{9.55}\ \ell n\ \text{PRESSURE}$$

$$R^2 = .87 \qquad F(4,30) = 51.01 \qquad S.E. = 12.14$$

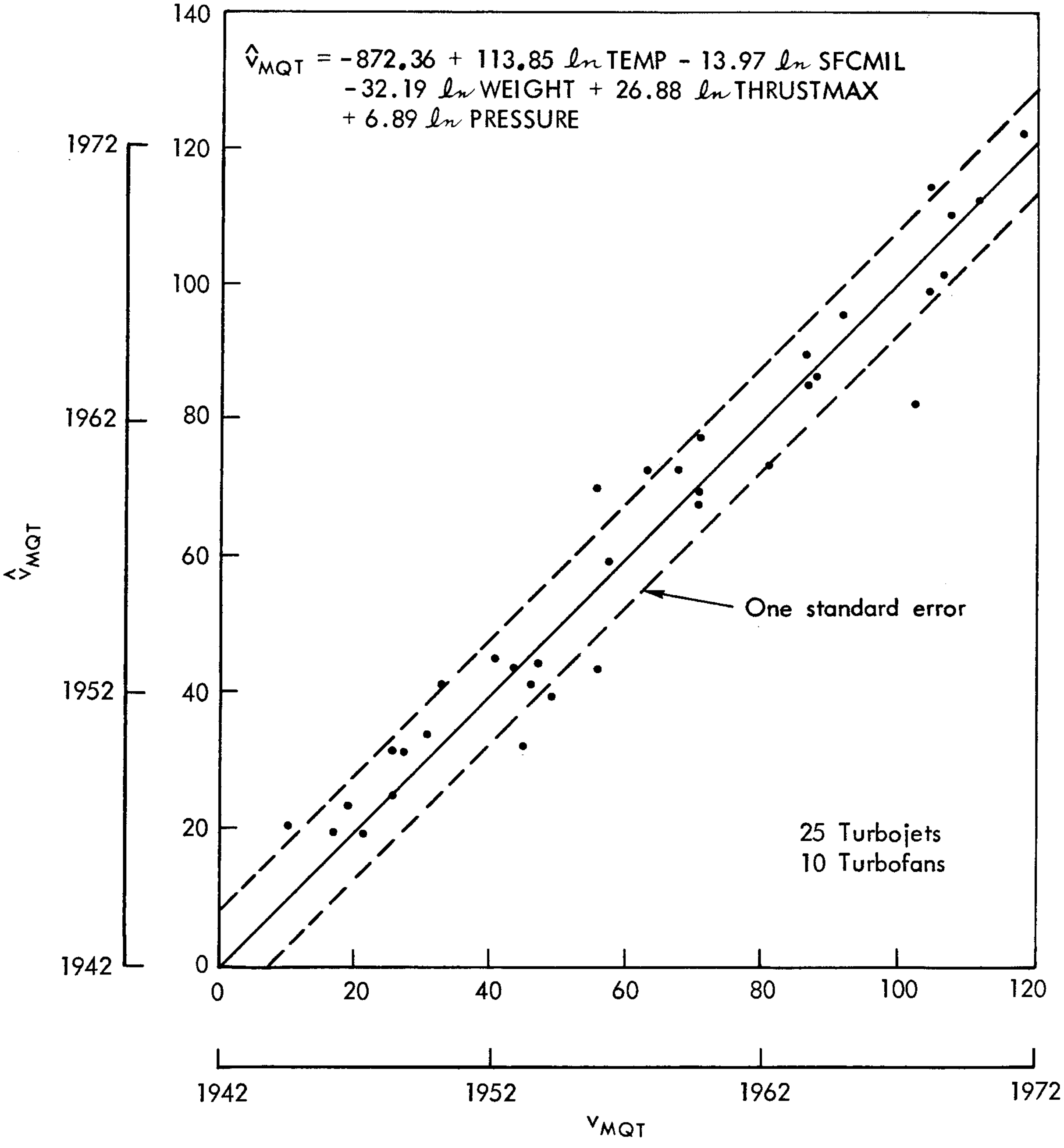

Fig. 1 — Best semilogarithmic equation for actual versus calculated values of v_{MQT} for original engines

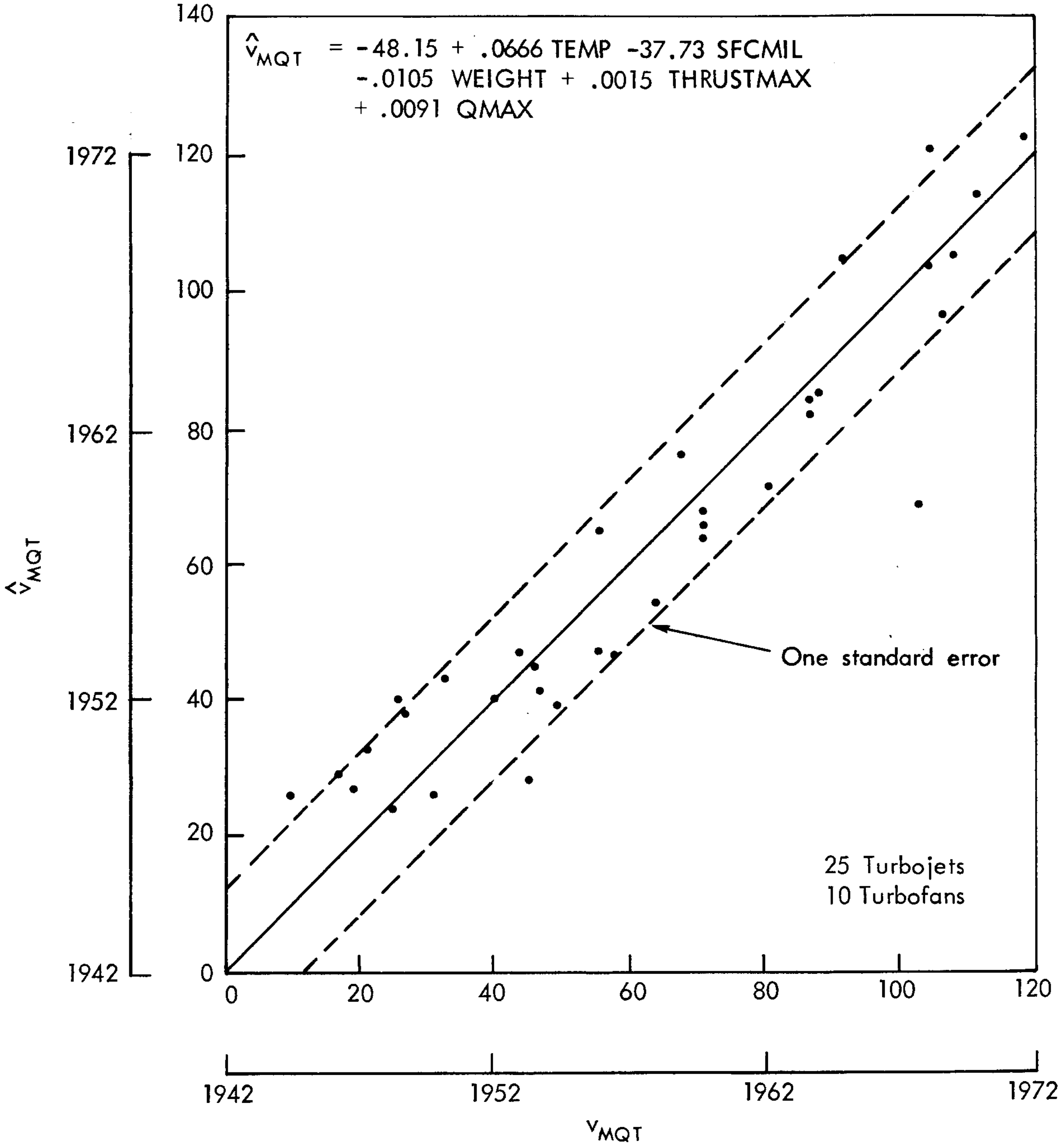

Fig. 2 — Best linear equation for actual versus calculated values of v_{MQT} for original engines

separate regressions were run for each subsample. Using the Chow F-test to determine if the two sets of coefficients were statistically different, it was found that for equations (8) and (9), the null hypothesis that both subsamples belong to the same regression model could not be rejected at the five percent level of significance. For equation (10), the null hypothesis could not be rejected at the one percent level of significance.[1] These results indicated that the semilogarithmic form was probably superior for prediction purposes.

The Chow F-test was also used to determine if there were any differences in the engines according to manufacturer--that is, General Electric versus Pratt & Whitney--and according to type--that is, turbojet versus turbofan. In each case no significant difference was found.

Equations (8) through (10) represent an index of technology derived from observations of primary engines. Suppose a primary engine is observed at time t_1 precisely on the technological possibilities frontier prevailing at that time. In terms of the index of technology, this primary engine lies right on the 45° line as shown on the right in Fig. 3. At some time t_2, the technological possibilities frontier has advanced, represented on the left in Fig. 3 as a shifting out of the frontier. A product-improvement version of the primary engine

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[1] Under the null hypothesis that both subsamples of observations belong to the same regression model, the ratio

$$\frac{Q_1-Q_2-Q_3}{p} \Bigg/ \frac{Q_2+Q_3}{n+m-2p} \text{ is distributed as } F(p,n+m-2p),$$

where

$Q_1 = \Sigma$ (residuals)^2 from the regression estimated by the combined sample of n+m observations, with n-p degrees of freedom,

$Q_2 = \Sigma$ (residuals)^2 from the regression estimated by the first subsample of n observations, with n-p degrees of freedom, and

$Q_3 = \Sigma$ (residuals)^2 from the regression estimated by the second subsample of m observations, with m-p degrees of freedom. For equation (8), the F(6,23) ratio was 0.60, and for equation (9) the F(6,23) ratio was 1.57. To interpret the later observations as coming from a different structure at the five percent level of significance, F would have to be at least 2.53. For equation (10), the F(6,23) ratio was 3.65. To make the same interpretation at the one percent level, F would have to be at least 3.71.

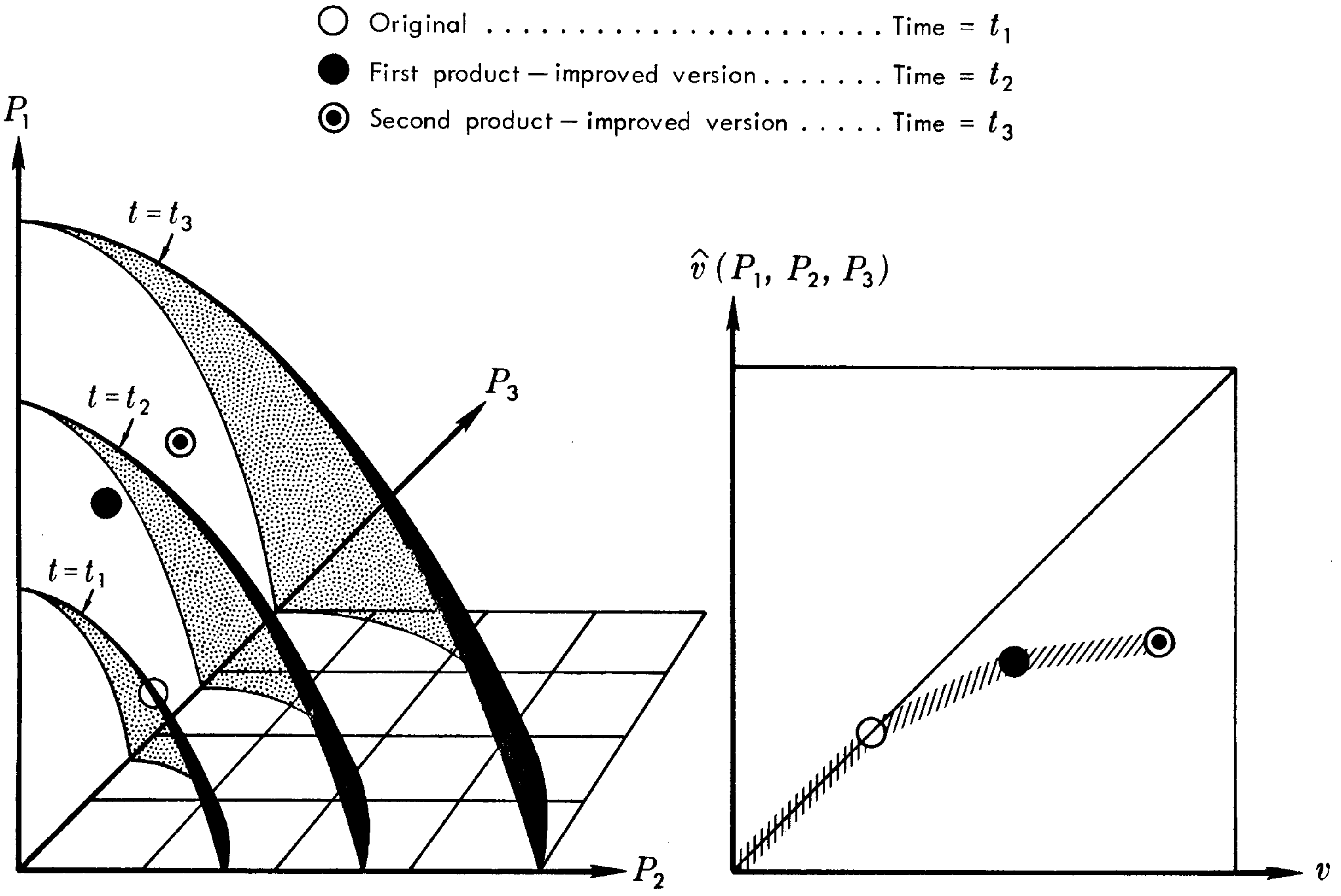

Fig. 3 — Technological change during product improvement

appearing at time t_2 might be expected to be more advanced than the primary engine but not so advanced as to be on the t.p.f. at time t_2. In any attempt to improve an existing engine, many features must remain frozen. This means that improvements are the result of constrained solutions to problems that arise in the product-improvement program. Thus one would expect a product-improvement engine to lie behind the frontier existing at the time of its appearance. In terms of the index of technology, there should be a "falling off" from the 45° line.

