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THE ECONOMICS OF SOUNDING ROCKET UTILIZATION

Wolfgang Schaechter

THIOKOL CHEMICAL CORPORATION
ASTRO-MET DIVISION
P. O. BOX 1497, OGDEN, UTAH
84402

Contract No. AF19-(628)-6009

Project: 7659
Task: 765904
Work Unit: 76590401

FINAL REPORT

Period Covered: 1 June 1966 through 16 May 1969

Date of Report: 16 May 1969

Contract Monitor: Edward S. Mansfield
Aerospace Instrumentation Laboratory

Prepared for

AIR FORCE CABRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
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FOREWORD

This report was authorized by Contract AF19-(628)-6009 sponsored by the Aerospace Instrumentation Laboratory, Air Force Cambridge Research Laboratories, Bedford, Massachusetts, with Mr. Edward S. Mansfield (CRE) serving as contract monitor.

Work was performed under Project 7659, Task 765904, by Thiokol Chemical Corporation, Astro-Met Division, P. O. Box 1497, Ogden, Utah, 84402.

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This technical report has been reviewed and is approved.

EDWARD S. MANSFIELD
Research Probe Flight Branch
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ABSTRACT

Analytical methods, that could be used to make scientific sounding rocket procurement and utilization more economically effective, are described. A Figure of Merit comparator, on which sounding rocket procurement and vehicle development decisions can be based, is proposed. The cost optimization of combinations of sounding rocket types for a user agency's vehicle inventory, selected on the basis of the Figure of Merit, is demonstrated. It is shown that optimum combinations of vehicle types can produce significant savings in the overall costs of a sounding rocket inventory.

Techniques for predicting mission requirements are discussed, and one of these, polynomial extrapolations of actual utilization histories, is applied to historical utilization data from AFCRL and NASA/GSFC. More sophisticated statistical prediction techniques are examined for their applicability to this problem.

Bayesian decision theory is discussed in its potential application to inventory optimization.

Methods of estimating the cost effectiveness of a proposed sounding rocket vehicle development program are examined. Considerations of success criteria, projected mission requirements, and reliability growth, are included in the guidelines for the cost effectiveness evaluation.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

The analyses presented in this report were prepared for the Research Probe Flight Branch, CREK, of the Air Force Cambridge Research Laboratories under Contract No. AF19-(628)-6009. The information contained in this document is intended to fulfill the requirements set forth in that contract.

The report describes various analytical methods that can be used to formulate cost effectiveness guidelines in sounding rocket procurement and utilization. Techniques for predicting mission requirement are examined and a sample optimization problem is presented in the analysis.

Advanced statistical prediction techniques and the application of Bayesian decision theory to inventory optimization are discussed. Methods of examining cost effectiveness of new vehicle development are considered.

II. SUMMARY

The purpose of this report is to outline some analytical methods that could be used to make sounding rocket procurement more economically effective. Methods are proposed with which an optimum sounding rocket inventory can be selected, and techniques are discussed by which the economic sensibility of developing a new sounding rocket motor or vehicle can be judged.

We believe that an analytical approach to the economics of sounding rocket procurement and utilization is feasible, and can provide guidelines and immediately applicable information with which inventory management and new vehicle development can be economically evaluated.

Rational economic evaluation techniques are imperative because sounding rocket programs in past years have predominately been characterized by failures. When you consider the evidence shown in Figure 1, it illustrates that a mere 14 vehicle types have completed more than 90% of all sounding rocket flights since efforts in this field began in the U.S.A., more than 20 years ago. These fourteen types constitute less than 22% of the sounding rocket vehicles that have been proposed, studied, initiated, or in which only a few flights were completed before the program was dropped.

The record becomes even more disturbing when one considers that four of those fourteen extensively used types were associated with a specific defense application, such as weapons testing (Asp, Nike-Asp, Deacon-Arrow, Viper-Arrow), and one was a war surplus windfall (V-2); none of these were pursued beyond the end of their respective program.

Another important reason for improving the decision-making process in sounding rocket logistics is the inevitably increasing cost of new vehicle development. This is caused by today's higher labor costs and higher payload costs which demand a more highly "proven" vehicle before being committed to flight--in turn resulting in more extensive development programs.

The problem is, therefore, real. One can readily predict that

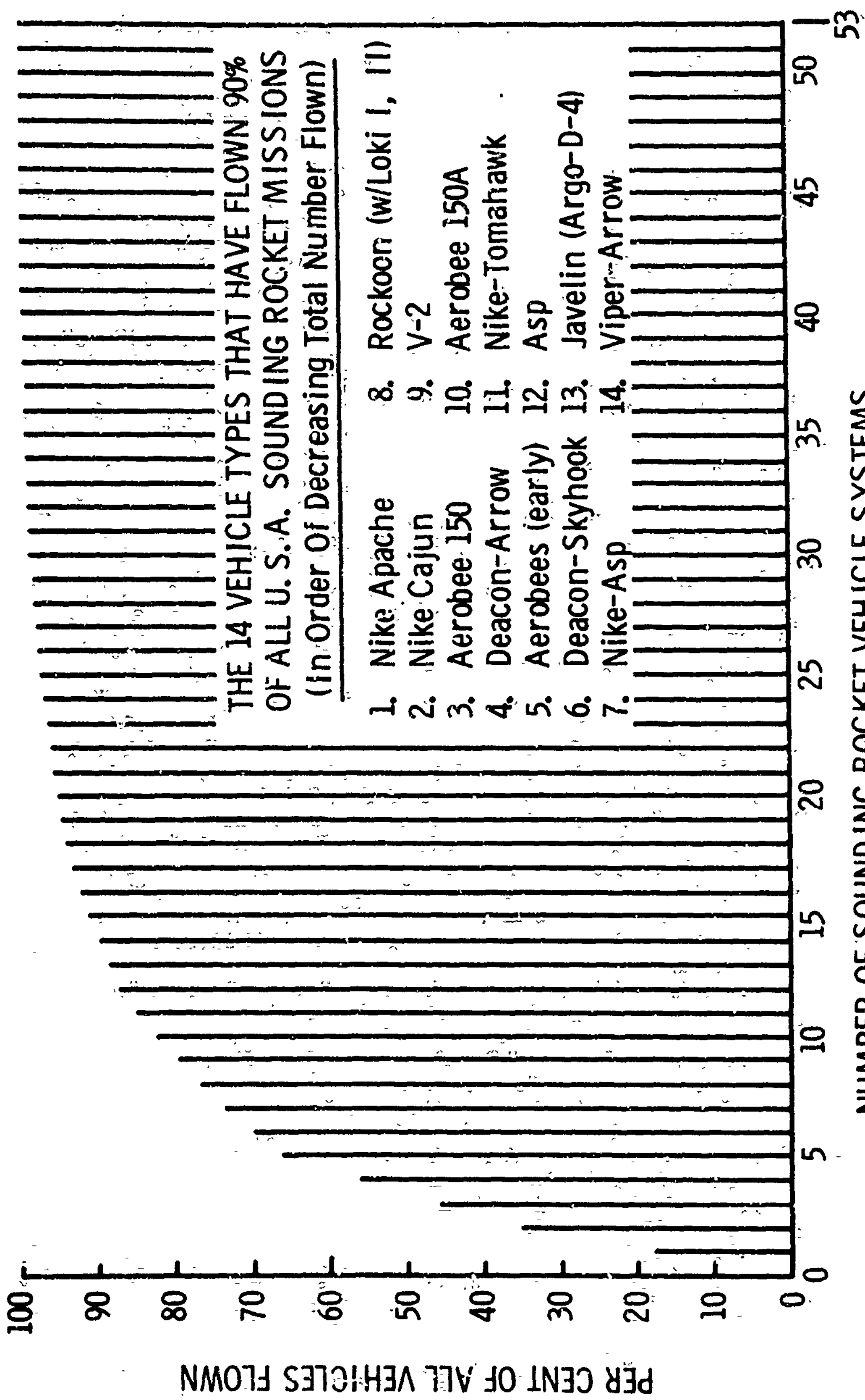


Figure 1.

THE DISTRIBUTION OF TOTAL FLIGHTS AMONG SOUNDING ROCKET SYSTEMS because of the higher costs involved, there will be fewer development programs in the future, their costs will rise, and the penalties for failure (already high) will become higher.

What can be done about this? An oversimplified answer is "be very careful how you spend your money." How do we do this? The work described in this report is a partial answer to this question.

In this analysis we attempt to answer a two-fold question:

1. What type of inventory mix of sounding rocket vehicles is optimum?
2. Is it "economically sensible" to develop a given new vehicle type for addition to an existing stable?

To answer these questions, we must first know what will be asked of the stable, or, what type of missions must be accomplished, or putting it another way, what are our future mission requirements?

For a number of reasons, to be discussed later, we attempt to answer this question statistically. This is done by categorizing past missions flown by payload weight and apogee altitude on a per-year basis going back as far as the records are available. To date we have considered the utilization histories of the Air Force Cambridge Research Laboratories and the Goddard Space Flight Center of the National Aeronautics and Space Administration. Data from other agencies and users were also examined but were not included because of their restrictive nature. Future utilization is predicted by fitting least squares polynomials to this historical data for number flown in each weight-altitude category against calendar time.

Statistical techniques were selected because of the limitations of the traditional approach to predicting future requirements, which has been to interview potential customers regarding their individual plans because of the subjective nature of the latter.

Once the requirements were predicted, determination of the optimum vehicle inventory, in terms of cost effectiveness, was examined by overlaying the apogee altitude/payload weight grid, which contains the number required in each mission category, with the performance characteristics of each rocket. Missions that fall inside the performance envelope of each vehicle type can be accomplished by that configuration by the addition of ballast.

An inventory mix is defined to consist of several specific rocket types (not the number required per unit time of each type). Once a stable is selected as a candidate for analysis, it is usually found that some missions may be performed by more than one vehicle type. The heuristic method employed in these situations is to assign the mission to the rocket with the lowest total cost--(vehicle price plus payload cost)--divided by rocket reliability.

Discrimination among several vehicle stables can be accomplished by comparing their respective Figures of Merit. As a Figure of Merit (FM), we propose the overall, or user agency-wide total pound-miles actually achieved divided by the total vehicle costs. Since the requirements and the availability of rocket types both vary with time, the Figure of Merit (FM) is restricted to a specific time interval, one year in this case.

FM's are arrived at for several mixes for a projected period of time. The combination of vehicle types possessing the highest FM for the time period used in the utilization prediction is considered to be the "optimum" inventory.

The report includes a sample problem in which the optimum inventory mix of a mythical user agency (AFNA), over a period of five years, is examined. Several combinations of vehicle types are considered in an attempt to define the optimum inventory over the projected time period.

Advanced techniques in statistical prediction and inventory optimization are also examined. Linear mean-square estimation theory, constrained least squares curve fit, and random number generator simulation systems are reviewed for their applicability to the prediction problem.

The application of Bayesian decision theory as an alternate to the Figure of Merit concept of inventory optimization is discussed. Ground rules for a Bayesian decision tree are proposed and a simple problem is examined.

The introduction of a new vehicle on the Figure of Merit of the various inventory combinations is evaluated.

Arriving at the FM for stables that contain a to-be-developed vehicle, is, however, an iterative process since the price of the new vehicle depends on the number of it flown each year because of the need to amortize development costs. This cost affects the user agency if they sponsor development, or the vehicle manufacturer, who must amortize this development over a limited amount of time. It is possible to use this technique to explore the consequences of various amortization programs.

Reliability of the newly developed rocket is an important consideration in the early phases of its development. Since diagnostically instrumented flights can have payloads costing from \$50,000 - \$100,000, the reliability growth of a new vehicle in the early flights can drastically affect the total development costs. We have, therefore, postulated a reliability model which considers as separate parameters the number of possible failure modes, their probability of occurrence, and their probability of detection. Estimates of the optimum amount of diagnostic instrumentation to be flown on the new rocket can be added as a refinement to the cost model since reliability growth and its value can be considered.

III. ANALYSIS

Two economic aspects of sounding rocket utilization are examined in the analysis:

- Optimization of a Sounding Rocket Inventory
- Development Cost Effectiveness of a New Sounding Rocket Vehicle

The two are somewhat linked since the cost effectiveness of a new development is strongly dependent on the impact the new vehicle would have on an existing sounding rocket inventory. However, each subject deserves considerable attention on its own. Therefore, the discussions of inventory optimization and new development cost effectiveness have been separated so that the ideas peculiar to each concept can be more clearly explained.

A. Optimization of a Sounding Rocket Inventory

What is an optimum sounding rocket inventory? One which does the best job at the least cost. Although the underlined answer is essentially correct, the statement must be carefully considered in detail.

