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ABSTRACT

The Growth Dynamics of an Industrial Research Laboratory in the Aerospace Industry

by

Arthur Wade Blackman, Jr.

Submitted to the Alfred P. Sloan School of Management
on May 20, 1966, in partial fulfillment
of the requirements of Master of Science.

The techniques of industrial dynamics were applied to simulate the growth of a hypothetical industrial research laboratory employing approximately 700 people and operating on an annual budget of approximately 12 million dollars. Input data for the simulation were obtained from an anonymous research laboratory in the aerospace industry.

It was shown that government support plays a dominant role in the growth of the laboratory, and the growth behavior of the laboratory is highly influenced by various forms of managerial control. Government support for the research laboratory appeared to depend on the laboratory's output, the efforts exerted by the laboratory's management toward attracting government business, and the laboratory's inventory of facilities.

Personnel and facilities acquisition policies based on long term growth objectives rather than on short term backlogs appeared to be necessary in order to achieve smooth, nonoscillatory patterns of growth.

Thesis Adviser: Edward B. Roberts
Associate Professor of Management

Professor William C. Greene
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dear Professor Greene:

In accordance with the requirements for graduation, I herewith submit a thesis entitled "The Growth Dynamics of an Industrial Research Laboratory in the Aerospace Industry."

I am deeply indebted to Professors E. B. Roberts and D. G. Marquis for their help, encouragement, and interest throughout the study.

Mrs. John. J. Schwabe and Mrs. Patrick F. Papineau provided invaluable assistance with the computations and manuscript, respectively.

The cooperation of the management of the anonymous research laboratory which provided input data for this study is gratefully acknowledged.

Sincerely,

ehp Arthur Wade Blackman, Jr.

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CHAPTER I

INTRODUCTION

The aerospace industry represents the largest privately owned aggregation of research facilities and technically trained manpower in the world. Two salient features of this industry are (1) its characteristic of rapid and unpredictable change generated by changing world political and military situations and (2) the increasing dependency of a firm's competitive position within the industry on the viability, creativity, and volume of its research output. It follows that future success in the aerospace industry must be predicated on establishing a research organization that produces a high output of creative ideas in an environment characterized by change. A high output of creative ideas generally requires a large research effort. Hence, in the aerospace industry a successful firm that desires to increase its share of the market must develop a successful strategy of growth for its research effort.

The dynamic interactions among the many factors that control the rate of growth of an industrial research laboratory in today's aerospace industry are complex indeed. In the past it has been difficult if not impossible to quantify these interactions to the extent necessary to obtain *a priori* determination of the optimum managerial policies and strategies necessary to obtain a desired rate of growth. Lately, however, such problems that heretofore have appeared insoluble are being solved through application of the techniques of industrial dynamics as developed by Forrester (Ref. 1) for general managerial problems and by Roberts and others (Refs. 2 through 12) for research and development problems. The problems of growth have been investigated by Nord (Ref. 13) and Packer (Ref. 14), but these treatments have not been concerned with the somewhat unique characteristics of the growth of research organizations.

The primary objective of the work described herein is to apply the industrial dynamics techniques to investigate the managerial policies and strategies necessary to achieve a desired growth rate in a hypothetical industrial research organization in the aerospace industry. A secondary objective is to investigate the role of governmental support as a determinant of growth.

CHAPTER II

METHOD OF APPROACH

To achieve the objectives of this study, namely, to investigate the policies and strategies necessary for an industrial aerospace research laboratory to achieve a desired rate of growth, an approach is necessary that allows evaluation of the effect of growth rate on a number of different policies and strategies evaluated over a period of a number of years. The required approach would realistically evaluate the complex interactions between various segments of the laboratory, allow for realistic time variations, and yet not be too complex or costly to preclude solution. A mathematical modeling approach based on the techniques of industrial dynamics (Ref. 1) developed by Professor Jay W. Forrester and his associates at M.I.T. appears to possess the characteristics required for this investigation.

Industrial dynamics is based on servomechanism theory and other techniques of system analysis and is predicated on the ability of high speed digital computers to solve large numbers (hundreds) of equations in short periods of time. The equations are mathematical descriptions of the operation of the system being simulated and are in the form of expressions for levels of various types which change at rates controlled by decision functions. The level equations represent accumulations within the system of such variables as dollars, personnel, facilities, etc., and the rate equations govern the change of the levels with time.

The decision functions represent either implicit or explicit policies established for the system operation.

Mathematical simulation of a system can only represent a real system to the extent that the equations describing the operation of the components of the system accurately describe the operations of the real system components. It is usually impossible to include equations for all of the myriad components of a real system because the simulation rapidly becomes too complex. It is, therefore, necessary to obtain an abstraction of the real system based on judgment and assumptions regarding which components of the real system are those which control overall system operation.

In order for this study to be as meaningful as possible, it is based on data obtained from an anonymous industrial research laboratory in the aerospace industry. This was felt to be desirable because the operations of many industrial research laboratories tend to vary greatly and each laboratory tends to have its own unique operational characteristics. Hence, this investigation tends to be of the nature of a case study and broad generalizations can be made only in those instances where operational similarity exists. It is possible, however, to apply the approach used in a general fashion as long as suitable modifications are made in the equations to reflect the different operating methods and policies of different laboratories.

The data and assumptions upon which this study is based were obtained from the records of the research laboratory and from interviews with its management. The data presented herein, however, do not represent the operations of the anonymous research laboratory but have been scaled to represent operation of a hypothetical research laboratory employing approximately 700 people and operating on an annual budget of approximately 12 million dollars. Most of the data obtained from the "real" laboratory were from one operating section representing approximately one-fourth of the entire laboratory's research engineering effort.

CHAPTER III

ANALYSIS

Feedback Analysis

The primary feedback loops assumed to affect the growth of the research laboratory studied are shown in Fig. III-1. The backlog of unallocated funds of the research laboratory (i.e., the funds available for expenditure at the beginning of a time period) is assumed to control the number of engineers and scientists employed which in turn controls the overall employment level. The number of engineers and scientists employed have an influence (Loop 1) on the efforts of management to attract new business (in the form of government contracts)--the larger the number of engineers and scientists employed, the greater will be management's efforts to attract new business to keep them productively employed. Also, the number of engineers and scientists employed will affect the rate of expenditure of funds which affects the output of the laboratory which will in turn affect new business (Loop 2). Similarly, the greater the number of engineers and scientists, the greater must be the inventory of facilities for their use. A larger facilities inventory (Loop 3) should have a favorable effect on attracting new business. The rate of expenditure will also affect the level of the backlog of unallocated funds of the research laboratory which will in turn affect the level of the work force which can be supported (Loop 4). It can be seen that Loops 1 through 3 are positive feedback loops because an increase in the

FEEDBACK LOOPS AFFECTING GROWTH

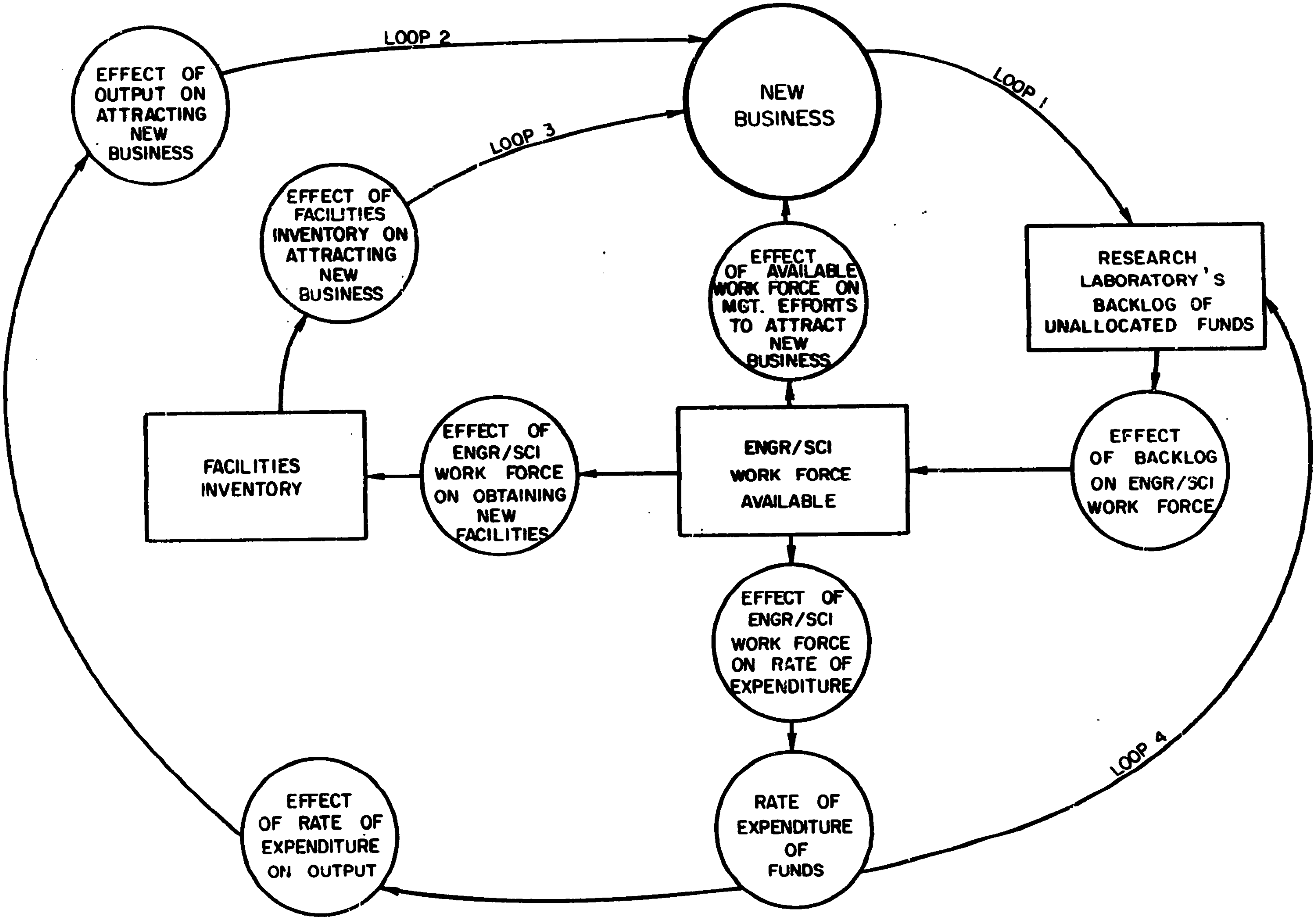


FIG. III-1

variables in the loop causes the other variables to increase in time; e.g., increasing the backlog in Loop 1 generates new business which further increases the backlog. Conversely, Loop 4 can be seen to be a negative feedback loop; i.e., an increase in the backlog increases the rate of expenditure which tends to decrease the backlog.

Analysis of Assumptions

In order to justify the assumptions made in the preceding section relative to the key feedback loops affecting growth, data were obtained from the real laboratory that served as the basis for this study. These data were obtained from laboratory records and are presented in Table III-1. They have been normalized with respect to three- or four-year averages to protect the proprietary interests of the laboratory supplying them.

Because the extent of new business is a key variable in the study, it is necessary to investigate those factors that influenced this variable. It is hypothesized that the management effort to attract new business is related to the level of the engineer/scientist work force. Therefore, new business should be related to the professional work force available. It is also expected that the extent of new business attracted should depend on the general reputation of the laboratory for doing good work. This reputation is hypothesized to be related to the laboratory's output which in turn should depend on the rate of expenditure of funds. The facilities inventory is also expected to attract new business because

TABLE III-1

DATA
(Normalized)

Year	1962	1963	1964	1965
Output of papers and presentations/4-yr. avg.	0.62	0.69	1.23	1.46
Output of patents/3-yr. avg.	0.53	0.71	1.77	-
Number of engr-sci/4-yr. avg.	0.68	1.04	0.96	1.32
Number of engr-sci/3-yr. avg.	0.76	1.16	1.08	-
Expenditure rate/4-yr. avg.	0.76	0.79	1.13	1.33
Expenditure rate/3-yr. avg.	0.85	0.89	1.27	-
$/yr. rec'd. from new contracts/4-yr. avg.	0.46	1.20	0.26	2.10
Facilities inventory or net fixed assets/4-yr. avg.	0.73	1.06	1.04	1.17 (Est.)
Budget/4-yr. avg.	0.76	0.79	1.13	1.33

the greater the extent of facilities, the greater the probability of the laboratory having the special equipment required for a requested research job. Hence, it is hypothesized that the key variables affecting new business are: (1) the engineer/scientist work force, (2) the rate of expenditure of funds, and (3) the facilities inventory. The dollars per year received from new government contracts is used as a measure of the extent of new business, and its variation with time is shown in Fig. III-2. It can be seen that the extent of new business received varies considerably. Because of the fluctuations with time, it was decided to smooth the data by utilizing a two-year moving average. A line was fitted through the smoothed points by the method of least squares (see Ref. 15). As can be seen from Table III-1, the data are such that the three key variables assumed to affect the extent of new business all vary simultaneously. To isolate the effects of the variables, it is desirable to know the variation of the extent of new business with one of the key variables with the other two held constant. To achieve this end, multiple regression analysis (Ref. 16) was employed to derive an equation which related the least-square, smoothed values of the extent of new business to the three key variables discussed above. The equation obtained was

$$y = 0.635x_1 + 0.363x_2 - 0.010x_3 - 0.189 \qquad (1)$$

where

$$y = \frac{\text{\$/year received from new contracts}}{\text{four-year average of \$/year received}}$$

$/YEAR RECEIVED FROM NEW CONTRACTS VS. TIME

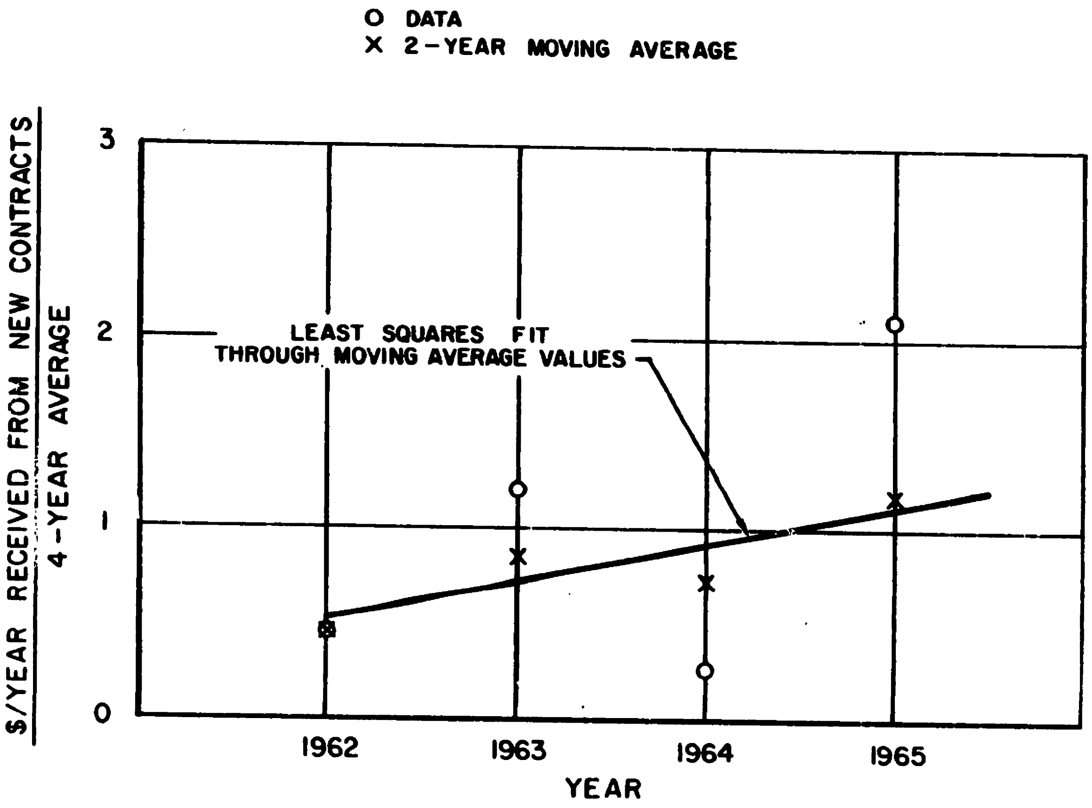


FIG. III-2

$$x_1 = \frac{\text{\$ spent/year}}{\text{four-year average of \$ spent/year}}$$

$$x_2 = \frac{\text{number of engineers and scientists}}{\text{four-year average of engineers and scientists}}$$

$$x_3 = \frac{\text{net fixed assets}}{\text{four-year average of net fixed assets}}$$

A multiple correlation coefficient of 0.988 was determined for the equation, and the agreement between the actual data and Eq. (1) is shown in Fig. III-3. The agreement between the computed values and the smoothed data is excellent (the standard error of estimate was determined to be 3.16 percent) which gives justification to the assumption that the three key variables utilized are the controlling ones.

An examination of the relation between output and rate of expenditure of funds gives further justification. It was believed initially that output should be related to the number of engineers and scientists on the work force. To test this belief, it was decided to use the number of papers and presentations made and the number of patents produced as measures of output. When these variables were plotted vs. the number of engineers/scientists in the work force the relatively poor correlations (variations of greater than 40 percent from a straight line through the data) of Figs. III-4 and III-5 were obtained. However, when these variables were plotted vs. the expenditure rate, the obviously good correlations (variations of less than 5 percent from a straight line through the data) of Figs. III-6 and III-7 resulted.

