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NAVY METHODOLOGY FOR PREDICTING AIRCRAFT ENGINE PRODUCTION COSTS USING THE MAURER FACTOR CONCEPT

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S U M M A R Y

This report documents a method developed whereby correlations for engine cost dependency were related to physical and metallurgical characteristics of current Navy propulsion systems. As an outgrowth of these correlations, an electronic data processing system for the collection, storage, and retrieval of historical cost and engineering data was developed to provide an accurate and timely computer data bank of information. From the correlations of historical cost and performance parameters, a cost model was developed to predict the production costs of future aircraft propulsion systems, and thereby, provide a budgetary, planning and evaluation costing tool for the Naval Air Systems Command (NAVAIR).

The method developed in this study provides sufficient depth and accuracy so that the costing technique can be applied to all procurements of military aircraft propulsion systems.

ACKNOWLEDGEMENTS

Much of the work reported in this document was accomplished over a period of several years. The principal contributors to this effort were: Thomas J. Brennan, John L. Birkler, Charles R. Lampert, Robert N. Taylor, and Joseph J. Zanine, all of the Naval Air Development Center. Most of the proprietary cost data obtained from Pratt and Whitney (PWA), General Electric (G.E.), and the Allison Gas Turbine Division (AGTD) of General Motors was due to the combined efforts of Mr. Richard J. Maurer, Mr. A.S. Atkinson, Mr. A. Pressman, and Mr. A.G. Steinert of the Naval Air Systems Command. The U.S. Air Force and the U.S. Army cooperated with the Navy by providing their turbine engine cost data. This report was made possible as a result of the cooperative efforts of the above people and the three military services.

INTRODUCTION

Increased emphasis is being placed on all elements that contribute to a military weapon systems Life Cycle Cost (LCC) in an effort to reduce such costs in both current and future systems.

Although aircraft turbine engines are a weapons subsystem, they account for billions of dollars annually in the Research and Development (R&D), Production, and Operating and Support (O&S) phases of their life cycle. Historically, decisions affecting Naval aircraft engines have been made emphasizing performance with little consideration of cost. The actual engine performance can, generally, be accurately estimated several years prior to the development of an engine. With the advent of more sophisticated weapon and propulsion systems a conscious understanding of the cost implications and their relationship with specified performance requirements is necessary. These implications necessitate an in-depth understanding of the life cycle cost during the three phases of the propulsion system acquisition: Research and Development, Production, Operation, and Support. It is anticipated that future requirements will demand engine component (i.e., compressor, burner, turbine, etc.) life cycle costs versus performance trade-offs be performed during the conceptual phase prior to full scale development.

Future justification of military weapon systems, and their major subsystems, will not withstand scrutiny if poorly defined subsystem costs result in uncertain system life cycle costs.

The Naval Air Systems Command (NAVAIR) requested the Naval Air Development Center (NAVAIRDEVCCEN) to initiate development of an up-to-date tool for the planning and budgeting of future costs for these systems as a foremost objective.

Cost prediction techniques applicable to the R&D were investigated and reported in references (a) and (b), and prediction techniques for O&S costs are under investigation. This report deals with the development of production cost prediction methods. Together, these cost prediction methods will provide an entire life-cycle costing technique for Naval gas turbine engines.

APPROACH

The approach of the engine production cost study consisted of several phases, the first of which was a literature search. Most of the cost information was obtained from published literature but much of the cost data was provided by NAVAIR (AIR-536).

The second phase of the approach was to evaluate and use cost analysis methods found in the literature for comparison with historical costs for gas turbine engines procured by the Navy. Results of these comparisons were then used as a standard for the NAVAIRDEVCCEN developed methodology.

Production costs were used for correlations with selected engine parameters. In addition engine costs were also correlated with engine material content. Initially PWA provided the material information used in the correlations. Later when abbreviated summary bills of materials became available, computations were made using the material content and PWA weighting factors.

Since cost correlated more closely with material content than with all other engine parameters, this was selected as the principal parameter for computing production engine cost.

Some interim results related to this study were reported in reference (c).

DISCUSSION AND RESULTS

SURVEY AND REVIEW OF PREVIOUS STUDIES

Prior to the formulation of a rigid method of approach for the study, an investigation into the results of similar studies was conducted to provide insight as to the methodologies and techniques used by previous analysts. A bibliography of reports and papers was compiled and noted herein, which describe various methods and approaches, most of which provide statistical analyses of the variables concerned. It should be noted that several of the reports combined data or placed a high significance on certain variables in such a way as to indicate that the results were questionable solely from engineering logic. Other reports indicated some logical results but the statistical significance of these correlations was too low to provide accurate predictions. Although several reports indicated that the materials used in a propulsion system should have an effect on the cost, there was no analysis that suggested these considerations were analyzed rigorously.

A comprehensive engine cost study by the Naval Surface Weapons Center (NAVSWC), Dahlgren, was conducted in support of an ad hoc task committee in 1966. This committee was formed in response to an Office of the Secretary of Defense directive to the Navy and Air Force that they jointly accomplish cost studies on the entire F-111 weapon system program. NAVSWC was tasked with developing statistical correlations which would accurately describe the prime indicators of engine cost. Twenty-four different engines were analyzed. By selective processes, the "best" combination of variables (as determined by the coefficient of determination for linear, quadratic, exponential, and geometric equations for both single and multi-variable correlations) used to estimate engine cost was found to be a complex analytical expression which included specific thrust, airflow, total number of parts, and exotic material content. Although the expressions derived in some cases lacked engineering logic, the study was, in fact, the first to incorporate a variable for material content.

DEVELOPMENT OF PRESENT METHODOLOGY

With the results of past studies as a background, a method of approach to the NAVAIR-DEVCON study was formulated through successive meetings with NAVAIR. Initially, correlations between engine parameters such as temperature, airflow, etc. and production costs were not as good as those between materials and cost. The approach considered another statistical analysis of cost versus performance parameters unnecessary; rather, a concentrated effort would be applied to further investigate the factors driving engine costs. Thus, a search for more meaningful parameters to add engineering logic to analytic expressions was begun. As an example of poor engineering rationale, assume that, from historical data, a significant correlation exists between cost and Thrust/Weight (T/W) ratio of the engine. This relationship would be valuable as a prediction device if the T/W could be predicted in the future. Even if this prediction were possible, the underlying reasons as to why or how T/W affects the cost is still missing. The actual technology involved with increasing the T/W would be of greater interest than the mere fact that a cost relationship exists.

By employing the rationale that the cost of the engine is governed, in large part, if not entirely, by the raw material content used in the manufacture of an engine, a useful parameter was sought. This rationale assumes that most of the physical and thermodynamic areas associated with engines, i.e., compressor stage loading, maximum turbine inlet temperature, specific weight, etc. are closely interrelated with the metallurgical technology. *This interrelationship is probably more akin to the aircraft engine industry than any other aerospace industry because of the severe stress and thermal environment experienced by an aircraft engine.* This approach required that the materials and manufacturing techniques used in the engine industry be investigated.

Engine Cost Considerations

1. Materials

The severity of the operational environment, temperatures and stresses to which engine components, particularly turbine blades and vanes are subjected has required the continuous development of specialized materials and alloys. Because these engine materials use rare elements such as cobalt and columbium, they are termed exotic. The limited usage of these exotic materials is illustrated in the use of titanium by PWA when it first began making titanium engine parts in 1954. At that time 50 percent of the then world's supply of titanium was used by PWA for fabrication of aircraft engine parts. The cost of exotic materials, when first used in engines is very high because of the limited application. As the use of a material becomes widespread the cost decreases.

2. Fabrication

Gas turbine engine components are expensive, not only because they are made from exotic materials, but also due to the high cost of fabrication. Because of the function they must perform, almost all engine parts are machined on all surfaces, and as a result, much of the raw material is lost during the fabrication process. Figure 1 shows the typical percentage of finished to raw material weight for the three basic material forms. This material loss is even worse because over 60 percent of the modern gas turbine engine is composed of forgings and castings. Although new fabrication techniques have been developed, most of the machining is still being done by conventional methods. The fact is, however, that the material lost in the fabrication process is the single most important reason for the high production cost of gas turbine engines.

Development of the Maurer Factor Concept

Conscious of the fact that engine input material is so expensive and so little of it becomes a finished engine part, Mr. R.J. Maurer of the NAVAIR Propulsion and Power Division conceived the idea of a material factor to serve as a variable for correlating engine costs. This factor has since been renamed the Maurer Factor as a posthumous tribute to its originator. In determining the Maurer Factor each material used in the fabrication of an aircraft engine is given a relative weighting factor that reflects not only the initial cost of the material, but also its machinability. Low alloy iron is used as a reference and is assigned a weighting factor of two. Other materials are then grouped into classifications by relative weight factor as shown in figure 2 according to material cost and machining difficulty. The Maurer Factor is determined by the summation of the product of the relative weighting factor and the material input weight for each classification as follows:

$$\text{Maurer Factor} = \sum (\text{relative weighting factor} \times \text{material input weight}).$$

A more detailed discussion of the use of the bill of materials in producing the Maurer Factor is given in reference (c).

Cost Data Base

Early in the cost study the value of these relative weighting factors were provided by PWA. Inspection of the available cost data from PWA, the primary source of the original cost data, revealed that the engine cost was subdivided into the major cost accounting areas (i.e., material costs, labor costs, manufacturing overhead costs, etc.). This cost data will not be published because of its proprietary nature. The available cost data provided a cost breakdown for all PWA engines produced since 1951. The cost data had to be segregated by engine model, the production years applicable to each model, and the specific cost applicable to each model by year. This combination of variables (model, production years, and cost) was organized into a three dimensional matrix array to facilitate computer operation.