"Best job, least cost" requires at least the following:

- The maximum number of experimenters be accommodated in the period for which the inventory was purchased.
- The minimum number of vehicles be left over at the end of the inventory year.
- The satisfaction of the experimenters be high in terms of minimization of vehicle induced payload failures.
- The vehicle inventoy cost be a minimum consistent with the above goals.

The cost subject warrants more specific attention. Suppose a particular inventory could satisfy all mission requirements at relatively low vehicle cost. If the reliability of its vehicles is low, it might be very uneconomical from an overall standpoint. This can occur because, in the vast majority of cases, the price of the sounding rocket vehicle is but a fraction of the cost of the experiments it carries. To express this interaction between vehicle cost and reliability a Figure of Merit that takes both factors into account can be used.

1. The Figure of Merit

We suggest a Figure of Merit (FM), which includes the cost and reliability aspects of the optimization of a sounding rocket inventory as follows:

$$FM = \frac{\sum_{j=1}^{t} \sum_{i=1}^{m} (n_i h_i W_i r_j)_j}{\sum_{j=1}^{t} \sum_{i=1}^{m} (n_i C_j)_j} \qquad (1)$$

Where the variables are:

- t Number of Vehicle Types in the Inventory
- m Number of Payload/Altitude Missions Assigned to a Vehicle in the Inventory
- n_i Number of Vehicles to be Flown for the "ith" Mission
- W_i Payload Weight to be Flown in the "ith" Mission
- h_i Altitude to be Reached in the "ith" Mission
- r_j Reliability of the "jth" Vehicle in the Inventory
- C_j Unit Price of the "jth" Vehicle in the Inventory.

The double summation indicated by Equation 1 assumes that there are t vehicle types in the inventory each of which can satisfy m number of missions in a given payload/altitude regime.

The Figure of Merit is calculated as follows:

1. The year-by-year prediction of missions to a given altitude with a given payload is determined.
2. For each year a number of inventory combinations are proposed that will satisfy the mission requirements.
3. The vehicle unit price and reliability of each type is determined or estimated.
4. Assuming that a proposed stable has t vehicle types in it, each of the t types is assigned m missions. m will, of course, vary from type to type.

5. It frequently happens that a specific mission may be accomplished by more than one vehicle. In these cases the reliability-weighted cost of each alternative way of doing the mission must be computed. This mission cost is:

$$\frac{C_{\text{Vehicle}} + C_{\text{Payload}}}{\text{Vehicle Reliability}}$$

The conflicts are resolved by assigning the mission to that vehicle which has the lowest mission cost as defined above. When payload costs are not well known, an average figure of several hundred dollars per pound of payload might be used.

6. Equation 1 is applied, in turn, to each proposed stable and its FM is determined.

7. For the particular year being examined, the FM is determined for each proposed inventory combination. The stable offering the highest overall Pound-Miles per Dollar value is selected as the optimum.

The Figure of Merit so determined is only an approximation to the real-life situation. It takes no account of the following:

a. Stable Management Costs are not a Factor

A complex inventory consisting of many types may have an overall FM lower than one containing only two or three vehicle configurations. However, support costs such as analytical services, range safety documentation, launch crew costs, remote site logistical support, and procurement expenses may outweigh the FM economies gained by applying many vehicles to the mission requirements.

b. No Quantity Discounts for Vehicles

We have assumed the cost of a particular type to be independent of the number used per year. One would expect to pay a lower unit price for 50 than 5. Surprisingly, as will be described later, assuming unit cost to be independent of lot size is a good approximation.

c. Reliability is Independent of Lot Size

Human factors are involved here; it would be reasonable to assume that a launch crew would make fewer mistakes with a vehicle they were thoroughly familiar with than one which they only flew on rare occasions. However, sometimes the inverse can be true where familiarity breeds carelessness.

d. Reliability is Independent of Mission

Since weight and altitude do not completely define a mission, we expect that some vehicle problems would cause some missions to fail, but would not so affect others with similar performance goals.

These simplifying assumptions were, however, adopted because they most clearly illustrate the ideas put forth in the analysis while keeping the problem within manageable proportions.

We now turn to the data required for the FM determination.

2. Predicting Future Mission Requirements

The prediction of future requirements is a key problem in inventory optimization. Unfortunately, completely reliable predictions of the future are simply not possible. Therefore, whatever the results of the predictions, they are only approximations.

A possible approach to predicting future requirements would be to ask the people who use the rockets what their plans are. Unfortunately, project scientists' statements about their future vehicle needs cannot correlate well with their requirements, as they actually materialize, for more than an interval of only a year or so, sometimes less. This is not a question of good faith, however; sounding rocket experimenters follow up interesting results obtained in some regions of the atmosphere by immediately scheduling other experiments in that area. (The sounding rocket field is attractive to them for this very reason.) Therefore, long lead time experiments and the planning that is thereby possible do not characterize the field. Other means must, therefore, be found to predict future requirements.

The attempts to look at the future in this analysis are based on the assumption that "tomorrow is a mirror of yesterday." We have done this by gathering statistics of past sounding rocket utilization and extrapolating these into the future by least squares and more sophisticated prediction techniques.

a. Utilization Histories

The statistics are categorized on a yearly basis according to payload weight and apogee altitude as indicated in Figure 2, for example, for the year 1962. The utilization record is subdivided into 20 statute mile by 20 pound cells. The small circles within some of the cells contain a number identifying the vehicle type used to perform the mission; this is indicated in an enlarged section of Figure 2, shown as Figure 3.

To date, we have catalogued the sounding rocket utilization histories of the Air Force Cambridge Research Laboratories (AFCRL) and the Goddard Space Flight Center of the National Aeronautics and Space Administration (NASA/GSFC) beginning in 1950 (for AFCRL) and ending in 1965. Data were also collected from the Sandia Corporation, the Naval Research Laboratory (NRL), and the World Data Center A - Rockets and Satellites of the National Science Foundation (NSF). In the case of the Sandia Corporation, the data were of a specialized nature and are concentrated in a very few altitude/payload cells. The available NRL records were solely for the Aerobee vehicle. The NSF data were a compilation of U.S. and international results, voluntarily contributed by the various sounding rocket users and, therefore, necessarily limited in overall completeness. Because of these drawbacks, no Sandia, NRL or NSF data were used in the predictions.

b. Requirement Prediction Technique

Year-by-year data for a particular mission (designated by one 20 statute mile altitude by 20 pound payload cell on the utilization grid) were mathematically smoothed with the aid of a least squares curve-fit computer program. The results, in the form of first through seventh order polynomials, were equations that described the number of missions in a particular weight category to a given altitude as a function of time.

We used the historical base, so established, to predict future requirements for a number of years by simply substituting future years into the Utilization vs. Time equation. A second degree polynomial was

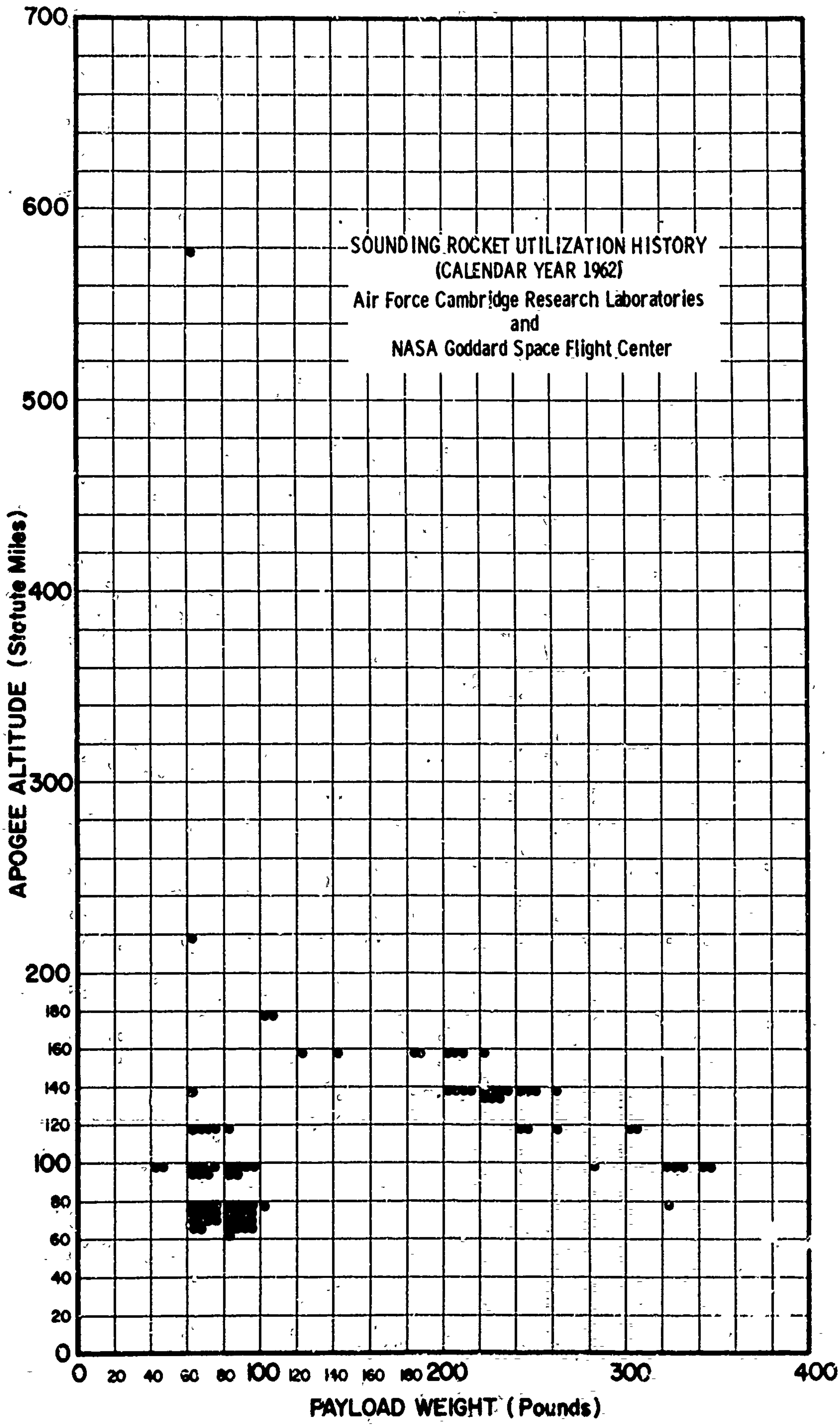


Figure 2. A TYPICAL SOUNDING ROCKET UTILIZATION RECORD

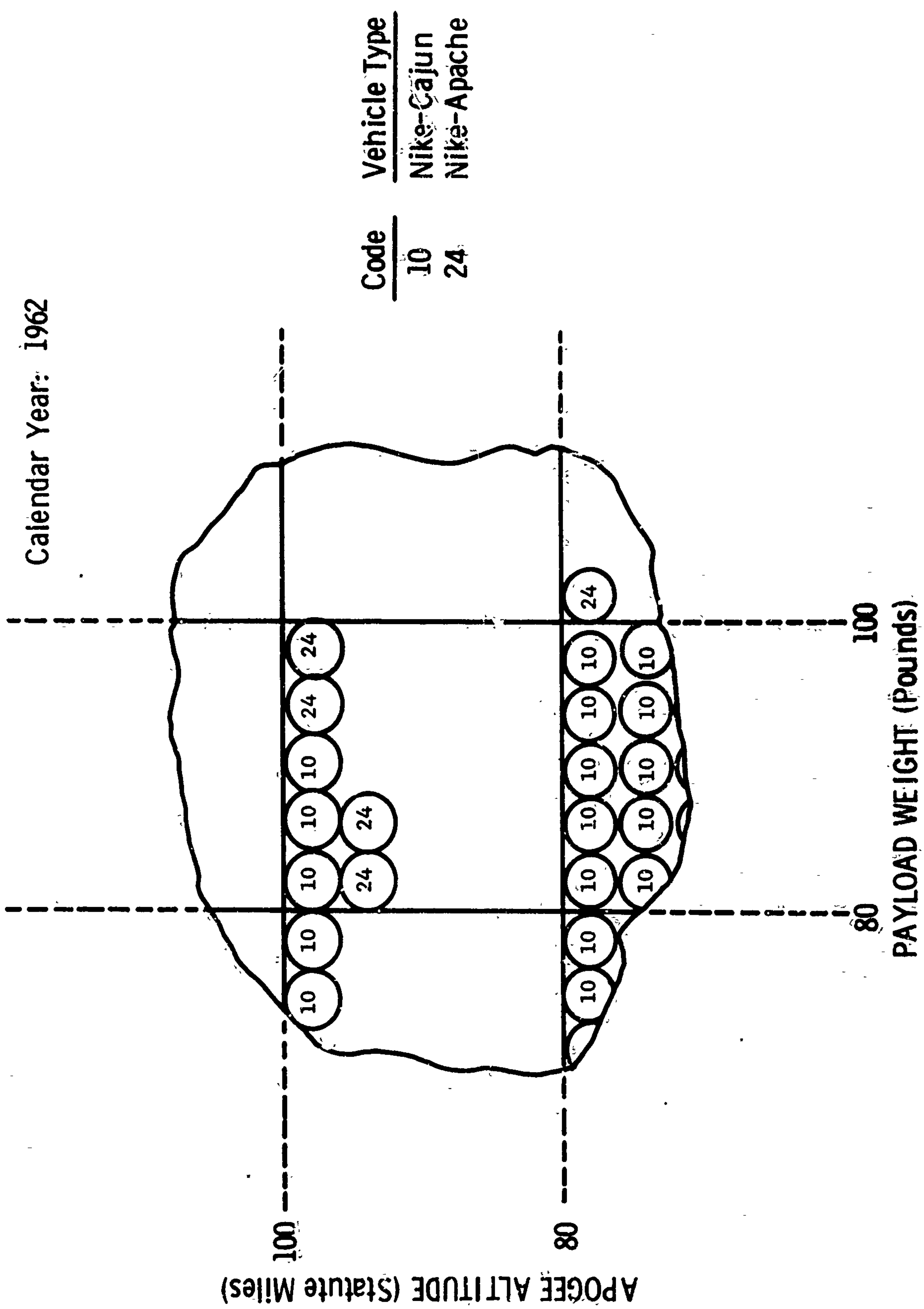


Figure 3. ONE APOGEE ALTITUDE/PAYLOAD WEIGHT GRID CELL

selected for the prediction of requirements. The process is briefly illustrated in Figure 4 for the 200 - 220 pounds to 120 - 140 miles mission.