AGREEMENT BETWEEN SMOOTHED VALUES AND VALUES CALCULATED FROM EQ. I

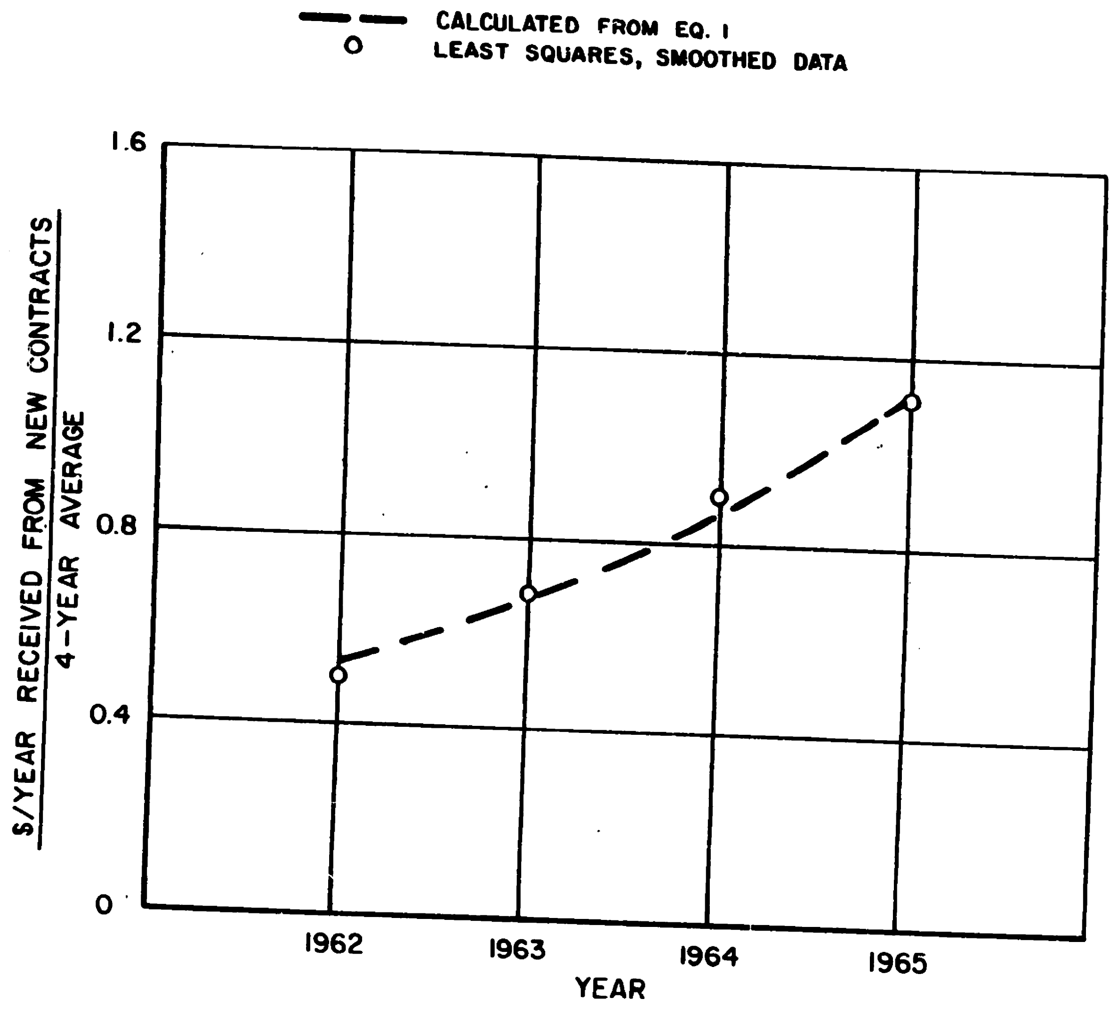


FIG. III-3

EFFECT OF NUMBER OF ENGINEERS / SCIENTISTS ON THE OUTPUT OF PAPERS AND PRESENTATIONS

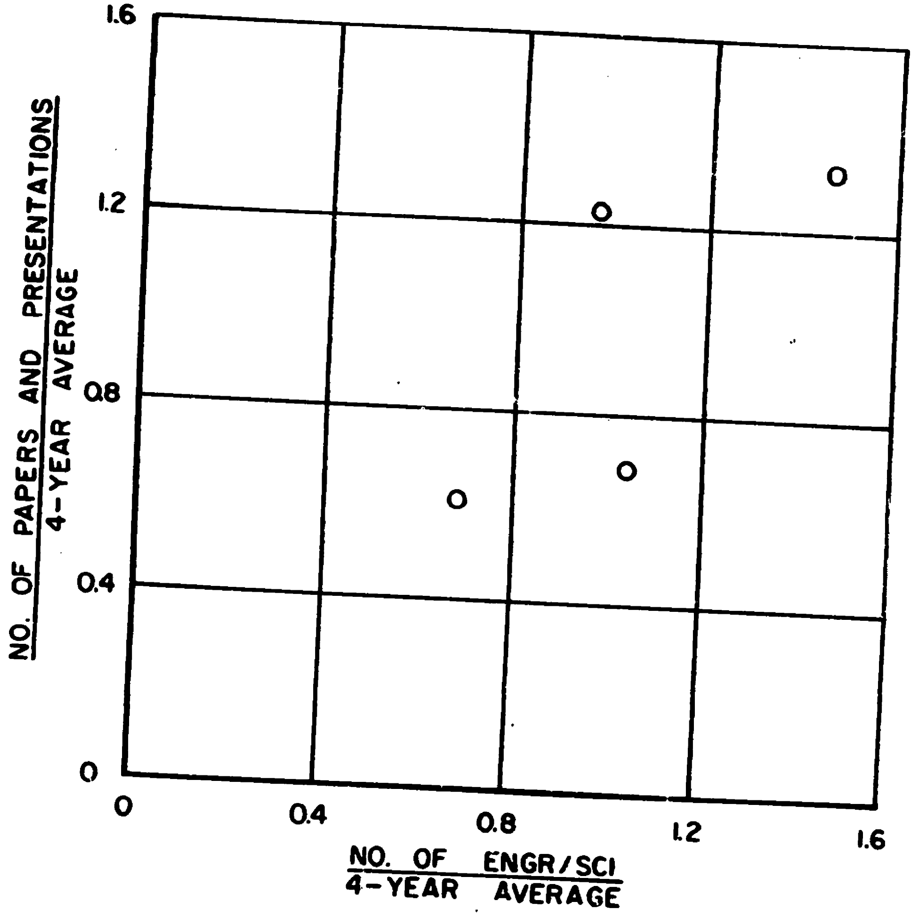
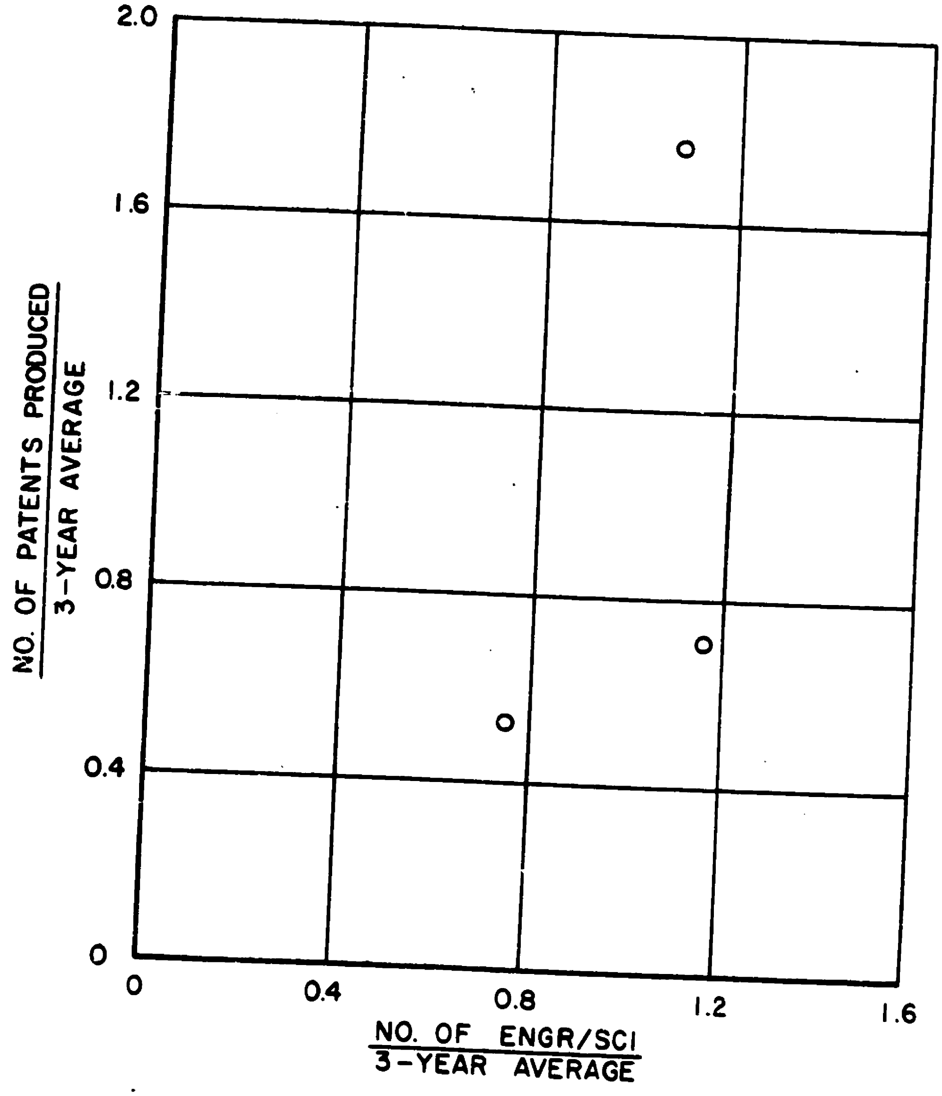


FIG. III - 4

FIG. III-5

EFFECT OF NUMBER OF ENGINEERS/SCIENTISTS ON THE NUMBER OF PATENTS PRODUCED



EFFECT OF $ SPENT/YEAR ON OUTPUT OF PAPERS AND PRESENTATIONS

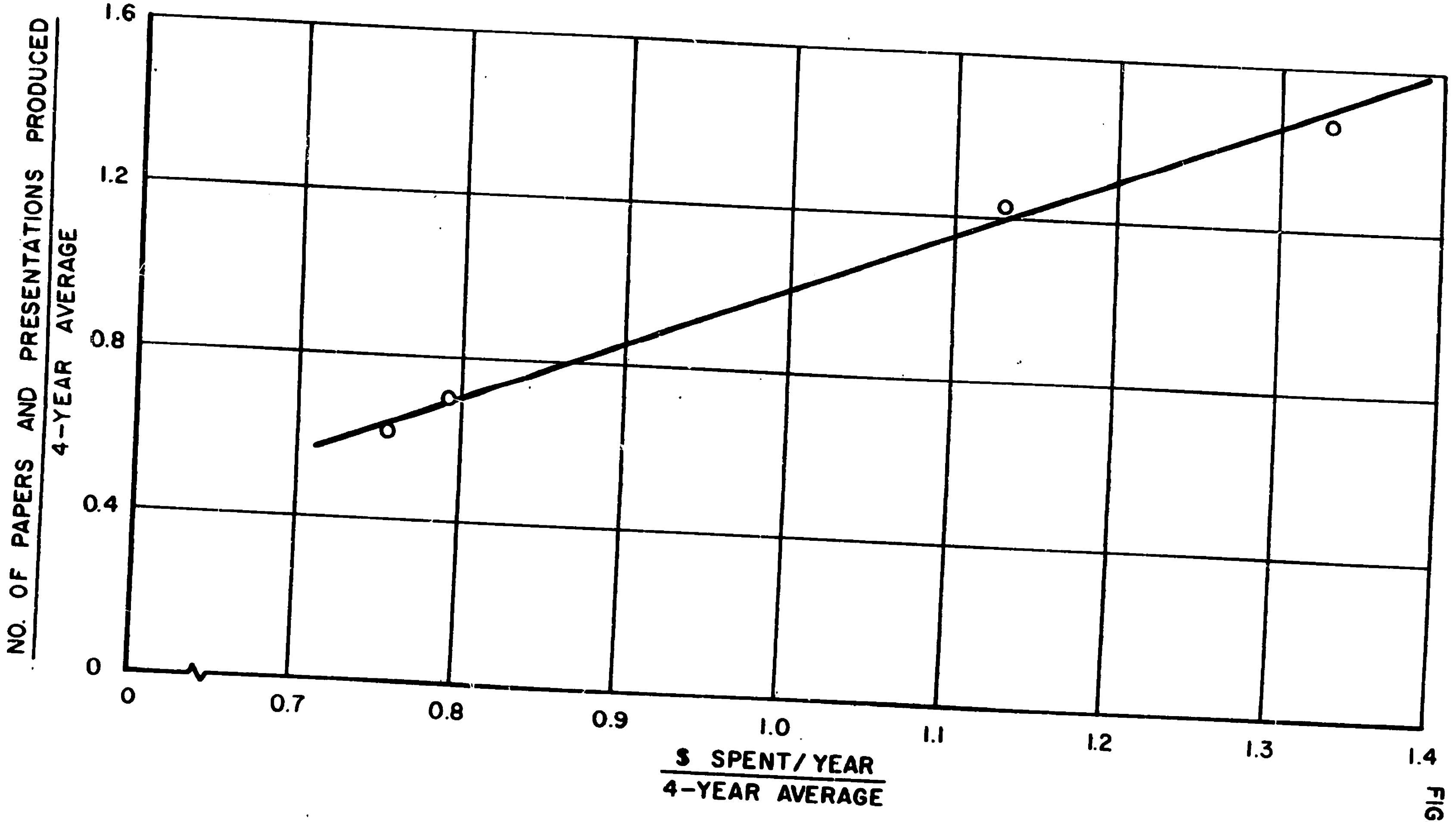


FIG. III-6

EFFECT OF $ SPENT/YEAR ON THE NUMBER OF PATENTS PRODUCED

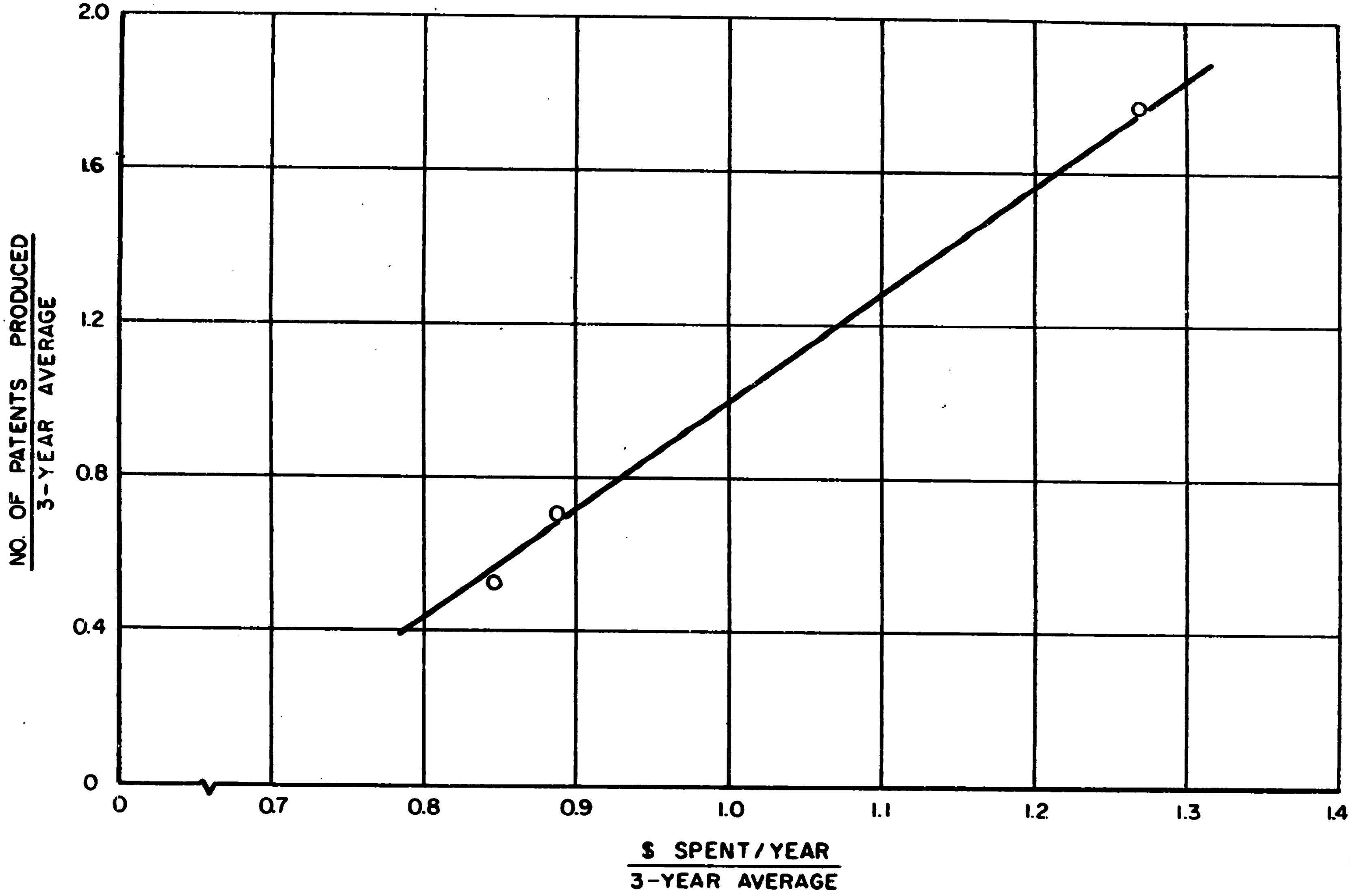


FIG. III-7

In summary, the key variables affecting the extent of new business appear to be (1) the rate of expenditure of funds, (2) the engineer/scientist work force, and (3) the facilities inventory. The output of the laboratory appears to be related to the rate of expenditure of funds to a much greater degree than to the engineer/scientist work force. The facilities inventory has a very small effect within the range of the data.

Further analysis of the assumptions made will be discussed in relation to the feedback loops shown in Fig. III-1.

Loop 1

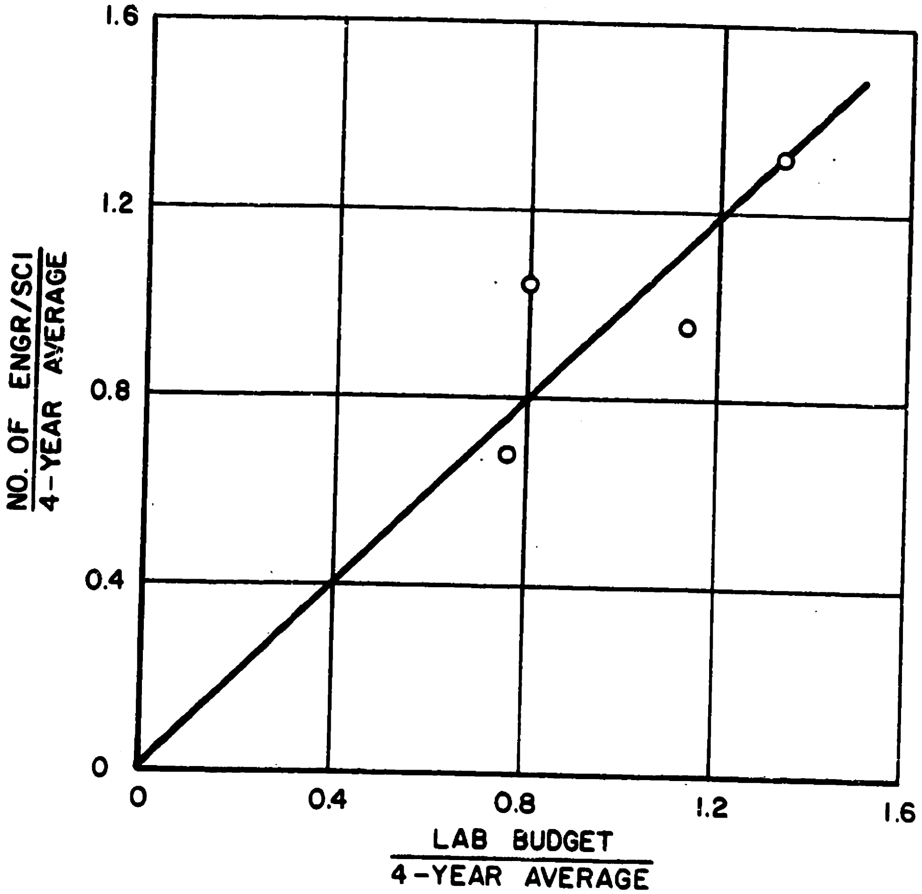
Figure III-8 presents a correlation (maximum variation approximately 25 percent from a straight line through the data) between the research laboratory budget and the number of engineers and scientists in the work force. The curve appears to justify the assumption made in Loop 1 that the level of the professional work force depends on the backlog of unallocated funds.

It has been assumed that the management effort to attract new business is related to the level of the professional work force. The effect of the extent of new business with variations in the professional work force was calculated from Eq. (1) with x_1 and x_3 held equal to 1.0 and the results are presented in Fig. III-9.