Referring again to Fig. 3, suppose at some time t_3 still later, the t.p.f. has "shifted out" even further, and a second product-improvement version makes its appearance. This second product-improvement version ought to lie ahead of the first product-improvement version, perhaps even ahead of the t.p.f. at time t_2 as shown, but even further behind the t.p.f. at time t_3. In terms of the index of technology, there should be a further falling off from the 45° line.

Of the original 35 turbojet and turbofan engines, 13 had major product-improvement versions. These 13 engines are listed in Table 4 and the data for these engines appear in Appendix C.

Table 4

DATA BASE FOR TURBOJET AND TURBOFAN ENGINES HAVING PRODUCT-IMPROVEMENT VERSIONS

J33	J52	J69	J79
J35	J57	J71	J85
J47	J60	J75	TF30
			TF33

Figure 4 is a plot of the actual versus calculated values of v_{MOT} for the 13 original engines and their most recent product-improvement versions. Equation (8) was used to compute $\hat{v}_{MOT}$. Figure 5 is a similar plot with equation (10) used to compute $\hat{v}_{MOT}$.

A cursory look at these figures suggests two things: first, there was an increase in the level of technology between a primary engine and its most recent product-improvement version; and second, the slope of the line connecting a primary engine with its most recent product-

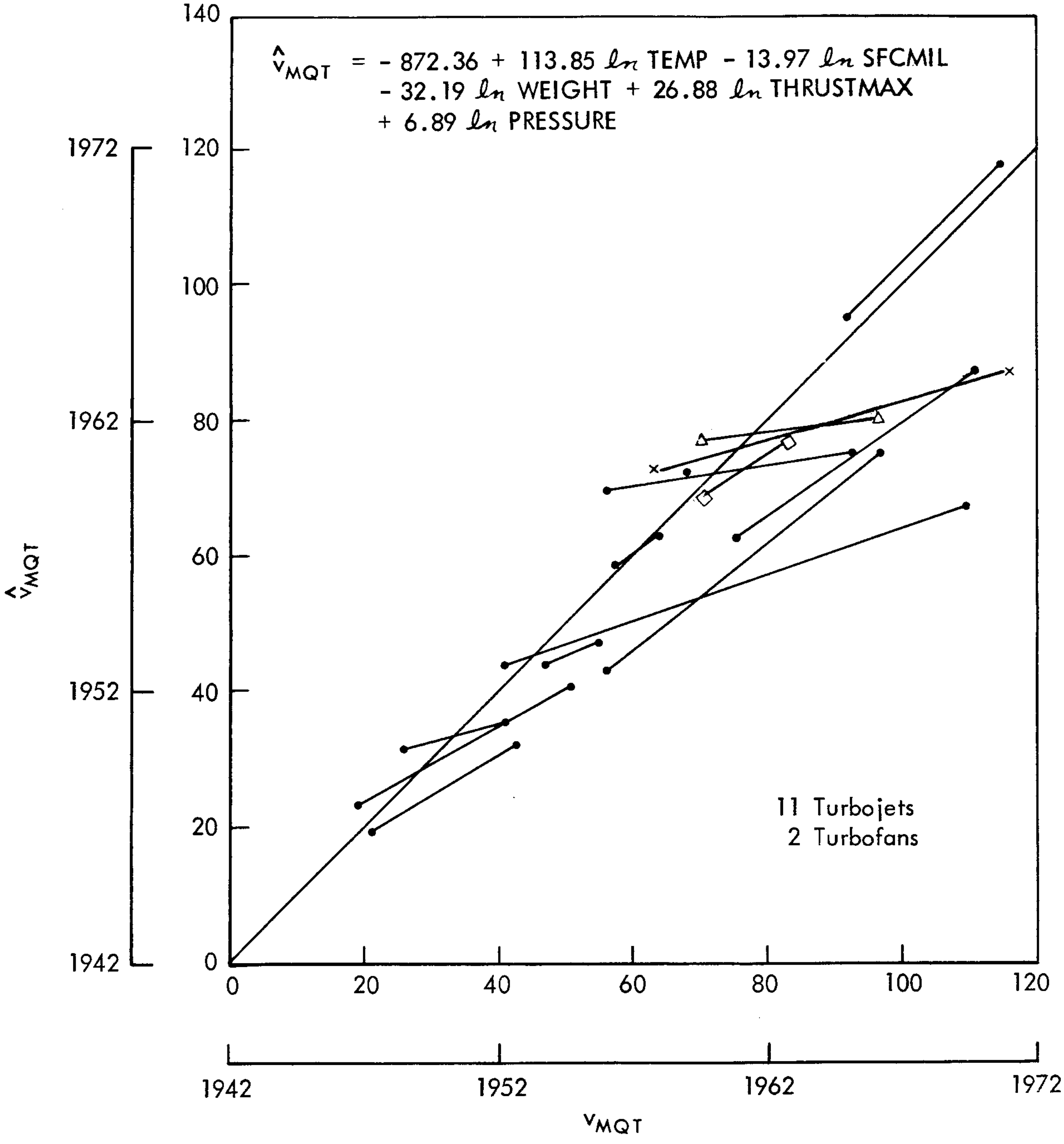

Fig. 4 — Best logarithmic equation for actual versus calculated values for v_{MQT} for product-improvement engines

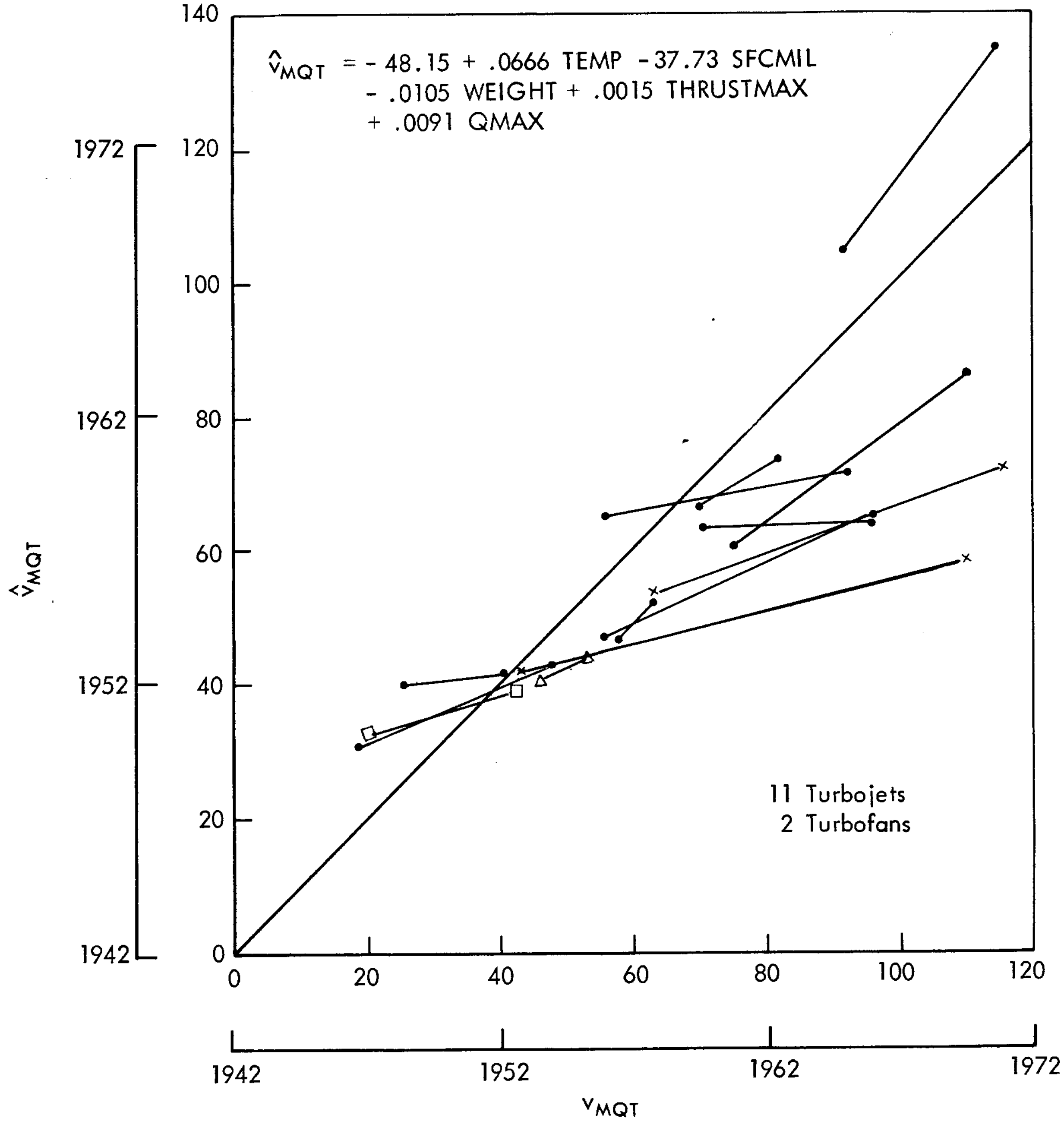

Fig. 5 — Best linear equation for actual versus calculated values for v_{MQT} for product-improvement engines

improvement version was in general less than 45°. These two observations conform exactly to expectations of what theory would say about a primary engine and its most advanced product-improvement version.

Why are these observations significant? If product-improvement is sufficient to keep pace with general changes in technology, then one would expect a slope of approximately one. If, on the other hand, product improvement could take advantage of only some of the available technology, then there should be a positive slope less than one.

It was possible to be more precise about these observations. To test the hypothesis that the slope α is positive but less than one, $\hat{v}_{MQT}$ (product-improvement version) - $\hat{v}_{MQT}$ (original version) was regressed on v_{MQT} (product-improvement version) - v_{MQT} (original version) with the intercept constrained to be zero; that is, the following equation was estimated for each way (equations (8) through (10)) of computing $\hat{v}_{MQT}$.

$$\hat{v}_{MQT}(\text{p.i.}) - \hat{v}_{MQT}(\text{orig.}) = \alpha\,[v_{MQT}(\text{p.i.}) - v_{MQT}(\text{orig.})] \quad (11)$$

Each pair consisting of the original engine and its most recent product-improvement version represented an observation.

Using equation (8) to compute $\hat{v}_{MQT}$, equation (11) was estimated to be:

$$\hat{v}_{MQT}(\text{p.i.}) - \hat{v}_{MQT}(\text{orig.}) = \underset{(.067)}{.428}\,[v_{MQT}(\text{p.i.}) - v_{MQT}(\text{orig.})] \quad (12)$$

$$R^2 = .32 \qquad \text{S.E.} = 8.12$$

The null hypothesis that α lies outside of the interval (0,1) was rejected at the .00005 significance level.

Using equation (9) to compute $\hat{v}_{MQT}$, equation (11) was estimated to be:

$$\hat{v}_{MQT}(\text{p.i.}) - \hat{v}_{MQT}(\text{orig.}) = \underset{(.065)}{.424}\,[v_{MQT}(\text{p.i.}) - v_{MQT}(\text{orig.})] \quad (13)$$

$$R^2 = .38 \qquad \text{S.E.} = 7.91$$

The null hypothesis that α lies outside the interval (0,1) was again rejected at the .00005 significance level.

Using equation (10) equation (11) was estimated to be:

$$\hat{v}_{MQT}(p.i.) - \hat{v}_{MQT}(orig.) = \underset{(.070)}{.361} \; [v_{MQT}(p.i.) - v_{MQT}(orig.)] \qquad (14)$$

$R^2 = .22$ S.E. = 8.46

and the null hypothesis that α lies outside (0,1) was rejected here too at the .0005 significance level.[1]

Although these results hold for the sample of product-improvement engines as a whole, there are individual engines for which the slope of the line connecting the original version with its latest product-improvement version is quite steep; in one such product-improvement program however, it was known that the average funding rate in constant 1969 dollars was about twice as great as during the original development program. What is the effect on the rate of advancement of the funding rate during the product-improvement program.

In Figure 6 the actual versus calculated values of v_{MQT} are plotted for several engines for which R&D expenditures over time were available. These engines are listed in Table 5.

Several of these engines, the J52, J57, J79, J85, and TF30, had major intermediate product-improvement versions. In this unadjusted form, it is difficult to confirm the pattern of technological growth hypothesized in Figure 3. Some allowance must be made for the fact that the slope of the line connecting one engine with a subsequent

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[1] In order to demonstrate that the estimate of α was not a function of the length of time between the appearance of an engine and the appearance of its product-improvement version, the slope

$$[\hat{v}_{MQT}(p.i.) - \hat{v}_{MQT}(orig.)] / [v_{MQT}(p.i.) - v_{MQT}(orig.)]$$

was regressed against

$$v_{MQT}(p.i.) - v_{MQT}(orig.)$$

using the 13 observations.
The following result was obtained when equation (8) was used to compute $\hat{v}_{MQT}$.

$$\alpha = .624 - \underset{(.00439)}{.00407} \; [v_{MQT}(p.i.) - v_{MQT}(orig.)]$$