c. Requirement Prediction Results

The results obtained by extrapolating the second order curve-fit equations are briefly summarized for a period of five years beginning with an arbitrarily established Year 0 (the present) in Figures 5 through 5e.

In Year 0 (Figure 5) the highest utilization frequency is 60 - 80 Miles in the 60 - 80 pounds region. Twenty-six payloads are launched on that mission. Considerable activity, in this payload/weight range, is also found from the 80 - 100 and 100 - 120 miles altitude. In the heavier and larger payloads, the utilization frequency is about equally distributed over 200 - 300 pounds to 80 - 160 miles

In Year 1 (Figure 5a), the previously most active category (60 - 80 pounds to 60 - 80 miles) remains constant at 26 vehicles.* Directly above it in the same weight range, missions to 100 - 120 miles increase sharply from 15 in Year 0 to 27 in Year 1. Activity in the 200 - 300 pound payloads increases slightly.

In Year 2 (Figure 5b), the 60 - 80 pound payloads to 100 - 120 miles continue to show a strong increase, while others in this category are holding their own. Heavy payloads in the 260 - 280 pound class to the same altitude are also increasing.

In Year 3 (Figure 5c), the lower weight payloads show a steady increase with one exception: 40 - 60 pounds to 100 - 120 miles. The heavier payloads also increase in all categories but by a much slower rate. The trends in Year 4 (Figure 5d) are similar to those so far indicated.

*Note that the mission requirements in the 60 - 80 pounds to 60 - 80 miles cell do not change from Year 0 to Year 1, but increase in succeeding years. This is because Year 0 represents an arbitrarily chosen starting point for which utilization is known. Year 1, however, is an extrapolation of a curve-fit of historical data. At the junction of Year 0 (actual data) and Year 1 (extrapolated data), the mission requirements are very similar, but not identical.

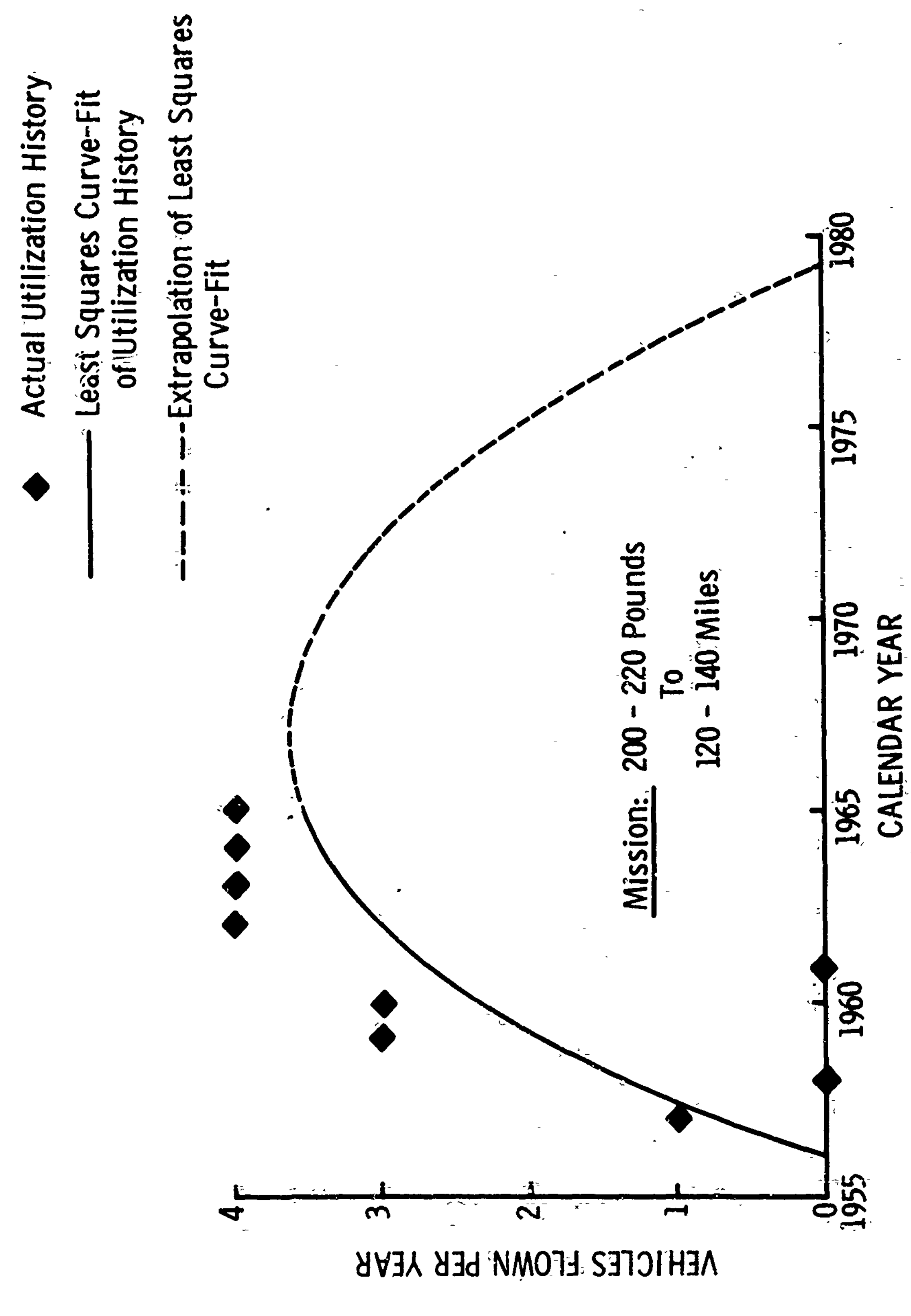


Figure 4.

ACTUAL DATA, CURVE-FIT, AND EXTRAPOLATION OF UTILIZATION HISTORY

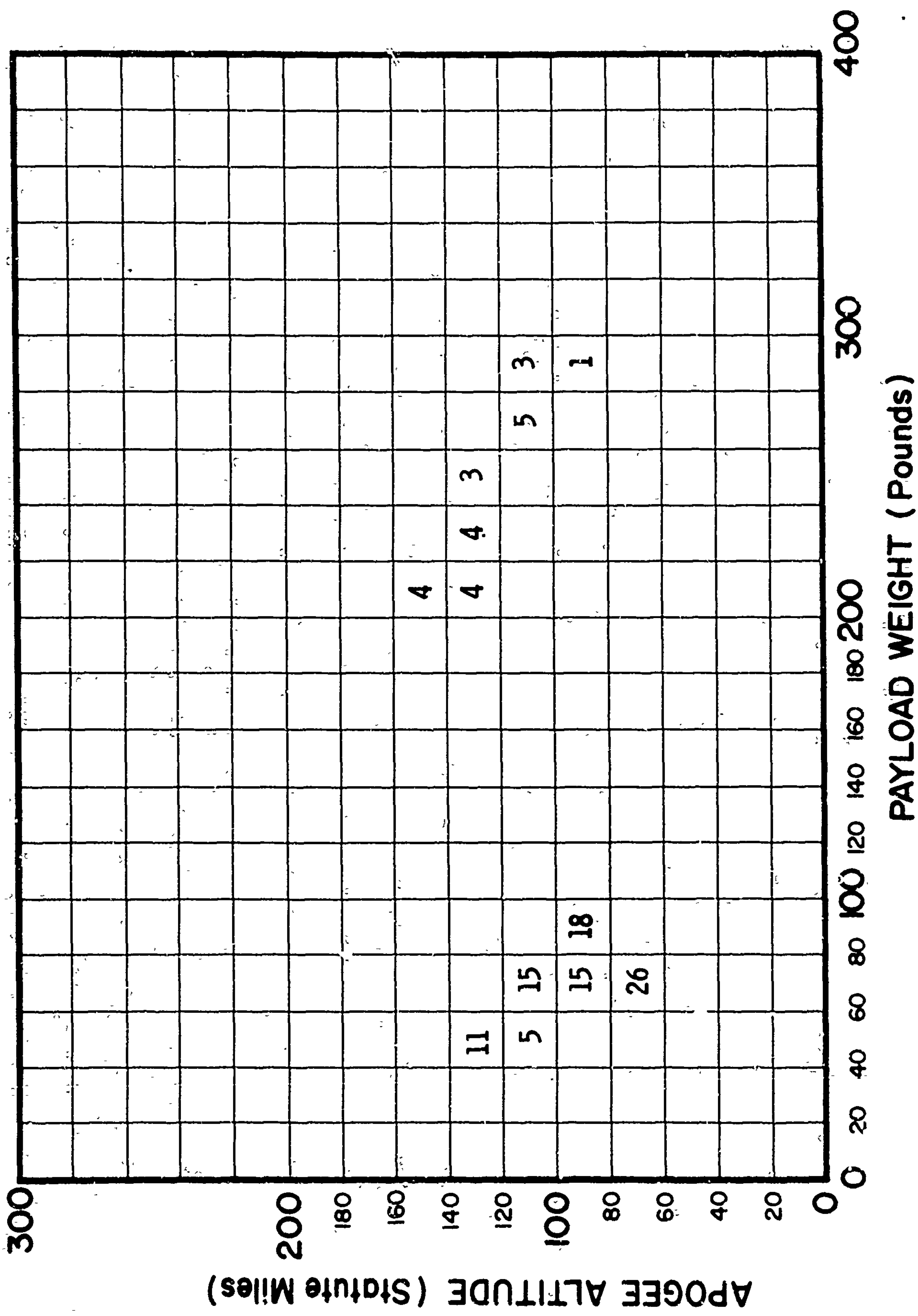


Figure 5. ACTUAL SOUNDING ROCKET UTILIZATION - YEAR (0)

