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AN ANALYSIS OF THE DYNAMIC BEHAVIOR OF A RESEARCH AND DEVELOPMENT ORGANIZATION

by

GILLETT WELLES, III

B.E., YALE UNIVERSITY
(1961)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

at the

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1963

Signature of Author...
School of Industrial Management

Certified by ....
Faculty Advisor of the Thesis

21 Ellery Street
Cambridge, Massachusetts
May 14, 1963

Professor Philip Franklin
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Professor Franklin:

In accordance with the requirements for graduation, I herewith submit a thesis entitled "An Analysis of the Dynamic Behavior of a Research and Development Organization".

Sincerely yours,

Gillett Welles, III

ABSTRACT

AN ANALYSIS OF THE DYNAMIC BEHAVIOR OF A RESEARCH AND DEVELOPMENT ORGANIZATION

by

GILLETT WELLES, III

Submitted to the School of Industrial Management on May 14, 1963, in partial fulfillment of the requirements for the degree of Master of Science.

A conceptual framework for representing the process of research and development is formulated. The framework is oriented towards allowing analysis of the dynamic behavior of a typical research and development organization and its customer interfaces. It includes interactions between the customer and the R and D firm in terms of flows of information, and awarded and completed contracts. Internally, interactions among technical manpower, technical effort, technical effectiveness due to past work, and management decisions are treated. Several basic features of the conceptual framework are 1.) the division of the type of work performed by the organization into advanced research, and design and development, 2.) the division of the technical effort performed by the organization into volume and quality effort, 3.) the concept of a market sector where the customer makes his award decisions based on consideration of past performance, present cost and delivery estimates, and the extent and type of present marketing effort, 4.) the determination of required marketing effort by the capacity of the organization, and 5.) the existence of technical effectiveness as an important factor in all sectors of the system.

The conceptual framework is used as a basis for the construction of an Industrial Dynamics model. Extensive computer simulations of the dynamic behavior of the system are reported and analyzed. Basically, it is found that the characteristics of technical effectiveness are the most important determinant of the dynamic behavior exhibited by the system. This conclusion in conjunction with the vague definition of technical effectiveness and the lack of knowledge of its characteristics is seen to indicate a need for extensive further research in this area.

Growth is found to be an inherently unstable process, and the importance of managerial policies affecting growth is demonstrated. A counter-cyclical marketing effort policy is shown to be most effective in controlling a high growth rate.

The validity of the conceptual framework is demonstrated by the reasonable dynamic behavior exhibited by the system. It is concluded that this framework can be helpful in fields other than Industrial Dynamics as an aid to understanding the process of research and development, and as a guide to further research.

Thesis Advisor: Edward B. Roberts

Title: Assistant Professor of Industrial Management

Acknowledgements

Appreciation must be expressed to many people for their considerable help in all stages of this thesis. The most thanks goes to my advisor, Professor Edward B. Roberts. His knowledge of the research and development field proved invaluable as a source of ideas and as a standard against which to test the concepts developed in this thesis. His direction of my efforts into those areas most deserving of research and his ever ready willingness to discuss the thesis as it developed, and to criticize it when necessary,must be given considerable credit for whatever meaningful results have emerged from this study.

To my colleague, Leo P. Kane goes my sincere appreciation for the many hours of discussion and labor that he contributed to the development of the conceptual framework and the model. The continuing feedback of the results of his study of an actual R and D laboratory was also very valuable.

Three groups must be cited for their contributions. The National Aeronautics and Space Administration, whose grant for the establishment of the Organizational Studies Group at the School of Industrial Management has supported my research in this area, must be wholeheartedly thanked.

Gratitude must also be expressed to the MIT Instrumentation Laboratory, and especially to Mr. J.B. Feldman. Their outstanding cooperation with regards to the study performed by Mr. Kane proved to be of great help in contributing to both his and my thesis.

All of the computer simulations for this thesis were performed at the MIT Computation Center. It is unnecessary to stress the importance of this contribution.

One other person contributing extensively to this work has been my wife, Frances. Besides performing the monumental job of typing this thesis under considerable time pressure, she helped a great deal with the proofreading.

To all of the people and groups mentioned above I express my sincerest appreciation.

Gillett Welles, III

Gillett Welles, III

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Chapter I: Introduction

The importance of research and development to the maintenance of the national defense capability, to the development of the national economy, and to the growth of individual firms and industries is widely recognized. The increasing size of both military and and private R and D budgets is but one indication of this. The March, 1963 issue of the IEEE Student Journal states that the United States Government will spend $14.7 billion for R and D in fiscal 1963. This figure represents an increase of $3.5 billion over the amount spent for the same purpose in 1962. Private R and D budgets show much the same kind of growth.

One reason for the increasing expenditures on R and D is the increasing rate of technological advancement being experienced by this country. New discoveries are becoming obsolete in an ever decreasing amount of time and consequently, more R and D is necessary just to keep up with the times. The process appears to be a cumulative one, where a higher obsolescence rate results in more R and D being performed, which in turn further speeds up the obsolescence rate. We can only guess as to what heights this process will carry us.

The increasing recognition of the importance of research and development is also manifested by the increasing effort to develop procedures for improving the quality of managerial decisions in R and D. There is definitely a need to increase the quality of R and D management. Project failure rates are high and many complex systems are obsolete even before their development is finished. The great majority of efforts to increase the quality of R and D management decisions seem, however, to suffer from lack of understanding of the problem. By and large, these attempts take tools and techniques developed in other areas and search for applications of them in R and D. For example, the December, 1962 issue of the _IRE Transactions on Engineering Management_ (Vol. EM-9, No.4) included articles on the application of linear programming to the allocation of R and D efforts, the application of dynamic programming to R and D budgeting, and cost control through the use of PERT. The typical approach used by R and D researchers seems to ignore one basic rule - that the first step in any research project is to gain an understanding of the area in which impoovements are to be made, and to use this understanding to define the important problems. Admittedly, progress has been made, but it is felt that the extent of this progress is much less than would have been possible if the important problems had been defined and effort concentrated on them.

The apparent need, therefore, is for basic research to be performed on the characteristics of research and development. Although a few authors have done notable work in this area,[1,2] their contribution is not nearly enough. If a better understanding of the basic process of research and development can be obtained, it can be used to identify the important problems for researchers. Such a channeling of effort cannot help but improve the efficiency and quality of R and D.

Perhaps one reason for the present lack of understanding of research and development is the intangible nature of many of the basic phenomena to be observed. Researchers tend to gravitate towards concrete problems involving variables that can be measured. This may explain why important concepts like engineering effectiveness, creativity, or accomplishment remain just that, important concepts which no one can really define or control. The present intangible nature of such concepts merely further emphasizes the need for better understanding of the basic process of research and development.

Purpose and Methodology

The main purpose of this study is to increase the understanding of the R and D process through the development of a conceptual framework

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1 The Weapons Acquisition Process: An Economic Analysis, by M.J. Peck and F.M.Scherer, Graduate School of Business Administration, Harvard University, Boston, 1962.

2 The Dynamics of Research and Development, by Edward B. Roberts, Harper and Row, New York, In Press.

for viewing the process and identification of the important determinants of success for an R and D organization.

These are several possible ways to approach the above goals. Research and development can be studied in either the context of the individual research project, or in the context of the entire research organization. Since Roberts of the MIT School of Industrial Management has done an excellent job using the former approach[3], the latter one will be used here.

A basic framework for viewing the behavior of R and D organizations will be developed. Implicit in the development of such a framework will be the concept that research and development is not a random process, but that it is definitely an ordered process obeying certain laws of cause and effect. The general procedure to be used here is that developed in a new approach to the study of socio-economic systems called Industrial Dynamics. Industrial Dynamics

> treats the time-varying (dynamic) behavior of industrial organizations......Industrial Dynamics is the study of the information feedback characteristics of industrial activity to show how organization structure, amplification (in policies) and time delays (in decisions and actions) interact to influence the success of an enterprise. It treats the interactions between the flows of information, money, orders, materials, personnel, and capital equipment in a company, an industry, or a national economy..... It is a quantitative and experimental approach for relating organizational structure and corporate policy to industrial growth and stability.[4]

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3 *Ibid.*

4 Jay W. Forrester, *Industrial Dynamics* (Cambridge: The MIT Press, and New York: John Wiley and Sons, Inc., 1961), p.13.

The Industrial Dynamics approach progresses through several stages. The first is the identification of a key economic or industrial problem which merits study. The importance of the problem selected was discussed earlier in this chapter.

The next step is the development of a conceptual framework through which study of the system can be accomplished. A verbal description of this framework is first completed, and emphasis is placed on isolating the important information feedback loops and decision policies in the system. Chapters II-VI develop such a conceptual framework for a typical research and development organization.

The third step involves the construction of a mathematical model of the research and development system. This model will include all the concepts and relationships developed in the conceptual framework. The model finally developed for this study is described and explained in Appendix A.

The fourth step is the simulation over time of the behavior of the R and D system. Digital computer simulation techniques are used and the results are compared with information about the real world. These comparisons are used to make revisions in the model until it is deemed satisfactory for more intensive study of the system. The model described in Appendix A is the one that resulted from the efforts of this stage of the study.[5]

The next phase involves extensive simulation with the goals in mind of 1.) determining the factors represented in the model which seem most important in determining the success of an R and D organization and 2.) determining the amount and type of system redesign (usually decision policies) necessary to actually improve the dynamic behavior of the system. This phase of the study is reported in Chapter VII.

Ideally, the final stage of an Industrial Dynamics study requires the introduction of the redesigned decision policies into the actual system. However, the emphasis of this investigation was on increasing the understanding of the R and D process, rather than the explicit design of better decision policies. Also, the study was of a general rather than specific nature. For policy changes to be implemented into a specific organization, intensive study of that organization would have to be undertaken first. The general conclusions reached here would also have to be redefined in a more specific manner, a task which would be impossible without a great deal of further study along the lines indicated by this investigation.

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5 For a report on how the concepts represented in the model actually compared to those found in an actual R and D laboratory, see "A Model Oriented Approach to Studying the Structure and Performance of a Research and Development Organization", by Leo P. Kane (unpublished Master of Science thesis, MIT School of Industrial Management, 1963).

Major Conclusions

The conceptual framework presented in Chapters II-VI appeared to produce valid dynamic behavior when the computer simulations were run. It is felt that this framework is valuable not only as the basis for a mathematical model, but as an aid to understanding the process of research and development and as a guide for further research.

The development of the conceptual framework and the results of the model simulations indicated that the most important determinant of an organization's relative success is the characteristic of technical effectiveness. Technical effectiveness is a measure of the technical ability of an organization's engineers to perform technical work, and it depends mainly on the amount and type of the past work performed relative to the requirements of present work being performed by the organization. As defined in this study, it is a relatively vague concept. The discovery of its importance points up a pressing need for additional research to determine the important characteristics of technical effectiveness with more accuracy.

Another major conclusion resulting from the study was that growth of an R and D organization is an inherently unstable process, and unless management acts to keep it under control, the organization will be heavily penalized. Extensive growth hurts an organization because it tends to dilute the effective knowledge held by the organization and results in a lowering of technical effectiveness.

A management policy of counter-cyclical marketing effort was found to be effective in stabilizing growth. This policy increases marketing effort when technical effectiveness is low, in an effort to keep the organization busy, and decreases marketing effort when effectiveness is high, in an effort to keep the growth rate within that successfully attainable by the organization.

Although some conclusions may be drawn from this study as to how R and D organizations can be better managed, the main contributions are a better definition of the process of research and development through the presentation of a conceptual framework and an indication of the areas of research and development towards which future research should be aimed.

Chapter II. Technical Effort

A General System Description

The next five chapters will be concerned with developing a conceptual framework for describing the typical research and development organization. This framework will be oriented towards 1.) simplification of future study of R and D, 2.) contribution to present knowledge and understanding of R and D, and 3.) generation of a dynamic model suitable for simulation.

The general structure of the conceptual framework to be presented is shown in Figure II-1. The system can be described as

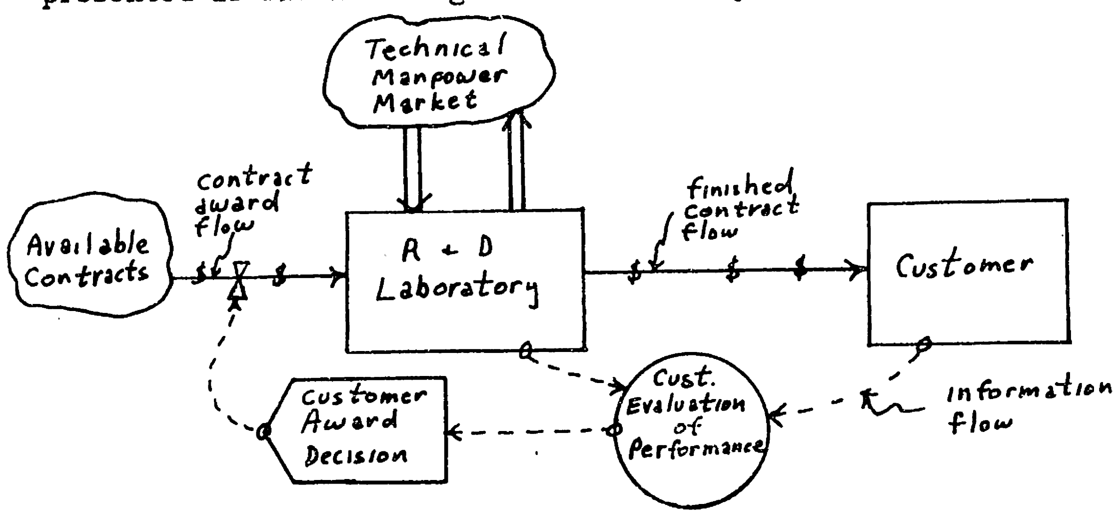

Figure II-1: General Flow Diagram for R and D Laboratory

follows. Contracts for R and D work are awarded to the organization. These contracts are essentially requirements for technical effort and the R and D organization's primary function is to supply this effort. Due to changing conditions, such as increasing or decreasing contract awards, the organization is sometimes forced to adjust its technical labor supply, thus leading to an inflow or outflow of personnel as shown. When effort equal to the requirements of a contract has been supplied, the finished contract is delivered to the customer in the form of study or feasibility reports, operational systems, operational components, etc. The process does not stop with delivery, however. It is evident that it is possible to do a good, bad, or indifferent job on an R and D contract, just as it is on anything else. The customer will take the performance of the laboratory on past and present contracts into account when he considers making more contract awards to the organization. Thus, if the organization does a poor job, future award rate will be decreased. If the customer is thought of as being an aggregate customer representing all the individual customers, performance on any job will affect all future awards. This is a realistic representation since performance generates a reputation, be it good or bad, which will affect all individual customers' dealings with the organization. It now becomes evident that the typical R and D laboratory is part of a system in which information about the output feeds back to affect the input. With the right combination of system delays and policy amplification, it is possible that this system will exhibit unstable dynamic behavior. This conclusion is further reinforced by observation of the drastic ups and downs apparent in many existing R and D organizations.

Technical Effort: Types of Work

The conceptual framework to be presented in the next five chapters has been outlined above in the form of a general system description. A more detailed presentation of the technical effort function of the typical R and D laboratory will now be given.

The primary function of the research and development organization is to exert technical effort towards the requirements of awarded contracts and to deliver the desired results to the customer within a reasonable period of time. Contract requirements have a very diverse character, however, and the kinds of effort necessary to complete two different contracts may be very different. This appears at first to be a significant barrier to developing a meaningful, but simple, representation for technical effort. This barrier can be overcome, though, by dividing technical effort into two kinds of work: advanced research, and design and development. These two kinds of work are different in the amount and type of effort required to meet requirements, in the kinds of thing deemed important in the final result by both the customer and the R and D organization, and in the actual contract requirements. These differences can be clarified by describing the kinds of work involved. Design and development can be thought of as work which results in an operational system, component, or concept. No significant advances of the state of the art are necessary to complete the usual design and development contract. Typically, existing techniques, concepts, and even hardware are used as is, without significant change being involved. Advanced research, on the other hand, can be thought of as work which results in feasibility reports or advanced concepts for systems or components. Typically, advanced research does advance the state of the art. It is effort aimed at solving unsolved problems or doing new things with new techniques rather than doing new things with old techniques.

These two categories constitute a somewhat arbitrary distinction which would perhaps be of little help in describing the great variety of contracts seen in the real world, especially if one attempts to fit an entire contract into one category or the other. However, if each contract can be divided into small work packages or requirements, and if the packages are made small enough, these work packages can be made to have the characteristics of either advanced research or design and development. Very seldom could an entire contract be placed in one category or the other, but each of the many small work requirements can be classified in one of the two above categories.

In keeping with the present discussion, the flow of contract awards into the laboratory will not be represented by discontinuous awards of blocks of funds for discrete programs. Although this is the way many may view R and D awards, the flow is really much more continuous in time and character. Work requirements, and the funding for them, become known and available in a gradual manner. The award of a large program to a laboratory seems to be a sudden discrete affair. Actually such awards are often vague, with the terms and actual work to be done remaining to be worked out. One factor contributing to the gradual flow of work requirements is that often the extent and type of work scheduled for later in a program cannot be defined until the earlier work is completed. For the same reason, funds are only made available gradually. Also, the customer will often curtail or increase funding upon learning about the content of past work on the contract. Usually, the customer is constantly reviewing progress and only makes funds available when needed. Thus contract awards (ie., funds and work requirements) can be represented by a continuous flow of small work units or amounts of money rather than discrete awards for large programs extending far into the future. This manner of representation also simplifies the problem of the cancelled contract due to poor performance. It allows us to treat the cancelled part as never having been awarded in the first place, since the customer is seen as making a continuous decision about future awards.

Volume and Quality Effort

The R and D organization has available for exerting technical effort a pool of trained technical manpower. The effort of these people is applied towards contractual requirements and results in work being finished and delivered to the customer. The ability of technical manpower to perform technical work is not a constant, however, nor is the amount of effort aimed at getting the job done as soon as possible, or as well as possible. These three factors combine to produce variations in the rate at which contracts are finished and in the quality of finished contracts.

The ability of technical manpower to perform technical work is felt to depend mainly on past experience in the field. The concept of technical effectiveness was developed to represent this effect. Technical effectiveness will be fully explained in Chapter IV, but very briefly, it is a measure of the technical capabilities, with respect to the job at hand, of the average engineer in the organization. It depends on the amount and type of past work performed by people in the organization and on the requirements of present work. Past advanced research will contribute more in magnitude of impact to technical effectiveness than past design and development work and will thus result in a greater contribution by each engineer to present work in the same general area. If an organization is growing fast, however, there will be a high number of inexperienced people, and the technical effectiveness will be low.

For any technical effectiveness, an engineer has a certain capability for exerting technical effort. This does not mean that contracts will be finished at a certain rate, however. The organization or the individual engineer influences the allocation of the engineer's time to completing work as quickly as possible, or to going somewhat slower and doing a better job. Given a certain technical effectiveness, then, the more valid technical effort that is spent on a job, the better that job will be done and vice versa. This phenomenon can be cast into a conceptual framework by dividing technical effort into two categories, volume effort and quality effort. Volume effort can be described as effort which results in a contract unit being finished in as short a time as possible. The minimum amount of work necessary to meet work requirements is performed and the design is frozen at the earliest possible stage. Quality effort is work aimed at improving the quality of the end result delivered to the customer. Quality effort has no effect in moving a contract closer to completion, but it instead increases performance or reliability by redesigning circuitry, providing back-up circuits, testing extensively, etc. An example of quality effort would be designing a better circuit to replace onethat worked sufficiently satisfactorily to meet contract specifications.

This division of technical effort into two kinds of work may seem as arbitrary as the advanced research-design and development split. It does, however, provide a good picture of the real world upon further inspection. Since the fraction allocations of time to volume or quality are completely variable, this framework allows representation for infinite combinations of contract quality and completion time. A simple example might help in establishing the validity of this concept. Suppose a contract requires two man years of technical effort in order to meet just the minimal requirements and further suppose that the organization in question has two engineers available to work on this contract. If the engineers try to do the job as fast as possible (ie., their time is entirely allocated to volume effort), then the job will take just one year. But let us suppose the organization involved has a commitment to high quality work and half the engineers' time is spent improving and developing the performance of the end result beyond the minimum contract requirements. Doing a better job than required will take more time, in this case utilizing two years to finish the contract. Graphically, this example can be portrayed as in Figure II-2. The time to finish the contract is plotted against the percentage allocation of the two engineers' time to improving the end result beyond minimum contract requirements.

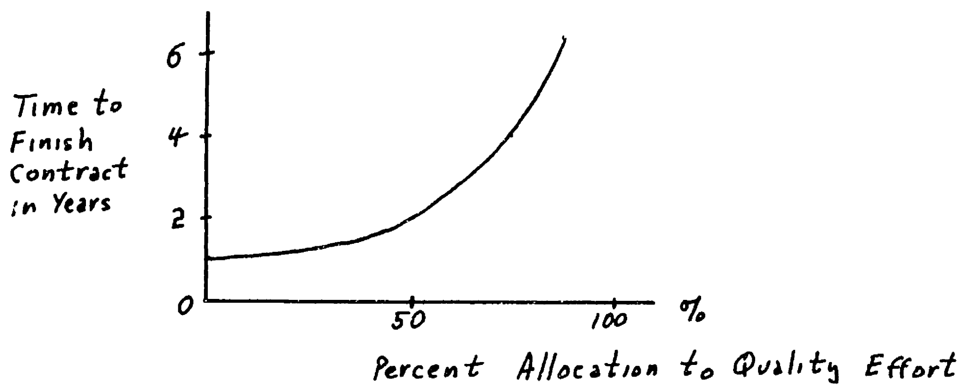

Figure II-2: Contract Completion Time versus Allocation to Quality Effort.

The rate and quality of technical effort can be seen to depend on the technical competence of trained technical manpower and the relative allocations of time to volume and quality effort. The obvious question to consider at this point is how the relative allocation of time to volume and quality effort is determined. However, it is first necessary to describe in greater detail the contract flow through the laboratory.

Contract Flow

As described above, contracts are awarded to the R and D organization, technical effort is performed upon them, and the results are delivered to the customer. The actual flow, however, is not as smooth as might be inferred from this description. Typically, full scale effort will not be started on a contract immediately upon the award. The usual R and D organization is wary of committing people and facilities to a program until it has been awarded without a doubt. Two possible delays can result. First, on any program of greater than trivial scope, extensive planning must be done in order to determine the order and amount of technical effort to be applied. This planning requires the time of relatively few people, and constitutes only an insignificant portion of the total effort needed for finishing the contract. Secondly, delays can result if the organization must expand its manpower level. It takes time to hire and then train new personnel. Alternatively, a delay may result from management waiting for a present program to phase out and thus free the necessary manpower. Thus, the internal contract flow can be represented by a framework in which contracts awarded enter a planning phase, during which no significant effort is expended. Depending on the ability of the organization to exert technical effort, the contracts will then enter an in-process phase during which active progress towards completion takes place. It is also prudent to expect that personnel may be shifted from one in process program to work on another more urgent program. Thus, partially completed work may be allowed to lie dormant for a while before being finished. This description of contract flow is illustrated in Figure II-3.

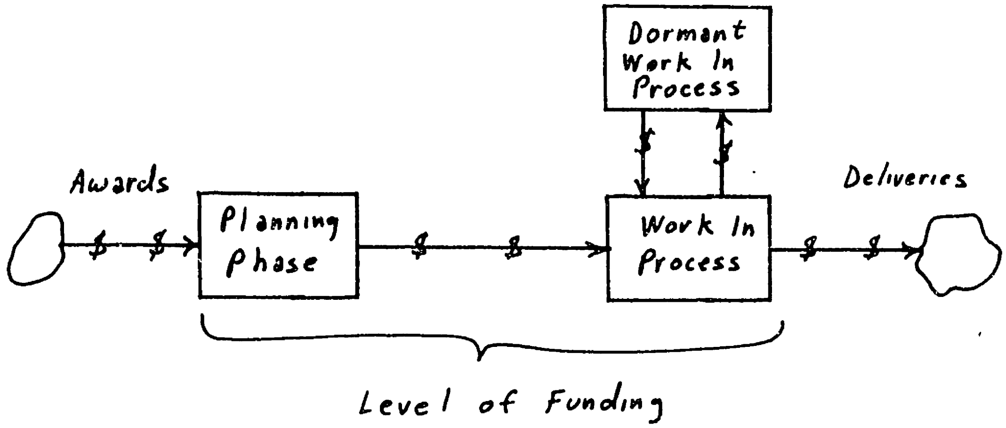

Figure II-3: Internal Contract Flow.

Management Control

The total value of contracts within the organization (ie., contracts awarded, but not completed) can be described as the level of funding of the laboratory. This is an important concept for management. Many decisions are directly affected by the amount of work, in terms of time to completion, that the organization has. When the organization's ability to perform technical effort (a function of technical competence and the level of technical manpower) appears to be much more or much less than that corresponding to the level of funding, management will take definite corrective action. Two kinds of corrective action are immediately obvious. Management can either attempt to adjust the level of funding through changing the award rate or they can attempt to change the contract finishing rate. A possible method of affecting the award rate is through an adjustment of marketing effort. This decision will be discussed further in Chapter VI. Management can make several decisions which affect the contract completion rate, however. The two most obvious are 1.) its decision on the number of technical personnel for the organization to employ, and 2.) its decision on the relative allocation of time to volume or quality effort.

Implicit in these decisions is the concept of a comparison of a desired level of funding to the organization's actual level. The desired level of funding can be viewed as depending primarily on the contract award rate. It might also be argued that the desired level of funding should depend on the number of people employed, or alternatively on the finishing rate. However, in a steady state situation where the organization is neither growing nor declining, the award rate will equal the finishing rate. In a transient situation, the organization will be attempting to change the finishing rate so it is equal to the award rate. Thus the desired level of funding will, in the long run, depend on the perceived award rate. Often, the desired level of funding is stated in terms of contract dollars awarded, but it may also be expressed as a certain number of years of work. In other words, management might state that their desire is to have in the organization enough work to keep the present people busy for three years. Assuming again that in the long run management will try to adjust the finishing rate to equal the award rate, the desired level of funding can be expressed as the number of years of work desired times the contract award rate.

It is obvious that the number of years of work desired by the organization is not necessarily a constant. This may grow shorter as the organization becomes over-staffed, for example. Such an adjustment serves as a quick stop-gap method for easing organizational stresses. The long run response to a condition of over-staffing would be to either allow attrition to reduce the size of the organization, to fire people, or to exert more marketing effort. The change in the desired number of years of work would operate to reduce pressures on management until a permanent solution can be found and implemented. Thus, the desired level of funding will also depend on how over or under-staffed the laboratory is.

Two factors which affect management's decisions for controlling the contract completion rate have been introduced. Management will attempt to 1.) adjust the effort rate of the organization to equal the award rate, and 2.) allow the effort rate to vary from the award rate just enough to correct the actual level of funding to that desired.

Now, we shall return to the explicit managerial decisions on manpower level and time allocation. The question of how many technical personnel the organization should employ will be discussed in detail in Chapter III. In brief, however, management looks at the contract award rate and the difference between the desired and actual level of funding, and from this information decides on a desired future effort rate. This desired effort rate along with the perceived technical competence is used to determine the desired level of manpower. Finally, hiring or firing policies result from a comparison of actual and desired manpower.

Allocation of Technical Manpower Time

The process of time allocation can be represented most easily by thinking in terms of the fraction of engineering time allocated to quality effort and the fraction of time allocated to volume effort. The level of technical manpower available and their technical effectiveness will be treated as given for the purposes of this discussion. The time allocation process is not directly affected by either of these, but instead depends on several other factors which management can perceive.

The concept of allocating time between two activities (ie., volume and quality) implies a compromise situation where one gains performance in one aspect of a situation only by giving it up somewhere else. In any organization there will be people desiring to perform a job better in one area and people against making the necessary sacrifices. Such a situation can be described by saying that there is pressure for an activity requiring limited resources in one area due to certain factors, and pressure for another activity requiring the same limited resources in another area due to other factors. Actual allocation of the limited resources will be determined by resolution of the two pressures. In our case, the limited resource is engineering time.

There remains to be discussed the factors affecting the generation of pressures for volume or quality effort. The pressure for volume effort will increase when the organization finds itself falling behind in finishing contracts. A good measure of how well an organization is doing in finishing contracts in accordance with their schedule is a comparison of the actual level of funding to that desired. If the actual level is bigger than that desired, then the organization is taking longer than was initially planned to finish its contracts. However, as the actual level of funding gets much bigger compared to that desired, the organization will come to accept to some extent its poor situation and will not increase the pressure for volume as drastically. This is shown in Figure II-4 by the way the pressure curve saturates as the ratio of the actual to the desired level of

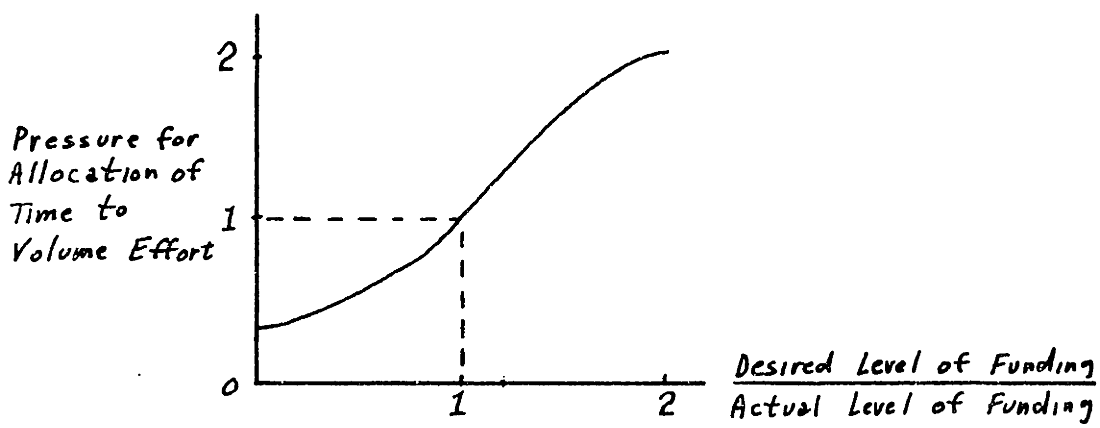

Figure II-4: Pressure for Volume Effort

funding increases. Somewhat the same kind of phenomenon occurs as the actual level falls below that desired. Pressure never falls to zero since there is always a feeling that something must be accomplished.

Quality effort results in higher performance, reliability, etc. of the end product. The quality of work produced by a laboratory is perceived, though perhaps incorrectly, by both the laboratory and the customer. The perceived quality is invariably judged by some standard of expected quality. If actual quality is higher than expected, the customer will be happy, providing cost and delivery delay were within reason, and the laboratory will certainly be happy. If, on the other hand, quality is lower than expected, the customer will be unhappy and will probably complain. This feedback combined with the organization's own disappointment in itself will result in efforts to improve in the future. Thus, we can expect that low quality work will result in pressures to improve, while attainment of a higher quality will result in the easing of these pressures.

A possible representation for the generation of pressure for quality effort would be as follows. Pressure for allocation of time to quality work depends on the difference between the quality of the organization's current work, as perceived by the organization, and the traditional level of quality previously maintained by the organization. Two important concepts are involved here. The organization's perception of the quality of its work depends on 1.) a delayed perception of its actual quality and 2.) on feedback from the customer regarding its perception of the organization's work quality. There is not immediate perception of the quality of expended effort.

The other important concept is that of a traditional quality which tends to represent a quality goal. This is not, as might be imagined, a constant level but varies over time depending on the actual quality performance of the organization. One should not be misled into thinking that because traditional quality is a goal of the organization, it cannot change. Suppose, for example, that an organization has a certain quality goal. If over the next several years, this organization is unable to attain the desired quality performance, the difference between traditional and actual quality will result in stress in the organization which the organization will try to reduce by raising their actual quality. Failure to do this, however, results in a gradual forgetting of the old traditions and gradual adoption of a newer, less ambitious, quality goal. It is a characteristic of both human beings and organizations of human beings that a discrepancy between the actual perceived self and the desired or ideal self will not be allowed to persist. The discrepancy is usually reduced by changing the desired self. Thus, the organization, when frustrated in its attempts to attain an impossible goal, will merely change the goal. This same principle also holds true for discrepancies of the opposite kind. For example, if an organization consistently performs better than it has intended, it will soon raise its goals to conform with its abilities.

Thus, traditional quality, or the standard to which perceived quality is compared, will vary over time as the organization's ability to produce quality output changes. There will be a significant delay, perhaps on the order of ten years, for traditional quality to reflect completely a permanent change in actual quality.

As was mentioned previously, pressure for allocation of time to quality effort depends on the relation of perceived quality to traditional quality. As the ratio of perceived to actual quality decreases, there will be a significant increase in pressure for more quality-oriented effort. As the ratio increases, however, there will not be too much of a decrease in pressure, since an organization that is doing well typically likes to continue to do so. Figure II-5 illustrates a possible variation of pressure for quality effort.

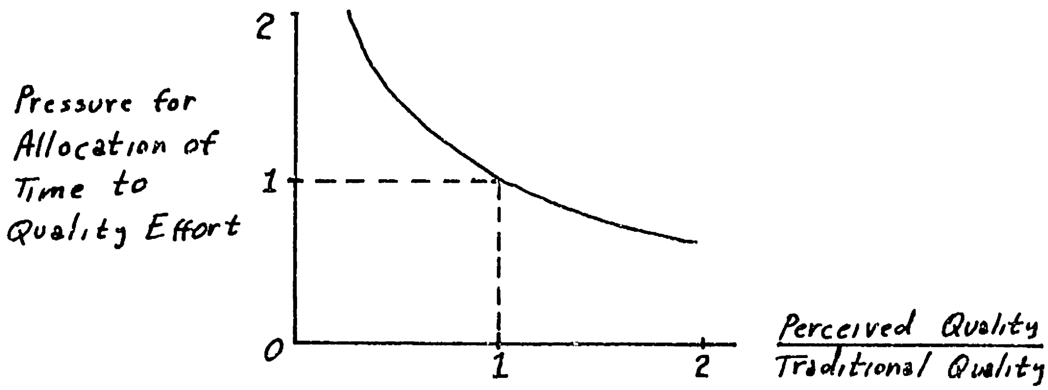

Figure II-5: Pressure for Quality Effort.

Differences Between Advanced Research and Design and Development

The general discussion above which has outlined an approach for conceptual representation of the technical effort sector of a research and development organization is applicable for the most part to both advanced research and design and development effort. Most differences between the two are minor and would involve, for example, different parameter values.

There is, however, one basic difference which requires a somewhat more complex representation for design and development technical effort. The nature of design and development work is that it results in actual hardware (ie., operational systems or components) or designs which are to be used either directly by the customer or produced in quantity by a production contractor for customer use. Therefore the job is not finished once the design is completed and several operational prototypes are delivered. The R and D organization still has the job of user education and/or production contractor education, even when the production activity is part of the same company as the R and D organization. This job requires liaison activity in which technical personnel transfer information about the designs involved and therefore are unavailable for new technical effort within the organization. The design and development contract flow is shown schematically in Figure II-6 which illustrates that after delivery, contracts require liaison effort. Typically, finished and delivered contracts require liaison effort for up to two years after delivery. Liaison effort is heaviest a short time after delivery and tapers off thereafter. A typical liaison activity curve is shown is Figure II-7.

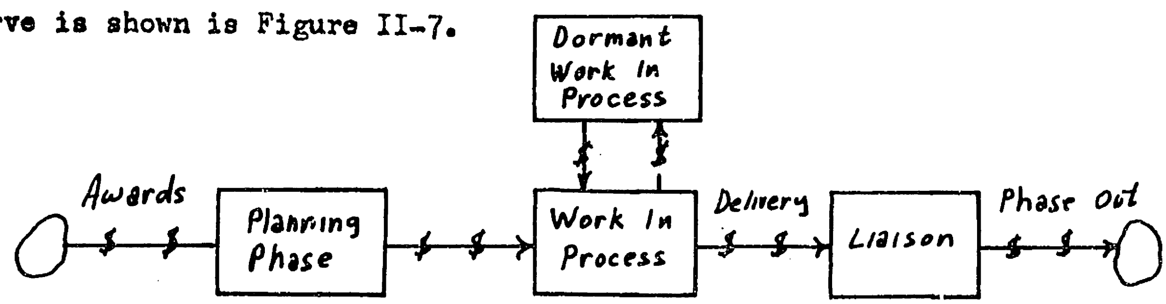

Figure II-6: Design and Development Contract Flow

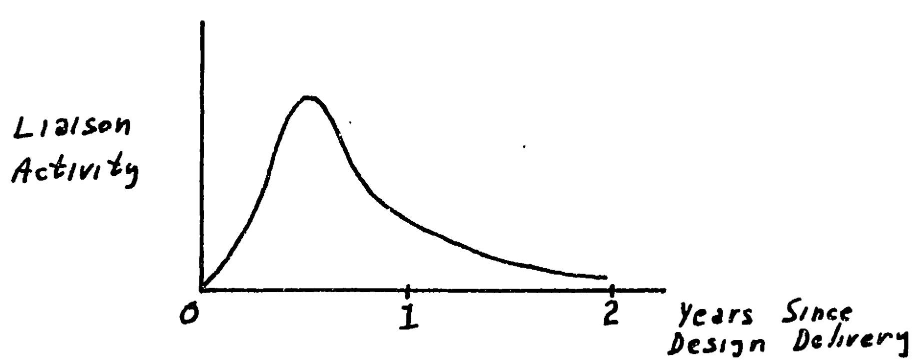

Figure II-7: Liaison Activity

The addition of liaison activity to the technical effort sector requires a more complex set of concepts for representation of the allocation of technical manpower time. The generation of pressures for volume and quality effort remains the same as discussed previously, but now the pressure for liaison activity must also be considered. This pressure varies as a function of the quality of delivered work as perceived by the customer. Pressure for liaison effort is usually dependent on the customer's perception of quality since an R and D organization rarely initiates production liaison activity on its own. The pressure on the R and D organization for production support is rather determined by the customer or production contracting organization's need for such support. The R and D organization has no interest in liaison activity from the technical point of view because the work contributes relatively little to organization knowledge. The organization's main interest in liaison activity is derived from its interest in the customer's perception of the organization's ability with respect to future contract awards. Also, however, the typical R and D laboratory takes great pride in its work and it wishes to receive its due credit. Since the proof of a design is in its operation, there is often motivation to indulge in liaison activity in order to insure that the production contractor does not foul up and by implication cast a stigma upon the laboratory's reputation. Another factor contributing to pressure for liaison activity is an organization's pride in doing a complete job.

However, the most important factor affecting pressure for liaison activity is still the fact that liaison work is inherently unprofitable to the organization in terms of generating future technical competence. Thus, the R and D organization will typically perform the smallest amount of production liaison activity that is consistent with its goals.

Liaison activity is undertaken in an effort to raise the customer's perception of the effectiveness of the final product or result. However, the ability to undo past errors through liaison activity is limited. The amount of liaison effort necessary to establish a normal quality for the final product will vary with the quality of the original job done by the R and D organization. Due to the high technical complexity of present-day R and D, some liaison effort will always be needed, regardless of the quality of the original job. The production contracting organization can easily claim that the design is unproducible and then proceed to prove it if the R and D organization does not keep close watch and exert sufficient educational pressure through liaison. On the other end of the scale, a very poorly done design and development job will be perceived as poor, no matter how much liaison effort is expended. Thus, the curve representing the amount of liaison effort necessary to achieve normal quality will vary with the quality of the laboratory's output, as shown in Figure II-8.

