AD-A093 821 RAND CORP SANTA MONICA CA F/G 21/5
DEVELOPMENT, ACQUISITION, AND OPERATING AND SUPPORT COST METHOD--ETC(U)
SEP 78 J L BIRKLER, J R NELSON
UNCLASSIFIED RAND/P-6214 NL

1 OF 1
AD
A093821

END
DATE
FILMED
2-84
DTIC

DEVELOPMENT, ACQUISITION, AND OPERATING AND SUPPORT COST METHODS FOR AIRCRAFT TURBINE ENGINES

John L. Birkler
and
J. R. Nelson

September 1978

P-6214

The Rand Corporation
Santa Monica, California 90406

1

DEVELOPMENT, ACQUISITION, AND OPERATING AND SUPPORT COST METHODS FOR AIRCRAFT TURBINE ENGINES

John L. Birkler

J. R. Nelson

Sept~~ember~~ 1978

(1)

This morning's earlier presentations have focused on small, inexpensive, non-man rated engines. The context of my remarks will be quite different. The class of engine I will be discussing is large, man-rated engines that have thrust levels ranging from a few thousand pounds to approximately 50,000 pounds. The development costs can be as much as a half a billion dollars, with unit costs for some in excess of a million dollars.

DEVELOPMENT, ACQUISTION, AND OPERATING AND SUPPORT COST METHODS FOR AIRCRAFT TURBINE ENGINES

(2)

My objectives are two fold. First I would like to discuss two successful engine costing methodologies, and, second, to clearly show why man rated engines have become so expensive, and what can be done to reduce engine costs.

The procedure will be to outline the RAND and Navy methods. The RAND work, sponsored by the USAF, was done by my co-author, J.R. Nelson. The Navy work was done at the Naval Air Development Center for the Naval Air Systems Command

My purpose is not to compare the two methods, but rather to show what two creative organizations were able to achieve using the same data.

OBJECTIVE

- DISCUSS EXAMPLES OF ENGINE COST METHODS AND APPLICATIONS

PROCEDURES

- RAND METHODS
- NAVY METHODS

(3)

RAND has developed methods[*] which address the three phases of an engine's life cycle: development, acquisition, and operating and support.

---

[*] Watts, F. A., *Aircraft Turbine Engines: Development and Procurement Cost*, The Rand Corporation, RM-4670-PR (Abridged), November 1965; Large, J. P., *Estimating Aircraft Turbine Engine Costs*, The Rand Corporation, RM-6384/1-PR, September 1970; Pinkel, B. and J. R. Nelson, *A Critique of Turbine Engine Development Policy*, The Rand Corporation, RM-6100/1-PR, April 1970; Alexander, A. J., and J. R. Nelson, *Measuring Technological Change: Aircraft Turbine Engines*, The Rand Corporation, R-1017-ARPA/PR, April 1972; Shishko, R., *Technological Change Through Product Improvement in Aircraft Turbine Engines*, The Rand Corporation, R-1061-PR, May 1973; Nelson, J. R. and F. S. Timson, *Relating Technology to Acquisition Costs: Aircraft Turbine Engines*, The Rand Corporation, R-1288-PR, March 1974; and Nelson, J. R., *Performance/Schedule/Cost Tradeoffs and Risk Analysis for the Acquisition of Aircraft Turbine Engines: Applications of R-1288-PR Methodology*, The Rand Corporation, R-1781-PR, June 1975; J. R. Nelson, *Life-Cycle Analysis of Aircraft Turbine Engines: Executive Summary*, The Rand Corporation, R-2103-AF, November 1977.

RAND METHODS

- DEVELOPMENT
- ACQUISITION
- OPERATING AND SUPPORT

(4)

The technique employed for assessing the state-of-the art of aircraft turbine engines relates the time of arrival of the 150-hour Model Qualification Test, or the equivalent commercial certification, to a bundle of engine performance characteristics desired in the engine. The 150-hour Model Qualification Test date, and the equivalent FAA certification date for commerical engines, is the time at which the engine is generally considered suitable for operational use. Data for 37 military and commercial engine programs, covering 30 years of experience from 1942 to 1972 were used to develop a temporal relationship in which time of arrival is a proxy for state-of-the-art. In the Rand study, the time of arrival and "delta" time of arrival (the characteristics sought at a certain date compared to when those characteristics were expected to arrive) are both employed in the cost models. This facilitates measurement of the cost implications of the trend of the state-of-the-art, assessment of whether a particular engine design is "pushing" the state-of-the-art within the trend of time and if so, its cost implications.

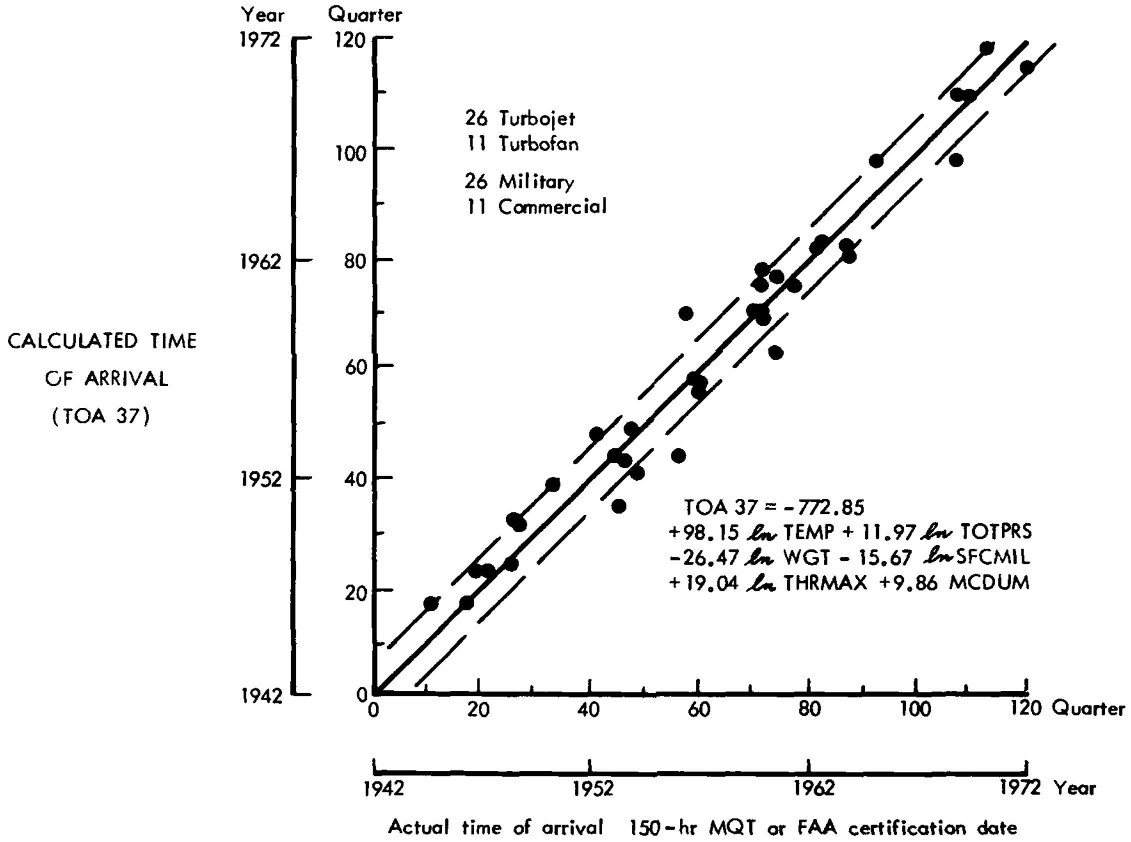
TIME OF ARRIVAL METHODOLOGY

- MULTIPLE REGRESSION TECHNIQUE TO OBTAIN AN EQUATION THAT PREDICTS THE TIME OF ARRIVAL (TOA) OF THE 150-HOUR MODEL QUALIFICATION TEST AS A FUNCTION OF ENGINE PERFORMANCE PARAMETERS
- DETERMINED BY: (VARIABLES)
  - $\text{THRUST}_{\text{max,}}$ SLS
  - WEIGHT
  - TURBINE INLET TEMPERATURE
  - $\text{SPECIFIC FUEL CONSUMPTION}_{\text{mil,}}$ SLS
  - PRESSURE TERM
- ADDITIONAL VARIABLES DO NOT ADD SIGNIFICANTLY TO THE QUALITY OF THE EQUATION