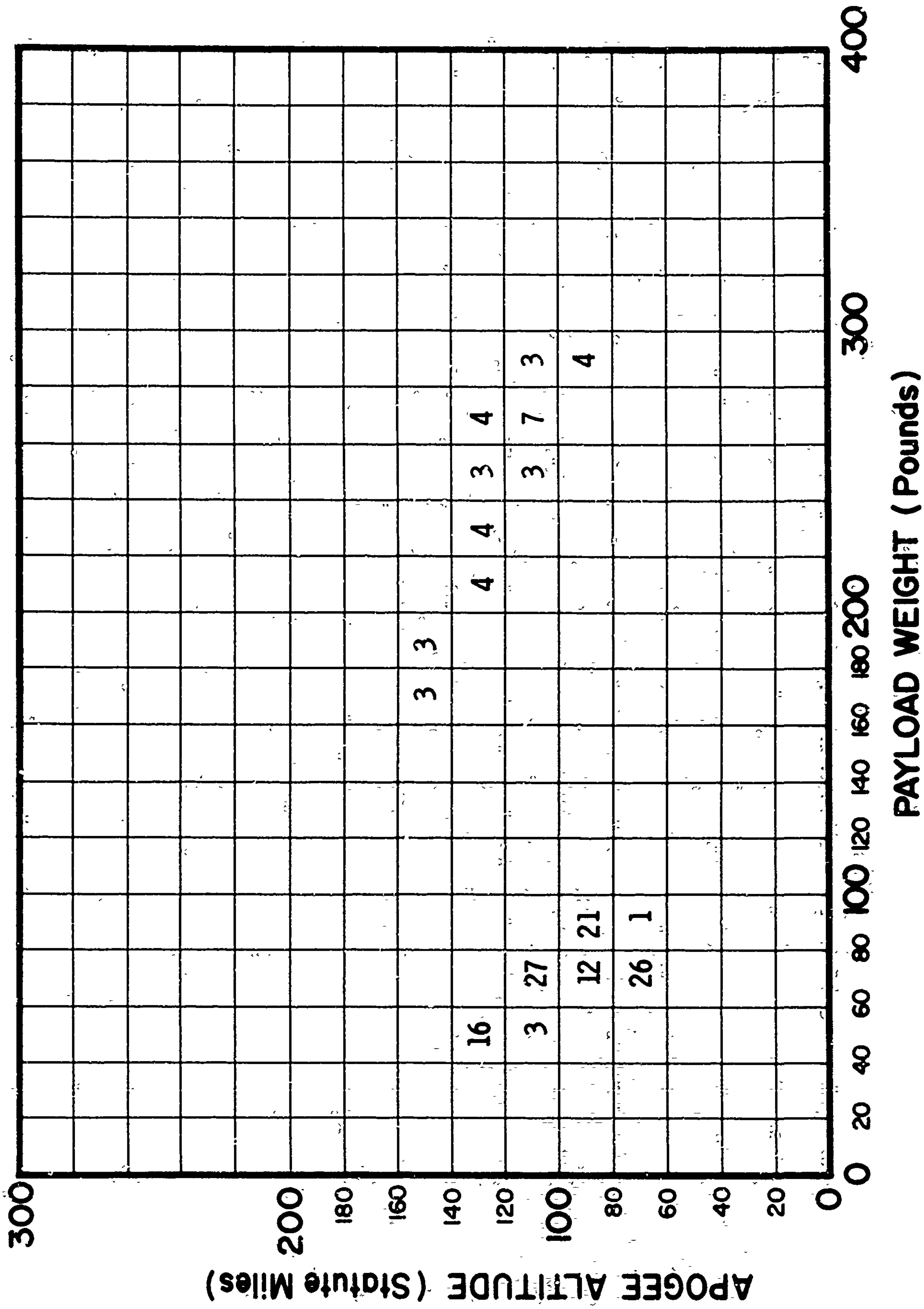


Figure 5a. PREDICTED SOUNDING ROCKET UTILIZATION - YEAR (1)

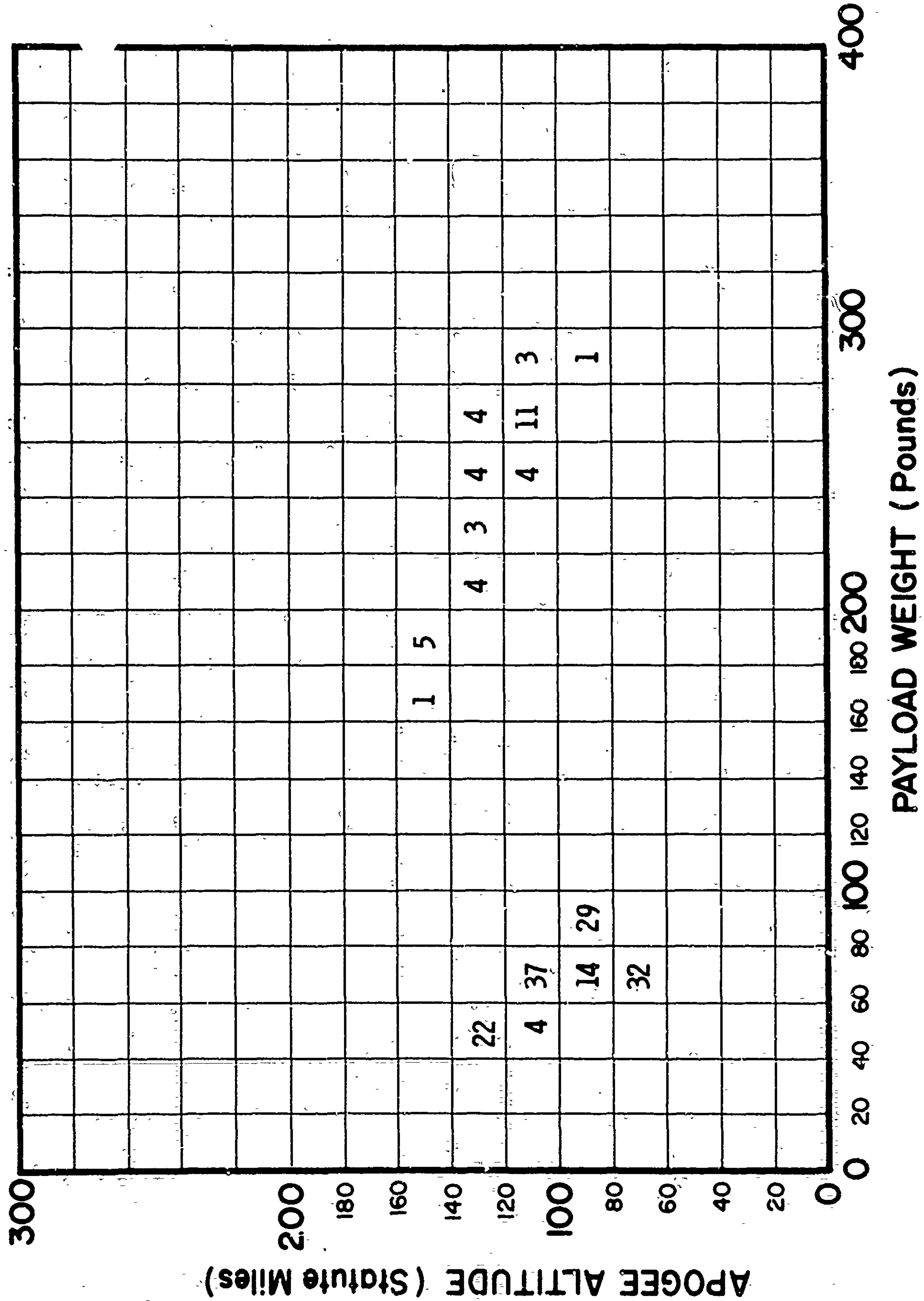


Figure 5b. PREDICTED SOUNDING ROCKET UTILIZATION - YEAR (2)

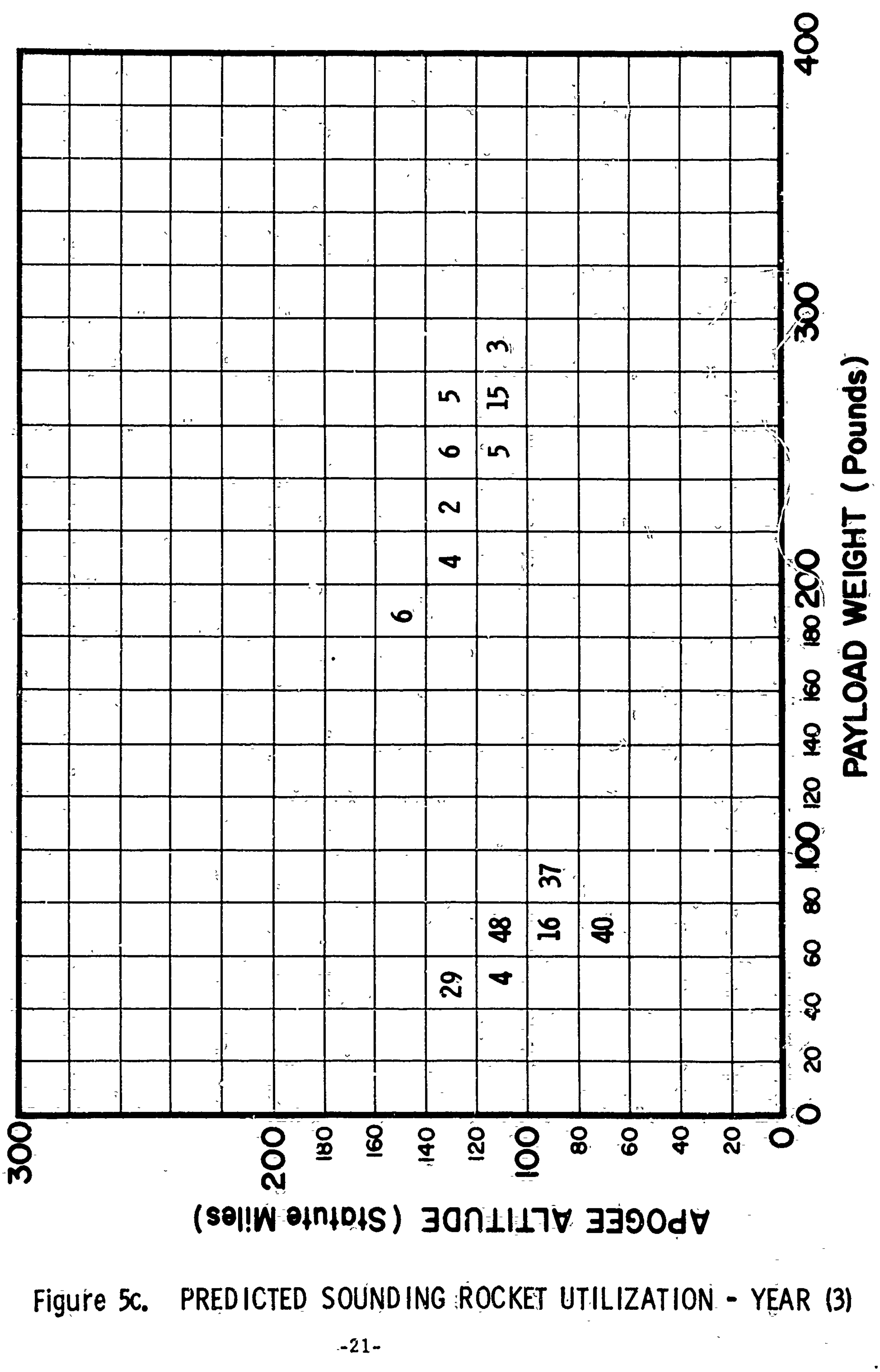


Figure 5c. PREDICTED SOUNDING ROCKET UTILIZATION - YEAR (3)

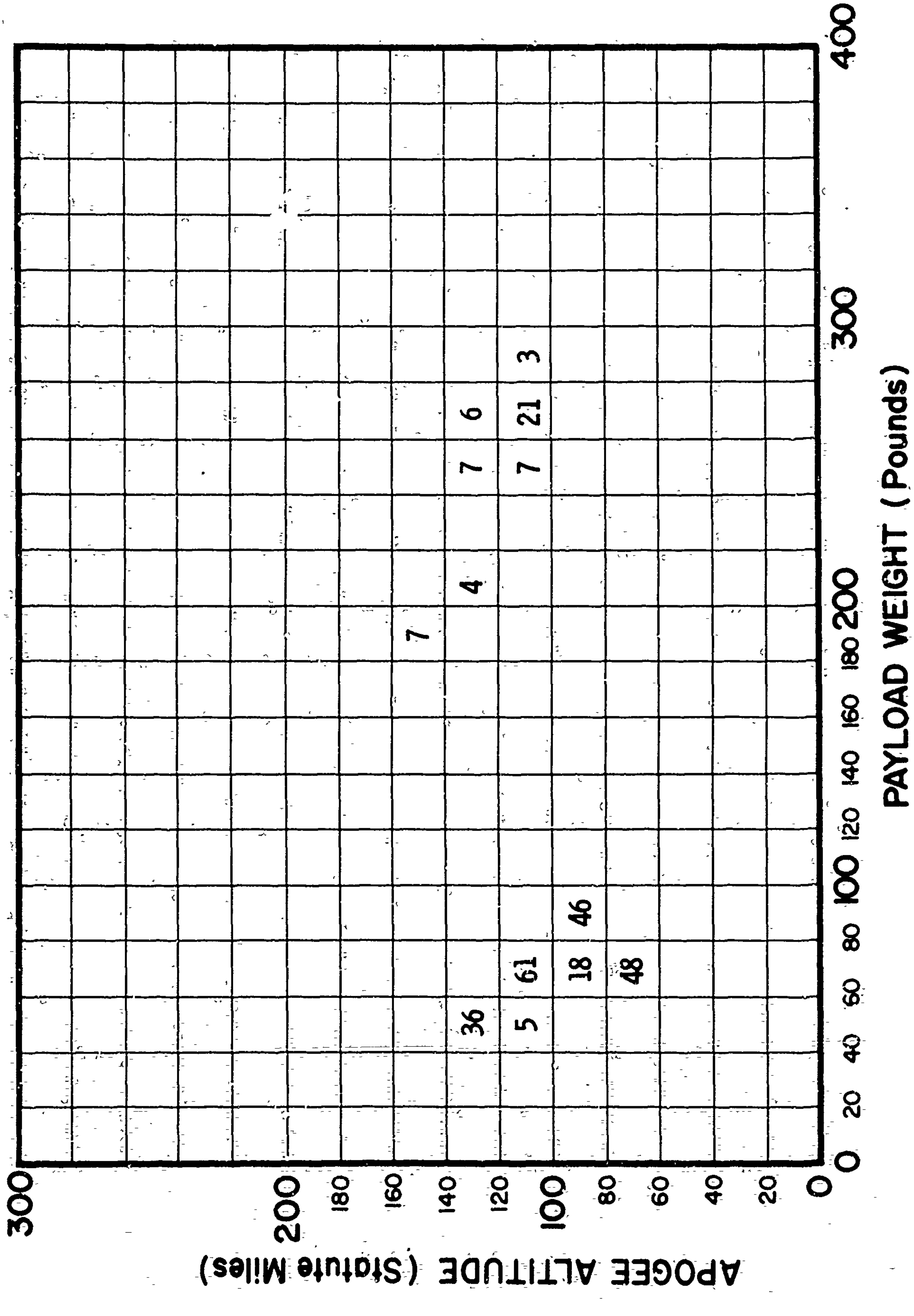


Figure 5d. PREDICTED SOUNDING ROCKET UTILIZATION - YEAR (4)