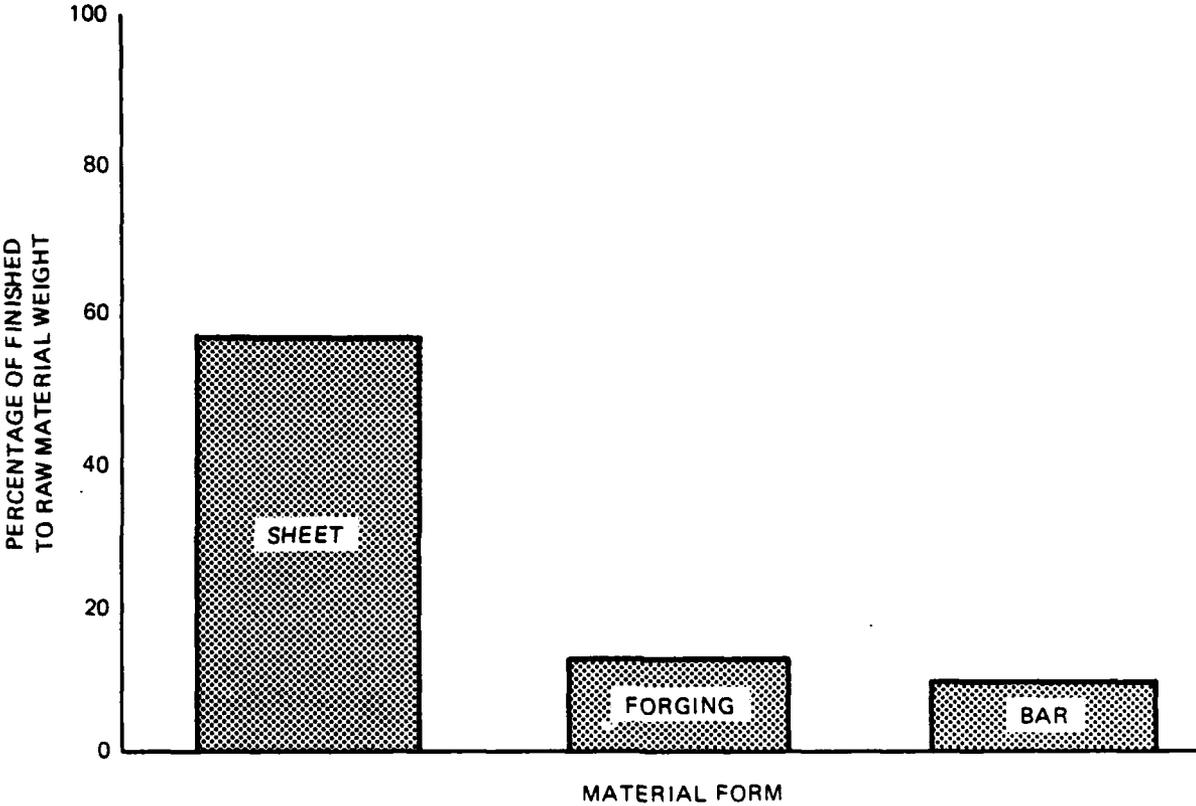


Figure 1. Manufacturing Weight Loss by Material Form

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| CATEGORIES | WEIGHTING FACTORS | TYPICAL MATERIALS |
|------------|-------------------|-------------------------------------|
| A | 2 | ALUMINUM, MAGNESIUM, A-286 |
| B | 6 | INCONEL 718, WASPALLOY, HASTELLOY X |
| C | 10 | TITANIUM |
| D | 14 | M252, N-155 |
| E | 18 | L605, S816 |
| F | 22 | UDIMET 500 |
| G | 26 | ASTROLOY, RENE 41, RENE 80 |
| H | 30 | HS21, X40 |
| I | 34 | RENE 77, RENE 95 |
| J | 38 | UDIMET 700 |

Figure 2. Material Classifications

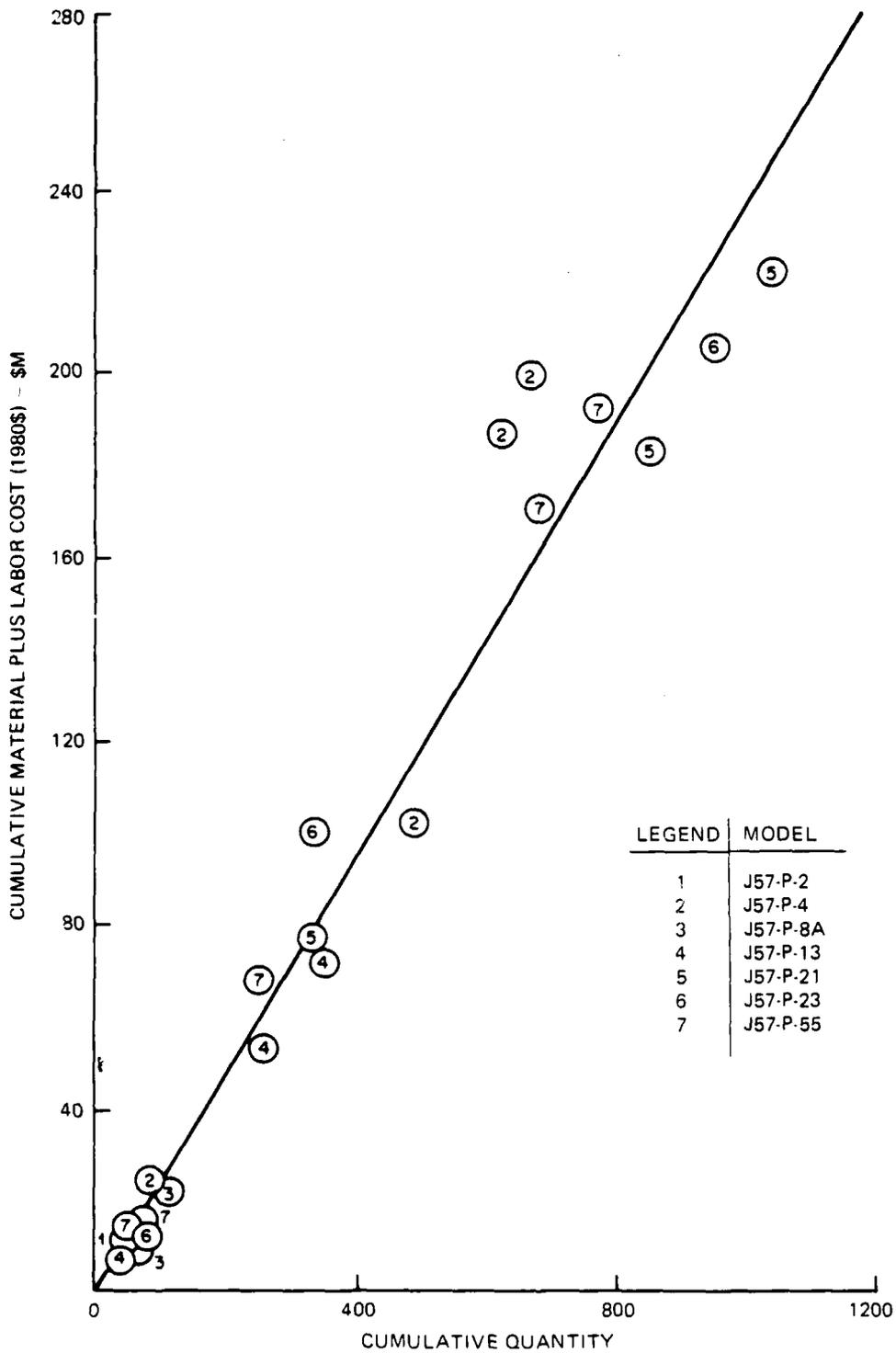


Figure 11. Cumulative Cost vs. Quantity. First Year Large Buy, Afterburning Engines