(5)

This chart presents the plot of the engine data base using the time-of-arrival technique as explained in several previous Rand publications. The notion is that engines follow an evolutionary trend, and that a given engine's time-of-arrival (TOA) is calculated on the basis of a bundle of performance characteristics sought at a given date. An engine that arrives when expected is considered a trend engine; an engine falling significantly above the 45 deg line (i.e., its bundle of characteristics indicate that it would be expected to show up at a certain date, but it actually shows up earlier) is considered to be an advanced engine.

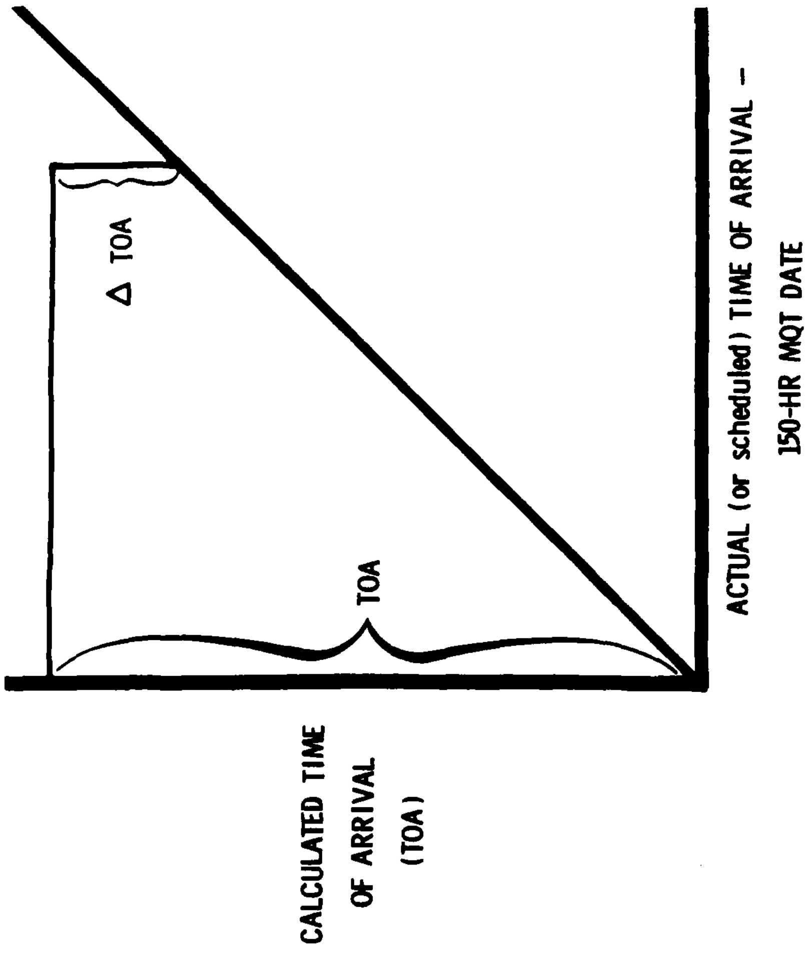
MILITARY AND COMMERCIAL TURBINE ENGINE TIME OF ARRIVAL



(6)

This TOA approach may be used to estimate, first, development and production costs during acquisition, and then ownership costs, using two time measures along with other parameters that are expected to be significant in the cost-estimating relationship (CERs). This chart presents these terms. TOA is the time-of-arrival level for a particular engine calculated from the equation shown on the prior chart and measured from the origin. ΔTOA is the difference between the calculated TOA when an engine is expected to pass its MQT and the actual or scheduled MQT measured from the 45-degree trend line.

It must be emphasized that the TOA methodology does not measure a trend of technology, per se, but rather a time trend of the parameters associated with the successful application of technology: the development, production, and use of products to meet user demand.


Δ TOA
TOA
ACTUAL (or scheduled) TIME OF ARRIVAL –
150-HR MQT DATE
CALCULATED TIME
OF ARRIVAL
(TOA)

(7)

This chart presents the models derived to date. The state-of-the-art trend (time of arrival) is shown with important characteristics sought in an engine: temperature, weight, pressure, specific fuel consumption, and thrust. Below each of the variables is the sign of the coefficient as it enters the model. All of the models and constituent variables are statistically significant; moreover, the variables appear to behave correctly with regard to theoretical engine design relationships. They corroborate the experience of the designers and users in that the direction (sign) of the variables is correct, giving added confidence in the validity of the models. This is true for all the models presented. For instance, in the state-of-the-art trend, where it is expected that technology will be improving with time, increasing turbine inlet temperature is a highly desirable characteristic in an engine; it is constantly increased, it does indeed improve with time, and we do have a positive coefficient for how it enters the TOA relationship. The same with the pressure term; it is expected to increase with time. Variables that would be expected to be reduced with time, such as weight and specific fuel consumption, are entering with negative coefficients. Thrust is positive; the average thrust size of engines have been growing with time.

We make use of TOA and ΔTOA in the cost models. For instance, we've derived a model for development cost. Here, the cost of the engine to be developed to the 150-hour test is a function of development time period (how long the engine was under development), the physical size of the engine, the Δ time of arrival (how the engine was pushing the state-of-the-art), and the complexity of the engine (Mach number measuring the flight environment). All of these variables enter positively, each having the effect of increasing the development cost of the engine.

MILITARY LIFE-CYCLE ANALYSIS MODELS

- State-of-Art Trend: $f(\underset{+}{\text{TEMP}},\ \underset{+}{\text{TOTPRS}},\ \underset{-}{\text{WEIGHT}},\ \underset{-}{\text{SFC}},\ \underset{+}{\text{MAX THRUST}})$
- Development Cost (\$M): $f(\underset{+}{\text{DEVEL TIME}},\ \underset{+}{\text{MAX THRUST}},\ \underset{+}{\Delta\text{TOA}},\ \underset{+}{\text{MACH NO.}})$
- Component Improvement Cost (\$M): $f(\underset{+}{\text{MAX THRUST}},\ \underset{+}{\Delta\text{TOA}},\ \underset{+}{\text{OPERTIME}})$
- Total Development Cost (\$M): $f(\underset{+}{\text{MACH NO.}},\ \underset{+}{\text{QTY}},\ \underset{+}{\text{MAX THRUST}},\ \underset{+}{\Delta\text{TOA}})$
- 1000th Unit Cost (\$M): $f(\underset{+}{\text{MAX THRUST}},\ \underset{+}{\text{TOA}},\ \underset{+}{\text{MACH NO.}},\ \underset{+}{\Delta\text{TOA}})$
- Cumulative Production Quantity Cost (\$M): $f(\underset{+}{\text{QTY}},\ \underset{+}{\text{MAX THRUST}},\ \underset{+}{\text{MFR}},\ \underset{+}{\Delta\text{TOA}},\ \underset{+}{\text{MACH NO.}},\ \underset{+}{\text{TOA}})$