$R^2 = .07$ F(1,11) = .86 S.E. = .276

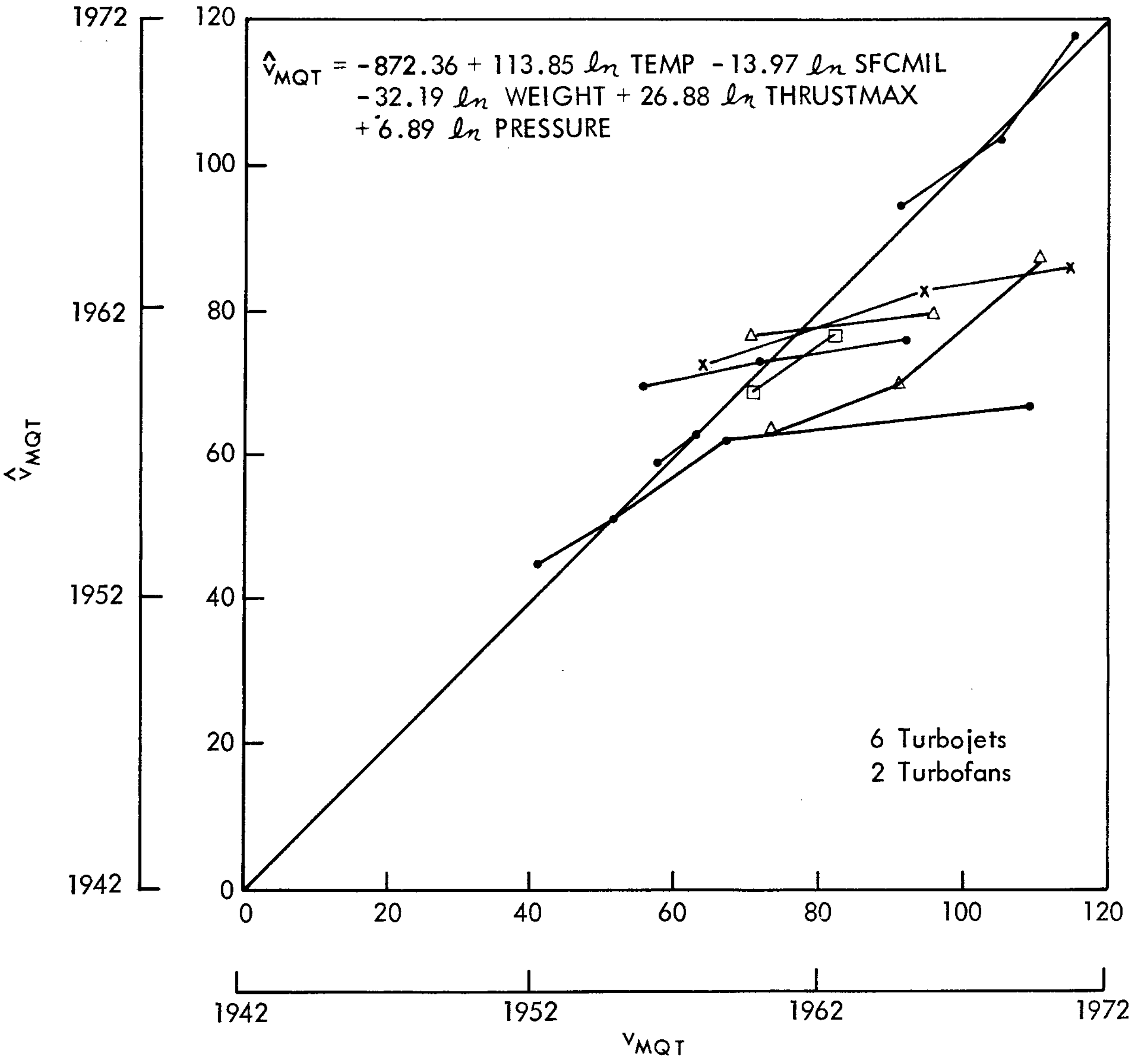

Fig. 6 — Actual versus calculated values of v_{MQT} for intermediate product-improvement engines unadjusted for funding rate

Table 5

DATA BASE FOR FUNDING RATE ADJUSTMENT

J52	J79
J57	J85
J60	TF30
J75	TF33

product-improvement version can be affected by the dollar resources poured into a product-improvement program in a given amount of time; the greater this funding rate, the steeper the slope.

In Figure 7, the funding rate is adjusted in a particular way in order to look at technological growth during product improvement controlling for the impact of differing funding rates during that phase of the program. This adjustment was made by assuming that the average rate of expenditure during the initial development program was maintained during the entire product-improvement program. In the construction of Figure 7, it was assumed that spending the same total dollars during an engine product-improvement program would produce an improved version of that engine with the same calculated technological level. The "adjusted actual" MQT was then calculated for each product-improvement version.[1]

This adjustment mechanism could be improved in at least two ways. First, it assumes a rather flat tradeoff of schedule and dollars in order to achieve a particular technological growth. A better understanding of the time-cost tradeoff could improve the adjustment if

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A t-statistic of .927 for the estimated coefficient indicated decisively that α was not a function the length of time between the original MQT date and product-improvement MQT date. Similar results were obtained when equations (9) and (10) were used to compute $\hat{v}_{MQT}$.

[1] Dividing the total dollars spent during a product-improvement program up to the time of the MQT of an improved version by the average rate of expenditure during the initial development program and adding that number of quarters to the quarter of the MQT of the original version gives the "adjusted actual" MQT of the product-improvement version. All dollar amounts and rates are in constant 1969 dollars. Note that this adjustment operates in the direction of stretching some programs but compressing others.

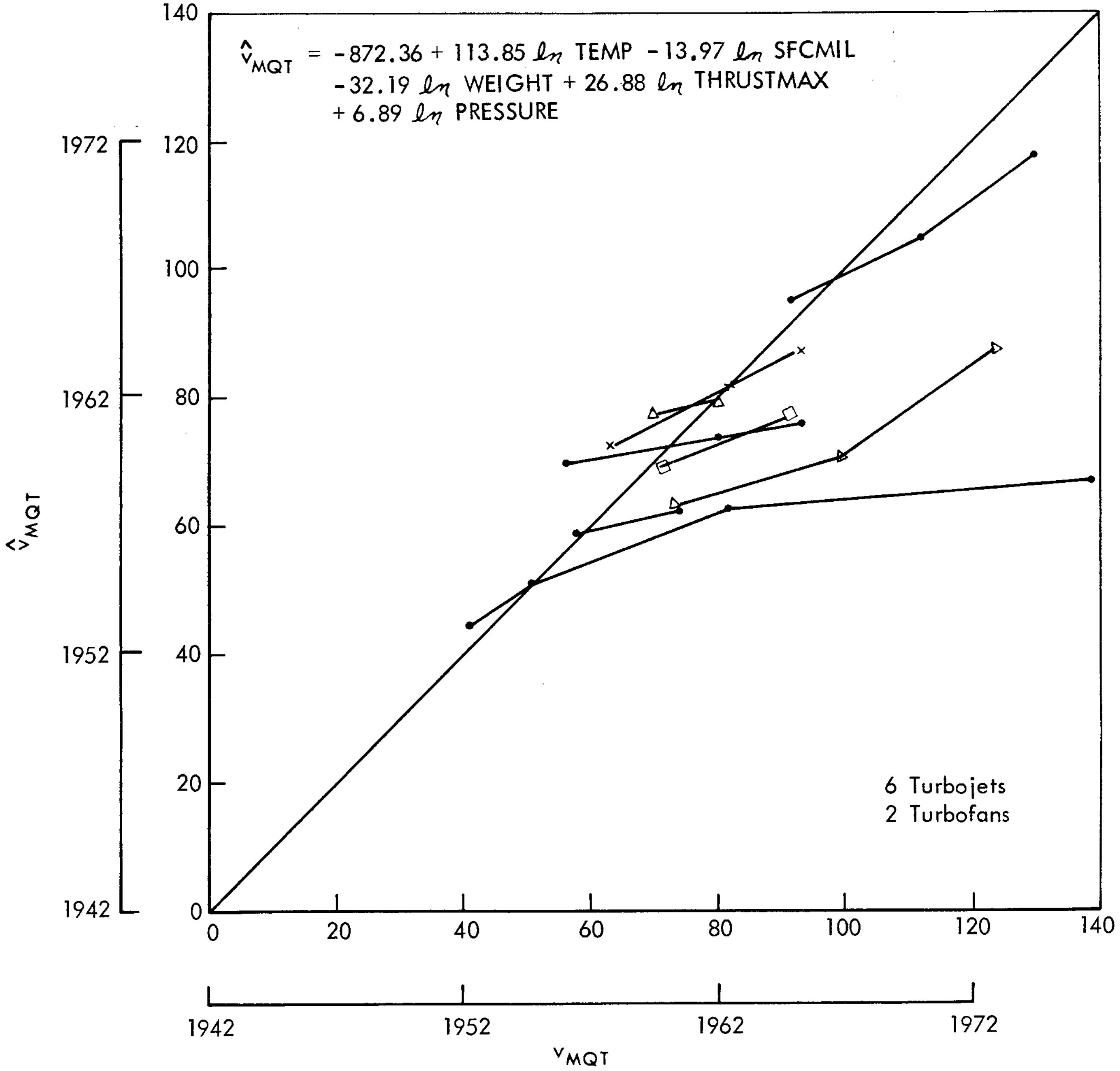

Fig. 7 — Actual versus calculated values of v_{MQT} for intermediate product-improvement engines adjusted for funding rate

this tradeoff is not reasonably flat within the range generally observed. Second, the adjustment implicitly assumes that product-improvement versions of engines are developed sequentially--one model is the object of R&D until it passes the MQT and then work on another model begins. In fact, of course, several advanced models may be developed simultaneously, as in the case of the TF30-408 and -100. By assuming sequential development, the adjustment is biased downward for the more advanced model if concurrent development actually took place.

Equation (11) can now be estimated taking into account the adjustment for funding rate to test the hypothesis that product improvement can take advantage of only some of the available technology; that is, that the slope α is positive but less than one. Using equation (8) to compute $\hat{v}_{MQT}$ and letting v^*_{MQT} be the "adjusted actual" MQT date, equation (11) was estimated:

$$\hat{v}_{MQT}(\text{p.i.}) - \hat{v}_{MQT}(\text{orig.}) = \underset{(.055)}{.311}\ [v^*_{MQT}(\text{p.i.}) - v_{MQT}(\text{orig.})] \qquad (15)$$

$$R^2 = .42 \qquad\qquad \text{S.E.} = 6.97$$

The null hypothesis that α lies outside of the integral (0,1) was rejected at the .0005 significance level.

Using equation (9) to compute $\hat{v}_{MQT}$, equation (11) was estimated:

$$\hat{v}_{MQT}(\text{p.i.}) - \hat{v}_{MQT}(\text{orig.}) = \underset{(.053)}{.306}\ [v^*_{MQT}(\text{p.i.}) - v_{MQT}(\text{orig.})] \qquad (16)$$

$$R^2 = .47 \qquad\qquad \text{S.E.} = 6.76$$

The null hypothesis that α lies outside the interval (0,1) was again rejected at the .0005 significance level.

Using equation (10), equation (11) was estimated:

$$\hat{v}_{MQT}(\text{p.i.}) - \hat{v}_{MQT}(\text{orig.}) = \underset{(.082)}{.305}\ [v^*_{MQT}(\text{p.i.}) - v_{MQT}(\text{orig.})] \qquad (17)$$

$$R^2 = .07 \qquad\qquad \text{S.E.} = 10.45$$

and the null hypothesis that α lies outside (0,1) was rejected here too at the .005 significance level.[1]

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[1] Regressing the slope α against the length of time between the appearance of its product-improvement version, with equation (8) used to compute α, yielded the following result:

Do these "adjusted" slopes differ significantly from the unadjusted estimates? Using equation (8) to compute technological level and assuming the covariance between the estimated coefficient in equation (12) and the estimated coefficient in equation (15) is zero, the answer is no. When equations (9) and (10) are used to compute technological level and the corresponding assumptions about the covariances are made,[1] the answer is the same.

These results strongly suggest that a product-improvement engine embodies a higher level of technology than its original version, but that the rate of improvement on average is such that ultimately a new engine will embody a higher level of technology. This was not unexpected. Some new technology can be incorporated into an existing engine, but to take advantage of all of the available technology, one must essentially "start from scratch."

This last point has a bearing on the economics literature of technological progress associated with the vintage approach to capital theory. With no "technological manna" falling from heaven, technological progress is captured only if new capital goods are added to the existing capital stock. This technological progress is *embodied* in new machines that are more productive than those previously built but that do not change the productivity of existing machines. Furthermore, machines unalterably embody the level of technology of their vintage. In other words, whatever the source of technological progress, once a machine is built, the cost of altering its level of technology is infinite.

$$\alpha = .382 - \underset{(.00234)}{.000557}\,[v^*_{MQT}(\text{p.i.}) - v_{MQT}(\text{orig.})]$$

$R^2 = .01$ $\quad F(1,6) = .06$ $\quad$ S.E. = .173

A t-statistic of .238 indicated that α is not simply a measure of the length of time between the original MQT date and the product-improvement MQT date. Similar results were obtained when equations (9) and (10) were used to compute α.

[1] A test of the equality of the estimated coefficients, i.e., α, in equations (12) and (15) yielded a t-statistic of 1.35. To reject the null hypothesis that the slopes are the same at the .05 significance level, the t-statistic would have to be at least 2.09. Similar results were obtained when the alternative equations were used.

In this section an index of technology is constructed based on new machines and applied to later versions of those machines. The technological level in fact was found to have been altered, though at a rate less than the long-run average experienced by new machines. Although the indexes of technology used are not indisputable, using the raw technical and performance data in constructing an index is both sensible and empirically fruitful. The next logical step is to ascertain just what it costs to alter the technological level of a machine.

ESTIMATING THE PERFORMANCE-IMPROVEMENT INDIRECT PRODUCTION FUNCTION, ϕ (X)

The thrust growth of an engine as a result of product improvement was estimated as a function of the cumulative dollars for performance improvement. Thrust growth was taken as the measure of performance improvement because there was a sufficiently large sample of engines for which greater thrust was the principal goal of the product-improvement program. *A priori* expectations about this function then represented testable hypotheses about the product-improvement process.

By assumption, all development money spent after the MQT of the original version of an engine was considered to be sustaining development or product-improvement money. The problem in estimating this function was that U.S. engine manufacturers do not keep track of product-improvement costs by the three functional categories. However, it was known when a particular product-improved version of an engine was first available by the date of its MQT. Data on its performance characteristics and the performance characteristics of its original (unimproved) version were also available. In addition, engine manufacturers had data on development costs by engine and by year.

The model of thrust growth that was tested is shown as:

$$\Delta P_t = e^{\gamma_0} P_0^{\gamma_1} X_t^{\gamma_2} \varepsilon_t \tag{18}$$

where

ΔP_t is the increase in maximum thrust in pounds at time t of an engine over its initial thrust, that is $\Delta P_t = P_t - P_0$,

P_0 is the maximum thrust in pounds of the original unimproved version of the engine.