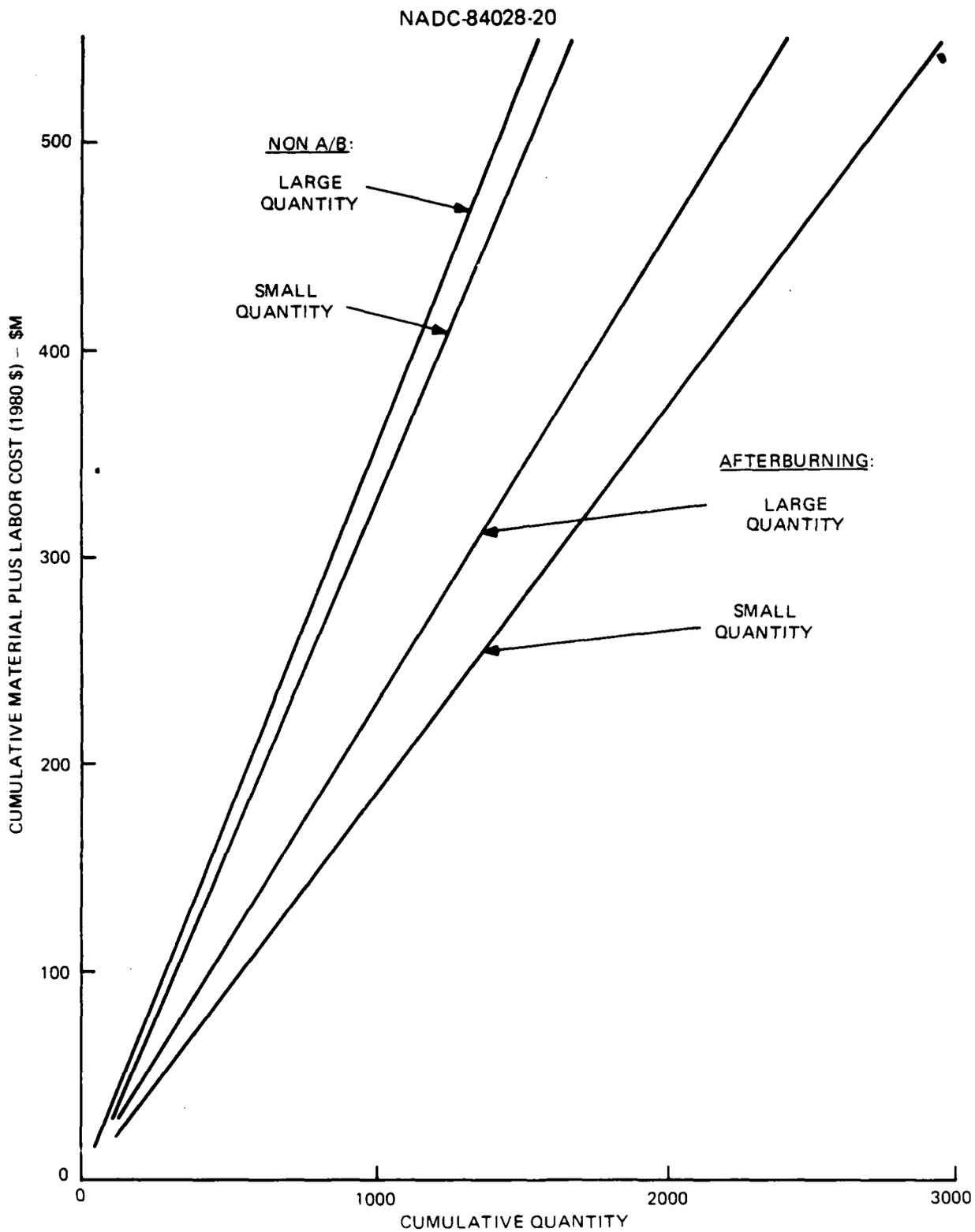


Figure 10. Cost-Quantity Trends

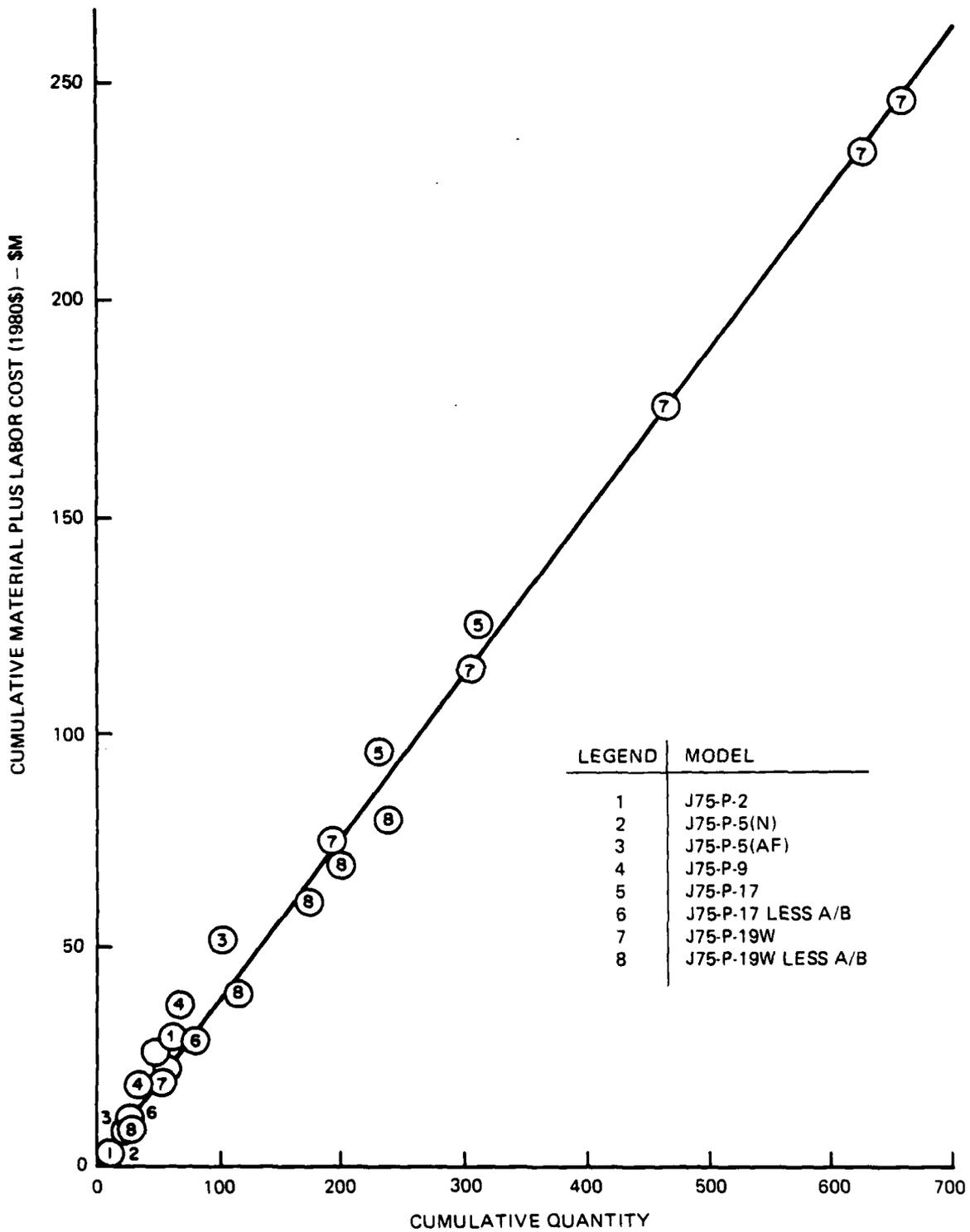


Figure 9. Cost Variation with Quantity for J75 Engine

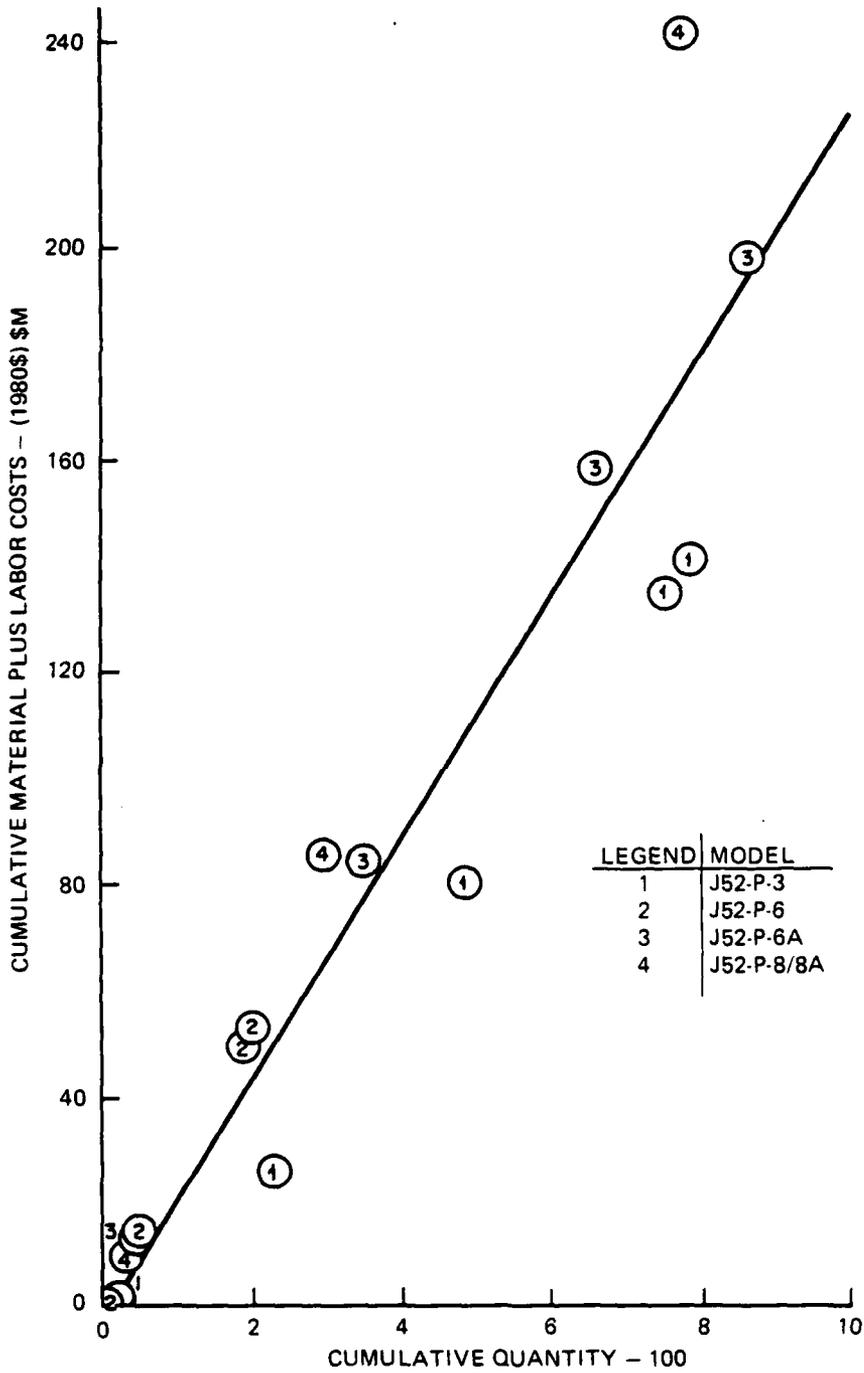


Figure 8. Cost Variation with Quantity for J52 Engine

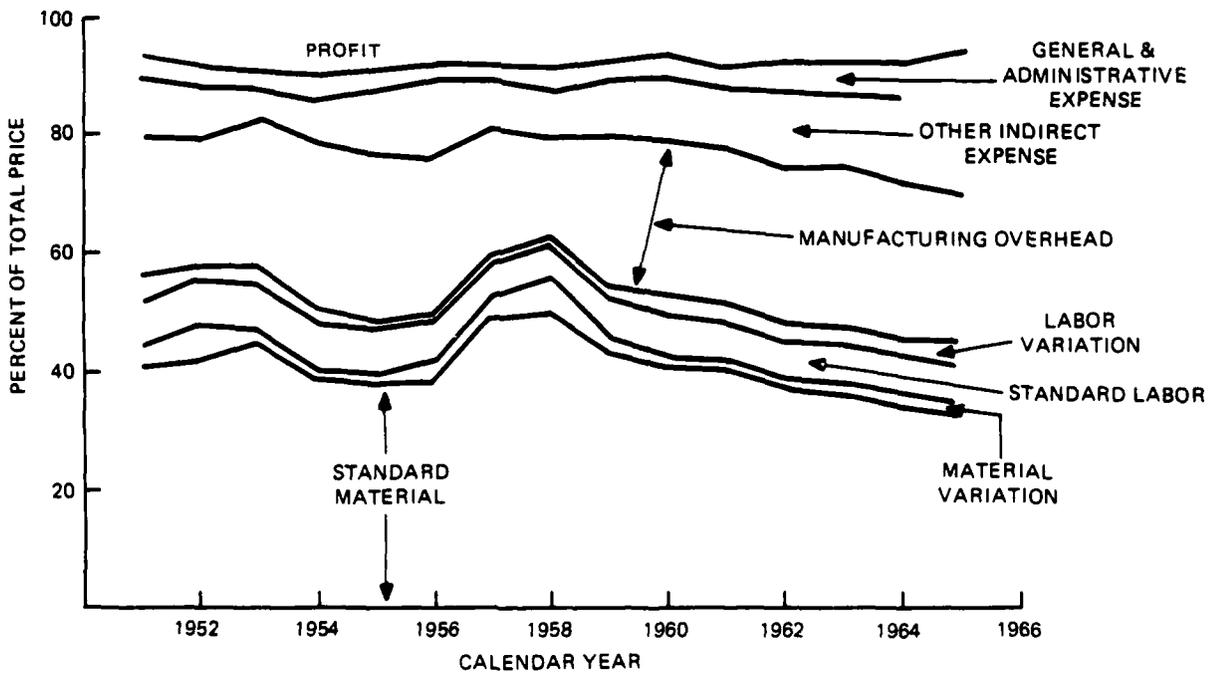


Figure 7. Cost Variation with Time

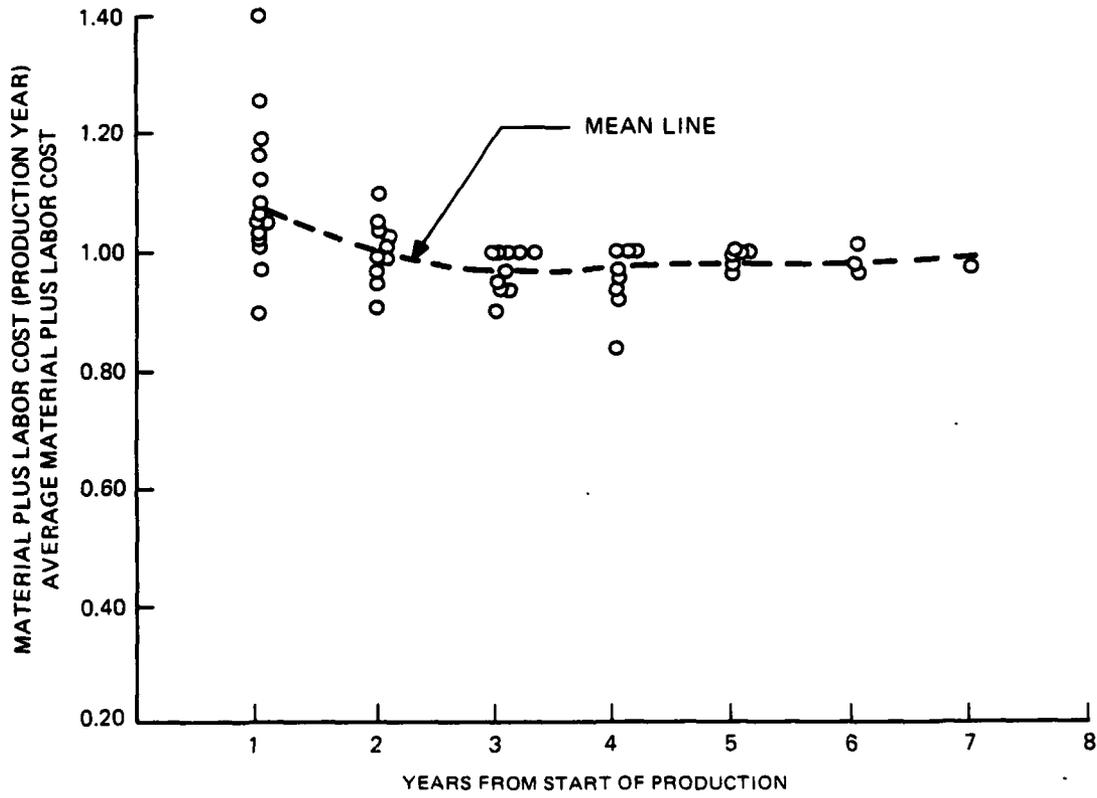


Figure 6. Material and Labor Cost Learning Curve

Thus, these engines are "more expensive" than an engine cost described by the regression line (for comparable material factors). It might also be noted that other engines represent first-of-the-line engines yet fall below (less expensive) the regression line. However, one of the engines was produced in large quantities for a significant period of time, and was employed as a missile engine so that the specification requirements were not as demanding as a manned aircraft engine. Another engine, although it was the first of the line to be produced, was not truly a new design, but a follow-on to another basic engine, so that only minimal increases in the core engine technology were necessary. The relative position of most of the other engine models may also be explained qualitatively using the same three factors as a basis of consideration.