Loop 2

The effect of the number of engineers and scientists in the work force on the rate of expenditure is shown in Fig. III-10 (maximum variation approximately 25 percent) and the relationship between the expenditure

EFFECT OF LAB BUDGET ON ENGINEER/SCIENTIST WORK FORCE



EFFECT OF PROFESSIONAL WORK FORCE ON ATTRACTING NEW BUSINESS CALCULATED FROM EQ. I

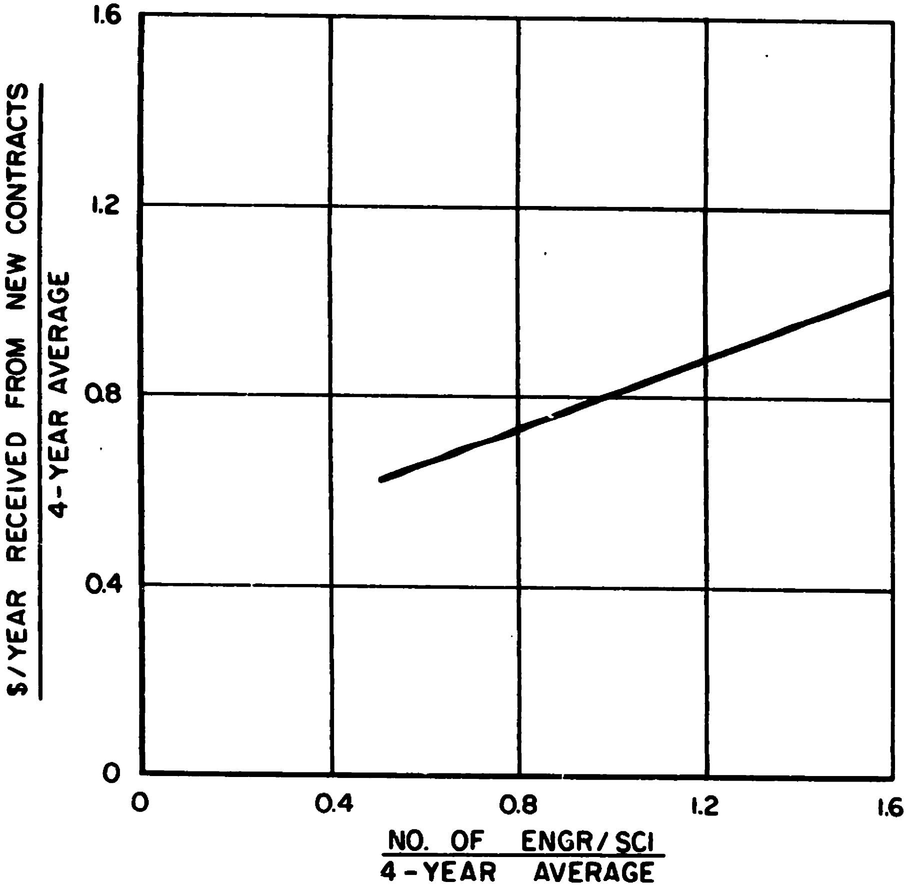
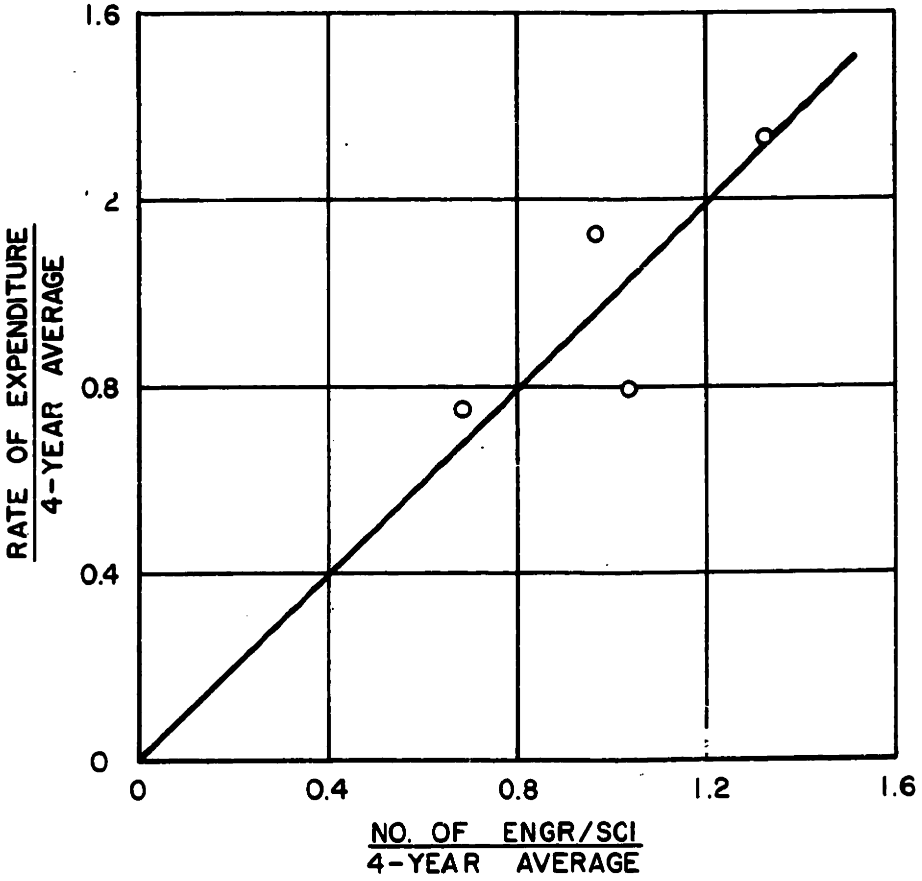


FIG. III-9

FIG. III-10

EFFECT OF THE NUMBER OF ENGINEERS/SCIENTISTS ON $ SPENT/YEAR



rate and the laboratory output has been discussed previously. The effect of the rate of expenditures (and hence output) on attracting new business was calculated from Eq. (1) with x_2 and x_3 held equal to 1.0 and is presented in Fig. III-11.

Loop 3

The effect of the number of engineers and scientists in the work force on the facilities inventory is shown in Fig. III-12 (maximum variation approximately 8 percent from a straight line through the data). On the basis of this correlation the facilities desired by the engineers and scientists were assumed to vary linearly with the number of engineers and scientists in the work force.

The relationship between new business and the facilities inventory was calculated from Eq. (1) with x_1 and x_2 held equal to 1.0, and the results are shown in Fig. III-13. It can be seen that the facilities inventory has a very small effect on new business in the range for which data were available. However, at lower values of the facilities inventory some effect would be expected. This is discussed further in Appendix A in connection with Eq. (42,A).

Loop 4

Because the level of the backlog of unallocated funds is a function of the rate of expenditure of funds (see Eq. (1,L) in Appendix A), this last assumption is simply justified by definition.

EFFECT OF RATE OF EXPENDITURE ON ATTRACTING NEW BUSINESS CALCULATED FROM EQ. I

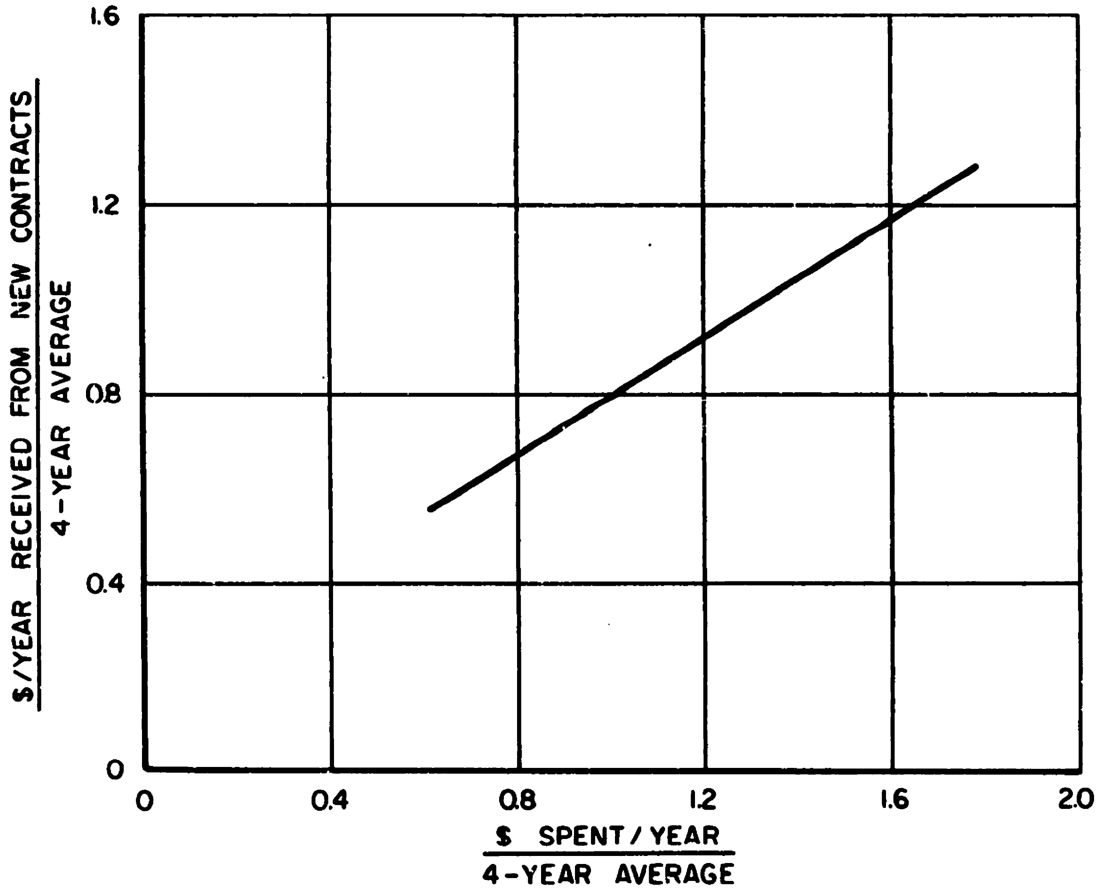


FIG. III-11

EFFECT OF NUMBER OF ENGINEERS / SCIENTISTS ON THE FACILITIES INVENTORY

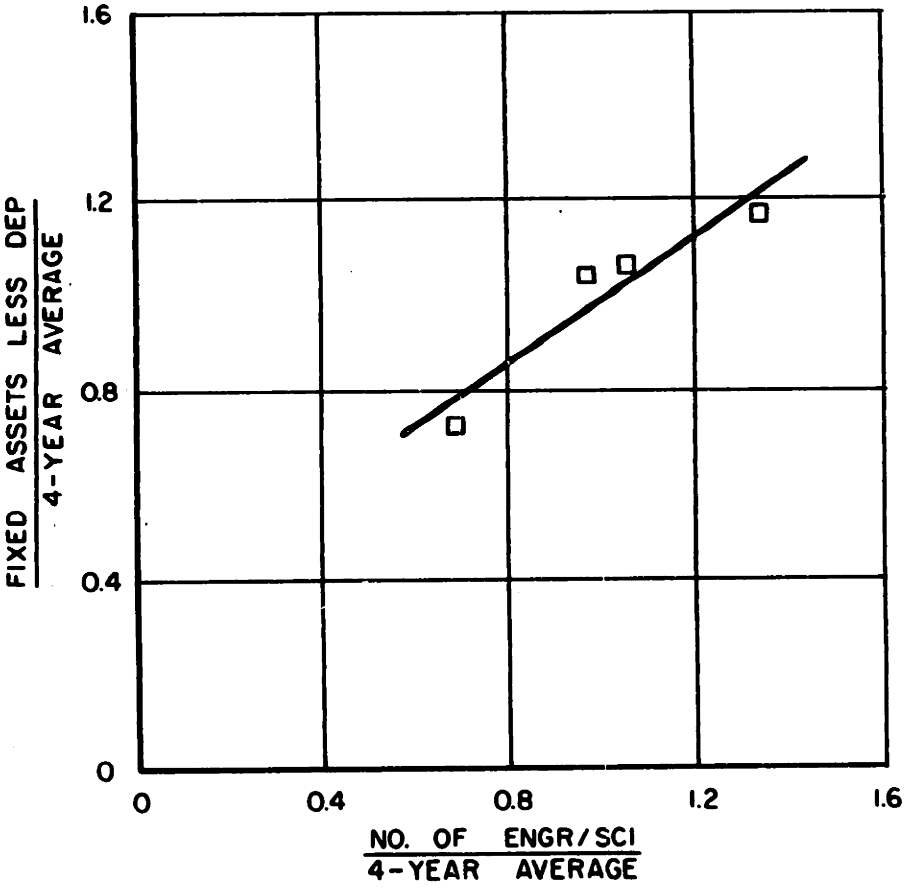
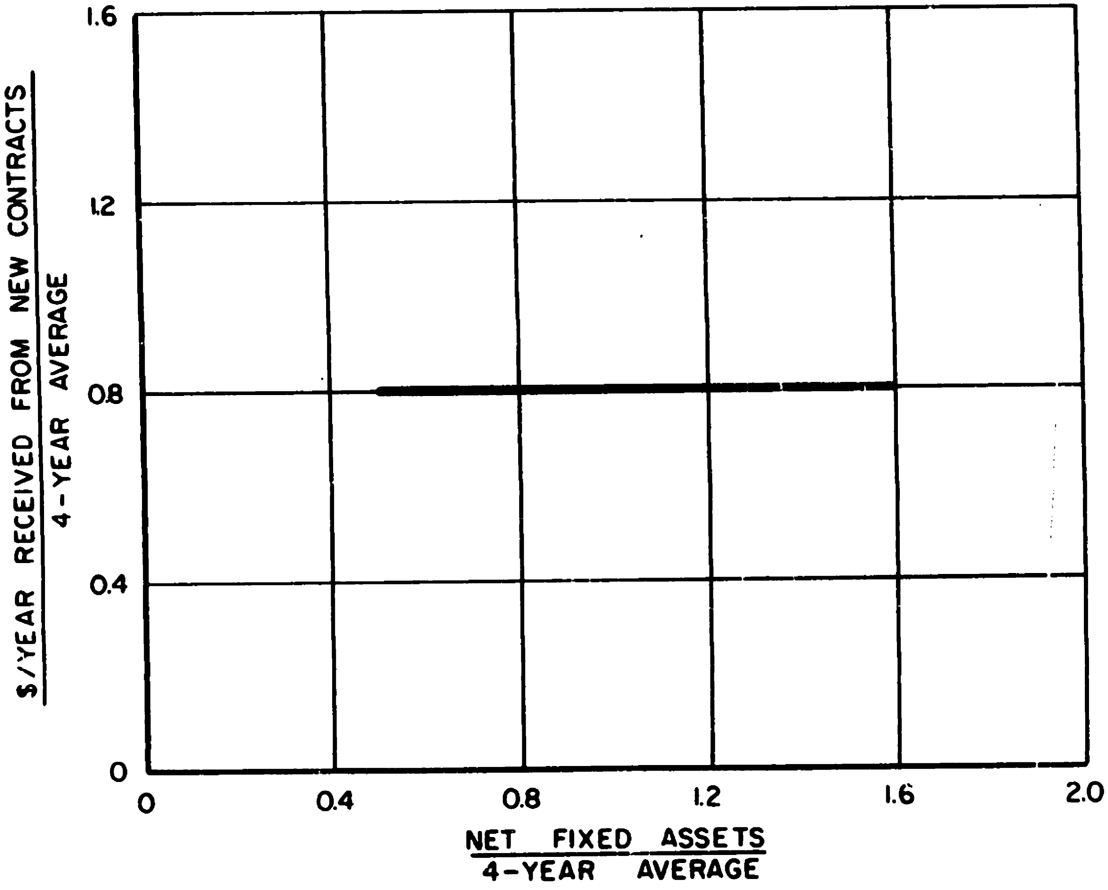


FIG. III-12

FIG. III-13

EFFECT OF FACILITIES INVENTORY ON ATTRACTING NEW BUSINESS CALCULATED FROM EQ. I



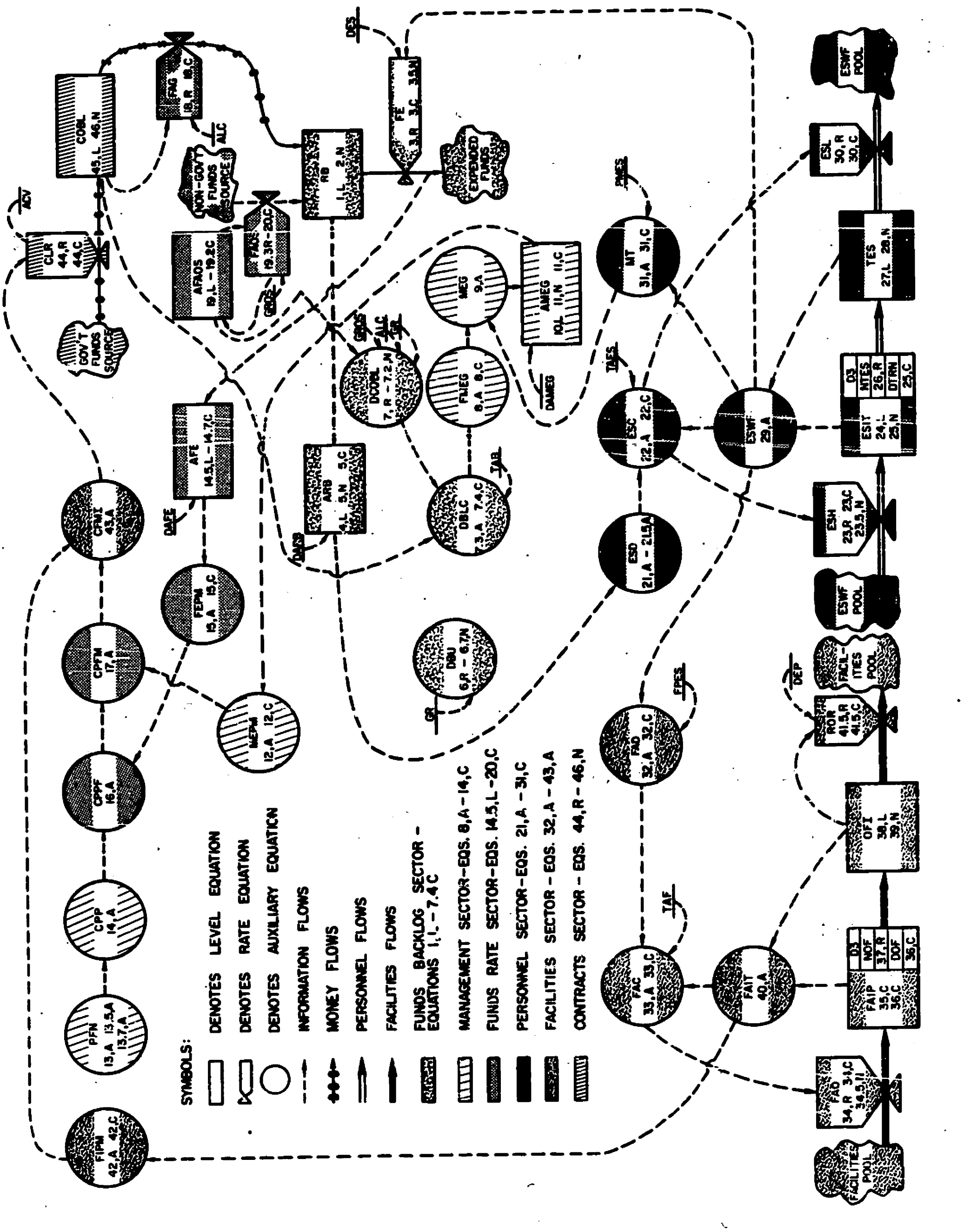
Model Analysis

The detailed industrial dynamics model shown in Fig. III-14 was developed from the assumed key feedback patterns. It contains about fifty equations which are developed and discussed in detail in Appendix A. This model represents a hypothetical research organization that is believed to be representative of some real organizations, but the degree of similarity will of course vary. The model necessarily contains many assumptions that can be justified in varying degrees as is discussed in the preceding section and in Appendix A.

The model shown in Fig. III-14 contains six sectors:

1. The <u>funds backlog sector</u> (Eqs. (1,L) through (7.4,C)) describes how the funds backlog responds to the organization's activities and desired growth rate.
2. The <u>management sector</u> (Eqs. (8,A) through (14,C)) represents the effects of management's efforts on attracting new government business and describes the flow of contractual support from the government.
3. The <u>funds-rate sector</u> (Eqs. (14.5,L) through (20,C)) describes the exogenous flow of funds from non-government sources, the flow of funds from government sources, and the effects of the rate of expenditure on the inflow of government funds.
4. The <u>personnel sector</u> (Eqs. (21,A) through (31,C)) represents the hiring and firing decisions and their influence on the professional work force.

FLOW DIAGRAM OF MODEL



5. The facilities sector (Eqs. (32,A) through (43,A)) represents the inventory of facilities, its change to fluctuations in the professional work force, and its influence on the receipt of government contractual support.

6. The contracts sector (Eqs. (44,R) through (46,N)) describes the rate of receipt of government contractual support and the contractual support backlog.

CHAPTER IV

RESULTS AND DISCUSSION

The industrial dynamics model developed in Chapter III was run on an IBM 7094 computer utilizing the DYNAMO compiler simulator program (Ref. 17).