- Depot Maintenance Cost per Engine Flying Hour Restored (\$/EFHR): $f(\underset{-}{\text{AVG. TBO}},\ \underset{+}{\text{UNIT COST}},\ \underset{+}{\text{OPERTIME}}\ \ \underset{-}{\Delta\text{TOA}})$
- Base Maintenance Cost per Engine Flying Hour Consumed (\$/EFHC): $f(\underset{-}{\text{MAX. TBO}},\ \underset{+}{\text{OPERTIME}},\ \underset{+}{\text{UNIT COST}})$

(8)

Of particular interest during early planning at the conceptual phase would be an engine design that falls outside the standard error on the high side; namely, a significantly advanced engine in terms of the data base. Some data points do fall outside the standard error on the high side, such as the J79 example shown. Although an advanced engine may be achievable, the TOA model suggests that it be more difficult than achieving an engine with average characteristics. It is to be expected that an advanced engine will have higher exposure to performance shortfalls and schedule slips and, as will be shown subsequently, will tend to be more expensive to develop and procure. There is also some qualitative evidence (but as yet insufficiently supported by quantitative data) that such an engine may be more susceptible to "teething" problems when introduced into operational service.

AIRCRAFT TURBINE ENGINE TIME-OF-ARRIVAL (TOA) EQUATION

$$\text{TOA26} = -856.4 + 110.10 \ln \text{TEMP} + 11.41 \ln \text{TOTPRS} - 26.08 \ln \text{WGT} - 16.02 \ln \text{SFCMIL} + 18.37 \ln \text{THRMAX}$$

$R^2 = 0.96$
SE = 6.9
F = 92 (5, 20)

EXAMPLE: J79 ENGINE

VARIABLE	VALUE	CALCULATION
Constant	-856.4	-856.4
TEMP	2160	+845.3
TOTPRS	18056	+111.8
WGT	3225	-210.7
SFC	.87	+2.2
THRMAX	15000	+176.6
TOA26		68.8
MQTQTR		57

(9)

Example calculations for the J79 are presented in the next two charts. For J79 development costs the largest contributor is thrust, with development time second. ΔTOA does contribute significantly to cost; the development cost is substantially higher because the engine is being "pushed." The estimating technique more effectively captures the additional cost of a "pushed" engine design.

COST MODEL FOR DEVELOPMENT TO MQT

(IN MILLIONS OF 1975 DOLLARS)

$$\ln \text{DMQTC} = -1.3098 + 0.08538\ \text{DEVTIME} + 0.49630 \ln \text{THRMAX} + 0.04099\ \Delta\text{TOA26} + 0.41368 \ln \text{MACH}$$

$R^2 = 0.961$
$SE = 0.182$
$F = 55.7\ (4, 9)$

<u>EXAMPLE:</u> J79 ENGINE

VARIABLE	VALUE	CALCULATION
Constant	-1.3098	-1.3098
DEVTIME	18	+1.53684
THRMAX	15000	+4.77232
Δ TOA26	11.8	+0.48368
MACH	2.0	+0.28674
$\ln$ DMQTC		5.76978
DMQTC		320.0
Actual DMQTC		324.0

(10)

For the thousandth-unit production cost model, the largest contributor again is thrust. TOA and ΔTOA are again contributors, with Mach number also significant.

COST MODEL FOR THOUSANDTH PRODUCTION UNIT SELLING PRICE

(IN MILLIONS OF 1975 DOLLARS)

$$\ln \text{KPUSP} = -8.2070 + 0.70532 \ln \text{THRMAX} + 0.00674\ \text{TOA26}$$

$$+ 0.45710 \ln \text{MACH} + 0.01804\ \Delta\ \text{TOA26}$$

$R^2 = 0.951$
SE = 0.215
F = 63.0 (4, 13)

<u>EXAMPLE:</u> J79 ENGINE

VARIABLE	VALUE	CALCULATION
Constant	-8.2070	-8.2070
THRMAX	15000	6.78222
TOA26	68.8	0.46371
MACH	2.0	0.31684
Δ TOA26	11.8	0.21287
ln KPUSP		-0.43136
KPUSP		0.650
Actual KPUSP		0.631

(11)

This chart presents a hypothetical baseline program to calculate life-cycle costs for three different generations of tactical fighter engines which are discussed in the following chart. Costs are in constant 1975 dollars; no discounting has been employed in this example, nor are any costs allocated for fuel or attrition.

A LIFE-CYCLE COST EXAMPLE

FIGHTER ENGINES 1950s/1960s/1970s

HYPOTHETICAL PROGRAM: 1975 DOLLARS

5 YEAR DEVELOPMENT (ADVANCED ENGINES)

15 YEAR OPERATIONAL SPAN

6 MILLION ENGINE FLYING HOURS CONSUMED

5 MILLION ENGINE FLYING HOURS RESTORED

1935 ENGINES

90% LEARNING (PRODUCTION)

750/1200 ATBO/MTBO

NO FUEL OR ATTRITION INCLUDED

(12)

This chart illustrates the increasing cost of engines due to improvements in the state-of-the-art over the past three decades.

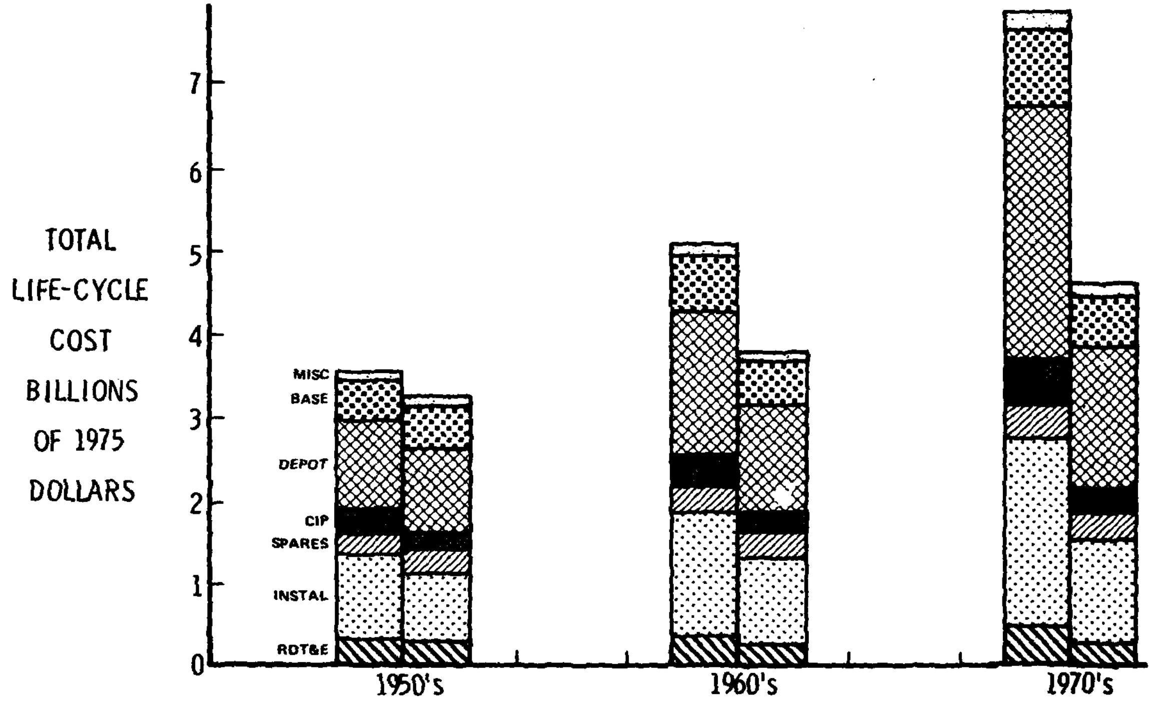
The bars on the left of each set show the increase in costs which result from demanding higher engine performance at a date earlier than indicated by the TOA trend together with increases in thrust and Mach number that have been achieved during these three decades. Of particular interest is that the depot cost is growing not only in terms of magnitude of dollars, but also as an increasing percentage of the total. The bars on the right of each set present trend engines of equal thrust and Mach number so that only the increase due to state-of-the-art improvements over the three decades are captured.