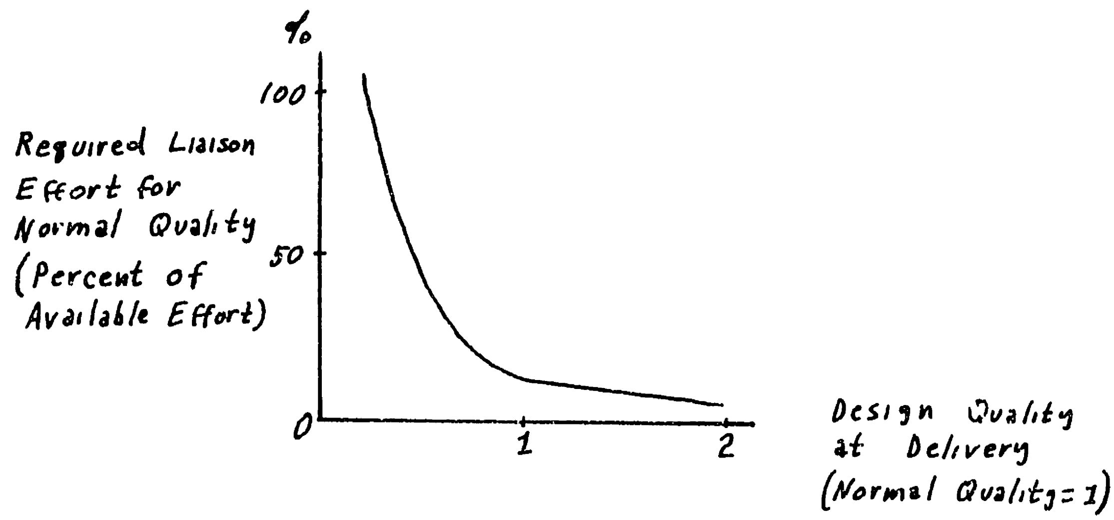

Figure II-8: Required Liaison for Normal Quality

With the above concept describing the necessary liaison effort for normal quality, it is easy to see that the actual quality of work in liaison will depend on the amount of actual liaison effort compared to that necessary. The perception of final quality by the customer tends to feed back to the laboratory and thus helps to determine the pressure for production liaison effort as well as internal quality effort, thus completing one of the many feedback loops present in the research and development system.

Chapter III: Technical Manpower

In this chapter, the processes by which the R and D organization hires, trains, and fires people will be discussed, as well as the factors which determine the effective number of personnel available at any one time.

Personnel Flow

We shall first concern ourselves with the actual physical flow of technical personnel. A general representation for both advanced research and design and development personnel will be developed first, and then the differences and interaction between the two types will be discussed.

When technical people are hired, they do not become immediately effective. They must first undergo a period of relatively low effectiveness while they learn what the job is all about. Thus, there is a learning or training delay before newly hired people become fully effective members of the organization. We can visualize the physical flow of personnel by first thinking in terms of a pool of trained technical personnel, which is experiencing simultaneous inflows and outflows of people. The inflow would consist of people leaving the training or learning period, and the outflow would consist of personnel leaving the laboratory of their own volition (attrition) and personnel leaving involuntarily. Figure III-1 illustrates this physical flow.

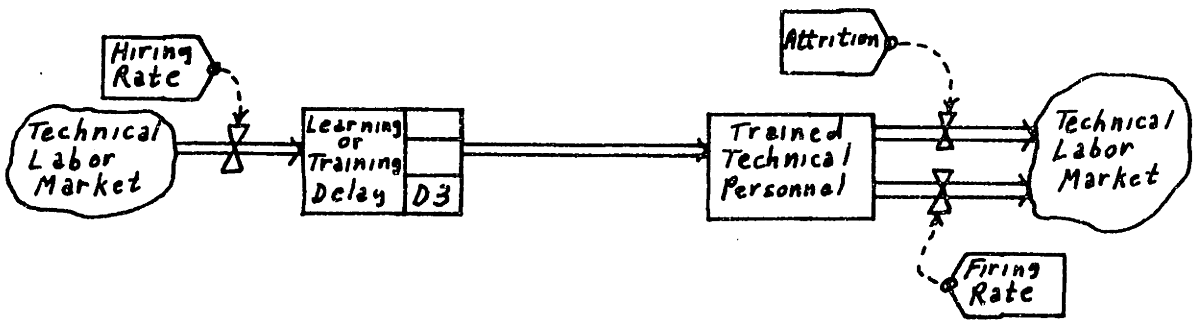

Figure III-1: Physical Personnel Flow

Learning Period, or Training Delay

It is important to emphasize that when one is talking about a learning period, this is not the same thing as the period spent in a formal training program. The product of a formal training program still knows relatively little about company organization or his work requirements. Typically, the newly hired engineer enters the organization, sits around for a few weeks doing nothing until he receives a security clearance (at least this is the case for defense contractors), then finally begins to learn something once he obtains access to classified reports. The usual procedure is not to have a formal training program, but to start the new engineer off on a job that he can handle, ie., one fairly congruent with his background. Then, by working on jobs of increasing complexity, the new engineer gradually learns about the organization, about the requirements of his job, about the new skills he must pick up, and about the short cuts that the organization will allow him to take. The new engineer gradually grows in effectiveness and it is usually estimated that he reaches the average effectiveness of the organization in from three or six months to one and a half or two years. His progress might be as depicted by the learning curve shown in Figure III-2.

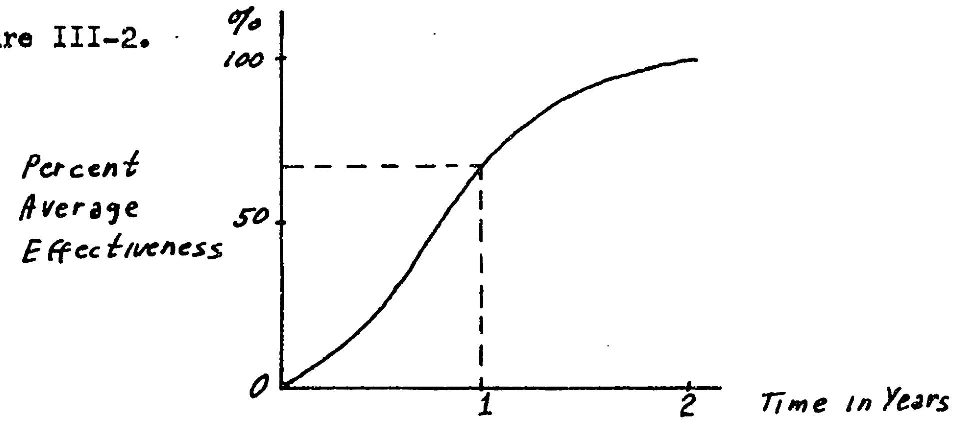

Figure III-2: Technical Personnel Learning Curve

Whenever this idea of a learning curve is presented, someone will object on the grounds that the curve depends on the individual hired. In other words, the experienced engineer will have a much shorter learning period than the engineer fresh out of college. This is, of course, a valid objection, and can only be countered in this case by restating the goals of the study. Since the goal is to examine the behavior of the R and D organization from the over-all or aggregate point of view, it is necessary to think in terms of the average engineer and the average learning curve. To attempt to distinguish between individual people and individual contracts would lead to a representation of such complexity that it would have no advantage over the actual real world framework. It can be further argued that the over-all organizational behavior is not affected any differently by myriad individual learning curves than it is by the aggregate curve which represents the average of all the individual learning curves.

Note that the implication of the learning curve in Figure III-2 is that the new engineer gradually reaches average effectiveness over a period of time. He does not enter the organization and then after a period of time suddenly rise from zero to average effectiveness. This concept can be represented by having him gradually leave the training or learning delay. A possible scheme is to make the outflow of the delay a third order exponentially delayed version of the inflow. The outflow, given a one man impulse and a third order delayed output, would look like the curve in Figure III-3. Such an outflow would result in the level of trained personnel increasing in the manner of the curve shown in Figure III-2.

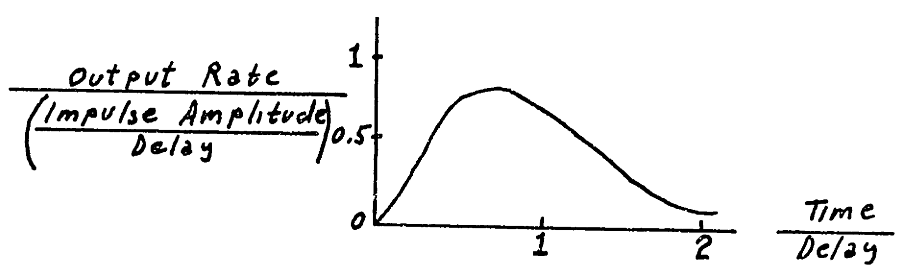

Figure III-3: Response of Third Order Delay to a Unit Impulse[1]

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1 For an explanation of third order delays, see: Forrester, <u>Industrial Dynamics</u>, MIT Press, 1961, Chapter 9 and Appendix H.

Effective Trained Personnel

People leaving the training delay enter the pool of trained technical manpower. It is people in this pool or category who perform the technical effort of the organization. However, the entire pool of trained technical manpower is not available for pure technical effort. Various administrative activities are required to help the R and D organization function. Certainly many different activities which prevent technical effort could be suggested, but we are interested only in the ones which are important to dynamic system behavior. Thus, activities such as report writing and traveling will be ignored. The activities to be included in a representation of the organization are those which vary with important dynamic variables. Three such activities are 1). hiring, 2). training, and 3). marketing effort.

Hiring and training activities are included because they act to reduce the effective number of people precisely at the point when the organization needs people the most. (ie., during expansion in size.) Hiring activities on the part of the engineer do not take up a major part of his time since administrative and staff personnel will do most of the work. However, when hiring for technical jobs, it is necessary to check on the technical competence of the applicant, and this is best done through interviews with engineers in the relevant fields of work. Such interviews then require time spent on evaluation of the interview and then on communication with the members of management involved. It can also be expected that as the expansion rate of the organization increases, the time spent by technical personnel on hiring activities will increase more than linearly, due to strains on administrative personnel. A curve illustrating the percent of technical manpower time spent on hiring activities versus the percent expansion per year is shown in Figure III-4.

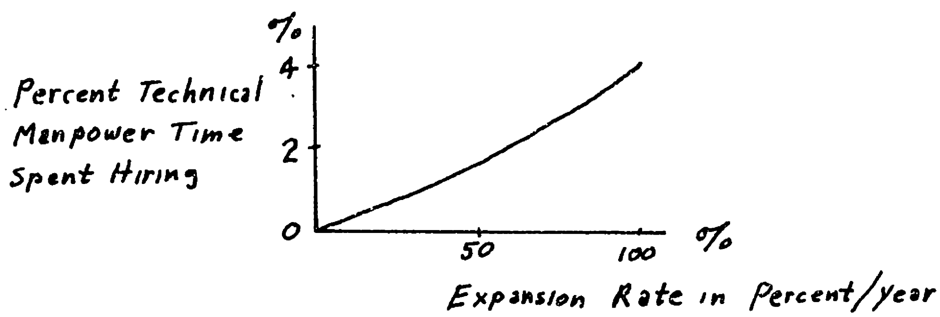

Figure III-4: % Tec'nical Manpower Time Spent Hiring versus Expansion Rate

Training activities can be expected to be much more demanding of technical manpower time than hiring since with or without a formal training program, the new engineer essentially learns the ropes by asking questions. Such a process of what one might call accidental indoctrination works fairly well if the number of new personnel is small compared to the size of the organization. However, as the percentage of trainees rises, the efficiency of experienced personnel begins to drop off more than linearly due to foul-ups caused by the lack of knowledge of the new people. Also, lessons learned by the new personnel are not retained as well because there is less exposure to experienced people acting in a way which can be seen as utilizing the new information. Thus, when new people enter the organization, there is a drop in the number of effective people due to 1). training activities and 2). a decrease in organizational efficiency. Figure III-5 illustrates this phenomenon by plotting percent efficiency of trained personnel versus the percent of untrained personnel in the organization.

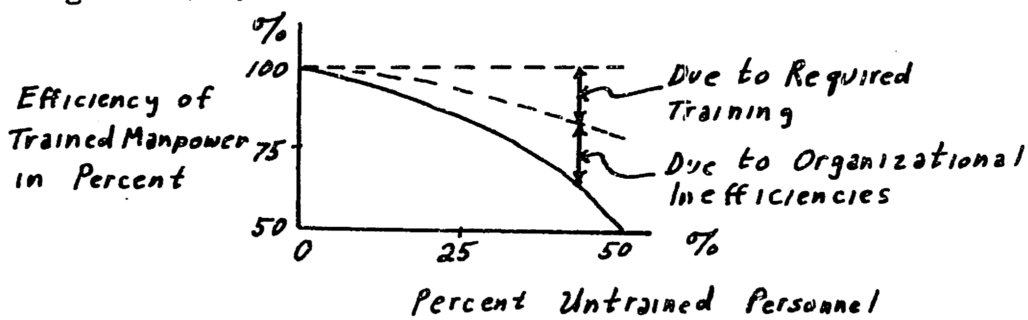

Figure III-5: Effect of Untrained Personnel on Efficiency of Trained Personnel

Thus far we have discussed the reduction in efficiency of the average engineer due to hiring and training activities. It is obvious that an equivalent way of describing this situation in the aggregate is to regard it as reducing the number of effective technical personnel available to the organization.

Marketing Effort

Marketing effort is another activity which tends to reduce the effectiveness of technical personnel with respect to technical effort. The decision regarding the amount of marketing effort to be spent and the effect of such effort on the customer will be discussed in Chapters VI and V, respectively. Assuming then, that the decision to expend marketing effort has been made, what effect does this have on the engineer? Marketing effort consists in part of time spent by top management and/or sales personnel in visiting potential customers and either searching out promising situations for R and D work or presenting general proposals for work. However, an R and D organization is selling its technical competence, and administrative personnel are not able to completely convey a realistic picture. This is why in many situations where possible work has been discovered, the R and D organization is requested to submit a proposal, so that the prospective customer can better evaluate the organization's capabilities. Proposals are usually based upon past work, whether it was a development contract or a study contract, and for clarity and efficiency must be written by someone close to the previous job. This is usually someone with technical responsibilities who would otherwise be doing creative technical work. Thus, marketing effort requires technical personnel to spend unproductive time essentially recapitulating past work by writing proposals. Also, time may be spent talking to management or even the prospective customer. An organization expending effort towards seeking new contracts can be expected, then, to be reducing the effective number of technical personnel available for technical effort.

This discussion of various activities which act to lessen the number of effective technical personnel in an organization essentially completes the discussion of the flow of people through the organization. (Except for a flow resulting from the difference between advanced research and design and development to be discussed later.) Next, a framework for representing the hiring and firing decision will be presented.

The Manpower Level Decision

One of the most important decisions made by an R and D organization is the decision concerning future technical manpower needs. The importance of this decision is a result mainly of the large expenditure of time and effort necessary to develop a competent, experienced engineer. The R and D organization is not usually able to increase its capacity while maintaining its technical competence merely by hiring new people. As discussed above, new people require training and actually reduce the efficiency of experienced people when they enter the organization. Thus it is important for the organization to be able to judge future manpower requirements far enough ahead so that people can be hired and trained. It is, however, a well known fact that this is not the way most organizations operate. They do not commit themselves to an expansion program until the expected work has actually been awarded, and thus lose a significant amount of time while new people are hired and trained. Because of the large investment necessary to acquire and develop additional technical personnel, the R and D organization is usually unwilling to make a move until the need is definite.

In the opposite situation, the typical R and D organization is motivated to keep on experienced personnel, even when there is no work for them. It is obviously cheaper up to a certain point to carry experienced unoccupied personnel on the payroll until work can be obtained rather than to fire them and have to invest time and expenditures in training new people when new work is obtained. Here again, the forecast of future work is of utmost importance in determining which course of action would be best. Usually, however, no one is laid off even if very little additional work is visible in the future, because the organization feels that the new job is probably just around the corner.

From strictly a cost point of view, it might appear that top management should have the most control over change of manpower decisions. Although such a policy might be stated or implied, it usually is not the case, however. Groups or projects determine their future manpower needs, often utilizing relatively little information, and on this basis hire if necessary. On the other hand, if forecasts indicate that fewer people will be needed, a well known principle comes into effect. The present work expands to the point where it requires all of the present personnel for its completion. This phenomenon is, of course, a result of the group leader's hoarding instinct. He is able to rationalize such a decision on the basis of his need to outperform other groups as well as his need to perform well on possible future work. The important result of having project groups primarily responsible for hiring and firing policy is that a much larger amount of hoarding is possible since many people are each contributing a little. Much less hoarding would be tolerated if top management were more active in the personnel decision, but the nature of a large R and D organization results in a situation where top management lacks the knowledge of technical requirements and the time necessary to make the actual decision. About all they can do is to attempt to control the situation, but this is usually pretty ineffective since group leaders can easily create needs for existing personnel by coming up with new research ideas or by claiming that they are needed on present programs.

A Conceptual Framework for the Manpower Decision

The fact that the decision to change the level of technical manpower in an R and D organization is usually the resultant of many small internal decisions does not limit our ability to develop a framework for the aggregate decision, however. The small decisions are all being made in the same manner and thus can be represented by a single aggregated decision. Essentially, the manpower decision is made by examining the forecast for future work and from this determining the desired level of technical manpower. The desired level of technical manpower is then compared (at least implicitly) to the actual level, and if a difference exists, this difference is corrected over a period of time by either hiring, firing, or just allowing attrition to take its toll. It might be argued that no one ever goes through such an organized process of making this decision. However, merely estimating whether present personnel can handle future expected work implies such a process, although all the steps may not be explicitly thought out.

As mentioned above, the typical R and D manager is reluctant to let people go even when they are not needed. This means that the response to an observed surplus of manpower will be much less than the response to an equal deficit of manpower. This effect can be illustrated by the hypothetical curve in Figure III-6 which plots a possible organizational policy for expanding or decreasing the size of the organization versus the ratio of desired to actual manpower.

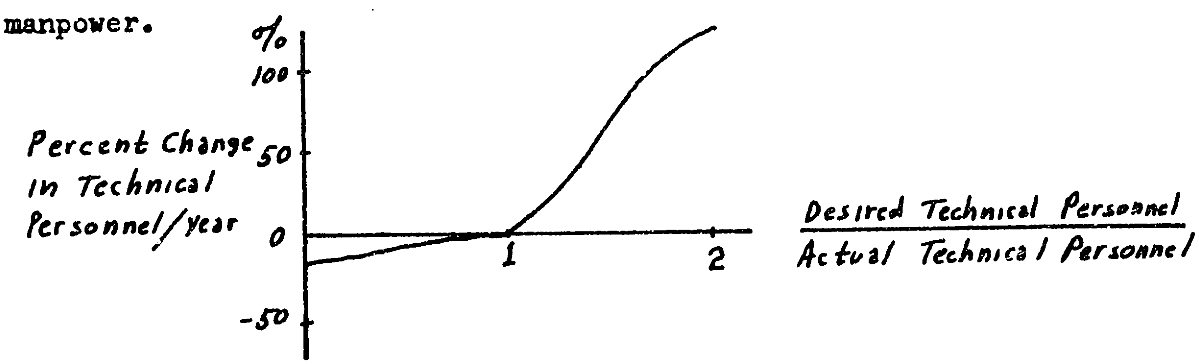

Figure III-6: Percent Change in Organizational Size/Year versus Desired to Actual Technical Personnel Ratio

It is important to remember that people leaving the organization because they have been fired are not the only ones leaving. Regardless of the policy for increasing or decreasing the size of the organization, some personnel will be leaving due to personal reasons, retirement, or death. Exclusive of people fired, it is possible to find the average employment period for technical personnel. If, for example, an average employment period of ten years were found, this would mean that one tenth of the technical people employed left each year, exclusive of organizational hirings or firings. Hirings or firings merely increase or decrease the effective rate at which technical personnel enter or leave the organization. It is because of this factor that manpower hoarding is not always as expensive as it might seem. Also, this fact allows many organizations to adopt a no-firing policy, since they are able to decrease the size of the organization when necessary merely by allowing attrition to take its toll.

There is another important idea with respect to firing policy that should be considered. Many organizations will deny that they ever fire anyone except for gross negligence. Yet, it is quite obvious that the rate of people leaving, or the average employment period, varies to a large extent over the years. This can be explained by the fact that the technical personnel themselves can sense whether the organization is going up or down. An engineer who is "sitting on his hands" is quite likely to begin looking for a more satisfying job. And although the organization does not fire anyone, in periods of slack they do not go to any pains to keep people from leaving, either. Thus, in a highly technical field where professional achievement is often just as important to a man as salary, it is often unnecessary to ever fire a man, since he will have left long before that task becomes necessary.

The actual mechanisms by which an organization corrects for differences between desired and actual levels of technical manpower have been discussed above. Now, it is time to turn to the actual determination of the desired level of manpower. This process can best be represented by using some of the same concepts developed in Chapter II for determination of the allocation of time to volume effort. The volume effort decision was made by comparing the desired backlog or level of funding to the actual backlog, and on the basis of this comparison generating a pressure for volume effort which was resolved with a corresponding pressure for quality effort. The level of desired manpower, on the other hand, is derived by first deciding on the amount of work to be done in a certain time. This is equivalent to deciding on a desired rate for the R and D organization to finish work. This desired rate is made up of two components, one equal to the incoming rate of contract awards, and the second equal to a rate designed to correct the level of funding to that desired. The first component is self-explanatory. The organization obviously wants to finish incoming work and will attempt to do so within a reasonable period of time. The second component, however, is a bit more complicated. Suppose work is being performed at a rate equal to that of incoming awards, but that the level of funding or years of work in the organization is lower than that desired. Then the organization will, among other things, slow down a bit in an effort to build up the level of funding. Obviously other responses aiming towards increasing awards are also possible. The phenomenon of changing the effort rate in order to correct the backlog towards that desired can, of course, work in both directions, and the desired rate of performing work may be greater or less than the award rate, depending on the funding situation.

Once a desired rate of effort has been determined, it is compared by management to the perceived productivity of technical manpower, and the desired level of manpower is determined. At this point, an objection against the ability of management to know the productivity of an engineer will undoubtedly arise. It is true that if one asks an engineering manager what the productivity of his average engineer is, he will probably laugh at you. But in the next minute, he will with a straight face tell you that it will probably take three engineers six months to finish the X contract. Such a statement involves an implicit judgment of the productivity of his engineers. It must not be forgotten then, that in many cases, the conceptual framework being presented includes explicit representations of implicit decisions or opinions. Whether a decision is made explicitly or implicitly, it must be included in the framework being discussed if a valid result is hoped for.

A recapitulation of the manpower decision would be as follows: Management (group leaders) decides on a rate at which work is to be done. This rate is set so as to handle the present award rate and to correct the level of funding to that desired over a period of time. The desired rate of effort is then compared with the perceived productivity of the average engineer in order to get the desired level of technical manpower. The desired manpower level is finally compared with the actual manpower level to determine the hiring or firing policy.

Chapter IV: Technical Effectiveness

Technical effectiveness is a characteristic of research and development organizations which describes their capability to perform technical work. More specifically, it describes the capability of the average engineer in the organization to perform technical work and depends mainly on the amount and type of the past work experience of present personnel with respect to present work requirements. Technical effectiveness should, however, be distinguished from that capability resulting from having a certain amount of trained technical manpower ready to be called upon for technical effort. It is instead a measure of the technical ability of the members of the R and D organization.

Technical effectiveness is an important variable in so many parts of the system under study that it can be identified as one of the major determinants of the dynamic behavior of the R and D system. First, it affects the organization's ability to perform volume and quality effort, as was described in Chapter II. Second, it is perceived by the customer who takes it into account in making his contract award decision. A name the customer might more often use than technical effectiveness would be technical reputation. Third, technical effectiveness has an important effect on several managerial decisions. It affects perceived productivity which is important in determining the desired level of technical manpower.

It also has an important effect on the amount of marketing effort exerted by the organization. As will be explained in Chapter VI, management has several alternatives as to how it allows technical effectiveness to influence marketing effort. Management can either try to take advantage of increasing technical effectiveness by increasing marketing effort when technical effectiveness rises, or it may try to further improve the technical reputation of the laboratory by decreasing marketing effort and waiting for the better contracts. The results of these two policies will be compared in Chapter VII.

Effective Technical Knowledge

The above discussion has presented the general characteristics and major effects of technical effectiveness. To gain further understanding, however, it will be necessary to develop a more precise conceptual framework. Work done by the R and D organization generates knowledge and experience, which, after a delay, become useful to the organization for performing new work. The knowledge becoming available to the R and D organization because of past experience can be visualized as flowing into a pool of effective knowledge. This pool of knowledge is a measure of the amount of knowledge held by the organization that is effective at any one time. It must be remembered that the size of the pool of effective knowledge is not the only determinant of technical effectiveness. Present work requirements and the size of the organization will also have an important effect. Discussion of the actual determination of technical effectiveness will be deferred, however, until after the factors contributing to the size of the pool of effective knowledge have been examined.

The main factors effecting the size of the pool of effective knowledge can be divided into inflows and outflows of knowledge. The inflows consist of knowledge becoming effective because of past work and of knowledge being brought in by new people entering the organization. Outflows consist of knowledge becoming obsolete, and knowledge leaving with people who are leaving the organization. Figure IV-1 is a simple diagram depicting the major determinants of technical effectiveness.

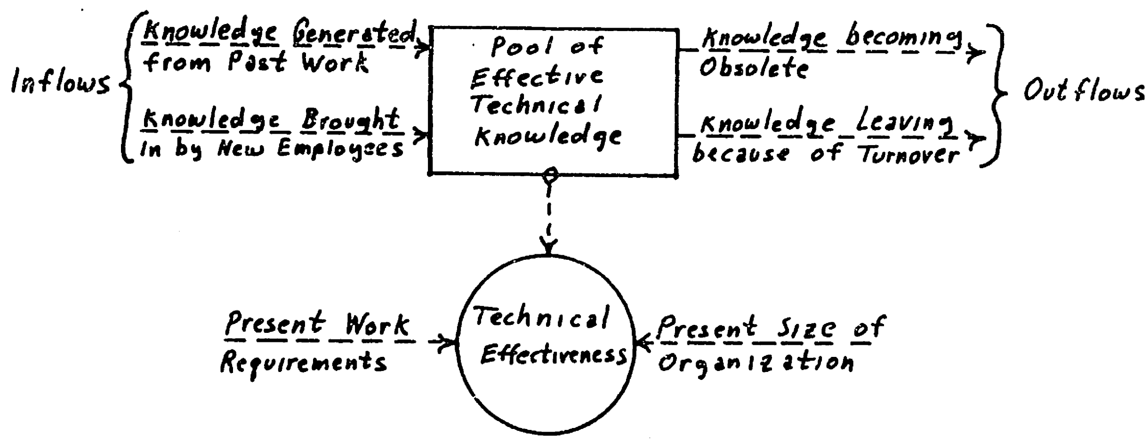

Figure IV-1: Generation of Technical Effectiveness

Generation of technical knowledge will depend on the amount and type of past work. Work in advanced research will generate the most knowledge since this kind of work usually borders on the state of the art. Successful work in this area gives an organization knowledge its competitors do not have, and is very effective in producing capability to handle future work. Design and development work will not contribute as much to technical knowledge since it involves using existing principles and techniques to develop operational hardware. This kind of work usually does not advance the state of the art to any great extent, but rather develops capabilities to handle present work requirements. Too much concentration in this type of work by an organization will result in definite drop in technical effectiveness over time as new concepts and techniques result in the obsolescence of the ones in which the firm is experienced. Liaison effort contributes very little to technical effectiveness since it is merely effort to pass on information about finished work to the customer or a production contractor. Very seldom are new ideas developed in this kind of work.

There is another concept that is important in the generation of technical effort. Work performed in advanced research, for example, does not become immediately effective towards present work requirements. There is a definite delay which occurs for several reasons. One is that a new concept or technique is never immediately accepted by an organization, even if originated by its own scientists. The management and even the rank and file engineers must be shown the validity and applicability of the new idea, and this takes time. A second reason is that the customer will also treat new concepts and techniques with some wariness, and thus will not fund further work until he is convinced of the worth of the research. Thus, new ideas take time to be accepted, which time is in addition to that time necessary to develop a new theory into an applicable technique. There will also be a delay, albeit a shorter one, before design and development work results in knowledge becoming useful to the organization. This delay might be better described as being due to the time lag necessary for experience on a design and development job to result in improved techniques that will eliminate some of the previously experienced problems. The time lag connected with liaison effort is, however, very short, since the feedback about design performance is met very quickly by corrective action. The reasons for the delay in technical effort producing effective knowledge are thus many fold, but it is obvious that they exist.

The two concepts presented above, that of different relative amounts of technical knowledge being produced by different kinds of technical effort, and that of different delays for effort to result in effective knowledge, are presented pictorially in Figure IV-2. Assuming a unit impulse of technical effort for each of the three kinds of effort discussed, the resulting inflows of technical knowledge into the pool of effective knowledge are plotted versus time. The relative peaks of the different curves indicate the relative contributions of different kinds of technical effort, while the time to each peak is indicative of the average time for effort to become effective. Note that the delay for knowledge to become effective is not a discrete one, but a distributed one. The inflow of effective knowledge arising from past effort will occur over a period of time, thus signifying that new ideas gradually become useful, instead of becoming useful all at once.

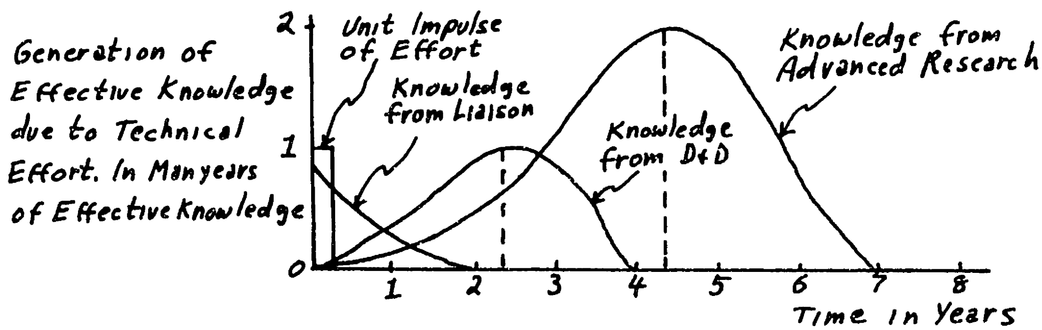

Figure IV-2: Generation of Effective Knowledge through Technical Effort

Knowledge newly contributed to the organization will not remain effective forever. Due to the constantly high rate of technological advancement in the whole economy, knowledge will have a certain period of effective applicability to current problems, after which it becomes obsolete. Thus, one of the important outflows of the pool of effective knowledge is due to obsolescence of knowledge. Knowledge is probably effective for an average period of about ten years, although this period is rapidly growing shorter as the rate of technological advancement in the economy increases. It is quite possible that in R and D work, the period of effectiveness is already significantly less than ten years.

The pool of effective knowledge is also affected by the rates at which technical personnel enter and leave the organization. Personnel leaving the organization carry away their own personal experience with past work, thus lowering the pool of effective knowledge. Personnel entering the organization bring in new knowledge, but this knowledge is not usually as high on the average as what might have been gained through direct experience with the previous work of the firm. Thus personnel entering the organization will bring in less knowledge than personnel leaving will take away. It is evident from this point of view above that it is to an R and D organization's advantage to limit turnover as much as possible.

Technical Effectiveness

It was mentioned earlier that the pool of effective knowledge is not the sole determinant of the technical effectiveness of an organization. The size of the organization and the requirements of present work also are important. The effect of the size of the organization will be discussed first. The pool of effective knowledge represents a finite amount of experience and ideas generated through past work. This experience is, however, held in the minds of the technical personnel of the organization, each of whom can be visualized as having the average amount of experience that would result if the total pool of knowledge were distributed evenly throughout the organization. Of course, this is not true in the real world since some people will have more experience and technical capabilities than others, but the capability of an organization must be judged by the average capability of each of its members.

The other important determinant of technical effectiveness is the requirements of present work. In a rapidly advancing technology, the work requirements may change so much in a short time that the past experience of the R and D organization will not be adequate or particularly relevant. There are two types of phenomena that might operate here. First, the technical demands of present work might be increasing at a faster rate than the organization can generate technical knowledge. The result of such a situation is a decline in the effectiveness of the organization which can eventually lead to collapse and bankruptcy. The other phenomenon might result from an attempted change in the kind of work the R and D organization wants to do. For example, an R and D laboratory experiencing difficulties might attempt to enter a new field in an effort to improve its fortunes. This is usually unsuccessful, however, since if the new field is at all different from the laboratory's old one, much of its stored-up experience and knowledge will be useless. The knowledge and experience of the R and D organization must be applicable to the kind of work at hand in order for the organization to be technically competent enough to be competitive.

Therefore, technical effectiveness of an organization will depend on a comparison of the knowledge and experience of the average engineer with the complexity and type of technical requirements presented by present work.

Chapter V. The R and D Market

Contract awards are the life blood of the research and development laboratory. Unless funded work is supplied to the laboratory, it cannot long exist. Thus, the market sector of the system under study is of utmost importance. In the market sector, the customer evaluates laboratory performance and proposals, and estimates future capabilities with the purpose of determining future awards. The basic structure of the market interaction between the R and D laboratory and the customer is shown in Figure V-1.

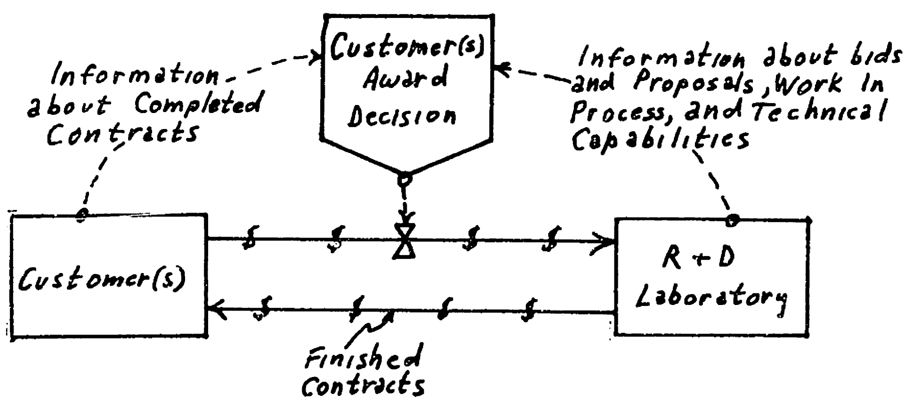

Figure V-1: The R and D Market

As indicated by Figure V-1, the customer takes many different kinds of information into account when making his award decision. He is interested in the quality of work he can expect, in how much the job will cost and how long it will take, in the technical reputation and market share of the laboratory, and in the quality of the proposal presented by the laboratory. Knowledge about these many different factors is brought together, and the customer makes his award decision based on the sum total of this information. All the factors important to the customer award decision are continuously interacting, thus making it hard to pick out at any one time the factors having the most significant effect on awards. In this chapter, however, a conceptual framework has been used that allows examination of each single factor separate from its fellows. Each factor, such as perceived quality of past work, is examined under the assumption that all other factors important to awards remain constant. The effect of variations of the factor under study on awards can be presented in terms of the fraction or percent of an optimal flow of awards that the organization is receiving. For example, a high perceived quality of past work will result in a high percent of the optimal award rate being received, while a low perceived quality will result in a low percent being received. The effect of variations in perceived quality can be presented as a curve of the percent optimal award rate versus perceived quality. (See Figure V-2.) The actual award rate for any given set of conditions can be found by multiplying the various percent optimal award rates and the optimal award rate. Thus, the different factors can be separated for analysis, and later combined to give the cumulative effect on awards.

One of the most important factors affecting contract awards is the expectation by the customer of the quality of work the organization is capable of turning out. There are essentially three things which determine this expectation, the customer's perception of the quality of past work, the technical reputation of the laboratory, and the quality of the technical proposal submitted by the laboratory. Although these three concepts are somewhat interrelated, they can be separated in the following manner. Direct experience with work of a laboratory will result in an estimate of the quality to be expected in future work. This, however, can be modified by the technical reputation held by the organization throughout the industry. The technical reputation will depend on the history of the laboratory with respect to advancing the state of the art. A high technical reputation implies the ability to perform a high quality job on present requirements because of knowledge of the state of the art. However, the capability to perform a good job does not necessarily lead to good performance. The organization might possibly spread its technical manpower too thinly, and consequently do a poor job. Thus, both perceived quality of past work and perceived technical effectiveness will determine the customer's expectation of the quality of future work. The quality of the technical proposal will depend on the allocation of marketing effort, a concept to be discussed later.

A more explicit representation for the two concepts presented above will now be given. The customer's perception of the quality of work being produced by the organization depends primarily on the quality of the work previously delivered to the customer. Chapter II stated that design and development contracts require liaison activity and that the actual quality of the work may differ from the perceived quality if liaison effort is more or less than necessary.

A laboratory may do a good design job, but lose future contracts because insufficient liaison activity leads to customer perception that the job is worse than it actually is. The fact that the customer perceives a certain quality of work being performed by the organization implies that he has a certain inclination towards awarding new contracts which depends on this perception. If this is approached from the R and D laboratory's point of view, the laboratory can be visualized as receiving a certain share of an optimal number of contracts, the share depending on the perceived quality of present work. Figure V-2 illustrates this concept. The percent of the possible contract award rate is plotted versus a ratio of perceived quality to a standard quality. The standard quality may be visualized as the standard or average of the industry. Since it is always possible to do better than average, the fraction of awards will increase as quality gets higher, but the curve eventually saturates since at some point, quality will be so high that it will no longer act as a limitation on awards, although other factors will presumably still be limiting. On the other end of the scale, the percentage drops to zero at a finite quality, since below some quality performance the resulting work will be so poor that no one will want it.

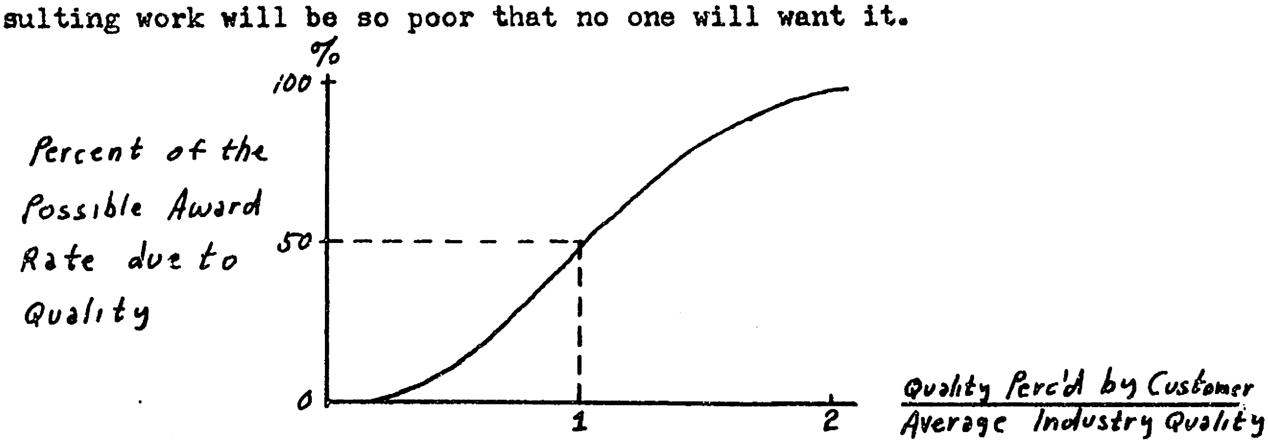

Figure V-2: Fraction Possible Contract Awards due to Quality perceived by the Customer

As suggested above, perceived technical effectiveness is a good measure of the long range technical reputation of a laboratory, especially since technical effectiveness depends primarily on past work performed by the laboratory. Variations of perceived technical effectiveness will affect the award rate as shown in Figure V-3.