Refined Correlation

Thus, with the initial assumptions of the study confirmed (i.e., the cost of an engine is directly related to the type and amount of raw material (Maurer Factor) in the engine), additional variables were sought to relate other cost factors to this average material plus labor cost. Specifically, several cost ratios were calculated in an attempt to define a nondimensional factor for production cycle dependence. A trend is shown in figure 6 where the ratio of the material cost plus labor cost in a specific production year to the average total material and labor was compared to the production year. The results of figure 6 were determined by selecting all engine models produced for three or more years. The larger scatter of data was found to be significantly attributable to engines produced in 1957 and 1958. Further analyses indicated that proportions of the material plus labor costs varied considerably due to a large plant volume during these years. Because of the high volume of production, many parts that would normally be produced "in-house" were procured from outside vendors. This "buy" situation increased the material costs significantly (since vendor labor is considered part of material costs) and only slightly reduced the direct labor costs so that the overall material plus labor costs for these years increased and caused an anomaly in the data for those engines whose production cycle included 1957 to 1958. As shown in figure 7, these trends would not have been as noticeable by using a Total Manufacturing Cost (material plus labor plus manufacturing overhead), since the manufacturing overhead dropped considerably in those years and thus offset the abnormal material plus labor costs.

Regression analysis were also performed to determine correlation of the engine material plus labor cost with production quantity. Figures 8 and 9 show the cost-quantity relationships of two engines for models produced for two or more years. This analysis shows a near-perfect linear relationship exists for individual models, indicating no decrease in costs for large quantity procurements. Similar cost-quantity regression analyses were performed for other engines. From a comparison of these data it was found that the engine costs were controlled by parameters other than just quantity. Figure 10 shows this variation with engine type and quantity. Figures 11 through 14 show the relationships of the four possible combinations of these two variables, and indicate the linear relationship of the engines in each group. Trends for individual models were similar to those trends for first two engines cited; namely, no decrease in costs with quantity. Further analysis indicated that other significant factors which affected the cost were the quantity size (large or small) or if the engine had an afterburner. Large quantity is defined as the number of models produced during more than one year with a total production over one hundred engines with at least twenty-five engines produced the first year.

The "no-learning" characteristic (no decrease in cost with quantity) of the engine models was of particular interest because of its apparent conflict with data shown in figure 6. Figure 6 showed some learning tendencies over the production cycle, particularly in the first production year.

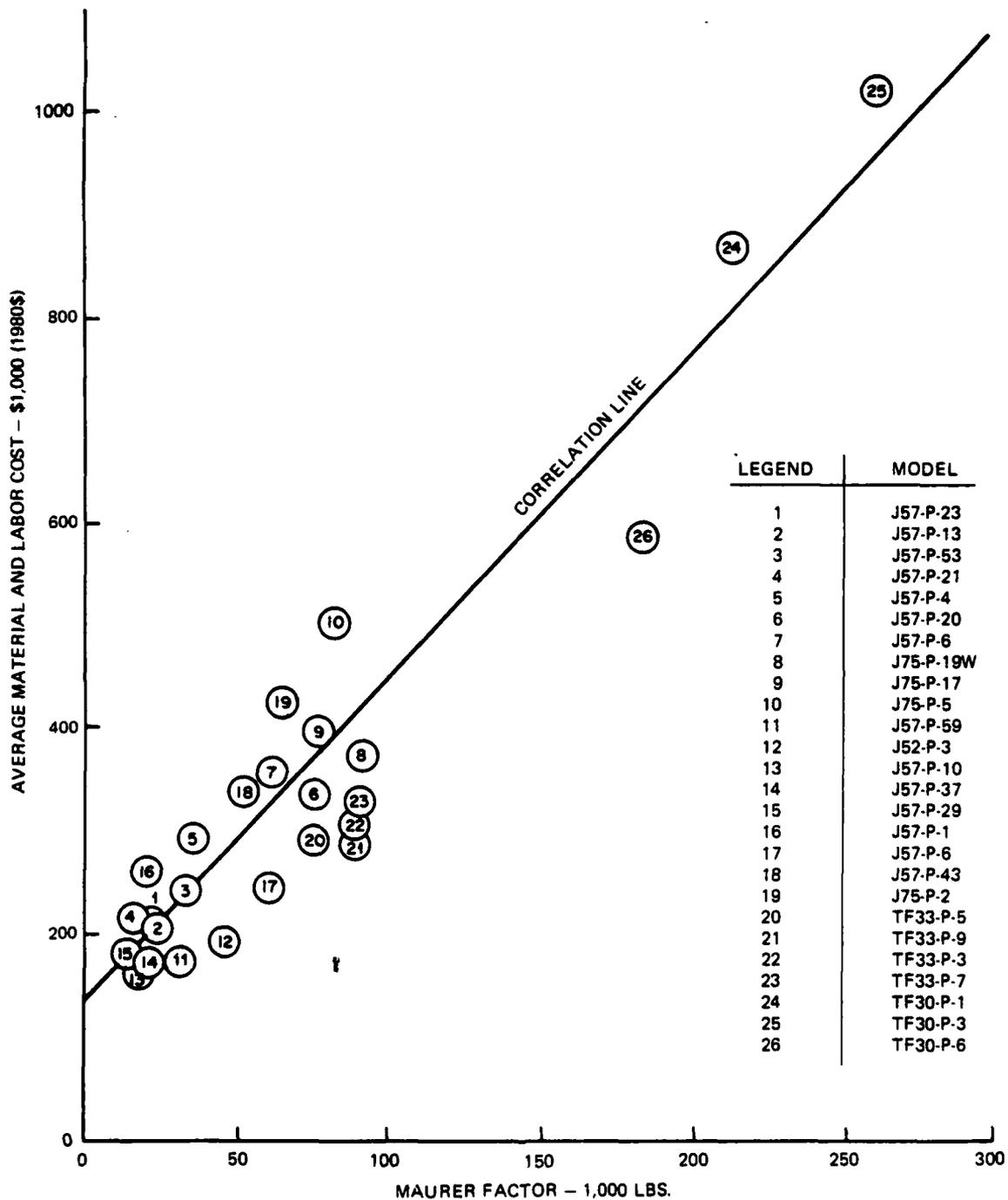


Figure 5. Maurer Factor Correlation with Material and Labor Cost

where

c = average manufacturing cost

P_i = unit cost in 1982 dollars for a given year

n = production span in years

Q_i = quantity purchased in a given year

This average cost eliminated the effect on cost of learning or cost improvement with the quantity of engines produced.

Correlation studies for cost versus Maurer Factor were then initiated in an attempt to justify the material rationale of the study. Graphs were constructed of various costs versus Maurer Factor of 26 engine models. At this point, it was necessary to introduce a method for measuring the absolute correlation of variables. A statistical correlation method was employed which permitted consistent comparisons of variable correlations. This method, the regression technique, provided a least squares (minimizing the square of the differences between actual and predicted points) curve-fitting routine to the data and determine the "best" equation to approximate the data. The "best" equation is based on the initial assumption of the equation form (i.e., linear, multilinear, logarithmic, etc.). Other outputs of this technique are: coefficients of correlation, standard error of estimate (sigma) limits, explained and total variance, F-ratio, etc. A regression computer program developed on the NAVAIRDEVGEN Central Computer System was used for correlation work. Reference (i) provides a detailed discussion of the computer program and the significance of the outputs.

The regression program output, coefficient of correlation, was the statistical parameter used as the primary measure of effectiveness in the above correlations as well as in subsequent correlations since the square of this value is directly related to the absolute correlation of the variables. Various forms of equations were used.

3. Initial Correlation Results

Analyses were conducted to determine the relationship between the original 26 engines for which cost and Maurer Factor data were available. Several regressions of Maurer Factor with various costs were made, and results showed that labor costs alone did not correlate well with Maurer Factor, nor did raw material costs or purchased parts costs. However, if one considers the manufacturing cost of an engine to be divided among labor, raw material, and purchased parts in a given year and is dependent on the make-buy structure of that year, then the combined cost of the material plus labor provides a more significant correlation. Figure 5 shows this correlation of raw material + labor cost for 26 engines. Further analysis of figure 5 data scatter indicated that additional factors which impact cost could improve the correlation. It should be noted from the figure that certain engines are positioned above the mean regression line. These engines have one or more of the following characteristics:

- a. New design (i.e., first-of-the-line engine models)
- b. Produced in relatively small quantities
- c. Produced for only a short period of time

TABLE I
GAS TURBINE ENGINE ESCALATION INDEX

| YEAR | INDEX |
|-------------|--------------|
| 1950 | 0.639 |
| 1951 | 0.703 |
| 1952 | 0.714 |
| 1953 | 0.725 |
| 1954 | 0.723 |
| 1955 | 0.779 |
| 1956 | 0.836 |
| 1957 | 0.836 |
| 1958 | 0.838 |
| 1959 | 0.870 |
| 1960 | 0.870 |
| 1961 | 0.881 |
| 1962 | 0.882 |
| 1963 | 0.894 |
| 1964 | 0.922 |
| 1965 | 0.954 |
| 1966 | 0.992 |
| 1967 | 1.000 |
| 1968 | 1.063 |
| 1969 | 1.114 |
| 1970 | 1.177 |
| 1971 | 1.208 |
| 1972 | 1.230 |
| 1973 | 1.401 |
| 1974 | 1.657 |
| 1975 | 1.713 |
| 1976 | 1.847 |
| 1977 | 1.958 |
| 1978 | 2.160 |
| 1979 | 2.429 |
| 1980 | 2.496 |