Figure IV-1 presents the results of these calculations in the form of plots of the data obtained from the DYNAMO output. The several variables that are plotted against time are: the average backlog of unallocated funds, ARB; the contract backlog, COBL; the average managerial effort toward attracting additional government business, AMEG; the engineer/scientist work force, ESWF; and the total facilities inventory, FAIT. These plots represent the operation of the hypothetical research laboratory for a period of ten years with a desired growth rate of 5 percent per year. Conditions are assumed to be initially in a steady-state and operation of the model begins at time equal to zero. During the first months of operation the backlog of unallocated funds and the professional work force begin to expand slightly but the contract backlog decreases because of a paucity of new contracts. This reduced contract backlog causes the unallocated funds backlog to begin to decrease. At about the same time the facilities inventory begins to increase as a result of the earlier increase in professional work force. The reduced funds backlog causes a greater management effort toward attracting new government business which works with the

TEN-YEAR SIMULATION OF LABORATORY OPERATIONS

GROWTH RATE = 5%/YEAR

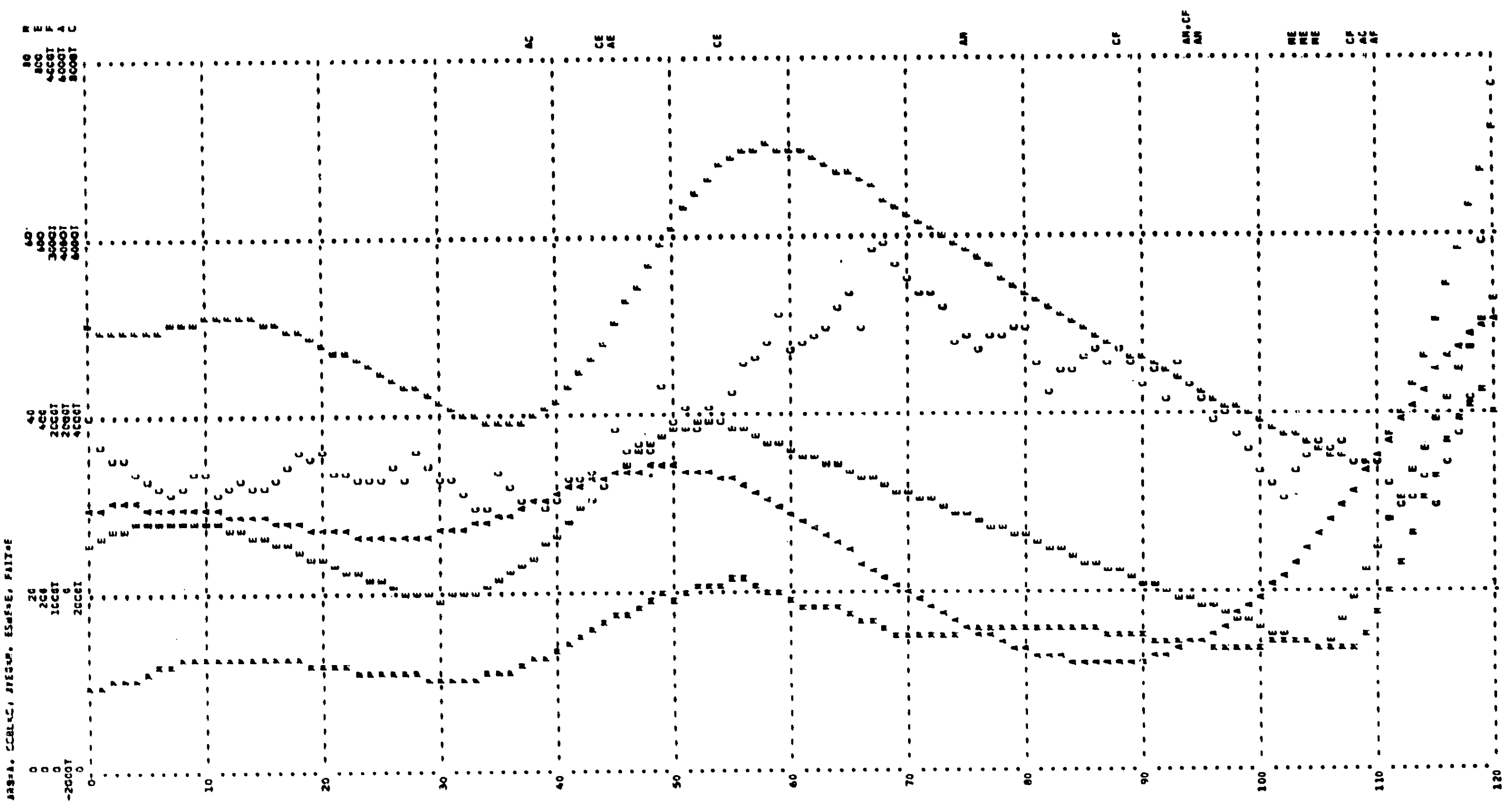


FIG. IV-1

increase in facilities to cause an increase in the contract backlog which causes the funds backlog to go up again around the 20th month. This overall pattern repeats itself and oscillations of increasing amplitude (almost 50 percent increase in the funds backlog in the first cycle) characterize the growth pattern over the ten year period. The period of the oscillations in the funds backlog increases with time. The first cycle has a period of approximately 40 months and the second, approximately 72 months. The oscillations result from the negative feedback loop (Loop 4, Figure III-1) and the increasing amplitude results from the positive feedback loops (Loops 1 through 3, Figure III-1). Such oscillations although highly undesirable are nevertheless characteristic of the growth patterns of many organizations as discussed in Ref. 14.

Clearly, the operating policies employed in the hypothetical model which produce such oscillations in the growth patterns are undesirable, and operating policies must be sought which will result in smoother growth patterns. It is instructive to observe that oscillating growth behavior can be produced by a set of operating policies which appear to be logically consistent and which would superficially at least have been predicted to produce stable growth. Stability can only be determined *a posteriori* from the simulation results, which makes obvious the usefulness of simulation techniques as a management tool.

Revised Policies

Because the oscillations of increasing amplitude result from the feedback loops, policy revisions were sought which would tend to decouple the system and reduce somewhat the effects of feedback.

Personnel Sector

To this end, it was decided that a hiring policy for engineers and scientists which depended in large measure on the desired funds backlog and to a lesser extent on an average of the actual funds backlog would be desirable. Such a policy would insulate the hiring decisions from the short range fluctuations in the funds backlog and make them depend to a greater extent on the longer range considerations of the desired growth rate. This would be consistent with the efforts to attract additional government business which also depend on the desired growth rate. In other words, a hiring policy based to some degree on the desired future growth would tend to compensate for the lag times which are inevitable in hiring competent professional personnel.

Funds Backlog Sector

The assumption made earlier that the laboratory expenditure rate depended only on the level of the professional work force was re-examined. It was decided that it would be more realistic to assume that the expenditure rate depends both on the level of the professional work force and on the overall management policy concerning expenditures. For example, if in a given period few contracts were received and the addition of government funds to the unallocated funds backlog was at a reduced rate, management might exercise caution and expend funds at a reduced rate to maintain the desired funds backlog. This could be accomplished by reducing the support personnel used on the project, revising scheduling, deferring material and computational expenditures, tighter cost control, etc. Of course, the variation which could be achieved would have prescribed limits; i.e., a lower limit would be imposed by the minimum costs of the existing personnel. The scatter in the data of Fig. III-10 presents some further justification for the reality of the revised assumption.

One additional revision which appeared desirable was a change in the policy assumed concerning management efforts to attract additional government business. Instead of basing the efforts to attract new business solely on the difference between the desired contract backlog (i.e., that required for a given growth rate) and the actual contract backlog, it appeared desirable to also have these efforts depend on the difference between the desired and actual funds backlog levels.

The revised equations for the policy changes discussed above are presented in Appendix B.

Figure IV-2 presents the results (for a growth rate of 5 percent per year) of calculations carried out with the previously discussed policy revisions incorporated in the program. Examination of these results indicates that the new policies have been successful in eliminating some of the difficulties previously encountered with large amplitude oscillatory growth patterns. The growth patterns for the

TEN-YEAR SIMULATION OF LABORATORY OPERATIONS

GROWTH RATE = 5% / YEAR

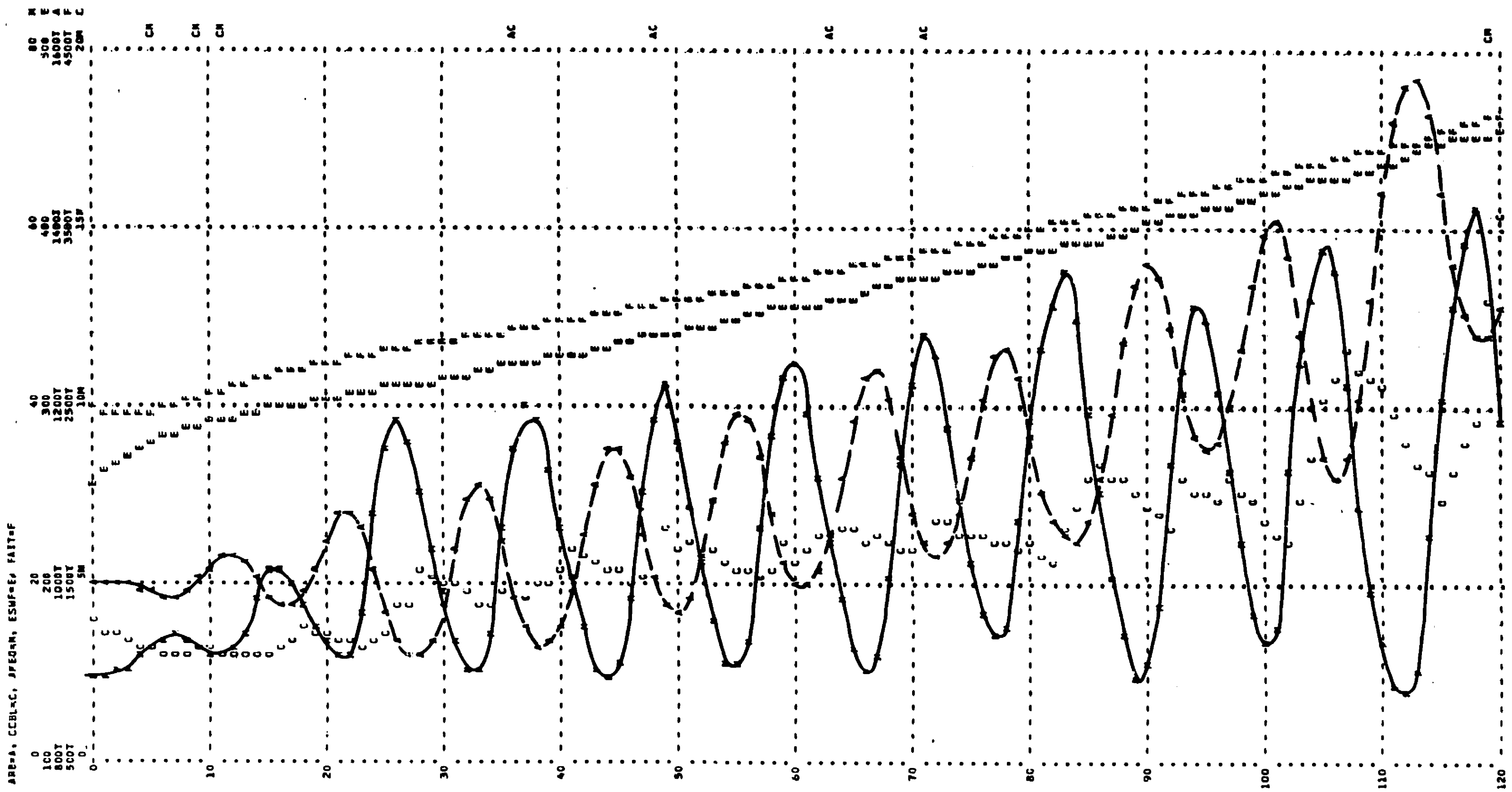


FIG. IV-2

professional work force, ESWF, and the facilities inventory, FAIT, are essentially smooth with no appreciable oscillations. However, oscillations with slowly increasing amplitude and a period of approximately 10 months appear in the average funds backlog, ARB, and the average management effort toward attracting additional government business, AMEG.

In an effort to find the cause of these oscillations, additional runs were made with the model to investigate its sensitivity of response to changes in some of the key variables as discussed below.

Discussion of Sensitivity Results

The model behavior presented previously is based on assumptions about some variables which must of necessity be inexact because in most cases management does not have the knowledge required in an exact form. It must be required, therefore, that the variation in model behavior be known for a reasonable variation in these variables. To test the effects of some of these key variables, runs were made with the new policy formulation (with a growth rate of 5 percent per year unless otherwise indicated) as each variable was systematically changed.

Variations in FTN

The value of FTN in Eq. 21 was changed from a value of 0.1 to 1.0. The effect of this change was to base the hiring decision for new professional employees on the current averaged funds backlog rather than primarily on the funds backlog desired to achieve the target rate of growth. This change makes the hiring decision sensitive to short run fluctuations as shown in Fig. IV-3 which presents a plot of the professional work force vs. time for the two different policies. Although oscillations do appear with a value of FTN = 1.0, they are not nearly so pronounced as they were with the original policies (cf. Fig. IV-1) and relatively large variations could occur in the value of FTN without catastrophic effects.

Variations in ACV

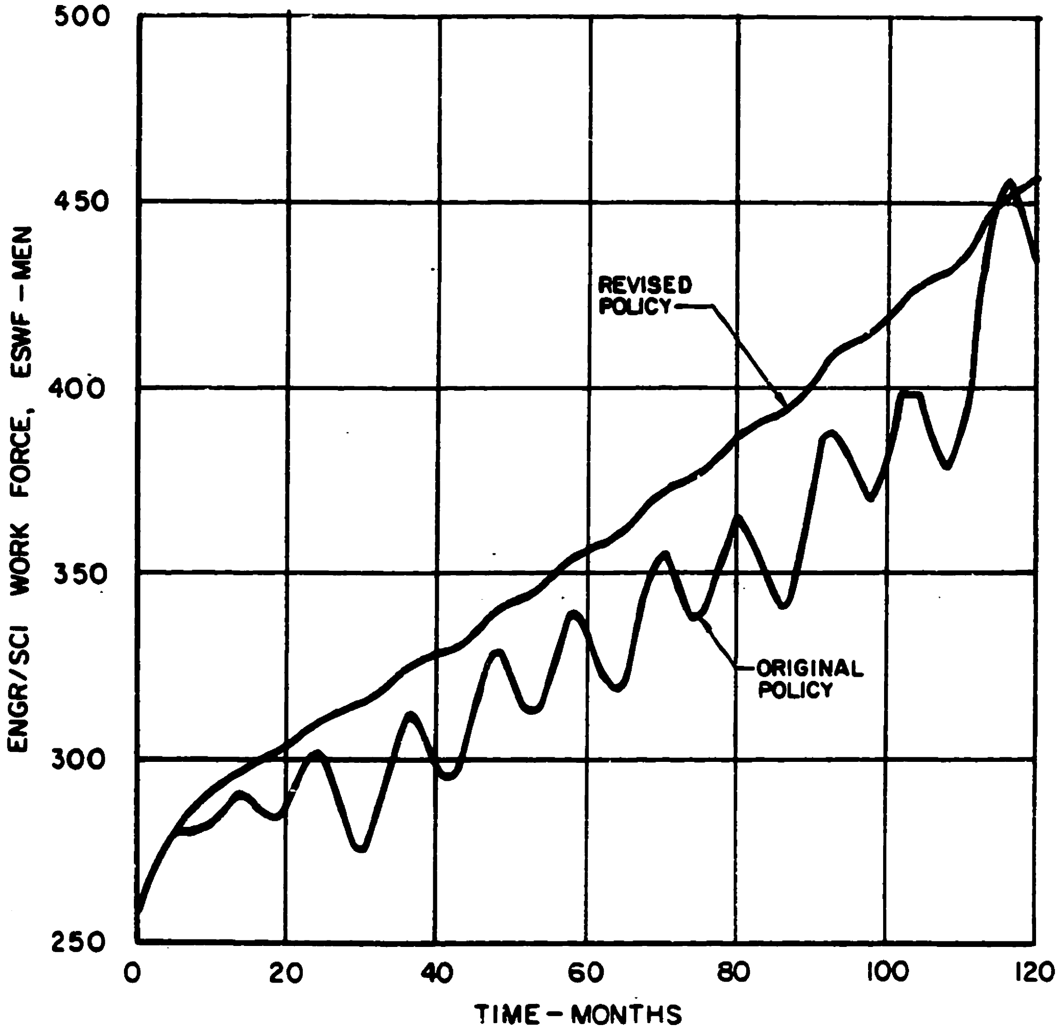
The value of ACV, the average contract value, in Eq. 44C was changed from $100,000 to $150,000 and run for the usual 10 year simulation. With the exception of changes in the schedule of the average management efforts toward attracting additional government business, AMEG, the other variables were affected to only a minor extent. The changes in AMEG simply reflect the fact that a different sales effort is required to maintain the desired funds backlog if the value of the contracts is increased.

Variations in PFN1

The values of PFN1 in Eq. 13 are the values of the random members which govern the number of contracts received per month. A value of zero was assigned to this variable which had the effect of requiring a constant number of contracts to be received per month (i.e., the mean of the Poisson distribution, see Eqs. 13-14C), and the effect of changes in the random distribution function of the number of contracts received per month was thereby determined. With the exception of minor changes in the funds backlog, RB, and changes in the average

FIG. IV-3

VARIATION OF ENGR/SCI WORK FORCE WITH TIME



management efforts toward attracting additional government business, AMEG, which reflected the changes in the average contract value, the results were insensitive to this change. This would indicate that the shape of the distribution function which governs the number of contracts received per period does not have an important effect on the simulation results.

Variations in FMEG

Three variations (as shown in Fig. IV-4) of the schedule of the fraction of management effort toward attracting additional government business, FMEG, vs. the desired backlog change, DBLC (see Eq. 8), were run. It was found that amplitude of the oscillations in variables such as funds backlog, RB, and the average management effort toward attracting new government business, AMEG, was reduced as the slope of the FMEG vs. DBLC curves were reduced. The effect of this change was to make management efforts less responsive to small fluctuations in the desired backlog change and thereby to smooth the oscillations.

Variations in DAMEG

Values for the delay in average management effort toward attracting additional government business, DAMEG (see Eq. 10), of 1, 9, and 18 months were run for a growth rate of 10 percent per year. The results showed that the amplitude of the oscillations in variables such as funds backlog, RB, etc. decreased as DAMEG increased. This result occurred because an increase in DAMEG causes the average management

VARIATION IN ASSUMED RELATIONSHIP BETWEEN DESIRED BACKLOG CHANGE AND FRACTIONAL MGT. EFFORT

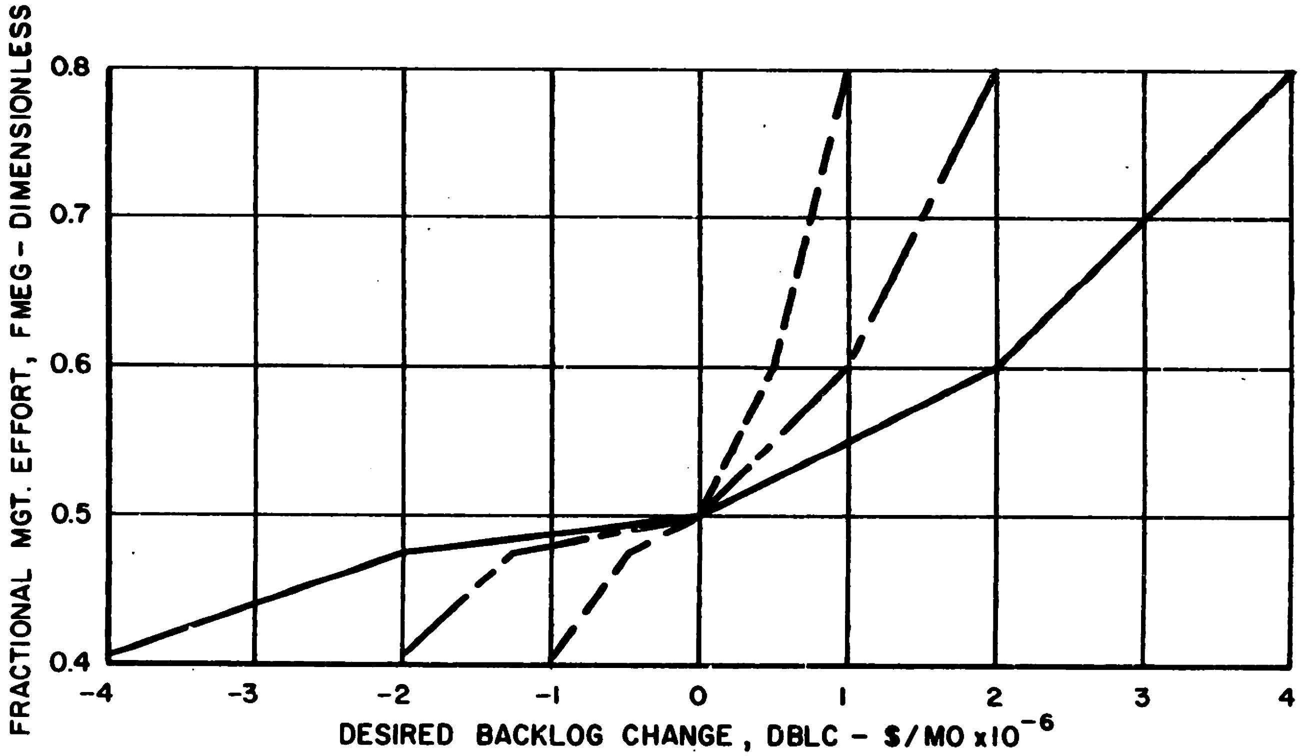


FIG. IV-4

effort toward attracting additional government business, AMEG, to be less responsive to short run fluctuations and respond more to the long term desired growth rate.

Best Policy Revision

The results of the sensitivity runs were incorporated into a final set of revised policies which appeared to be the best compromise between the variables to produce the most stable growth patterns. The final set of equations are presented in Appendix C. The results of simulation runs for these policies for a growth rate of 10 percent per year are presented in Fig. IV-5. A detailed print-out of the computed results for a growth rate of 10 percent per year is presented in Appendix D.

The agreement between the simulated results for a growth rate of 20 percent per year and the actual data obtained from the operation of the research laboratory used as a basis for this investigation is presented in Figs. IV-6 through IV-8. The first four years of the simulated results are compared with the data of Table III-1 for: the funds expenditure rate, FE; the engineer/scientist work force, ESWF; and the facilities inventory, FAIT. The results agreed within standard deviations of ± 7.4% for FE, ± 9.7% for ESWF, and ± 10.2% for FAIT. This agreement is thought to be very good considering the scatter which exists in the data of Table III-1 and provides *ex post facto* support for the assumptions upon which the model was based.