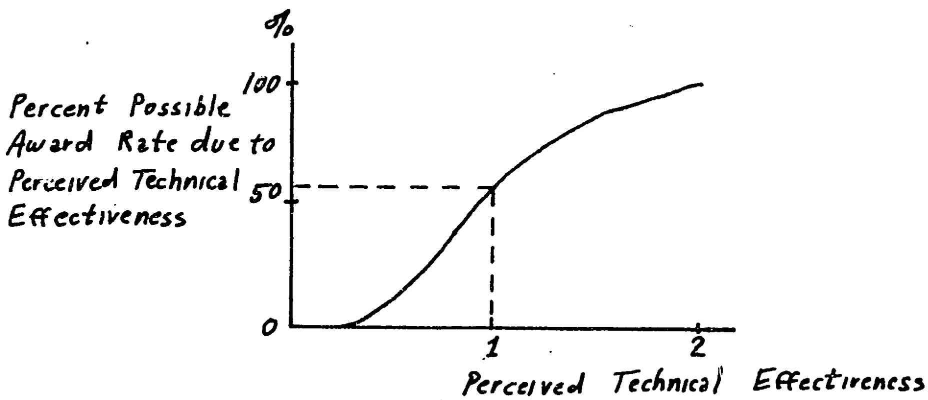

Figure V-3: Percent Contract Awards due to Technical Effectiveness

A technical effectiveness of one is defined as representing the technical capability necessary to do a satisfactory job on present work requirements. A technical effectiveness of greater than one represents the ability to do a better than satisfactory job, and vice versa for less than one. This curve saturates at both ends for the same reasons that the fraction awards due to quality curve saturated.

Two other important factors which the customer takes into account when making his award decision are cost and time to deliver. There are two dimensions to both of these considerations. The customer at any one time will have an expected figure for future costs or delivery time. This expected figure is the basis of two comparisons, one with the cost or delivery performance promised by the R and D organization, and one with the average or standard industry performance. Forgetting for the moment how the customer arrives at his estimate for project costs or delivery times, let us investigate these two comparisons. The logic of a comparison of an expected cost or delivery time to an industry average or standard is readily apparent. If there is someone who can do the job faster or cheaper, all other things being equal, they will get the job. Thus, as the delivery delay or cost performance of an R and D organization becomes worse than average, awards will decrease, and vice versa. This concept is illustrated in Figures V-4 and V-5. Note that some awards can

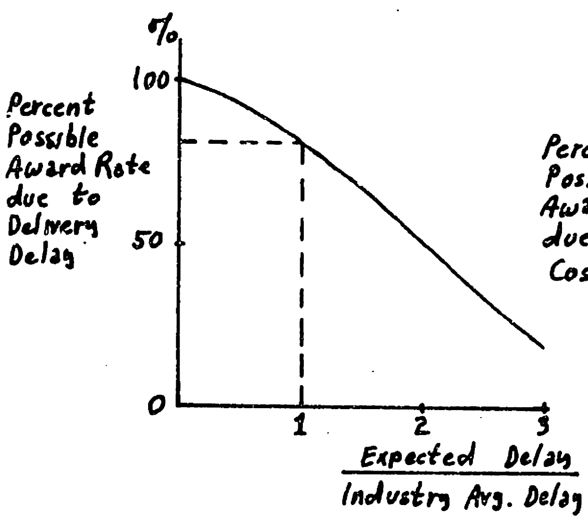

Figure V-4: Percent Contract Award due to Delivery Delay

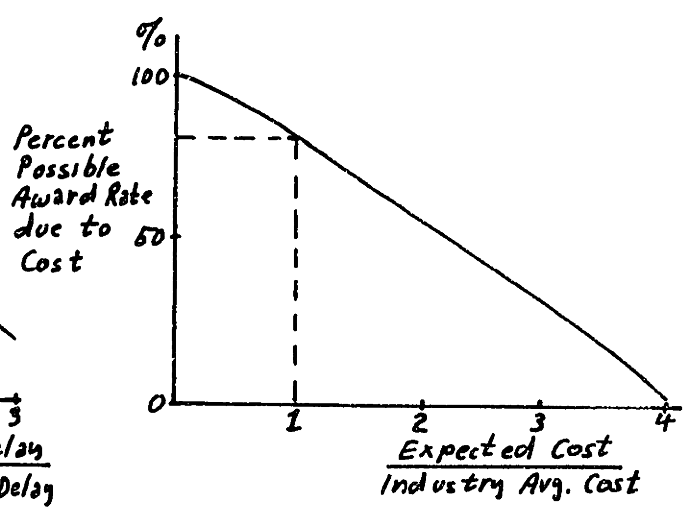

Figure V-5: Percent Contract Awards due to Cost Performance

be gained by doing better than the rest of the industry, but that poor delivery or cost performance have much more potential for decreasing awards than good performance has for increasing them.

The other comparison made by the customer with respect to costs and delays is that of the expected figure with the figure promised by the laboratory. If the cost and delivery time promised by the R and D organization differs markedly from that expected by the customer, contract awards will be affected. This effect is one quite apart from that caused by comparisons to average industry figures. A possible curve for representing this phenomenon is shown in Figure V-6. This curve describes the fraction of possible contracts awarded due to the customer's comparison of promised to expected cost. The delivery time curve would be quite similar. Note that maximum contracts are awarded with approximately a 20%

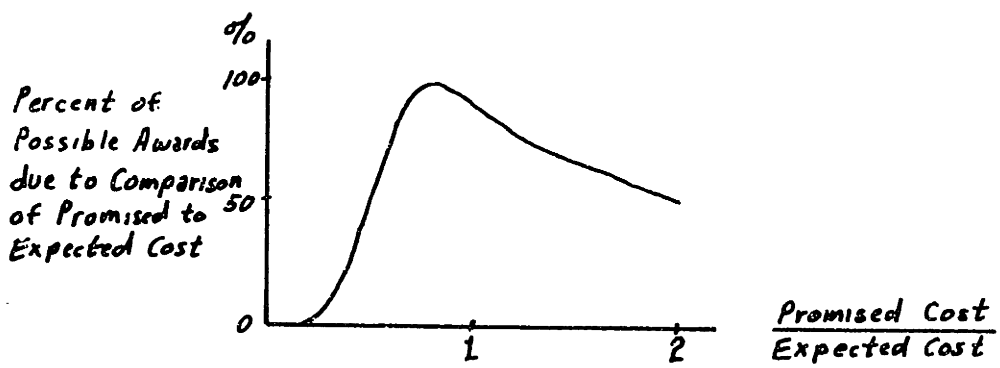

Figure V-6: Variation in Contract Awards due to Comparison of Promised To Expected Costs

understatement of costs. This reflects the fact that a certain amount of cost overrun is expected, and that a firm can be penalized for being truthful since other firms will underbid it. The fact that firms with low bids do not expect to meet costs, and that the customer does not expect them to meet costs either, does not seem to matter. Note, however, that if bids get too far out of line on the low side (ie., promised costs become much less than expected costs), awards drop off sharply. This is because beyond a certain point, it becomes obvious to the customer that the bidding firm is being unrealistic and that the quality of the work will probably suffer. As bids become pessimistic, awards drop off, but not a great deal. Limitations on awards here will result mainly from a comparison of expected costs to the industry average, rather than from a comparison of promised to actual costs.

As a clarification of the above point, it is necessary to describe how the customer determines the figures he expects for costs and delays. The expected figure is determined mainly by two things, 1.) the experience of the customer with respect to past cost and delivery performance of the organization and 2.) the figures promised or bid. The relative weighting of these two factors will depend on past experience with the integrity of the organization and on the type of work involved. It is now possible to see that as bids become pessimistic, the expected costs or delays will increase and the primary limitation on awards will result from a comparison of expected figures to industry standards. On the other hand, with very optimistic bids, the primary limitation arises from a comparison of promised to expected figures.

How the R and D organization arrives at the decision to submit a pessimistic or optimistic bid will be explained in Chapter VI. Briefly, however, any organization possesses a characteristic called integrity which determines how the organization makes its bids in response to internal stresses. For example, if there is not enough work to keep everyone employed by the organization busy, there will be a tendency to lower bids in an attempt to get work. The extent to which an organization succumbs to this temptation is determined by the amount of work needed and the integrity of the organization.

The R and D organization has another way of adjusting to internal pressures for more or less work. This is by changing the amount of marketing effort exerted. Marketing effort includes all effort expended towards gaining new contracts. Trips to seek out new areas for the organization to work in and proposal preparation and presentation are examples. An increase of marketing effort will increase contract awards up to a certain point. Of course, if work quality is bad, increased marketing effort will not help awards to any great extent, but all other things being equal, increasing it will increase awards and decreasing it will decrease awards. Marketing effort cannot rank as one of the most important factors affecting contract awards since the customer is primarily interested in results, but it certainly has a significant effect. It must also be remembered that a change in marketing effort will not lead to an immediate change in awards since there is a delay before such effort has any effect.

Another factor affecting the contracts awarded to an R and D organization is the market share held by the organization. At the present time, the government is the biggest single customer of R and D organizations, and the government definitely has a policy of spreading work around in an attempt to stimulate all areas of the economy. As an R and D organization performs better and better, its market share will tend to increase. As the share increases, however, there is an inhibiting effect on contract awards due to the government's policy of trying to spread the work around. This factor has limited effect since it is obvious that the vastly superior firm will get most of the work even over industry protests (for example, the Instrumentation Laboratory at MIT dominates the inertial guidance field due mainly to ability to perform an excellent job). However, given two firms of equal ability, the customer will tend to award a job to the one with the lower market share. Thus, in the middle range, the effect of market share is significant.

Award Factors Dependent on the Type of Work

There are several differences in the factors which affect awards of advanced research and design and development contracts. Advanced research contracts usually involve work that borders on the state of the art. Typically, there has been little or no previous experience with this kind of work and as a result the customer is not able to compare expected costs and delivery times with an industry standard or average. He is still able to form an expectation of cost or delivery time from previous experience with the firm in other kinds of work that may be related and from the performance promised, however. This allows the comparison between promised and expected values to be made, but essentially because of the lack of knowledge associated with new work, this comparison is only an indication of the integrity of the firm. Thus, the customer in considering cost and time estimates for advanced research programs, is essentially forced to take into account primarily the integrity of the firm with which he is dealing.

With design and development contracts, the customer has many more factors to consider. Since design and development usually involves application of existing state of the art techniques, there exists a reservoir of experience with the kind of work at hand to draw upon. The prospective design and development customer can help his decision by judging the previous experience of the firm under consideration in the type of work to be awarded. It is generally true that the best design and development work is done by the same organization which performed the original advanced research on the concepts and techniques involved. Experience in advancing the state of the art is perhaps the most effective generator of technical effectiveness in a field. Therefore, the customer considering the award of a design and development contract will certainly take into account the amount of successful advanced research work performed in the field by the organization under consideration.

In summary, the market sector of the R and D laboratory - customer system under study describes the interaction between the laboratory and the customer. It is here that the customer takes into account the factors important to determining his award decision, and then makes the contract awards. The factors important to the decision will vary with the type of work involved, and the actual factors which limit awards to a certain laboratory will vary with the performance of the laboratory.

Chapter VI: Management Decision Sector

Several decisions made by the higher levels of management in the typical R and D laboratory have significant effect on the dynamic behavior of the system and therefore should be included in the conceptual framework being presented. Three major decisions should be considered, 1.) the decision on the desired level of technical manpower (which determines hiring or firing policies), 2.) the decision on the amount of marketing effort to be exerted, and 3.) the decision as to the amount of bias due to organizational requirements for more or less work to be allowed to affect bids, proposals, and the desired level of funding.

The decision on the desired level of technical manpower has already been described in Chapter III. Since this decision is essentially made by each project group in response to the needs of each individual group, and top management only tries to keep the laboratory policy within broad limits, it was felt that this decision should not be included in the top management decision sector. It was therefore described in the section on technical manpower as depending on the level of manpower necessary to support the level of funding in the laboratory.

Marketing effort is exerted in order to maintain the desired flow of awards into the organization. It would include such activities as proposal and bid preparation, trips to Washington to see influential people, and even laboratory funded study programs. Management takes several things into account when making its decision as to the amount of marketing effort that the organization should exert. Basically, however, marketing effort is determined by the number of people in the organization. Management, from its knowledge of the level of technical manpower in the organization and of their average technical capability, determines a desired flow of contract awards that will keep all the people presently in the organization busy. Management then tries to exert the proper amount of marketing effort to bring the desired flow of work into the organization.

Several other factors are important, though. If, for example, the level of funding in the laboratory is different from that desired, management will want the award flow to be either above or below that desired merely to keep people busy, in order to correct the actual level of funding to that desired. This is attempted by changing marketing effort to adjust the award flow. This concept is illustrated in Figure VI-1 where a Normal Marketing Effort Multiplier is plotted versus the ratio of the actual level of funding to that desired. Note that in the area where the level of funding closely approaches that desired, the adjustment to marketing effort is small, but that for large deviations, especially for too little funding, large changes are made as the organization recognizes the impending danger of collapse.

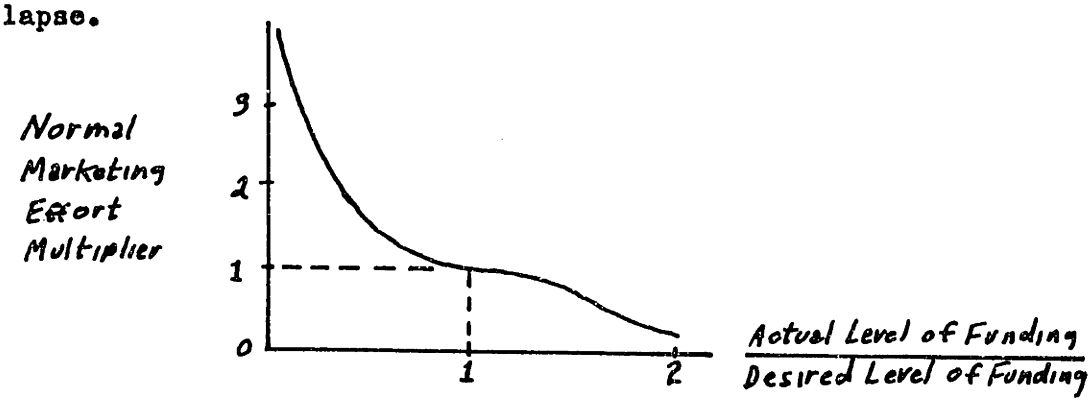

Figure VI-1: Marketing Effort Multiplier due to Level of Funding

Another factor which affects marketing effort is the technical effectiveness of the organization. Two basic policies are possible here. As the organization gets more effective technically, it can curtail its marketing effort and wait for the best jobs. This kind of policy tends to increase technical effectiveness even further, and in the long run to greatly help chances for a successful R and D organization. The other possible policy increases marketing effort as technical effectiveness increases, in an effort to cash in on the organization's new found capability. Unfortunately, this policy tends to lead to overexpansion of the organization, to dilution of the new found technical effectiveness, and to a general down-grading of the quality of work.

A final factor affecting marketing effort is determined by the philosophy of the particular R and D organization. This factor can be called the growth orientation of the organization. Different organizations will have different viewpoints towards expansion. The two main opposites that come to mind are the non-profit R and D laboratory affiliated with an educational institution and the commercial R and D laboratory rising very fast in the industry. The first will have relatively little desire to grow and the amount of marketing effort will reflect this. The commercial laboratory will, on the other hand, have definite expansionist plans and will exert relatively more marketing effort. The growth factor will also depend on the relative success experienced in the past few years by the firm. A firm that is growing will have more plans and desires for future growth than one that is going downhill. The R and D laboratory whose business is decreasing will be more concerned with stopping the downhill trend than with starting back up again. This tendency to want to go higher while going up and to merely try and stop while going down undoubtedly is a major cause of the violent ups and downs experienced in R and D. Any policy which attempts to increase the peaks of normal cycles while doing nothing to decrease the valleys is bound to make things worse.

The reader should notice that a major feedback loop in the system under study has now been closed. The desired level of technical manpower, which determines the actual level, depends primarily on the amount of work or level of funding in the organization. The amount of work in the organization is controlled to a large extent by the marketing effort exerted. The marketing effort exerted depends primarily on the capacity of the organization to handle work which in turn depends primarily on the level of technical manpower. This internal feedback loop in the decision making structure may be yet another cause of the undesireable dynamic behavior so often exhibited by R and D organizations. The loop is depicted schematically in Figure VI-2.

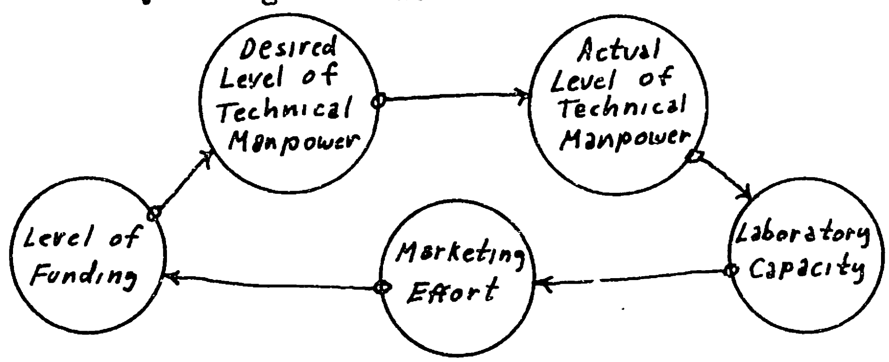

Figure VI-2: Major Feedback Loop in Management Decision Making Structure

The organization growth factor is now more readily seen to be important. The feedback loop described above will exhibit degenerative behavior under normal circumstances. That is, if a decrease in any of the quantities in the loop results from an external cause, the decrease will be propagated around the loop and actually cause a further decrease in the size of the organization. This tendency for degenerative behavior is best combated by having a growth factor of greater than one, or in other words, by having the organization exhibit a desire to grow regardless of the circumstances.

The last management decision to be presented is that concerning the amount of bias, due to organizational requirements for more work, to be allowed to affect proposals, bids, and the desired level of funding. Under organizational stress due to requirements for more work, bids and proposals will understate cost and delivery time estimates in an effort to get the needed additional work. The extent to which cost and delivery time estimates are understated depends on the relative need for work and a characteristic which we shall call the integrity of the organization. Different laboratories will have different integrity characteristics. For example, one firm might feel a responsibility to accurately state estimated costs and delivery times, no matter how bad their situation, while another would not be above cutting internal estimates in half in an effort to escape a poor situation.

As was argued above, a good measure for an organization's need for work is the ratio of the actual level of funding to that desired. When this ratio is less than one, the organization is in need of more work to build up its level of funding, and when the ratio is greater than one, the organization has more work than needed and is presumably incurring penalties because of too long a delivery time. As a description of the integrity of a firm, the decision bias affecting bids and proposals can be plotted versus the ratio of actual to desired level of funding. This is done in Figure VI-3 for several different integrity characteristics. The perfectly truthful

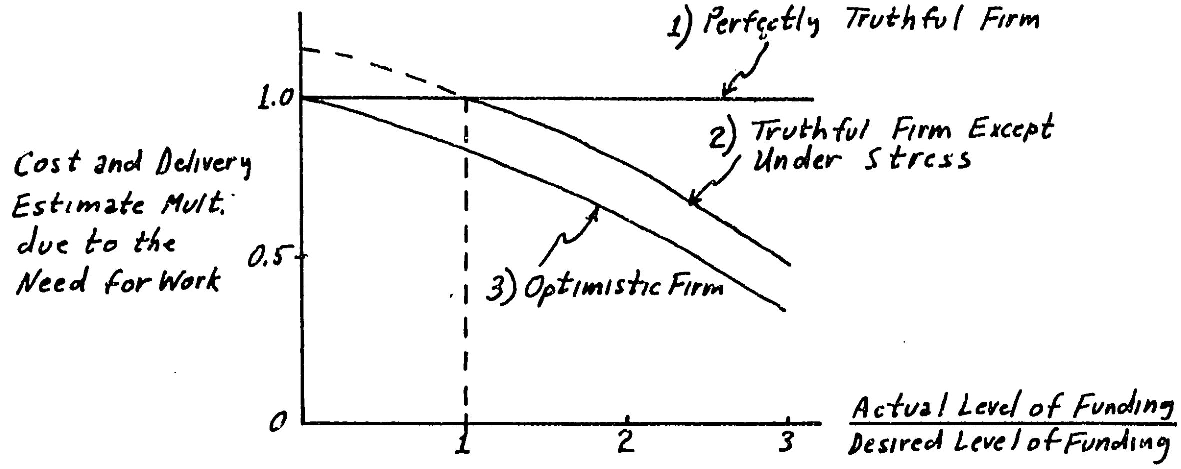

Figure VI-3: Integrity Characteristics of Typical R and D Firms

firm will always present what it believes the actual costs and times will be. (Curve #1) About the best that can be expected, however, is the firm which does not start understating estimates until it is in fairly bad trouble. (Curve #2) A common integrity characteristic that is to be found understates estimates even when actual work is equal to that desired.(Curve #3) Note the dotted continuation of Curve #2. This represents the occasional firm, usually possessing a high technical effectiveness, that prefers to overstate estimates. The motivation behind such behavior is to make sure that the laboratory only gets customers who are primarily interested in the quality of the work, rather than the cost or delivery time. This is, of course, the position many R and D firms strive to attain, that of being independent of cost and time considerations and concerned only with advancing the state of the art and turning out high quality work.

The typical R and D organization does not only misrepresent cost and time estimates to its customers, however. It usually lies to itself, also. Chapter II on Technical Effort described the level of funding desired by the organization as also dependent on the decision bias due to the need for work. The organization will react to needs for more work by reducing its desired level of funding so that things do not really look so bad after all. As a result of this policy, by the time affairs appear to be in a bad state, they are really in poor shape, and the organization is already past the point where the situation could have been corrected relatively easily.

There is one last determinant of this decision bias that must be discussed. As in marketing effort, the perceived technical effectiveness of the firm will have an effect and again as in marketing effort, two basically different policies may be employed. First, the R and D organization may try and wait for the best contracts when faced by a situation of rising technical effectiveness. In order to do this, the organization will reduce any decision bias that may have existed due to a need for work and will try to represent its capabilities more truthfully. This will result in the awarded contracts having more realistic cost and time requirements, and will allow the R and D organization to do a better job thus further raising its technical effectiveness. On the other hand, the organization may try to capitalize on its increased technical effectiveness by expanding and taking all the contracts it can get. In order to do this, management will increase the understatement of cost and delivery time estimates. As a result, new contracts will flow in at a greater rate but they will have more stringent cost and time requirements. The required expansion of the organization will dilute the high technical effectiveness, and the time and cost requirements will severely limit the organization's ability to do a good job, thus after a time further lowering technical effectiveness.

It appears that the integrity characteristic of the R and D organization and the way it reacts to increasing technical effectiveness are major determinants of the dynamic behavior exhibited by the system. In fact, all of the decision functions described above appear to have significant effect. In the simulation of the above system, different ways for making the above decisions were tried, and the results will be discussed in Chapter VII.

Chapter VII: Simulation of the System

The preceding five chapters have developed a verbalized conceptual framework within which it is possible to study and understand the dynamic behavior of a research and development organization. Descriptions of the cause and effect interactions, information feedback loops, and decision policies existing in the system were given. The next step is the study of the actual dynamic behavior of the system through simulation. To accomplish this, a mathematical model was built from the verbal description given previously. The model equations, flow diagrams, and a brief explanation of some of the more complex model representations are given in Appendix A. The model was simulated on the IBM 7090 computer using the DYNAMO compiler and simulator program.[1]

There are two basic objectives to simulating a dynamic system. The first, and most important, is to use the results of the simulation to gain a better understanding of the system. It is well worth the effort of a study such as this just to identify the basic characteristics of a system which are the major causes of the dynamic behavior. Once in possession of the knowledge of what is important

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1 See DYNAMO User's Manual, The MIT Press, 1961, by Alexander L. Pugh, III.

in a system and what is not, the solution of seemingly hopeless problems becomes much easier, while other problems are seen not to exist at all.

The second objective, which necessarily follows the first, is to use the tool of simulation as an aid in bettering the design of the system. New decision policies can be designed and tested relatively cheaply through computer simulation. It must be emphasized, however, that even if this objective is not directly attained, successful completion of the first objective cannot help but improve future decisions since, in the very least, the important determinants of system behavior will have been identified. Thus, the manager can avoid spending time in trying to improve unimportant operations or decisions, but instead can focus on the real trouble spots in the organization.

This chapter will analyze the results of the system simulation in the following manner: First, two simulations will be examined with the goal in mind of trying to increase the reader's understanding of the dynamic behavior of R and D organizations. Then, the emphasis will shift to the determination of the important causes of the charactersic system behavior. And finally, the simulation of several different decision policies will be discussed.

Dynamic Behavior of an R and D Organization

Since the boundaries of this study were set to include only the R and D organization and its customer interfaces, it is necessary to supply an exogenous input to the model for each simulation. Basically, there are two types of exogenous inputs. One attempts to resemble reality as much as possible and usually is quite complicated mathematically. This type is, however, valuable for checking whether the model truly represents reality and for gaining an initial understanding of the system. Such an input will be used for the first simulation discussed. The second type is of a pure mathematical form such as a step function or a ramp. This type is valuable for further research into the dynamic interactions within the system because its pure mathematical form allows the causes of variations in model variables to be traced much more easily. This type will be used in the majority of the simulations analyzed here.

The exogenous input to the model consists of the advanced research, and design and development contract award rates available. This input must be distinguished from the total amount of business in a research and development area. It rather represents the maximum possible business in a field given that all the firms in the field are operating in an optimal manner. A certain area of technology can support a characteristic amount of R & D business that will vary over time as the surrounding technology advances. The actual amount of business generated will depend on the ability of the firms in the field and on the past work performed which was effective in advancing the state of the art. Thus the maximum possible award rate available does not necessarily, or usually, equal the actual total award rate in the industry.

It is typical of an area of technology that early in its life, advanced research contracts will be more numerous, while later on, as the state of the art is advanced, design and development work outstrips advanced research. This concept is illustrated in Figure VII-1 where the advanced research and design and development award rates available for an area of technology are plotted versus time.

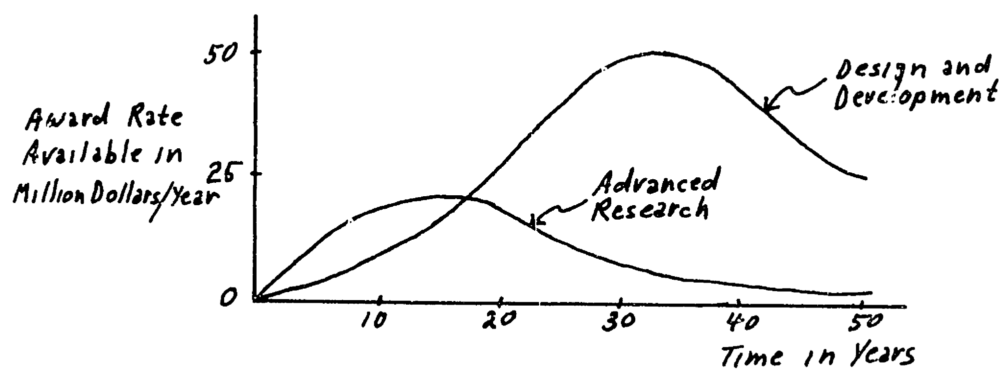

Figure VII-1: Available Award Rates versus Time

This is the type of input supplied to the model for the first simulation that will be discussed. The behavior of the two contract award rates and the level of total technical manpower versus time is in the computer output plot depicted in Figure VII-2. Study of this one plot reveals some quite interesting behavior. In terms of

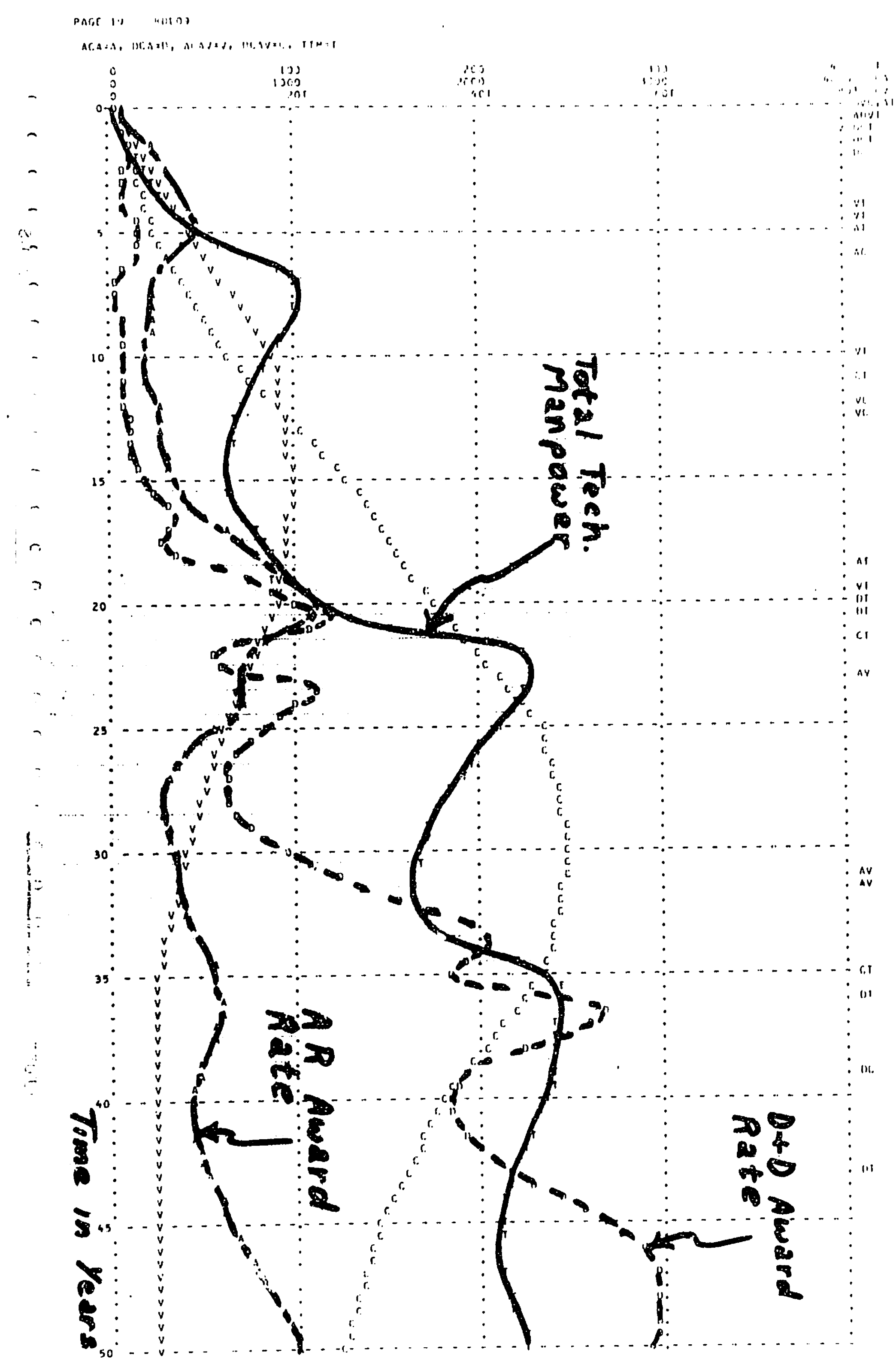

Figure VII-2: Programmed Input

technical manpower, the organization seems to go through relatively short periods of rapid growth followed by relatively longer periods of decline. The reason for this can be partially discovered through study of the relative phasing of award rate variations with respect to manpower variations. The level of technical manpower is seen to turn up only after awards have turned up. This can be explained by the fact that the desired level of manpower in the organization depends in part on the amount of work the organization has to do. Thus, as awards increase above the rate at which the organization can handle work, the backlog will begin to build and this in turn will result in an increased level of manpower. It is also seen that the manpower level turns down after the award rate has turned down for the same kind of reason. What causes the peak in the award rate? It would appear that rapid expansion, such as between years fifteen and twenty-two, has a detrimental effect on the organization which results in decreased contract awards. This slump in business seems to hold back more expansion for a period of about nine or ten years. Expansion and contraction patterns of this type are not uncommon in the research and development industry.

A look at Figure VII-3 will demonstrate that the major cause of the variations in Figure VII-2 is variations in the technical effectiveness of the organization. Technical effectiveness is an important determinant of many of the model variables, and it has an

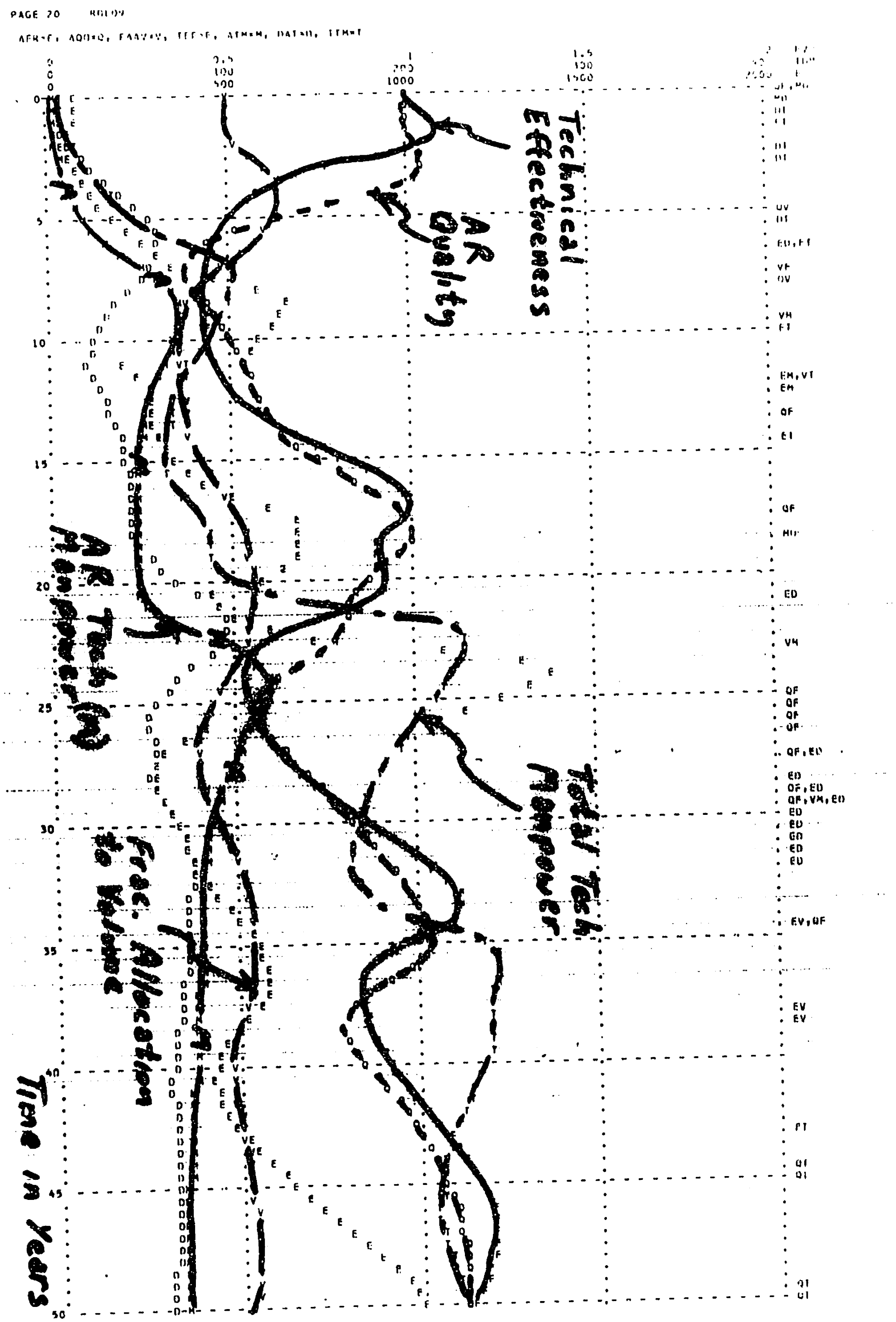

Figure VII-3: Programmed Input, Advanced Research Effort especially important effect on the customer's award decision, both directly and indirectly. A look at Figure VII-3 shows that technical effectiveness usually increases when the organization is static, or decreasing in size. This is due to the fact that each person in the organization is becoming more experienced and the average technical effectiveness per engineer is rising. When the organization is expanding rapidly, however, the average technical effectiveness per engineer falls because of the influx of new people. This fall in technical effectiveness cuts quality and productivity, among other things, and through many delayed mechanisms causes the award rate to fall. The cycle starting at year fifteen can be recreated as follows: over the previous eight years, from year seven, the organization has decreased in size by about 40%. The previous expansion had left the organization with a technical effectiveness of about 0.45 at seven and a half years. Throughout the period from seven and a half to fifteen years, technical effectiveness increased slowly at first and then faster later on as experience built up. Rising technical effectiveness resulted in higher quality and higher productivity with associated lower costs, and as a result contract awards began to turn up slightly at twelve years. Throughout the period from year twelve to fifteen, the manpower level continued to decrease even though awards increased, because rising technical effectiveness caused productivity to increase the capacity of existing people at a faster rate than awards were increasing. At about fifteen years, however, increasing technical effectiveness, through its direct and indirect effects on the market place, resulted in award rates increasing business at a faster rate than the existing level of personnel could handle. Thus, another cycle of expansion started as the organization attempted to hire the necessary people. Once expansion is started, its rate and extent are compounded by several things. Once-productive personnel are required to spend their time hiring and training, and the decrease in technical effectiveness due to expansion requires even further expansion to meet the demand for more productive capacity. Technical effectiveness began to decrease at about seventeen years or just after the expansion started in earnest. The rate of decrease can be seen to have increased as more and more expansion was needed to reach the desired capacity due to decreasing productivity. By year twenty, however, the decreasing technical effectiveness began to have an effect on the award rates also, and a distinct peak is apparent. By year twenty-two, the decreasing award rates coupled with increasing manpower finally caused the organization to reach the position where no more people were required and the expansion finally turned down also. Over the next nine years, the slowly decreasing size of the organization allowed technical effectiveness to again rise, thus setting things up for the next radical expansion beginning at year thirty-three.

The extreme importance of an organization's ability to generate technical effectiveness is seen quite well in the above description.

Apparently, the model represents an organization that takes quite a long time to generate technical effectiveness. This characteristic limits this organization's ability to grow, and indeed, even results in the organization's having its largest award rates at the end of fifty years when possibilities have declined significantly. This particular organization is just not able to grow fast enough, while still maintaining a relatively high technical effectiveness, to take advantage of the peak possibilities occurring at about the thirty year point. Trying to take advantage of a situation of increasing possibilities seems to cause it quite some trouble while, in a situation of decreasing possibilities, the organization maintains a fairly stable manpower level and keeps them busy by increasing its technical effectiveness.

The behavior of several internal variables throughout this simulation is also quite interesting. Figure VII-3 shows some of these variables for the advanced research sector. The dependence of the quality of the output on technical effectiveness is quite evident. Variations in quality essentially follow variations in technical effectiveness, but lagging by about a year and a half. This lag is primarily due to the delay necessary for performing technical effort on contracts. It should be noted, however, that due to the effects of a varying allocation of technical manpower time, the quality variations do not follow the technical effectiveness variations exactly. There is an important interaction between the fraction allocation to volume and quality performance. Decreasing quality, as in the period from eighteen to twenty-five years, results in increasing pressure for quality work. It also operates through the market sector to decrease the award rate. This results in an accompanying decrease in the pressure for volume effort and the fraction allocation to volume decreases from year twenty-one through year twenty-six. The up-turn in volume allocation lags the up-turn in quality primarily because the delay for the customer to realize the laboratory is doing better also delays his increasing the award rate. The interdependence of all these variables is most easily demonstrated by noting that the decreasing oscillations of technical effectiveness from year thirty to year fifty also result in decreasing oscillations in quality performance, fraction allocation to volume effort, and the manpower level.