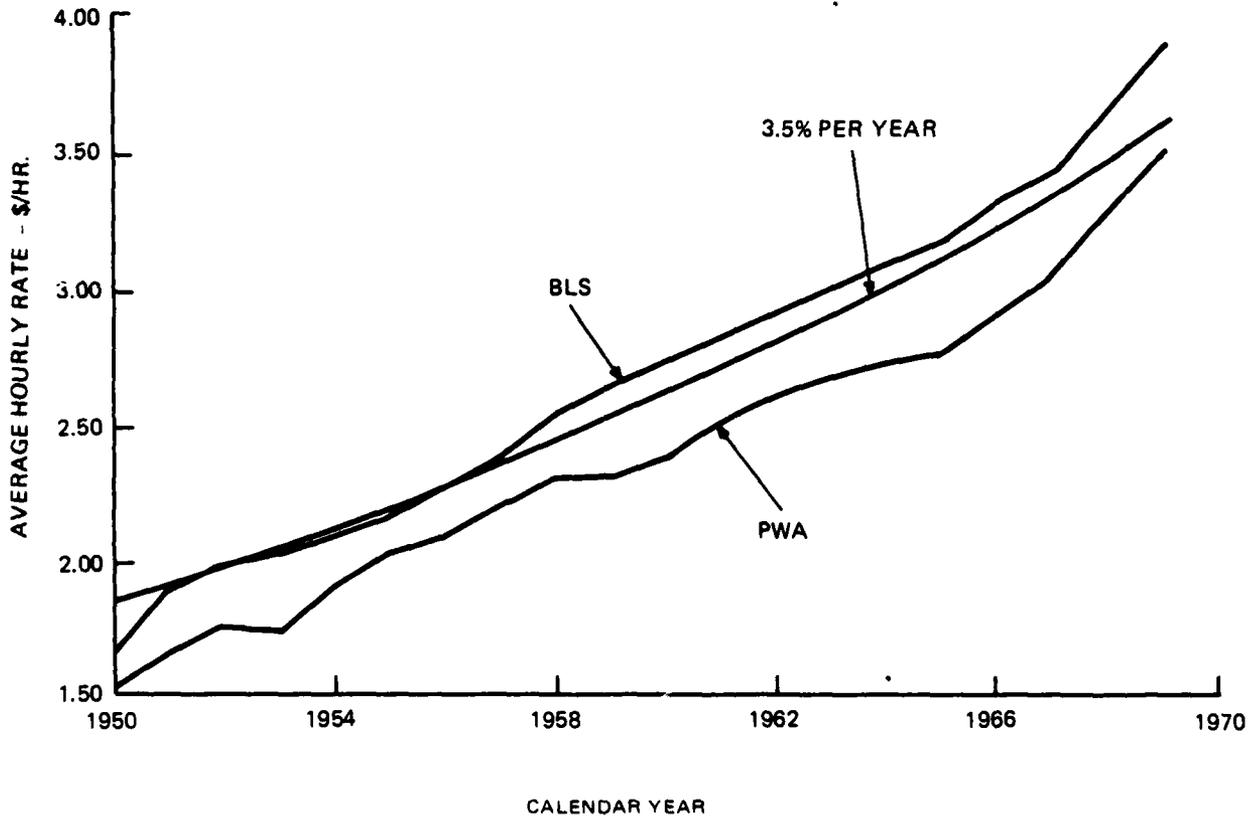


Figure 4. Labor Index

2. Labor

Economic trends for labor were more definable, particularly in the time period of interest. BLS publishes employment and wage earning statistics in reference (d), for individual and selected groups of production categories. The BLS does list the "Aircraft Engine and Engine Parts" industry employment and wage earnings separately. Figure 4 shows the average hourly rate obtained from BLS statistics and is considered to be the most indicative index of the labor dollar throughout the years. For comparison, figure 4 also shows a constant 3.5 percent escalation (compounded annually) and actual labor rates from PWA. From 1958 to 1967, figure 4 shows good correlation of the actual index with the 3.5 percent escalation increase. After 1958, a 4.5 percent increase per year appears to be more representative of that time period than the 3.5 percent shown in figure 4. For the period 1967 to 1976, the average yearly increase was 6.7 percent. Similar hourly wage indexes available from each engine manufacturer correlated equally as well as the PWA index in figure 4. It was concluded that the overall BLS index of figure 4 is satisfactory for all labor cost data because the aircraft industry is limited to relatively few manufacturers and the largest producers, in general, follow the trends indicated by the overall BLS index.

Table I provides a listing of the factors required to escalate (or de-escalate) material costs to a base year of 1967. This base year (1967) was an arbitrary choice of the BLS analysts and can be easily changed to another base year by employing the following relationship:

$$\text{Escalation Factor}_{ij} = \frac{\text{Escalation Factor}_{jk}}{\text{Escalation Factor}_{jk}} \quad (1)$$

where

i = production year

j = new base year

k = old base year (1967)

Cost Model Formulation

1. Initial Approach

Initial studies of cost correlations were concentrated specifically using the PWA data. As previously discussed under initial studies and approach, a computer program was initiated for calculation of cost and economic data using "common dollars."

Since many engine models were produced over the many years in their production cycle, it was necessary to formulate an average engine unit cost which would be representative of the engine model throughout its production life. It was considered that a quantity-weighted evaluation of the production costs would provide the most meaningful indicator of engine unit cost and the following relationship was established:

$$c = \frac{\sum_{i=1}^n P_i Q_i}{\sum Q_i}$$

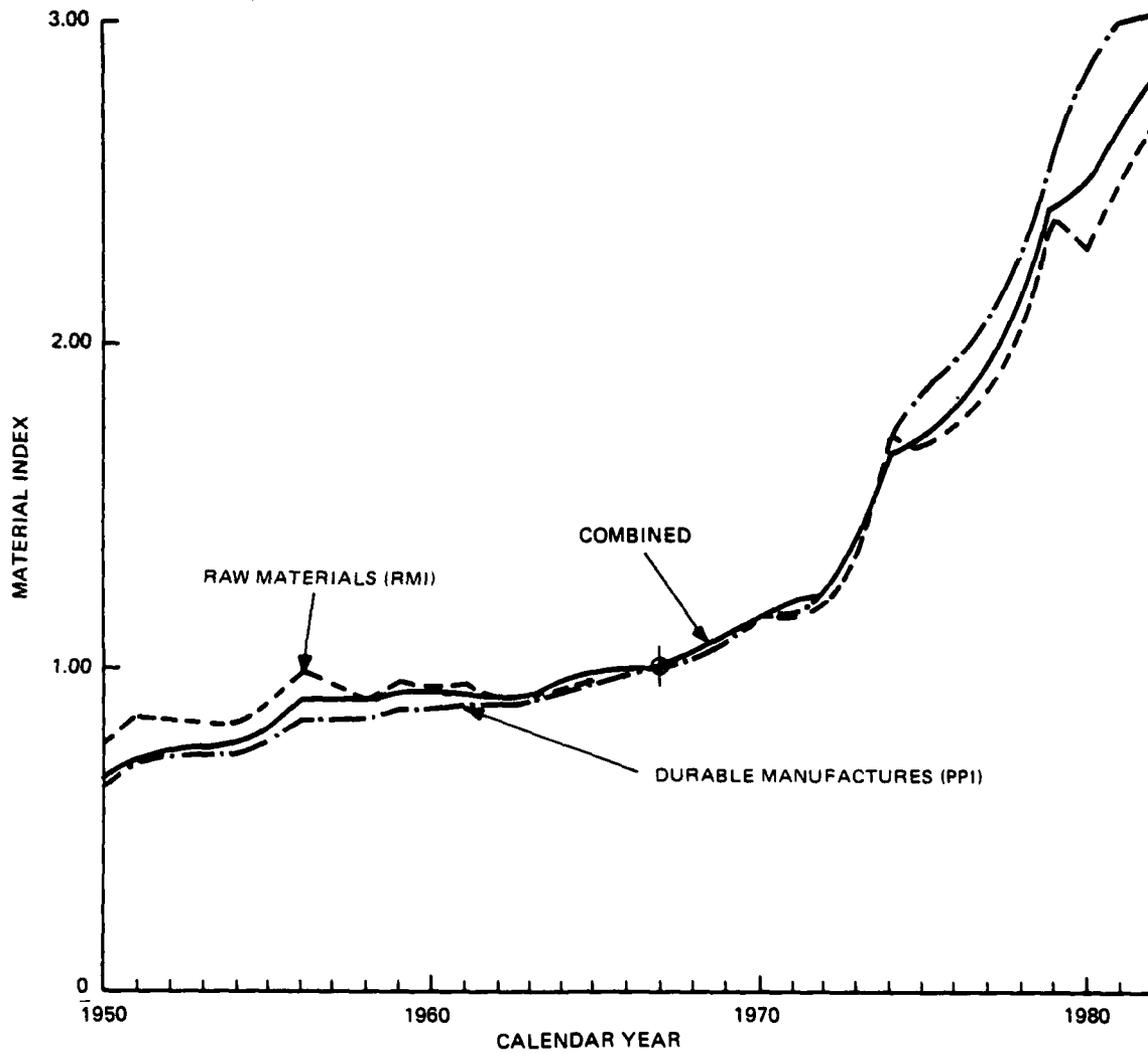


Figure 3. Material Index

Similar preliminary investigations into the available engineering data resulted in a two-dimensional matrix array with the engine model and the specific engineering characteristic as the two elements. The engineering characteristics were chosen to reflect those parameters which, through engineering logic, should provide a key to the determination of cost. Those parameters will not be published because of their proprietary nature.

As the study progressed, cost and engineering data on other manufacturers' engines were obtained, and will be discussed in greater detail later in this report. These data were also arranged in the aforementioned data banks.

Effects of Inflation

1. Materials

The third part of the data base was constructed to provide a source of economic escalation and de-escalation of costs. This part is necessary in the use of historical cost data for analysis purposes to adjust the cost data for "common dollar" comparison. This "common dollar" comparison is particularly acute when adjusting the data over a 20 year time span. A survey of literature and previous cost analyses revealed no significant factors which could be employed as guidelines for meaningful trends in the material, labor and overhead costs of aircraft engines. However, perusal of Bureau of Labor Statistics (BLS) surveys and correspondence (references (d) and (e)) with BLS personnel indicated that economic indices with sole application to aerospace materials were nonexistent. Further studies shown in references (f) and (g) provided methods of manipulating BLS data to provide aerospace materials and labor price indices by weighted percentages of those materials applicable to the aerospace industry. Although these references provided an insight as to the complex nature of economic adjustments and furnished indices which were applicable to the airframe, they specifically avoided the projection of future aircraft engine indices because of the exotic nature of the materials employed by the engine industry.

With these findings, another more suitable index was sought. Because of the nature of the materials industry, the BLS Wholesale Price Index (WPI), reference (h), was chosen as the primary source for establishing economic trends for materials. This index measures average changes in prices of commodities sold in the primary markets of the United States and represents a sample of over two thousand products. The WPI is calculated on weighted averages of price changes for the applicable commodities over a given period of time, and at the present time is referenced to a base year of 1982. Based on analyses of the various indices, the WPI categories for the state of processing and desirable durability of the product—namely, (1) durable raw or slightly processed goods representing a raw material index (RMI) and (2) durable manufactures representing a purchased parts index (PPI) were selected as two categories of indices for material trends. Although each category content used in these indices is not in total or even in a majority applicable to the aerospace propulsion industry the trends of the indices are assumed to correlate closely with the actual propulsion material trends. Figure 3 shows the curves for both the RMI and the PPI trends for these indices from 1950 to the present. This Metals and Metals Products index contributes to approximately 30 percent of the PPI and shows that, in general, the trend of metal products is similar to the overall equation curve. Other major categories included in the makeup of the PPI relative to aerospace materials processing are machinery and equipment, and transportation equipment which contribute approximately 40 percent and 15 percent, respectively to the overall index thus indicating similar trends. For the PPI, analysis of figure 3 shows the inflation trends of the 1950s followed by the recession years of the early 1960s, and finally, the inflation trends of the past few years, all of which are somewhat indicative of the gross economy at that time. The RMI, however, shows the erratic trends of primarily the iron and steel industry. The raw material index trends are assumed to follow materials used in the propulsion industry.