These costs are for the engine only, a subsystem, and not related in any way to the impact that this engine has on total weapon system cost. It may well be that advanced engine technology is well worth the cost when viewed in the context of improved mission capability, reduced fuel consumption, and reduced airframe size.

LIFE-CYCLE COST TREND EXAMPLE

ADVANCED ENGINES: GROWTH THRUST, MACH*

TOA TREND ENGINES: CONSTANT THRUST, MACH**



* Left bar of each set

** Right bar of each set

(13)

Our study at the subsystem level has shown that it is possible to develop techniques in which life-cycle cost estimates can be made sensitive to performance and schedule so that cost magnitudes, proportions and trends, key cost drivers, and tradeoffs may be visible to a weapon system planner early in the concept formulation process.

Our findings indicate that improvements in engine performance alone will increase engine life-cycle costs, and obtaining that engine performance earlier will further increase engine life-cycle cost.

CONCLUSIONS

METHODOLOGY ALLOWS

- ADVANCED PLANNING
- RELATIVE COST DIFFERENCES

(14)

The Navy has developed a different approach to the estimation of the engine costs. For the Navy methods only development and production methods will be discussed.

The approach I will take here is to freely draw on my and erstwhile Navy colleagues' experience and writings--notably Mr. T. Brennan and Mr. L. Finizie of the Naval Air Development Center--to provide background for and insight into the Navy methods.

NAVY METHODS

- DEVELOPMENT
- PRODUCTION

(15)

During 1973 the Naval Air Systems Command tasked the Naval Air Development Center with developing a credible means of forecasting RDT&E (Research, Development, Testing and Evaluation) costs for aircraft engines (turbojet and turbofan).

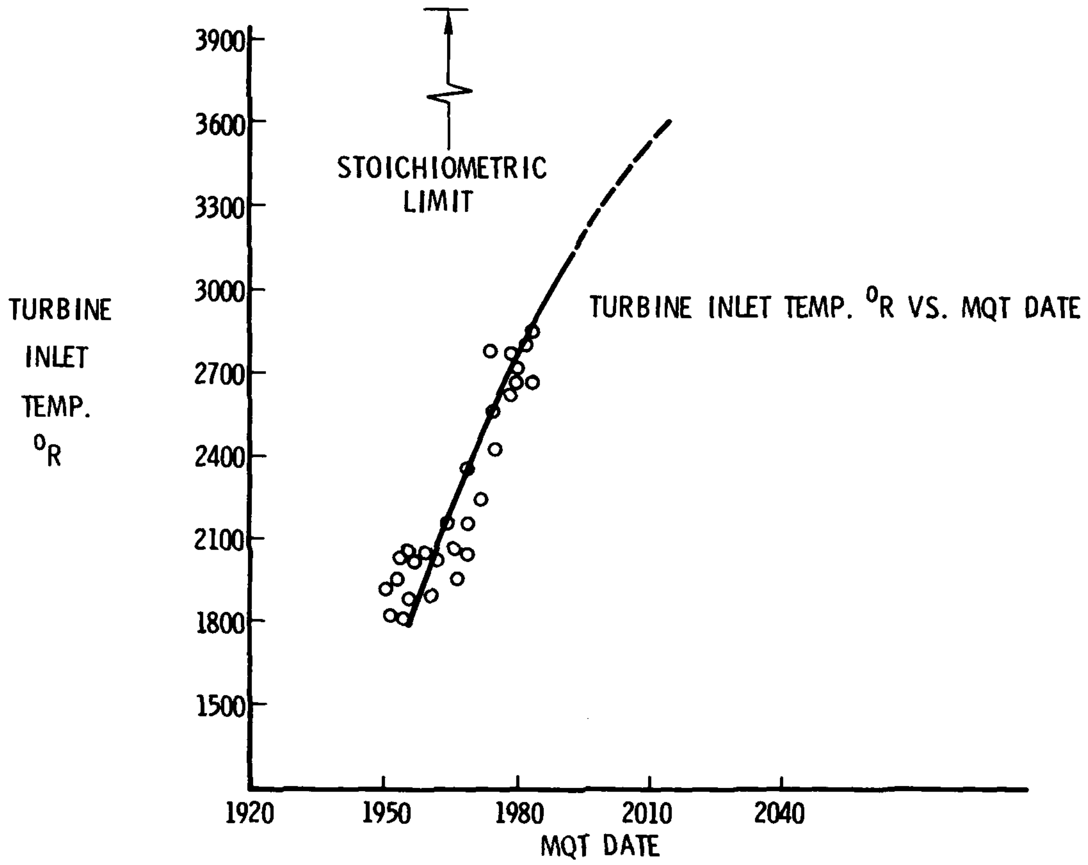
The approach taken was to establish a hypothesis as to the factors expected to affect the RDT&E cost of turbine engines. Having postulated the parametric relationships, historical data were assembled and used to verify the hypothesis and establish the CER (Cost Estimating Relationships) coefficients. Finally, the resulting methodology was tested by simulating predictions that might have been made using it throughout the time period of the data base. Thus, a heuristic measure that says something about the reliability of future estimates was assessed.

Hypothesis

Clearly one of the dominant parameters in the engine cycle is TIT. It governs performance and dictates the engine's complexity. However, in order to develop CER's based on TIT, the relationship between TIT and state-of-the-art must be determined.

Two basic assumptions were made regarding the relationship between TIT and state-of-the-art. The first is TIT will increase with time, becoming increasingly more expensive and difficult to achieve as stoichiometric temperatures are approached. A technological forecasting trend curve confirms this assumption, and shows the relationship between time and temperature for the time frame of interest, 1950-1985.

TECHNOLOGICAL FORECASTING



(16)

The second assumption was that: the directed development effort to achieve a specific TIT reduces with time. This is due to the steady level of R&D effort being spent on engine technology. Let me expand on this constant Turbine Inlet Temperature Line concept.

The first and most important area to identify is the non-linear form of the constant TIT line. The shape of the constant TIT line in the MQT cost vs. time plane is shown. The line can be divided into three regions:

Region 1: A non-linear region where the first turbine stage materials are not or are just becoming available.