Note that in the above analysis, we have looked only at variables in the advanced research sector. Behavior of the corresponding variables in design and development is essentially the same, due to the predominance of technical effectiveness as the determining factor, and it is therefore unnecessary to discuss them also. Figures VII-4 and VII-5 have been included, however, to show the dynamic behavior of important variables in the design and development sector.

It has been stated above that technical effectiveness, operating

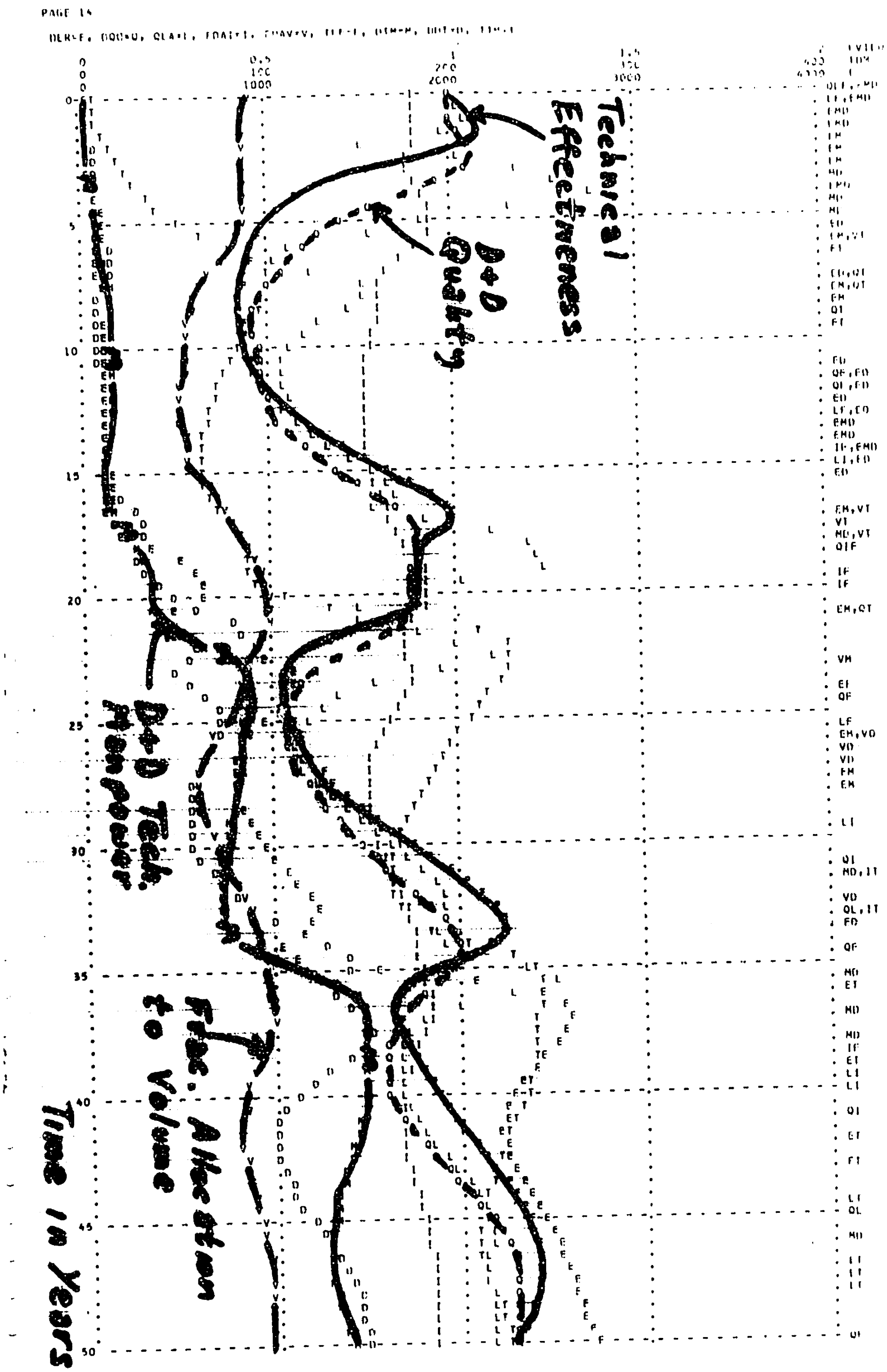

Figure VIII-4: Programmed Input, D + D Effort

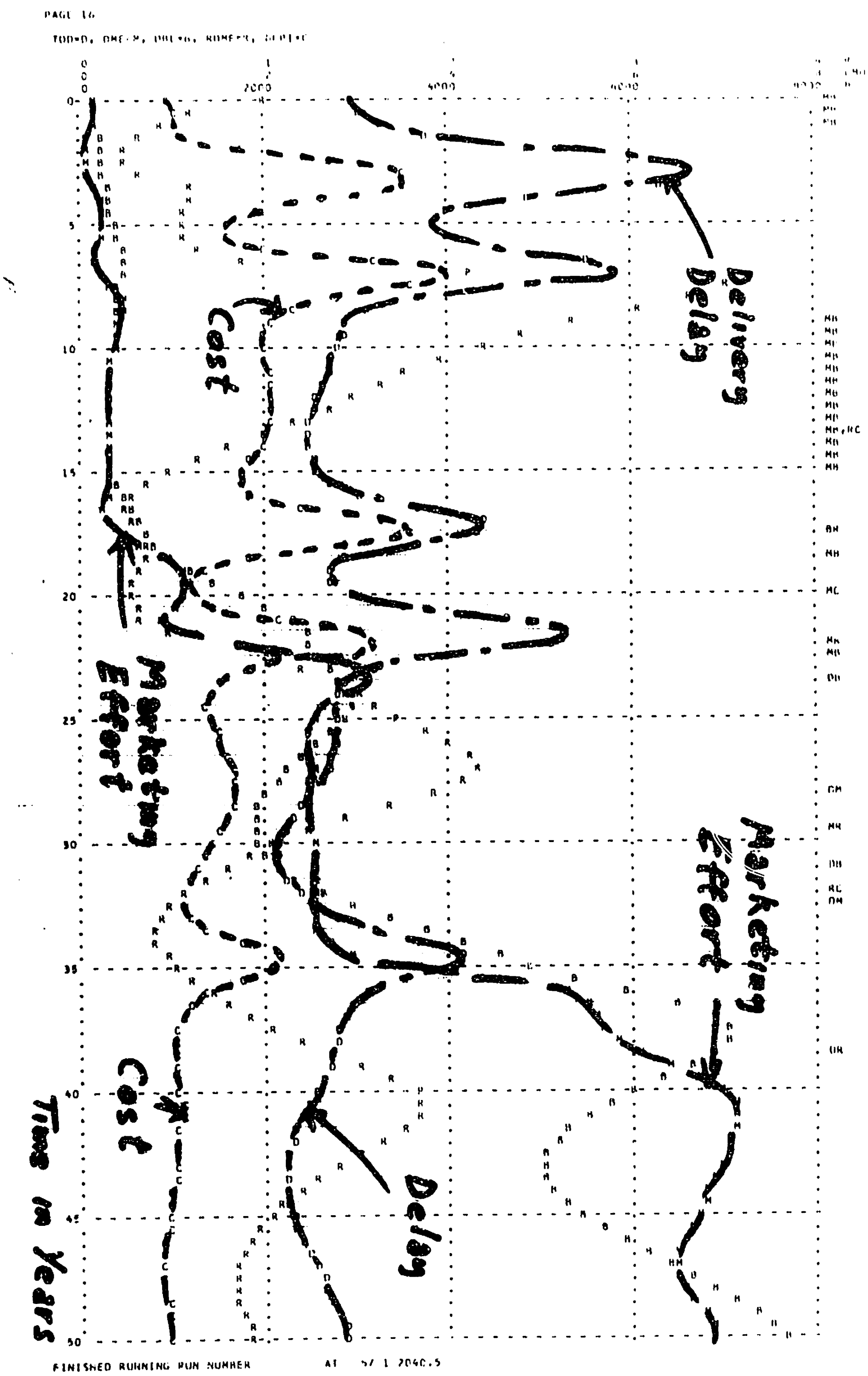

Figure VII-5: Programmed Input, D+D Market Variables directly and through quality comparisons, is the major determinant of fluctuations in contract awards. There are several other ways by which technical effectiveness also affects contract awards. Effect on the cost performance of the laboratory is one. Since the cost measure is essentially equal to the level of technical manpower divided by the effort rate, it is very dependent on productivity which in turn depends primarily on technical effectiveness. Cost performance will also depend on the growth rate, since a high growth rate will tend to decrease the percentage of effective people in the organization. Figure VII-6 plots the cost index versus time, and it is apparent that for the most part, costs rise when technical effectiveness falls, and vice versa.

Delivery delay is another important variable in the market place which depends indirectly on technical effectiveness. The presence of the delivery delay comparison tends to worsen the previously discussed award rate fluctuations which were primarily caused by variations in technical effectiveness. Falling technical effectiveness, as in year seventeen through twenty-four, results in falling productivity. As a result, the organization's backlog rises,not withstanding hiring efforts. The rising backlog causes the delivery delay to increase, which in turn also operates to decrease the customer's award rate. Figure VII-6 shows that delivery delay does indeed tend to rise with falling technical effectiveness.

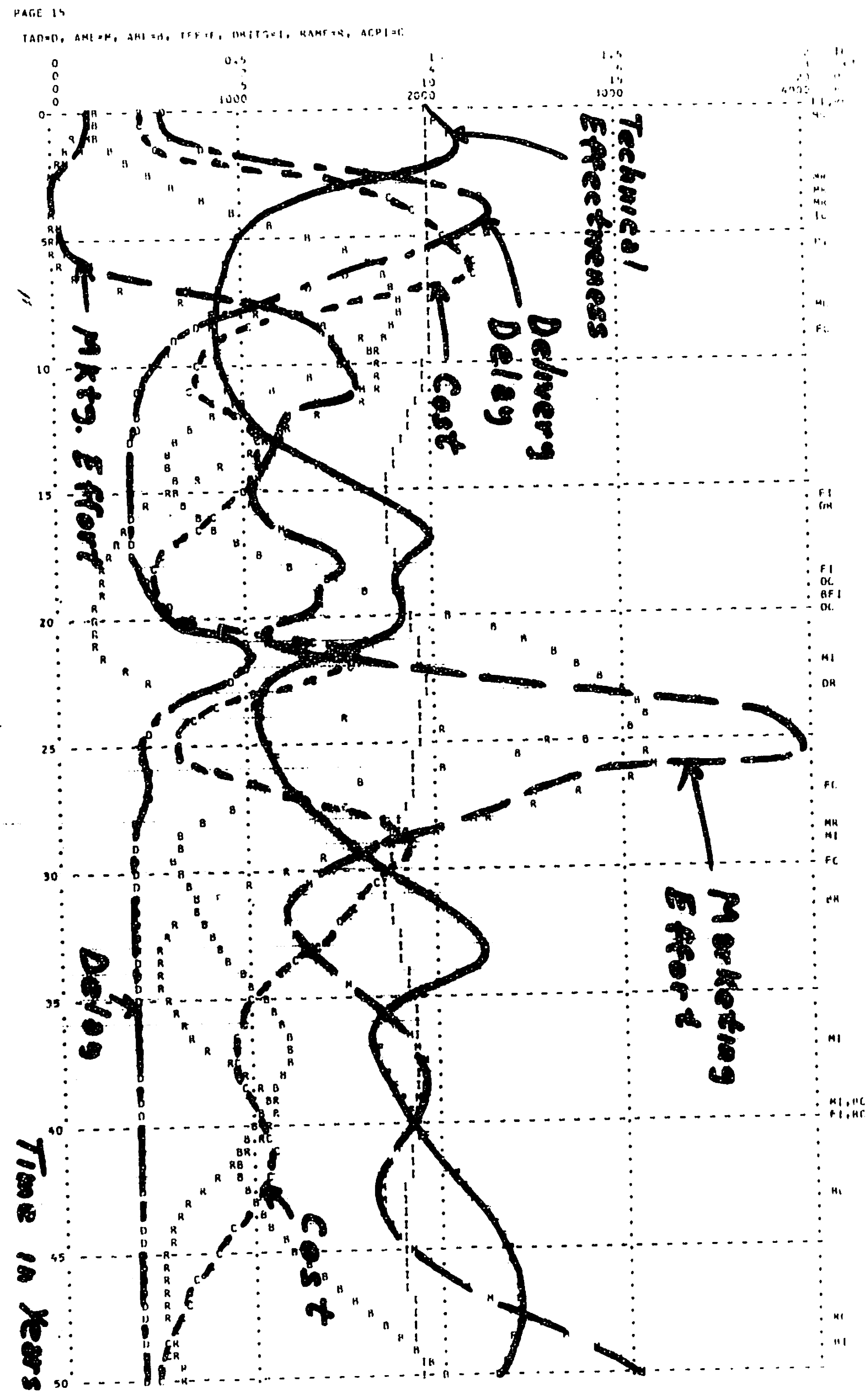

Figure VII-6: Programmed Input, AR Market Variables

A word of caution is needed about interpreting the delivery delay as formulated here. At about the fourth year, the delay has risen to a value of about twelve years for advanced research. This is, of course, highly unrealistic. But, the delay, as formulated here, represents the time necessary to perform work presently in the backlog, given the present level of personnel and the present technical effectiveness. Obviously, the organization reacts to such a situation by hiring more people and it does not actually take twelve years to finish the work in house at year four.

Variations in marketing effort will be the last discussed in relation to this first simulation. The goal of marketing effort is to provide work to keep the existing capacity of the organization occupied. Therefore, it is determined mainly by the perceived productivity, which depends on technical effectiveness, and the level of technical manpower within the organization. By referring to Figures VII-3 and VII-6, this relationship can be confirmed for advanced research marketing effort. The period between year ten and year seventeen is characterized by rising technical effectiveness which in turn causes an expansion in advanced research personnel between years twenty and twenty-four. Through years fifteen to twenty, however, the level of advanced research personnel is steady, and the variation in marketing effort follows that of technical effectiveness, although lagging by a few years because of the perception delay. Thus, because of decreasing technical effectiveness, marketing effort decreases from year eighteen through twenty-one. At this point, however, increasing capacity due to the result of increasing manpower begins to overcome decreasing productivity, and marketing effort swings up again, following the increasing level of technical manpower. From this analysis, it is clear that marketing effort depends on both technical effectiveness and technical manpower, and whichever one is varying the most is at that moment the important determining factor.

The second simulation to be discussed uses a ramp for the exogenous input. This is a particularly valuable input with which to test this system, because it is a good representation of an actual growth situation, and yet is relatively pure mathematically. All following simulations will use this ramp input and will be discussed with respect to the differences between them and this base run.

Figure VII-7 shows the behavior of the organization over a fifty year period. The same cycles of rapid growth alternating with slow decline that were evident in the previous run are seen here. Reference to Figure VII-8 shows that variations in technical effectiveness are again the most important determinant of the system's dynamic behavior. It should be noted that since the possible contract award rates do not level off and decrease as in the previous run, the oscillations in technical effectiveness and other important variables do not die out. This is because the organization continues to try

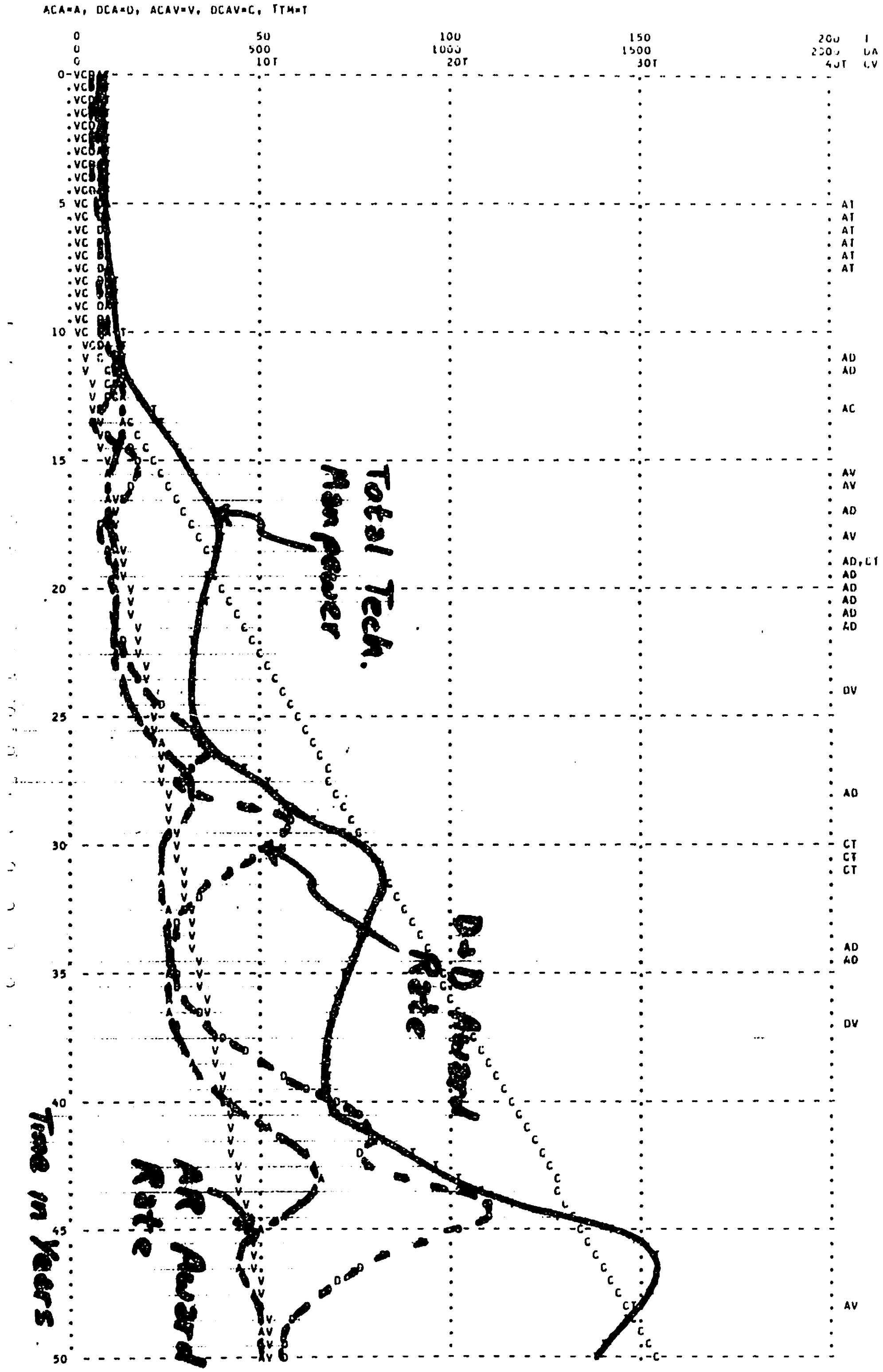

Figure VII-7: Ramp Input, Base Run.

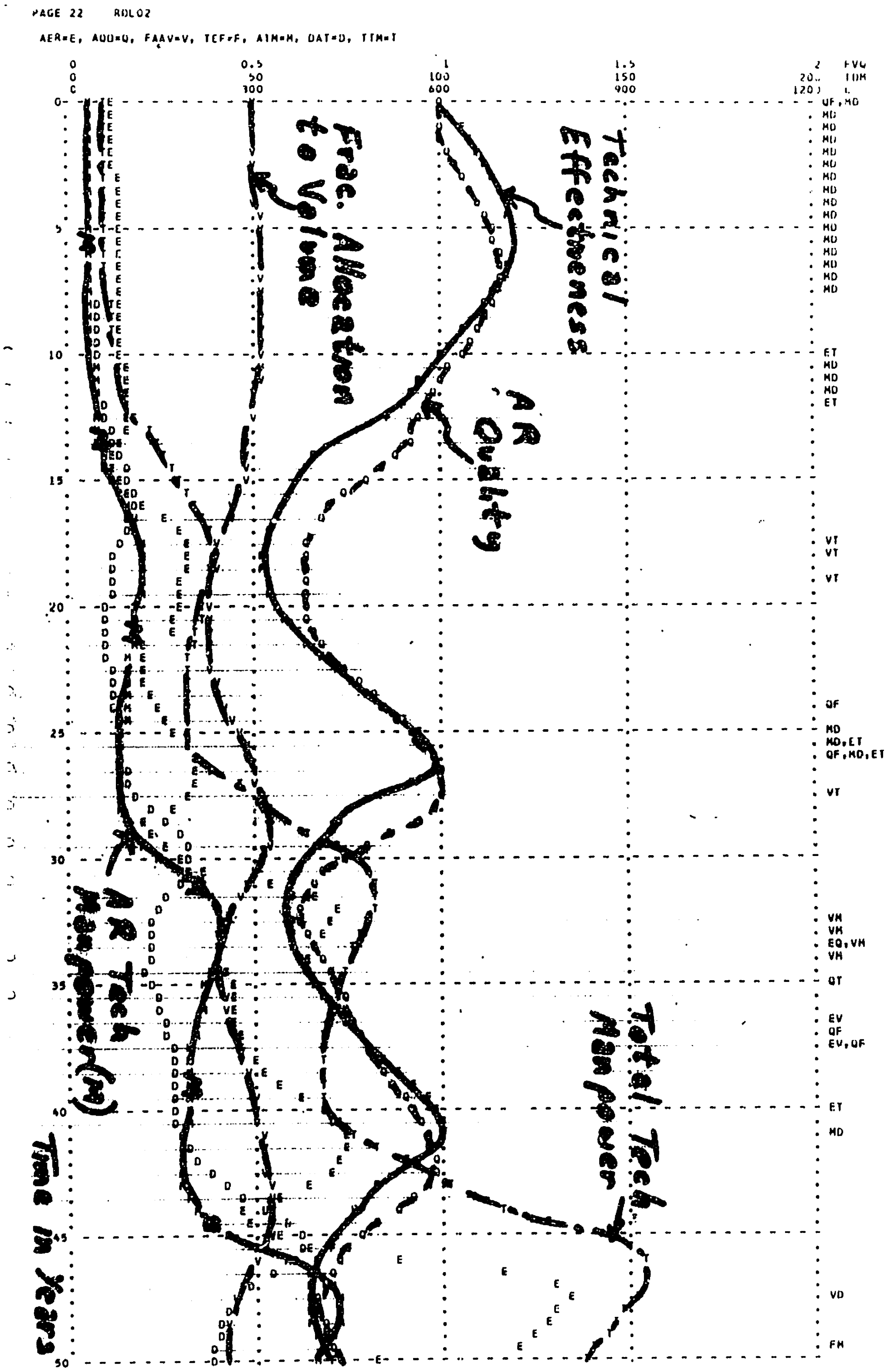

Figure VII-8: Base Run, Advanced Research Effort to grow instead of reaching a static position where growth stops and technical effectiveness is able to increase. Perhaps the most important lesson to be learned from these simulations is that growth has a tendency to be an unstable process, and that management must pay very close attention to maintaining control over a growth organization. During the first ten years of the simulation, technical effectiveness is fluctuating about a fairly high level (1 to 1.2). The ramp input starts increasing possible awards at year ten and it is shortly after this that the organization begins to grow in earnest. The beginning of substantial growth (about year twelve) can be seen to coincide with the start of a drastic decrease in technical effectiveness to a level of 0.5. Following this decrease, technical effectiveness can be seen to settle down to steady fluctuations about a much lower level than was true in the first ten years. This behavior can be explained by the fact that starting at year ten, the organization makes a transition from a somewhat steady situation into a growth situation. The lower average level of technical effectiveness during growth is due to the continuous influx of new personnel which results in a dilution of effective knowledge. Since there is a significant delay before new personnel become productive and before their effort becomes effective, technical effectiveness will always average lower during growth. The stabilization of technical effectiveness into a steady pattern of fluctuation indicates that the organization has settled into some sort of steady growth pattern, of which these fluctuations are characteristic.

Figure VII-9 shows the dynamic behavior of some of the advanced research market variables for this run. Note that the marketing effort curve gradually increases over time as the capacity of the organization increases. This behavior is due to the fact that on the average, a certain amount of marketing effort must be performed for each contract awarded. The variance of the actual marketing effort per contract available to the laboratory about the usual effort per contract available will cause variations in the actual award rate. Marketing effort can thus be used to adjust the award rate to the capacity of the organization. In usual circumstances, however, the amount of marketing effort will follow variations in organizational capacity fairly closely.

Since the behavior of this simulation essentially is the same as for the previous one, the other factors plotted will not be discussed in detail, but the computer outputs have been presented as a basis for later comparisons.

It appears from the preceding analysis that the characteristics of technical effectiveness are the major determinant of the type of dynamic behavior exhibited by an R and D organization. In order partially to test this conclusion, a run was made in which the knowledge effectiveness period was shortened from fifteen to ten years. This

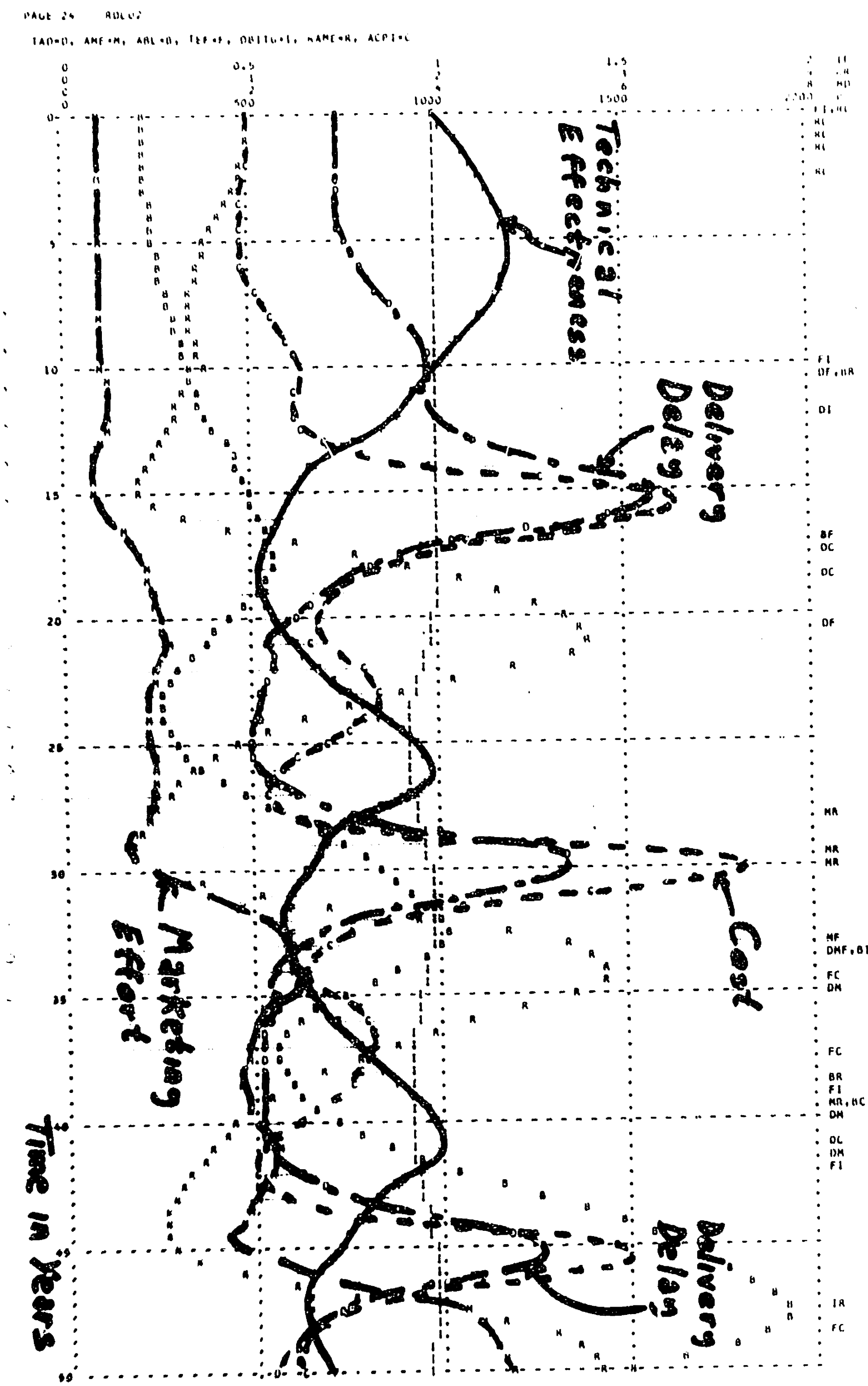

Figure VII-9: Base Run, AR Market Variables means that knowledge generated through past work becomes obsolete significantly sooner, and unless the rate of generation of effective knowledge is increased, the technical effectiveness of the organization will fall. It was hypothesized that because of the important effect of technical effectiveness throughout the R and D system, there would be a significant decrease in the amount of growth exhibited by the organization over fifty years. That this was indeed true can be seen by comparing Figure VII-10 with Figures VII-8 and VII-9. Although the same type of dynamic behavior is obviously taking place, growth in terms of personnel is only 64.4 percent as much, and contract awards have suffered in a like manner. This would be expected since decreasing the knowledge effectiveness period does not change the basic system characteristics of the technical effectiveness sector, but only lowers the steady state level of technical effectiveness. Actually, the extreme sensitivity of this system to changes in technical effectiveness can be seen by comparing the average technical effectiveness over the last ten years of the base run and this run. In this run, the average technical effectiveness dropped to about 0.75 from an average of about 0.82 in the base run. That such a small drop results in a thirty-six percent drop in growth is strong evidence of the importance of the technical effectiveness sector to this modelled system.

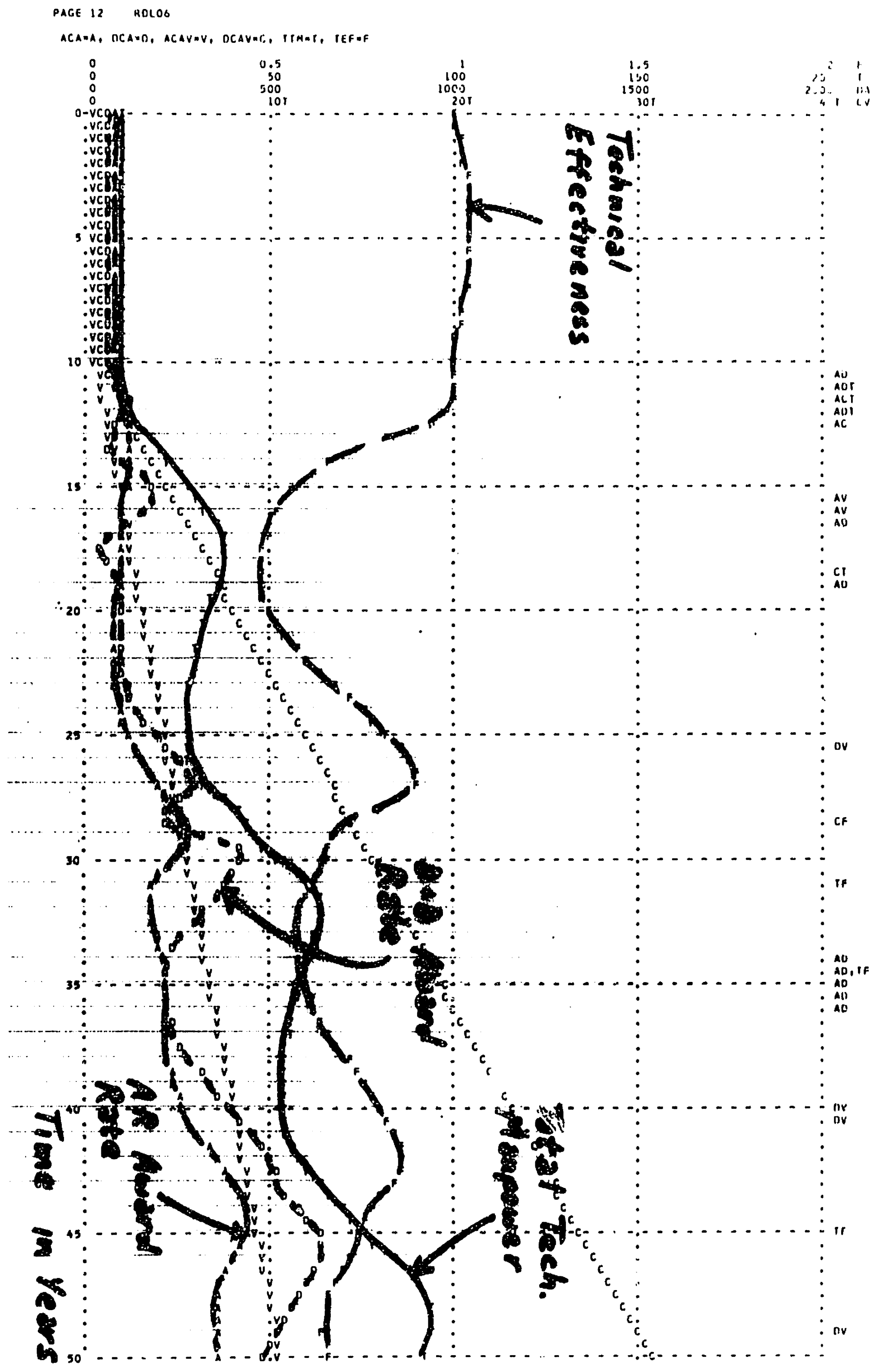

Figure VII-10: Decreased Knowledge Effectiveness Period

Policy Simulations

The basic model makes various assumptions about the quality of various management decisions made within the typical R and D laboratory. In most cases the assumption was that the decisions were made in a fairly reasonable manner, even though this is often not true in the real world. The first part of this section, therefore, will deal with simulations which will attempt to show the effects of several different examples of poor decision making policy.

Manpower Change Not Taking Account of Attrition

The hiring decision in the basic model was formulated so as to take into account the fact that the organization is experiencing continuous attrition. In other words, management realizes that there is a basic level of turnover, no matter how good are the conditions at the laboratory. In making the manpower change decision, management recognizes and accounts for this basic level of turnover. Such recognition does not eliminate the problems of turnover, as the new people must still be trained. But it does appear to help to some extent. A manpower change policy ignoring turnover and only recognizing it after the fact was simulated. The results are shown in Figure VII-11. The behavior of the organization is more unstable than in the base run. Growth cycles appear to be delayed by about five years from the base situation, but peaks in both total technical manpower and the award rates are higher. While

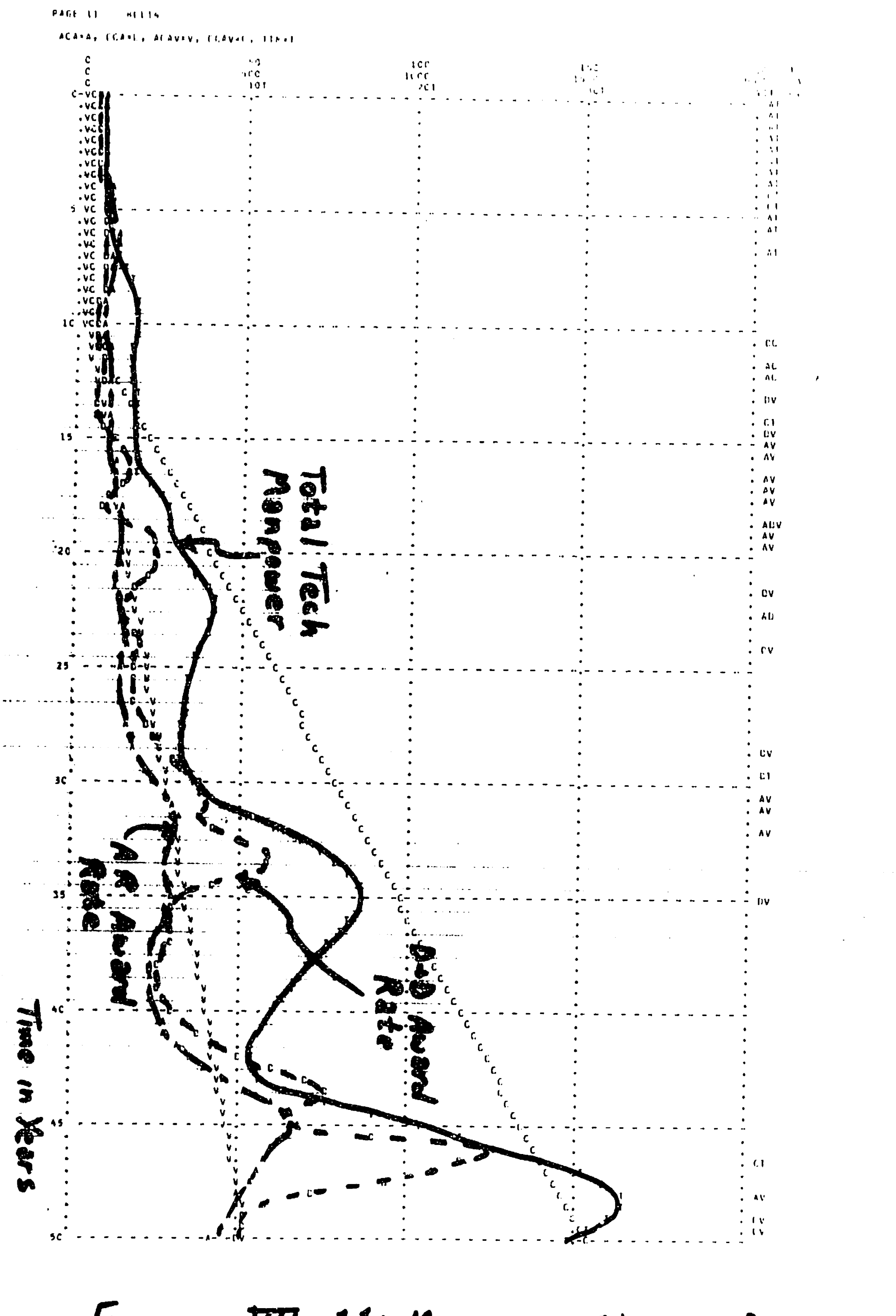

Figure VII-11: Manpower Change Does Not Take Account of Attrition this may seem at first to be more desireable, in that the organization is bigger at the end of the run than before, it is not really better because of the increased instability. Unstable growth behavior is quite unhealthy for a company in that the bad periods may become worse until at some point the organization is unable to recover. This model appears to lack such catastrophic response, but the possibility should be added to the model in any major future extensions of this work.

The relatively greater instability of this policy can be explained in the following manner. Since management does not anticipate turnover, it takes longer for the organization to react to a need for additional technical manpower. As a result, the growth portions of the organizational cycles are apt to be delayed in beginning and as a result are much steeper and peak higher. Such behavior causes technical effectiveness to fall even further during expansion and even results in growing oscillations in technical effectiveness. (See Figure VII-12.) Thus, the growing instability feeds on itself and the organization never even begins to settle down to a steady growth rate.