TEN-YEAR SIMULATION OF LABORATORY OPERATIONS

GROWTH RATE = 10%/YEAR

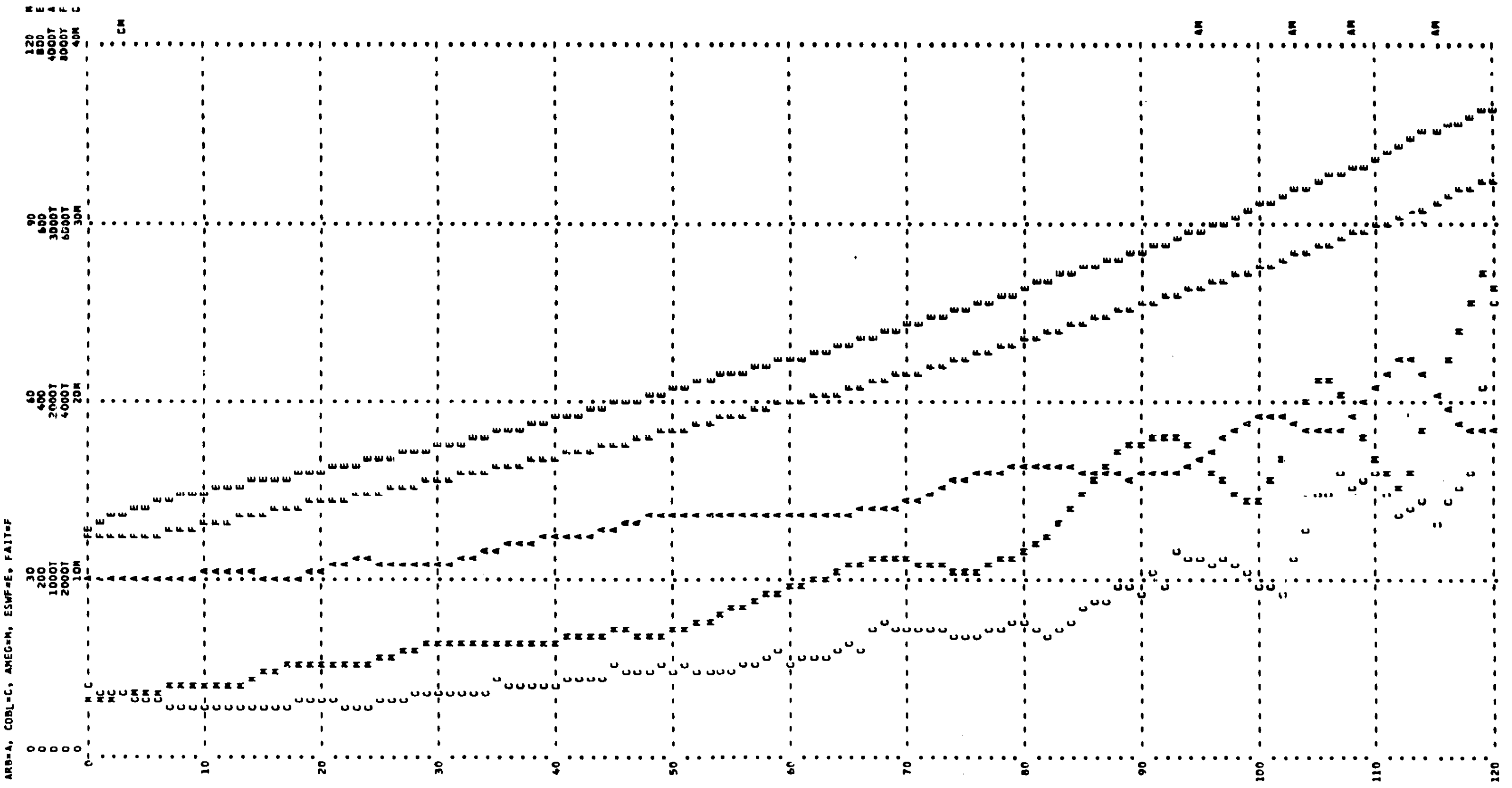


FIG. IV-5

COMPARISON OF PREDICTED AND ACTUAL FUNDS EXPENDITURE RATES

STANDARD DEVIATION ± 7.4%

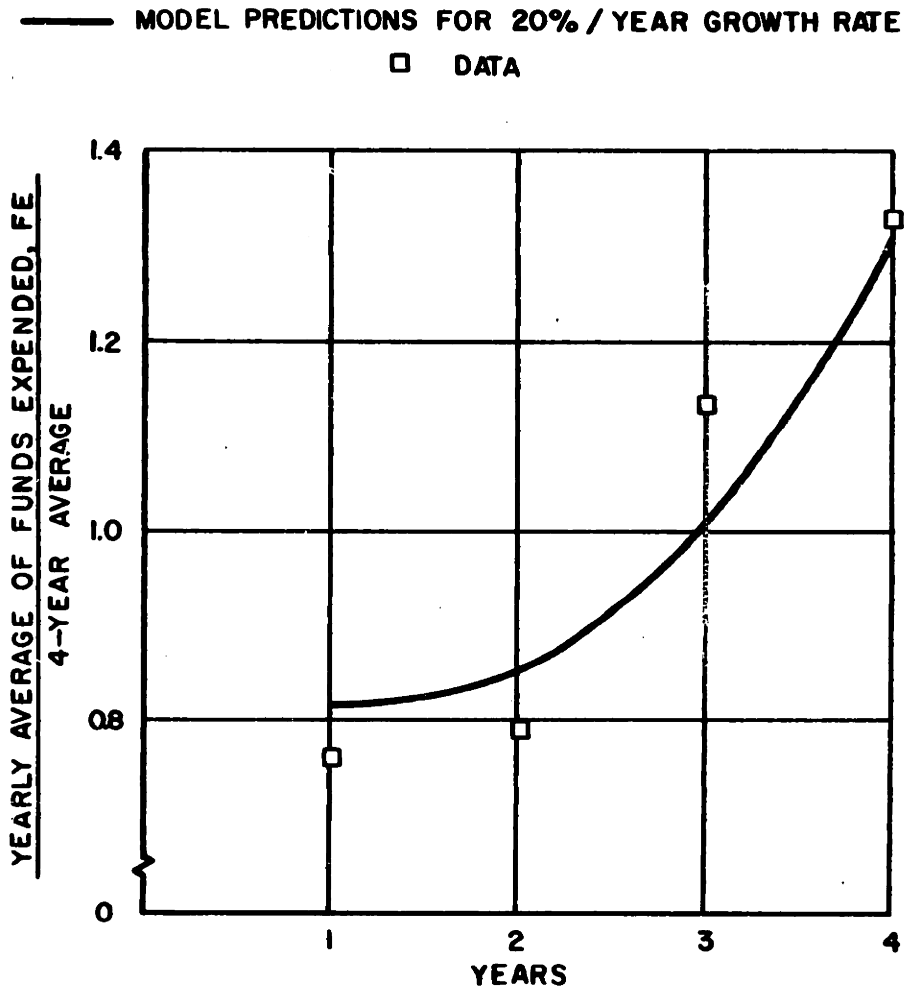


FIG. IV-6

COMPARISON OF PREDICTED AND ACTUAL PROFESSIONAL WORK FORCE

STANDARD DEVIATION ± 9.7%

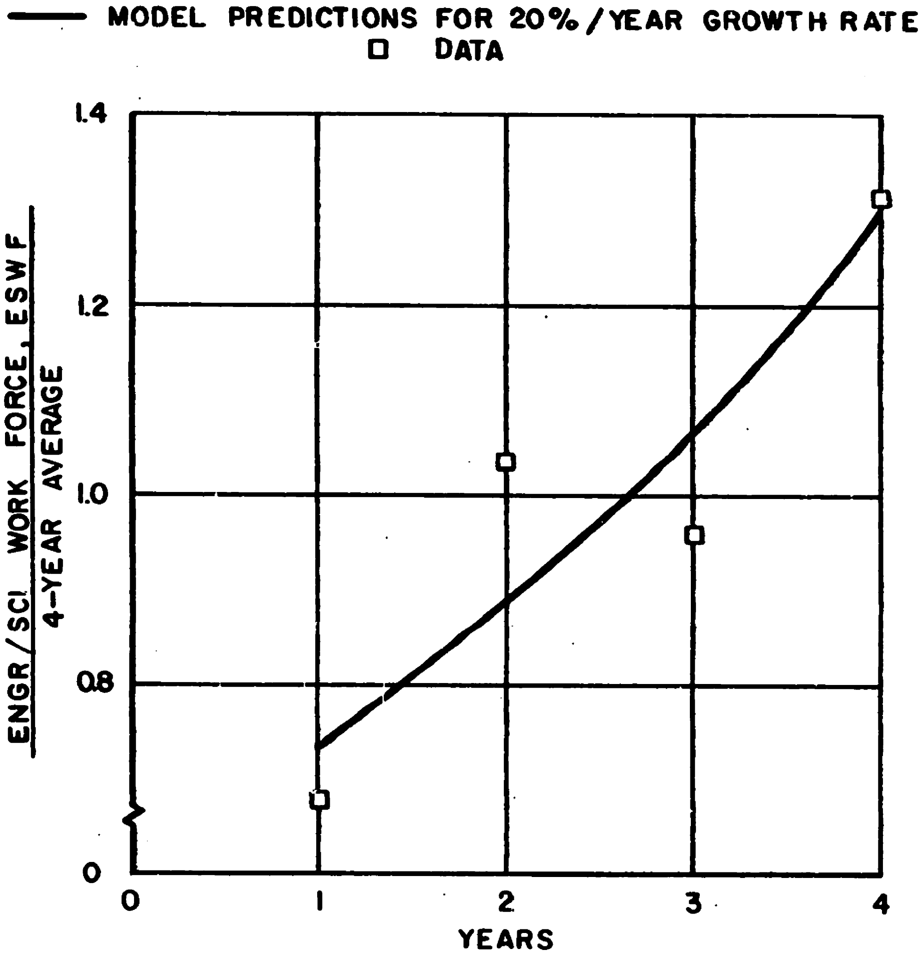


FIG. IV-7

COMPARISON OF PREDICTED AND ACTUAL FACILITIES INVENTORIES

STANDARD DEVIATION ± 10.2%

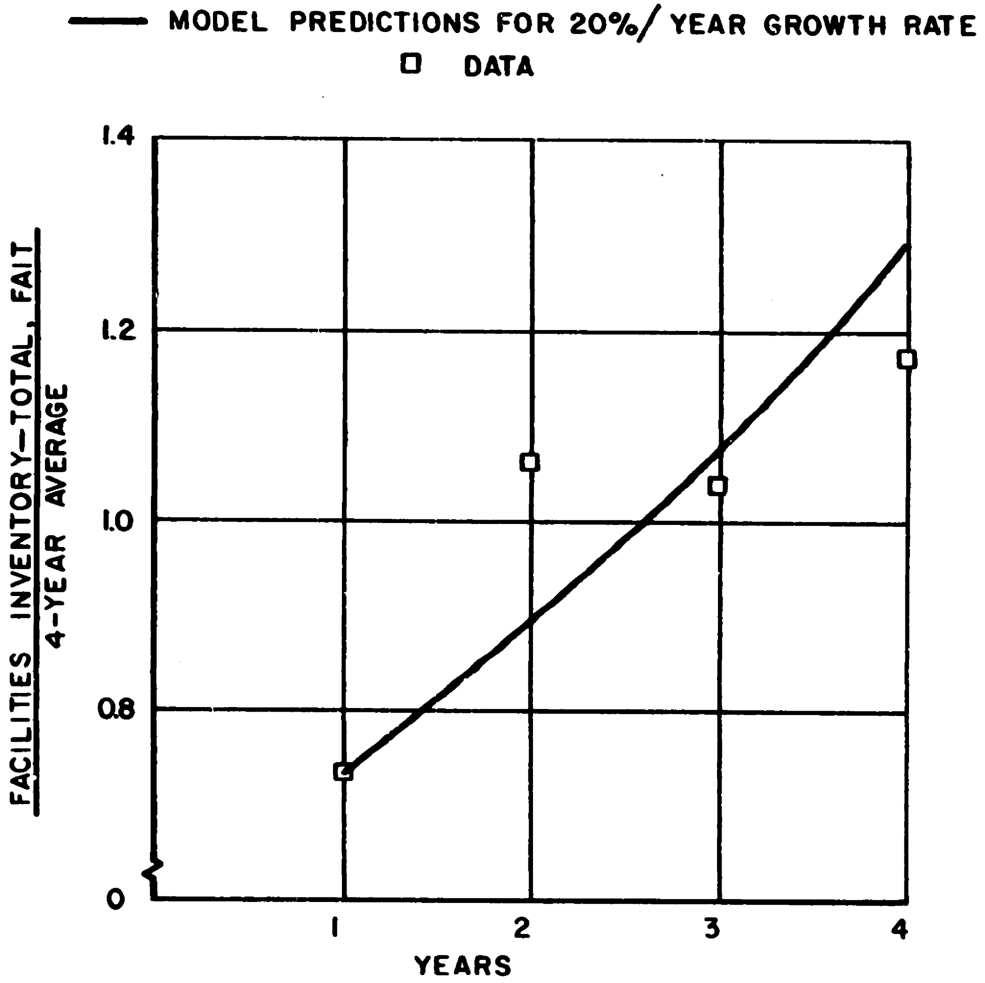


FIG. IV-8

Several points can be derived from these results which have useful implications for the management of research laboratories. If a high rate of growth is desired or required from competitive pressures and this rate of growth cannot be attained internally from the supporting organization or from external commercial sources, then the rate of government support is the most important single factor in achieving a desired growth rate. Management must seek this support aggressively. It is necessary to increase the effort devoted to attracting government business as the laboratory grows in size. The efforts exerted in attracting new business can be expected to exhibit short-term fluctuations which will be subject to random variations in the incidence of government requirements for additional research. It will, therefore, be necessary to have a technical sales force which is flexible or can be easily expanded to respond to these varying requirements.

It is desirable to base personnel policies and facilities acquisition policies on the long-term desired rate of growth rather than short-term backlogs in funds. A consequence of this result is the necessity of assuming the risk of not having sufficient future support for the personnel hired. This, however, must be faced and planned for or smooth growth patterns cannot be achieved. It is also necessary to assume the risk involved for the commitment of funds for facilities as the professional work force increases. It is essential to have these funds available without too much delay because the effectiveness of the newly hired personnel will be limited if sufficient facilities are not available, their output will decrease, and it will be more difficult for the laboratory to attain the level of new government business necessary for their support.

Therefore, in summary, the most essential ingredient for growth would appear to be a management policy committed to long-term growth. Concommitant with such a growth commitment must be the willingness to assume the risk involved in the commitment of funds for the personnel and facilities required to achieve the desired long-term growth. Although such a policy may involve risk, such risks may be the price which must be paid for long-term survival in the highly competitive, rapidly changing aerospace industry.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Conclusions

1. The growth behavior of industrial research laboratories is highly influenced by various forms of managerial control. The successful management of growth will therefore require a deep understanding of the fundamental processes at work and the role of managerial action in influencing these processes.
2. If a high rate of growth is desired and funds which can be attained internally or from external commercial sources are insufficient to achieve the desired rate of growth, then government support assumes a role of primary importance in determining the growth rate. Achieving the desired rate of growth will depend on management's ability to attract and maintain a high level of government support.
3. Government support for industrial research laboratories appears to depend on the laboratory's output, the efforts exerted by the laboratory management toward attracting new government business, and on the laboratory's facilities inventory.
4. Personnel and facilities acquisition policies based on long-term growth objectives rather than short-term backlogs appear to be necessary if smooth growth is to be achieved. This necessarily implies that growth will require the planned future commitment of resources in order to achieve a planned future growth rate. To

achieve growth, it will, therefore, be necessary to assume the associated risk which growth will entail.

Recommendations

A desirable extension of the work reported herein would be an investigation of the rate of return to a firm in the aerospace industry for investment in research. Such a study would involve first a determination of the capital costs, the timing of the outlays, and the costs of financing required for various assumed rates of growth of the firm's research effort. Secondly, criteria should be developed for evaluating the worth to the firm of the increasing research effort, and the point in time at which the value of the research results would accrue to the firm. Finally, after the first two parts of the investigation were completed, it would then be possible to determine the rate of return to the firm for investing in research and the optimum amount to be allocated.

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APPENDIX A

MODEL FORMULATION

A detailed formulation of the equation used in the industrial dynamics model is presented herein. All equations appear in the format required by the DYNAMO compiler simulator program (see Ref. 17). The DYNAMO program uses a time notation as follows:

.K denotes the present time

.J denotes the preceding time

.L denotes the next time

.JK denotes a rate of flow between times J and K

.KL denotes a rate of flow between times K and L

DT denotes the computation interval, Delta Time, that separates time steps.

Three equation types are used: levels, rates, and auxiliaries. Level equations express accumulations of physical quantities or averages of information, and rates express flows between levels. Auxiliary equations are used in the information channels between levels and rates to facilitate formulation of the rate equations. Letters following the equation number (L, R, or A) denote the equation type. Equations defining constants are indicated by C, and those equations defining initial conditions are denoted by N.

The flow diagram for the model is presented in Fig. III-14, and the numbers on the diagram correspond to the numbers of the equations developed below.

Funds Backlog Sector

Equations (1,L) through (7.4,C)

The first equation to be written defines the level of the backlog of unallocated funds of the laboratory, and it depends on the rate of inflow of government and non-government funds less the rate of expenditure of these funds.

$$\mathrm{RB.K = RB.J + (DT)\,(FAG.JK + FAOS.JK - FE.JK + 0)} \tag{1,L}$$

$$\mathrm{RB = 1{,}000{,}000} \tag{2,N}$$

RB = Research Backlog of unallocated funds ($)

FAG = Funds Added from Government ($/mo)

FAOS = Funds Added from Other Sources ($/mo)

FE = Funds Expended ($/mo)

The rate of expenditure of funds is assumed to be governed by the number of engineers and scientists currently in the work force. An initial value is assigned to the expenditure rate. The value for DES was obtained from data from the laboratory serving as a basis for this investigation.

$$\mathrm{FE.KL = (DES)\,(ESWF.K)} \tag{3,R}$$

$$\mathrm{FE = 900{,}000} \tag{3.5,N}$$

$$\mathrm{DES = 3{,}500} \tag{3,C}$$

FE = Funds Expenditure rate ($/mo)

DES = Average Dollars spent per month per Engineer/Scientist ($/man)

ESWF = Engineers and Scientists (engr/sci) in Work Force (men)

The average research backlog of unallocated funds is an exponential average of the research backlog used to smooth out short-term fluctuations. It can be written as a first order exponential smoothing equation (see Ref. 1, pp. 406-411).

$$\mathrm{ARB.K} = \mathrm{ARB.J} + (\mathrm{DT})(1/\mathrm{DARB})(\mathrm{RB.J} - \mathrm{ARB.J}) \qquad (4,\mathrm{L})$$

$$\mathrm{ARB} = 1{,}000{,}000 \qquad (5,\mathrm{N})$$

$$\mathrm{DARB} = 12 \qquad (5,\mathrm{C})$$

ARB = Average Research Backlog of unallocated funds ($)

DARB = Delay in Averaging Research Budget (mo)

RB = Research Backlog of unallocated funds ($)

The desired backlog can be expressed by a level equation which increases at the desired growth rate.

$$\mathrm{BUR.KL} = (\mathrm{GR})(\mathrm{DBU.K}) \qquad (6,\mathrm{R})$$

$$\mathrm{GR} = 0.00416 = (5\%/\mathrm{year})/12\ \mathrm{mo} \qquad (6,\mathrm{C})$$

$$\mathrm{DBU.K} = \mathrm{DBU.J} + (\mathrm{DT})(\mathrm{BUR.JK} - 0) \qquad (6.5,\mathrm{L})$$

$$\mathrm{DBU} = 1{,}000{,}000 \qquad (6.7,\mathrm{N})$$

BUR = Backlog of Unallocated funds Rate of increase ($/mo)

GR = Growth Rate (dimensionless)

DBU = Desired Backlog of Unallocated funds ($)

In order to achieve a research backlog which approaches that desired, it is necessary to achieve a government contract backlog of government funds that has a level which increases at a rate sufficient to make up for the difference between the growth rate of the exogenous funds and the growth rate desired.

$$\mathrm{COR.KL} = (\mathrm{ALC})(\mathrm{GR})(\mathrm{AFAOS.K}) - (\mathrm{ALC})(\mathrm{GROS})(\mathrm{AFAOS.K}) + (\mathrm{GR})(\mathrm{DCOBL.K}) \qquad (7,\mathrm{R})$$

$$\mathrm{DCOBL.K} = \mathrm{DCOBL.J} + (\mathrm{DT})(\mathrm{COR.JK} + 0) \qquad (7.1,\mathrm{L})$$

$$\mathrm{DCOBL} = 3{,}600{,}000 \qquad (7.2,\mathrm{N})$$

COR = COntract Rate (\$/mo)

ALC = Average Length of Contract (mo)

AFAOS = Average Funds rate from non-government sources (\$/mo)

GROS = Growth Rate Other Sources (dimensionless)

DCOBL = Desired COntract BackLog (\$)

The desired change in the backlog of government contracts can be expressed as the difference between desired and actual contract backlog divided by the time required to adjust the backlog.

$$\mathrm{DBLC.K} = (1/\mathrm{TAB})(\mathrm{DCOBL.K} - \mathrm{COBL.K}) \qquad (7.3,\mathrm{A})$$

$$\mathrm{TAB} = 4 \qquad (7.4,\mathrm{C})$$

DBLC = Desired BackLog Change (\$/mo)

TAB = Time to Adjust Backlog (mo)

DCOBL = Desired COntract BackLog (\$)

COBL = COntract BackLog (\$)

Management Sector

Equations (8,A) through (14,C)

If the desired backlog of additional government work increases, it is necessary to increase the effort put in by management to attract more government business. The relationship assumed between the desired backlog of business and the fractional management effort toward attracting new business is shown in Fig. A-1 and is based on estimates made by the management of the research laboratory serving as a model for this study. Some small amount of management effort toward attracting new business is indicated even if the desired backlog is zero, because a small constant sales effort is needed to ensure future business.