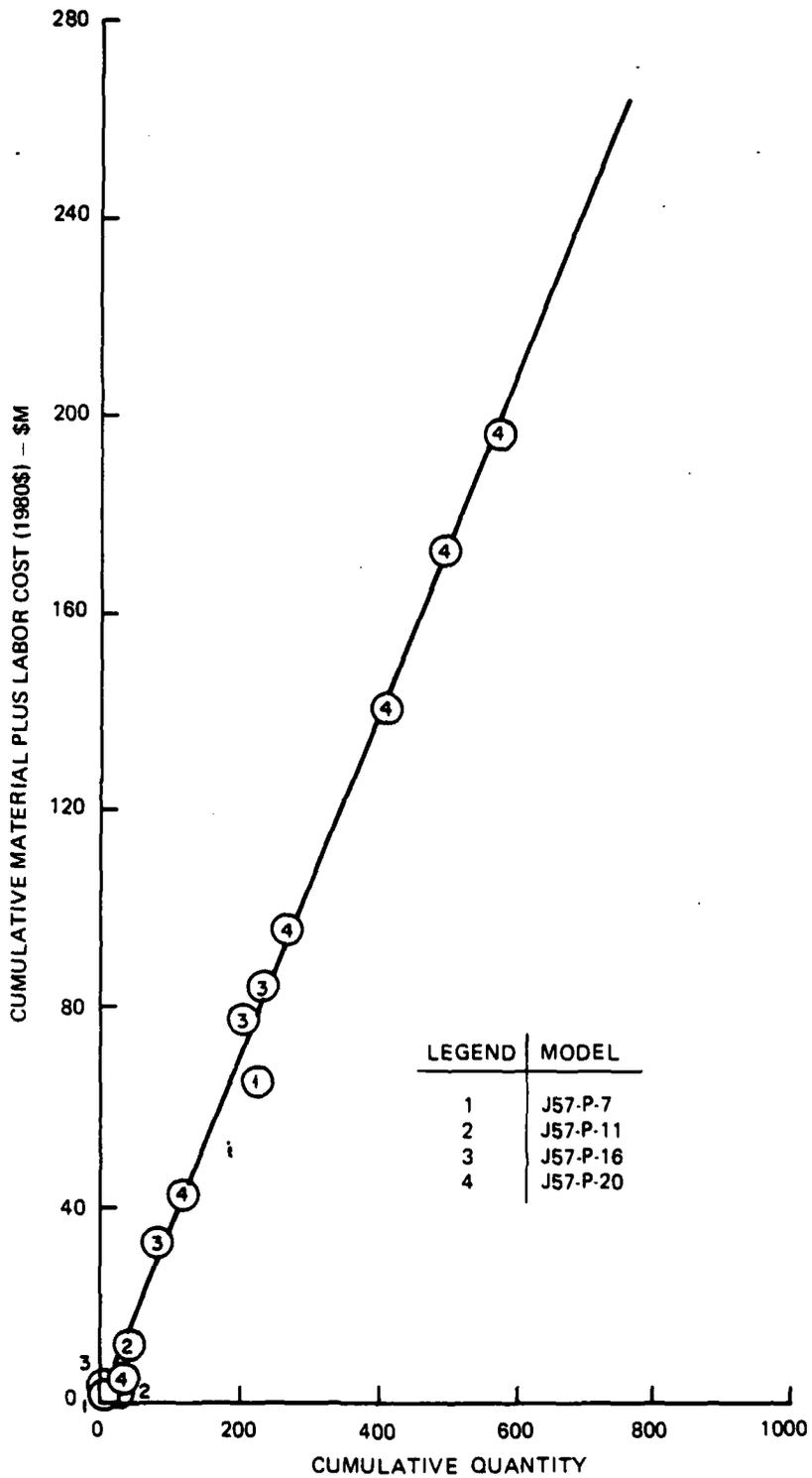


Figure 12. Cumulative Cost vs. Quantity. First Year Small Buy, Afterburning Engines.

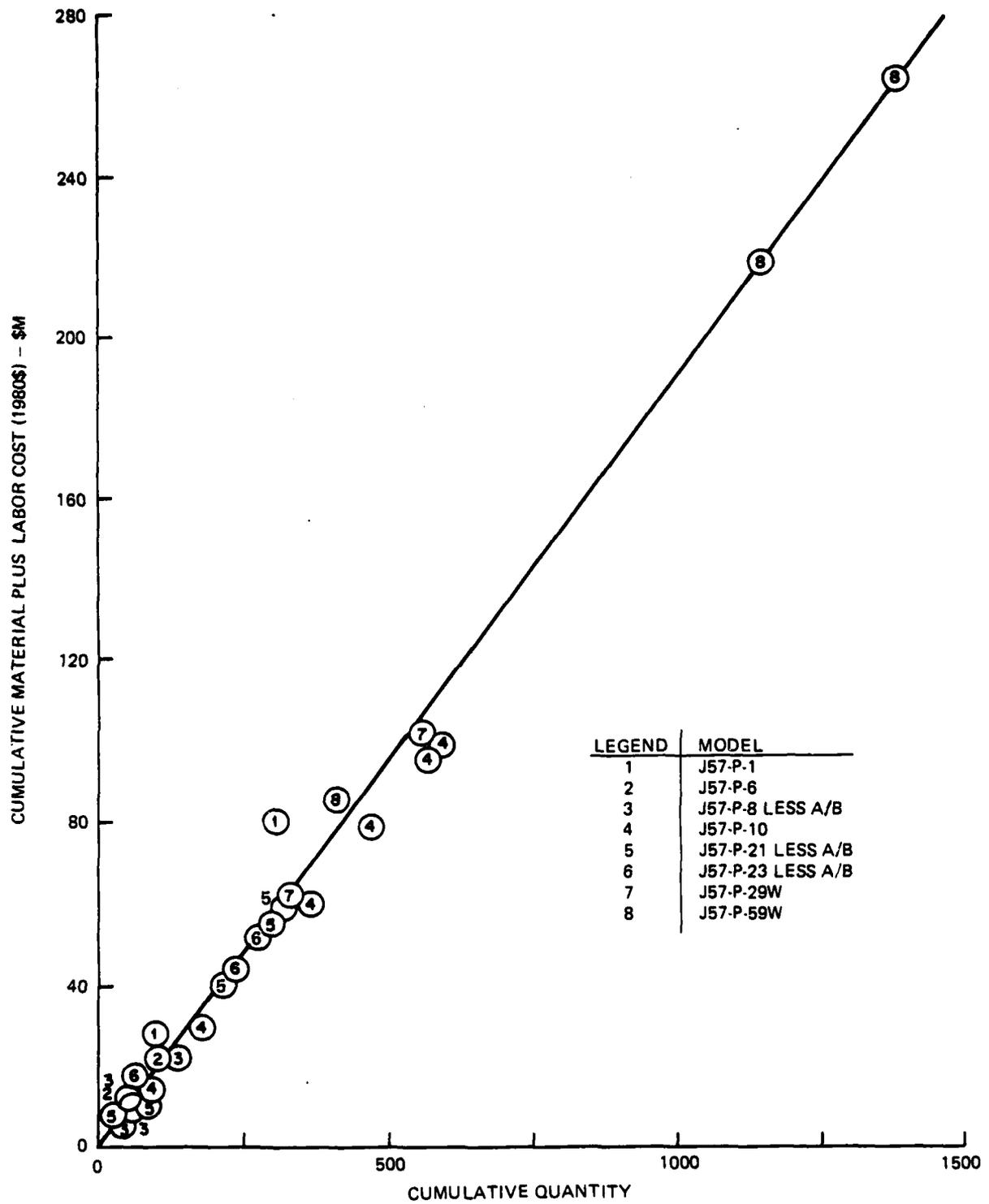


Figure 13. Cumulative Cost vs Quantity. First Year Large Buy, Non-Afterburning Engines.

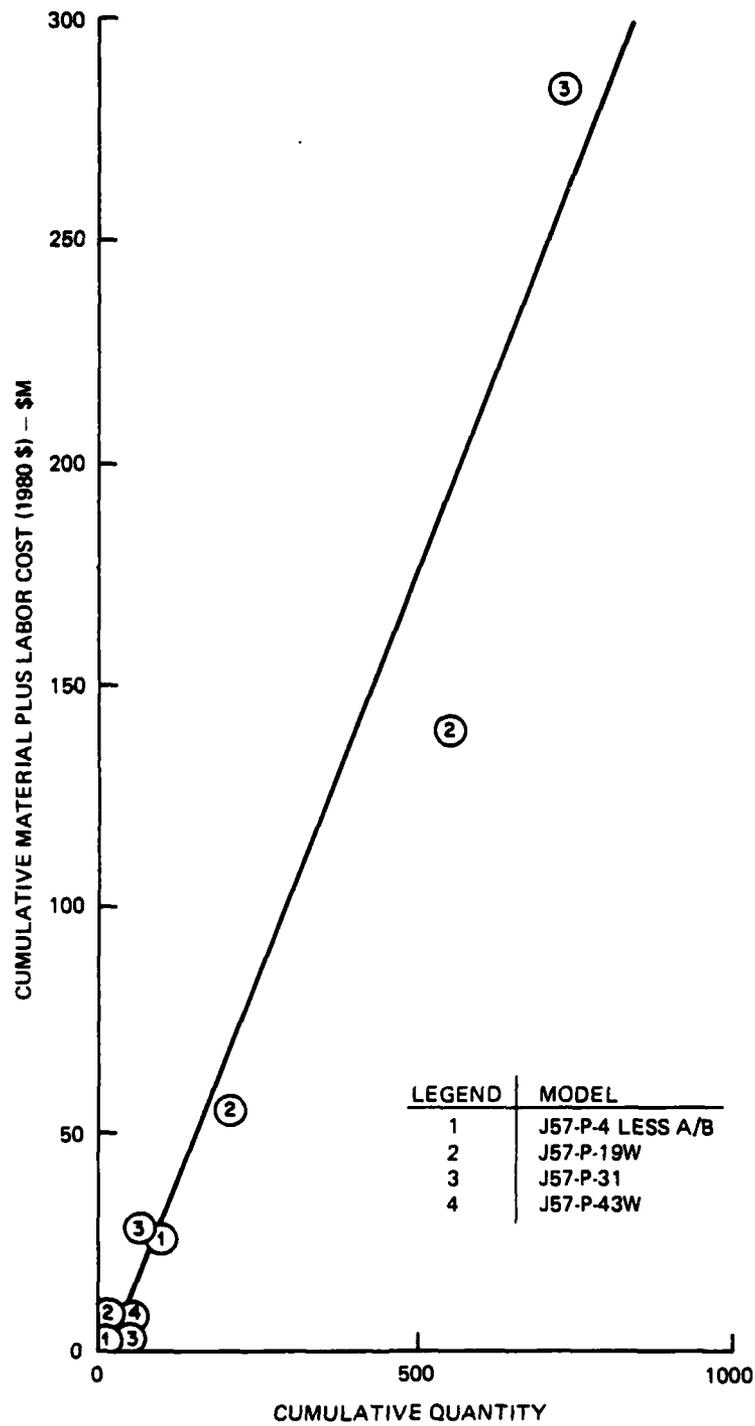


Figure 14. Cumulative Cost vs Quantity, First Year Small Buy, Non-Afterburning Engines.