Decrease of Delay in Changing Manpower

From the results of the previous run, one might be tempted to think that if management were to more quickly adjust the level of manpower to that desired, more growth would be possible. This policy

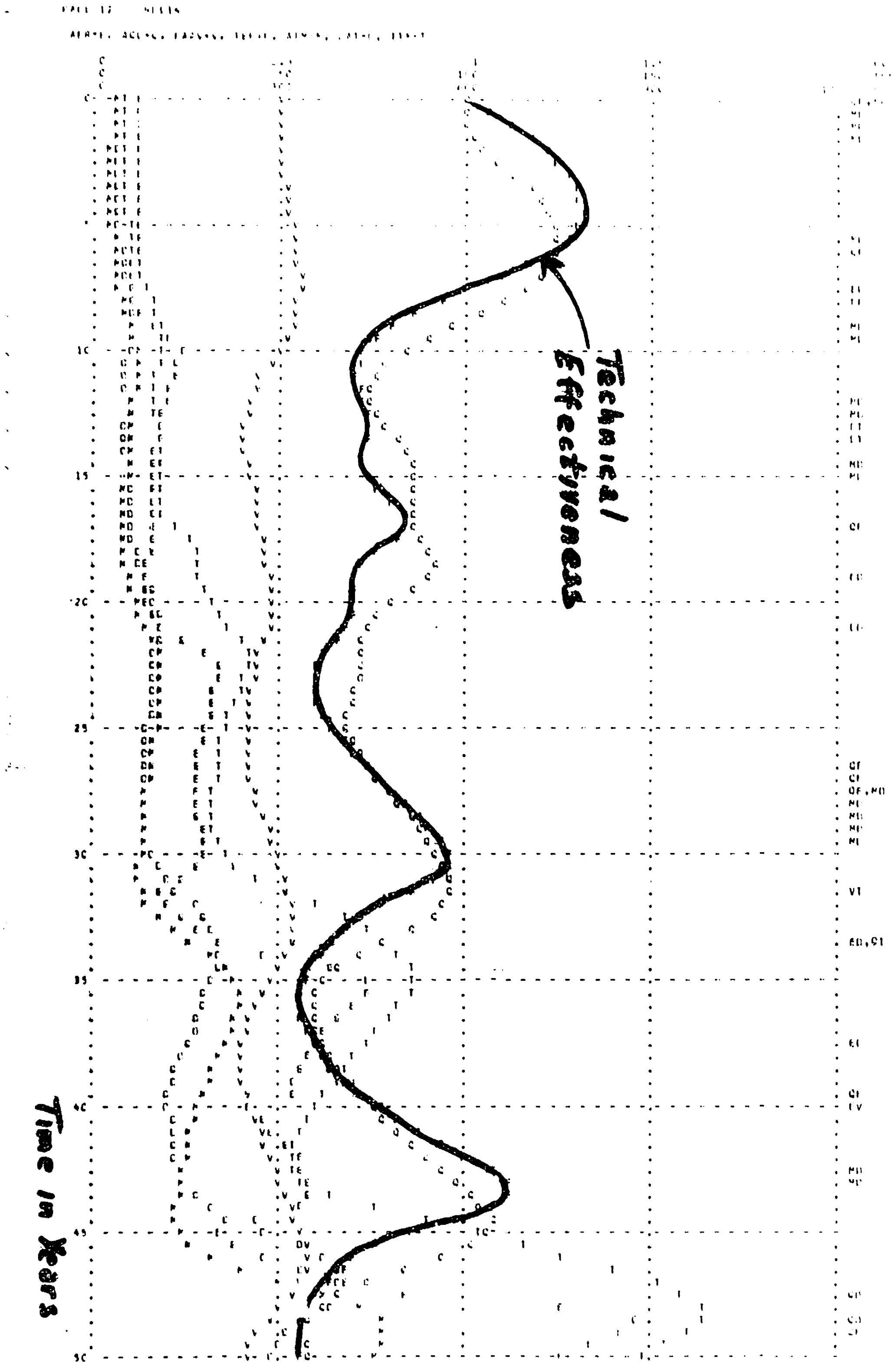

Figure VII-12: Manpower Change Does Not Take Account of Attrition was simulated by decreasing the delay in changing the manpower level from one to half a year. The results, however, do not indicate that this is a better policy. Instead, it is definitely a worse one. By comparing Figure VII-13 with Figure VII-7, this fact becomes obvious. While manpower peaks are almost as high as in the base run, the behavior is more unstable and the valleys are significantly lower. The most drastic effect is visible in the significantly lower contract award rates. The cause of the poorer performance is readily apparent. Note that the peaks of variations occur about three or four years earlier than in the base run. This indicates that the organization is trying to grow faster, as we know. However, the growth ability of this system is inherently limited by the time necessary to establish technical effectiveness. Thus, by trying to grow faster, the organization does in fact expand too quickly and technical effectiveness is lowered sooner than was the case with the original policy. As was explained earlier, this reflects throughout the system, cutting quality, productivity, and awards. At this point expansion stops, contraction starts, and technical effectiveness begins to build back up. But because of the new policy, as soon as the ability to grow further is gained back, the organization again takes off too fast, and again limits its final achievements.

The Effect of Integrity

In Chapters II and VI, the effect of the integrity characteristic

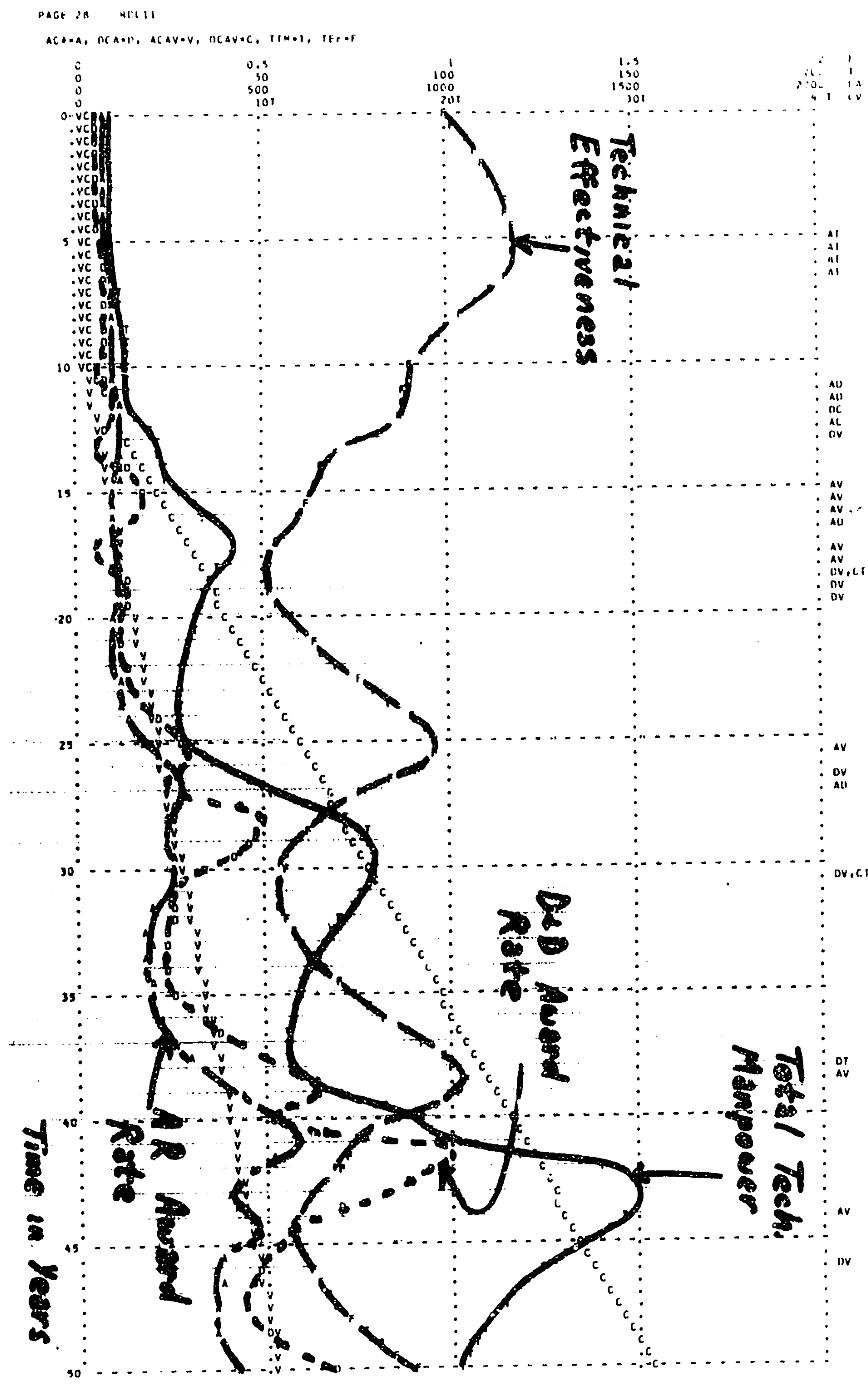

Figure VII-13: Decreased Delay in Changing Manpower of the R and D organization was discussed. It was explained that this characteristic determined how the organization reacted to pressures for more work in its cost, delivery, and desired level of funding estimates. The cost and delivery estimates directly effect the customer's award decision through his comparison of them with the cost and delivery he expects from experience. The desired level of funding estimate acts to decrease internal pressures by actually decreasing the desired level of funding when there is pressure for additional work. In other words, management will tell itself that there really is enough work in the organization and will act as if this were true.

All the previous runs were made with an integrity characteristic that resulted in true estimates when the level of funding was equal to or more than that desired. (Curve 2 of Figure VI-3) However, many firms today make underestimates in the ordinary course of business even when additional work is not badly needed. To simulate this, an integrity characteristic resulting in a fifteen percent under-estimate under ordinary circumstances (Curve 3 of Figure VI-3) was used in the model. The results are shown in Figure VII-14. Although the dynamic behavior is of the same type that we have come to expect from this system, total growth is about eighty-eight percent of that found in the base run, and variations in awards and manpower are less in amplitude. There are two possible reasons for this behavior.

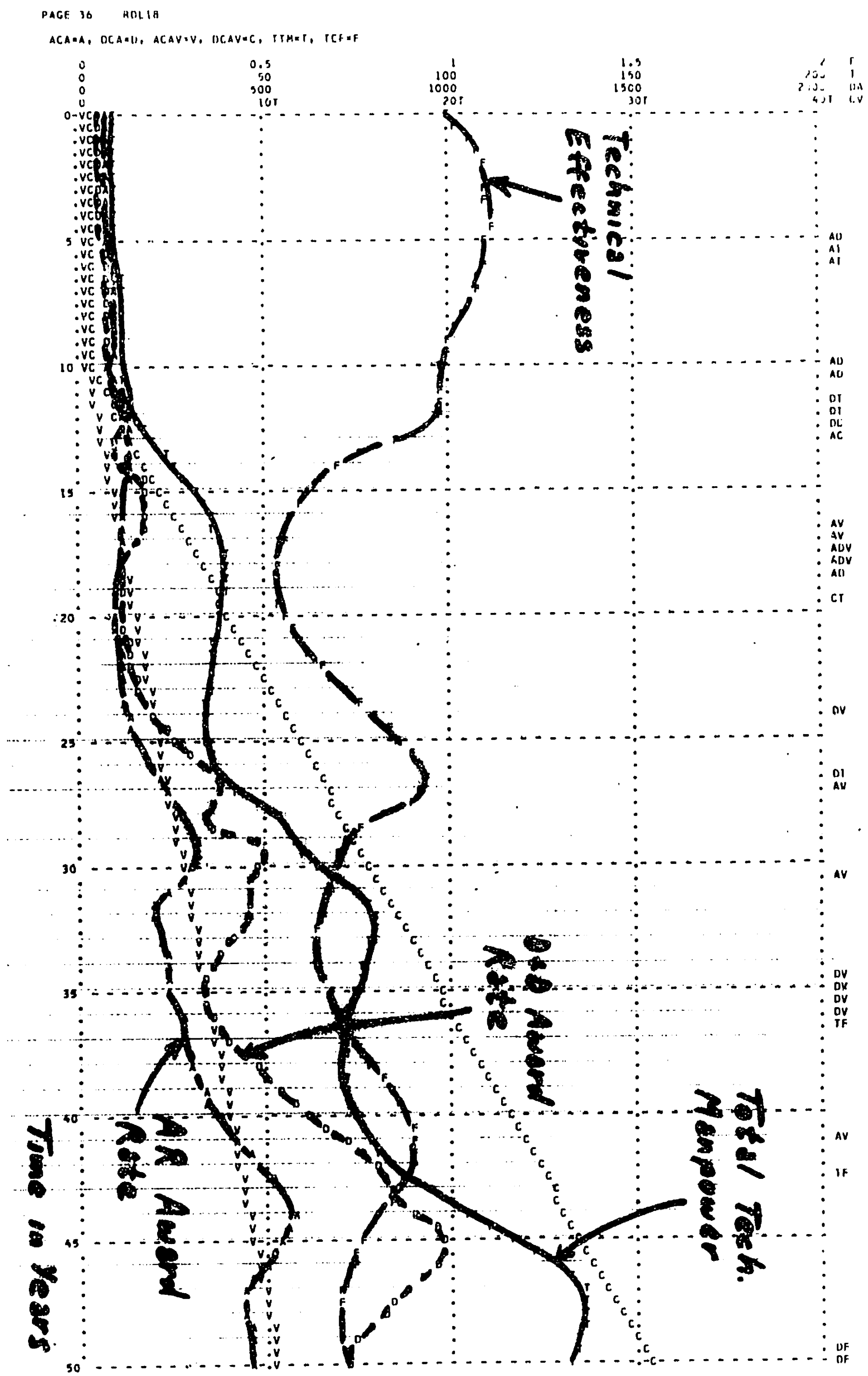

Figure VII-14: Underestimating Integrity Characteristic

One is that the cost and delivery underestimates had an undesireable effect on the customer so that awards were decreased. The other is that the decrease in the desired level of funding led to a decreased desire to expand during periods of growth when business was needed. In order to find out if one or the other or both were responsible, a second simulation was run with the underestimating integrity function used for cost and delivery estimates, and the normal integrity function used for the desired level of funding estimates. The results were almost the same as the base run, indicating that this particular underestimating integrity characteristic has relatively little effect on the customer, but that the internal underestimates made to decrease internal pressures have the effect of significantly affecting the growth of the organization. The decrease in growth during each expansion period comes about because of a decrease in marketing effort. One of the determinants of marketing effort is the difference between the desired and actual level of funding. If the desired level of funding is greater than the actual level, then relatively more marketing effort is exerted in an effort to increase the actual level. If, however, the desired level of funding is decreased in an effort to decrease internal pressures for more work, then it follows that the difference between the desired and actual level of funding will be less and marketing effort will be decreased. Among other things, then, this run demonstrates the relative importance of the managerial policy for generation of marketing effort.

Counter-cyclical Marketing Effort Policy

There are many managerial policies that can be followed in hopes of improving the performance of an organization. In a growth situation such as we are investigating here, perhaps the most important decision to make is when to increase marketing effort in an effort to get more work. It has been amply demonstrated that major system fluctuations are caused by variations in technical effectiveness. Therefore, a policy which tries to control variations in technical effectiveness might be effective. Since the laboratory can control the amount of work it receives, to some extent at least, through the amount of marketing effort it exerts, this seemed a promising area to investigate. It was hypothesized that a policy that varied marketing effort inversely in relation to technical effectiveness would have the desired effects. When technical effectiveness was lower than normal, such a policy would increase the marketing-generated pressure on the customer to make awards and would thus prevent the slack periods from being quite as bad. Also, with more work in slack periods, technical effectiveness would recover more quickly. On the other hand, when technical effectiveness rose above normal, marketing effort would be cut. Awards would increase significantly in any case due to the increased quality of performance, and decreased marketing effort would have the beneficial effect of slowing the rate of growth so that expansion would not cause as rapid and as drastic a reduction in technical effectiveness as we have seen previously. This policy is equivalent to slowing the natural rate of growth during growth periods in an effort to maintain high technical effectiveness, and to decreasing the natural rate of decline during poor periods. It is essentially a counter-cyclical policy.

For purposes of testing this policy, the relation between technical effectiveness and the marketing effort multiplier was chosen as shown in Figure VII-15. The results of the simulation

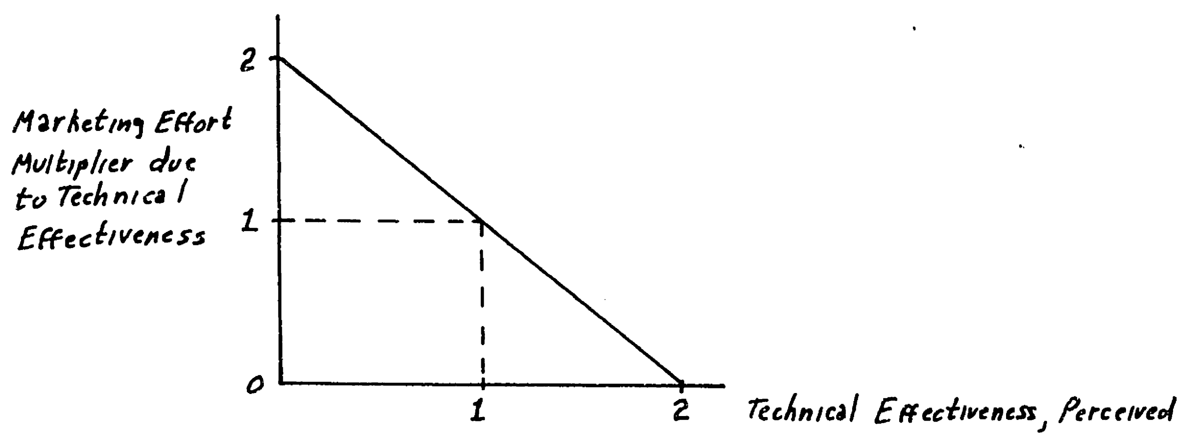

Figure VII-15: Marketing Effort Multiplier versus Perceived Technical Effectiveness

are shown in Figures VII-16 and VII-17. The improved behavior of the system is immediately evident. Variations in manpower and awards are significantly less than for the base run. The most notable improvement, however, can be seen in the relation between the level

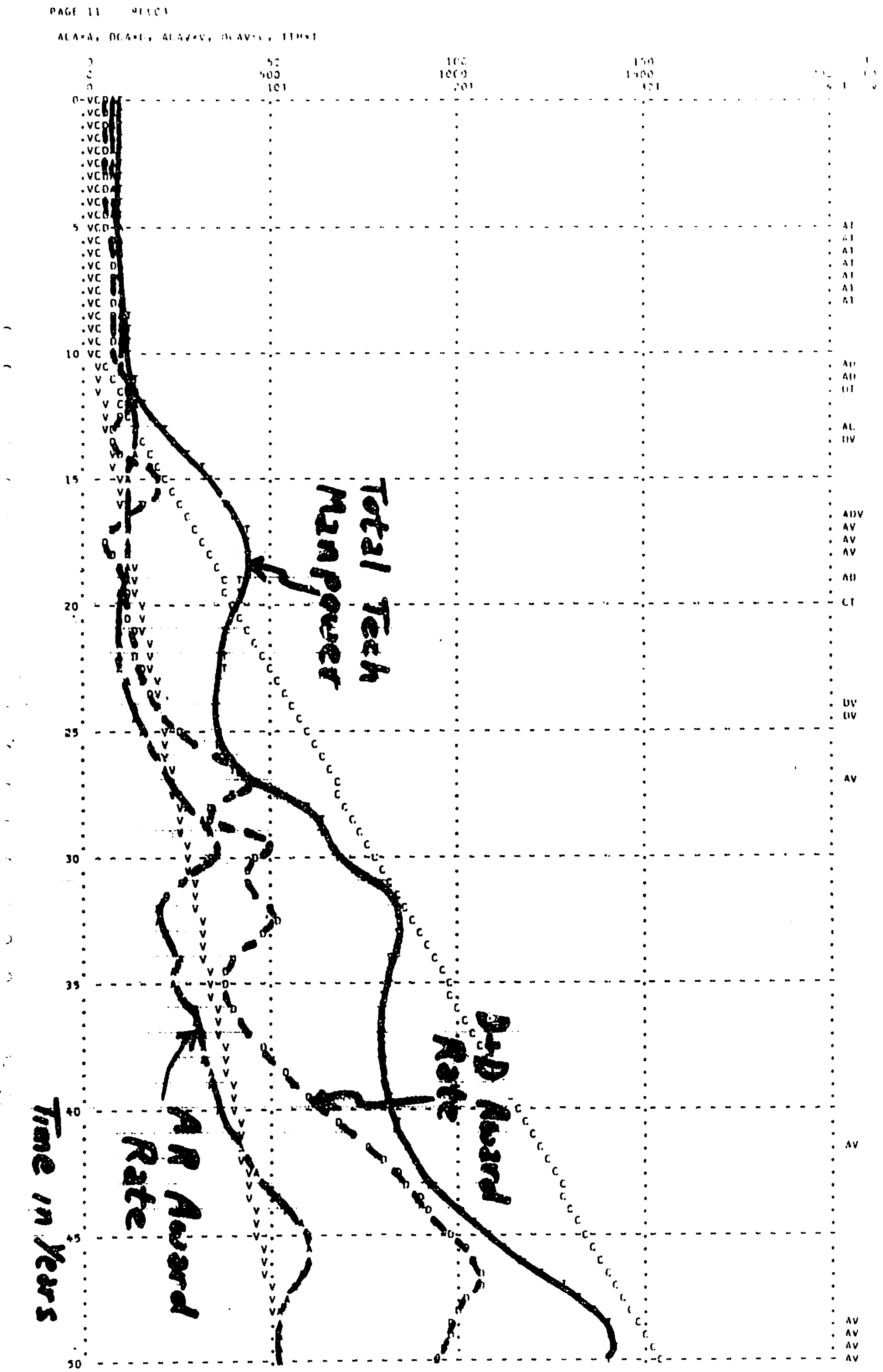

Figure VII-16: Counter-cyclical Marketing Effort Policy

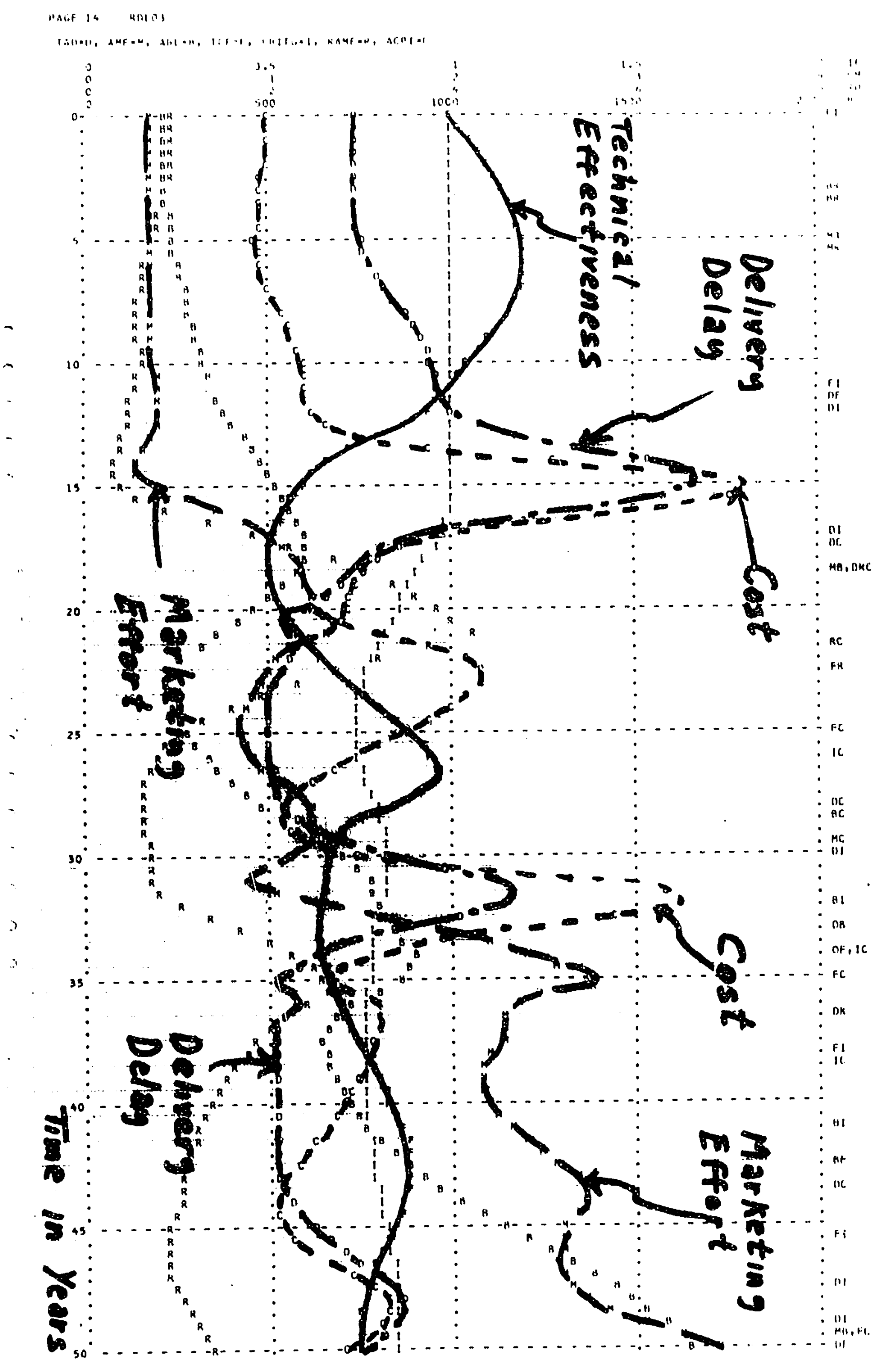

Figure VII-17: Counter-cyclical Marketing Effort Policy of technical manpower and contract awards. In terms of manpower, the organization experiences relatively smooth growth to a level of 140 technical personnel at fifty years, 90% of the peak growth exhibited in the base run. Peaks in awards are about the same height as for the base run, but because variations are much reduced, the average level of awards is significantly better. The beneficial effect of this policy on the system can be better seen in Figure VII-17. Variations in technical effectiveness decrease throughout the simulation reaching a relatively low level at the end. Thus, the counter-cyclical marketing effort policy was successful in attaining its goal. Some derivative benefits can be seen in the decreasing oscillations in advanced research cost and delivery delay. Equivalent behavior was apparent in the design and development sector.

To further test the validity of the counter-cyclical marketing effort policy, a simulation was made that varied marketing effort directly with technical effectiveness. This would be equivalent to the firm which tries to capitalize on increasing ability by expanding as much as possible. As might be expected, the system exhibited dynamic instability with ever increasing oscillations occuring in all major variables. Growth in terms of manpower was about equal to the base run, but the award rates were not nearly as good due to the larger oscillations of technical effectiveness induced by this policy.

Thus, a counter-cyclical marketing effort policy appears to be quite effective in improving the performance of an R and D organization. In view of the desires for growth,regardless of the situation, exhibited by many major R and D firms today, this conclusion is of some importance.

Variable Growth Attitude Factor

Another possible management policy is to attempt to increase the size of the organization only when the organization is perceived to be ready for expansion. One way of expressing this policy is in terms of a growth attitude factor which will express the desire of management to continue to increase the size of the organization when it is growing. Typically, management of an organization that is decreasing in size will not attempt to increase size, but will just attempt to maintain the existing conditions, unless things get really bad, when it will frantically attempt to grow. Such a policy will result in increased marketing effort during periods of growth and normal marketing effort during periods of moderate decline. It was hypothesized that such a policy would increase the growth of the organization, but that it would also increase the instability and worsen the periods of declining awards. This phenomenon was anticipated because the increased growth rate during growth periods was believed to further increase variations in technical effectiveness.

The above policy was represented in the model by a variable growth attitude factor which acted as a multiplier on normal marketing effort.[2] The relationship between the growth attitude factor and apparent growth is shown in Figure VII-18.

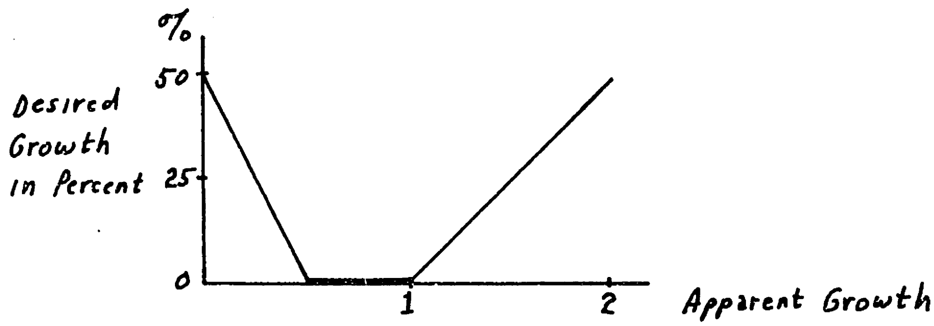

Figure VII-18: Desired Growth versus Apparent Growth

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2 The growth attitude factor was determined by the following equations. Basically, the present size of the organization is compared to a smoothed average of the past size, and this ratio is used with a table function to give the growth attitude factor.

GRF.K = TABHL(GRFT,APGR.K,0,2,0.5) A

APGR.K = TTM.K/TTMS.K A

TTMS.K = TTMS.J + (DT)(1/DTTM)(TTM.J-TTMS.J) L

GRF - GRowth attitude Factor

GRFT - GRF Table (See Figure VII-18)

APGR - APparent GRowth

TTM - Total Technical Manpower

TTMS - Total Technical Manpower, Smoothed

DTTM - Delay in smoothing TTM

The results of the computer simulation are shown in Figure VII-19. By comparing it to the base run (Figure VII-8) it can be seen that the hypothesis is substantiated. Peaks of growth are much more pronounced, but so are the valleys, so that the value of this policy is somewhat questionable.

From the forgoing simulations, one important fact seems to emerge. Technical capability or effectiveness is the most important asset an organization has.

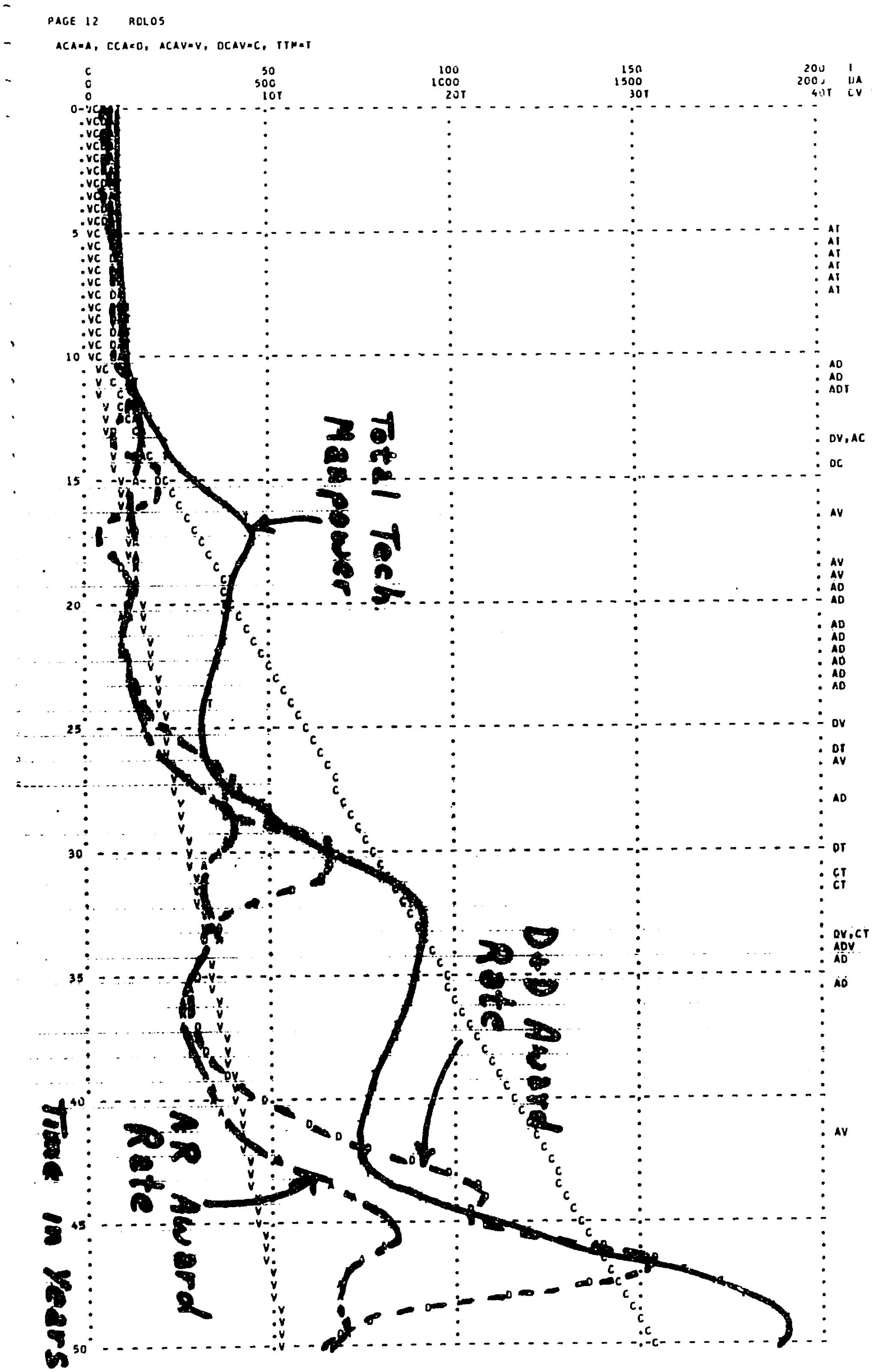

Figure VII-19: Variable Growth Attitude Factor

Chapter VIII. Conclusions

Throughout the preceding chapters, in the formulation of the conceptual framework and in the discussion of the computer simulations, it was evident that technical effectiveness was the most important variable in the system. Upon reflection, it appears reasonable to say that technical effectiveness, or the technical ability to perform technical work, is the most important determinant of the success of a research and development laboratory. This is perhaps obvious, but it is the most important conclusion discovered by this thesis.

Although many people will agree that technical effectiveness is important, it would probably be quite hard to get them to agree on many of its properties. To one it is creativity and to another it is experience. The formulation of the concept of technical effectiveness for this study was vague itself. To say that technical effectiveness depends on the amount and type of past effort and that it affects productivity and output quality leaves a large amount undefined. From this then, derives the importance of the above conclusion. A concept, vaguely defined, but hopefully realistically represented was proven to be very important. The next logical step following such a conclusion is to investigate the properties of this concept. Extensive research should be conducted with the object of discovering more exactly the properties of technical effectiveness, how it is created, how it is destroyed, and how it should be used. There is an unfortunate tendency in research to attack small problems about which a fair amount is known. An example would be research into the time allocation habits of engineers. The results of this investigation seem to indicate that there are far greater returns to be gained from attacking this very large and relatively undefined problem. Increased knowledge which would allow definite control of technical effectiveness would be invaluable in improving this country's performance in research and development.

There are several possibilities for research into this area. One obvious approach would be a direct attack on the problem through interviewing people in research and development organizations. Previous research done on creativity might be very valuable here. A second possible approach could be along the lines of the one used in this thesis. Knowledge of the importance of technical effectiveness obtained from this thesis could be used to build a relatively simple Industrial Dynamics model. This model could dispense with much of the detail included in the present model and could probably be constructed of less than fifty equations. A rough flow diagram for such a model is shown in Figure VIII-1. Note that the contract award rate depends only on technical effectiveness and the delivery delay, and that the contract finishing rate depends only on technical effectiveness and the level of technical manpower. All of the other

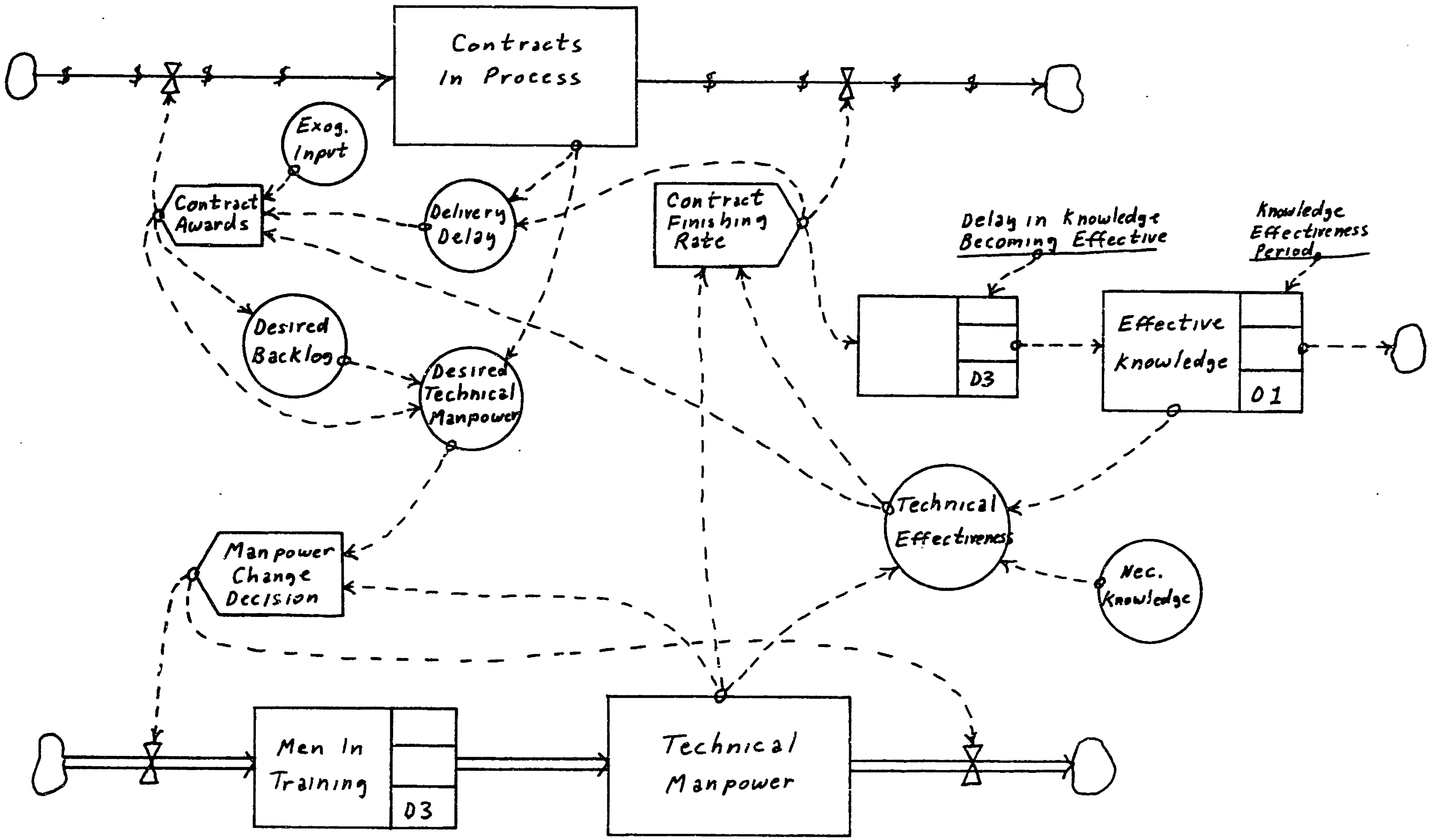

Figure VIII-1: Flow Diagram for Simple R and D Laboratory Model factors included in the present model could probably be eliminated because of their relatively small importance with respect to technical effectiveness. The most important part of this proposed model is, of course, the technical effectiveness sector. The model would provide a valuable research tool for testing different formulations of technical effectiveness, several of which were tested during the development of this thesis.