FMEG.K = TABHL (TFMG,DBLC.K, - 2E6,2E6,1EG) (8,A)

TFMG* = 0.01/0.15/0.2/0.4/0.8 (8,C)

FMEG = Fraction of Management Effort toward attracting additional Government business (dimensionless)

TFMG = Table for Fractional Management effort toward attracting additional Government business

DBLC = Desired BackLog Change ($/mo)

TABHL = Functional notation

The total managerial time spent toward attracting new government business is obtained by multiplying the total management time by the fraction spent on attracting new business.

MEG.K = (FMEG.K) (MT.K) (9,A)

MEG = Management Effort toward attracting additional Government business (man-mos/mo)

FMEG = Fraction of Management Effort toward attracting additional Government business (dimensionless)

MT = Managerial Time (man-mos/mo)

ASSUMED RELATIONSHIP BETWEEN DESIRED BACKLOG CHANGE AND FRACTIONAL MGT. EFFORT

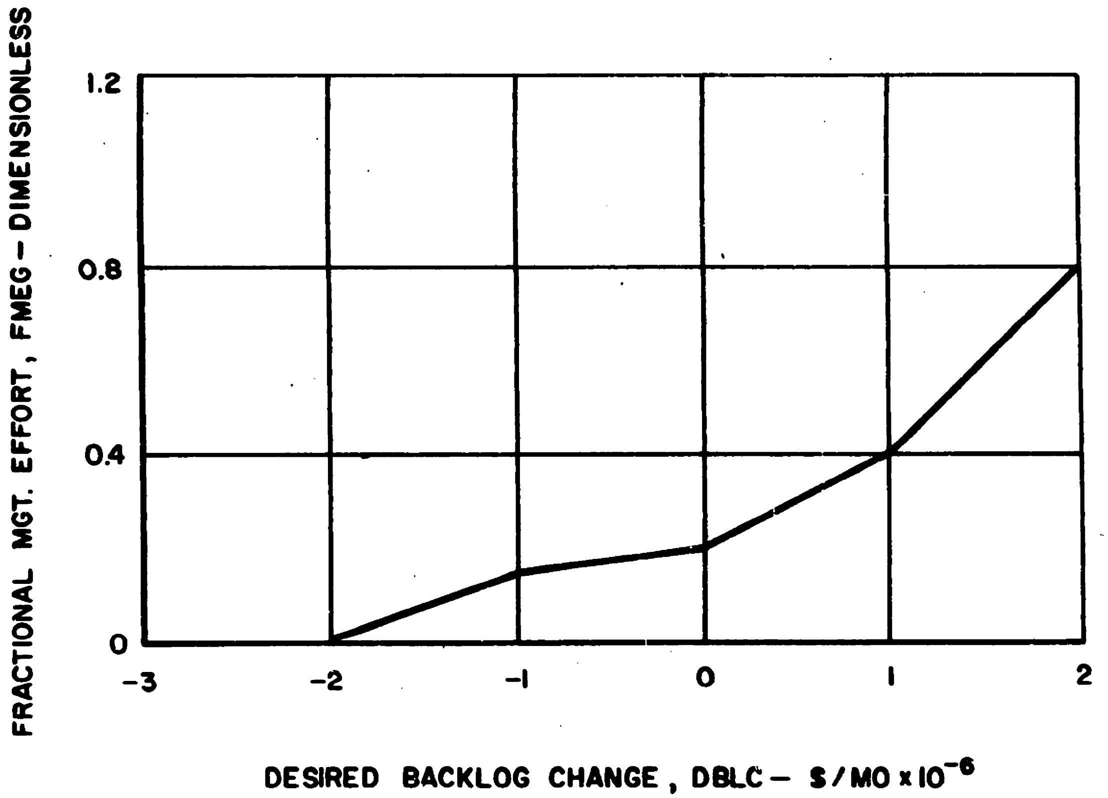


FIG. A-1

The government does not respond immediately to management's efforts to attract new business, and if it responds at all, some delay will be involved. This can be expressed by exponentially smoothing management's efforts toward attracting new business.

$$AMEG.K = AMEG.J + (DT)(1/DAMEG)(MEG.J - AMEG.J) \qquad (10,L)$$

$$AMEG = MEG \qquad (11,N)$$

$$DAMEG = 3 \qquad (11,C)$$

AMEG = Average Management Effort toward attracting additional Government business (man-mos/mo)

DAMEG = Delay in Average Management Effort toward attracting additional Government business (mo)

MEG = Management Effort toward attracting additional Government business (management time/mo)

The number of engineers and scientists in the work force was found to correlate with the rate of increase of new government business as shown in Fig. III-9. It has been assumed that the total management time expended in efforts to attract new business is related to the number of engineers and scientists employed, and it would appear plausible to assume that the increase in new business is a result of management's efforts to attract new business rather than the mere fact that engineers and scientists are employed. Therefore, the curve was replotted in terms of management effort as shown in Fig. A-2. The abscissa was transformed into the man-months/month of management time spent on attracting new business and the ordinate was renamed Management Efforts Probability

VARIATION OF MGT. EFFORTS PROB. MULT. (MEPM) WITH AVERAGE MGT. EFFORT TOWARD ATTRACTING ADDITIONAL GOVT. BUSINESS (AMEG)

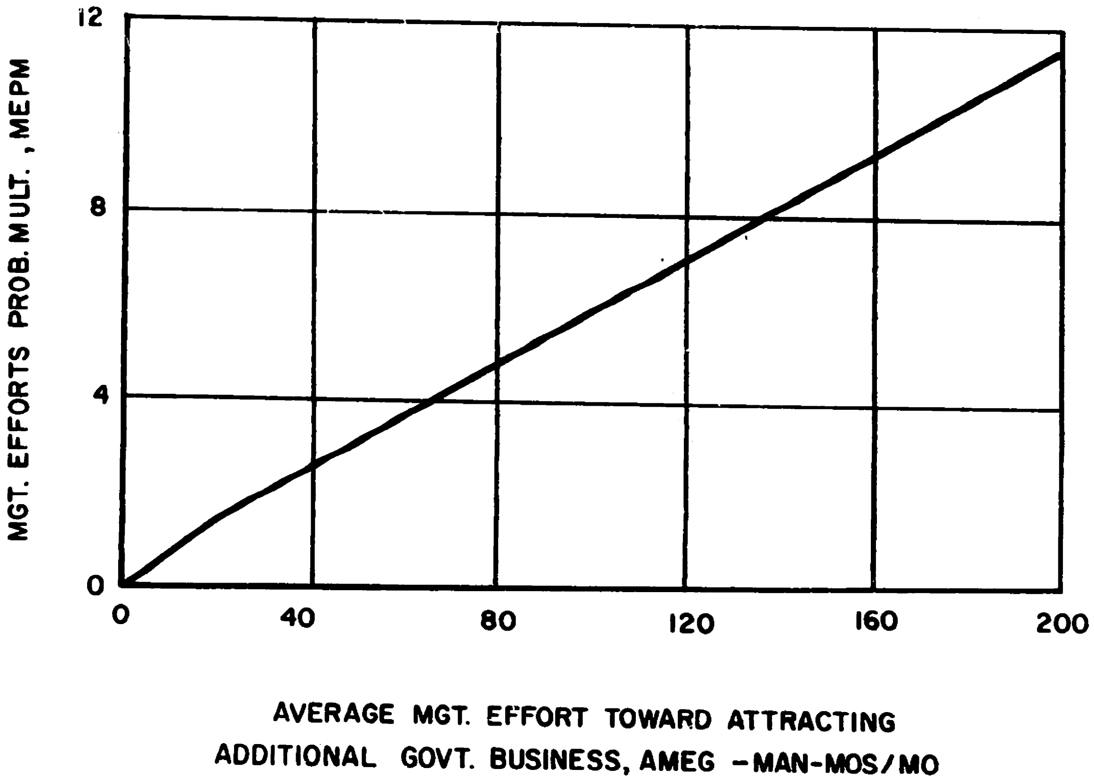


FIG. A-2

Multiplier for use in Eq. (12,A) to reflect this effect on the funds increase per period from new contracts. The average managerial effort assumed to correspond to that required to obtain the average new business that prevailed was based on estimates obtained from the management of the research laboratory used as a basis for this study. The probability multiplier was assumed to go to zero as management effort approached zero.

MEPM.K = TABHL (TMPM,AMEG.K,0,200,20) (12,A)

TMPM* = 0/1.56/2.66/3.76/4.86/5.96/7.1/8.1/9.2/10.4/11.5 (12,C)

MEPM = Management Efforts Probability Multiplier (dimensionless)

TMPM = Table of Management efforts Probability Multiplier values

AMEG = Average Management Effort toward attracting additional Government business (man-mos/mo)

A Monte-Carlo simulation approach was utilized to represent the government contracts received by the laboratory. A Poisson distribution function was assumed to represent the contracts received, because this distribution is a good model for processes that are of rare occurrence and random in time. Values for the mean of the distribution were based on data obtained from the laboratory used as the basis for this study, and the distribution presented in Fig. A-3 was calculated using the charts of Ref. 18. Random numbers were generated by the following equations.

PFN1.K = (1) NOISE (13,A)

PFN2.K = 0.5 + PFN1.K (13.5,A)

PFN.K = SAMPLE (PFN2.K,1) (13.7,A)

VARIATION OF CONTRACTS PER PERIOD (CPP) WITH (PFN)

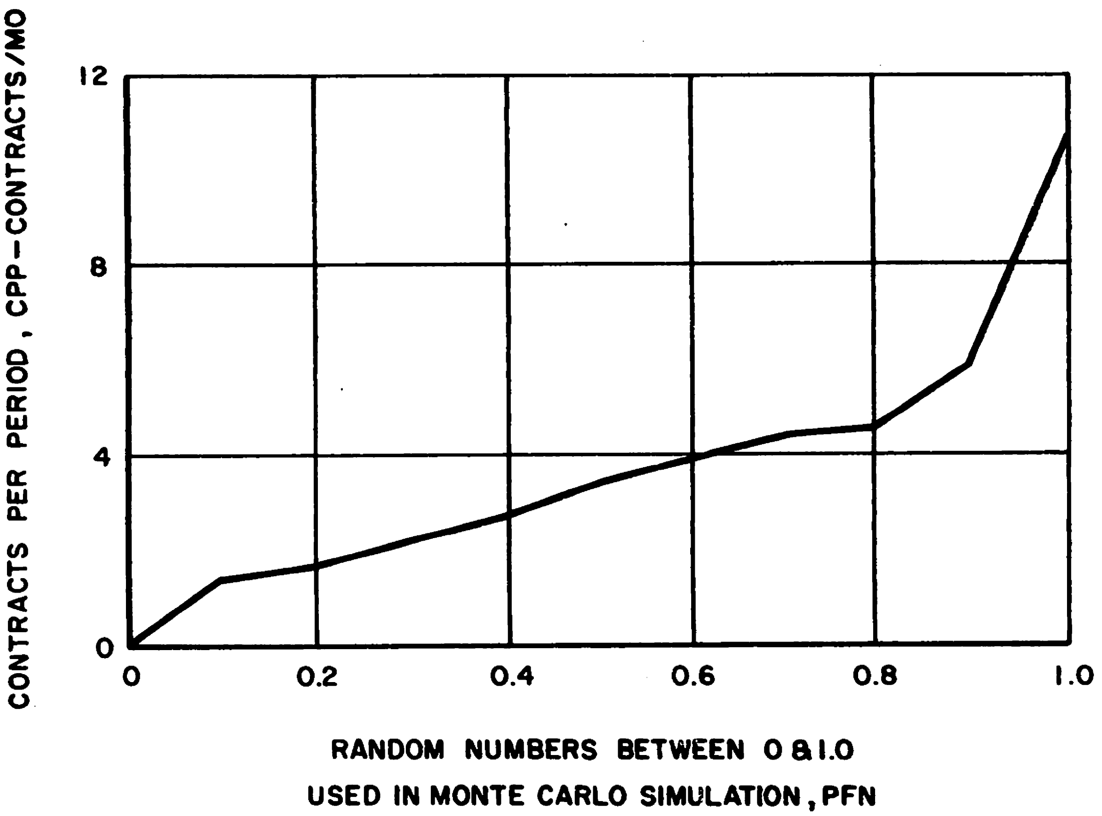


FIG. A-3

PFN1 = Probability FunctioN 1

PFN2 = Probability FunctioN 2

PFN = Probability FunctioN, the random numbers between 0 and 1 used in the Monte Carlo simulation

NOISE = DYNAMO functional notation for a random number generator

SAMPLE = DYNAMO notation for a periodic sampling function

The contracts received per period were determined by entering the probability distribution (Fig. A-3) with the random numbers as determined above.

CPP.K = TABHL (TCPP,PFN.K,0,1,0.1) (14,A)

TCPP* = 0/1.3/1.8/2.2/2.7/3.4/3.9/4.4/4.7/6.0/10.5 (14,C)

CPP = Contracts Per Period (contracts/mo)

TCPP = Table of Contracts Per Period

PFN = Random numbers between 0 and 1 used in Monte Carlo simulation

Funds-Rate Sector

Equations (14.5,L) through (20,C)

The influence of the rate of expenditure of funds on attracting new business has been previously discussed in the Analysis Section and is shown in Fig. III-11. To mirror this effect in the model, the ordinate of Fig. III-11 was used to obtain values for a contract probability multiplier and the abscissa was transformed into a funds expenditure rate by multiplying the values obtained from Fig. III-11 by an average expenditure rate. The resulting curve is shown in Fig. A-4. The probability

VARIATION OF FUNDS EXPENDITURE PROB. MULT. (FEPM)
WITH FUNDS EXPENDITURE RATE (FE)

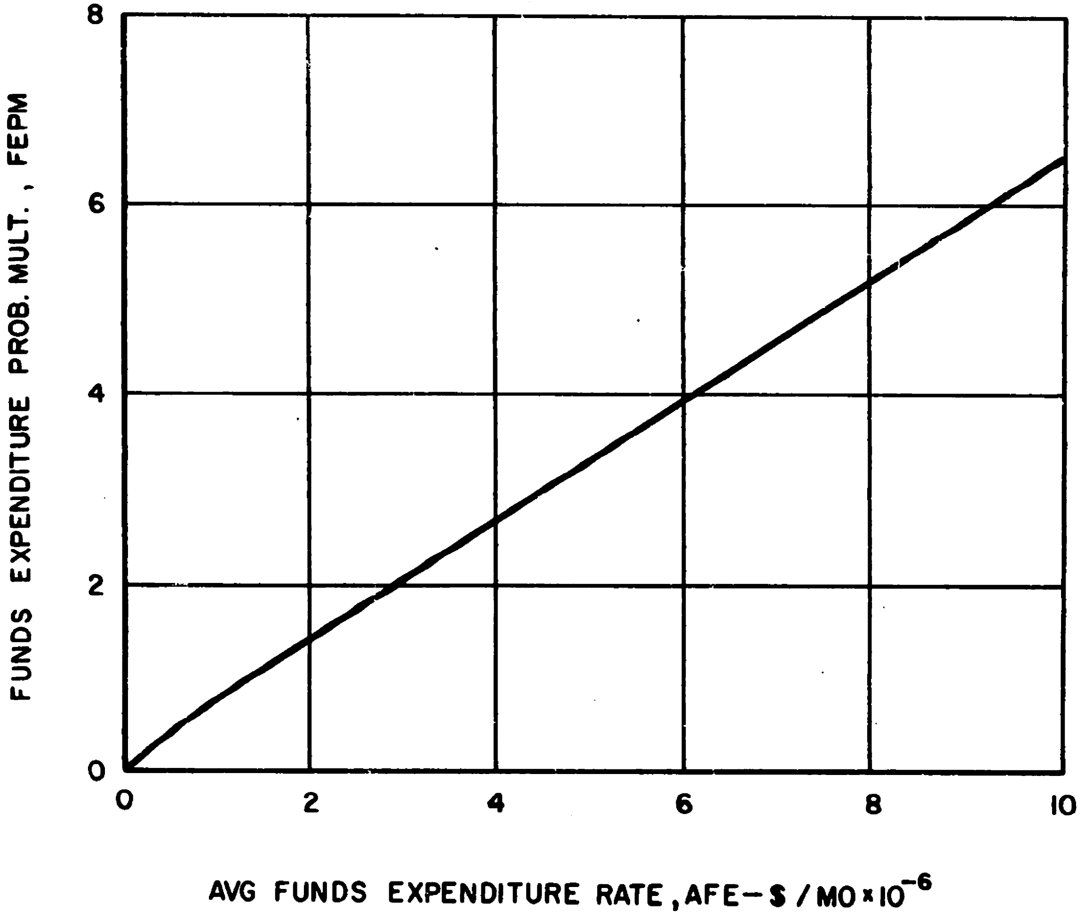


FIG. A-4

multiplier was assumed to go to zero as the funds expenditure rate goes to zero; this variation is expressed by Eq. (15).

AFE.K = AFE.J + (DT) (1/DAFE) (FE.JK - AFE.J) (14.5,L)

AFE = FE (14.7,N)

DAFE = 12 (14.7,C)

AFE = Average Funds Expenditure rate ($/mo)

DAFE = Delay in Average of Funds Expenditure rate (mo)

FE = Funds Expended ($/mo)

FEPM.K = TABHL (TFPM,AFE.K,0,10E6,1E6) (15,A)

TFPM* = 0/0.8/1.4/2.1/2.7/3.4/4.0/4.6/5.3/5.9/6.6 (15,C)

FEPM = Funds Expenditure Probability Multiplier (dimensionless)

TFPM = Table of the Funds expenditure Probability Multiplier

AFE = Average Funds Expenditure rate ($/mo)

The contracts per period modified by the funds expenditure effect is determined by multiplying the contracts received per period by the funds expenditure probability multiplier.

CPPF.K = (CPP.K) (FEPM.K) (16,A)

CPPF = Contracts Per Period modified by Funds expenditure effect (contract/mo)

CPP = Contracts Per Period (contracts/mo)

FEPM = Funds Expenditure Probability Multiplier (dimensionless)

The effect of management's efforts toward attracting new business is expressed by multiplying the contracts per period modified by the funds expenditure effect by the management efforts probability multiplier discussed previously.

CPFM.K = (CPPF.K) (MEPM.K) (17,A)

CPFM = Contracts per Period modified by the effects of Funds expenditure rate and Management efforts (contracts/mo)

CPPF = Contracts Per Period modified by Funds expenditure effect (contracts/mo)

MEPM = Management Efforts Probability Multiplier (dimensionless)

The rate of addition of funds from government sources can be expressed as the total backlog of contracts divided by the average length of the contracts.

FAG.KL = COBL.K/ALC (18,R)

ALC = 12 (18,C)

FAG = Funds Added per month from Government sources ($/mo)

COBL = COntract BackLog ($)

ALC = Average Length of Contract (mo)

The rate of addition of funds from non-government sources is assumed to be an exogenous input to the model. These funds are assumed to have a finite growth rate which is in general lower than the overall growth rate desired by management.