X_t is the cumulative sustaining development in constant dollars spent on performance improvement up to time t,

ε_t is a random variable such that $\ell n\ \varepsilon_t \sim N(0,\sigma^2_{\ell n \varepsilon_t})$,

and γ_0, γ_1, γ_2 are constants such that

$0 < \gamma_1, \gamma_2 < 1.$

The condition that $0 < \gamma_2 < 1$ is just the statement that the function ϕ (X) is strictly concave. Consequently the model predicts that each increment to thrust becomes more difficult and more costly to achieve. The second condition that $0 < \gamma_1 < 1$ derives from the following considerations: for a given level of expenditure (that is, X constant), the greater the thrust of the original version, the larger the absolute increase in thrust in the product-improved version, but the smaller the percentage increase. Detailed studies of post-1968 engine product-improvement programs supported the hypothesis that for engines that undergo substantial thrust growth, a constant proportion, roughly 20 percent, of product-improvement funds (including product support and CIP funding) is spent on that effort. This additional piece of information is embodied in equation (19).

$$X_t = \eta(CSD_t) \tag{19}$$

CSD_t is the cumulative sustaining development in constant dollars up to time t, and $0 < \eta < 1$.

Combining equations (18) and (19) the following equation was estimated:

$$\Delta P_t = e^{\gamma_0} P_0^{\gamma_1} (\eta CSD_t)^{\gamma_2} \varepsilon_t \tag{20}$$

or in log-linear form:

$$\begin{aligned} \ell n\ \Delta P_t &= \gamma_0 + \gamma_2\ \ell n\ \eta + \gamma_1\ \ell n\ P_0 + \gamma_2\ \ell n\ CSD_t + \ell n\ \varepsilon_t \\ &= \gamma^*_0 + \gamma_1\ \ell n\ P_0 + \gamma_2\ \ell n\ CSD_t + \ell n\ \varepsilon_t \qquad (20') \end{aligned}$$

The data used in running this regression were based on eight engines, listed in Table 5, that have experienced substantial thrust growth. Three of those engines had four or more thrust growth versions.

√ As Figure 8 demonstrates, these three engines, which must remain unidentified because of the proprietary nature of the information contained in the figure, display rather similar thrust growth curves, the differences being accounted for primarily by differences in initial thrust. It was this somewhat remarkable similarity that bore out the choice of equation (20) or (20') as the functional form for the model of thrust growth. Naturally, certain adjustments were made to the raw numbers to make the data compatible and consistent with the proposed model. First, the annual expenditures on sustaining development were adjusted to 1969 dollars by using the price index in Table 6, which is based on the average hourly earnings of production workers in the aircraft industry.

Table 6

PRICE LEVEL INDEX FOR AIRCRAFT ENGINES[a]

Year	Index	Year	Index
1947	2.81	1959	1.47
1948	2.55	1960	1.42
1949	2.47	1961	1.38
1950	2.34	1962	1.33
1951	2.10	1963	1.30
1952	2.00	1964	1.26
1953	1.95	1965	1.22
1954	1.89	1966	1.17
1955	1.82	1967	1.13
1956	1.73	1968	1.06
1957	1.65	1969	1.00
1958	1.55	1970	.94

[a] Based on the average hourly earnings of production workers in the aircraft industry as given in Bureau of Labor Statistics, *Employment and Earnings*, U.S. Department of Labor, Washington, D. C.

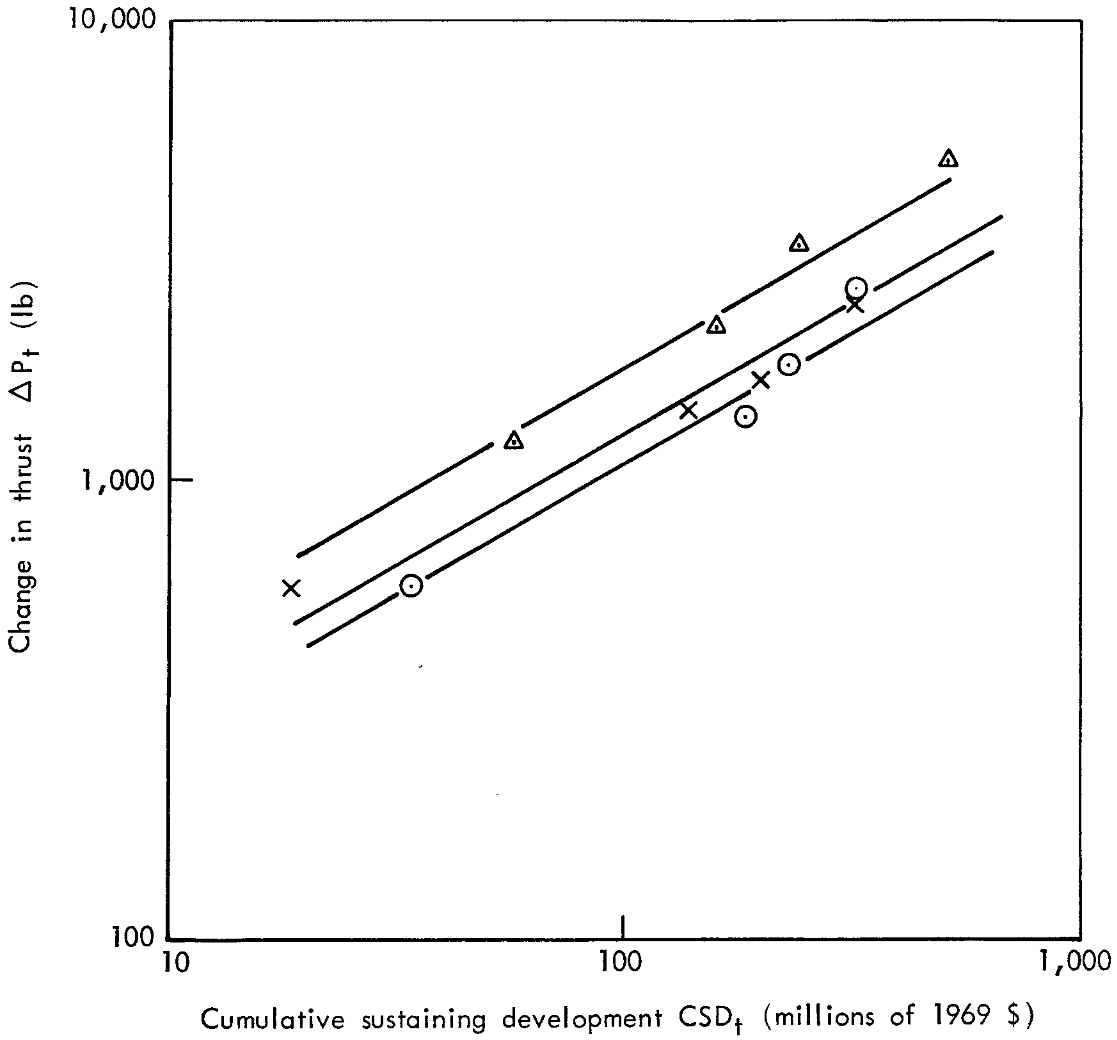

Fig.8 — Thrust growth

Of great concern in connection with the use of this index is that design and engineering labor costs may have risen faster or slower than production labor costs, and that in any case the use of a labor cost index does not take into account the fact that about one-half of the cost of getting to an MQT is the purchase of hardware. Evidence for the first concern is skimpy. During this period, the industry as a whole grew quite rapidly with increasing demand for both production labor and design and engineering labor, making it unlikely that increases in the cost of one type of labor have outrun increases in the other.

As for the second concern, material costs have been more stable as measured by conventional Bureau of Labor Statistics indexes, but the amount of raw material going into an engine is relatively small in dollar value. Most of what is classified as material is purchased equipment, purchased assemblies, and highly machined parts, and these have a high labor component.

Because sustaining development expenditures were available by calendar year only, it was necessary to devise a rule to deal with an MQT occurring at some time *during* the year. For each month up to and including the month of an MQT, sustaining development was counted at 1/12th the annual rate for that year.

A third adjustment to the data was made to account for engines that have both afterburning versions (usually Air Force) and non-afterburning versions (usually Navy). The military thrust rating (that is, nonafterburning thrust), of the original version was used as P_0 and the military thrust rating of a product-improved version was used to complete subsequent ΔP_t.

Equation (20') was estimated by OLS to be:[1]

$$\ell n\ \Delta P_t = .436 + \underset{\substack{(.0819)\\ t\,=\,5.425}}{.444}\ \ell n\ P_0 + \underset{\substack{(.0738)\\ t\,=\,7.916}}{.584}\ \ell n\ CSD_t \qquad (21)$$

$$R^2 = .844 \qquad F(2,22) = 66.9 \qquad S.E. = .308$$

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[1] The numbers in parentheses indicate the standard errors of the estimated coefficients. Two additional regressions incorporating a calendar time variable were also run to test whether the function has

The null hypothesis that γ_1 lies outside of the interval (0,1) must be rejected at the .00005 significance level. Similarly, the null hypothesis that γ_2 lies outside of this interval must also be rejected at the .00005 significance level.

These statistical results are quite strong, and one is led to ask why γ_1, for example, is approximately .44 instead of .90 or .10; that is, what is γ_1 a function of? And why is γ_2 in the neighborhood of .58? The answer to the first question, I believe, is tied up with the way engine product-improvement programs are conducted. About one-half of the cost of an engine product-improvement program is due to the cost of the test engines. The cost of each test engine in turn is a function of the size, as measured by its thrust, for example, of the engine, whereas the number of test engines bought depends on the test schedule and the severity of the test program. The implication is that a change in certain policies affecting the above considerations might produce a change in the magnitude of γ_1.

As for the second question, there is little that one can say without studying product improvement in other high technology areas to determine whether this value of γ_2 is common to the performance-improvement process or whether it is the result of the "X-efficiency" in the aircraft engine R&D industry.

SUMMARY

Product improvement can alter the technological level of a jet engine, but as this process proceeds, the divergence in technology between the product-improvement version and a new engine incorporating all of the available technology must inevitably grow larger. One might still continue to invest in product-improvement R&D for an engine if it were cheap enough relative to the cost of developing a new engine. However, the indirect production function for thrust growth R&D, which

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shifted over time. In one regression, time entered linearly; in the other, logarithmically. In both cases the coefficient of the time variable was not significant, but the coefficients of $\ell n\ P_0$ and $\ell n\ CSD_t$ were significant.

served as a proxy for general performance-improvement R&D, exhibited diminishing returns with respect to dollar resources. Consequently, at some point product improvement ceases to be an efficient way of obtaining additional performance.

III. PRODUCT-IMPROVEMENT ACTIVITY IN U.S. JET ENGINES--COST-REDUCING CHANGES

In this section, I present estimates of the reduction in manufacturing costs for U.S. jet engines as a result of cost-reducing activities in product-improvement programs, and I discuss the implications of these estimates for R&D policy. Admittedly, the incentives for reducing manufacturing costs are not always there. This may be because there is an insufficient rate of return to this kind of activity for engine manufacturers, or simply because cost-reducing product improvement is rarely viewed as an alternative way of spending R&D resources.

It has been observed that costs of manufacturing decrease as the cumulative quantity of engines produced increases. This is the so-called learning curve phenomenon. Yet as Table 7 shows, there is a substantial degree of variability in the rate of learning. One explanation for this observed variability is that in some engine programs a deliberate effort is made in the product-improvement phase to reduce production costs.

A second explanation I have called the "sawtooth" effect and is illustrated in Fig. 9. In the sawtooth effect, the existence of numerous modified versions or dash numbers cancels some of the benefits of large production quantities. So in fact while the true learning process is learning curve (a) in Fig. 9, what we actually observe is learning curve (b). The number of sawtooths in (a), a set of short-run learning curves, affects the overall slope of (b), the long-run learning curve.

Evidence for this type of effect is not conclusive. For example, the J57 had over 30 dash number versions procured by the Air Force and Navy over a period of years, as well as a commercial version, the JT3. One would expect a rather shallow learning curve, and in fact that is what is observed. The learning curve had a slope implying about a 95 percent rate. The J79, on the other hand, went through almost 20 dash numbers between 1956 and 1968 and yet it had a much steeper slope, one implying about an 83 percent rate of learning.

Table 7

RATES OF LEARNING FOR JET ENGINES FROM U.S. EXPERIENCE[a]

Type	Percent Learning[b]	Number of Engines
Turbojets	80-84	5
	85-89	2
	90-94	3
	95-100	3
Turbofans	90-94	2
	95-100	2
		17

[a] Adapted from J. P. Large, *Estimating Aircraft Turbine Engine Costs*, RM-6384-PR, The Rand Corporation, September 1970.

[b] Percent learning indicates the ratio of production cost between the Qth and 2Qth engine.

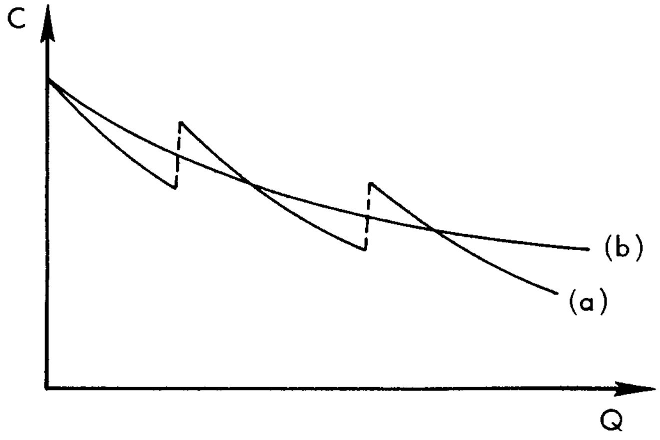

Fig.9 — The "sawtooth" effect

A third possible reason for the variability of the rate of learning is problems with the data. In computing the rate of learning, the analyst is often forced to use the engine's selling price, but what should be used is the manufacturing cost. Selling price can go up or down for reasons unconnected with the cost of manufacturing. One extreme case of decoupling the selling price and the cost of manufacturing is the practice of quoting one price for a particular dash number delivered in a given year, as is the case at Pratt & Whitney. No learning curve can then be inferred. Similarly, precise knowledge of the production quantity is often not available. When a manufacturer produces a military version and a commercial version of the same engine, the cost reduction could appear to be greater than is actually the case if the production quantity for only one of the versions is taken as the correct quantity.