A second conclusion somewhat related to the one just presented is that growth in an R and D organization is an inherently unstable process and that good management is a prerequisite if successful growth is to be attained. It was noted earlier that with the technical effectiveness formulation used, a considerable amount of time was needed to build technical effectiveness back up after a low period. Also, rapid growth had the effect of diluting the knowledge held by the organization and resulted in drastic lowering of technical effectiveness. Thus, too rapid a growth rate had the effect of causing a decline which persisted for a period of seven to eight years during which the organization was unable to take advantage of any new opportunities. While the time periods may be different, this conclusion appears to be quite applicable to the real world. Too rapid an expansion is known to subject the organization experiencing it to a severe strain.

The importance of technical effectiveness and the inherent instability of the growth process points to a definite need for better management control of R and D. Lacking more specific knowledge of the characteristics of technical effectiveness, management should pay close attention to the fact that too rapid an expansion will result in a dilution of effective knowledge which results in a lower technical effectiveness and eventually a drastic curtailment of the contract awards to the organization. The results of this study indicate that a good method of management control of the organization's growth rate is through variation of the organization's policy for seeking and accepting contract awards. The model simulated lacked a specific mechanism for actually rejecting contract awards, but the effect of marketing effort on awards was increased somewhat to account for this.

The most successful management policy simulated was the counter-cyclical marketing effort policy. This policy increased marketing effort when technical effectiveness was low in an effort to keep the organization busy. When technical effectiveness increased, however, marketing effort was curtailed in an effort to lessen the growth rate so that a high technical effectiveness could be maintained. This policy is not the same as sitting back and waiting for the best contracts to come along, but would even counsel refusing the "plum" if it would require too much growth. The beneficial effect of this policy in smoothing out fluctuations and allowing a relatively smooth controlled growth rate was demonstrated in the simulation. A modern day example is given by the Instrumentation Laboratory at the Massachusetts Institute of Technology. Institute policy has placed a strong restraint on Instrumentation Laboratory growth, and the Laboratory has primarily grown only when it has been impossible to turn down a project for reasons of national interest. As a result, the Instrumentation Laboratory possesses a history of being very effective technically and has never suffered from a significant lack of funded work in its twenty-five year history.[1] Thus, one of the most important policies an R and D organization can have is to resist the impulse to expand at a faster rate than the organization can really successfully support.

The conceptual framework developed in Chapters II-VI appeared to produce valid dynamic behavior when the computer simulations were run. It is felt, however, that the value of this conceptual framework

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1 The worst decline experienced by the Instrumentation Laboratory occurred in 1950-51 when the level of funding dropped by 20% from $4 million to $3.2 million. For additional details, see "A Model Oriented Approach to Studying the Structure and Performance of a Research and Development Organization", by Leo P. Kane, (Unpublished Master of Science Thesis, MIT School of Industrial Management, 1963).

is not limited to providing a basis for a mathematical model. If it can be accepted as a reasonable representation for a research and development organization, it also supplies a valuable framework for organization of future study of the research and development process. By contributing to an immediate understanding of the process, the framework will help the researcher to concentrate his efforts on the more critical aspects of R and D with a resultant increase in the contributions made to knowledge of the process.

Several basic features of the conceptual framework seem to stand out in importance. They are 1.) the division of the type of work performed by the organization into advanced research, and design and development, 2.) the division of the technical effort performed by the organization into volume and quality effort, 3.) the concept of a market sector where the customer makes his award decisions based on consideration of past performance, present cost and delivery estimates, and, the extent and type of present marketing effort, 4.) the determination of required marketing effort by the capacity of the organization, and 5.) the existence of technical effectiveness as an important factor in all sectors of the system.

It is sincerely hoped that the conceptual framework developed in this thesis can and will be used outside the field of Industrial Dynamics to help foster further understanding of the research and development process and to help direct further research in this area.

Appendix A: The Mathematical Model

The general system description given in Chapters II through VI was used as a basis for the construction of a mathematical model with which to simulate the behavior over time of a typical R and D laboratory. The results of these simulations and the conclusions reached were discussed in Chapters VII and VIII. A complete understanding of the details of the mathematical model is not necessary for an understanding of the general system charactersitics and the conclusions of the study, but it is felt that such an understanding might be helpful to anyone attempting further research in this area. Therefore, this appendix will discuss the mathematical representations for some of the more complex concepts included in the model. The model consists of a series of linear and nonlinear, algebraic, and difference equations. For each sector in the model, a list of equations and a flow diagram depicting the interrelationships between the equations will be presented. The reader will also be referred to the chapter presenting the general non-mathematical discussion on the sector at hand. For each sector, the more complex relationships will then be explained. In this explanation, a knowledge of Industrial Dynamics conventions for flow diagramming and equation writing will be assumed.[1] The equations will be presented

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1 See Chapters 7 and 8 of Forrester's Industrial Dynamics for a general discussion of equations and flow diagrams.

in a form required by the DYNAMO compiler and simulator program for the IBM 709 and 7090 computers.[2]

Technical Effort Sector, Advanced Research (Chapter II)

The flow diagram for this sub-sector is shown in Figures A-1 and A-2 and the equations are listed on the next page. In keeping with the above stated policy of explaining in detail only the more complicated mathematical representations, it will be left to the reader to gain a general understanding of each sector through study of the flow diagrams and equations. This should be done before proceeding with the discussion.

There are three important concepts in this sector that will be discussed. They are 1). the volume effort rate, 2). actual quality produced, and 3). allocation of technical manpower time between these two activities.

The volume effort rate is basically a function of the average productivity of each engineer, the number of effective engineers, and the fraction allocation of engineers to volume effort. Note, however, that the equation below generates an effort rate to be tried.

AERT.K = (APRD.K)(EFAT.K) (FAAV.K)   006RL,A

AERT - Advanced Research Effort Rate to be Tried - dollars/year

APRD - A R PRoDuctivity - dollars/year/man

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2 See DYNAMO User's Manual, the MIT Press, 1961, by Alexander L. Pugh, III, for complete details, or Appendix A of Industrial Dynamics, by Jay W. Forrester, for a general discussion.

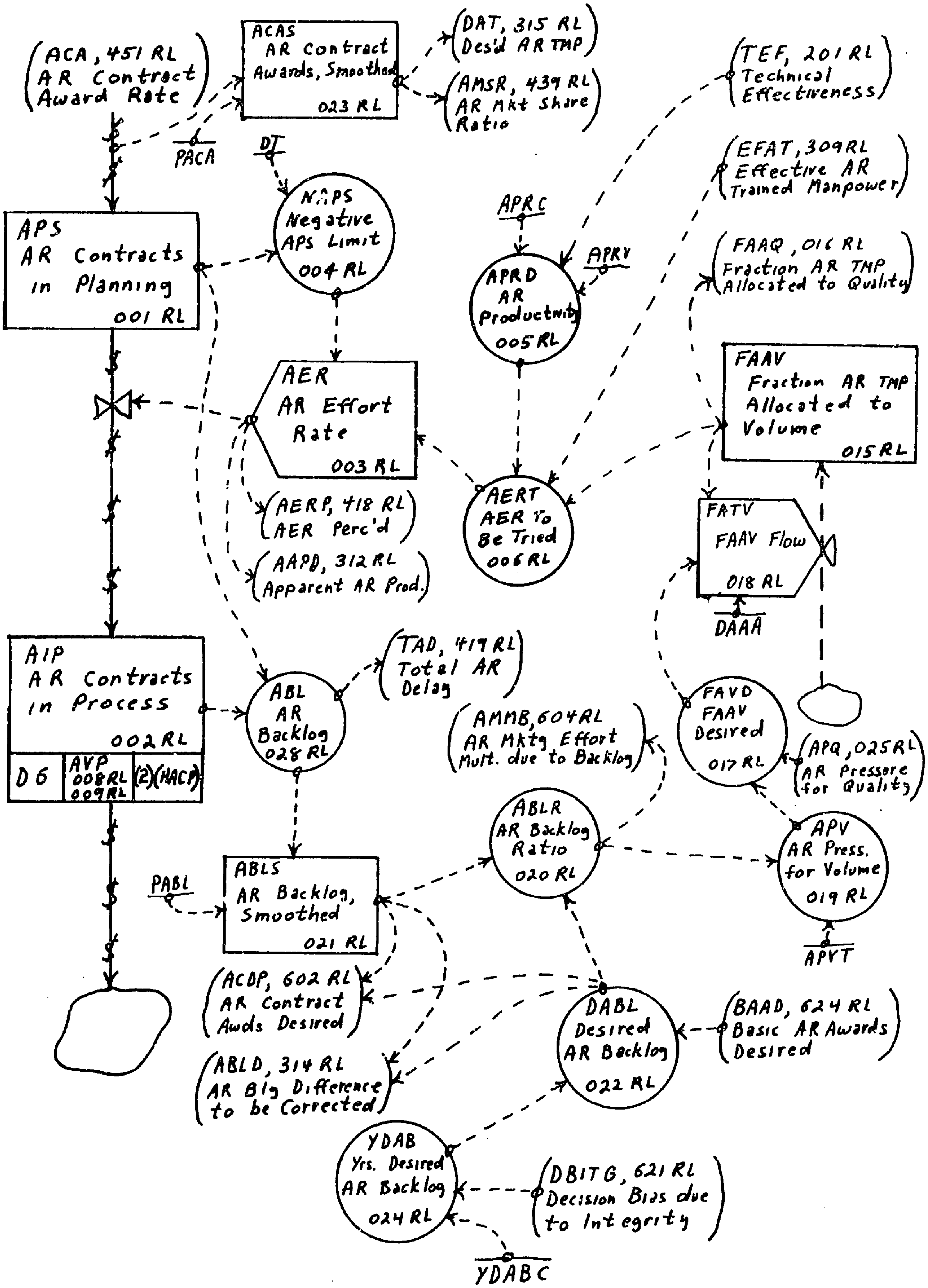

Figure A-1: Advanced Research Sector, Volume Effort

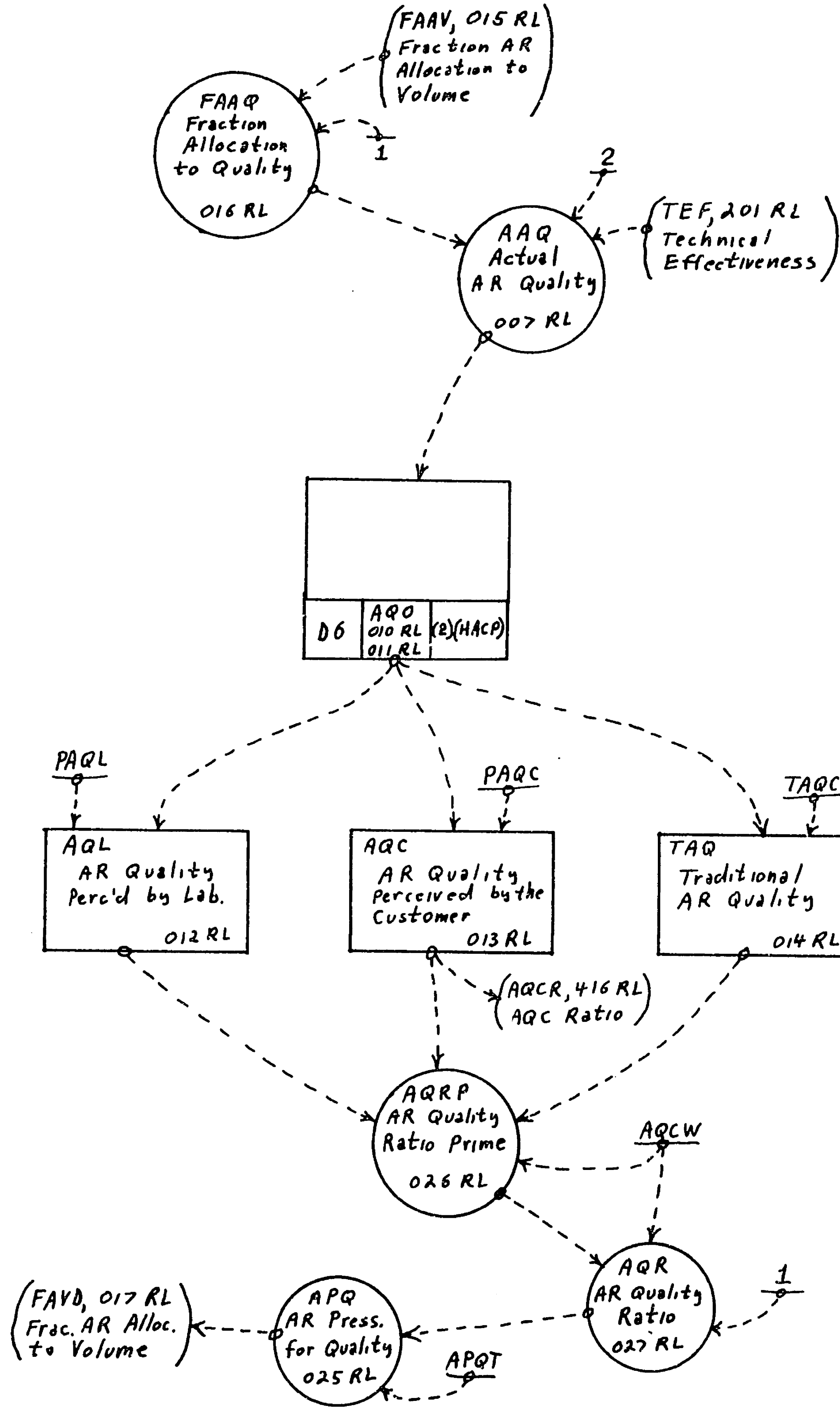

Figure A-2: Advanced Research Sector; Quality Effort

```
NØTE  ADV RESEARCH TECH EFFØRT SECTØR
NØTE
1L    APS.K=APS.J+(DT)(ACA.JK-AER.JK)                    AR CTS IN PLNNG STAGE        001RL
1L    AIP.K=AIP.J+(DT)(AER.JK-AVP.JK)                    AR IN PRØCESS                002RL
54R   AER.KL=MIN(NAPS.K,AERT.K)                          AR EFFØRT RATE               003RL
20A   NAPS.K=APS.K/DT                                    NEG APS LIMIT                004RL
14A   APRD.K=APRC+(APRV)(TEF.K)                          AR PRØDUCTIVITY              005RL
C     APRC=20
C     APRV=10
13A   AERT.K=(APRD.K)(EFAT.K)(FAAV.K)                    AR EFF RATE TØ BE TRIED      006RL
13A   AAQ.K=(FAAQ.K)(TEF.K)(2)                           ACTUAL AR QUALITY            007RL
39R   AVP.KL=DELAY3(AVPP.JK,HACP)                        AR VØL OUTPUT RATE           008RL
39R   AVPP.KL=DELAY3(AER.JK,HACP)                        AR VØL OUTPUT PRIME          009RL
C     HACP=1                                             HALF AR CIP DELAY
39R   AQØ.KL=DELAY3(AQØP.JK,HACP)                        AR QUALITY OUTPUT            010RL
39R   AQØP.KL=DELAY3(AAQ.K,HACP)                         AR QUALITY OUTPUT PRIME      011RL
3L    AQL.K=AQL.J+(DT)(1/PAQL)(AQØ.JK-AQL.J)             AR QUALITY PERCD BY LAB      012RL
C     PAQL=0.5                                           DELAY IN PERC OF AQL
3L    AQC.K=AQC.J+(DT)(1/PAQC)(AQØ.JK-AQC.J)             AR QUAL PERCD BY CUST        013RL
C     PAQC=1.5                                           DELAY IN PERC OF AQC
3L    TAQ.K=TAQ.J+(DT)(1/TAQC)(AQØ.JK-TAQ.J)             TRAD AR QUAL                 014RL
C     TAQC=10
1L    FAAV.K=FAAV.J+(DT)(FATV.JK+0)                      FRAC ATM ALLØ TØ VØL         015RL
7A    FAAQ.K=1-FAAV.K                                    FRAC ATM ALLØ TØ QUAL        016RL
48A   FAVD.K=APV.K/(APV.K+APQ.K)                         FAAV DESIRED                 017RL
21R   FATV.KL=(1/DAAA)(FAVD.K-FAAV.K)                    FAAV FLØW                    018RL
C     DAAA=1
58A   APV.K=TABHL(APVT,ABLR.K,0,2,0.2)                   AR PRESSURE FØR VØL          019RL
C     APVT*=0/.4/.7/.9/.95/1/1.05/1.1/1.3/1.6/2
20A   ABLR.K=ABLS.K/DABL.K                               AR BIG RATIØ                 020RL
3L    ABLS.K=ABLS.J+(DT)(1/PABL)(ABL.J-ABLS.J)           ABL SMØØTHED                 021RL
C     PABL=0.25                                          DEL IN PERC ØF ABL
12A   DABL.K=(YDAB.K)(BAAD.K)                            DESIRED ABL                  022RL
3L    ACAS.K=ACAS.J+(DT)(1/PACA)(ACA.JK-ACAS.J)          AR CØNT AWARDS SMØØTHED      023RL
C     PACA=2                                             DEL IN PERC ØF ACA
12A   YDAB.K=(YDABC)(DBITG.K)                            YRS DESD ABL                 024RL
C     YDABC=3                                            YRS DESD ABL CØNST
58A   APQ.K=TABHL(APQT,AQR.K,0,2,0.2)                    AR PRESSURE FØR QUAL         025RL
22A   AQRP.K=(1/TAQ.K)((AQL.K)(1)+(AQC.K)(AQCW))         AR QUAL RATIØ PRIME          026RL
```

```
C      APQT*=2/1.98/1.93/1.8/1.5/1/.8/.72/.71/.7/.7
48A    AQR.K=AQRP.K/(1+AQCW)                          AR QUAL RATIO       027RL
C      AQCW=1                                         AQC WGTG FACTOR
7A     ABL.K=APS.K+AIP.K                              AR BACKLOG          028R
18N    APS=(ACA)(YDABC-ACP)
13N    AIP=(2)(HACP)(ACA)
6N     AER=ACA
6N     AAQ=1
6N     AQL=AAQ
6N     AQC=AAQ
6N     TAQ=AAQ
6N     FAAV=0.5
6N     ABLS=ABL
6N     ACAS=ACA
```

EFAT - EFfective A R Technical manpower - men

FAAV Fraction A R Technical manpower Allocation to Volume

In order to insure that the level of contracts in the planning stage cannot go negative, the following additional equations were required.

AER.KL = MIN(NAPS.K, AERT.K)   003RL,R

NAPS.K = APS.K/DT   004RL,A

AER - A R Effort Rate - dollars/year

NAPS - Negative APS limit - dollars/year

APS - A R contracts in Planning Stage - dollars

The productivity of the average engineer depends on the technical effectiveness of the organization.

APRD.K = APRC + (APRV)(TEF.K)   005RL,A

APRD - A R PRoDuctivity - dollars/year/man

APRC - A R PRoductivity Constant - dollars/year/man

APRV - A R PRoductivity Variable - dollars/year/man

TEF - Technical EFfectiveness - dimensionless

The quality produced will depend on the fraction of effective technical manpower allocated to quality effort and on technical effectiveness.

AAQ.K = (FAAQ.K)(TEF.K)(1)   007RL,A

AAQ - Actual A R Quality - dimensionless

FAAQ - Fraction A R technical manpower Allocation to Quality - dimensionless

The most important concept in this sector is the allocation of time between volume and quality effort. This is accomplished through resolution of the pressures for volume and quality effort. The fraction allocation to volume desired is first calculated as the ratio of the pressure for volume effort to total pressure. Then the desired allocation is compared to the actual allocation, and the difference is corrected over a period of time. The fraction allocation to quality is merely one minus the fraction allocation to volume.

FAVD.K = APV.K/(APV.K + APQ.K) 017RL,A

FATV.KL = (1/DAAA)(FAVD.K–FAAV.K) 018RL,R

FAAV.K = FAAV.J + (DT)(FATV.JK) 015RL,L

FAAQ.K = 1–FAAV.K 016RL,A

FAVD – Fraction A R Allocation to Volume Desired – dimensionless

APV – A R Pressure for Volume effort – dimensionless

APQ – A R Pressure for Quality effort – dimensionless

FATV – Fraction Allocation To Volume flow – dimensionless

DAAA – Delay in Adjusting A R Allocation of time – years

FAAV – Fraction Allocation of A R technical manpower to Volume – dimensionless

FAAQ – Fraction Allocation of A R technical manpower to Quality – dimensionless

The pressure for volume effort will depend on the ratio of the perceived backlog to the desired backlog. The relationship of the pressure to this ratio is given by a table function. (Figure II-4) Pressure for quality effort is likewise given by a table function with the entering variable being the ratio of perceived quality to traditional quality.

APV.K = TABHL (APVT, ABLR.K,0,2,0.2) 019RL,A

ABLR.K = ABLS.K/DABL.K 020RL,A

APV - A R Pressure for Volume effort - dimensionless

APVT - APV Table - dimensionless

ABLR - A R BackLog Ratio - dimensionless

ABLS - A R BackLog, Smoothed - dollars

DABL - Desired A R BackLog - dollars

Technical Effort Sector, Design and Development (Chapter II)

This sector essentially parallels the previous one and similar concepts will not be presented again. However, there is one major difference that requires explanation. The design and development technical effort sector includes liaison activity with the customer and production contractors. This liaison activity requires an allocation of technical manpower and results in a quality of contracts in liaison, two concepts not present in the advanced research technical effort sector.

The determination of the quality of contracts in liaison is

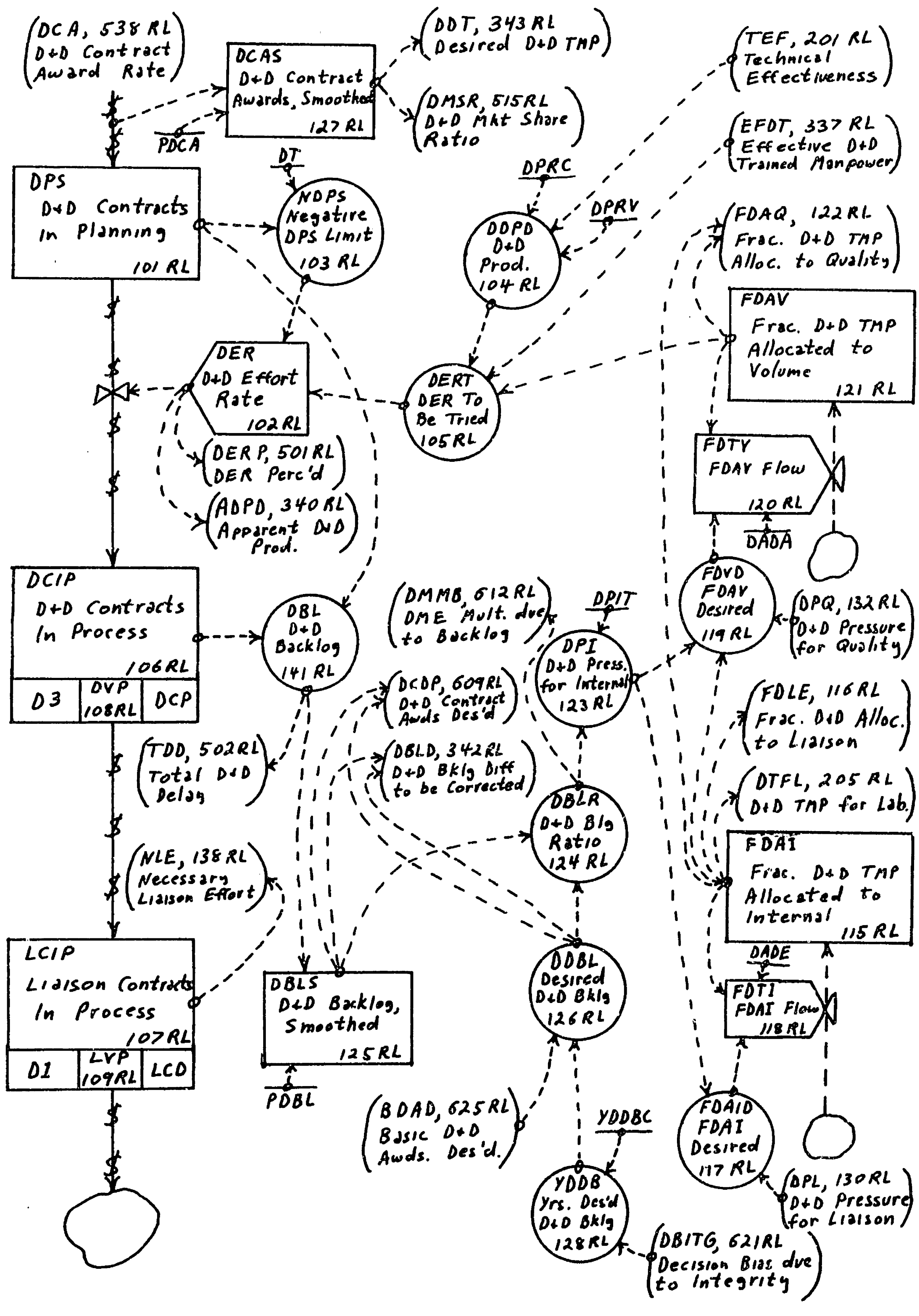

Figure A-3: Design and Development Sector, Volume Effort

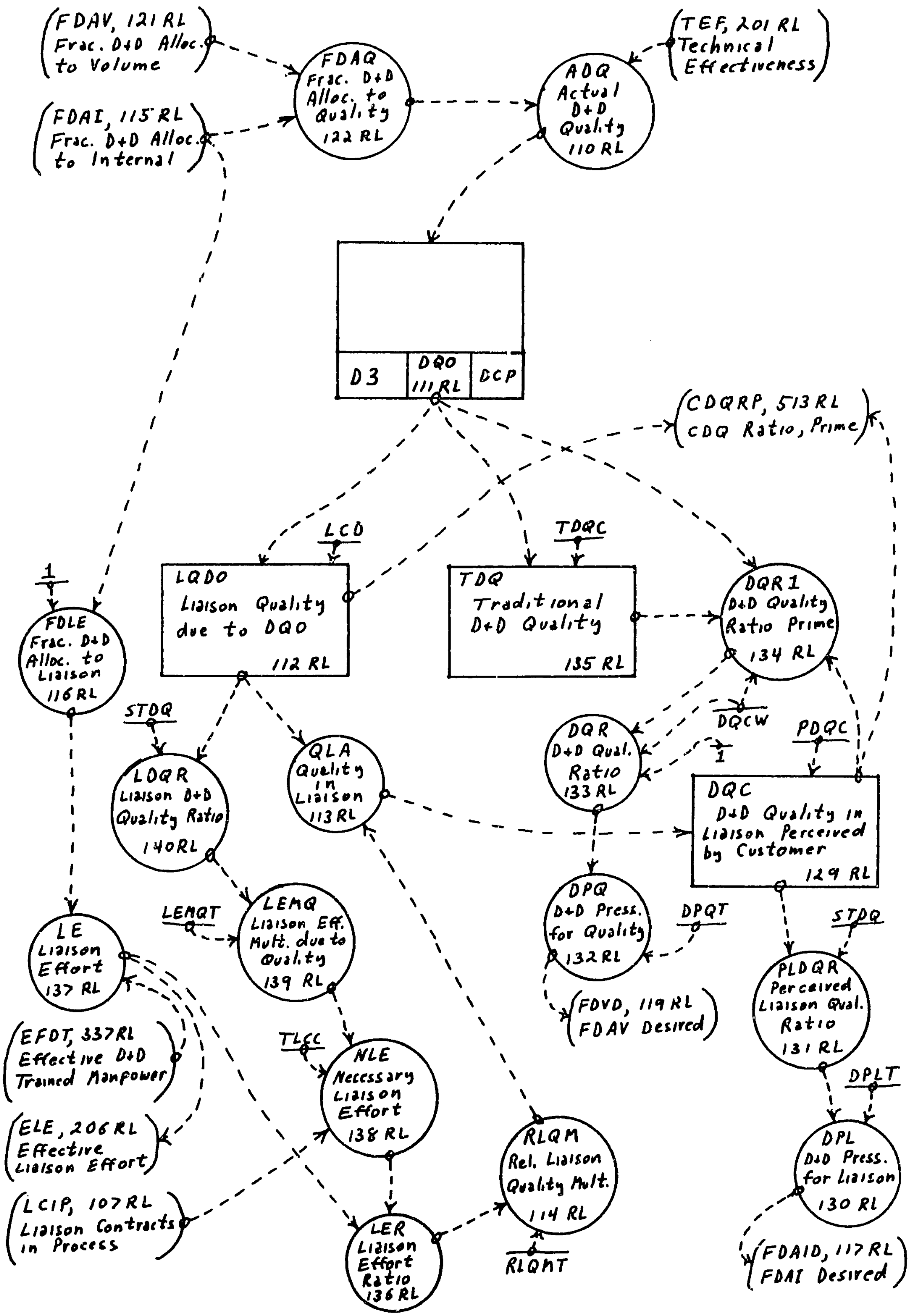

Figure A-4: Design and Development Sector, Quality Effort

```
NØTE  DESIGN AND DEVELØPMENT TECH EFFØRT SECTØR
NØTE
1L    DPS.K=DPS.J+(DT)(DCA.JK-DER.JK)                   D*D CIS IN PLNNG STAGE      101RL
54R   DER.KL=MIN(NDPS.K,DERT.K)                         D*D EFFØRT RATE             102RL
20A   NDPS.K=DPS.K/DT                                   NEG DPS LIMIT               103RL
14A   DDPD.K=DPRC+(DPRV)(TEF.K)                         D*D PRØDUCTIVITY            104RL
C     DPRC=20
C     DPRV=20
13A   DERT.K=(DDPD.K)(FDAV.K)(FEDT.K)                   D*D EFF RATE TØ BE TRD      105RL
1L    DCIP.K=DCIP.J+(DT)(DER.JK-DVP.JK)                 D*D CIP                     106RL
1L    LCIP.K=LCIP.J+(DT)(DVP.JK-LVP.JK)                 LIAISØN CIP                 107RL
39R   DVP.KL=DELAY3(DER.JK,DCP)                         D*D VØL ØUTPUT RATE         108RL
C     DCP=1.5                                           D*D CIP DELAY
20R   LVP.KL=LCIP.K/LCD                                 LIAISØN VØL ØUTPUT RATE     109RL
C     LCD=1                                             LIAISØN CIP DELAY
13A   ADQ.K=(FDAQ.K)(TEF.K)(2.1978)                     ACTUAL D*D QUALITY          110RL
39R   DQØ.KL=DELAY3(ADQ.K,DCP)                  D*D QUAL ØUTPUT                     111RL
3L    LQDØ.K=LQDØ.J+(DT)(1/LCD)(DQØ.JK-LQDØ.J)          LIASØN QUAL DUE TØ DQØ      112RL
12A   QLA.K=(LQDØ.K)(RLQM.K)                            QUAL IN LIASØN              113RL
58A   RLQM.K=TABHL(RLQMT,LER.K,0,2,0.5)                 REL LIAISØN QUAL MULT       114RL
C     RLQMT*=.5/.6/1/1.2/1.4
1L    FDAI.K=FDAI.J+(DT)(FDTI.JK+0)                     FRAC D*D ALLØ TØ INTER      115RL
7A    FDLE.K=1-FDAI.K                                   FR D*D ALLØC TØ LIAISØN     116RL
48A   FDAID.K=DPI.K/(DPI.K+DPL.K)                       FDAI DESIRED                117RL
21R   FDTI.KL=(1/DADE)(FDAID.K-FDAI.K)                  FRAC D*D TØ INT FLØW        118RL
C     DADE=0.5                                          DELAY IN ADJSTG FDAI
50A   FDVD.K=(DPI.K)(FDAI.K)/(DPI.K+DPQ.K)      FRAC D*D TØ VØL DESD                119RL
21R   FDTV.KL=(1/DADA)(FDVD.K-FDAV.K)                   FRAC D*D TØ VØL FLØW        120RL
C     DADA=1
1L    FDAV.K=FDAV.J+(DT)(FDTV.JK+0)                     FRAC D*D ALLØC TØ VØL       121RL
7A    FDAQ.K=FDAI.K-FDAV.K                      FRAC D*D ALLØC TØ QUAL              122RL
58A   DPI.K=TABHL(DPIT,DBLR.K,0,2,0.2)                  D*D PRES FØR INT ALLØC      123RL
C     DPIT*=.3/.5/.7/.8/.85/.9/.95/1/1.2/1.6/2
20A   DBLR.K=DBLS.K/DDBL.K                              DBL RATIØ                   124RL
3L    DBLS.K=DBLS.J+(DT)(1/PDBL)(DBL.J-DBLS.J)          DBL SMØØTHED                125RL
C     PDBL=0.25                                         DEL IN PERC ØF DBL
12A   DDBL.K=(YDDB.K)(BDAD.K)                           DESIRED DBL                 126RL
3L    DCAS.K=DCAS.J+(DT)(1/PDCA)(DCA.JK-DCAS.J)         D*D CØNT AW SMØØTHED        127RL
C     PDCA=2                                            DEL IN PERC ØF DCA
```

```
12A  YDDB.K=(YDDBC)(DBITG.K)                                YRS DESD DBL                    128RL
C    YDDBC=3                                                YRS DESD DBL
3L   DQC.K=DQC.J+(DT)(1/PDQC)(QLA.J-DQC.J)                  D*D QUAL LIAISØN CUST           129RL
C    PDQC=1                                                 DEL IN PERC ØF DQC
58A  DPL.K=TABHL(DPLT,PLDQR.K,0,2,0.2)                      D*D PRESS FØR LIAISØN           130RL
20A  PLDQR.K=DQC.K/STDQ                                     PERC LIAS D QUAL RATIØ          131RL
C    DPLT*=.36/.35/.32/.28/.20/.1/.05/.03/.02/.015/.01
C    STDQ=1                                                 STD D*D QUAL
58A  DPQ.K=TABHL(DPQT,DQR.K,0,2,0.2)                        D*D PRES FØR QUAL               132RL
C    DPQT*=2/1.98/1.93/1.8/1.5/1/.8/.72/.71/.7/.7
48A  DQR.K=DQR1.K/(1+DQCW)                              D*D QUAL RATIØ                      133RL
22A  DQR1.K=(1/TDQ.K)((DQØ.K)(1)+(DQC.K)(DQCW))         D*D QUAL RATIØ 1                    134RL
C    DQCW=1                                                 DQC WGTG FACTØR
3L   TDQ.K=TDQ.J+(DT)(1/TDQC)(DQØ.JK-TDQ.J)                 TRAD D*D QUAL                   135RL
C    TDQC=10
20A  LER.K=LE.K/NLE.K                                       LIAISØN EFFØRT RATIØ            136RL
12A  LE.K=(EFDT.K)(FDLE.K)                                  LIAISØN EFFØRT                  137RL
13A  NLE.K=(TLCC)(LCIP.K)(LEMQ.K)                           NEC LIA EFF FØR STD QUAL        138RL
C    TLCC=0.004945                                      TMP/LIASØN CØNTRACT
58A  LEMQ.K=TABHL(LEMQT,LDQR.K,0,2,0.2)                     LIA EFF MULT DUE TØ QUAL        139RL
C    LEMQT*=20/8/5/3/1.7/1/.9/.75/.7/.65/.6
20A  LDQR.K=LQDØ.K/STDQ                                     LIA D*D QUAL RATIØ              140RL
7A   DBL.K=DPS.K+DCIP.K                                     D*D BACKLØG                     141RL
18N  DPS=(DCA)(YDDBC-DCP)
12N  DCIP=(DCP)(DCA)
12N  LCIP=(LCD)(DCA)
6N   DER=DCA
6N   ADQ=1
6N   LQDØ=ADQ
6N   EDAI=0.91
6N   EDAV=0.455
6N   DBLS=DBL
6N   DCAS=DCA
6N   DQC=ADQ
6N   TDQ=ADQ
```

fairly complex. Contracts entering liaison have a basic quality resulting from the quality of the R and D laboratory's work. This basic quality can be raised or lowered by the relative amount of liaison expended by the laboratory.

QLA.K = (LQDO.K)(RLQM.K) 113RL, A

RLQM.K = TABHL(RLQMT,LER.K,0,2,0.5) 114RL,A

LER.K = LE.K/NLE.K 136RL, A

QLA - Quality in LiAison - dimensionless

LQDO - Liaison Quality due to D & D quality Output - dimensionless

RLQM - Relative Liaison Quality Multiplier - dimensionless

RLQMT - RLQM Table - dimensionless

LER - Liaison Effort Ratio - dimensionless

LE - Liaison Effort - men

NLE - Necessary Liaison Effort - men

The relative liaison quality multiplier (RLQM) determines how much liaison quality can be increased or decreased from the normal value by exerting more or less liaison effort than that necessary for normal quality. The necessary liaison effort for normal quality (NLE) is not constant, however. It depends on the number of contracts in liaison and on the basic quality of the laboratory's work.

NLE.K = (TLCC)(LCIP.K)(LEMQ.K) 138RL,A

LEMQ.K = TABHL(LEMQT,LDQR.K,0,2,0.2) 139RL, A

LDQR.K = LQDO.K/STDQ 140RL, A

NLE - Necessary Liaison Effort - men

TLCC - Technical manpower/Liaison Contract Constant - men/dollars

LCIP - Liaison Contracts In Process - dollars

LEMQ - Liaison Effort Multiplier due to basic Quality - dimensionless

LEMQT - LEMQ Table (Figure II-8) - dimensionless

LDQR - Liaison D & D Quality Ratio - dimensionless

LQDO - Liaison Quality due to D & D quality Output - dimensionless

STDQ - Standard D & D Quality - dimensionless

The basic quality of the organization's work is compared to the industry standard and this ratio determines a multiplier for the necessary liaison effort per contract. (See Figure II-8) The multiplier times a constant and the number of contracts gives the necessary effort for normal quality.

Since technical manpower time must be allocated to an additional activity in this sector, the time allocation mechanism is necessarily somewhat more complex. A mathematical representation for straight time allocation among the three activities, volume effort, quality effort, and liaison effort, was felt to be too complicated. Therefore, a somewhat simpler scheme was chosen. Since allocation of time to two activities, as was done in the advanced research part of the technical effort sector, is quite simple, it was decided to stick to two-way allocations. Technical manpower time is first divided between liaison effort and internal effort by the same type of pressure mechanism as previously, and then the total allocation to internal effort is divided between volume and quality effort, again by the same type of mechanism. It should not be necessary to repeat the equations for the allocation at this point since the above description should enable the reader to understand the concept by studying the listing of equations for this sector.

<u>Technical Effectiveness Sector</u> (Chapter IV)

The mathematical representation for technical effectiveness is quite straight forward. Technical effectiveness is generated by a table function dependent on the ratio of effective knowledge per man to necessary knowledge per man.