AFAOS.K = AFAOS.J + (DT) (1/DAFOS) (FAOS.JK - AFAOS.J) (19,L)

AFAOS = FAOS (19.1,N)

DAFOS = 1 (19.2,C)

FAOS.KL = (AFAOS.K) (1 + GROS) (19.3,R)

$$\text{FAOS} = 600,000 \tag{20,N}$$

$$\text{GROS} = 0.00166 = (2\%/\text{yr})/(12\ \text{mo}) \tag{20,C}$$

AFAOS = Average Funds rate from non-government Sources ($/mo)

DAFOS = Delay in Average of Funds rate from non-government sources (mo)

FAOS = Funds rate from non-government Sources ($/mo)

GROS = Growth Rate Other Sources (dimensionless)

Personnel Sector

Equations (21,A) through (31,C)

The number of engineers and scientists desired in the work force can be determined by dividing the average research budget by the average number of dollars spent per month by an engineer or scientist.

$$\text{ESD.K} = \text{ARB.K/DES} \tag{21,A}$$

ESD = Engr/Sci Desired (men)

ARB = Average Research Budget ($)

DES = average Dollars spent per month per Engr/Sci ($/man)

The change in the existing engineer/scientist work force is expressed by the time required to adjust the work force divided into the difference between the work force desired and the work force which currently exists. This formulation reflects a gradual adjustment of the work force to a desired change and allows for the time lag associated with finding, interviewing, and employing new men.

$$\text{ESC.K} = (1/\text{TAES})\ (\text{ESD.K} = \text{ESWF.K}) \tag{22,A}$$

TAES = 4 (22,C)

ESC = Engr/Sci work force Change (men/mo)

TAES = Time to Adjust Engr/Sci work force (mo)

ESD = Engr/Sci Desired (men)

ESWF = Engr/Sci in Work Force (men)

The change in the engineering/scientist work force is related to the hiring rate as shown in Fig. A-5 and expressed by

ESH.KL = TABHL (TESH,ESC.K,-2,28,2) (23,R)

TESH* = 0/0.5/2/4/6/8/10/12/14/16/18/20/22/24/26/28 (23,C)

ESH = 2 (23.5,N)

ESH = Engr/Sci Hiring rate (men/mo)

TESH = Table of Engr/Sci Hiring rate (men/mo)

ESC = Engr/Sci work force Change (men/mo)

As can be seen from Fig. A-5 an average turnover of 0.5 men/mo has been assumed (based on estimates of the management of the research laboratory serving as a model for this study).

Newly hired engineers and scientists must undergo training when they arrive, and a delay is involved before they become productive. A constant average training delay has been assumed as well as assuming that no engineers or scientists leave during this training period.

ESIT.K = ESIT.J + (DT) (ESH.JK - NTES.JK) (24,L)

ESIT = 5 (25,N)

DTRN = 9 (25,C)

NTES.KL = DELAY 3(ESH.JK,DTRN) (26,R)

VARIATION OF ENG/SCI HIRING AND LEAVING RATES WITH WORK FORCE CHANGE

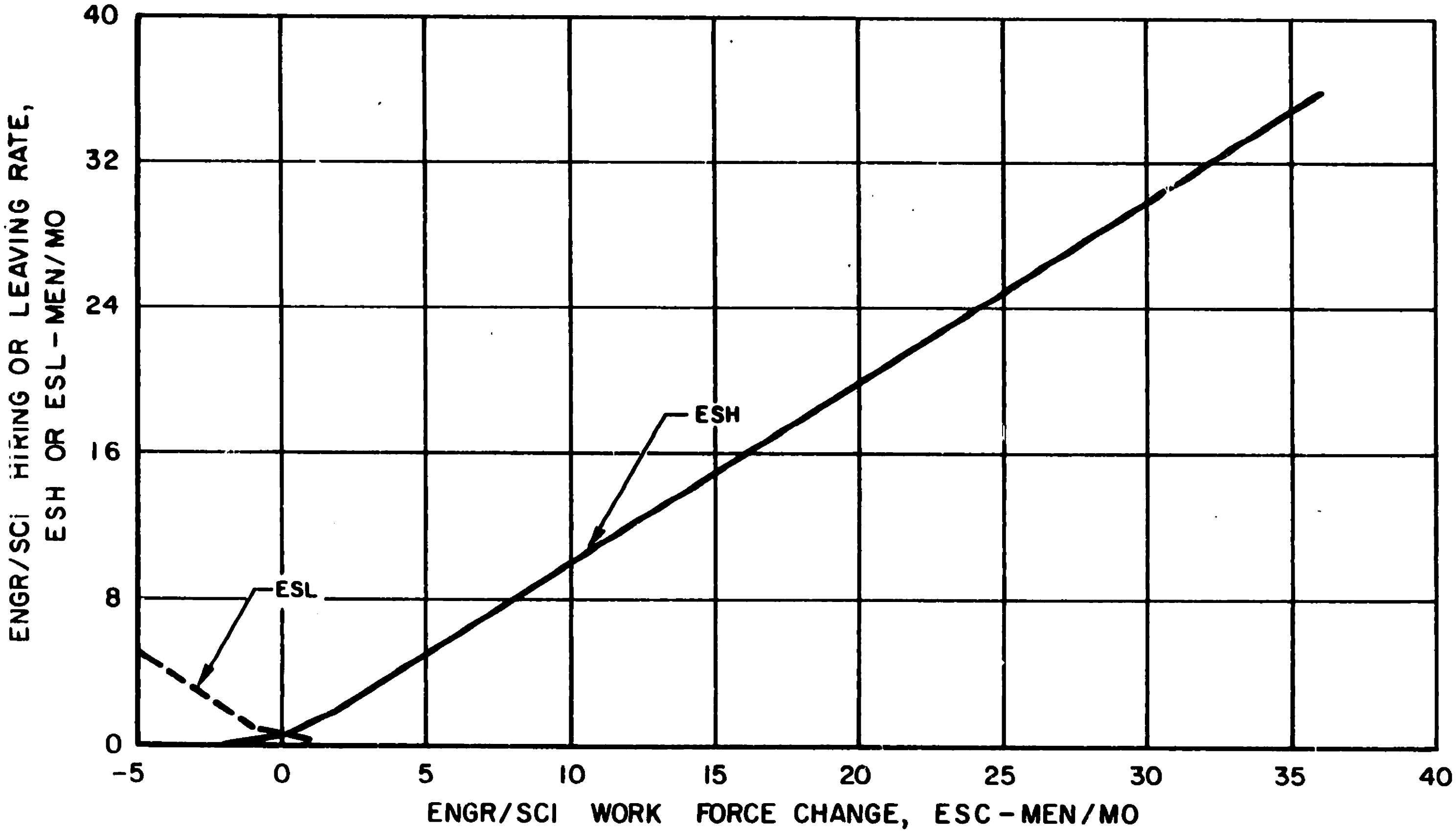


FIG. A-5

ESIT = Engr/Sci In Training (men)

ESH = Engr/Sci Hiring rate (men/mo)

NTES = Newly Trained Engr/Sci (men/mo)

DTRN = Delay in TRaiNing (mo)

DELAY 3 = DYNAMO notation for a third-order exponential delay

The trained engineer/scientist work force is formulated as a level equation with an inflow of newly trained personnel and an outflow of personnel leaving.

TES.K = TES.J + (DT) (NTES.JK - ESL.JK) (27,L)

TES = 250 (28,N)

TES = Trained Engr/Sci (men)

NTES = Newly Trained Engr/Sci (men/mo)

ESL = Engr/Sci Leaving (men/mo)

The total engineer/scientist work force is the sum of the trained personnel and the personnel in training.

ESWF.K = TES.K + ESIT.K (29,A)

ESWF = Engr/Sci Work Force (men)

TES = Trained Engr/Sci (men)

ESIT = Engr/Sci In Training (men)

The rate of workers leaving consists of the normal turnover and workers fired. It is related to the change in the work force as shown in Fig. A-5 and expressed by Eq. (30).

ESL.KL = TABHL (TESL,ESC.K,-5,5,1) (30,R)

TESL* = 5/4/3/2/1/0.5/0.1/0/0/0/0 (30,C)

ESL = Engr/Sci Leaving rate (men/mo)

TESL = Table of Engr/Sci Leaving

ESC = Engr/Sci work force Change (men/mo)

The management personnel available in a period is assumed to be a constant percentage of the engineer/scientist work force based on the opinion of the management of the research laboratory serving as a model for this study.

$$MT.K = (ESWF.K)\,(PMES) \qquad (31,A)$$

$$PMES = 0.2 \qquad (31,C)$$

MT = Management Time (men-mos/mo)

ESWF = Engr/Sci Work Force (men)

PMES = Percent Management time per Engr/Sci (dimensionless)

Facilities Sector

Equations (32,A) through (43,A)

The general formulation of the equations for the Facilities Sector follows the same pattern as the Personnel Sector.

As discussed previously in the Analysis Section, the desired facility inventory is assumed to be related to the engineer/scientist work force. The value for FPES was obtained from data from the laboratory serving as a model for this investigation.

$$FAD.K = (ESWF.K)\,(FPES) \qquad (32,A)$$

$$FPES = 10{,}000 \qquad (32,C)$$

FAD = FAcilities Desired (facility units)

ESWF = Engr/Sci Work Force (men)

FPES = Facilities Per Engr/Sci (facilities/man)

A change in the facilities inventory will occur only after a delay period because of the time required for making a facilities decision, obtaining the necessary approvals, etc. The facilities change is expressed as the difference between the desired facilities and the existing facilities divided by the time required to decide to adjust the facilities inventory.

FAC.K = (1/TAF) (FAD.K - FAIT.K) (33,A)

TAF = 6 (33,C)

FAC = FAcilities Change (facility units/mo)

TAF = Time to decide to Adjust Facilities (mo)

FAD = FAcilities Desired (facility units)

FAIT = FAcilities Inventory - Total (facility units)

The facilities obtained is assumed to be related to the facilities change by the curve shown in Fig. A-6 and is expressed by

FAO.KL = TABHL (TFAO,FAC.K,-250,000, 250,000, 50,000) (34,R)

TFAO* = 0/0/0/0/100/3000/5E4/1E5/15E4/20E4/25E4 (34,C)

FAO = 1000 (34.5,N)

FAO = Rate of obtaining new facilities (facility units/mo)

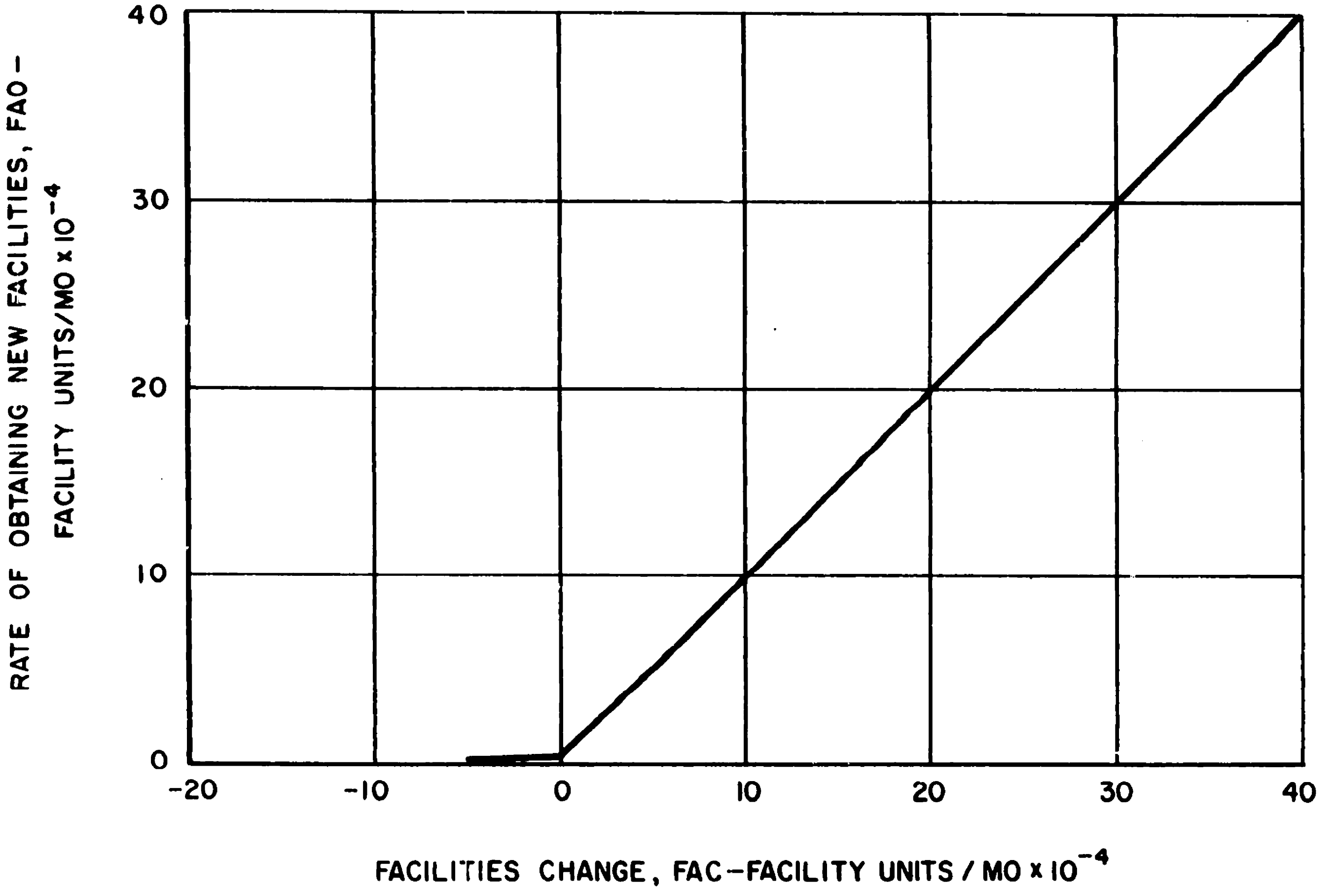
TFAO = Table of FAcilities change

FAC = FAcilities Change (facility units/mo)

A small rate of obtaining facilities is indicated in Fig. A-6 when the facilities change is zero to allow for obsolescence.

FIG. A-6

RATE OF OBTAINING NEW FACILITIES (FAO) VS. FACILITIES CHANGE (FAC)



Facilities can be obtained only after a delay either associated with delivery time or construction times. Facilities in process can be expressed as a level equation utilizing the rate of obtaining new facilities expressed as a third order exponential delay with an average delay value.

FAIP.K = FAIP.J + (DT) (FAO.JK - NOF.JK) (35,L)

FAIP = 10,000 (36,N)

DOF = 12 (36,C)

NOF.KL = DELAY 3(FAO.JK, DOF) (37,R)

FAIP = FAcilities In Process (facility units/mo)

FAO = Rate of obtaining new facilities (facility units/mo)

NOF = Newly Obtained Facilities (facility units/mo)

DOF = Delay in Obtaining Facilities (mo)

The operating facilities inventory is expressed as a level equation with an inflow of newly obtained facilities and as outflow of retired facilities.

OFI.K = OFI.J + (DT) (NOF.JK - ROR.JK) (38,L)

OFI = 2.5E6 (39,N)

OFI = Operating Facilities Inventory (facility units)

NOF = Newly Obtained Facilities (facility units/mo)

ROR = Rate of Retirement of facilities (facility units/mo)

The total facilities inventory is the sum of the operating facilities inventory and the facilities in process that have been purchased but not yet delivered or completely constructed.

FAIT.K = OFI.K + FAIP.K (40,A)

FAIT = FAcilities Inventory - Total (facility units)

OFI = Operating Facilities Inventory (facility units)

FAIP = FAcilities In Process (facility units)

The rate of retirement of facilities is assumed to be a constant average percentage of the operating facilities inventory. This amounts to assuming an average lifetime for all facilities.

ROR.KL = (DEP) (OFI.K) (41.5,R)

DEP = 0.0166 (41.5,C)

ROR = Rate Of Retirement of facilities (facility units/mo)

DEP = Retirement constant (1/mo)

OFI = Operating Facilities Inventory (facility units)

As previously discussed in the Analysis Section, within the range of variation of the data the total facilities inventory was shown to have little effect on the extent of new business as shown in Fig. III-13. However, at low values of facilities inventory, it is logical to assume that new business will be attracted at a reduced rate. To mirror this effect in the model formulation, the ordinate of Fig. III-3 was renamed Facilities Inventory Probability Multiplier and assumed to have a value of 1.0 for high values of the facilities inventory. The abscissa was multiplied by the average facilities inventory to yield the curve shown in Fig. A-7. The probability multiplier was assumed to go to zero at low values of facilities inventory to reflect the requirement for a facilities threshold in order to attract any contracts at all. The curve can be expressed as

VARIATION OF FACILITIES INVENTORY PROB. MULT. (FIPM) WITH FACILITIES INVENTORY - TOTAL (FAIT)

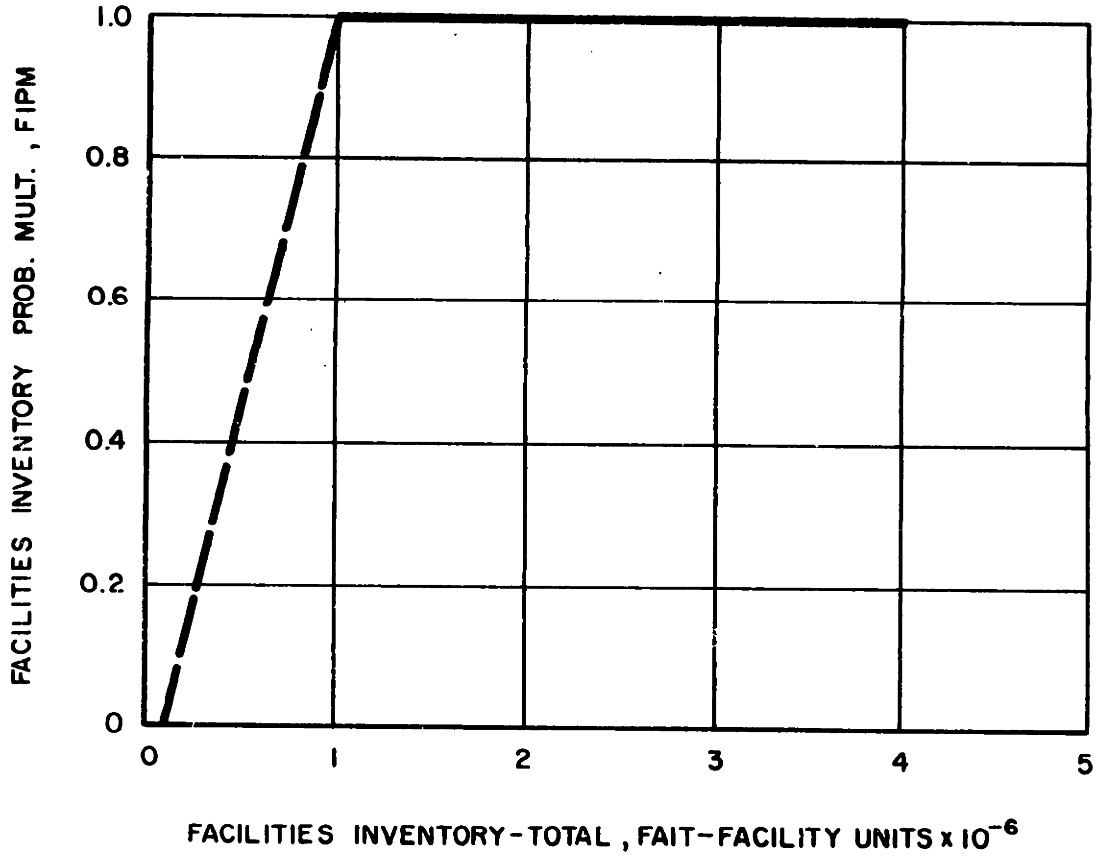


FIG. A-7

FIPM.K = TABHL (TIPM,FAIT.K,0,4E6,0.5E6) (42,A)

TIPM* = 0/0.45/1.0/1.0/1.0/1.0/1.0/1.0/1.0 (42,C)

FIPM = Facilities Inventory Probability Multiplier (dimensionless)

TIPM = Table of facilities Inventory Probability Multiplier values (dimensionless)

FAIT = FAcilities Inventory - Total (facility units)

The product of the contracts per period (as previously modified by the effects of expenditure rate and management efforts) and the facilities inventory probability multiplier gives the final value for the contracts per period.

CFMI.K = (CPFM.K) (FIPM.K) (43,A)

CFMI = Contracts/period modified by the effects of Funds expenditure rate, Management efforts, and facilities Inventory (contracts/mo)

CPFM = Contracts/Period modified by the effects of Funds expenditures rate and Management efforts (contracts/mo)

FIPM = Facilities Inventory Probability Multiplier (dimensionless)

Contracts Sector

Equations (44,R) through (46,N)

The value of funds received per period from government sources is expressed by the product of the average value of contracts and the number of contracts received.

CLR.KL = (ACV) (CFMI.K) (44,R)

ACV = 100,000 (44,C)

CLR = Contract Loading Rate ($/mo)

ACV = Average Contract Value ($/contract)

CFMI = Contracts/period modified by the effects of Funds expenditure rate, Management efforts, and facilities Inventory (contracts/mo)

The backlog of government contracts is expressed as a level equation with an inflow of the contract loading rate and an outflow of the government funds spent per period.

COBL.K = COBL.J + (DT) (CLR.JK - FAG.JK) (45,L)

COBL = 4E6 (46,N)

COBL = COntract BackLog ($)

CLR = Contract Loading Rate ($/mo)

FAG = Funds Added per month from Government sources ($/mo)

APPENDIX B

REVISED POLICY EQUATIONS

Personnel Sector

The equations for the revised personnel policies discussed in Chapter IV can be expressed as follows.