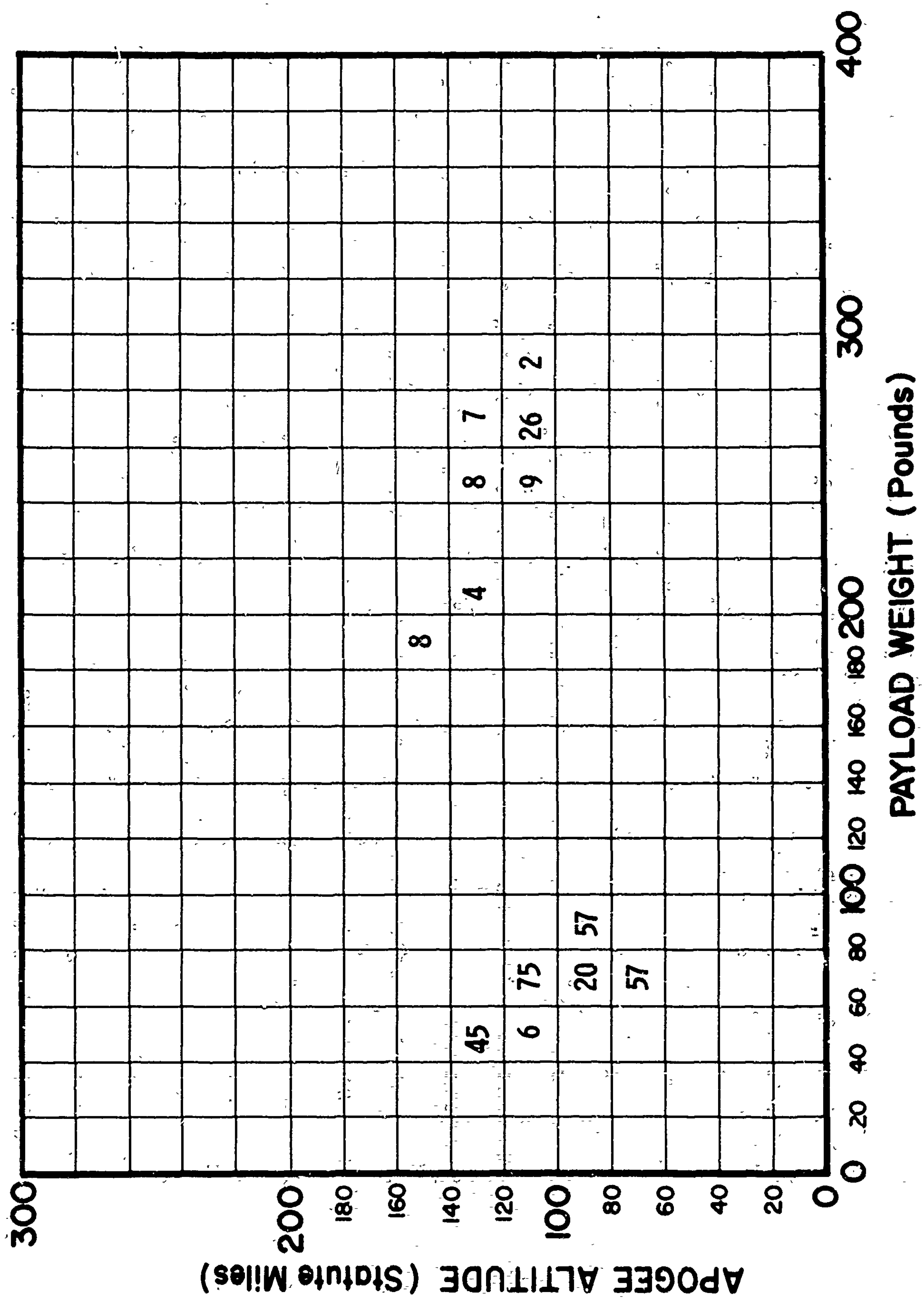


Figure 5e. PREDICTED SOUNDING ROCKET UTILIZATION - YEAR (5)

In Year 5 (Figure 5e), the last one considered in the requirement prediction, we find the three most active categories to be: 60 - 80 pounds to 100 - 120 miles; 80 - 100 pounds to 80 - 100 miles; 60 - 80 pounds to 60 - 80 miles, and 40 - 60 pounds to 120 - 140 miles. In the heavier payloads, the three most active are: 260 - 280 pounds to 100 - 120 miles; 240 - 260 pounds to 100 - 120 miles, and 180 - 200 pounds 140 - 160 miles.

Not surprisingly, the requirements predictions indicate a strong and continued interest in the 80 - 120 mile region with payloads varying from a low of 60 pounds to a high in the upper 200's. At this point it should be remembered that these predictions are based on only the utilization histories available from AFCRL and NASA/GSFC.

The picture could change, perhaps substantially, if data from other agencies were included. Thus, the concentration of payloads in the two areas shown in the figures is somewhat of a mirror of the current vehicle inventories of AFCRL and NASA/GSFC.

d. Accuracy of the Prediction Technique

Note that no requirements are predicted in altitude above 300 miles. The omission in this area was deliberate because the data for such high flying vehicles, at least in the AFCRL and NASA inventories, are too sparse to permit a reasonably accurate prediction. (For example, only three Javelins [100 - 200 pounds to roughly 400 - 600 miles] have been flown at AFCRL; 50 Javelins have been flown by NASA/GSFC through early 1969.) This omission points out a very important aspect of the requirements problem: The predictions are probably most reliable when the available historical data is substantial.

This was illustrated by our efforts to check the accuracy of our prediction scheme by using fewer years of data than were available and seeing how the curve looked without two or three years of the most recent information. This was done as follows: If we had six years of data for a particular requirement, we would compute a curve-fit for six years. We would also calculate curve-fits using only the first three and four years of history. The resulting coefficients were then compared against each other to see if Years 4, 5 and 6 could have been predicted from the information available for only Years 1, 2 and 3.

We found that two or three years of requirements could be accurately predicted if substantial data were available from an historical base of three or four years (see Figure 6). This strongly emphasized the point that a comprehensive and accurate utilization history is required to predict future requirements.

Another important point arising from our effort to forecast sounding rocket utilization is that predictions for individual user agencies cannot be based on the historical data for that specific agency alone. There are several reasons for this. First, data for any agency, taken alone, is usually very meager. The small numbers will thereby limit the statistical validity of the information. Second, no sounding rocket user agency operates in a vacuum. Although the relationships with other agencies are difficult to define, a feedback system does exist and the cross-fertilization of interest is undoubtedly significant. Third, the overall responsibilities of agencies change with time and some may, through management decisions, leave the sounding rocket field altogether. However, the effect on the total utilization of sounding rocket vehicles of the scope change of any one agency is relatively small; the field goes on and the total number of rockets flown are relatively unaffected by its departure.

Our attempts to improve the elementary prediction technique need some further improvement. However, even the elementary techniques we did use will give acceptable results for time spans for at least two (and, with less confidence, three or four) years in those areas where the sounding rocket vehicle utilization history is well established.

3. Sounding Rocket Vehicle Costs

The cost of a sounding rocket inventory consists of a number of components of which the basic vehicle price is a major part. At least the following items are involved:

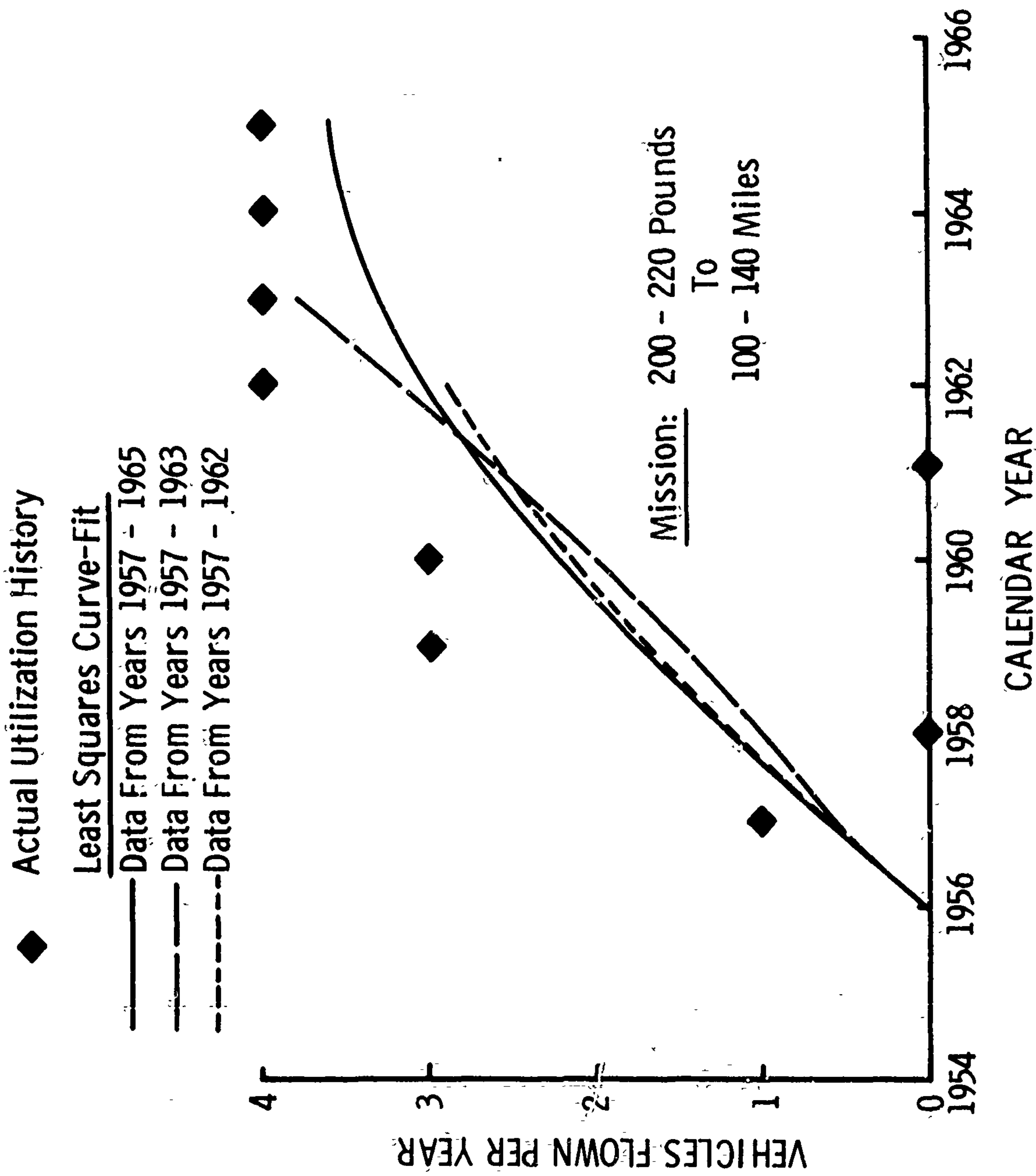


Figure 6.