TEF.K = TABHL(TEFT,TEFR.K,0,2,0.2,) 201RL, A

TEFR.K = EFKM.K/NEKM.K 214RL, A

TEF - Technical EFfectiveness - dimensionless

TEFT - TEF Table - dimensionless

TEFR - TEF Ratio - dimensionless

EFKM - EFfective Knowledge per Man - dimensionless

NEKM - NEcessary Knowledge per Man - dimensionless

The generation of the level of effective knowledge is a bit more complex, however. The major inflow into the level consists of knowledge resulting from effective technical effort. Technical

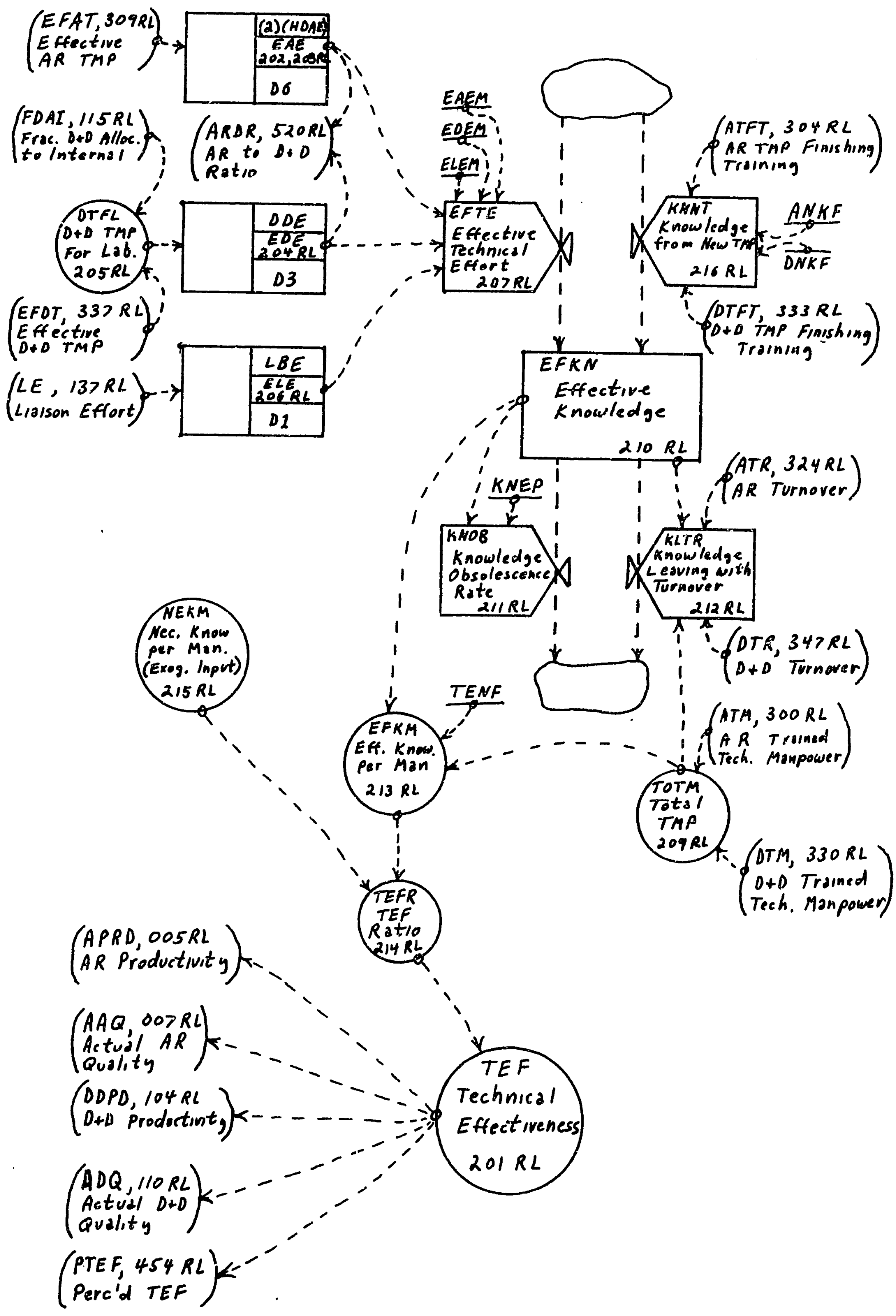

Figure A-5: Technical Effectiveness Sector

```
NØTE  TECHNICAL EFFECTIVENESS SECTØR
NØTE
58A   TEF.K=TABHL(TEFT,TEFR.K.0,2,0.2)                   TECHNICAL EFFECTIVENESS  201RL
C     TEFT*=0.4/.43/.5/.64/.8/1/1.24/1.52/1.75/1.92/2
39R   EAE.KL=DELAY3(EAE1.JK,HDAE)                        EFF AR EFFØRT            202RL
39R   EAE1.KL=DELAY3(EFAT.K,HDAE)                        EFF AS EFFØRT ØNE        203RL
C     HDAE=2.5
39R   EDE.KL=DELAY3(DTFL.K,DDE)                          EFF D*D EFFØRT           204RL
12A   DTFL.K=(FDAI.K)(EFDT.K)                            D*D TMP FØR LAB          205RL
C     DDE=2.5
3L    ELE.K=ELE.J+(DT)(1/LBE)(LE.J-ELE.J)                EFF LIAISØN EFFØRT       206RL
C     LBE=1
16R   EFTE.KL=(EAEM)(EAE.JK)+(EDEM)(EDE.JK)+(ELEM)(ELE.JK)+(0)(0)                 207RL
C     EAEM=2.5
C     EDEM=1.5
C     ELEM=0.5
52L   EFKN.K=EFKN.J+(DT)(EFTE.JK+KNNT.JK-KLTR.JK-KNØB.JK)    EFF KNØW             210RL
20R   KNØB.KL=EFKN.K/KNEP                                KNØW ØBSØLESCENCE RATE   211RL
C     KNEP=15
22R   KLTR.KL=(1/TØTM.K)((EFKN.K)(ATR.JK)+(EFKN.K)(DTR.JK)) KNGE LVG TRN          212RL
42A   EFKM.K=EFKN.K/((TØTM.K)(TENF))                     EFF KNØW PER MAN         213RL
7A    TØTM.K=ATM.K+DTM.K                                 TØT TRND TMP             209RL
C     TENF=11.73323
20A   TEFR.K=EFKM.K/NEKM.K                               TEF RATIØ                214RL
45A   NEKM.K=STEP(NEKC,NST)                              NEC KNØW PER MAN         215RL
C     NEKC=1.5
C     NST=51
15R   KNNT.KL=(ANKF)(ATFT.JK)+(DNKF)(DTFT.JK)            KNØW FRØM NEW TMP        216RL
C     ANKF=1
C     DNKF=0.5
6N    ELE=LE
6N    EFKN=100
6N    NEKM=1
6N    TEF=1
```

effort will result in effective knowledge only after a delay, and some kinds of work are more valuable than others in producing knowledge. This is represented mathematically by using different forms of lagged relationships and weighting factors for each kind of work. The number of effective technical personnel in each kind of work at any one time is used as a measure of the technical effort being generated.

EFTE.KL = (EAEM)(EAE.JK) + (EDEM)(EDE.JK) + (ELEM)(ELE.K) 207RL, R

EAE.KL = DELAY6(EFAT.K,DAE) 202RL, 203RL, R

EDE.KL = DELAY3(DTFL.K,DDE) 204RL, R

ELE.K = ELE.J + (DT)(1/LBE)(LE.J-ELE.J) 206RL, L

EFTE - EFfective Technical Effort - men/year

EAEM - Effective A R Effort Multiplier - dimensionless

EAE - Effective A R Effort - men/year

EDEM - Effective D & D Effort Multiplier - dimensionless

EDE - Effective D & D Effort - men/year

ELEM - Effective Liaison Effort Multiplier - dimensionless

ELE - Effective Liaison Effort - men/year

EFAT - EFfective A R Technical manpower - men

DAE - Delay in A R Effort becoming effective - years

DTFL - D & D Technical manpower For Laboratory - men

DDE - Delay in D & D Effort becoming effective - years

LBE - delay in Liaison effort Becoming Effective - years

LE - Liaison Effort - men

The other flows affecting effective knowledge are the knowledge obsolescence rate, the inflow of knowledge accompanying new people, and the outflow of knowledge accompanying people leaving. These flows are quite straight forward and will not be discussed further.

Technical Manpower Sector (Chapter III)

The technical manpower sector involves two major concepts that will be discussed here. They are 1). the determination of the level of effective technical manpower, and 2). the determination of the rates at which technical personnel enter and leave the organization. Since the advanced research and design and development parts of this sector essentially parallel each other, the explanation will be presented only for advanced research.

The entire number of trained technical personnel in an organization is not effective in producing technical effort. Various subsidiary activities such as hiring and training of new personnel, and marketing also require the efforts of trained personnel, thus reducing the number fully-effective technically. This concept is represented in the model in the following manner: the amount of training activity necessary depends on the percentage of new people in the organization. A multiplier due to training requirements is generated and depends on the ratio of personnel in training to trained personnel. Likewise, the amount of hiring activity required will depend on the extent of hiring. The multiplier due to hiring

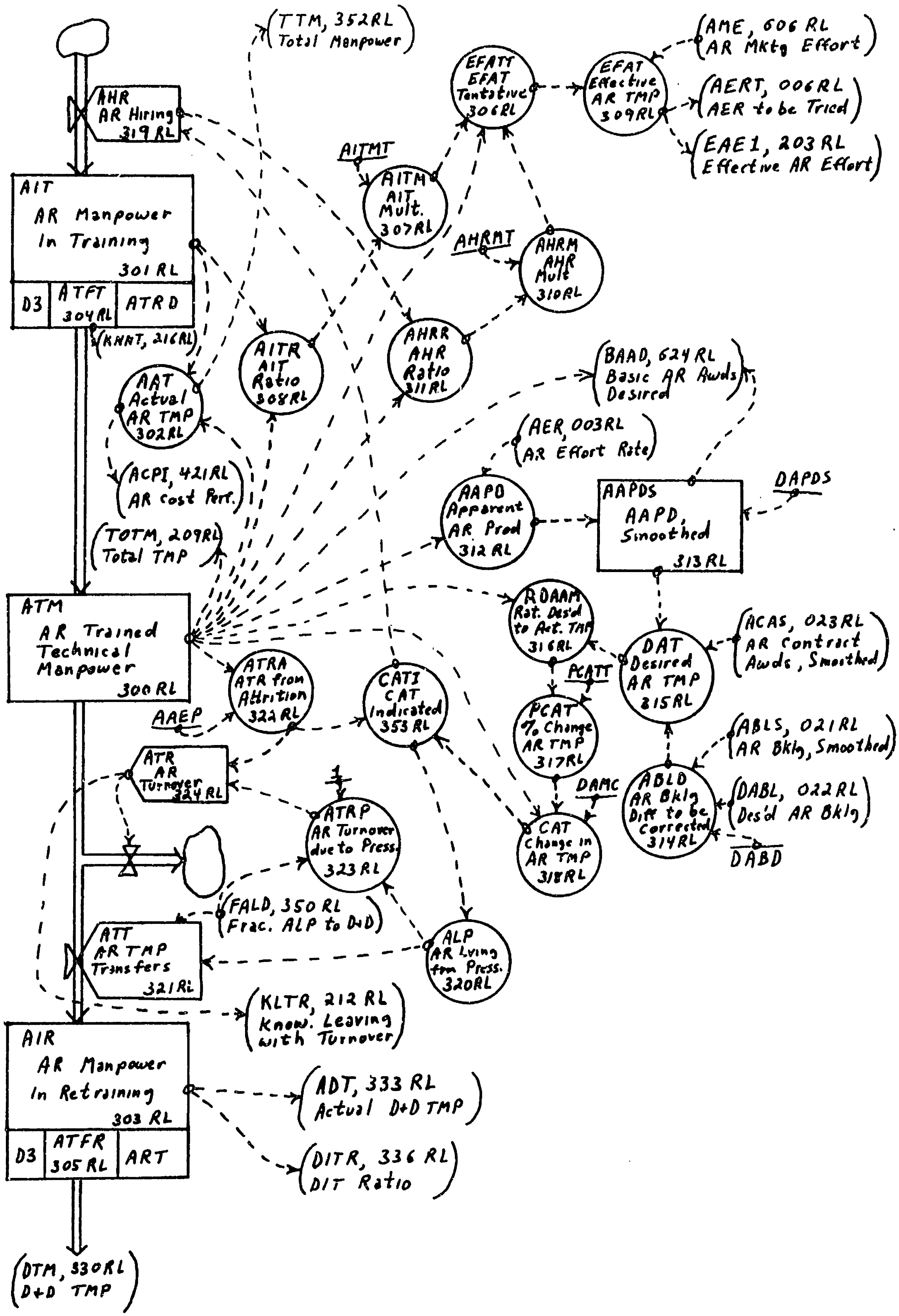

Figure A-6: Technical Manpower Sector, AR Manpower

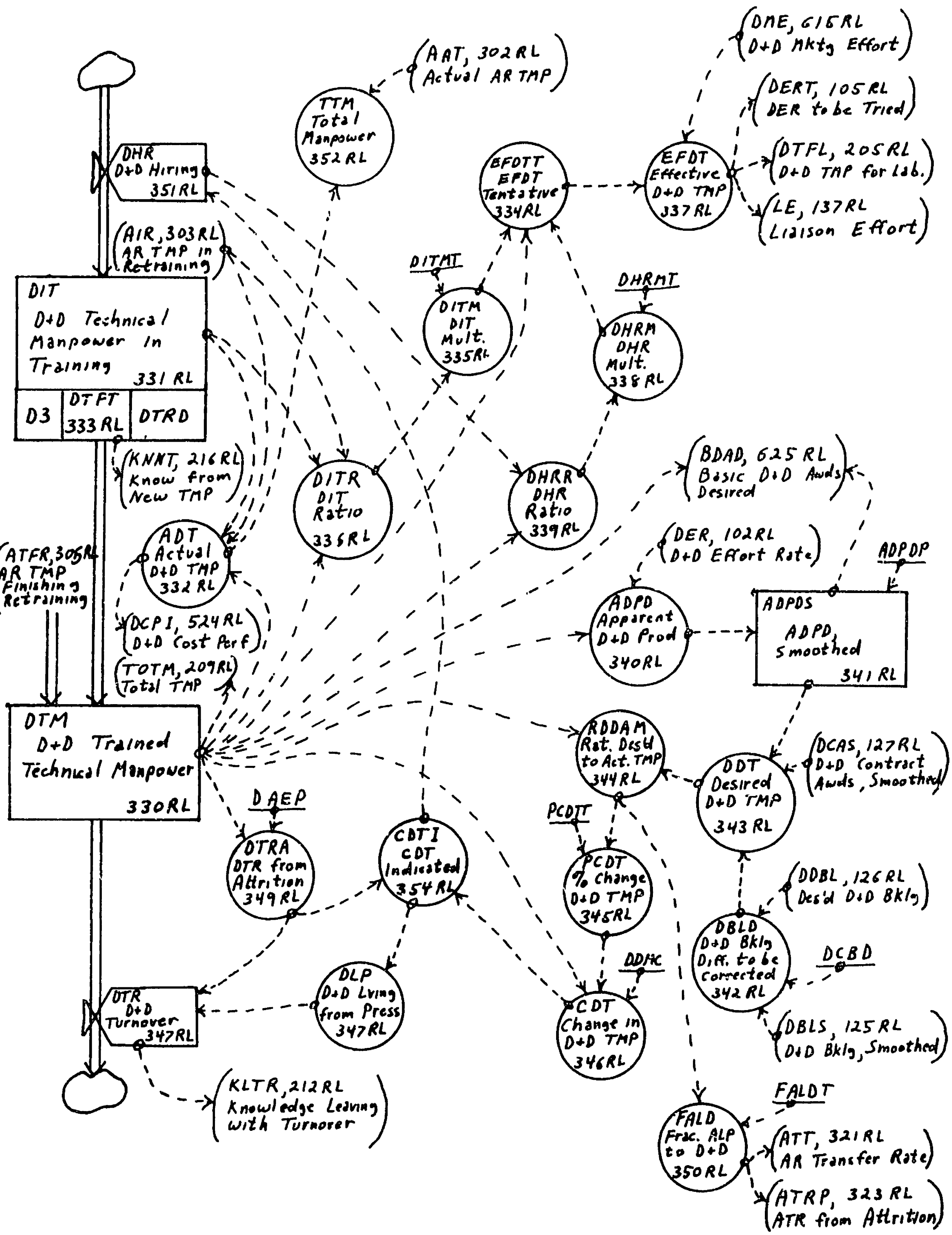

Figure A-7: Technical Manpower Sector, Design and Development

```
NØTE  TECHNICAL MANPØWER SECTØR
NØTE
52L   ATM.K=ATM.J+(DT)(ATFT.JK-ATR.JK-ATT.JK+0)    AR TRND TECH MNPWR          300RL
1L    AIT.K=AIT.J+(DT)(AHR.JK-ATFT.JK)             AR TMP IN TRNG              301RL
7A    AAT.K=ATM.K+AIT.K                            ACTUAL AR TMP               302RL
1L    AIR.K=AIR.J+(DT)(ATT.JK-ATFR.JK)             AR TMP IN RETRNG            303RL
39R   ATFT.KL=DELAY3(AHR.JK,ATRD)                  AR TMP FINISHG TRNG         304RL
C     ATRD=1.5                                     AR TMP TRNG DEL
39R   ATFR.KL=DELAY3(ATT.JK,ART)                   AR TMP FINISHG RETRNG       305RL
C     ART=0.5                                      AR TMP RETRNG DEL
13A   EFATT.K=(ATM.K)(AITM.K)(AHRM.K)              EFF AR TMP TENTATIVE        306RL
58A   AITM.K=TABHL(AITMT,AITR.K,0,.5,.1)           AIT MULT                    307RL
C     AITMT*=1/1/.9/.8/.7/.6
20A   AITR.K=AIT.K/ATM.K                           AIT RATIØ                   308RL
7A    EFAT.K=EFATT.K-AME.K                         EFF AR TMP                  309RL
58A   AHRM.K=TABHL(AHRMT,AHRR.K,0,1,0.2)           AR TMP HIRING MULT          310RL
C     AHRMT*=1/.995/.99/.98/.97/.96
20A   AHRR.K=AHR.JK/ATM.K                          AHR RATIØ                   311RL
20A   AAPD.K=AER.JK/ATM.K                          APPARENT AR PRØD            312RL
3L    AAPDS.K=AAPDS.J+(DT)(1/DAPDS)(AAPD.J-AAPDS.J)                            313RL
C     DAPDS=2                                      DEL IN PERC AAPD
21A   ABLD.K=(1/DABD)(ABLS.K-DABL.K)               AR BLG DIFF TØ BE CØRR      314RL
C     DABD=4                                       DEL IN CØRR AR BLG DIFF
22A   DAT.K=(1/AAPDS.K)((ACAS.K)(MEAM.K)+(ABLD.K)(MEAM.K))  DESD AR TMP        315RL
58A   MEAM.K=TABHL(MEAMT,PTEF.K,0,2,0.5)           MGT ENCØURAGT ØF AR MUL     354RL
C     MEAMT*=1/1/1/1/1
20A   RDAAM.K=DAT.K/ATM.K                          RAT DES TØ ACT TMP          316RL
58A   PCAT.K=TABHL(PCATT,RDAAM.K,0,2,0.2)          PERCENT CNGE IN AR TMP      317RL
C     PCATT*=-.2/-.17/-.1/-.05/-.02/0/.1/.3/.7/.9/1
44A   CAT.K=(PCAT.K)(ATM.K)/DAMC                   CHGE IN AR TMP              318RL
C     DAMC=1
7A    CATI.K=CAT.K+ATRA.K                          CHG IN AR TMP IND           353RL
56R   AHR.KL=MAX(CATI.K,0)                         AR HIRING AATE              319RL
56A   ALP.K=MAX(-CATI.K,0)                         AR LVG RATE DUTØ PRESS      320RL
12R   ATT.KL=(FALD.K)(ALP.K)                       AR TMP TRANSFER RATE        321RL
20A   ATRA.K=ATM.K/AAEP                            AR TNØV FRM ATTRITIØN       322RL
C     AAEP=20                                      AVG AR EMP PD
18A   ATRP.K=(ALP.K)(1-FALD.K)                     AR TNØVR DUE TØ PRESS       323RL
7R    ATR.KL=ATRP.K+ATRA.K                         AR TURNØVER RATE            324RL
```

```
52L  DTM.K=DTM.J+(DT)(DTFT.JK+ATFR.JK-DTR.JK+0)  D*D TRND TMP                  330RL
1L   DIT.K=DIT.J+(DT)(DHR.JK-DTFT.JK)       D*D TMP IN TRNG                    331RL
8A   ADT.K=DIT.K+DTM.K+AIR.K                     ACT D*D TMP                   332RL
39R  DTFT.KL=DELAY3(DHR.JK,DTRD)            D*D TMP FINISHG TRNG               333RL
C    DTRD=1                                      D*D TRNG DEL
13A  EFDTT.K=(DTM.K)(DITM.K)(DHRM.K)             EFF D*D TMP TENTATIVE         334RL
58A  DITM.K=TABHL(DITMT,DITR.K,0,.5,.1)          DIT MULT                      335RL
C    DITMT*=1/1/.9/.8/.7/.6
21A  DITR.K=(1/DTM.K)(DIT.K+AIR.K)               DIT RATIØ                     336RL
7A   EFDT.K=EFDTT.K-DME.K                        EFF D*D TMP                   337RL
58A  DHRM.K=TABHL(DHRMT,DHRR.K,0,1,0.2)          D*D HIRING RATE MULT          338RL
C    DHRMT*=1/.995/.99/.98/.97/.96
20A  DHRR.K=DHR.JK/DTM.K                         D*D HIRING RATE RATIØ         339RL
20A  ADPD.K=DER.JK/DTM.K                         APP D*D PRØD                  340RL
3L   ADPDS.K=ADPDS.J+(DT)(1/ADPDP)(ADPD.J-ADPDS.J)    APP D*D PR SM            341RL
C    ADPDP=2                                     DEL IN PERC D*D PRØD
21A  DBLD.K=(1/DCBD)(DBLS.K-DDBL.K)              D*D BIG DIFF TØ BE CØR        342RL
C    DCBD=2                                      DEL IN CØRR D*D BLG DIF
21A  DDT.K=(1/ADPDS.K)(DCAS.K+DBLD.K)            DESIRED D*D TMP               343RL
20A  RDDAM.K=DDT.K/DTM.K                         RAT DESD TØ ACT D*D TMP       344RL
58A  PCDT.K=TABHL(PCDTT,RDDAM.K,0.2,0.2)         PERCENT CHGE IN D*D TMP       345RL
C    PCDTT*=-.2/-.17/-.1/-.05/-.02/0/.1/.3/.7/.9/1
44A  CDT.K=(PCDT.K)(DTM.K)/DDMC                  CHGE IN D*D TMP               346RL
C    DDMC=1
7A   CDTI.K=CDT.K+DTRA.K                    CHG IN D*D TMP IND                 354RL
7R   DTR.KL=DLP.K+DTRA.K                         D*D TURNØVER RATE             347RL
56A  DLP.K=MAX(-CDTI.K,0)                   D*D LVG RATE DUTØ PRESS            348RL
20A  DTRA.K=DTM.K/DAEP                           D*D TRNØVER FRØM ATTRI        349RL
C    DAEP=15
58A  FALD.K=TABHL(FALDT,RDDAM.K,0.5,2,0.5)    FR ALP TØ D*D                    350RL
C    FALDT*=0/.1/.25/.5
56R  DHR.KL=MAX(CDTI.K,0)                   D*D HIRING RATE                    351RL
7A   TTM.K=AAT.K+ADT.K                           TØT TECH MANPWR               352RL
6N   ATM=5.3811
12N  AIT=(ATRD)(AHR)
6N   AIR=0
6N   AAPDS=AAPD
6N   AHR=ATRA
6N   DTM=3.1417
```

```
12N   DIT=(DTRD)(DHR)
6N    ADPDS=ADPD
6N    DHR=DTRA
```

requirements depends on the ratio of the hiring rate to trained technical manpower. The number of trained technical personnel is multiplied by these two multipliers to give a tentative effective manpower level, and finally the people required for marketing effort are subtracted to give the actual level of effective technical manpower.

EFAT.K = (ATM.K)(AITM.K)(AHRM.K)-AME.K 306RL,309RL, A

AITM.K = TABHL(AITMT,AITR.K,0,.5,0.1) 307RL, A

AITR.K = AIT.K/ATM.K 308RL, A

AHRM.K = TABHL(AHRMT,AHRR.K,0,1,0.2) 310RL, A

AHRR.K = AHR.JK/ATM.K 311RL, A

EFAT - EFfective A R Technical manpower - men

ATM - A R Trained technical Manpower - men

AITM - A R technical manpower In Training Multiplier - dimensionless

AHRM - A R technical manpower Hiring Rate Multiplier - dimensionless

AME - A R Marketing Effort - men

AITMT - AITM Table - dimensionless

AITR - A R technical manpower In Training Ratio - dimensionless

AIT - A R technical manpower In Training - men

AHRMT - AHRM Table - dimensionless

AHRR - A R Hiring Rate Ratio - dimensionless

AHR - A R Hiring Rate - men/year

The representation for the manpower change decision is fairly complex. Basically, a desired level of technical manpower based on the organization's backlog is compared to the actual level of manpower, and the appropriate action (hiring or increasing pressure for personnel to leave) is taken. The situation is somewhat complicated by the fact that there are always some people leaving of their own accord. The desired level of technical manpower is found by dividing the desired rate at which work is to be started by the perceived productivity of the average engineer. The desired rate at which work is to be started is the sum of the perceived contract award rate and the backlog difference to be corrected. The backlog difference to be corrected represents the organization's attempt to adjust the actual backlog to the level desired over a period of time in order to meet schedules while ensuring stability.

DAT.K = (1/AAPDS.K)(ACAS.K+ ABLD.K) 315RL, A

ABLD.K = (1/DABD)(ABLS.K–DABL.K) 314RL, A

AAPD.K = AER.JK/ATM.K 312RL, A

AAPDS.K = AAPDS.J + (DT)(1/DAPDS)(AAPD.J–AAPDS.J) 313RL, L

DAT – Desired A R Technical manpower – men

AAPDS – Apparent A R Productivity, Smoothed – dollars/year/man

ACAS – A R Contract Award rate, Smoothed – dollars/year

ABLD – A R BackLog Difference to be corrected – dollars/year

DABD - Delay in correcting A R Backlog Difference - years

ABLS - A R BackLog, Smoothed - dollars

DABL - Desired A R BackLog - dollars

AAPD - Apparent A R ProDuctivity - dollars/year/man

AER - A R Effort Rate - dollars/year

ATM - A R Technical Manpower - men

DAPDS - Delay in perception of AAPD - years

The desired level of technical manpower is then compared to the actual level and the percent change in the size of the organization to be attempted over a certain period of time is given by a table function. This percent change multiplied by the existing level of manpower and divided by the delay in carrying out the change gives the desired change rate in men per year. At this point, the picture is somewhat complicated by the phenomenon of attrition. People will always leave, no matter how good business is. This is represented by having an outflow of people equal to the level of people in the organization divided by the average employment period. In the manpower change policy, it is possible for management to either overlook attrition, or to take it into account. In the deck listing, it is taken into account, but it will be ignored here for simplicity. Under this assumption, if an increase in technical manpower is indicated, the inflow of people will equal the hiring rate and the outflow will equal attrition. If a decrease is indicated, there will be no hiring and the outflow will consist of natural attrition and people leaving due to pressure.

PCAT.K = TABHL(PCATT,RDAAM.K,0,2,0.2) 317RL, A

RDAAM.K = DAT.K/ATM.K 316RL, A

CAT.K = (PCAT.K)(ATM.K)/DAMC 318RL, A

AHR.KL = MAX(CAT.K,0) 319RL, R

ALP.K = MAX(-CAT.K,0) 320RL, A

ATRA.K = ATM.K/AAEP 322RL, A

PCAT - Percent Change in A R Technical manpower - dimensionless

PCATT - PCAT Table (Figure III-6) - dimensionless

RDAAM - Ratio Desired to Actual A R Manpower - dimensionless

CAT - Change in A R Technical manpower rate - men/year

DAMC - Delay in Adjusting A R Manpower Constant - years

AHR - A R Hiring Rate - men/year

ALP - A R Leaving rate due to Pressure - men/year

ATRA - A R TurnoveR from Attrition - men/year

AAEP - Average A R Employment Period - years

Quite often, if there is pressure to reduce the size of the advanced research portion of an organization, while there is also need for personnel in design and development, then some of the people leaving advanced research will transfer into design and development.

This happens usually as a certain concept moves from A R to D & D, and certain people stay with it the whole way through. This is accomplished in the model by having a fraction of the people leaving A R due to pressure go to design and development. The fraction of personnel following this route will of course depend on the need for people in design and development. A possible relationship is illustrated in Figure A-8.

ATT.KL=(FALD.K)(ALP.K) 321RL, R

FALD.K = TABHL(FALDT,RDDAM.K,0.5,2,0.5) 350RL, A

RDDAM.K = DDT.K/DTM.K 344RL, A

ATR.KL = ATRP.K + ATRA.K 324RL,R

ATRP.K = (ALP.K)(1-FALD.K) 323RL, A

ATT - A R Technical manpower Transfer rate - men/year

FALD - Fraction A R personnel Leaving from pressure to D & D - dimensionless

FALDT - FALD Table (see Figure A-8) - dimensionless

RDDAM - Ratio DesireD to Actual D & D technical Manpower-dimensionless

DDT - Desired D & D Technical manpower - men

DTM - D & D Technical Manpower - men

ATR - A R Turnover Rate - men/year

ATRP - A R Turnover Rate due to Pressure - men/year

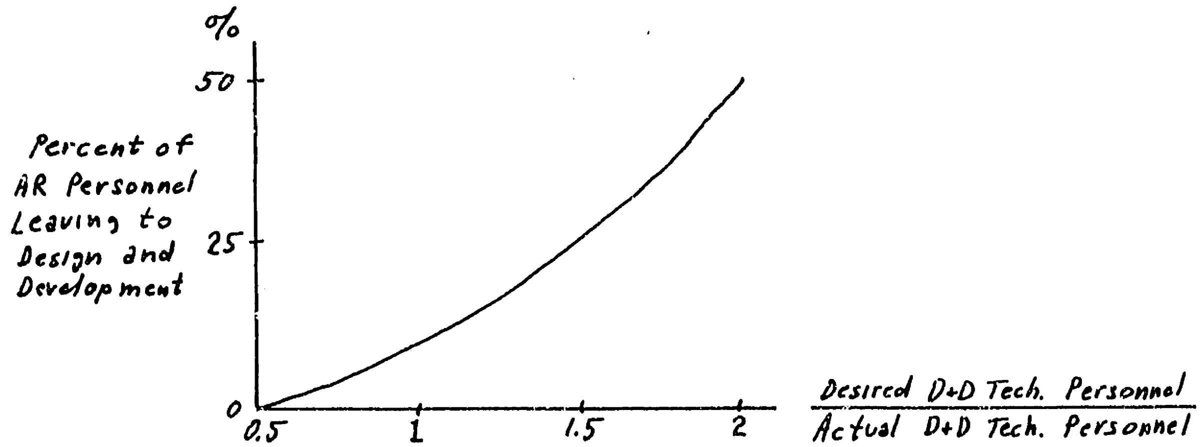

Figure A-8: Percent A R Personnel Leaving to D & D versus Ratio of Desired to Actual D & D Technical Manpower

Market Sector - Advanced Research (Chapter V)

In the market sector, the customer makes his contract award decision based on his evaluation of various factors. The model represents this decision in a multiplicative fashion. The evaluation of each factor by the customer results in a multiplier which represents the effect of performance in a certain area on the award rate. Each multiplier can be visualized as the fraction of the award rate due to all the other factors affecting the award rate, that is actually awarded to the laboratory. The value of each multiplier obviously depends on the relative performance of the laboratory in the respective area. The final award rate is found by multiplying all the multipliers due to different factors and the possible award rate (an exogenous input) together. The following equations perform this function for the advanced research sector. Note that the actual award rate is delayed due to time necessary for negotiations, etc.

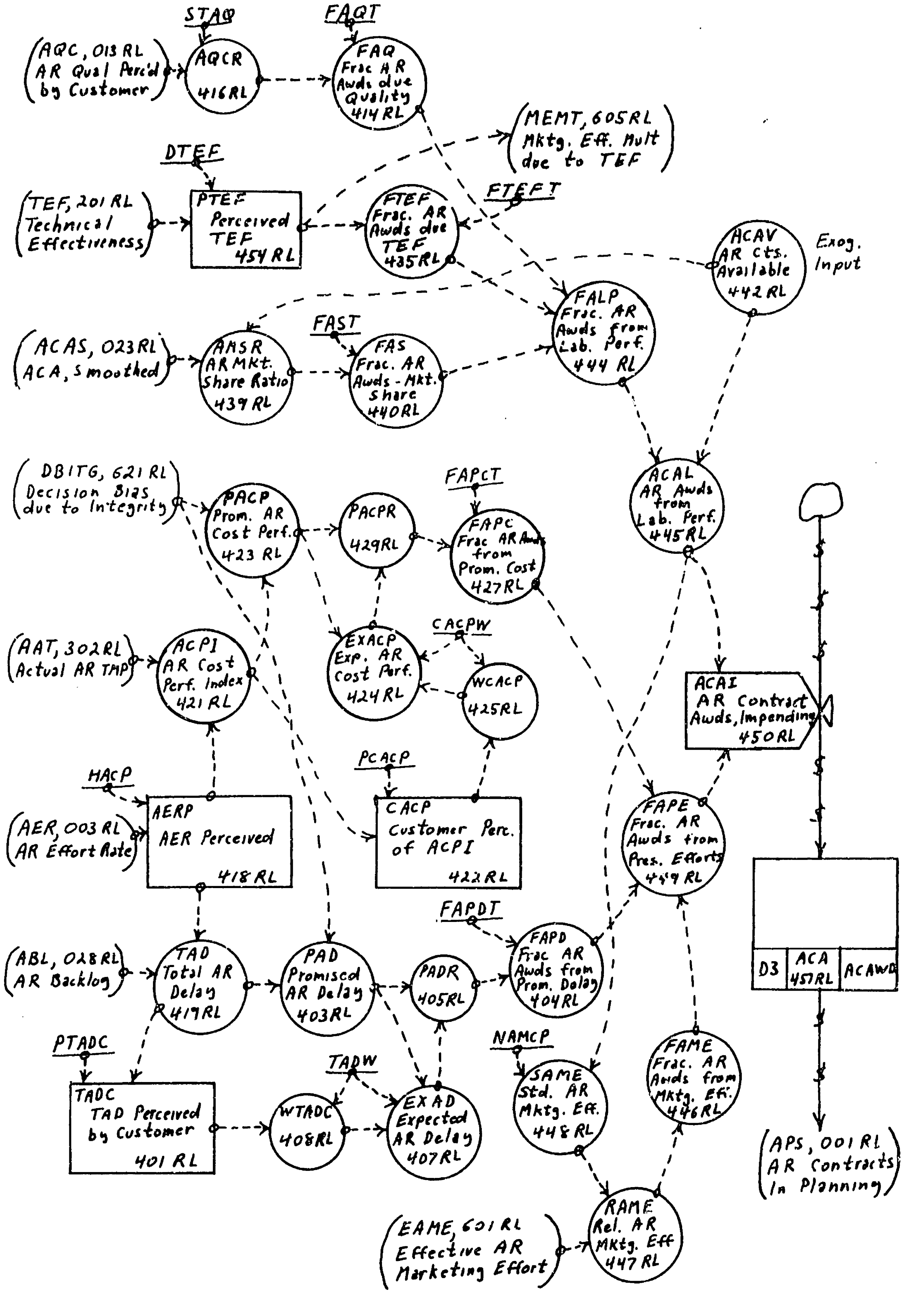

Figure A-9: Market Sector, Advanced Research

```
NØTE  MARKET SECTØR  AR CØNTRACTS
NØTE
3L    TADC.K=TADC.J+(DT)(1/PTADC)(TAD.J-TADC.J)    TAD PERC BY CUST            401RL
C     PTADC=3                                                                  402RL
12A   PAD.K=(TAD.K)(DBITG.K)                       PRØM AR CØNTR DEL           403RL
58A   FAPD.K=TABHL(FAPDT,PADR.K,0,2,0.2)           FRAC AR CØNT FRM PAD        404RL
20A   PADR.K=PAD.K/EXAD.K                          PAD RATIØ                   405RL
C     FAPDT*=0/0/.3/.7/1/.95/.88/.8/.73/.67/.6
26A   EXAD.K=(PAD.K+WTADC.K+0)/(1+TADW+0)          EXPECTED AR DELAY           407RL
12A   WTADC.K=(TADW)(TADC.K)                       WEIGHTED TADC               408RL
C     TADW=0.5                                     TAD WEIGHING FACTØR
58A   FAQ.K=TABHL(FAQT,AQCR.K,0,2,0.2)             FRAC AR CØNT FRM QUAL       414RL
C     FAQT*=0/0/.07/.17/.3/.5/.66/.8/.9/.97/1
20A   AQCR.K=AQC.K/STAQ                            AQC RATIØ                   416RL
C     STAQ=1                                       STD AR QUAL
3L    AERP.K=AERP.J+(DT)(1/HACP)(AER.JK-AERP.J)    AR EFFØRT RATE PERCD        418RL
20A   TAD.K=ABL.K/AERP.K                           TØT AR DELAY                419RL
12A   ACP.K=(2)(HACP)                                                          420RL
42A   ACPI.K=AAT.K/((AERP.K)(0.07713))             AR CØST PERF INDEX          421RL
3L    CACP.K=CACP.J+(DT)(1/PCACP)(ACPI.J-CACP.J)   CUST PERC ØF AR CØ PERF     422RL
C     PCACP=3
12A   PACP.K=(ACPI.K)(DBITG.K)                     PRØM AR CØST PERF           423RL
26A   EXACP.K=(PACP.K+WCACP.K+0)/(1+CACPW+0)       EXP AR CØST PERF            424RL
12A   WCACP.K=(CACPW)(CACP.K)                      WEIGHTED CACP               425RL
C     CACPW=1                                      CACP WEIGHING FACTØR        426RL
58A   FAPC.K=TABHL(FAPCT,PACPR.K,0,2,0.2)          FRAC AR CØNT DU PRØM CØ     427RL
C     FAPCT*=0/0/.3/.7/1/.95/.88/.8/.73/.67/.6
20A   PACPR.K=PACP.K/EXACP.K                       PRØM AR CØST PER RAT        429RL
58A   FTEF.K=TABHL(FTEFT,PTEF.K,0,2,0.2)           FRAC CTS DUTØ TEF           435RL
3L    PTEF.K=PTEF.J+(DT)(1/DTEF)(TEF.J-PTEF.J)     PERCD TEF                   454RL
C     DTEF=5
C     FTEFT*=0/0/.07/.14/.26/.4/.57/.7/.84/.95/1
20A   AMSR.K=ACAS.K/ACAV.K                         AR MKT SHARE RATIØ          439RL
58A   FAS.K=TABHL(FAST,AMSR.K,0,1,0.2)             FR AR CT DU MKT SHARE       440RL
C     FAST*=1/1/.96/.87/.72/.5
49A   ACAV.K=SWITCH(INAV,ACAV1.K,ACSW)             AR CTS AVAIL                442RL
C     INAV=593
C     ACSW=1
58A   ACAV1.K=TABHL(ACAVT,TIME.K,0,50,5)
```

```
C     ACAVT*=593/8600/18E3/20E3/18E3/12E3/8E3/5E3/5E3/5E3/5E3
13A   FALP.K=(FAQ.K)(FTEF.K)(FAS.K)                       FRAC AR CTS DU LAD PERF    444RL
12A   ACAL.K=(FALP.K)(ACAV.K)                             AR CTS AWD DUTZ PERF       445RL
58A   FAME.K=TABHL(FAMET,RAME.K,0,3,0.5)                  FR AR CTS DUTZ MKTG EFF    446RL
C     FAMET*=.5/.6/.7/.78/.87/.95/1
20A   RAME.K=EAME.K/SAME.K                                REL MKTG EFFORT            447RL
12A   SAME.K=(ACAL.K)(NAMCP)                              STD AR MKTG EFF            443RL
C     NAMCP=0.003163
13A   FAPE.K=(FAPC.K)(FAME.K)(FAPD.K)                     FRAC AVAIL CTS PRESS       449RL
12A   ACAI.K=(ACAL.K)(FAPE.K)                             AR CTS AWDS IMPENDG        450RL
39R   ACA.KL=DELAY3(ACAI.K,ACAWD)                         AR CT AWD RATE             451RL
C     ACAWD=0.5                                           AR CT AWD DEL              452RL
6N    TADC=TAD
6N    AERP=ACA
6N    CACP=ACPI
6N    ACAI=75
6N    ACAV1=INAV
6N    PTEF=TEF
```

ACAI.K = (ACAL.K)(FAPC.K)(FAPD.K)(FAME.K) 450RL, 449RL, A

ACAL.K = (ACAV.K)(FAQ.K)(FTEF.K)(FAS.K) 445RL, 444RL, A

ACA.KL = DELAY3(ACAI.K, ACAWD) 451RL, R

ACAI - A R Contract awards Impending - dollars/year

ACAL - A R Contract Awards due to Lab performance - dollars/year

FAPC - Fraction A R awards due to Promised Cost - dimensionless

FAPD - Fraction A R awards due to Promised Delivery - dimensionless

FAME - Fraction A R awards due to Marketing Effort - dimensionless

ACAV - A R Contract Awards aVailable - dollars/year

FAQ - Fraction A R awards due to Quality - dimensionless

FTEF - Fraction A R awards due to Technical EFfectiveness - dimensionless

FAS - Fraction A R awards due to market Share - dimensionless

ACA - A R Contract Award rate - dollars/year

ACAWD - A R Contract AWard Delay - years

Each fraction of possible awards (multiplier) is generated through the use of a table function entered by a ratio of the actual value of the factor being considered to a standard or desired value. Since all the factors use somewhat the same technique, just one will be described. The fraction advanced research awards due to quality is given by a table function entered by the ratio of the quality perceived by the customer to a standard quality. As perceived quality increases relative to standard quality, the fraction of possible awards increases. The relationship is shown in Figure V-2 in Chapter V.