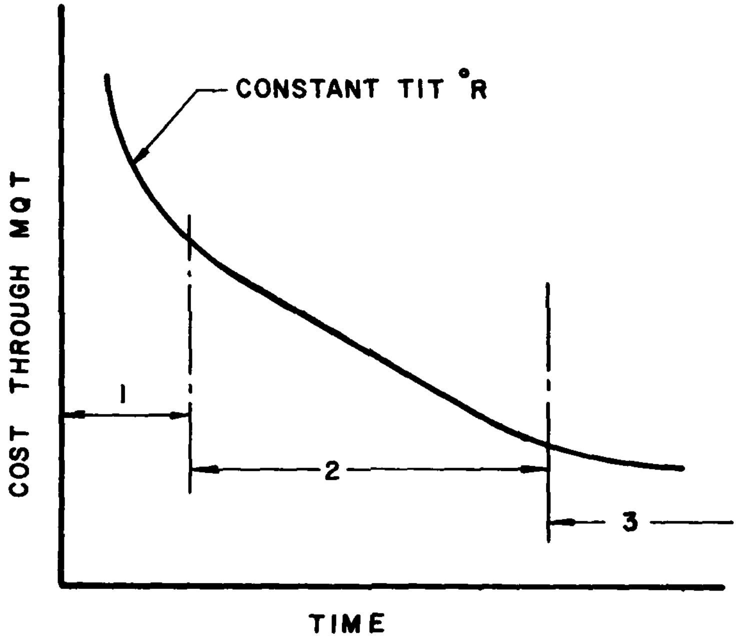
Region 2: A linear region where the first stage turbine materials are available and where most engines are developed and the CER's are valid.

Region 3: A region where a turbine temperature and its associated technology is well established and the cost decay with time for a given temperature is complete.

The value of this curve is the knowledge that engines with turbine temperatures in Region 1 will be disproportionately expensive due to the time and effort necessary to achieve the reliability required to satisfy MQT requirements. Additionally, Region 3 shows that regardless of the TIT, a point in time is reached when the engine will cost and continue to cost a minimum to develop.

COST-TIME RELATIONSHIP

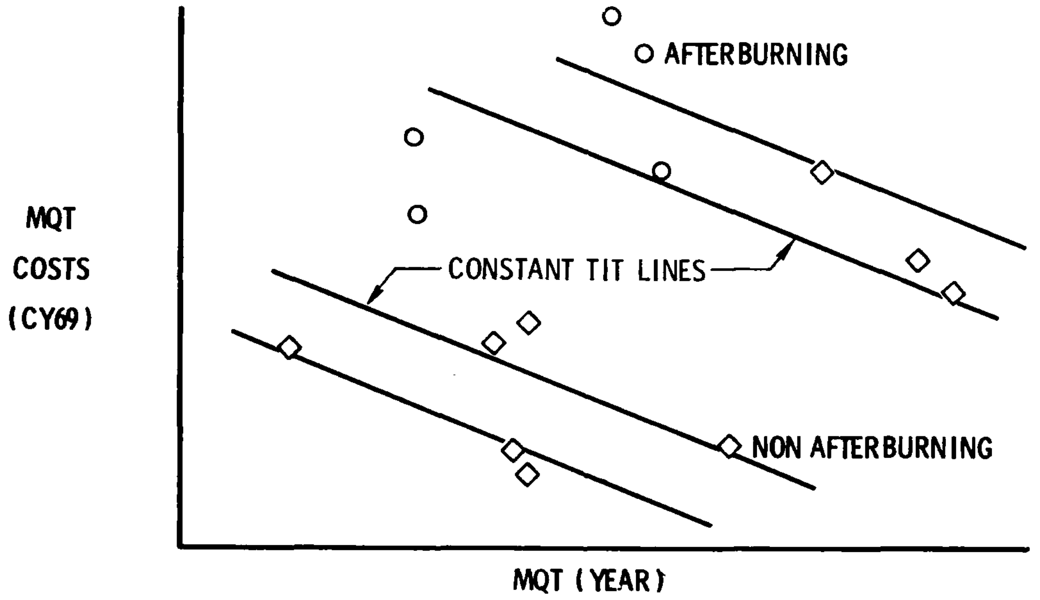
FOR CONSTANT TURBINE INLET TEMPERATURE



(17)

To test this second hypothesis MQT, cost vs MQT date were plotted for the turbine engines of interest. The shotgun scatter of data reveals little useful information until stratified lines of constant turbine temperature are overlaid.

ENGINE DEVELOPMENT COSTS



(18)

This figure is an expansion of the lower left quadrant previous slide. The points plotted here represent engines with similar TIT. The constant TIT line shows *clearly* a linear cost decay with time for the time frame of interest.

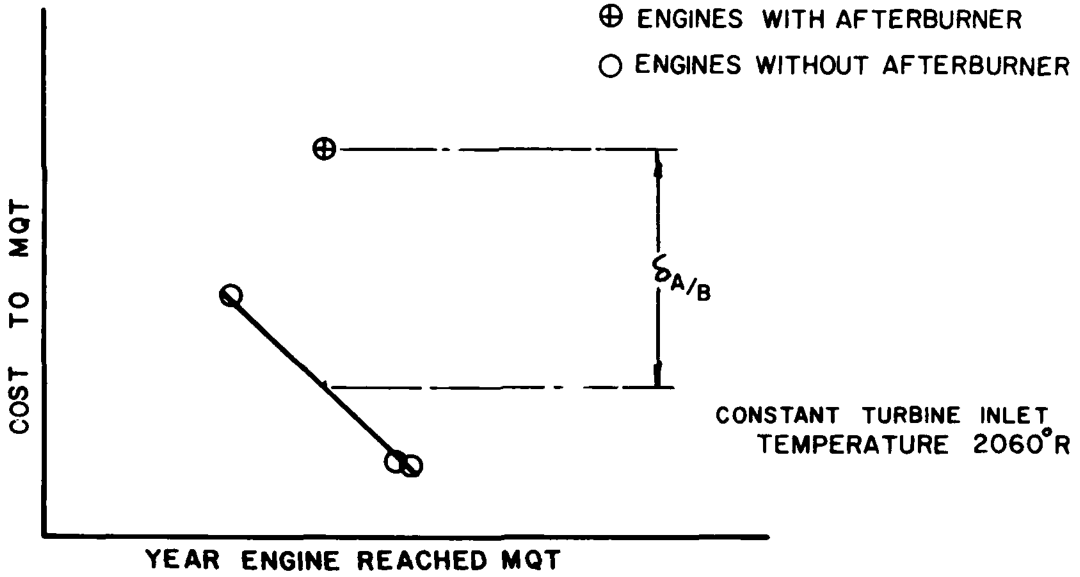
This inverse relationship is due to the learning process, advanced materials, and improved fabrication techniques associated with an achieved temperature, thus serving as building blocks of future engine RDT&E efforts

TIT, *together* with time, should then define the *state-of-the-art* and level of complexity. In a linear CET, TIT and MQT date were expected to reflect RDT&E costs of non-afterburning engines.

Afterburning Engines

This figure *also* provides the basis for a third assumption that there is an incremental increase in RDT&E costs for afterburning engines. This incremental increase is due to the design and testing effort associated with the afterburner and its interaction with gas generator performance. Thus, a *dummy* variable, δ_{AB}, was added to the *TIT and time* factor to account for the expected incremental increase in development costs.

CONSTANT TIT LINE IN THE MQT COST VS. MQT TIME PLANE



Translations of the hypothesis into mathematical terms yielded the equation below:

$$\$ = A_0 + A_1\delta_{AB} + A_2(TIT) + A_3(MQT) \qquad (1)$$

where

$\$$ = the total RDT&E cost to the government (through MQT) expressed in millions dollars

MQT = as used in the CER's is the year and fraction thereof when the engine satisfied the Model Qualification Test minus 1900

TIT = Turbine Inlet Temperature ^{o}R

δ_{AB} = dummy variable for afterburning engines

$\delta_{AB} = 0$; non-afterburning engines

$\delta_{AB} = 1$; afterburning engines

and

A_0, A_1, and A_3 are the coefficients to be determined.