LEAST SQUARES CURVE-FIT WITH 8, 6, AND 5 YEARS OF UTILIZATION DATA

a. Basic Vehicle Price

This includes the charges for the complete rocket motors, the fins, the interstage, and the launcher accessory hardware.

b. Analytical Support Services

Each vehicle in the inventory requires considerable analytical support in the way of trajectory data, wind weighting information, dispersion estimates, etc. In addition, special payloads may require vehicle integrity analyses and, as problems develop in flight testing, analytical efforts to solve the latter. Analytical expenses are maximum in the first two to three years after a vehicle is incorporated into the inventory, but still remain a significant cost item throughout its useful lifetime.

c. Storage and Logistics

Each vehicle type can have storage and logistics requirements that are peculiar to it. Therefore, if many types are held in inventory the specific attention devoted to each one can become a significant cost factor. A large number of remote site operations can further make this a significant cost item.

d. Launch Crew Support

If a rocket stable contains only a few vehicle types then the job of the launch crew becomes much simpler because the familiarization process with each type is simplified. Should the launching of many types be required, the amount of individual attention required for each vehicle and the possibility of an error by the crew both increase.

e. Accessory Hardware

In the question of a few vehicle types against many, standardized components can give the former inventory a cost advantage.

f. Unit Costs

In the analysis, we have considered only one inventory cost--the basic vehicle price. This was done in an attempt to simplify the computations. However, if the optimum inventory mix (as determined by the Figure of Merit) proves to be many types of vehicles as opposed to a few, this assumption must be re-examined. If the Figure of Merit computation shows an inventory mix consisting of fewer types to be nearly as favorable as one containing many, the former must be selected in view of the peripheral costs discussed above.

g. Quantity Discounts for Lot Purchases

In gathering vehicle unit costs, an interesting and somewhat unexpected fact came to light: Lot size is not a very important factor in the basic price of sounding rocket vehicles. Examining the price quotations of several rocket motor and vehicle suppliers, it became apparent that a discount of 10% or less was the only economic advantage to be gained by buying vehicles in lots of 50 as opposed to lots of 1, 5, or 10.

The main reason for this surprising fact seems to be the inflexibility of rocket motor costs. (This inflexibility probably arises because most sounding rocket motor buys are too small--even in 50 unit lots--to warrant the capital expenditures required for real mass production.) The 10% price advantage of 50 over 5 unit lots arises mostly from the economies achieved in the manufacture of accessory hardware such as fins, interstages, etc.

A major price break is undoubtedly possible at some lot size. The break may occur at 100 vehicles or perhaps an even larger lot size. Unfortunately, annual sounding rocket buys seldom reach this level from any one customer. Furthermore, although the 10% discount is real, it is quite unimportant when compared to the total cost of an inventory.

The Figure of Merit computations that are shown below, as an example in the analysis, will not be significantly affected by the omission of a lot discount in the few instances where large buys are indicated. Therefore, we assumed unit vehicle costs to be unaffected by lot size.

4. Sounding Rocket Reliability

The effect of reliability on the cost of a sounding rocket inventory is critical. The reason for its importance lies not so much in the cost of the vehicle itself as in the price of a payload that an unsuccessful rocket destroys.

In the vast majority of sounding rocket launches, the payload costs more than the launch vehicle. Ratios of payload to vehicle cost usually range from 3 to 5 and in some instances can reach a value of 10 or even 20. Vehicles costing $30,000 have been used to launch $500,000 payloads, and $12,000 rockets have boosted instruments costing nearly $250,000. The emphasis on putting reliable vehicles in a stable is, therefore, well justified.

a. The Effect of Reliability on Mission Cost

If two or more vehicles available in an inventory can perform the same mission the mission assignment should be made to the vehicle with the lowest effective mission cost. We suggest the following formula for Effective Mission Cost (EMC):

$$EMC = \frac{C_v + C_{PL}}{r_v} \qquad (2)$$

where C_v is the vehicle unit cost, C_{PL} the payload cost, and r_v the vehicle reliability.

Given a choice of two vehicles (1 and 2), the break-even point is reached when:

$$EMC_1 = EMC_2 = \frac{C_{v_1} + C_{PL}}{r_{v_1}} = \frac{C_{v_2} + C_{PL}}{r_{v_2}} \qquad (3)$$

Equation (3), above, can be solved to determine how much the payload must cost before it becomes economically worthwhile to switch to a more expensive launch vehicle if the latter is more reliable. (Of course, if the more expensive vehicle is not more reliable then it makes no sense to switch.) Reworking Equation (3) to solve for the cost of the payload, we have:

$$C_{PL} = \frac{C_{v_2} r_{v_1} - C_{v_1} r_{v_2}}{r_{v_2} - r_{v_1}} \tag{4}$$

Assuming that r_{v_2} does not differ significantly from r_{v_1}, Equation (4) can be approximated by:

$$C_{PL} \cong \frac{C_{v_2} - C_{v_1}}{(r_{v_2} - r_{v_1})/r_v} = \frac{\Delta C_v}{\Delta r_v / r_v} \tag{5}$$

Where ΔC_v is the difference in unit costs of the two vehicles under consideration, and $\Delta r_v / r_v$ is the relative difference in reliability. Thus, if a higher priced vehicle costs \$2,000 more than its competitor, and is, in turn, 5% more reliable, then the payload price would have to be approximately \$40,000 for the more reliable vehicle to be selected. Figure 7 illustrates the relationship between payload price, vehicle cost difference, and relative reliability.

It is evident that the switch from a less reliable and cheaper vehicle to one with greater reliability and higher cost is thus justified when payload costs are high, or the reliability to be gained is significant.

5. Computing the Figure of Merit for an Inventory Mix

Computing the Figure of Merit of the various sounding rocket inventories is the final step in optimizing a vehicle stable. The computation process is quite straightforward requiring nothing more than elementary mathematics. The process is illustrated in the sample problem which follows in the next section.

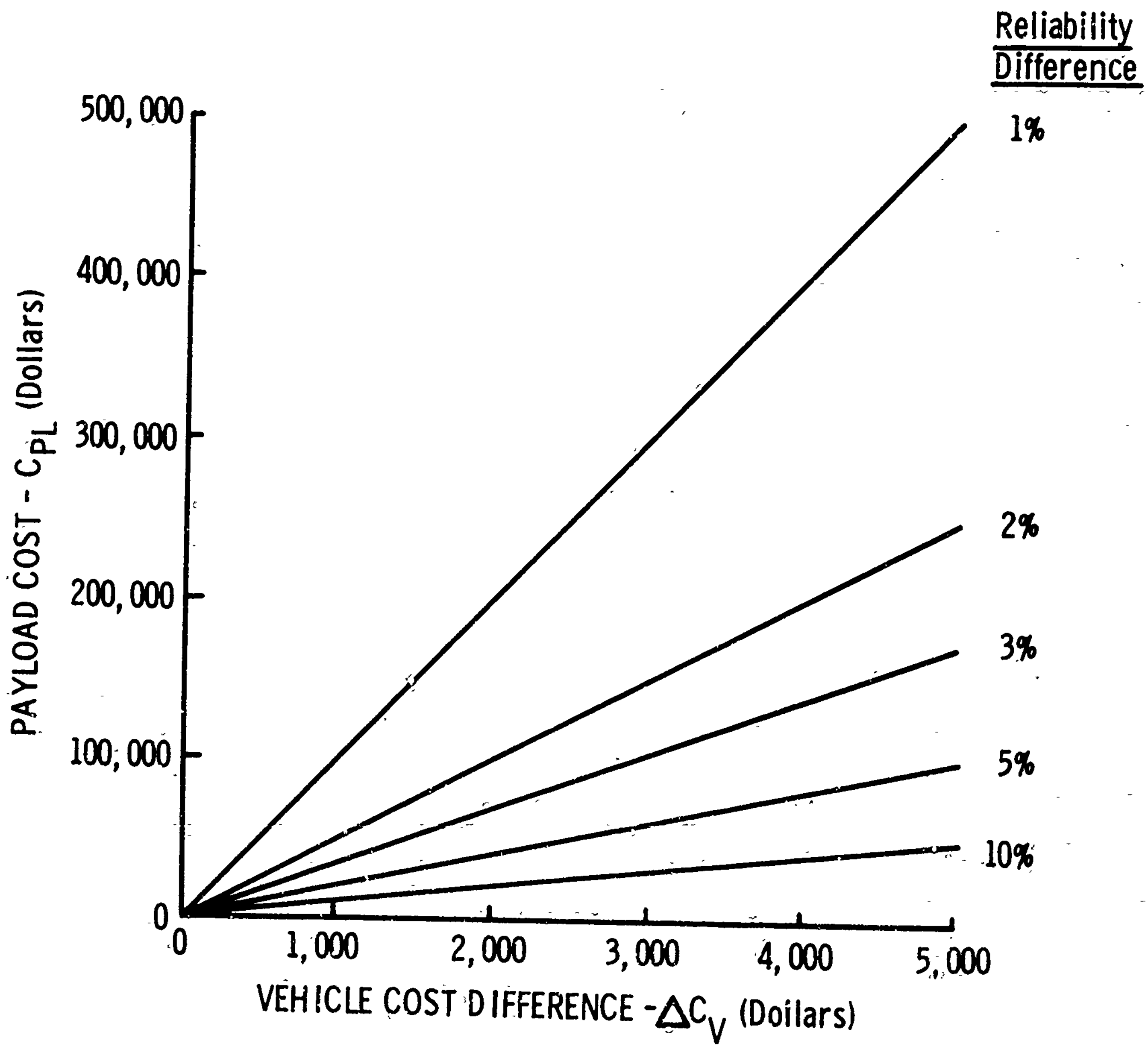


Figure 7.

THE EFFECT OF RELIABILITY AND VEHICLE COST DIFFERENCE ON PAYLOAD COST

B. Optimization of a Sounding Rocket Inventory (A Sample Problem)

A sample problem is presented below to demonstrate the application of the concepts described in the previous sections. As an example, we created an imaginary sounding rocket user agency called AFNA. We have comprehensive sounding rocket utilization records for AFNA dating back a considerable number of years. Based on this use history, we predicted the future requirements of AFNA and attempted to select an optimum sounding rocket inventory for this agency for a future time span of five years.

1. Assumptions

For the AFNA agency we assumed that:

1. Five vehicles (Type A through E) are candidates for the AFNA inventory. The performance characteristics, estimated cost, and reliability of each of these vehicles is indicated in Figure 8.
2. No restrictions are placed on the combinations of Type A through E vehicles that may be adopted for the inventory.
3. Any missions falling to the left of the altitude/payload curve of a vehicle can be performed by that type with the addition of ballast.
4. Any vehicle can meet the mission requirements of any altitude/payload grid cells into which its performance curve penetrates or touches.
5. The reliability of the vehicles considered for inclusion in the inventory will remain constant, at the value initially assumed, for the projected time span.
6. The unit cost, initially assumed for each of the vehicle types, will not change over the projected time span.

2. Choosing the Possible Mixes

Since five vehicle types are candidates for the inventory, there are (statistically) many possible combinations to look at. However, we restricted the combinations to six inventory mixes. As a minimum, an inventory consisting of Type B, and Type A, or Type D vehicles can perform all of the missions in the projected time span of five years. As a maximum, all five types can be held in inventory and will, of course, also satisfy all mission requirements.