FAQ.K = TABHL(FAQT,AQR.K,0,2,0.2) 414RL, A

AQR.K = AQC.K/STAQ 416RL, A

FAQ - Fraction A R contracts due to Quality - dimensionless

FAQT - FAQ Table - dimensionless

AQR - A R Quality Ratio - dimensionless

AQC - A R Quality perceived by Customer - dimensionless

STAQ - STandard A R Quality - dimensionless

Two other concepts included in the market sector need to be considered. They are the generation of the total delivery delay and the cost performance index, both of which are important to contract awards. The delivery delay perceived is equal to the backlog (total funding in the laboratory) divided by the perceived effort rate.

TAD.K = ABL.K/AERP.K 419RL, A

TAD - Total A R Delay - years

ABL - A R BackLog - dollars

AERP - A R Effort Rate, Perceived - dollars/year

The cost performance index is equal to the level of personnel in the organization, including trainees, divided by the perceived effort rate times a normalization factor. Thus, as the number of people increases with respect to the effort rate, the cost index will rise and vice versa.

ACPI.K = AAT.K/((AERP.K)(ACPNF)) 421RL, A

ACPI - A R Cost Performance Index - man years/dollar

AAT - Actual A R Technical manpower - men

AERP - A R Effort Rate, Perceived - dollars/year

ACPNF - A R Cost Performance Normalization Factor - dimensionless

Market Sector - Design and Development (Chapter V)

The design and development sector of the market sector uses exactly the same concepts and techniques as the advanced research section with the exception that a few more factors are considered in the award decision. All but one need not be mentioned, however, since they parallel what has been said before. The one factor to be discussed here is the fraction possible design and development contracts due to the relative amount of advanced research effort. Cutting back on advanced research work will penalize an organization by eventually reducing its technical effectiveness, but it will also penalize the organization through reducing the number of follow-on contracts awarded. An organization is usually more capable in design and development work if it has performed the advanced research

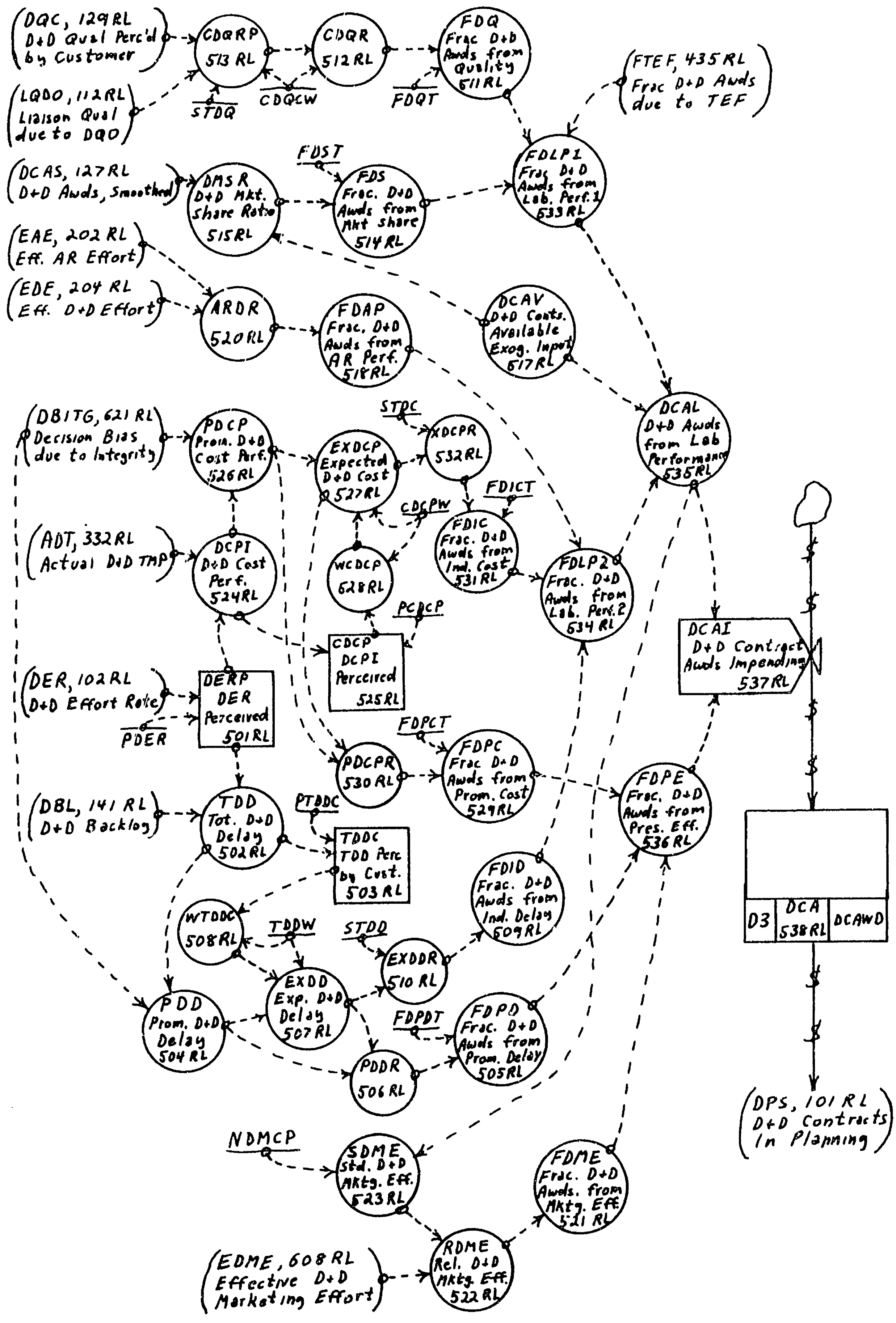

Figure A-10: Market Sector, Design and Development

```
NØTE  MARKET SECTØR  D*D CØNTRACTS
NØTE
3L    DERP.K=DERP.J+(DT)(1/PDER)(DER.JK-DERP.J)  D*D EFFZRT RT PERCD        501RL
C     PDER=0.75                                   DEL IN PERC ØF DER
20A   TDD.K=DBL.K/DERP.K                          TØTAL D*D DELAY            502RL
3L    TDDC.K=TDDC.J+(DT)(1/PTDDC)(TDD.J-TDDC.J)   TDD PERCD BY CUST          503RL
C     PTDDC=1.5                                   DEL IN PERC ØF TDD
12A   PDD.K=(TDD.K)(DBITG.K)                      PRØM D*D DEL               504RL
58A   FDPD.K=TABHL(FDPDT,PDDR.K,0,2,0.2)          FRAC D*D CTS DUTØ PDD      505RL
C     FDPDT*=0/0/.3/.7/1/.95/.88/.8/.73/.67/.6
20A   PDDR.K=PDD.K/EXDD.K                         PDD RATIØ                  506RL
26A   EXDD.K=(PDD.K+WTDDC.K+0)/(1+TDDW+0)         EXP D*D DELAY              507RL
12A   WTDDC.K=(TDDW)(TDDC.K)                      WEIGHTED TDDC              508RL
C     TDDW=1.5                                    TDD WEIGHING FACTØR
58A   FDID.K=TABHL(FDIDT,EXDDR.K,0,3,0.5)         FR D*D CTS DU STD DEL      509RL
C     FDIDT*=1/.95/.8/.65/.5/.35/.2
20A   EXDDR.K=EXDD.K/STDD                         EXDD RATIØ                 510RL
C     STDD=3                                      STD D*D DEL
58A   FDQ.K=TABHL(FDQT,CDQR.K,0,2,0.2)            FR D*D CTS DUTØ QUAL       511RL
C     FDQT*=0/0/.07/.17/.3/.5/.66/.8/.9/.97/1
48A   CDQR.K=CDQRP.K/(1+CDQCW)                    CUST D*D QUAL RATIØ        512RL
22A   CDQRP.K=(1/STDQ)((LQDØ.K)(1)+(DQC.K)(CDQCW))   CDQR PRIME              513RL
C     CDQCW=1                                     DQC WEIGHTG FACTØR
58A   FDS.K=TABHL(FDST,DMSR.K,0,1,0.2)            FR D*D CT DU MKT SHARE     514RL
C     FDST*=1/1/.96/.87/.72/.5
20A   DMSR.K=DCAS.K/DCAV.K                        D*D MKT SHARE RATIØ        515RL
49A   DCAV.K=SWITCH(INDV,DCAV1.K,DCSW)            D*D CTS AVAIL              517RL
C     INDV=675
C     DCSW=1
58A   DCAV1.K=TABHL(DCAVT,TIME.K,0,50,5)
C     DCAVT*=675/5100/13E3/26E3/35E3/47E3/50E3/47E3/36E3/29E3/25E3
58A   FDAP.K=TABHL(FDAPT,ARDR.K,0,1,0.2)          FRAC D*D CT DU AR PERF     518RL
C     FDAPT*=.2/.73/.87/.94/.98/1
20A   ARDR.K=EAE.JK/EDE.JK                        AR TØ D*D RATIØ            520RL
58A   FDME.K=TABHL(FDMET,RDME.K,0,3,0.5)          FR D*D CTS DU MKTG EFF     521RL
C     FDMET*=.5/.6/.7/.78/.87/.95/1
20A   RDME.K=EDME.K/SDME.K                        REL D*D MKTG EFF           522RL
12A   SDME.K=(DCAL.K)(NDMCP)                      STD D*D MKTG EFF           523RL
```

```
42A   DCPI.K=ADT.K/((DERP.K)(0.061395))                 D*D CØST PERF INDEX          524RL
3L    CDCP.K=CDCP.J+(DT)(1/PCDCP)(DCPI.J-CDCP.J)        CUST PERC ØF DCPI            525RL
C     PCDCP=1.5                                         DEL IN PERC ØF DCPI
12A   PDCP.K=(DCPI.K)(DBITG.K)                          PRØM D*D CØST PERF           526RL
26A   EXDCP.K=(PDCP.K+WCDCP.K+0)/(1+CDCPW+0)            EXP D*D CØST PERF            527RL
12A   WCDCP.K=(CDCP.K)(CDCPW)                           WEIGHTED CDCP                528RL
C     CDCPW=2                                           CDCP WEIGHING FACTØR
58A   FDPC.K=TABHL(FDPCT,PDCPR.K,0,2,0.2)               FR D*D CTS DU PRØM CØST      529RL
C     FDPCT*=0/0/.3/.7/1/.95/.88/.8/.73/.67/.6
20A   PDCPR.K=PDCP.K/EXDCP.K                            PDCP RATIØ                   530RL
58A   FDIC.K=TABHL(FDICT,XDCPR.K,0,4,1)                 FR D*D CTS DU STD CØSTS      531RL
C     FDICT*=1/.8/.6/.3/0
20A   XDCPR.K=EXDCP.K/STDC                              EXP D*D CST PERF RATIØ       532RL
C     STDC=1                                            STD D*D CØST
13A   FDLP1.K=(FDG.K)(FTEF.K)(FDS.K)                    FR D*D CTS DU PERF 1         533RL
13A   FDLP2.K=(FDAP.K)(FDIC.K)(FDID.K)               DR D*D CTS DU PERF 2            534RL
13A   DCAL.K=(DCAV.K)(FDLP1.K)(FDLP2.K)                 D*D CT AWD DU LAB PERF       535RL
13A   FDPE.K=(FDME.K)(FDPC.K)(FDPD.K)                   FR D*D CTS DU PRES EFF       536RL
12A   DCAI.K=(DCAL.K)(FDPE.K)                           D*D CT AWD IMPENDING         537RL
39R   DCA.KL=DELAY3(DCAI.K,DCAWD)                       D*D CT AWD RATE              538RL
C     DCAWD=0.3                                         D*D CT AWD DEL
6N    DERP=DCA
6N    TDDC=TDD
6N    CDCP=DCPI
6N    DCAI=54.6
6N    DCAV1=INDV
```

in the area concerned. Quite often, design and development contracts are awarded as a follow-on to advanced research effort. Thus, as the percentage of advanced research performed by an organization decreases, the number of follow-on design and development contracts also decreases. Thus, this multiplier acts to decrease the design and development award rate when the percentage of effective advanced research effort decreases.

FDAP.K = TABHL(FDAPT,ARDR.K,0,1,0.2) 518RL, A

ARDR.K = EAE.JK/EDE.JK 520RL, A

FDAP - Fraction D & D Contracts due to A R Performance - dimensionless

FDAPT - FDAP Table - dimensionless

ARDR - A R to D & D effort Ratio - dimensionless

EAE - Effective A R Effort - men/year

EDE - Effective D & D Effort - men/year

Top Management Decision Sector - Marketing Effort (Chapter VI)

Marketing effort is generated mainly on the basis of the perceived capacity of the organization to handle work. The award rate necessary to keep present personnel busy, at the present perceived level of productivity, is first determined and then a component calculated to correct the backlog situation over a period of time is added or subtracted to give the desired award rate. The normal level of marketing effort is then found by multiplying the normal marketing

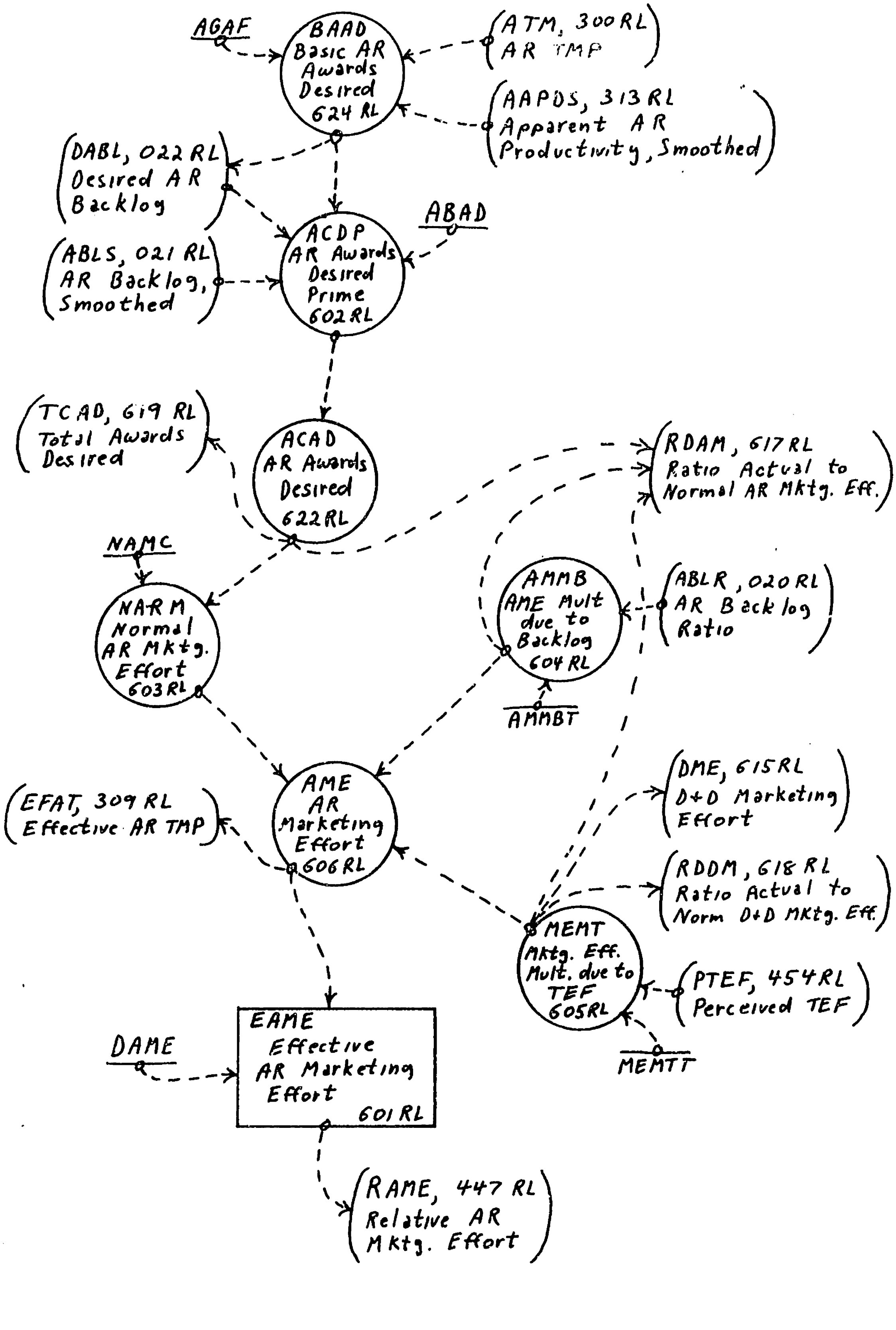

Figure A-11: Top Management Sector, Advanced Research Marketing Effort

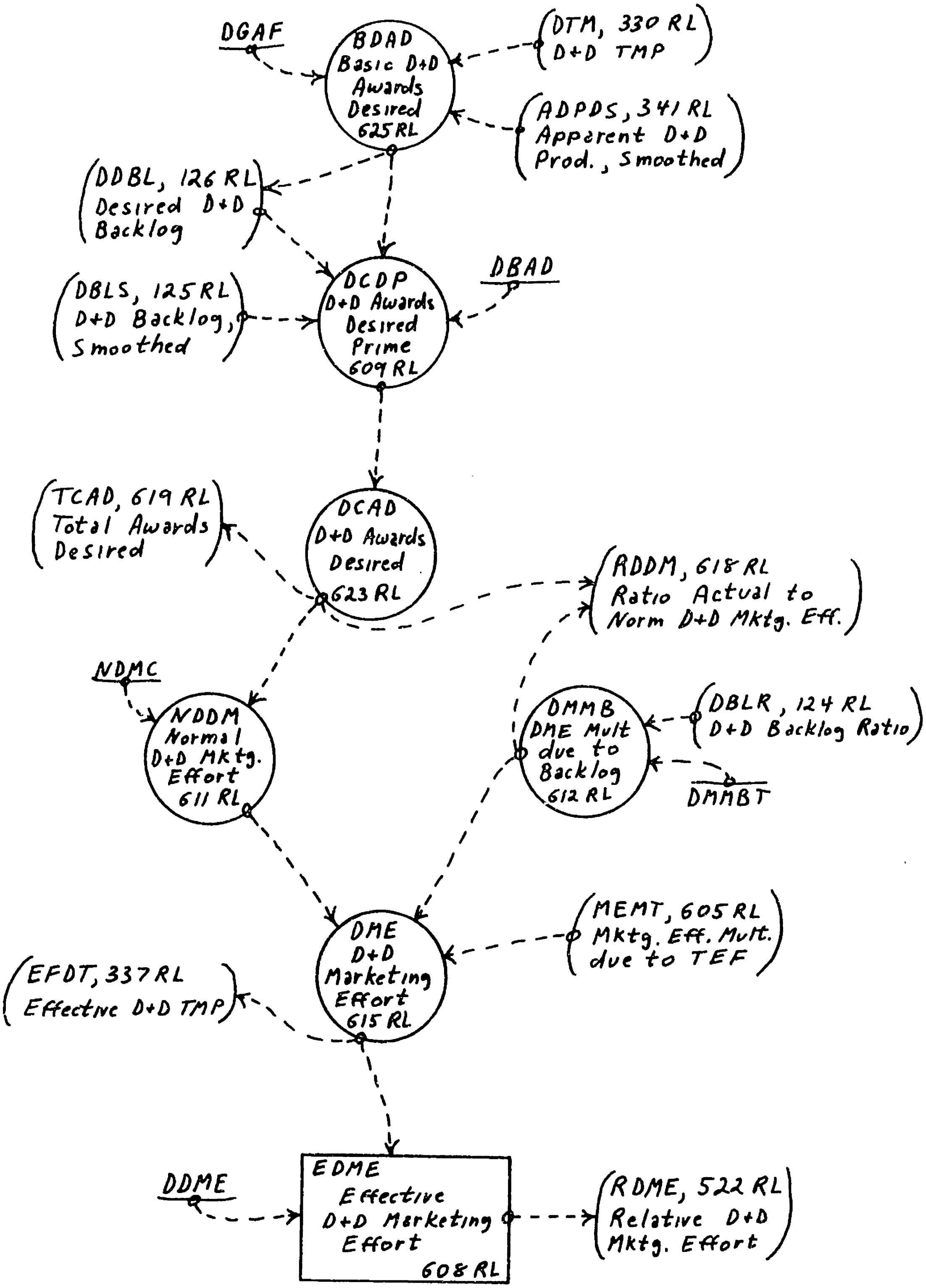

Figure A-12: Top Management Sector, Design and Development Marketing Effort

```
NØTE  TØP MANAGEMENT SECTØR
NØTE  MARKETING EFFØRT
NØTE
3L    EAME.K=EAME.J+(DT)(1/DAME)(AME.J-EAME.J)      EFF AR MKTG EFFØRT       601RL
C     DAME=0.5                                      DEL IN AME BECG EFF
40A   ACDP.K=BAAD.K+(1/ABAD)(DABL.K-ABLS.K)         AR CT AWD DESD PRM       602RL
13A   BAAD.K=(ATM.K)(AAPDS.K)(AGAF)                 BASIC AR AWARDS DESD     624RL
C     AGAF=1                                        AR GRØWTH ATT FACTØR
C     ABAD=5
56A   ACAD.K=MAX(ACDP.K,1)                          AR CT AWD DESD           622RL
12A   NARM.K=(NAMC)(ACAD.K)                         NØRM AR MKTG EFFØRT      603RL
C     NAMC=0.005                                    NØRM AME CØNST
58A   AMMB.K=TABHL(AMMBT,ABLR.K,0,2,0.2)            AME MULT DUTZ BLG        604RL
C     AMMBT*=2.6/2.2/1.8/1.5/1.2/1/1/.8/.6/.4/.2
58A   MEMT.K=TABHL(MEMTT,PTEF.K,0,2,0.5)            ME MULT DUTZ TEF         605RL
C     MEMTT*=1/1/1/1/1
13A   AME.K=(NARM.K)(AMMB.K)(MEMT.K)                AR MKTG EFF              606RL
3L    EDME.K=EDME.J+(DT)(1/DDME)(DME.J-EDME.J)      EFF D*D MKTG EFFØRT      608RL
C     DDME=0.3                                      DEL IN DME BECØMG EFF
40A   DCDP.K=BDAD.K+(1/DBAD)(DDBL.K-DBLS.K)         D*D CT AWD DESD PRM      609RL
13A   BDAD.K=(DTM.K)(ADPDS.K)(DGAF)                 BASIC D*D AWD DESD       625RL
C     DGAF=1                                        D*D GRØWTH ATT FACTØR
C     DBAD=3
56A   DCAD.K=MAX(DCDP.K,1)                          D*D CT AWD DESD          623RL
12A   NDDM.K=(NDMC)(DCAD.K)                         NØRM DME                 611RL
C     NDMC=0.0025                                   NØRM DME CØNST
58A   DMMB.K=TABHL(DMMBT,DBLR.K,0,2,0.2)            DME MULT DUTZ BLG        612RL
C     DMMBT*=2.6/2.2/1.8/1.5/1.2/1/1/.8/.6/.4/.2
13A   DME.K=(NDDM.K)(DMMB.K)(MEMT.K)                D*D MKTG EFF             615RL
6N    EAME=AME
6N    EDME=DME
```

effort per contract times the desired award rate. Note that provision for a growth attitude factor is also included in the generation of the basic awards desired. This growth attitude factor may be a variable, or a constant, depending on the policy being simulated.

BAAD.K = (ATM.K)(AAPDS.K)(AGAF) 624RL, A

ACAD.K = BAAD.K + (1/ABAD)(DABL.K-ABLS.K) 602RL, A

NARM.K = (NAMC)(ACAD.K) 603RL, A

BAAD - Basic A R Awards Desired - dollars/year

ATM - A R Technical Manpower - men

AAPDS - Apparent A R Productivity, Smoothed - dollars/year/man

AGAF - A R Growth Attitude Factor - dimensionless

ACAD - A R Contract Awards, Desired - dollars/year

ABAD - A R Backlog Adjusting Delay - years

DABL - Desired A R BackLog - dollars

ABLS - A R BackLog, Smoothed - dollars

NARM - Normal A R Marketing effort - men

NAMC - Normal A R Marketing effort Constant - men/dollars/year

There are two other factors which may cause management to change marketing effort from the level derived by the above equations. One is the amount of backlog imbalance. If the actual backlog is significantly different from that desired, management, in an effort to return to equilibrium as quickly as possible, will make more drastic changes in marketing effort than would be done by the above mechanism. This is represented by using a multiplicative table function in the manner shown below.

Another multiplier is also included. There are many possible management policies with respect to technical effort. For example, one organization might attempt to take advantage of increasing technical effectiveness and try to get more business, while another might want to limit its growth in an effort to increase technical effectiveness even further. These policies can be simulated by using different tables for the marketing effort multiplier due to technical effectiveness. These two multipliers essentially result in a nonlinear relationship between marketing effort and the factors which determine it.

AME.K = (NARM.K)(AMMB.K)(MEMT.K)	606RL, A
AMMB.K = TABHL(AMMBT,ABLR.K,0,2,0.2)	604RL, A
ABLR.K = ABLS.K/DABL.K	020RL, A
MEMT.K = TABHL(MEMTT,PTEF.K,0,2,0.5)	605RL, A

AME - A R Marketing Effort - men

AMMB - A R Marketing effort Multiplier due to Backlog - dimensionless

MEMT - Marketing Effort Multiplier due to Technical effectiveness - dimensionless

AMMBT - AMMB Table (Figure VI-1) - dimensionless

ABLR - A R BackLog Ratio - dimensionless

MEMTT - MEMT Table - dimensionless

PTEF - Perceived Technical EFfectiveness - dimensionless

Design and development marketing effort is determined in exactly the same manner as above.

Top Management Decision Sector, Decision Bias due to Integrity (Chapter VI)

Various estimates made by management, such as proposed costs and delivery times, and the desired level of funding, will reflect the organization's need and desire for more business. Some organizations will resist these pressures and remain relatively truthful, while others will give in and understate costs and deliveries to a significant degree. This concept is represented by the equations generating the decision bias due to integrity. The decision bias is given by a table function. The table itself will differ for organizations with different integrity characteristics. (See Chapter VI, Figure VI-3.) The entering variable which represents the organizational pressures for more or less work depends on the two multipliers affecting marketing effort. Since they represent the amount by which management wants to vary marketing from that considered normal, they are a good measure of pressures for more or less work. The two multipliers for each kind of work are multiplied together, weighted by the relative number of contracts desired in each kind of work, and added to give the variable determining the

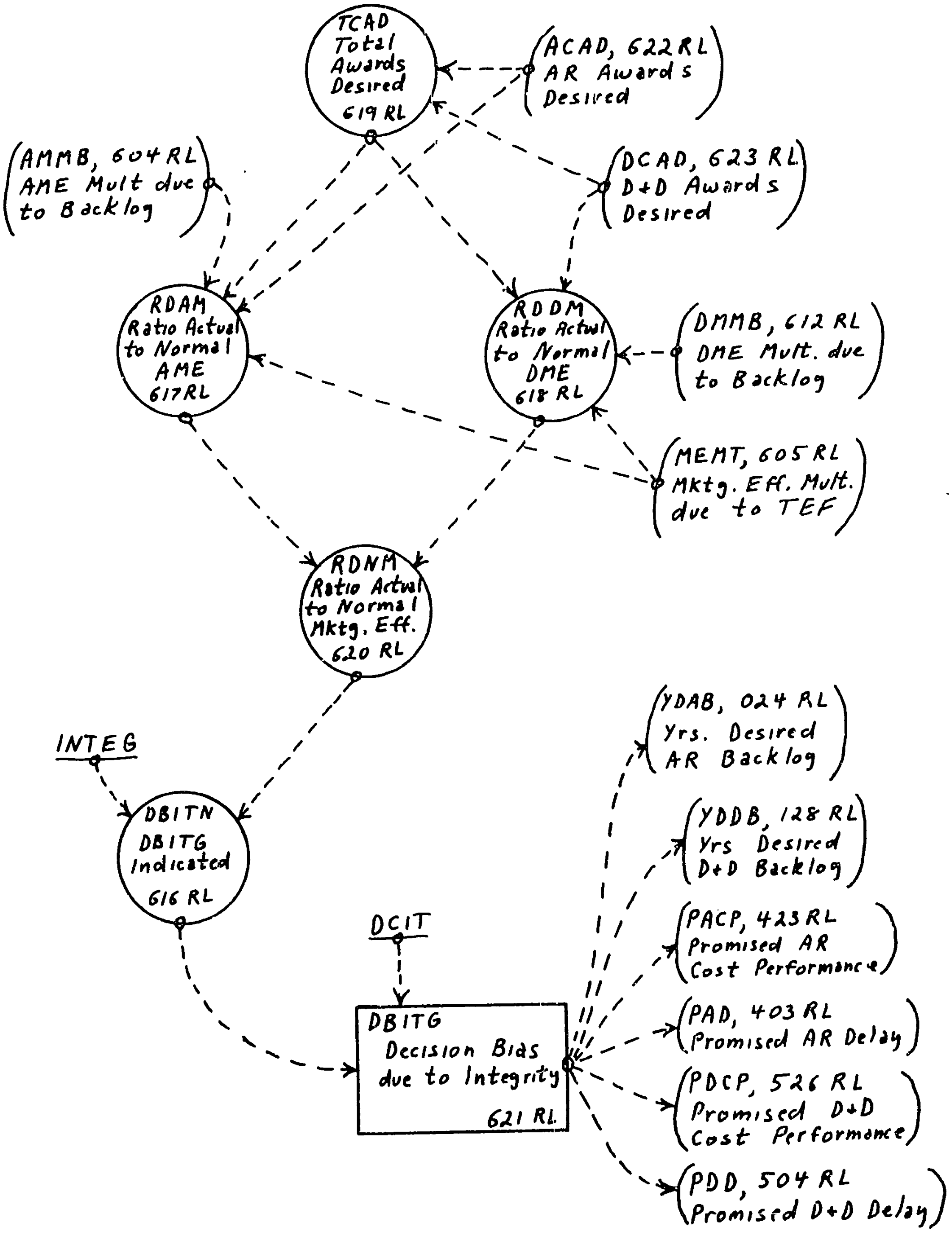

Figure A-13: Top Management Sector, Integrity

```
NØTE  TØP MANAGEMENT SECTØR
NØTE  INTEGRITY
NØTE
58A   DBITN.K=TABHL(INTEG,RDNM.K,.6,3,0.4)              DEC BIAS DU ITG IND      616RL
46A   RDAM.K=(AMMB.K)(MEMT.K)(ACAD.K)/((TCAD.K)(1)(1))                           617RL
46A   RDDM.K=(DMMB.K)(MEMT.K)(DCAD.K)/((TCAD.K)(1)(1))                           618RL
C     INTEG*=1/1/.7/.55/.47/.4/.3                        TRU FIRM
7A    TCAD.K=ACAD.K+DCAD.K                               TØT CT AWD DESD          619RL
7A    RDNM.K=RDAM.K+RDDM.K                               RATIØ DES TØ NØRM ME     620RL
3L    DBITG.K=DBITG.J+(DT)(1/DCIT)(DBITN.J-DBITG.J)   DECIS BIAS DUTØ ITG      621RL
C     DCIT=3                                             DEL IN CHGG INTEGRITY
6N    DBITG=1
```

decision bias.

```
DBITN.K = TABHL(INTEG,RDNM.K,.6,3,0.4)          616RL, A
RDNM.K = RDAM.K + RDDM.K                        620RL, A
RDAM.K = (AMMB.K)(MEMT.K)(ACAD.K)/(TCAD.K)      617RL, A
RDDM.K = (DMMB.K)(MEMT.K)(DCAD.K)/(TCAD.K)      618RL, A
TCAD.K = ACAD.K + DCAD.K                        619RL, A
```

DBITN - Decision Bias due to InTegrity, iNdicated - dimensionless

INTEG - INTEGrity table - dimensionless

RDNM - Ratio Desired to Normal Marketing effort - dimensionless

RDAM - Ratio Desired to normal A R Marketing effort, weighted - dimensionless

RDDM - Ratio Desired to normal D & D Marketing effort, weighted - dimensionless

TCAD - Total Contract Awards Desired - dollars/year

General Model Information

The interrelationships between the various model sectors discussed in this appendix are shown in Figure A-14. The actual model consists of 242 variable equations, 49 initial condition equations, and 117 constants.

The direction cards which were used to make the simulation runs discussed in Chapter VII are listed on the second page following.

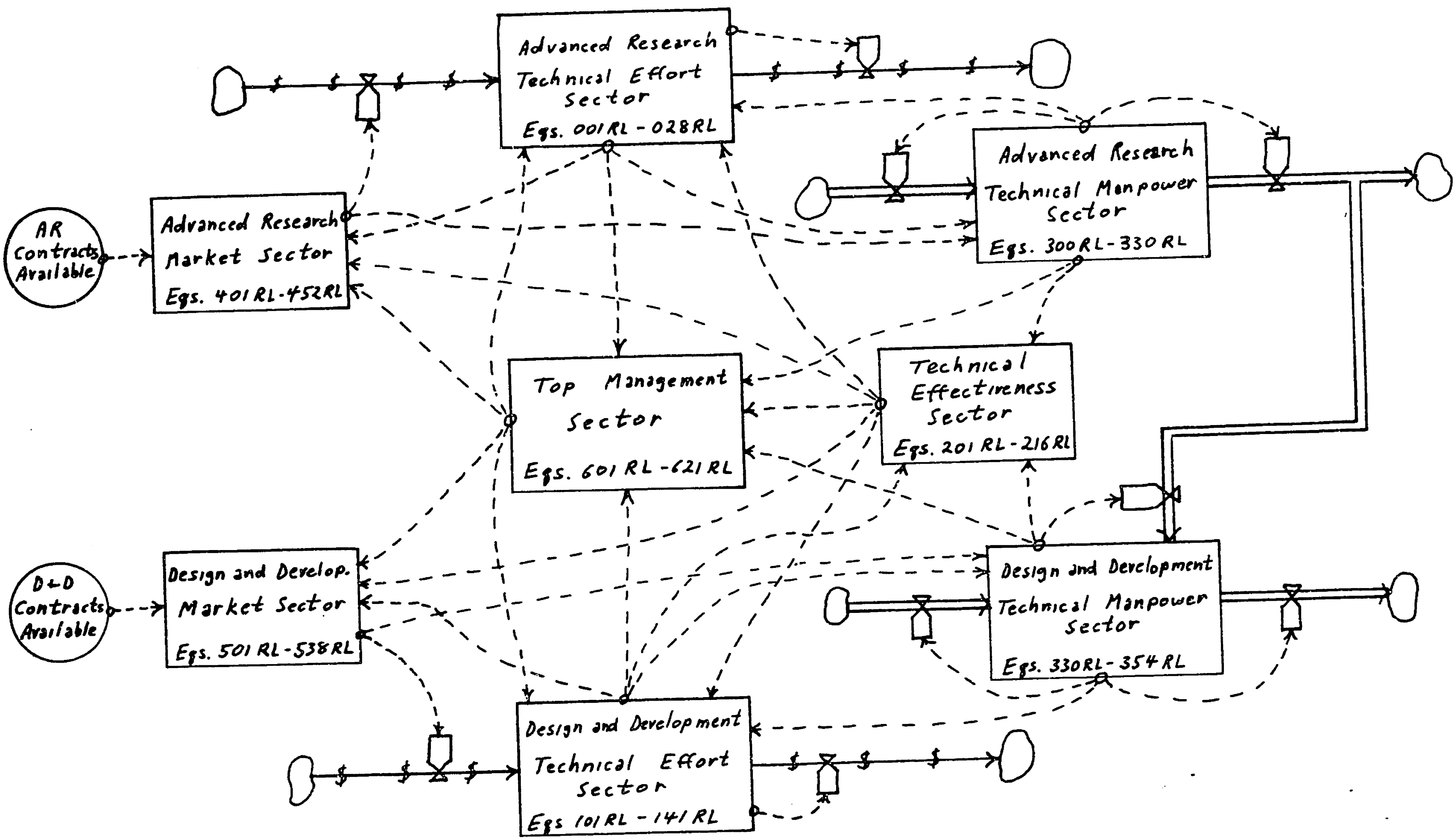

Figure A-14: Aggregate Flow Diagram, R and D Laboratory Model

```
*     M2549-2099,DYN,TEST,1,1,0,0         R AND D LAB, TIM WELLES
RUN
SPEC  DT=0.05/LENGTH=50/PRTPER=5/PLTPER=0.5
PRINT 1)ACA,ABL,AER,FAAV,AQØ/2)DCA,DBL,DER,DQØ,QLA,FDAI,FDAV,LER,LDQR/3)
X1    ATM,EFAT,AIT,DAT,AHR,ATT,ATR/4)DTM,EFDT,DIT,DDT,DHR,DTR,FALD/5)TAD
X2    ,PADR,AQCR,PACPR,AMSR,RAME/6)TDD,PDDR,EXDDR,CDQR,PDCPR,XDCPR,DMCR,
X3    RDME/7)EAME,ACAD,ACAL/8)EDME,DCAD,DCAL/9)TEF,DBITG/10)TAQ,TDQ
PLØT  ACA=A,DCA=D(0,*)/ACAV=V,DCAV=C(0,*)/TTM=T(0,*)
PLØT  AER=F(0,*)/AQØ=Q,FAAV=V,TEF=F(0.2)/ATM=M,DAT=D,TIM=T(0,*)
PLØT  DER=E(0,*)/DQØ=Q,QLA=L,FDAI=I,FDAV=V,TEF=F(0.2)/DTM=M,DDT=D,TTM=T(
X1    0,*)
PLØT  TAD=D(0,*)/AME=M(0,*)/ABL=B(0,*)/TEF=F,DBITG=I(0,2)/RAME=R(0,*)/AC
X1    PI=C(0,*)
PLØT  TDD=D(0,*)/DME=M(0,*)/DBL=B(0,*)/RDME=R(0,*)/DCPI=C(0,*)
```

With a solution interval (DT) of 0.05 years and using the direction cards listed, the simulation of a fifty year laboratory history requires 0.9 minutes on the IBM 7090 computer.

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