However, it should be noted that since relatively very small percentages of the engines of a model are produced in the first year, the cost-quantity relationships of engines produced in that year are generally insignificant when compared to the overall production cycle relationship. This factor, when combined with the interpretation of the slope of the line connecting individual points (i.e., the average cost of the engine), then clarifies this apparent anomaly between the results of figure 6 and the cost-quantity relationships. PWA indicated their "no-learning" cost characteristics were valid because their cost accounting system prior to 1971, employed for these models, prorates certain costs over the entire military volume of engines so that there is essentially no learning with large quantities. The high start-up costs and special tooling required for new engines is suppressed from appearing on the first lot costs of these engines by being prorated over the entire military (and commercial volume, if a commercial version of the military engine existed at that time). This method of recording costs was changed in January 1971 when PWA instituted a new accounting system to account directly for engine component costs which were unique to individual engine models, families of engine models, all military engines, or all military and commercial engines. This system was initiated to produce greater visibility of each engine cost and the effects of cost and "learning."

Validation of the Correlation

After the correlations were completed using the data applicable to PWA engines, the question arose as to the applicability of the cost methodology to other engine manufacturers. The scope of the cost study was increased to include engines from GE and AGTD of General Motors Corporation. GE provided cost data that included not only a quantitative history of the engines produced from 1959 but also their associated proprietary costs and pertinent engine parameters.

GE engine materials were classified to conform to those classifications used with PWA engine materials. Using GE specifications containing chemical composition, machinability data, and also material costs provided by form, the NAVAIRDEVCON determined Maurer Factors for all of the GE engines listed in table II. From the cost history of the GE engines, it was necessary to use an average cost over the complete procurement so that the effects of learning would be normalized as was done with the PWA data. Unlike the PWA costs (prior to 1971), the GE costs showed the effects of "learning" which reflected the different accounting criteria used by each manufacturer. Average manufacturing costs, which represent material and labor costs plus a percentage for overhead, were obtained for the GE engines in common year dollars for compatibility with PWA costs. Figure 15 shows the correlations between manufacturing cost and Maurer Factor. Some slight difference between PWA and GE engines in the correlations were expected, since some of the GE engines such as the J79 were produced in very large quantities. The coefficient of correlation which measures the trend of the data for both contractors was a near perfect 0.999, and the measure of the spread of the data as measured by the magnitude of the one sigma value was \$70,900 in 1980 dollars. This one sigma value is a relatively small quantity when compared to \$1,130,000 also in 1980 dollars, which is an approximate manufacturing cost for a Naval fighter aircraft engine.

Subsequent to the inclusion of the GE engines with the PWA engines, the AGTD was approached for their data in order to incorporate it into the cost study. Figure 16 shows forty-three engines from these manufacturers. The results of the correlation between Maurer Factor and costs for the engines from the three principal engine manufacturers, indicated that the cost methodology was not limited to only United States engine manufacturers, since approximately half the TF-41s, at the time, were British made. Subsequent exercises on source selection have confirmed the validity of the cost methodology. When the estimates have been put on the same basis, that is using the same learning, the same buying schedule, the same projected inflation factors, the Maurer Factor method has consistently shown agreement with contractor estimates.

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TABLE II
LIST OF GENERAL ELECTRIC ENGINES

| | |
|----|---------|
| 1 | TF34-2 |
| 2 | T58-3 |
| 3 | T58-5 |
| 4 | T58-8B |
| 5 | T58-10 |
| 6 | T64-6B |
| 7 | J79-8 |
| 8 | J79-10 |
| 9 | J79-15 |
| 10 | J79-17 |
| 11 | J79-19 |
| 12 | J85-13 |
| 13 | J85-15 |
| 14 | J85-17 |
| 15 | J85-17A |
| 16 | TF39-1 |

| LEGEND | MODEL | LEGEND | MODEL | LEGEND | MODEL | LEGEND | MODEL |
|--------|--------------|--------|-----------|--------|---------|--------|-------|
| 1 | J52 P 3 | 15 | J75 P 17 | 29 | J79-15 | | |
| 2 | J52 P 6 | 16 | J75 P 19W | 30 | J79-17 | | |
| 3 | J57 P 1 | 17 | J57 P 59W | 31 | J79-19 | | |
| 4 | J57 P 29W | 18 | TF30 P 1 | 32 | J85-13 | | |
| 5 | J57 P 37.37A | 19 | TF30 P 1A | 33 | J85-15 | | |
| 6 | J57 P 59 | 20 | TF30 P 6 | 34 | J85-17 | | |
| 7 | J57 P 4.4A | 21 | TF30 P 8 | 35 | J85-17A | | |
| 8 | J57 P 13 | 22 | J52 P 8A | 36 | T64-68 | | |
| 9 | J57 P 16 | 23 | TF30 P 12 | 37 | T58-3 | | |
| 10 | J57 P 21.21W | 24 | TF33 P 3 | 38 | T58-5 | | |
| 11 | J57 P 23.23A | 25 | TF33 P 7 | 39 | T58-88 | | |
| 12 | J57 P 55 | 26 | TF33 P 9 | 40 | T58-10 | | |
| 13 | J75 P 2 | 27 | J79-8 | 41 | TF34 | | |
| 14 | J75 P 5 | 28 | J79-10 | 42 | TF39 | | |

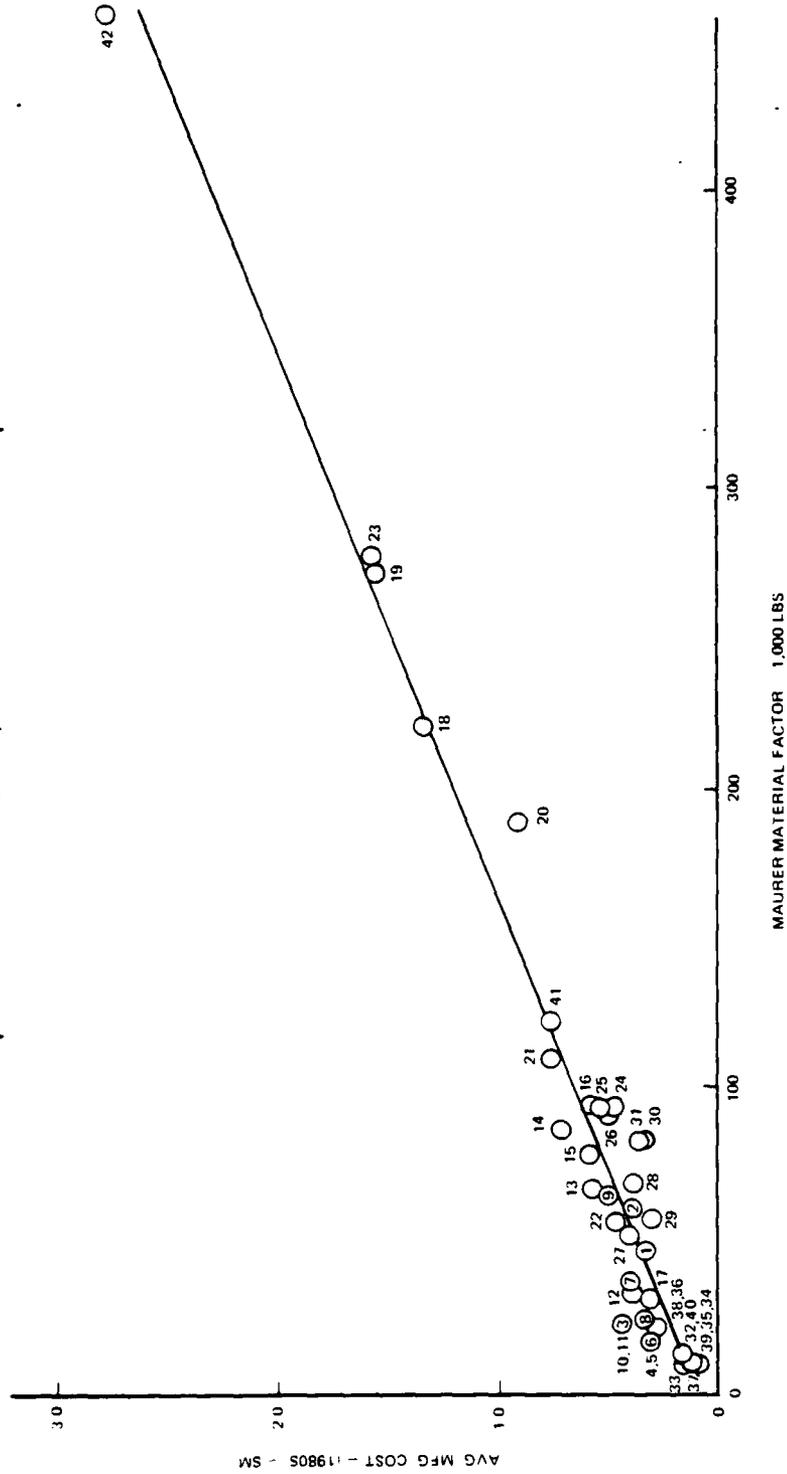


Figure 15. Maurer Material Factor Correlation with Cost for PWA and GE Engines

| LEGEND | MODEL | LEGEND | MODEL | LEGEND | MODEL |
|--------|--------------|--------|-----------|--------|---------|
| 1 | J52-P-3 | 15 | J75-P-17 | 29 | J79-15 |
| 2 | J52-P-6 | 16 | J75-P-19W | 30 | J79-17 |
| 3 | J57-P-1 | 17 | J57-P-59W | 31 | J79-19 |
| 4 | J57-P-29W | 18 | TF30-P-1 | 32 | J85-13 |
| 5 | J57-P-37,37A | 19 | TF30-P-1A | 33 | J85-15 |
| 6 | J57-P-59 | 20 | TF30-P-6 | 34 | J85-17 |
| 7 | J57-P-4,4A | 21 | TF30-P-8 | 35 | J85-17A |
| 8 | J57-P-13 | 22 | J52-P-8A | 36 | T64-68 |
| 9 | J57-P-16 | 23 | TF30-P-12 | 37 | T58-3 |
| 10 | J57-P-21,21W | 24 | TF33-P-3 | 38 | T58-5 |
| 11 | J57-P-23,23A | 25 | TF33-P-7 | 39 | T58-88 |
| 12 | J57-P-55 | 26 | TF33-P-9 | 40 | T58-10 |
| 13 | J75-P-2 | 27 | J79-8 | 41 | TF34 |
| 14 | J75-P-5 | 28 | J79-10 | 42 | TF39 |
| | | | | 43 | TF41 |