Regression theory is particularly adaptable when the form of the hypothesized CER is linear as in Equation (1). Examination of the various regression statistics such as coefficient of correlation, standard error of estimate, and confidence level will indicate the reliability and validity of the hypothesized CER's. Probabilistic statements about data points not contained in the original sample can then be made. The assumption, of course, is that the equation which fits the data best will predict best.

DEVELOPMENT COST METHODOLOGY

ENGINE DATA BASE

J52 TF30
J57 TF33
J58 TF34
J60 TF39
J75 JT8D
J79 JT9D
J85
J93$^+$

+ NON QUALIFIED

STEPWISE LINEAR REGRESSION

➡ $\$ = A_1 + A_2 TIT - A_3 MQT + A_4 \delta_{AB}$ ➡

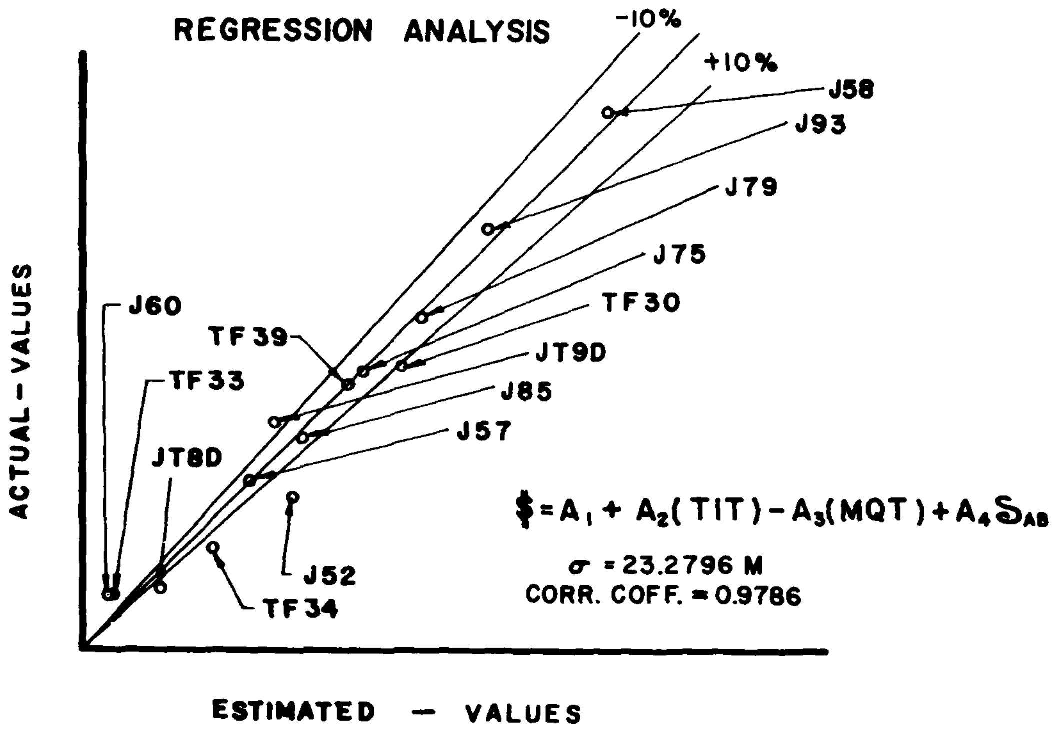
$\sigma = 23.3\overline{M}$ (CY69)
CORR. COEF. = .979

(20)

This figure illustrates how well Equation (1) fits the data within the sample (the axes are not labeled due to the proprietary nature of the cost data).

Thus, the original hypothesis and conclusions regarding the interaction among TIT, engine sizing parameters, time, and RDT&E costs, have been verified.

DEVELOPMENT COSTS



(21)

Historical Simulation

Equation (1) will predict future engine RDT&E costs, but if the theories and CER's have merit now, the same relationships should have worked in the past, thus predicting engine development costs accurately in the 1950's, 1960's and early 1970's.

The technique that tests this rationale is known as historical simulation. Regression theory assumes that "that which fits the data best predicts best." The inference from historical simulation is "that which predicted best in the past will continue to predict best." Conclusions concerning the validity and reliability of the hypothesized cost estimating procedure can then be assumed from the closeness of the simulated cost predictions to actual costs.

The historical simulation technique was implemented by arranging the engines in chronological order, and then performing a regression analysis on the first six engines (a sample size of 6). The regression coefficients obtained were then used to predict the development costs of the remaining engines. The process is incremental by one until only the development costs for the most recent engine remains to be predicted.

ESTIMATING TECHNIQUES

- STEP WISE LINEAR REGRESSION

  THAT WHICH FITS THE DATA BEST WILL
  PREDICT BEST

- HISTORICAL SIMULATION

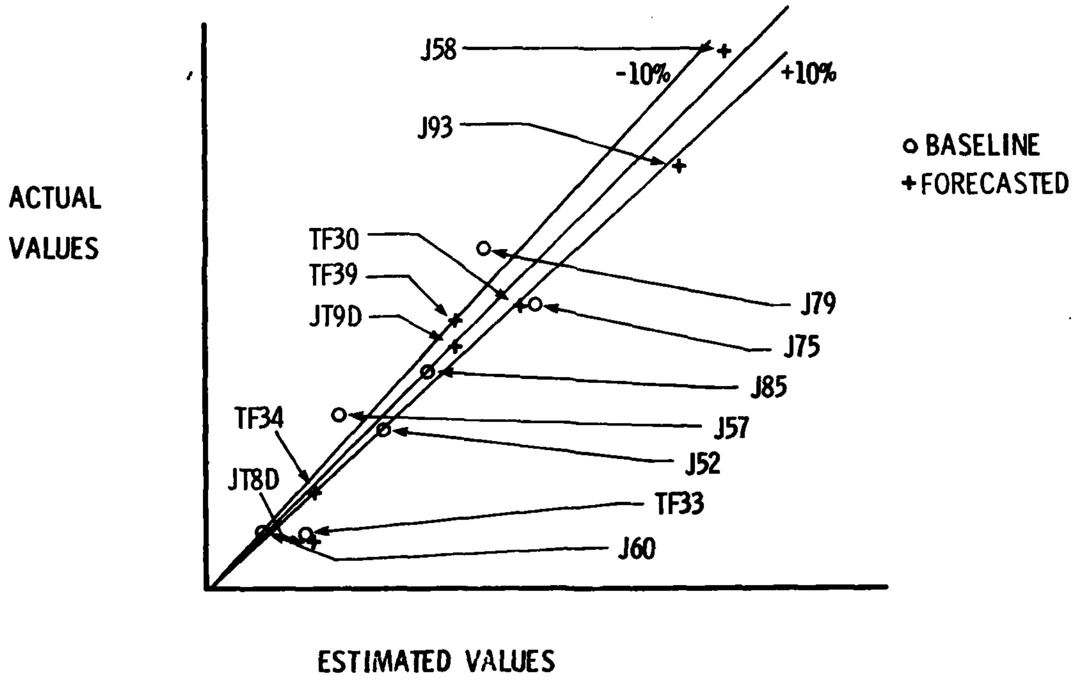
  THAT WHICH PREDICTED BEST IN THE
  PAST WILL CONTINUE TO PREDICT BEST

(22)

This figure illustrates an application of the historical simulation methodology utilizing a sample size of seven. The overlay, engines identified by pluses, shows how well the regression coefficients obtained would have predicted the actual development costs for engines (J58, J93, TF30, TF39, JT9D, TF39, JT8D) not included in the sample.