ESTIMATING THE EFFECT OF COST-REDUCING PRODUCT IMPROVEMENT

Cost-reducing product improvement has been put forth as one possible explanation of the observed variability in the rate of learning in the production of jet engines. One place that the effect of cost-reducing R&D should be observed directly is in manufacturing cost itself. Over the years, Rand has developed several cost-estimating relationships (CER) to predict the production cost of military jet engines. The first such widely circulated CER predicted unit cost on the basis of thrust and cumulative quantity.[1] A more recent version of Rand's engine production CER predicted unit cost on the basis of thrust, cumulative quantity, and technological class.[2]

In each of these equations, the effect of cost-reducing product improvement is statistically absorbed by the cumulative quantity

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[1] See A. Frank Watts, *Aircraft Turbine Engines: Development and Procurement Costs*, RM-4670-PR (abridged), The Rand Corporation, November 1965.

[2] See J. P. Large, *Estimating Aircraft Turbine Engine Costs*, RM-6384-PR (abridged), The Rand Corporation, September 1970. Technological class in the Large report is assigned on the basis of the author's *a priori* assessment, usually aided by such considerations as whether the turbine was cooled or uncooled, what percentage of superalloys are found in the engine, and so on.

variable. What I seek to measure is the effect of a deliberate attempt to reduce production costs by committing R&D resources to that effort during a product-improvement program. This effect is separate from and in addition to the cost-reducing effects of increasing cumulative quantity, which I call *inadvertent learning.*

I have hypothesized that cost-reducing product improvement acts to shift the whole cost-quantity relationship. To test for cost-reducing product improvement, a model encompassing thrust, cumulative quantity, technological class, and cumulative cost-reducing product improvement dollars was estimated. This is shown as equation (22).

$$C_t = e^{\beta_0+\beta_1 N} P_t^{\beta_2} Q_t^{\beta_3} R_t^{\beta_4} u_t \qquad R_t > 1 \qquad (22)$$

where

C_t is the unit cost of an engine in constant dollars produced at time t,

N is a dummy variable that takes on the value zero for Class II engines and one for Class III engines from Large's classification scheme.[1]

P_t is the maximum thrust of that engine in pounds at time t,

Q_t is the cumulative quantity including all versions of that engine produced up to time t,

R_t is the cumulative sustaining development in constant dollars spent on cost reduction up to time t, with a lower bound of 1,[2]

u_t is a random variable such that $\ell n\, u_t \sim N(0,\sigma^2_{\ell n u_t})$.

The engines used for estimating equation (22) are listed in Table 8.

Certain adjustments were made to the data before equation (22) was estimated. R_t was adjusted to millions of 1969 dollars using the price

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[1] Practically speaking, in estimating equation (22), all of the engines were in Class II (N=0) except for the TF30, which was Class III (N=1).

[2] R_t was computed as a residual by subtracting cumulative CIP funding and cumulative performance improvement dollars from cumulative sustaining development, CSD_t, all in constant 1969 dollars. It is helpful and not unreasonable to assume that the errors in R_t as a result of this computation are log-normally distributed.

Table 8

DATA BASE FOR COST-REDUCING EQUATION

J52	J79
J57	J85
J60	TF30
J75	TF33

level index of Table 6. Q_t was entered as year-end quantities. C_t was entered as selling price of the engine adjusted to thousands of 1969 dollars also using Table 6. The use of selling price instead of true manufacturing cost introduced a possible simultaneous equations problem. Selling price in a given year is surely affected by the success of cost-reducing sustaining development in lowering manufacturing costs, but it is also determined by overhead rates and development costs directly; that is, $C_t = f(R_t, OH_t\ (Q_t), \ldots)$. To the extent that simultaneous equations problems intrude in the estimation of equation (22), the coefficients will be biased. There is evidence to suggest, however, that selling price and the variable R_t are not closely connected in the sense that there are just too many other variables, both tangible and intangible, entering into the determination of selling price. It was decided therefore to proceed with the estimation of equation (22) by ordinary least squares (OLS).

Equation (22) was then estimated in log-linear form to be:[1]

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[1] A comparison of the three equations is illuminating:

Rand 1965 (Watts) $C(Q_t) = f_1(P_t, Q_t)$

$$\ell n\ C_t = -1.819 + 0.848\ \ell n\ P_t - 0.133\ \ell n\ O_t$$

Rand 1970 (Large) $C(Q_t) = f_2(P_t, Q_t, N)$

$$\ell n\ C_t = 0.959 + 0.605\ N + 0.60\ \ell n\ P_t - 0.154\ \ell n\ O_t$$

Rand 1972 $C(Q_t) = f_3(P_t, Q_t, N, R_t)$

$$\ell n\ C_t = 0.832 + 0.415\ N + 0.631\ \ell n\ P_t - 0.156\ \ell n\ Q_t - 0.031\ \ell n\ R_t$$

Note that the coefficients of N, $\ell n\ P_t$, and $\ell n\ Q_t$ in the last equation are not significantly different from those in the Large equation.

$$\ell n\ C_t = .832 + \underset{(.162)}{.415}\ N + \underset{(.085)}{.631}\ \ell n\ P_t - \underset{(.040)}{.156}\ \ell n\ Q_t - \underset{(.025)}{.031}\ \ell n\ R_t \qquad (23)$$

$$R^2 = .82 \qquad F(4,20) = 22.9 \qquad S.E. = .284$$

The simple correlation coefficient between $\ell n\ Q_t$ and $\ell n\ R_t$ was .08. In order to interpret a relationship between these two variables as being significant at even the .10 significance level, the simple correlation coefficient would have to be at least .36. Hence I concluded that $\ell n\ Q_t$ and $\ell n\ R_t$ were measuring different effects.

The sign of the coefficient of $\ell n\ R_t$ is in the expected direction, and the magnitude indicates that a one percent increase in cumulative cost-reducing product improvement dollars would decrease production cost by .03 percent. Statistically, the null hypothesis that this coefficient β_3 was non-negative was rejected at the .12 significance level.

This result is not as strong as might be desired. There is, however, an important econometric problem involved in the estimation of equation (22), because of the serious errors in the explanatory variable, $\ell n\ R_t$, which introduces a bias in the coefficients and the t-statistics. Furthermore, this bias does not disappear in the limit as the number of observations increases indefinitely. It has been shown that if the differences between the true and observed values of a single explanatory variable in a multiple regression model are normally distributed, independent, and uncorrelated with the true values of the explanatory variable, then (1) the estimated coefficient and the t-ratio of the (lone) variable with the error are biased toward zero, and (2) the direction of the biases of the coefficients and t-ratios of the remaining variables is indeterminate.[1]

Although the coefficients or the t-ratios of $\ell n\ P_t$ and $\ell n\ Q_t$ cannot be trusted, there is reason to believe that the coefficient of $\ell n\ R_t$ and its significance level have been understated. One can therefore conclude that the estimate of the effect of cost-reducing activity

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[1] See Richard V. L. Cooper and Joseph P. Newhouse, "Further Results in the Errors in the Variables Problem," P-4715, The Rand Corporation, October 1971.

within engine product-improvement programs represents a lower bound. More research ought to be done on this question.

A POLICY CONSIDERATION

The estimate of β_3 in equation (23) has important implications for the funding of cost-reducing product improvement. Suppose an investment in cost-reducing product improvement of $20 million is being considered at the start of the production phase. Since any production cost savings will accrue only as engines are built during subsequent production runs, there is a certain breakeven production quantity at which the $20 million will be exactly recouped. This breakeven quantity depends on the production rate, the discount rate, and the cost of the engine with *no* cost-reducing sustaining R&D. How much will a $20 million investment lower production costs and what will be the breakeven production quantity?

The $20 million lowers production costs by 8.9 percent (on each engine) as computed from equation (23). The total cost of producing engines in the tth month is given by:

$$TC(t,PR) = \int_{PR\cdot(t-1)}^{PR\cdot t} C(Q_t)\,dQ_t \qquad (24)$$

where PR is the monthly production rate, assumed to be constant, and $C(Q_t)$ is the unit cost of the Qth engine with *no* cost-reducing product improvement. The savings accruing the tth month from the $20 million investment is then:

$$S_t = (.089)\ TC(t,PR) \qquad (25)$$

This must be summed and discounted to obtain the breakeven month, t*:

$$f(t^*) = \sum_{t=1}^{t^*} S_t(1+r)^{-t} = \$20 \text{ million} \qquad (26)$$

where r is the monthly discount rate. The breakeven quantity is then given by:

$$N^* = PR \cdot t^* \qquad (27)$$

Tables 9 and 10 give the breakeven quantities for different assumptions about the production rate, the discount rate, and the cost of the engine in the absence of cost-reducing product improvement.

Table 9

BREAKEVEN QUANTITY FOR A PRODUCTION RATE OF
15 ENGINES PER MONTH

Cost of 100th Unit with no Cost-reducing Product Improvement C(100)	Discount Rate (monthly)		
	r = 0	r = .005	r = .01
$150,000	2025	3630	>4500
250,000	1110	1425	2220
500,000	485	540	615
750,000	300	330	345

Table 10

BREAKEVEN QUANTITY FOR A PRODUCTION RATE OF
30 ENGINES/PER MONTH

Cost of 100th Unit with no Cost-reducing Product Improvement C(100)	Discount Rate (monthly)		
	r = 0	r = .005	r = .01
$150,000	2025	2550	3660
250,000	1110	1260	1440
500,000	485	510	540
750,000	300	315	320

Typically cost-reducing product improvement would be carried out while production is going on. This means as a matter of policy that a total production of even more engines than shown in the tables would be necessary. Although a production run of 1000 engines is not very large (by 1950-1960 standards), it does represent an aircraft buy of perhaps 400 to 500, which by today's standards is quite large. Because there is a certain breakeven quantity phenomenon, uncertainty about quantity, particularly if initial predictions about quantity are optimistic, cost-reducing product improvement becomes less attractive as an investment.

IV. PRODUCT IMPROVEMENT AND NEW DEVELOPMENT

IS PRODUCT IMPROVEMENT LESS UNCERTAIN?

New product innovation and product improvement are subject to varying degrees of uncertainty in the real world. The uncertainty associated with the development of new weapon systems has been the subject of several studies, perhaps the best known of which is by Peck and Scherer who reported an average development cost overrun factor (actual cost of the development program, excluding the cost of improvement work after the weapon became operational, divided by original cost estimate) of 3.2 based on 11 new weapon programs.[1]

Peck and Scherer also compiled development time factors (actual time divided by original time estimate) for 11 weapon programs. The mean value of this factor was 1.36, indicating that development time for these 11 systems averaged 36 percent longer than the original estimates.

Even before Peck and Scherer's work, Marshall and Meckling analyzed 22 military development programs and found great unpredictability in production costs, schedule, and operational performance.[2] Production cost increases on the order of two to three times the original estimates and extensions of schedules by one-third to one-half were typical. By and large, the performance goals were more closely met, but this was definitely the result of a tradeoff of money and time. More recently, in a paper extending the findings of Marshall and Meckling, Harman has demonstrated that the unpredictability of costs is positively related to the degree of technological advance sought; and the uncertainty due to the technological advance factor (the A-factor for short) is compounded by the length of the development process.[3]

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[1] Merton J. Peck and Frederick Scherer, *The Weapons Acquisition Process*, Harvard University Press, 1962, p. 22.

[2] A. W. Marshall and W. H. Meckling, "Predictability of the Costs, Time, and Success of Development," P-1821, The Rand Corporation, October 14, 1959, revised December 11, 1959.

[3] Alvin J. Harman (assisted by S. Henrichsen), *A Methodology for Cost Factor Comparison and Prediction*, RM-6269-PR, The Rand Corporation, August 1970.

The difficulty in obtaining reasonably accurate cost estimates for military programs arises from several sources.[1] First there is inherent technical uncertainty in trying to advance the state of the art. Technical optimism, the belief that all of the technical problems both foreseen and unforeseen can be solved within the resources allotted, may also be a contributing factor in projects overrunning their predicted costs. To be sure, there are ways of reducing technical uncertainty. Parallel efforts in R&D,[2] prototype building, and incremental acquisition strategies[3] can probably make significant reductions in the probability of a disastrous development program, but technical uncertainty cannot be eliminated altogether.

A second source of error can be attributed to changes in scope. The term "scope change" is used to describe changes in program goals and technical specifications after the start of development. In the United States it takes, for example, an average of eight to 11 years to develop an advanced aircraft, depending on whose estimate is used. Over such a long period, objectives, strategies, and potential threats change, often forcing expensive changes in an ongoing development program. A third source of error is deliberate underestimation of costs to gain approval and funding for proposed projects.

Although these phenomena have been advanced to explain military R&D overruns, some or all are present in non-military R&D projects. The difference may only be how they are handled. Wagner found great unpredictability of development costs and time for a sample of 36 R&D projects in an industrial laboratory.[4] The average development cost factor was 2.75 for new product development programs. When classed

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[1] I am excluding from the discussion sources of cost estimating error such as changes in the number of units of a system procured or unanticipated inflation.

[2] R. R. Nelson, "Uncertainty, Learning, and the Economics of Parallel R&D Efforts," *Review of Economics and Statistics*, Vol. 43, No. 4, November 1971, pp. 351-364.

[3] Robert Perry *et al.*, *System Acquisition Strategies*, R-733-PR, The Rand Corporation, June 1971.

[4] Samuel Wagner, "An Empirical Study of the Cost, Time, Outcome, and Predictability of Industrial R&D," Ph.D. dissertation, University of Pennsylvania, 1971, pp. 142-156.

according to the degree of technical advance sought, projects with a medium or high classification had an average development cost factor of 5.46, and those with a low technical advance classification had an average factor of 2.21.

That new product development programs involve great uncertainties is a generally accepted fact of life. But how does the uncertainty of product-improvement programs compare with that of new product developments?

The Wagner dissertation sheds some light on this question. The average cost overrun factor for 33 product-improvement projects at the same industrial laboratory was 1.41 compared with 2.75 for new product development projects.[1] However, to determine what factors affect the size of the cost overrun factor for individual projects, Wagner constructed a model in which the logarithm of the ith project's cost overrun factor was the dependent variable and several project characteristics formed a set of independent variables. These characteristics included (1) the logarithm of the estimated cost of the ith project; (2) the logarithm of the ith project's actual length in months; (3) the logarithm of calendar time measured from 1960 when the original cost estimate was made for the ith project; (4) a dummy variable indicating whether the technical advance sought in the ith project was small or moderate to large; and (5) a dummy variable indicating whether the ith project was a product-improvement project or a new product development project.