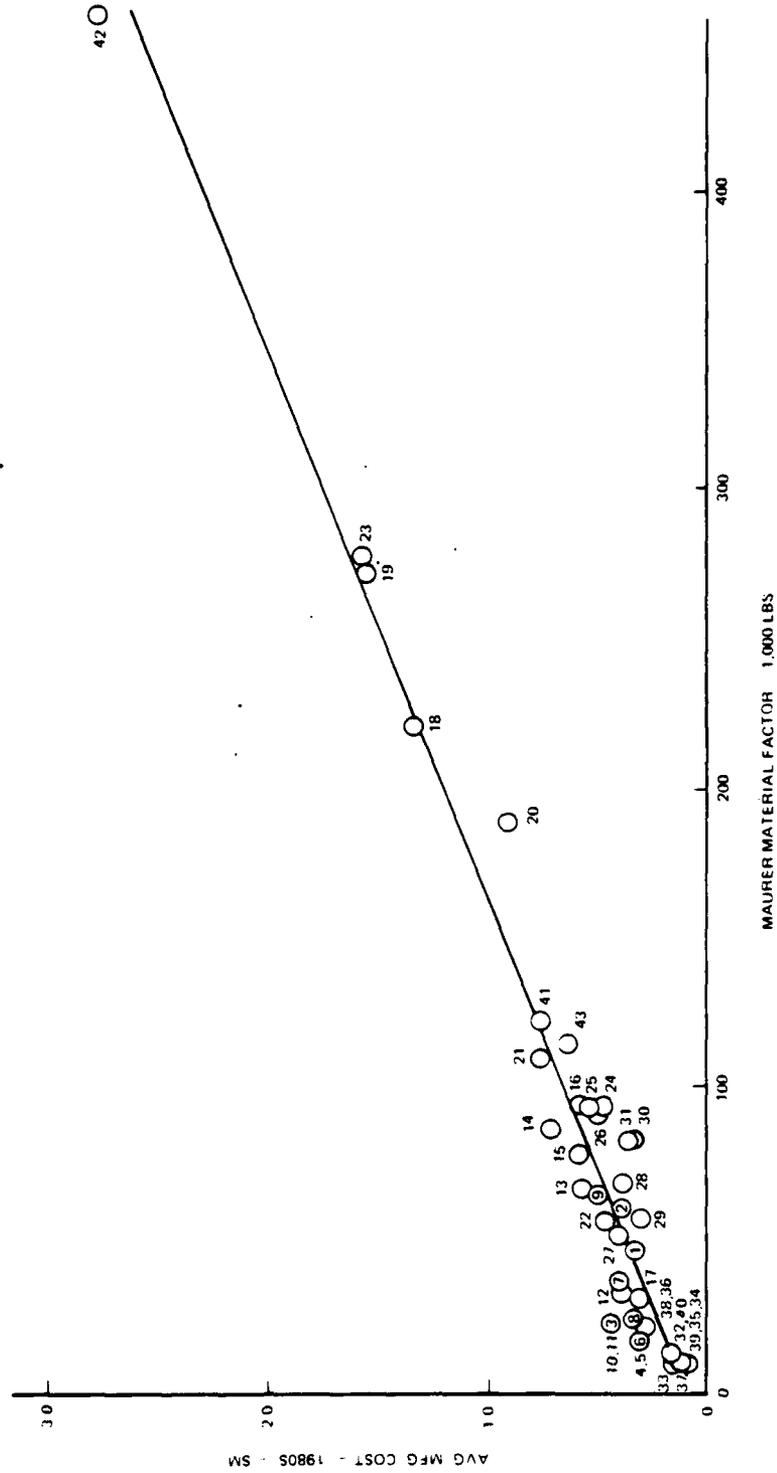


Figure 16. Maurer Material Factor Correlation with Cost

Correlations for Small Engines

Although the one sigma value of \$70,900 is acceptable for large engines with a manufacturing cost of about one million dollars each, it is excessive for small engines costing about \$100,000 each. For this reason correlations were made for those engines at the lower end of the cost curve weighing under 750 pounds. Figure 17 shows the results of the correlation for small engines. Although most of these engines were made for man rated aircraft, a few engines were designed for application with drone aircraft, and as a consequence, contribute to the spread of the data on the cost curve. However, the one sigma value for the data spread was reduced from \$70,900 for the large engines to \$16,395 for the small engines. This equation has been applied successfully to the engine for the Navy Harpoon Missile, the Supersonic Expendable Turbine Engine, and the National Aeronautics and Space Administration Low Cost Engine.

Utility and Application of the Maurer Factor

In addition to providing information enabling the prediction of production cost, the Maurer Factor was envisioned as a basis for quantitatively monitoring the changes in the material composition of an engine as it progresses from proposal through production and later through subsequent model changes. Knowledge of the Maurer Factor history of engines produced for Naval aircraft, permits a greater understanding of changes that may be expected when new engines are introduced into the fleet, and how much the Maurer Factor grows before another derivative engine is produced. Additionally, it is possible to track the cost of materials that constitute an aircraft engine as a function of time. In this way, the weighting factors are up-dated to reflect high costs associated with newly developed materials, and will also show the reduction of cost that results when these materials experience greater industrial usage.

Besides being useful in cost determination, the Maurer Factor is used as an indication of the efficiency of the production methods of an engine manufacturer. Since the Maurer Factor is a measure of the raw material or input weight that becomes an engine, it is possible to compute the material input-output weight ratio, and from this obtain a quantitative measure of how different a proposed gas turbine will be from its predecessors. This input-output ratio has been determined over the years for the engines produced for Naval aircraft. An indication of the manufacturing technology can be obtained from this ratio, and if it differs markedly from past engines, a judgment can be made on the reliability of the Maurer Factor as computed from the Abbreviated Summary Bill of Materials. As manufacturing technology develops, less material will be required to produce engine parts. Inertia welding is an excellent example of such a new technological process. Even dissimilar metals can be joined more quickly than before and produce a metallurgical bond. Inertia welding requires almost no excess material for production and it is much less expensive than welding by conventional methods. The ratio of raw material to finished material is very close to 1.0 for inertially welded parts having the shape of circular rings as compared to an average of about 4.0 for components machined from large single bars. Manufacturing costs are accordingly reduced. Hot Isostatic Pressing (HIP) is another method in which parts are produced near their finished dimensions. Conventional forging methods require a starting blank weighing five to six times the finished part weight. For the HIP process, the input weight is only about three times the finished weight. Directionally solidified castings, in which heat is removed from a chill plate supporting the molten casting in its mold, exceed the strength of conventional forgings while at the same time require much less material for their production.

Because components made by cast and HIP methods can be produced close to finished size, it is apparent that these methods will continue to be refined so that production costs of these parts, usually made of expensive alloys, will be reduced.

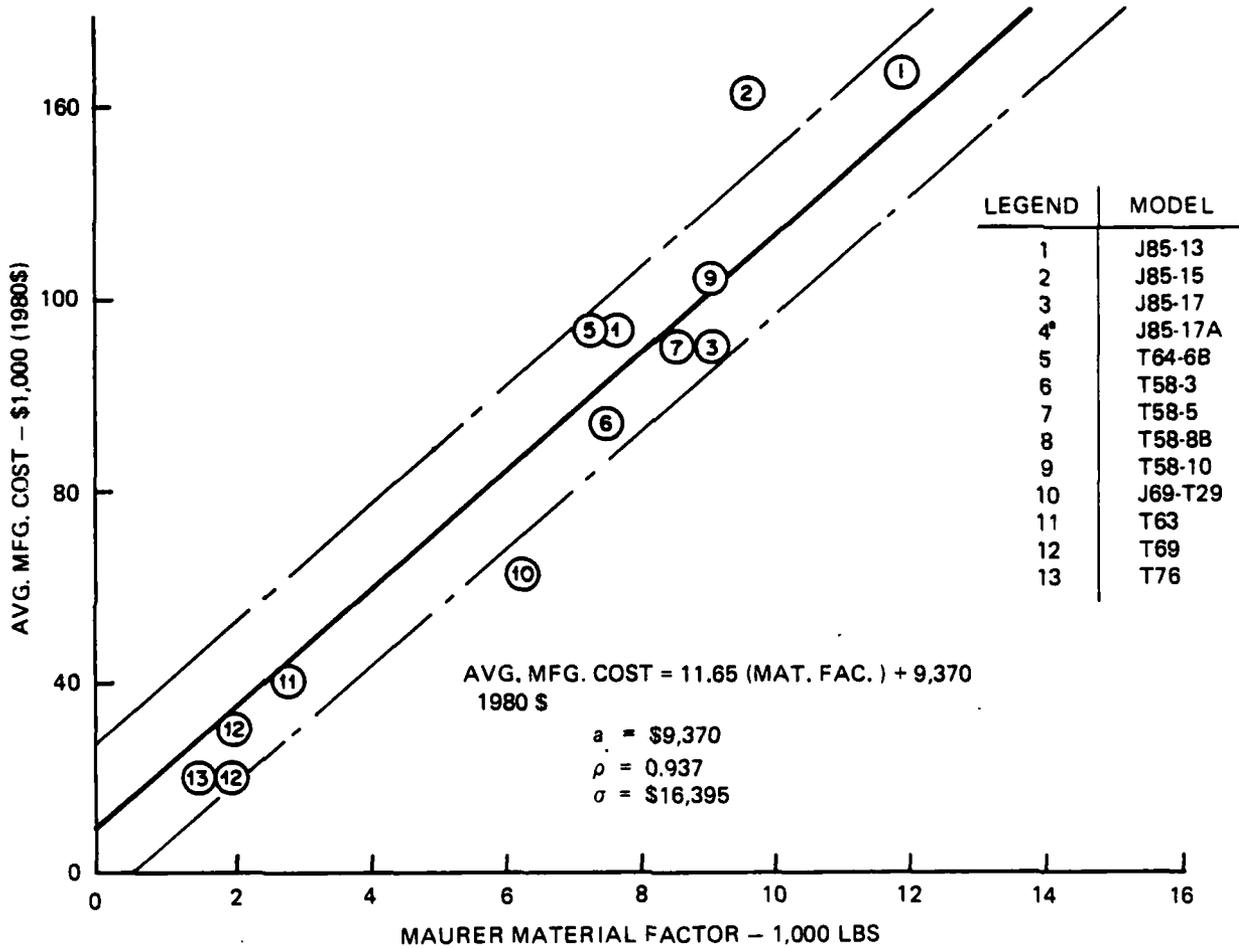


Figure 17. Maurer Factor Correlation with Cost for Small Engines

CONCLUSIONS

In the early years of the cost study very little cost data information was publicly disclosed because all the cost data had been obtained from engine manufacturers under the pledge of respecting the proprietary nature of the information and insufficient opportunity was available to test the validity of the cost methodology with cost data from actual engine proposals extending beyond the time period of the study. However, in subsequent years as the opportunity arose to test the Maurer Factor technique against engine proposals and procurements, it became apparent that the technique produced very good results.

An important factor contributing to the validity of the cost methodology is the fact that engine materials in the cost study have retained their relative position with respect to the cost of the raw materials and the machinability index. Additionally, it has been found that, notwithstanding the emphasis on exotic machining methods such as electro-chemical milling and laser beam drilling, the majority of the machining operations have not changed appreciably, and carbide cutting tools are still being used. An indication that the state-of-the-art of manufacturing technology for modern engines has not changed appreciably since the cost study began can be found in the relative constancy of the input-output ratio which varies between 4:1 to 5:1.

RECOMMENDATIONS

As this study effort proceeded a number of recommendations, which evolved from discussions between this Center and NAVAIR, have been implemented. These are:

1. The requirement that engine abbreviated summary bills of materials be provided on all engine contracts. Raw material input weight is provided which is used in the computation of the Maurer factor.
2. Separate correlations have been made for: (1) Large engines used for fighter, patrol and transport aircraft and (2) small engine used primarily in unmanned missiles and drone aircraft.
3. Using the ratio of the weight of the input to output material as an indicator of the state-of-the-art of the manufacturing technology employed in the production of an engine.
4. Maintaining an engine escalation index based on proportions of labor and material indices obtained from data compiled by the Bureau of Labor Statistics.
5. Periodic updating of cost correlations using additional procurements of engines already in the inventory as well as those added to the fleet since the last update.

Additional recommendations for future implementation are:

1. Computerization of the computations performed in order to calculate the Maurer factor.
2. Investigation of the correlation of costs and Maurer factor using material classifications based on content of chemical elements.
3. Investigation of the correlation of development and production costs of ramjet engines using materials or performance parameters as was done with gas turbine engines.

4. Record quantities and prices of Naval engines as they are procured. Maintain a list of performance parameters for each of those engines.

These Recommendations are made so that the effect of the latest technology is incorporated in the data base employed in determining the cost estimating relationships. This will make possible continued independent comparison of contractor pricing.

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