HISTORICAL SIMULATION

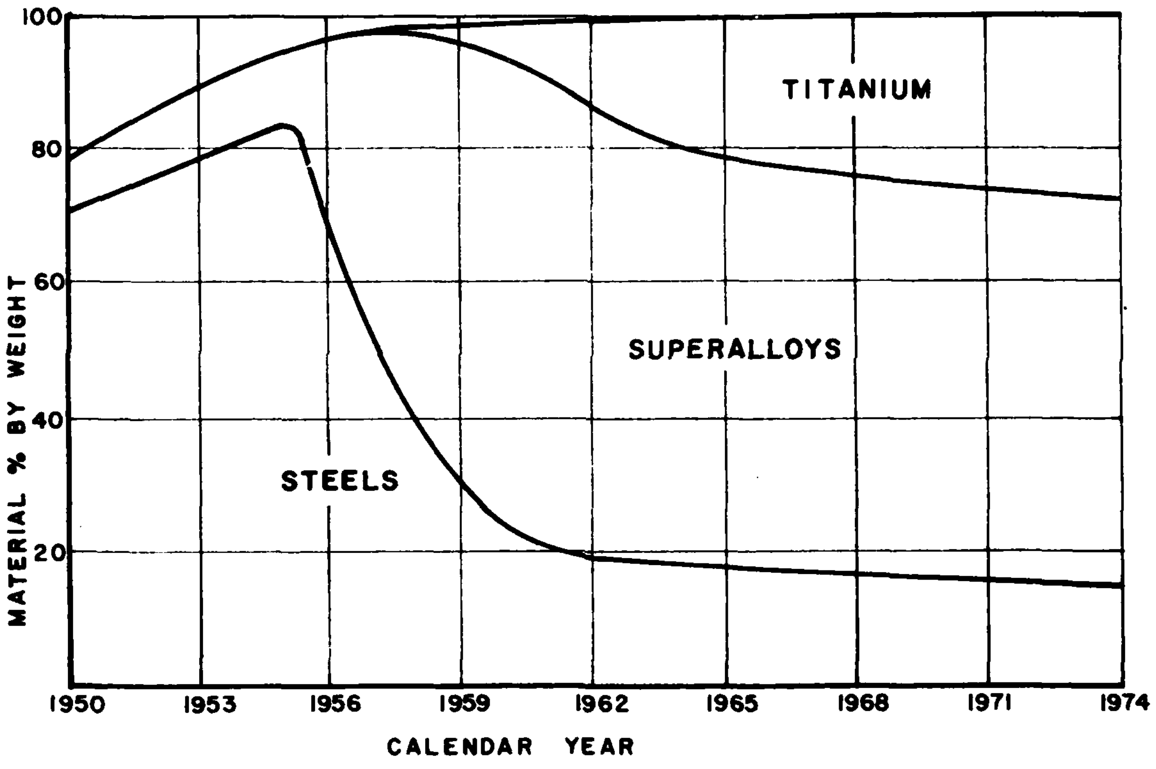
SAMPLE SIZE 7



(23)

Traditionally, the gas turbine industry has pioneered the high stress/temperature technologies for their specific application. This figure shows the change in complexion of engine materials during the past few decades. During the post World War II and Korean Conflict years, engines were produced primarily from carbon and low alloy stainless steels as well as magnesium and aluminum; in short, the "exotic" nature of the material used was low. This trend continued until the mid-1950s when the demand for high-Mach speeds and corresponding higher thrusts, component efficiencies, and turbine temperatures required the development and usage of cobalt-nickel-base alloys as well as titanium materials for weight reduction and strength increases. Inherent in the application of these materials is *increased* raw material cost and *difficulty* in machining and fabrication.

MATERIAL TRENDS



(24)

This figure shows the major classifications of materials that evolved through the years. As noted, the conventional materials are the carbon steels, some low-alloy stainless steels, aluminum and magnesium. All titanium alloys are classified under a single category and the more exotic alloys (higher-alloy stainless and various nickel and cobalt based alloys) were categorized into ascending alphabetical groups. The relative material and machining costs were determined by an average of the various input forms--billet, bar, sheet, etc.--and fabrication processes involved. The product of these relative costs provided a weighting factor for each classification as noted.

MATERIAL CLASSIFICATION

	MAJOR CASE, DISC, SPACER SHAFT					
	Ti	A	B	C	D	CONV
RELATIVE MATERIAL COST	7.0	3-4	4-5	5-7	7-10	1.0
RELATIVE MACHINING COSTS	1.5	1.9	3.1	4.0	3.5	1.0
RELATIVE WEIGHTING FACTOR	10.5	6.7	14.0	24.0	29.8	1.0
TYPICAL MATERIALS	6 AL – 4 V 6 AL – 6 V – 2 Sn	17-4 PH SS A-286 GREEK ASCOLOY	HASTELLOY-X HASTELLOY-B INCO-706	L-605 INCO-718 INCO-625	WASPALLOY RENE-41 ASTROLOY	321 SS CARBON STEEL ALUMINUM

(25)

The engine's Maurer Factor value is the summation of the product of the relative weighting factor and the raw material input weight for each material classification as shown. Note that the weight of a given material reflects the input weight prior to initiating the manufacturing process.

MAURER FACTOR DERIVATION

$$\text{MAURER FACTOR} = \sum_{i=1}^{n} w_i W_i$$

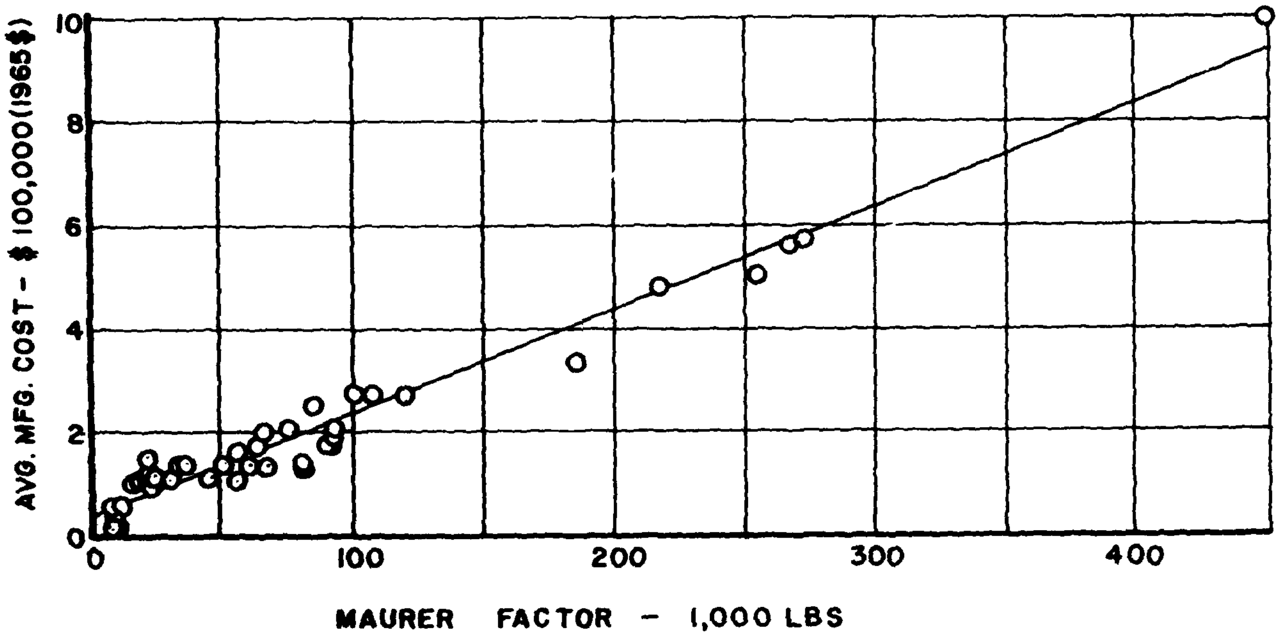
$$= (w_1 W_1 + w_2 W_2 + \ldots\ldots\ldots w_n W_n)$$

WHERE w_i IS THE WEIGHT OF THE ith PART &
W_i IS THE CORRESPONDING WEIGHTING FACTOR

(26)

Detailed studies were conducted to determine the exact relationship between the proposed "exotic material factor"--later renamed the Maurer Factor as a posthumous tribute to its Navy proponent--and the cost required to manufacture an engine. The manufacturing cost--namely material, labor, and shop overhead costs--averaged over the first 1500 production units was determined as the significant cost factor controlled by the material usage. This figure shows this correlation and the range of engines over which the data are applicable--virtually two decades of experience.