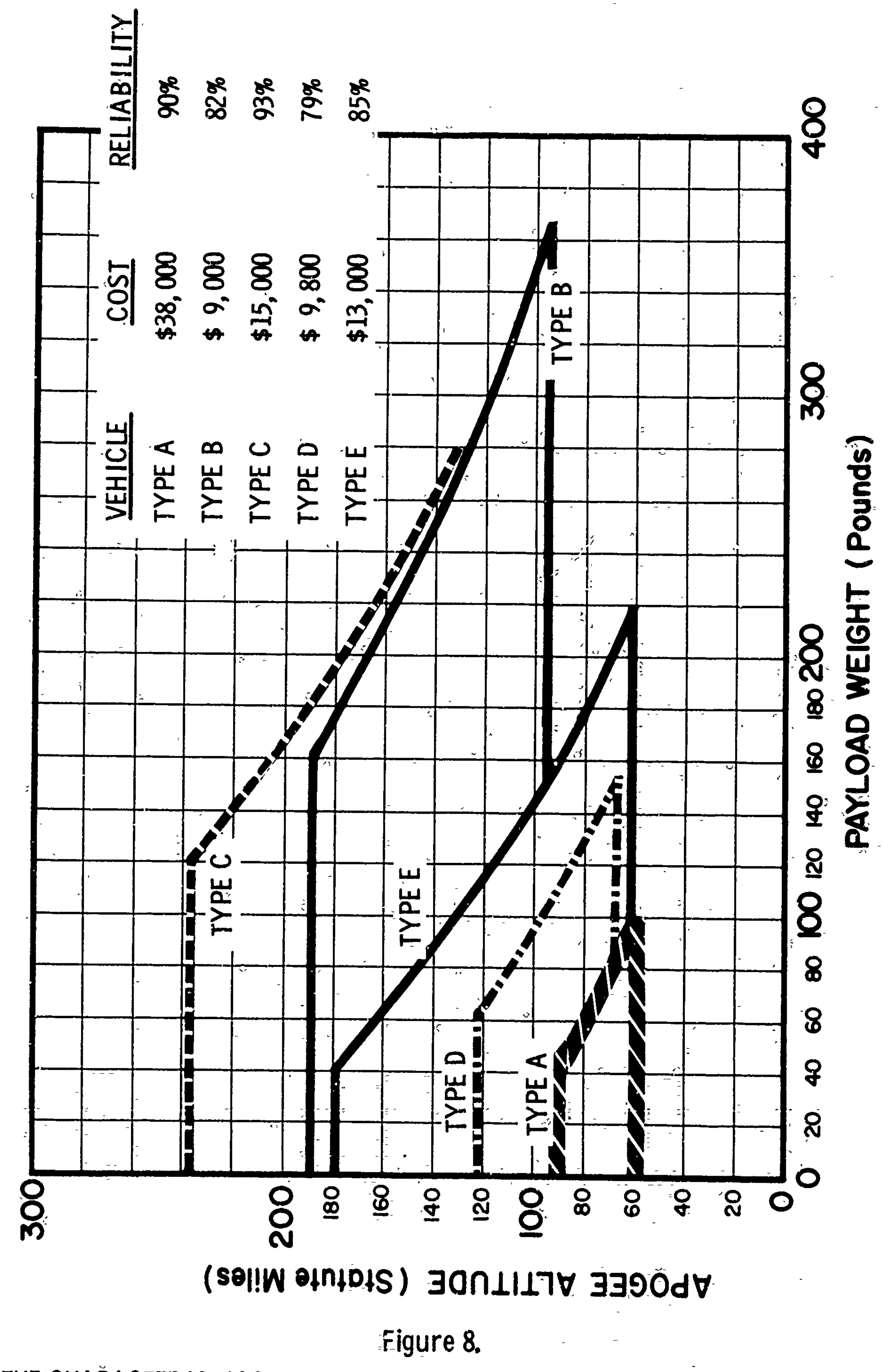


Figure 8.

THE CHARACTERISTICS OF A TYPICAL SOUNDING ROCKET VEHICLE INVENTORY

The six mixes selected for optimization are shown in Table 1 below.

TABLE I
VEHICLE MIXES SELECTED FOR INVENTORY OPTIMIZATION

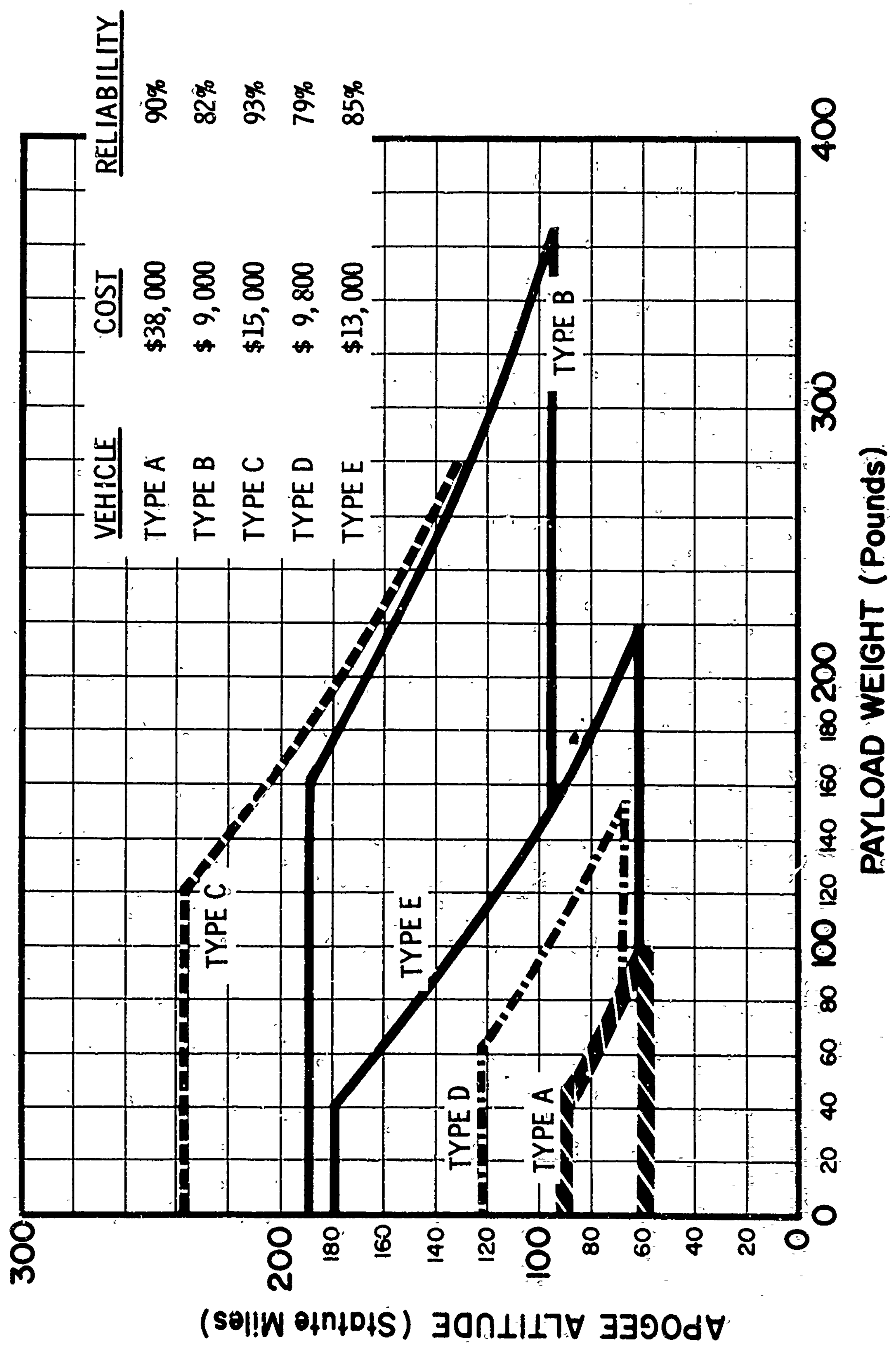
VEHICLE TYPE \ MIX NUMBER	1	2	3	4	5	6
A	✓					✓
B	✓	✓	✓	✓	✓	✓
C	✓			✓	✓	✓
D	✓		✓		✓	✓
E	✓	✓		✓		

Of the vehicles contained in the stable, only Type B is assured permanence; Type B is the only vehicle capable of carrying the payloads in the 240 - 300 pound class to altitudes of 80 - 120 miles. The rest of the types, A, C, D, and E owe their continued use to their favorable effect, if any, on the Figure of Merit.

Mix #1 contains all five types of rockets available for the vehicle inventory. Mix #2 and #3 are at the other end of the spectrum; each contains only two rocket types to illustrate the comparison between the "many vs. few" inventory philosophy. Mix #4 is similar to #2 with the exception that Type C has been added. Mix #5 is similar to Mix #3 with C added. Mix #6 contains all types except E.

3. Mission Requirements

Future requirements predicted for the AFNA agency were determined by extrapolating the least-squares curve-fits of the agency's



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D	✓		✓		✓	✓
E	✓	✓		✓		

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3. Mission Requirements

Future requirements predicted for the AFNA agency were determined by extrapolating the least-squares curve-fits of the agency's utilization history. The results of the extrapolation, previously illustrated in Figures 5 - 5e, are adopted for this sample problem and are summarized below in Table II. Year-by-year growth or decline of requirements in the various payload/altitude categories are given for some eighteen different missions.

TABLE II
PREDICTED MISSION REQUIREMENTS - AFNA AGENCY

PAYLOAD/ALTITUDE (Pounds)/(Miles)	YEAR 1	2	3	4	5
40-60/100-120	3	4	4	5	6
40-60/120-140	16	22	29	36	45
60-80/60-80	26	32	40	48	57
60-80/80-100	12	14	16	18	20
60-80/100-120	27	37	48	61	75
80-100/60-80	1	0	0	0	0
80-100/80-100	21	29	37	46	57
200-220/120-140	4	4	4	4	4
240-260/100-120	3	4	5	7	9
240-260/120-140	3	4	6	7	8
220-240/120-140	4	3	2	0	0
260-280/120-140	4	4	5	6	7
280-300/100-120	3	3	3	3	2
260-280/100-120	7	11	15	21	26
180-200/140-160	3	5	6	7	8
40-100/460-700	1	0	0	0	0
160-180/140-160	3	1	0	0	0
280-300/80-100	4	1	0	0	0

4. Results of the Optimization

The results of the optimization of the AFNA vehicle inventory are shown in Table III. The Figure of Merit value of each inventory mix is predicted for the 5-year time span considered in our example.

In Year 1, Mix #1 has the highest FM, 0.786 pound-miles/dollar. Mix #1 is closely followed by #6 and #5 with 0.778 and 0.768 pound-miles/dollar respectively. The FM of Mix #4 is approximately 10% less than that of Mix #1. In fifth and sixth places are Mix #2 and #3 respectively, approximately 30% below the best one.

TABLE III
FIGURE OF MERIT OF THE VEHICLE INVENTORY MIXES

	Figure of Merit (Pound-Miles/Dollar)				
MIX / YEAR	1	2	3	4	5
1	(0.786)	(0.757)	(0.743)	(0.722)	(0.714)
2	0.570	0.563	0.561	0.560	0.557
3	0.538	0.523	0.515	0.512	0.506
4	0.696	0.666	0.652	0.637	0.629
5	<0.768>	<0.739>	<0.724>	<0.705>	<0.696>
6	[0.778]	[0.748]	[0.734]	[0.714]	[0.705]

(Best Mix) [2nd Best] <3rd Best>

On the basis of these results, Mix #5 would be selected as the optimum vehicle inventory for the AFNA agency. Mix #5 would be selected because it contains only three vehicle types while having an FM less than 2% below that of Mix #1 (0.768 compared to 0.786). The savings obtained by the reduction of peripheral inventory costs, discussed in Section III.A.3, would more than outweigh its slight disadvantage in the FM.

5. Cost Savings

In the final analysis the pains taken to calculate the Figure of Merit of possible vehicle inventory mixes is justified only if significant financial savings can be realized. Comparing the expenditures required for the best as opposed to the worst mix, we find:

TABLE IV
YEARLY VEHICLE COSTS

Year	1	2	3	4	5
Total Mission Requirement (Pound-Miles)	1,827,000	2,126,000	2,565,000	3,111,000	3,496,000
Optimum Mix					
Figure of Merit (Pound-Miles/$)	0.768	0.739	0.724	0.705	0.696
Total Cost ($)	2,379,000	2,877,000	3,543,000	4,413,000	5,023,000
Worst Mix					
Figure of Merit (Pound-Miles/$)	0.538	0.523	0.515	0.512	0.506
Total Cost ($)	3,395,000	4,065,000	4,981,000	6,076,000	6,909,000
Optimum/Worst Mix Cost Difference ($)	1,016,000	1,188,000	1,438,000	1,663,000	1,886,000

It is apparent that the vehicle inventory selected as optimum would save the AFNA agency as much as $1,000,000 in its first year of use. As the total mission requirement (expressed as Pound-Miles) rises, the financial advantage obtained by using the optimum mix in the vehicle inventory increases until, in Year 5, almost $1,900,000 is saved.

It may be argued that the savings projected over the 5-year time span are illusory since management decisions and the availability of new vehicles may change the picture entirely. While this may be partially valid, consider that for a one-year time span the requirement predictions can be forecast with a great deal of accuracy. The $1,000,000 savings resulting from optimizing the vehicle inventory is real and substantial. Therefore, the savings are definetly of sufficient significance to make the optimization exercise a financially rewarding one.

C. Advanced Techniques in Inventory Optimization

Optimization of the sounding rocket inventory depends, as previously discussed, on a knowledge of future mission requirements. If future requirements were perfectly known the optimization process could be reduced to vehicle performance, cost, and logistics which would then be simply combined with the known projected mission profile. Sophisticated prediction techniques were, therefore, examined to see if these advanced methods could be used to obtain better data than those resulting from the polynomial curve fits discussed in Section III.A.2.b.