Equation (21,A) of the original formulation was replaced by

FDBL.K = (FTN) (DBU.K - ARB.K) (21,A)

FTN = 0.1 (21,C)

FDBL = Fractional influence of difference in BackLog ($)

FTN = FracTioN (dimensionless)

DBU = Desired Backlog of Unallocated funds ($)

ARB = Average Research Backlog of unallocated funds ($)

and

ESD.K = (1/ADES) (DBU.K - FDBL.K) (21.5,A)

ADES = 3500 (21.5,C)

ESD = Engr/Sci Desired (men)

ADES = Average Dollars spent per month per Engr/Sci ($/man)

DBU = Desired Backlog of Unallocated funds ($)

FDBL = Fractional influence of Difference in BackLog ($)

Funds Backlog Sector

The equations expressing the revised expenditure policy discussed in Chapter IV are presented below. For a given period, it is desired to spend funds at such a rate that the funds backlog at the beginning of the next period will be that desired for the specified rate of growth. This desired expenditure rate is expressed as

DFE.KL = FAG.JK + FAOS.JK - ADJ.JK (3.3,R)

DFE = Desired Funds Expenditure rate ($/mo)

FAG = Funds Added from Government ($/mo)

FAOS = Funds Added from Other Sources ($/mo)

ADJ.KL = (1/DT) (GDBU.K - RB.K) (3.2,R)

ADJ = ADJustment in unallocated funds backlog ($/mo)

RB = Research Backlog of unallocated funds ($)

GDBU.K = (DBU.K) (1 + GR) (3.1,A)

GDBU = Growth of Desired Backlog of Unallocated funds ($)

DBU = Desired Backlog of Unallocated funds ($)

GR = Growth Rate (dimensionless)

The desired overall average expenditure for each member of the professional work force can be expressed as

DDES.K = DFE.JK/ESWF.K (3.4,A)

DDES = Desired Dollar expenditure per Engr/Sci ($/man-mo)

DFE = Desired Funds Expenditure rate ($/mo)

ESWF = Engr/Sci Work Force (men)

The actual funds expended per period per professional employee can be expressed as

DES.K = TABHL (TDES, DDES.K, 2500, 4500, 500) (3.6,A)

TDES* = 2500/3000/3500/4000/4500 (3.7,C)

DES = Dollar expenditure per Engr/Sci (\$/man-mo)

TDES = Table of Dollar expenditure per Engr/Sci (\$/man-mo)

DDES = Desired Dollar expenditure per Engr/Sci (\$/man-mo)

The funds expended per period is then given by

FE.KL = (DES.K) (ESWF.K) (3,R)

FE = Funds Expenditure rate (\$/mo)

DES = Dollar expenditure per Engr/Sci (\$/man-mo)

ESWF = Engr/Sci Work Force (men)

As discussed in Chapter IV, the final revision concerning management's efforts to attract additional government business can be expressed as

DBLC.K = (1/TAB) (DCOBL.K -COBL.K + DRBC.K + 0 + 0 +0) (7.3,A)

DBLC = Desired BackLog Change

TAB = Time to Adjust Backlog (mo)

DCOBL = Desired COntract BackLog (\$)

COBL = COntract BackLog (\$)

where

DRBC.K = (ALC) (DBU.K - RB.K) (7.5,A)

DRBC = Desired Research funds Backlog Change (\$)

ALC = Average Length of Contract (mo)

DBU = Desired Backlog of Unallocated funds (\$)

RB = Research Backlog of unallocated funds (\$)

APPENDIX C

LIST OF EQUATIONS FOR BEST POLICY

```
PAGE 1

     *       M478-248,DYN,RESULTS,0.25,0.5,0,0

             RESEARCH MODEL BLACKMAN
     52L     RB.K=RB.J+(DT)(FAG.JK+FAOS.JK-FE.JK+0)                    1
     6N      RB=1E6                                                     2
     12R     FE.KL=(DES.K)(ESWF.K)                                      3
     18A     GDBU.K=(DBU.K)(1+GR)                                       3.1
     21R     ADJ.KL=(1/DT)(GDBU.K-RB.K)                                 3.2
     8R      DFE.KL=FAG.JK+FAOS.JK-ADJ.JK                               3.3
     20A     DDES.K=DFE.JK/ESWF.K                                       3.4
     6N      FE=900000                                                  3.5
     58A     DES.K=TABHL(TDES,DDES.K,2500,4500,500)                     3.6
     C       TDES*=2500/3000/3500/4000/4500                             3.7
     3L      ARB.K=ARB.J+(DT)(1/DARB)(RB.J-ARB.J)                       4
     6N      ARB=1E6                                                    5
     C       DARB=12                                                    5C
     12R     BUR.KL=(GR)(DBU.K)                                         6
     1L      DBU.K=DBU.J+(DT)(BUR.JK-0)                                 6.5
     6N      DBU=1E6                                                    6.7
     C       GR=0.00833                                                 6C
     17R     COR.KL=(ALC)(GR)(FAOS.JK)+(-ALC)(GROS)(FAOS.JK)+(1)(GR)(DCOBL.K) 7
     1L      DCOBL.K=DCOBL.J+(DT)(COR.JK+0)                             7.1
     6N      DCOBL=3.6E6                                                7.2
     24A     DBLC.K=(1/TAB)(DCOBL.K-COBL.K+DRBC.K+0+0+0)                7.3
     C       TAB=4                                                      7.4
     18A     DRBC.K=(ALC)(DBU.K-RB.K)                                   7.5
     58A     FMEG.K=TABHL(TFMG,DBLC.K,-4E6,4E6,2E6)                     8
     C       TFMG*=0.01/0.15/0.2/0.4/0.8                                8C
     12A     MEG.K=(FMEG.K)(MT.K)                                       9
     3L      AMEG.K=AMEG.J+(DT)(1/DAMEG)(MEG.J-AMEG.J)                  10
     6N      AMEG=MEG                                                   11
     C       DAMEG=9.0                                                  11C
     58A     MEPM.K=TABHL(TMPM,AMEG.K,0,200,20)                         12
     C       TMPM*=0/1.56/2.66/3.76/4.86/5.96/7.1/8.1/9.2/10.4/11.5     12C
     33A     PFN1.K=(1)NOISE                                            13
     7A      PFN2.K=0.5+PFN1.K                                          13.5
     43A     PFN.K=SAMPLE(PFN2.K,1)                                     13.7
     58A     CPP.K=TABHL(TCPP,PFN.K,0,1,0.1)                            14
     C       TCPP*=0/1.3/1.8/2.2/2.7/3.4/3.9/4.4/4.7/6.0/10.5           14C
     3L      AFE.K=AFE.J+(DT)(1/DAFE)(FE.JK-AFE.J)                      14.5
     6N      AFE=FE                                                     14.7
     C       DAFE=12                                                    14.7C
     58A     FEPM.K=TABHL(TFPM,AFE.K,0,10E6,1E6)                        15
     C       TFPM*=0/.8/1.4/2.1/2.7/3.4/4.0/4.6/5.3/5.9/6.6             15C
     12A     CPPF.K=(CPP.K)(FEPM.K)                                     16
     12A     CPFM.K=(CPPF.K)(MEPM.K)                                    17
     20R     FAG.KL=COBL.K/ALC                                          18
     C       ALC=12                                                     18C
     3L      AFAOS.K=AFAOS.J+(DT)(1/DAFOS)(FAOS.JK-AFAOS.J)             19
     6N      AFAOS=FAOS                                                 19.1
     C       DAFOS=1                                                    19.2
     18R     FAOS.KL=(AFAOS.K)(1+GROS)                                  19.3
     6N      FAOS=600000                                                20
     C       GROS=0.00166                                               20C
     18A     FDBL.K=(FTN)(DBU.K-ARB.K)                                  21
     C       FTN=0.1                                                    21C
     21A     ESD.K=(1/ADES)(DBU.K-FDBL.K)                               21.5
     C       ADES=3500                                                  21.7
```

```
PAGE 2

    21A    ESC.K=(1/TAES)(ESD.K-ESWF.K)                                           22
    C      TAES=4                                                                 22C
    58R    ESH.KL=TABHL(TESH,ESC.K,-2,36,2)                                       23
    6N     ESH=2                                                                  23.5
    C      TESH*=0/.5/2/4/6/8/10/12/14/16/18/20/22/24/26/28/30/32/34/36    23C
    1L     ESIT.K=ESIT.J+(DT)(ESH.JK-NTES.JK)                                     24
    6N     ESIT=5                                                                 25
    C      DTRN=9                                                                 25C
    39R    NTES.KL=DELAY3(ESH.JK,DTRN)                                            26
    1L     TES.K=TES.J+(DT)(NTES.JK-ESL.JK)                                       27
    6N     TES=250                                                                28
    7A     ESWF.K=TES.K+ESIT.K                                                    29
    58R    ESL.KL=TABHL(TESL,ESC.K,-5,5,1)                                        30
    C      TESL*=5/4/3/2/1/.5/.1/0/0/0/0                                          30C
    12A    MT.K=(ESWF.K)(PMES)                                                    31
    C      PMES=0.2                                                               31C
    12A    FAD.K=(ESWF.K)(FPES)                                                   32
    C      FPES=10000                                                             32C
    21A    FAC.K=(1/TAF)(FAD.K-FAIT.K)                                            33
    C      TAF=6                                                                  33C
    58R    FAO.KL=TABHL(TFAO,FAC.K,-250000,400000,50000)                          34
    6N     FAO=1000                                                               34.5
    C      TFAO*=0/0/0/0/100/3000/5E4/1E5/15E4/20E4/25E4/30E4/35E4/40E4    34C
    1L     FAIP.K=FAIP.J+(DT)(FAO.JK-NOF.JK)                                      35
    6N     FAIP=10000                                                             36
    C      DOF=12                                                                 36C
    39R    NOF.KL=DELAY3(FAO.JK,DOF)                                              37
    1L     OFI.K=OFI.J+(DT)(NOF.JK-ROR.JK)                                        38
    6N     OFI=2.5E6                                                              39
    7A     FAIT.K=OFI.K+FAIP.K                                                    40
    12R    ROR.KL=(DEP)(OFI.K)                                                    41.5
    C      DEP=0.0166                                                             41.5C
    58A    FIPM.K=TABHL(TIPM,FAIT.K,0,4E6,0.5E6)                                  42
    C      TIPM*=0/.45/1.0/1.0/1.0/1.0/1.0/1.0/1.0                                42C
    12A    CFMI.K=(CPFM.K)(FIPM.K)                                                43
    12R    CLR.KL=(ACV)(CFMI.K)                                                   44
    C      ACV=100000                                                             44C
    1L     COBL.K=COBL.J+(DT)(CLR.JK-FAG.JK)                                      45
    6N     COBL=4E6                                                               46
    PRINT  1)RB,ARB/2)FE,DBU/3)ESWF,ESH/4)ESL,FAO/5)FAIT/6)CLR,COBL/7)AMEG 47
    PLOT   ARB=A/COBL=C/AMEG=M/ESWF=E/FAIT=F                                      48
    SPEC   DT=1/LENGTH=120/PRTPER=2/PLTPER=1                                      49

    N      EQUATION FOR   DFE,  ADJ,  FAG, GDBU,  MEG,   MT, ESWF, FMEG, DBLC,
                          DRBC
```

APPENDIX D

COMPUTER PRINTOUT FOR BEST POLICY

```
PAGE 3

 TIME        RB        FE      ESWF       ESL      FAIT       CLR      AMEG
            ARB       DBU       ESH       FAD                COBL
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 E+00      E+03      E+03      E+00      E+00      E+03      E+03      E+00
           E+03      E+03      E+00      E+03                E+06
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  .00    1000.0     925.0    255.00        0.    2510.0        .0    10.072
         1000.0    1000.0    7.6786      9.27               4.000
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 2.00     991.9     926.0    268.97        0.    2463.3     189.4    10.121
         1000.8    1016.7    5.2663     38.48               3.516
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 4.00     950.1     862.7    278.73        0.    2469.1     139.1    10.530
          996.9    1033.7    3.8930     53.04               3.253
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 6.00    1013.1     783.8    286.07        0.    2502.1     153.0    11.193
          990.5    1051.0    3.1247     59.76               3.021
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 8.00    1161.0     812.0    292.11        0.    2548.4     287.6    11.618
         1000.3    1068.6    2.8143     62.12               2.941
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
10.00    1190.8     937.5    297.70        0.    2600.2      27.9    11.666
         1029.5    1086.5    2.7736     62.81               2.988
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
12.00     980.7     955.3    303.24        0.    2654.5     229.0    12.009
         1048.8    1104.7    2.6970     62.98               2.798
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
14.00     867.3     771.3    308.51        0.    2709.7     226.2    13.350
         1028.8    1123.1    2.4248     62.57               2.729
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
16.00    1004.7     783.1    313.26        0.    2763.8     366.6    14.695
         1009.0    1141.9    2.3036     61.46               2.816
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
18.00    1148.4     794.7    317.90        0.    2815.4     158.7    15.363
         1014.0    1161.0    2.4076     60.59               3.143
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
20.00    1307.6     858.8    322.81        0.    2865.0     117.1    15.402
         1042.7    1180.5    2.6322     60.52               3.149
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
22.00    1277.2    1000.9    328.21        0.    2913.8     211.6    15.117
         1087.1    1200.2    2.8697     61.37               2.983
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
24.00    1013.3     938.9    333.98        0.    2963.6     322.2    15.593
         1106.7    1220.3    2.8561     62.71               2.983
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
26.00     987.4     849.0    339.58        0.    3014.5     148.4    17.137
         1086.3    1240.7    2.6243     63.55               3.326
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
28.00    1082.6     861.9    344.78        0.    3065.4     217.6    18.345
         1075.2    1261.5    2.5794     63.74               3.730
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
30.00    1226.2     874.9    349.97        0.    3115.2     438.9    18.915
         1082.9    1282.6    2.6927     64.09               3.524
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
32.00    1333.5     888.6    355.46        0.    3154.6     256.2    19.060
         1110.0    1304.0    2.8945     65.00               3.452
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

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PAGE 4

 TIME        RB        FE      ESWF       ESL     FAIT      CLR     AMEG
            ARB       DBU       ESH       FAD               COBL
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 34.00    1375.0     940.0    361.35        0.   3214.7   1028.3   19.038
          1148.4    1325.8    3.0972     66.48              3.503
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 36.00    1392.7     965.9    367.62        0.   3266.5    177.7   19.012
          1183.6    1348.0    3.2081     68.27              4.062
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 38.00    1362.4    1010.0    374.08        0.   3320.6    261.5   19.077
          1217.9    1370.6    3.2876     70.03              3.929
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 40.00    1286.2     951.6    380.65        0.   3376.7    776.3   19.703
          1237.4    1393.5    3.2579     71.63              4.010
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 42.00    1365.5     967.8    387.13        0.   3434.5    446.8   20.533
          1247.3    1416.8    3.2079     72.80              4.455
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 44.00    1460.5     983.9    393.57        0.   3493.0   1112.4   20.930
          1270.2    1440.5    3.2842     73.79              4.366
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 46.00    1564.8    1018.3    400.20        0.   3552.1    505.3   21.009
          1302.8    1464.6    3.4083     74.99              4.793
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 48.00    1556.4    1136.0    407.11        0.   3612.3   1027.6   20.796
          1347.1    1489.1    3.5739     76.47              4.759
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 50.00    1405.5    1102.3    414.29        0.   3674.1    464.9   21.192
          1373.1    1514.0    3.5674     78.13              4.970
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 52.00    1387.9    1053.4    421.36        0.   3737.5    561.4   22.511
          1375.4    1539.4    3.4434     79.35              4.750
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 54.00    1389.3    1070.5    428.22        0.   3801.5    656.4   23.968
          1377.2    1565.1    3.3973     80.11              4.671
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 56.00    1356.2    1087.5    435.01        0.   3865.4    518.9   25.539
          1377.1    1591.3    3.3824     80.78              5.184
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 58.00    1364.1    1104.4    441.77        0.   3928.9    849.2   27.057
          1374.1    1617.9    3.3826     81.46              5.411
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 60.00    1406.3    1121.4    448.55        0.   3992.2    512.8   28.394
          1373.2    1645.0    3.4210     82.21              5.352
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 62.00    1381.5    1138.6    455.43        0.   4055.3    615.5   29.770
          1377.5    1672.5    3.4993     83.17              5.634
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 64.00    1380.0    1156.1    462.45        0.   4118.8    861.2   31.256
          1377.9    1700.5    3.5453     84.29              6.114
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 66.00    1444.9    1173.9    469.57        0.   4182.8   1855.3   32.479
          1380.0    1728.9    3.6103     85.49              5.983
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 68.00    1540.5    1192.1    476.85        0.   4247.5    409.6   33.367
          1390.0    1757.9    3.7202     86.84              7.572
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
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PAGE 5

   TIME       RB       FE     ESWF      ESL     FAIT      CLR     AMEG
             ARB      DBU      ESH      FAO              COBL
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  70.00   1737.1   1211.0   484.39       0.   4313.2    420.5   33.167
          1423.3   1787.3   3.9635    88.45              7.342
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  72.00   1864.1   1231.2   492.47       0.   4380.7    426.8   32.468
          1479.8   1817.2   4.2688    90.67              7.361
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  74.00   1932.0   1322.5   501.15       0.   4451.2    783.9   31.616
          1546.1   1847.6   4.5289    93.38              6.676
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  76.00   1749.0   1304.8   510.29       0.   4525.4    842.0   31.710
          1600.5   1878.5   4.6184    96.24              6.834
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  78.00   1683.2   1298.7   519.47       0.   4603.4    866.3   33.244
          1619.8   1909.9   4.4819    98.54              7.313
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  80.00   1684.0   1320.9   528.37       0.   4683.8    150.3   34.986
          1629.5   1941.8   4.3792    99.99              7.634
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  82.00   1636.7   1342.8   537.11       0.   4764.9   1210.6   37.275
          1638.3   1974.3   4.3468   101.04              6.701
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  84.00   1489.8   1364.4   545.77       0.   4846.1   1208.5   41.769
          1630.1   2007.4   4.2455   101.94              7.640
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  86.00   1454.1   1385.5   554.19       0.   4926.9    747.7   46.921
          1604.6   2040.9   4.1170   102.50              8.762
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  88.00   1522.0   1406.0   562.40       0.   5006.7    830.5   51.047
          1583.7   2075.1   4.1107   102.88              9.474
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  90.00   1674.2   1426.7   570.67       0.   5085.3   1687.7   53.273
          1580.4   2109.8   4.2519   103.57              9.325
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  92.00   1837.0   1448.2   579.29       0.   5163.3   2917.0   53.808
          1599.4   2145.1   4.5000   104.94              9.677
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  94.00   2119.2   1471.1   588.46       0.   5242.3    652.5   52.216
          1642.2   2181.0   4.8214   107.05             11.319
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  96.00   2433.1   1565.7   598.35       0.   5323.7   1443.0   48.585
          1732.9   2217.5   5.3427   109.97             10.606
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  98.00   2393.4   1785.7   609.30       0.   5409.3    570.2   44.752
          1846.7   2254.6   5.8014   113.96             10.703
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 100.00   1942.4   1719.0   620.99       0.   5500.9    617.8   43.773
          1918.4   2292.3   5.8174   118.16              9.642
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 102.00   1667.9   1581.0   632.41       0.   5598.3   2752.3   50.896
          1905.1   2330.6   5.3317   120.97              9.250
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 104.00   1624.0   1607.1   642.85       0.   5697.9   3068.1   60.412
          1859.0   2369.6   4.8997   121.75             12.612
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
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PAGE 6

  TIME          RB        FE      ESWF       ESL      FAIT       CLR      AMEG
               ARB       DRU       ESH       FAJ                COBL
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  106.00    2097.1    1631.4    652.55        0.    5796.2    2199.2    63.344
            1834.6    2409.3    4.8482    121.54              14.969
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  108.00    2830.6    1656.2    662.48        0.    5891.9    1475.8    58.178
            1904.3    2449.6    5.4539    122.15              15.274
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  110.00    3151.5    2352.4    673.89        0.    5987.5     242.3    50.853
            2080.2    2490.6    6.4931    125.24              16.079
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  112.00    2145.9    2701.4    687.22        0.    6088.1    1457.4    45.321
            2227.0    2532.2    6.8869    130.69              13.778
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  114.00     916.1    1751.5    700.58        0.    6197.0      45.9    54.621
            2144.9    2574.6    5.6839    134.80              14.438
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  116.00    1162.2    1777.9    711.18        0.    6309.1    2081.2    66.785
            1963.5    2617.6    4.5081    133.78              14.493
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  118.00    1541.6    1800.0    719.99        0.    6414.9    6098.0    76.730
            1848.7    2661.4    4.2999    130.84              16.190
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  120.00    2488.0    1821.9    728.76        0.    6512.4     296.3    79.743
            1823.0    2706.0    4.7867    129.19              25.604
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
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