In the resulting regression of OLS, the coefficients of the degree of technical advance sought, the estimated cost of the project, and the actual length of the project were statistically significant. The coefficient of project type was not significant, indicating that project type had no real effect on the cost overrun factor when the other variables were taken into account.[2]

It was not possible to test the same model on data from jet engine programs because data on estimated project cost were not available. As a result it was necessary to ask a different question and formulate

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[1] *Ibid.*, p. 145.

[2] *Ibid.*, pp. 147-151.

a different model. The question that was asked was: "Suppose a new engine could be developed by either improving upon an existing one, that is, product improvement, or by initiating an entirely new engine development program. How would our ability to predict the cost of these two alternatives compare?"

To answer this question I have constructed the following test.

First, from 17 previous *new* engine development programs, the following equation was estimated to predict development cost D_t for an engine of thrust P_t.

$$\ell n\ D_t = .502 + \underset{(.078)}{.501}\ \ell n\ P_t \qquad (28)$$

$$R^2 = .73 \qquad F(1,15) = 41.3 \qquad S.E. = .451$$

D_t is the R&D cost through MQT in millions of 1969 dollars. P_t is the thrust of the engine in pounds.

Second, an equation to predict the R&D component of an engine product-improvement program based on eight previous such programs was estimated. This equation, shown as equation (29), also used thrust as the independent variable, though separated into the thrust of the original engine P_0, and the required "thrust growth" ΔP_t.

$$\ell n\ X_t = -1.59 - \underset{(.158)}{.488}\ \ell n\ P_0 + \underset{(.163)}{1.264}\ \ell n\ \Delta P_t \qquad (29)$$

$$R^2 = .76 \qquad F(2,22) = 34.1 \qquad S.E. = .463$$

X_t is the R&D cost through MQT in millions of 1969 dollars. P_0 is the thrust of the original (unimproved) engine in pounds, and ΔP_t is the required increment on thrust in pounds to reach the goal of P_t. The equation was obtained essentially from the same data as was used to estimate equation (12).[1] Estimates produced in this way are normally distributed;

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[1] The estimation of equation (29) by OLS is not inconsistent with the estimation of equation (11), since the error terms in both are normally distributed. Both error terms have zero means but different

hence the standard errors of the estimates suffice to describe the uncertainty in the cost of the programs.

To test the proposition that product-improvement and new development R&D exhibit different degrees of cost uncertainty, the null hypothesis was set up that the estimated variances from equations (28) and (29) were the same. Because these estimated variances are distributed as independent χ^2, the F-test was appropriate. The null hypothesis could not be rejected even at the 50 percent (two-tail) significance level.[1]

It is possible that the estimate of the standard error in equation (29) is biased upward. This is the well-known result of errors in the dependent variable as would be the case if thrust growth funds were only approximately a constant proportion of all product-improvement funds; that is, if

$$X_t = \mu \cdot \eta \cdot CSD_t \tag{30}$$

where $\ell n\ \mu \sim N(0, \sigma^2_{\ell n \mu})$ and $0 < \eta < 1$.

In that case the estimate of the standard error of equation (29) includes the "true" standard error plus an estimate of $\sigma^2_{\ell n \mu}$, and the result might be that the null hypothesis would stand up. Had the F-test rejected the null hypothesis, at least the bias would have *a fortiori* strengthened the conclusion.

Because equations (28) and (29) are in logarithmic form, one standard fixed error interval represents a percentage error in the estimates. For a new engine development program, the development cost could be as

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variances. Implicit in equation (29) are estimates for γ_1 and γ_2. Solving for these values yields $\gamma_1^* = .4$ and $\gamma_2^* = .8$, which are not inconsistent with the estimates of γ_1 and γ_2 from equation (11).

[1] Under the null hypothesis, the F(22,15) ratio was 1.052. For the null hypothesis to be rejected at the 10 percent (two-tail) level of significance, F would have to be at least 2.31. For the null hypothesis to be rejected at the 50 percent (two-tail) level of significance, F would have to be at least 1.41.

much as 58 percent higher (or 37 percent lower) than that estimated by equation (28) and still be within one standard error. With no real difference in the standard errors between equations (28) and (29), a product-improvement program could experience the same potential overrun (or underrun) with the same probability. However, typical new engine development programs run three to five times larger than typical thrust growth programs, so that although the percentage error may be the same, the absolute number of dollars involved in a potential overrun is much smaller for a thrust growth program.

MODIFICATION ALTERNATIVES AND COSTS

Doing product-improvement R&D is only the first part of the product-improvement process. At the completion of the R&D phase, the job remains of modifying the existing machines so as to incorporate the various improvements. This phase can be called the retrofit or modification phase.

In the case of military jet engines, the modification phase is usually concerned with the installation of performance-improving or maintainability and reliability-improving equipment.[1] This modification process can be handled in several ways depending on the complexity of the changes to be made.

A product-improvement program on a jet engine may result in a "kit" such as the TF30-408 kit. Such a kit could be installed during a regular major overhaul. If it is a matter of replacing a compressor or a combustor when the engine is torn down during the overhaul, the modification would be a rather simple procedure. If more extensive modifications are required, these could also be scheduled to coincide with major overhauls. At such time, the engine could be returned to the plant and recycled through the production line as necessary. Perhaps

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[1] The modification of the J57-20 to the -420 by means of a kit provides an interesting example of the possible overlap between performance-improving and maintainability and reliability-improving changes. In service on the Navy's F-8 carrier-based fighter, the -420 provides the thousand pounds of additional thrust needed to get off the deck, even though the original intent of the "kit" was to prolong the life of the "hot sections" of the engine.

the complexity of a major modification or the lack of sufficient commonality with the improved model could be so great as to make it economical to build new engines and gradually replace older engines as they undergo overhaul.

Of these three alternative ways of obtaining the product-improved version, the first two essentially use the original engine carcass as the basis for the improved model, but in the third the improved engine is built from scratch. Can we relate the change in performance to the cost of making the performance-improving modifications? Is the cost of making performance-improving modifications positively related to the amount of change--that is, the size of the jump from the old vintage to the new one? When does it become economical to build the improved engine from scratch?

To answer these questions, a model of the cost of retrofitting was constructed for the case when performance was improved by an increase in thrust and when the old engine carcass formed the basis of the new engine. It was felt that the conversion or retrofit cost as a fraction of the production cost of a new engine of the same thrust should be a function of the percentage change in thrust resulting from the product-improvement program such that the higher that percentage change, the higher the fraction of conversion to production costs. At least this fulfills a consistency criterion--the larger the change in the engine to be made, the nearer the cost should be to the cost of a new engine of the same thrust. The data base for estimating such an equation was pitifully small. Conversion kits have been developed for the TF30(-408) and J57(-420) so kit prices and man-hours for installation were available from Navy sources. Labor costs were charged at $10/hr and were then added to the kit prices to get the total conversion costs. A third datum was obtained from a Republic Corporation contract to modify T56-A-7s to T56-A-15s. A fourth datum was obtained from American Airlines from their experience in modifying JT3Cs to JT3Ds for their 707s.[1]

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[1] See Appendix A for a brief history of this conversion.

The following equation was then estimated for small changes in thrust:[1]

$$\ln Z = 1.242 + \underset{\substack{(.173)\\ t = 9.1}}{1.577} \ln \frac{\Delta P_t}{P_0} \tag{31}$$

$$R^2 = .97 \qquad F(1,2) = 83.1 \qquad S.E. = .178$$

where $Z = \dfrac{\text{total cost of conversion for Q engines}}{\text{total production cost for Q engines}}$

From equation (31), it can be seen that as the size of the thrust growth increases, the closer the cost of making the required modifications comes to the cost of building the improved engine from scratch. By setting $\ln Z = 0$ in equation (31) the "breakeven point" is found to be a thrust growth of approximately 45 percent, although other factors, such as the necessity of removing engines from service for extended periods to make such modifications, may make it more economical to build new engines.

SUMMARY

In a study of an industrial laboratory, one researcher found that the average cost overrun factor was lower for product-improvement projects than for new product projects (1.41 versus 2.75). The same researcher found that when other variables--such as the length of the project, the original cost estimate, and the degree of technical advance sought--were taken into account, project type (that is, product improvement or new development) had no effect on the size of the cost overrun factor. This apparent inconsistency can be explained in many ways. First, there may be a systematic tendency to bias original cost estimates downward even more for new product development than for product improvements, particularly if more absolute resources are generally required in new product R&D. Second, there may be greater room for scope

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[1] The t-ratio is significant at the .015 level despite having only two degrees of freedom.

changes when doing new product R&D. Third, there may be a systematic though irrational tendency to keep funding unpromising new product R&D projects while cancelling unpromising product-improvement projects simply because sunk costs in a typical new product R&D project may be several times larger than in a typical product-improvement program by the time the unpromising nature of the project is recognized.

The validity of using cost overrun factors as a measure of cost uncertainty depends very heavily on how, when, and by whom the original cost estimates were made. Results like the ones above based on an *ex post* analysis of completed projects are not really conclusive since the method avoids the central question of how the cost estimates are made in the first place. In a direct test of the ability to predict R&D costs for the development of a jet engine, two equations were estimated--one for a new development program and one for a product-improvement program with the same performance goals. The standard errors of the estimates of these two equations were found to be statistically the same. Based on this, one must conclude that product improvement is not inherently less uncertain with respect to cost, but because product-improvement programs generally are shorter and involve fewer resources per unit time, the stakes involved are several times smaller.

A model of the costs of doing thrust growth modifications was shown to have the property that the larger the percentage change, the closer the costs of modification come to the production cost of an engine with that thrust.

V. IMPLICATIONS FOR ACQUISITION POLICIES

RESULTS

The results of this study have been summarized in the preceding sections, but a brief recapitulation may be useful. Two objectives of engine product-improvement programs have been explored. The first of these is the feasibility and cost of increasing the performance or "technological level" of an engine through product improvement. The second is the reduction of production cost of an engine by deliberately committing R&D funds to that effort during a product-improvement program.

To quantify what is meant by "technological level," multiple regression analysis was used to estimate a multidimensional technology tradeoff surface for new engine designs as a function of a set of engine performance parameters. This technology equation was then applied to subsequent product-improvement versions. The results indicated that on average product-improvement engines embody a higher level of technology than their original versions but that the rate at which technology can be incorporated into product-improvement versions is significantly less than the long-run average for new designs. This was not unexpected. Some new technology can be incorporated into an existing engine, but to take advantage of all of the available technology, one must essentially start from scratch.

On the cost side, a function was estimated representing the maximum performance growth (as measured by thrust) attainable at various expenditure levels. Each increment to thrust becomes more costly--that is, thrust growth is subject to diminishing returns with respect to dollar resources. Furthermore, for a given level of expenditure, the greater the thrust of the original version, the larger the absolute increase in thrust in the product-improvement version but the smaller the percentage increase. The cost of physically modifying engines to increase their thrust was also studied. Using regression techniques again, it was found that the larger the percentage change in thrust, the closer the costs of modification come to the production cost of an engine with the same thrust.

The possibility of undertaking cost-reducing product improvement to shift downward the whole relationship between production unit costs and cumulative quantity--the learning curve--has also been explored. To test this, a cost-estimating relationship (CER) encompassing thrust, cumulative quantity, technological class, and cumulative cost-reducing product-improvement dollars was estimated. This exercise resulted in modest evidence supporting the hypothesis. But problems in estimating the CER suggested that the magnitude (and statistical significance) of the effect have been understated; more research is needed on this question. Using the CER as estimated, a hypothetical investment of $20 million in cost-reducing product improvement would be recouped only after a production run of between 500 and 600 moderately large engines (for example, $500,000 at the 100th unit).

New product innovation and product improvement are both subject to varying degrees of uncertainty, as is the case for any form of R&D. To test if either is inherently less uncertain, two equations were estimated to predict R&D costs for the development of jet engines--one equation by new development programs and one by product-improvement programs. The standard errors of the estimates of these two equations, which measure the *percentage* uncertainty in these R&D costs, were found to be statistically the same. Product improvement, one must conclude, is not inherently less uncertain with respect to cost. But since product-improvement programs generally involve substantially fewer resources per unit of time, the *dollar* risk of product-improvement R&D is several times smaller, even though the percentage risk is the same.

Thus, product improvement seems to be a way of acquiring modest technological advances at modest cost (with a resultant decrease in the total risk) as well as a technique for reducing unit costs of production hardware.

IMPLICATIONS

The Air Force is continually engaged in product-improvement R&D and the modification of engines, aircraft, and other hardware. There are several reasons to believe that product improvement could be even more fully exploited. These reasons are closely tied up with Air Force weapon acquisition philosophy and organizational structure.

A typical justification for the development and procurement of a new system is that, in spite of R&D and new investment costs, the new system will cost less than an old system performing the same mission. A reason given for this is that, to be effective, the old system must be operated so intensively that it would be necessary to deploy additional units with resulting increases in operating costs. Furthermore, it is often asserted that aircraft, engines, and missiles become less maintainable as they get older, so even without any additional deployment, maintenance costs for an old system will increase steadily. For these reasons, and because of the difficulties of accurately estimating the future performance and R&D, investment, and operating costs of the new system, this type of argument can easily lead to the conclusion that the future costs of operating an existing system or an improved version of an existing system would be high relative to the new system.

But the assumed positive relationship between age and maintenance costs is not borne out by analysis.[1] A complex weapon system is continually being serviced, with new parts replacing older ones at regular intervals or as needed, so that the average age of the systems is hardly relevant. On the other hand, because new systems invariably have "bugs" in them that must be worked out, maintenance costs (not to mention out-of-service times) are usually much higher in the first few years after a system's initial operational capability than for a system that has been in operation for a longer period.

Finally, the argument for a new system focusing on the effectiveness side may suggest that over time a system suffers a degradation in effectiveness, or "draw-down."[2] The increasing "operational deficiency could occur as a result of several major factors, for example, an increased threat, a changing mission requirement, [or] obsolescence of the force."[3] Of course, a *new* system can be obsolete or relatively

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[1] One study on this subject is Milton Kamins, "The Effect of Calendar Age on Aircraft Maintenance Requirements," The Rand Corporation, December 1970 (unpublished).