MAURER FACTOR CORRELATION WITH COST



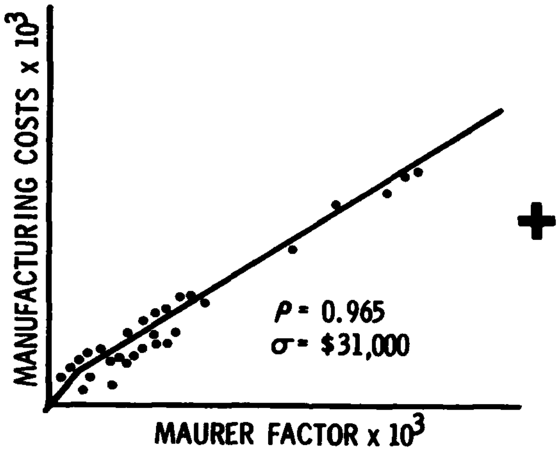
(27)

This figure illustrates the resulting pricing rationale used currently for advanced technology engine cost prediction. Much emphasis has been concentrated to establish meaningful escalation rates for labor and material as well as development of learning theory techniques and applications to individual manufacturers. These emphasis areas will not be addressed in detail here. The selling price to the government is determined by the manufacturing cost estimates provided by the Maurer Factor methodology plus the effect of G&A and profit.

PRODUCTION ENGINE COSTING

MAURER FACTOR = $(\omega_1 W_1 + \omega_2 W_2 + \ldots\ldots. \omega_n W_n)$

SELLING PRICE =



\+ ECONOMICS
LEARNING
O / H EVALUATION
PROFIT PROJECTION

(28)

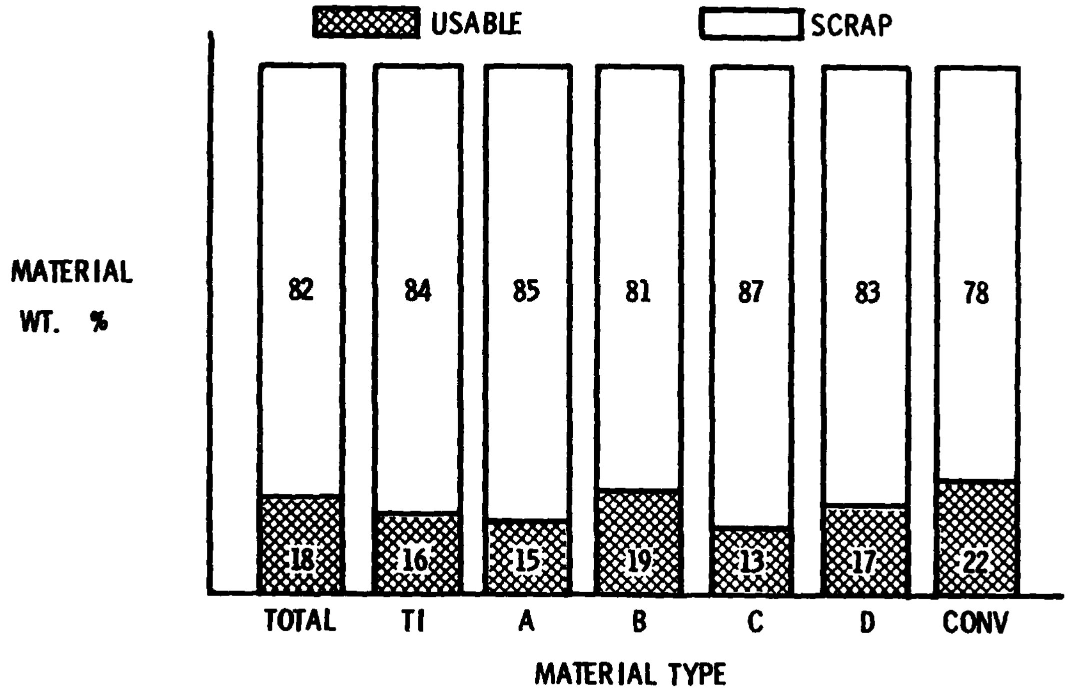
Future Design Influences

As a summation on the merits of a material approach to engine costing, its impact on future designs and manufacturing is discussed. Two paths exist to achieving lower engine costs. The first requires material research to develop advanced materials capable of enduring the high stress and temperature engine environment while providing lower material and machining costs. The obstacle to this path is that each succeeding generation of exotic materials has become increasingly more expensive and arduous to machine. The second path, however, offers more hope to reduce engine costs. This figure displays the material utilization for seven randomly selected engines. For the engine overall, more than five pounds of raw material are required to produce a pound of finished product. The more exotic materials peak interest because of their lower than average utilization.

The message ringing clear is that the path to engine cost reduction lies in reducing the scrap rate. The Maurer Factor has shown the pecuniary value of materials and, considering the enormous amount of funds expended in production engines and spare parts each year, the potential for cost savings as well as material conservation is substantial.

DESIGN INFLUENCES

INFLUENCING MANUFACTURING TECHNOLOGY



(29)

The models which have been described are useful aids to the planning and decision making process for the type of engines in the sample providing information reflective of historical experience. But, as with all models, limits to their applicability exist. The methodologies discussed today might be applied to small, non-man rated engines; the equations shown may not, since the development and acquisition philosophies are dissimilar and the extremes of engine size present different technological challenges. Thus, any engine costed must be consistent with the basic assumptions under which the CER's were derived. Specifically, the CER's apply to development and pricing practices similar to those of the 1950's, 1960's and early 1970's. However, the impact of the smokeless, quiet, and other new engine technologies as well as changes in policies must be calculated independently and used to adjust the cost predicted by the models.

USES AND ABUSES OF MODELS

- PURPOSE OF MODEL
    - PROVIDE INFORMATION
- STATISTICAL SIGNIFICANCE
    - DATA LIMITATIONS
- BEHAVIOR OF MODEL
    - BASED ON HISTORICAL DATA
    - INDUSTRY TRENDS
    - FUTURE EXPECTED TO BEHAVE LIKE PAST
- CAUTIONS
    - CHANGES IN POLICIES AND PROCESSES
    - "REAL" VS. "PAPER" CHANGES IN COST

(30)

More detailed discussion of the material covered is available in these documents.

AVAILABLE DOCUMENTS

NELSON, J.R. "LIFE-CYCLE ANALYSIS OF AIRCRAFT
TURBINE ENGINES"
RAND REPORT R-2103-AF
(Executive Summary R-2103/1-AF)

"PROCEEDINGS OF OSD AIRCRAFT ENGINE DESIGN &
LIFE CYCLE COST SEMINAR"
November, 1975