[2] See, for example, General Donavon F. Smith, "Development Planning: A Link Between Requirements and Systems," *Air University Review*, Vol. 22, No. 1, November/December 1970.

[3] *Ibid.*, p. 15.

ineffective by the time it is developed and deployed, if the enemy is able to counter its improved attributes quickly and with little effort. Moreover, the following circumstances can occur. As basic and applied research makes a new and desirable technology available, a cost-effectiveness study can be made revealing that a new system incorporating this technology would be effective over some planning horizon, *if* the system remains in the force the predicted length of time. Under this assumed planning horizon, the alternative of keeping the old system a few more years by improving and modifying it may be unattractive. Based on such a study, the new system is then developed. Subsequent unforeseen events, such as a newer technology or a slightly different threat, may make it unwise to keep the new system in the force as planned. If the new system is not adaptable (not easily "product-improved" itself) then it must be scrapped and a new one developed and procured to replace it. Of course, such frequent replacement of major systems can contribute to a strained defense budget. If it also turns out that each new system is more expensive per unit, fewer can be procured. The advanced performance can become relatively unimportant if so few units can be purchased that the balance of forces becomes unfavorable.

On the other hand, if a system is adaptable through product improvement and modification, it can be maintained in the force longer, postponing the acquisition of its replacement without serious loss of effectiveness. The payoff, in terms of the ability to delay replacement acquisition alone, may be high relative to the product-improvement costs. In addition, if more units must be added as the threat grows, these additional units benefit not only from any inadvertent "learning curve" unit cost reductions, but also from deliberate cost-reducing, maintainability, or reliability product-improvement R&D.

In the evaluation of alternatives designed to fulfill a needed capability, careful attention must be given to the choice of the time horizon (and, implicitly, the discount rate). To the extent that the findings based on past turbine engine experience reflect the general nature of product-improvement activities for other military hardware, fuller assessment of the possible future states of technology and the potential for incorporating these advances in technology through

Appendix A

EXAMPLES OF PRODUCT IMPROVEMENT IN THE PRIVATE SECTOR[1]

Buried in the R&D, inventive activity, and innovation literature is a small but interesting body of material on product and process improvement. Product and process improvement are a part of the same phenomenon; both are aimed at gaining an improvement in competitive position whether from a better product or from lower average costs. In the private sector, a better product allows the firm to command a higher price; lower average cost admits the possibility of successful economic warfare in the case of oligopolistic competition, or at least a (temporary) quasi-rent to the innovating firm in the case of atomistic firms in pure competition.

Parallels between innovation (product and process improvement) in the private sector and the military sector can be drawn. It seems clear that the propensity to innovate in either sector increases as perceptions of a threat increase, as when one firm is increasing its market share, or when a potentially hostile country is thought to be developing new and effective weapons. In both cases, arguments in favor of countermeasures increase in strength.

Yet as a theory of innovation, the satisficing behavior implied above is not wholly satisfactory. Certainly the opportunity for commercial profit in the private sector must play an important role in bringing about innovation. Similarly, the opportunity to exploit a scientific advance by developing a new weapon is not often overlooked in the military sector.

There may be, however, some asymmetries between "opportunity" and "threat" in the military sector that do not exist in the private sector. One would expect the military to react strongly if an advantage for the other side were perceived. Transitory judgments based on incomplete intelligence and assessments of effectiveness based on many

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[1] This section is derived from the author's Ph.D. dissertation in economics, Yale University, 1972.

intangibles probably play a larger role in the military sector than in the private sector, while in circumstances when "the nation's security is threatened," absolute cost might be viewed as a less important consideration. Even a temporary advantage by a potential adversary may be deemed unacceptable, whereas the jockeying for a better competitive position or larger market share among firms with different firms taking the lead at one time or another may be part of a game in which being second or even third to innovate does not ordinarily force a firm out of existence.

A second consideration concerns the way the private sector and the military sector obtain funds for innovative activities. Commercial firms can generate outside funds for R&D by appealing to the expected returns from the introduction of a new or improved product, but the armed services must rely on Congressional favor for a project to obtain appropriations. It is not difficult to see that the strength of the armed services in this bargaining process is generally more enhanced by the existence, or belief in the existence, of a "threat" rather than an "opportunity."

However, it is not the purpose of this study to dwell upon the motivations behind innovation. Product and process improvement in private sector industries, in particular, process innovation in the petroleum refining industry and innovation in civil aviation, will be presented to strengthen the conclusions of Sections II, III, and IV, which are based on a study of U.S. turbine engines.

PROCESS IMPROVEMENT IN THE PETROLEUM REFINING INDUSTRY

The material on petroleum refining presented here is based on two papers by John Enos.[1] I shall attempt to indicate the magnitude of the decline in the cost of producing gasoline due to improvements in the various ways of processing crude petroleum, and especially that due to improvements in particular processes.

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[1] John L. Enos, "A Measure of the Rate of Technological Progress in the Petroleum Refining Industry," *Journal of Industrial Economics*, June 1958, pp. 180-197; "Invention and Innovation in the Petroleum Refining Industry," *The Rate and Direction of Inventive Activity*, NBER, Princeton University Press, 1962. Also see John Enos, *Petroleum Progress and Profits--A History of Process Innovations*, MIT Press, 1962.

The purpose of petroleum refining is to convert crude petroleum into gasoline and other useful products. As demand for these products grew, new processes for their production were developed. The first such development was thermal cracking, in which intense heat is used to break down the molecular structure of crude petroleum. Combined with usual distillation processes, thermal cracking enabled producers to fulfill demand for engine gasolines until about 1930.

At that point, the need for a higher quality gasoline (as measured by the octane number) stimulated the development of the thermal reforming process. In that process, the low octane gasoline obtained from distillation is heated until its molecules reform into a higher octane gasoline.

The next important advance in refining technology was polymerization in which gaseous components of crude petroleum are joined together to yield the heavier liquids. This process enabled refiners to produce high octane motor and aviation fuels from certain byproducts of the cracking and reforming processes.

At the end of the 1930s a cracking process utilizing catalytic agents was developed. Since the yield of this process was greater both in quality and quantity than the thermal cracking process, catalytic cracking began to replace its less profitable thermal counterpart. In the 1950s a catalytic reforming process was developed. Again the higher profitability of this process over the thermal reforming process has caused the latter to be gradually replaced.

In his analysis, Enos divides each of the five advances--thermal cracking, thermal reforming, polymerization, catalytic cracking, and catalytic reforming--into two phases labeled alpha and beta. The alpha phase consists of the invention of the process, its operational development in the laboratory and pilot plant, and its incorporation into the first commercially successful plant. The beta phase consists of improvements incorporated into the process *after* the first venture proves to be a success. Enos attributes these improvements to three causes. First, there are improvements obtained through the construction of larger (operating) units that can take advantage of economies of scale. Second, there are improvements due to pecuniary external economies, for example, quantity purchases of factors of production, or technological advances in supplying factors of production. The latter includes technological progress in the capital goods industry allowing for more efficient construction of plants. Third, there are improvements due to a better understanding of the technical relationships entering into the process, leading to better equipment design, increases in operating efficiency, and the elimination of "bottlenecks."

I shall argue that this third cause of process improvement really consists of two operationally distinguishable causes. The first such is the accumulation of experience, the learning curve. Such learning is more inadvertent than deliberate, and its benefits can be secured merely by keeping good employees on the job. The second is a deliberate investment in cost-reducing sustaining development. Such development can be directed at redesigning a critical part to make it simpler or more reliable or toward engineering a better way to make the process work. In any case, cost-reducing development expenditures operate directly on the problem of lowering the cost of production.

Tables A-1 and A-2 have been adapted from Enos' articles. Table A-1 shows the ratio of capital costs for the most improved unit of a process type to the first unit of that type.[1] Since refining companies were reluctant to reveal operating costs, Enos was forced to use data on the construction cost of refineries as a measure of the improvement in existing processes that were embodied in new capital. Enos does not present any material on process improvement within a particular refinery through modifications of the process or other cost-reducing innovations. This raises the question as to how much of the decrease in cost per unit of output is due to scale effects. Although Enos admits that it is difficult if not impossible to measure the cost-reducing effects of each of the three causes separately, there is no *a priori* reason to believe that all of the decrease in cost per unit of output (of gasoline) was due to such scale effects.

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[1] In Table A-1 the figure for the thermal cracking process represents the ultimate improvement since the process became obsolete in the 1940s. The other processes are still profitable and further improvements can be expected if this is the direction in which economic forces will be pushing.

Table A-1

CAPITAL COST REDUCTION FROM THE IMPROVEMENT OF EXISTING PROCESSES[a]

Process	Date of First or Second Unit	Capital Costs per Barrel of Raw Material Capacity	Date of Most Improved Unit	Capital Cost per Barrel of Raw Material Capacity (constant dollars)[b]	Ratio of Capital Costs: Most Improved/First Unit
Thermal Cracking	1913 (first)	$194	1946	$ 43.1	0.22
Polymerization[c]	1934 (second)	1,675	1949	480	0.29
Catalytic Cracking	1937 (second)	270	1952	82.2	0.30
Catalytic Reforming	1949 (first)	778	1952	284	0.36

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[a] Adapted from Enos, "A Measure of the Rate of Technological Progress," *JIE*, June 1958.

[b] Converted to dollars of year of first unit.

[c] For polymerization, capital cost per barrel of gasoline produced.

Table A-2

TOTAL COST REDUCTION FROM IMPROVEMENTS IN PARTICULAR PROCESSES[a]

Process and Type	Phase in Process History	Consumption of Inputs (per 100,000 ton-miles of transportation output)[b] Labor (man-hours)	Fuel (10^8 BTUs)	Raw Material (1000 gallons)	Capital (current $)	Total Cost (constant 1939 $)	Cost Ratio: end β / end α
Burton (batch thermal cracking)	end of α (1913)	56.0	28.9	13.6	65.5	731.91	.548
	end of β (1922)	9.1	15.6	8.4	50.6	400.89	
Tube and Tank (continuous thermal cracking)	end of α (1922)	12.3	12.6	8.9	34.8	370.93	.600
	end of β (1938)	4.4	9.0	5.2	18.7	222.74	
Fluid catalytic cracking (continuous catalytic cracking)	end of α (1942)	.8	6.6	4.8	16.7	187.39	.608
	mid-β (1955)	.4	2.2	3.5	25.0	114.01	

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[a] Adapted from John Enos, "Invention and Innovation in the Petroleum Refining Industry," NBER, *The Rate and Direction of Inventive Activity*, Tables 4 and 5.

[b] Ton-miles of transportation output is a standard measure of gasoline quantity *and* quality, that is, a higher octane gasoline yields more ton-miles per gallon.

[c] Total cost in constant 1939 dollars was computed by multiplying the input rates of each factor by its 1939 price. Labor costs were assumed to be $.627/man-hour from BLS data on average hourly earnings in all manufacturing industries. This series agrees well with Enos' labor price series (Table 4). BLS data in *Economic Report to the President*, January 1965, Table B-30, p.225. Fuel costs were computed from 1954 *Census of Manufactures*, U.S. Department of Commerce, by weighting various fuel types to obtain an average cost per 10^8 BTU to the petroleum refining industry. Enos' fuel price index was used to arrive at a 1939 cost of $8.33/$10^8$ BTU. Raw material cost was the cost of crude petroleum in 1939 computed at $1.02/barrel (42 gals/barrel) from Signal Oil and Gas Company's Economics Library, Los Angeles, California. Capital costs were adjusted to 1939 dollars using Enos' construction price index (Table 4).

The numbers in Table A-1 do not take into account small but important changes in the quality of the output; in this case the octane number would be a good measure of that quality. Thus although Enos' beta phase dealt with increases in profitability, there were probably noticeable changes in the quality of the output in any given process from the end of the alpha phase to the end of the beta phase that went unnoticed in the analysis.

Table A-2 corrects this deficiency by expressing output in a way that includes quality changes. The cost of producing a unit of output declined as a result of improvements in *particular* processes. Here data on inputs were available along with price indexes for labor, fuel, raw material, and capital. From this information could be computed the *total cost* in 1939 dollars and the ratio of costs from the end of the alpha phase to the end or middle of the beta phase.

The main conclusion from the tables is that the beta phase--that is, the process and product-improvement phase--is quite important and in the words of Enos "as significant in its economic effect as is the alpha." In other words, even after the introduction of a new process competitive with the improved older process--and it would be unlikely to be introduced unless it was at least competitive--there are substantial opportunities for improvements. The impact of these improvements *ex post* usually exceeds that of the initial introduction.

RECENT EXAMPLES OF PRODUCT IMPROVEMENT IN CIVIL AVIATION

Product improvement in civil aviation to a greater degree than in the previous example is stimulated by direct interaction between the manufacturer and the customer, namely the airlines. Although this seems to be because of the highly organized and oligopolistic nature of the supply and demand sides of the market for large passenger aircraft, it is not clear that product-improvement activities are more efficient as a result.

There are several good books on the subject of technological evolution in the civil aviation industry.[1] They do not, however, dwell

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[1] See, for example, Ronald Miller and David Sawers, *The Technical Development of Modern Aviation*, Routledge & Kegan Paul, Ltd., London,

on the improvements incorporated into an existing aircraft design over the period of its economic life. Recent cases of product improvement in civil aviation provide a good example of what can be done. I shall concentrate on the histories of the well-known long-range passenger jet aircraft, Boeing's 707 and 720, Douglas' DC-8, and Convair's 880 and 990. Physical and performance parameters of these aircraft show definite changes from earlier models to later ones, generally in the direction of increased thrust, takeoff weight, and range, and decreased cost per seat-mile. Data on these changes appear in the open literature, primarily in aviation industry serials.

The most successful of the long-range passenger jets is the Boeing 707/720. The first model to be flown commercially was the 707-120. After a short time in service, it became clear that substantial improvements in its performance and profitability could be made. The main improvement was the installation of the newly developed turbofan engine, the JT3D-1 or -3. The advantages of the turbofan were several: takeoff thrust was increased about 25 percent and climb thrust by over 30 percent. Fuel consumption at the speed of the original 707 was about 20 percent lower; at optimal speed, Mach 0.91, fuel consumption was about 12-1/2 percent lower. In addition to the new power plant, changes were made in the wing shape and area to conform better with the so-called "area rule;" the size of the tail structure was increased to give better stability; a small ventral fin was installed at the bottom of the rear part of the fuselage; a power boost was substituted for manual control for the rudder control surface; and certain high lift devices were installed on the leading edge of the wing, giving better takeoff and landing performance.

American Airlines, first to have such modification done, recycled their 707s through the Boeing factory. The original engines, P&W JT3C-6s, were first converted into turbofans at American's Tulsa, Oklahoma maintenance facility and then shipped back to Boeing for installation. The first flight of the modified 707-120B was on June 22, 1960, and that of a similarly modified 720B was on October 6, 1960. The

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1968; or Almarin Phillips, *Technology and Market Structure*, D. C. Health & Company, Lexington, Mass., 1971.

first delivery of a production 707-120B was on February 3, 1961, so in effect the production version of the -120B came after the retrofit version.

The 707-320 and turbofan version -320B were the intercontinental versions of the 707. The fuselage and wingspan of the -320 were 8 feet and 12 feet longer respectively. These aircraft were modest growth versions of the earlier 707s. In early 1965, Boeing considered two substantially longer stretch versions of the 707, the -620 and -820. The former would be an extended 707 for domestic service and the latter was designed to replace the intercontinental -320B. In fact these versions never materialized. Ostensibly the reason was that it would have been necessary to reposition and strengthen the 707 landing gear, and this would have been too costly since basic structural changes in the 707 would have been necessary. In a sense the ability of the 707 to "grow" further was severely limited and the market for large passenger jets in the pre-jumbo era was left to Douglas with its extended DC-8. It might have been possible, though no doubt there would have been added costs and delays, to design in more growth potential for the 707.

The DC-8 came just slightly behind the 707. The Douglas strategy was to improve upon the original DC-8 until it was an acceptable airframe, to freeze the dimensions but offer five versions with four different engines.

In early 1965, Douglas announced three stretched versions of the DC-8. Unlike the 707, Douglas was able to "grow" the DC-8 into the -61, -62, and -63, each of which had a different performance or cost target. Utilizing the -55, the heaviest DC-8 available at that time, the -61 was created by extending the fuselage 36.7 feet. The idea was to reduce the seat-cost per mile for use on high-density routes. The DC-8-62 aimed specifically at longer range by improving the aerodynamics of the wings and engine pods. The -63 was to incorporate both the fuselage and wing changes of the -61 and -62 to reduce costs and increase range. All of these aircraft were powered by P&W JT3D-3B engines used in the DC-8-50 series, and in fact commonality between the -50 series and -60 series was stressed throughout.

The third entrant into the commercial passenger jet field was Convair with its 880 and 990. When the 880 was designed it was thought that an aircraft smaller than the planned 707 or DC-8 would be needed. Events proved Convair wrong when rapid growth in air traffic made larger capacity jets more profitable. Attempts by Convair to "grow" the 880 were not successful either, primarily because the narrow fuselage allowed only five abreast seating whereas the 707 and DC-8 offered six. Nevertheless Convair developed a modified 880 called the 880M for intercontinental use.

This version was created by adding a center-section fuel tank and increasing the size of the wing tanks, which increased fuel capacity by 18.5 percent. Additional modifications included a more powerful engine, strengthening of the landing gear, adding leading edge flaps to the wings, and incorporating a power-boost on the rudder control.

Rather radical changes were introduced on the 990 Convair in an effort to gain a larger share of the passenger jet market. This aircraft was essentially a growth version of the 880M with a longer fuselage, larger wings, more fuel capacity, and antishock fairings on the back edges of the wings. This last feature was installed to make the wing conform to the "area rule," and the result was about a four percent increase in speed.

Table A-3 summarizes the quantitative changes that have occurred as product-improvement versions of the three airliners discussed above were introduced. From the table one could say that there have been substantial improvements in first generation jet airliners. One could add that it appears that these improvements were easy and relatively cheap at first, but by the late 1960s had pretty much run their course. In Section II performance changes and costs were analyzed quantitatively with respect to U.S. turbine engines for evidence of a relationship, but it is hypothesized that what we observe is a common attribute of product-improvement activity.

Table A-3

PRODUCT IMPROVEMENT IN CIVIL AVIATION: LONG-RANGE JET AIRCRAFT

Aircraft	Powerplants	Max. Thrust (lbs)	Percent Change in Max. Thrust From First Model	Cruise Speed (kn)	Max. Take-off Weight (lbs)	Percent Change in Max. Takeoff From First Model	Range with Max. Payload (n.m.)	Percent Change in Range with Max. Payload From First Model
Boeing								
707-120	P&W JT3C-6	54,000	--	495	257,000	--	2,785	--
-120B	JT3D-3	72,000	33	540	257,000	0	3,670	32
-320	JT4A-11	70,000	30	525	312,000	21	4,155	49
-320B	JT3D-3B	72,000	33	527	327,000	27	5,340	92
720	JT3C-12	52,000	--	522	229,000	--	3,665	--
720B	JT3D-3	72,000	38	540	234,000	2	3,600	2
Douglas								
DC-8-10	JT3C-6	54,000	--	505	273,000	--	3,450	--
-20	JT4A-9	67,000	24	505	276,000	1	3,715	8
-30	JT4A-11	70,000	30	505	315,000	15	5,015	45
-40	Rolls Royce R.Co.12	70,000	30	505	315,000	15	4,855	41
-50	JT3D-3	72,000	33	505	315,000	15	5,505	60
-55	JT3D-3B	72,000	33	505	325,000	19	5,560	61
-61	JT3D-3B	72,000	33	505	325,000	19	3,300	-4
-62	JT3D-3B	72,000	33	509	335,000	23	6,600	91
-63	JT3D-3B	72,000	33	509	350,000	28	4,335	26
Convair								
880	GE CJ805-3	42,400	--	527	184,500	--	2,510	--
880M	CJ805-3B	44,800	6	509	193,000	5	2,500	0
990	CJ805-23B	56,800	34	537	253,000	37	3,300	32

Sources: See News Articles under bibliography.

Appendix B

Table B-1

DATA FOR U.S. TURBINE ENGINE TECHNOLOGY EQUATION

Engine Designation/ Manufacturer[a]	MQT Date (Mo/Yr)/ Quarter[b]	Thrust/SFC[c] @ A/B SLS	Thrust/SFC[c] @ Mil. SLS	Qmax/Cruise @ Alt/M (lb/ft^2)	SFC Cruise @ Alt/M (lb/hr/lb)	Weight (lb)	Airflow (lb/sec)	Maximum Diameter (in.)	Length (in.)	Compressor[d] Type	Overall Pressure Ratio/ Bypass Ratio	Turbine Inlet Temperature°R (cooled)
J30/W	12/46(17)	---/---	1560/1.17	475/263	1.80	686	30	19	94	A	3.5/0	1830 (no)
J31/GE	1/45(10)	---/---	1600/1.23	475/263	1.20	825	33	41.5	72	C	4.0/0	1930 (no)
J33/GE & A	4/47(19)	---/---	3825/1.18	825/263	1.29	1875	76	50.5	103	C	4.0/0	1960 (no)
J34/W	4/49(27)	---/---	3250/1.06	825/263	1.27	1200	59	27	120	A	4.0/0	1895 (no)
J35/GE & A	12/47(21)	---/---	3750/1.12	825/317	1.35	2425	72	39	168	A	4.0/0	2030 (no)
J40/W	11/53(45)	10900/2.70	7250/1.08	1250/263	1.21	3580[e]	141	41	287	A	4.6/0	1900 (no)
J42/PW	11/48(25)	---/---	5000/1.25	925/263	1.09	1729	88	49.5	103	C	4.0/0	1825 (no)
J44/F	5/50(31)	---/---	950/1.65	825/535	2.05	328	26	22.5	72	C	2.5/0	1960 (no)
J46/W	7/53(44)	6100/2.5	4080/1.01	1250/263	1.15	1863[e]	71	29	192	A	5.3/0	1985 (no)
J47/GE	3/49(26)	---/---	4850/1.10	1220/197	1.30	2475	91	37	144	A	4.3/0	2060 (no)
J48/PW	10/50(33)	---/---	6250/1.14	1220/263	1.35	2040	113	50	107	C	4.0/0	2030 (no)
J52/PW	7/59(68)	---/---										
J57/PW	12/52(41)	---/---	10000/0.80	1220/263	0.96	4200	162	41	158	A	12.0/0	2060 (no)
J58/PW	4/64(87)											
J60/PW	5/60(71)	---/---	3000/0.96	1220/263	1.16	460	50	24	80	A	7.0/0	2060 (no)
J65/CW	2/54(46)	---/---	7220/0.92	1220/263	1.12	2815	117	38	127	A	6.8/0	2030 (no)
J69/C	9/56(56)	---/---	1025/1.12	825/170	1.25	365	21	22.5	43.5	C	3.9/0	1985 (no)
J71/A	6/54(47)	---/---	9700/0.92	1220/263	1.19	4350	155	40	195	A	8.8/0	2160 (no)
J73/GE	10/54(49)	---/---	8920/0.92	1320/263	1.06	3825	142	37	147	A	7.0/0	2060 (no)
J75/PW	1/57(58)	24500/2.15	16100/0.82	1480/263	0.98	5950[e]	252	43	259	A	11.9/0	2070 (no)
J79/GE	8/56(56)	14500/2.05	9500/0.87	1480/263	1.13	3150[e]	162	37.5	208	A	12.2/0	2160 (no)
J85/GE	9/58(64)	---/---	2250/0.98	825/263	1.20	325	42	20	42	A	7.0/0	1970 (no)
J93/GE	9/64(88)											
J97/GE	9/69(108)	---/---										
J100/C	6/68(103)	---/---	2700/1.10	950/263	1.08	430	45	25	48	M	6.3/0	2250 (no)
TF30/PW	7/65(92)											
TF33/PW	4/60(71)	---/---	17000/0.52	1480/263	0.82	3900	458	53	136	A	12.9/1.4	2060 (no)
TF34/GE	6/72(119)	---/---										
TF35/GE	6/60(71)	---/---	16100/0.56	750/263	0.81	3800	430	53	130	A	13.0/1.5	2160 (no)
TF37/GE	5/64(87)	---/---	4200/0.69	1480/263	1.02	670	130	34	74	A	6.7/1.9	2160 (no)
TF39/GE	10/68(105)	---/---										
TF41/A	12/68(105)	---/---										
JT8D/PW	12/62(81)	---/---	14000/0.60	550/263	0.80	3156	315	43	120	A	16.2/1.1	2240 (no)
JT9D/PW	4/69(107)	---/---										
CF6/GE	9/70(112)	---/---										

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[a] A-Allison; B-Boeing; C-Continental; CW-Curtiss-Wright; F-Fairchild; G-Garrett; GE-General Electric; L-Lycoming; PW-Pratt & Whitney; W-Westinghouse.

[b] Quarter 1 = 4th quarter, 1942.

[c] Thrust in lb and SFC in lb/hr/lb.

[d] A-Axial; C-Centrifugal; M-Mixed.

[e] Weight with afterburner.

Most of the performance parameters of these 35 engines were available from open sources such as Janes' *Aircraft of the World* or *Aviation Week and Space Technology's* survey of U.S. gas turbine engines published yearly in March.
Blanks indicate data deleted to avoid security classification or compromising proprietary information.

Appendix C

Table C-1

U.S. GROWTH ENGINE DATA

Engine Designator/ Manufacturer	Engine Type	MQT Date (Mo/Yr)/Qtr[a]	Thrust @ A/B SLS	Thrust/SFC[b] @ Mil. SLS	Qmax (lbs/ft²)	Weight (lbs)	Total Pressure (lbs/ft²)	Turbine Inlet Temperature°R (cooled)
J33/A	TJ	6/55 (51)		5900/1.10	825	1954	3500	2065 (no)
J35/A	TJ	2/53 (42)		5450/1.11	825	2830	4125	2140 (no)
J47/GE	TJ	11/52 (41)		5970/1.06	1220	2707	6350	2060 (no)
J52,-6,-6A[c]/PW	TJ	1/61 (74)		8500/ .82	1220	2056	14640	2060 (no)
-8A,-8B/PW	TJ	6/65 (91)		9300/ .86	1220	2118	15860	2160 (no)
-408/PW[e]	TJ	5/70 (111)						
J57 -21/PW	TJ	4/55 (51)	16000	11200/ .78	1220	5160[d]	14640	2060 (no)
-20,-20A/PW	TJ	4/59 (67)	18000	11400/ .845	1220	4750[d]	14640	2185 (no)
-420/PW	TJ	10/69 (109)	19600	12400/ .868	1220	4840[d]	15740	2235 (yes)
J60 -4/PW	TJ	8/66 (96)		3300/ .96	1220	460	8540	2060 (no)
J69/C	TJ	11/66 (97)		1920/1.10	825	350	4370	2210 (no)
J71/A	TJ	5/56 (55)		10200/ .92	1220	4090	10750	2160 (no)
J75 -19W,-19WB/PW	TJ	6/58 (63)	26500	16100/ .82	1480	5875[d]	17625	2090 (no)
J79 -8,-15/GE	TJ	7/60 (72)	17000	10900/ .86	1480	3685[d]	19090	2235 (no)
-10,-17,-19/GE	TJ	12/65 (93)	17900	11870/ .84	1480	3835[d]	20000	2270 (no)
J85 -4/GE	TJ	5/66 (95)		2950/ .95	825	404	5200	2160 (no)
-21/GE	TJ	6/71 (115)	5000	3500/1.0	825	667[d]	6600	2250 (no)
TF30-9/PW[e]	TF	7/68 (105)						
-100/PW[e]	TF	6/71 (115)						
TF33-7/PW	TF	3/63 (82)		21000/ .61	1480	4605	23,700	2210 (no)

[a] Quarter 1 = 4th quarter 1942.

[b] Thrust in lbs. and SFC in lbs/hr/lb.

[c] First manned rated version.

[d] Weight with afterburner.

[e] Deleted to avoid security classification or compromising proprietary information.

Most of the performance parameters of these engines were available from open sources such as Janes' *Aircraft of the World* or *Aviation Week and Space Technology*'s survey of U.S. gas turbine engines published yearly in March.

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