Optimization methods in the class of "decision making in the face of uncertainty" were also examined because of the difficulty of predicting requirements. This technique, known formally as Subjectivistic Bayesian Decision Theory (Reference 1), was explored in its application to the AFCRL sounding rocket inventory situation.

1. Advanced Prediction Techniques

Three probabilistic prediction techniques are described below. They are Wiener Estimation Theory, Constrained Least Squares Curve Fit and GPSS.

a. Wiener Estimation Theory

To apply the "linear mean square estimation" theory, proposed by Wiener, to the problem of predicting sounding rocket utilization, we examined the ensemble utilization records for payloads of 80 - 99, 100 - 119, and 120 - 139 pounds flown to altitudes of 60 - 79, 80 - 99, and 100 - 119 statute miles. The time interval considered was 1957 - 1965 for records which were a composite of AFCRL and NASA/GSFC data. Table V shows the sounding rocket utilization history of these two agencies in the selected performance regime.

The selected ensemble forms a 9-cell by 9-year record in one of the most active payload/altitude regimes in sounding rocketry. The

Reference 1: Erickson, W. A.; DECISION MAKING UNDER UNCERTAINTIES; Short Course in Probabilistic Applications; University of Michigan; June 1967.

TABLE V

AFNA UTILIZATION HISTORY 1957 - 1965

Cell	1	2	3	4	5	6	7	8	9
Altitude (S. Mi.)	60-79	60-79	60-79	80-99	80-99	80-99	100-119	100-119	100-119
Payload (Pounds)	80-99	100-119	120-139	80-99	100-119	120-139	80-99	100-119	120-139
YEAR									
1965	10	1	0	2	10	0	10	5	0
1964	26	1	6	15	17	1	12	4	0
1963	9	3	0	1	6	0	19	2	0
1962	13	17	1	7	7	0	4	1	0
1961	7	1	0	2	0	0	1	4	0
1960	8	8	0	12	4	0	0	0	0
1959	6	3	0	4	0	0	2	0	0
1958	2	0	0	6	4	0	0	0	0
1957	0	0	0	0	0	0	0	0	0

9-cell by 9-year record was normalized:

1. Against the mean utilization in a given cell over 9 years
2. Against the mean of utilization in a given year over 9 cells
3. Against the ensemble mean over 81 cells.

Normalized correlation coefficients were computed for one cell from year to year against itself, and for one cell against other cells from year to year.

In performing these simple mathematical manipulations, we were deliberately ignoring the stationarity assumption inherent in the Wiener theory; stationarity implies that the future will be independent of the time period used to predict it. This is obviously not applicable to our problem as you can see .om a brief look at Table V. In the year 1957 no rockets were flown in the selected payload/altitude regime. Were we to base our prediction on that time interval, we would predict no future activity whatsoever in that regime, a rather extreme departure from the facts as they actually occurred.

There were other difficulties with this technique which can be summarized in the following disappointing results:

1. Further proof that the data was not stationary was indicated by the fact that the mean was not invarient with time for either the 9 by 9 or 5 by 5 cell groupings.
2. Time correlations within a cell were not readily describable by mathematical functions.
3. There was no functional relationship between utilization in different cells. In statistical terms, use in different cells was uncorrelated.

As a result of these facts we concluded that Wiener's theory would not be successful at predicting sounding rocket utilization to any greater extent than would simple polynomial extrapolation. Further, since polynomial extrapolation does not assume stationarity the mathematical validity of using this approach is probably greater.

b. Constrained Least-Squares Fit

Another possible approach to prediction of sounding rocket mission requirements is a variation of polynomial extrapolation: The constrained least-squares curve fit. In Reference 2, R. K. Brimhall of Thiokol's Wasatch Division introduces the concept of the constrained least-squares curve fit. An "estimating function" (the curve fit) is constrained to go through a selected number of actual data points and be least-squares with the rest of the available information.

The advantage of the constrained least-squares approach is that recent data can be constrained to strongly influence the utilization predictions. We, therefore, recommend that this technique be considered in future work on the subject.

c. GPSS

Another technique suggested for the prediction problem is the application of GPSS--General Purpose Simulation System (Reference 3). In this technique a mission profile could be generated by a random number process. The occurrence of a mission in a particular weight/altitude cell would be governed by the utilization history in that cell. The cell's utilization history can be described by a frequency distribution that approximates its actual utilization record. The output of GPSS would be a mission profile generated by a large number of passes through the problem.

The application of GPSS implies that sounding rocket utilization is at least functionally related to and can be expressed by the distribution of a random variable. It is, therefore, difficult to predict the value of GPSS in this application since the process has been primarily used in various types of maintenance and queue problems.

Reference 2: Brimhall, R. K.; DESIGN OPTIMIZATION USING MODEL ESTIMATION PROGRAMMING: Thiokol Chemical Corporation, Wasatch Division, Brigham City, Utah; Presented To AIAA, Jan. 1968.

Reference 3: GENERAL PURPOSE SIMULATION SYSTEM/360; IBM Application Program, IBM Corporation, Technical Publications Dept.

2. Problems in Vehicle Prediction

Problems of a frustrating nature have arisen in the pursuit of utilization prediction analysis. The first of these is the quality of sounding rocket utilization data. Utilization data have a very poor level of priority at most sounding rocket organizations. Therefore, information is not complete and accurate until at least one year and, in some cases, two years after the vehicles have been flown.

Another problem with the data is its scarcity in a large portion of the payload/altitude grid. Since the prediction results were poor unless there was a substantial amount of historical data, we must have relatively low confidence in the predictions for many segments of the payload/altitude grid.

New areas of utilization cannot, with our present methods, be predicted at all. If there is no history in a given altitude/weight cell, we can predict no utilization in that regime. Yet, as new vehicles become available we know that they will be used by experimenters to plug some of the holes in the weight/altitude grid.

This brings up another problem, the chicken/egg question: Was the new vehicle type developed to meet an existing but unsatisfied need, or did the need arise because the new vehicle type was available? Vehicles have come into sounding rocket use both ways.

These factors need much further study since they could significantly impair the validity of the work done in predicting sounding rocket utilization if they are not properly understood.

3. Application of Bayesian Decision Theory to Inventory Optimization

Bayesian decision theory can be very useful in the optimization of a sounding rocket inventory. It could be applied to answer the following question:

> "Given a fixed amount of money allocated to the purchase of a sounding rocket inventory for a budgetary period; furthermore, given a projected set of mission requirements for the same budgetary period and, given several sounding rocket vehicle types available for purchase: How do you allocate the budget among the several sounding rocket vehicles types so that the maximum number of experiments are flown within the budgetary time period, consistent with the financial constraints?"

This type of problem typifies a utility theory approach in which the risk element comprises the rockets left over at the end of the year plus the corps of unhappy experimenters; the gain comprises the total number of experiments successfully flown, and the uncertainties include at least the mission requirements and the flight reliability record of the vehicles. With only a minimum number of alternatives included, the decision tree framing this problem becomes very complex.

To illustrate the Bayesian theory approach to such a problem, we could formulate a case based on the following typical assumptions:

1. The total vehicle budget is S Dollars.
2. Four types of sounding rocket vehicles are available to be purchased for inventory. These are types A, B, C, and D.
3. The Altitude/Payload capability of Type D is such that it can handle any mission assigned to D - A. In turn, C can handle all C - A missions while B can handle all B and A missions, (Figure 9). From a performance standpoint this makes the mission assignment strategy the most flexible since no vehicle type enjoys a unique position (except D).
4. The relative cost of vehicles A - D can be modeled in several ways:
   - On the basis of existing vehicle types.
   - As a linear function of their payload capability.
   - As a linear function of their altitude capability.
   - On the basis of some fixed percentage of increasing cost with increasing performance; for example, Type B costs "X" percent more than Type A, Type C "X" percent more than Type B, etc.

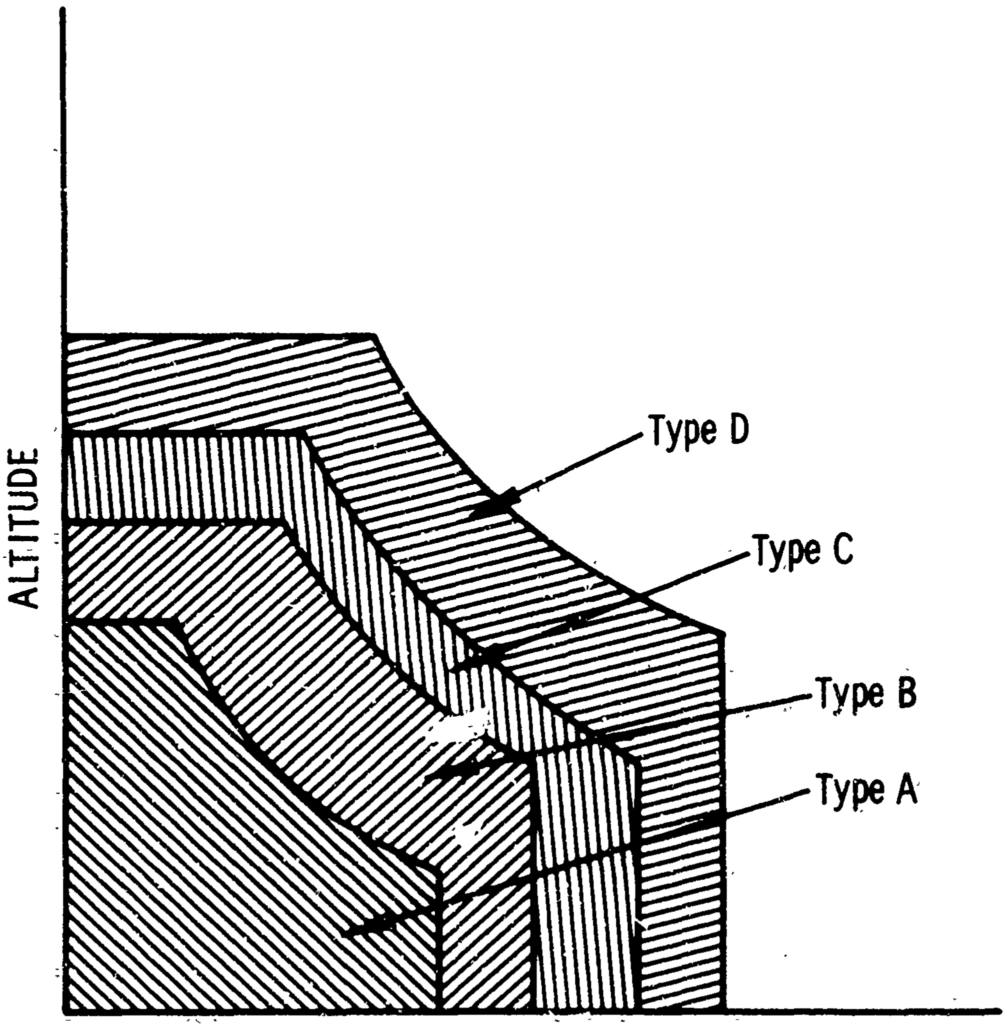

Figure 9. TYPICAL VEHICLE PERFORMANCE CAPABILITIES

5. As with cost there are several ways of approaching the problem of vehicle reliability:

- On the basis that all vehicle types are equally reliable. This is probably the best place to begin since the reliability of competitive vehicle types can be a subject of much heated discussion and is sometimes very difficult to define.
- On the basis of the number of vehicle stages.
- As a direct proportion of the vehicle cost.

Once a set of ground rules has been selected one would begin with the budgetary process which allots "S" dollars for a vehicle mix inventory based on the stated intentions of the scientific experimenters. This is the process by which the inventory is nominally selected today. Within the fixed constraint of "S" dollars, a number of options are now available to the sounding rocket purchaser:

1. Purchase exactly those vehicles for which the budget of "S" Dollars was approved.
2. Depart from the budget generated inventory in a way in which significant advantages will accrue to the experimenter.

Step 2 above is where the application of Bayesian decision theory can be useful. It can give the sounding rocket purchaser an idea of how to best allot the budgeted dollars between the different vehicle types so that he can satisfy a greater number of experimenters than if he had followed their stated plans. This can be done by running a number of different trial mixes through the decision process, assigning different probabilities of being the correct one to the several mixes and determining if (within the estimated probabilities) there is one mix which stands a better chance of achieving the maximum number of satisfied experimenters than any of the others. The decision tree (a statistical tool) for this process is illustrated in Figure 10. The process by which it is arrived at is briefly explained below.

Basically a decision tree consists of a succession of events in which a conscious act (choice) is followed by the probabilistic state of nature (chance). A succession of choice-chance-choice-chance steps

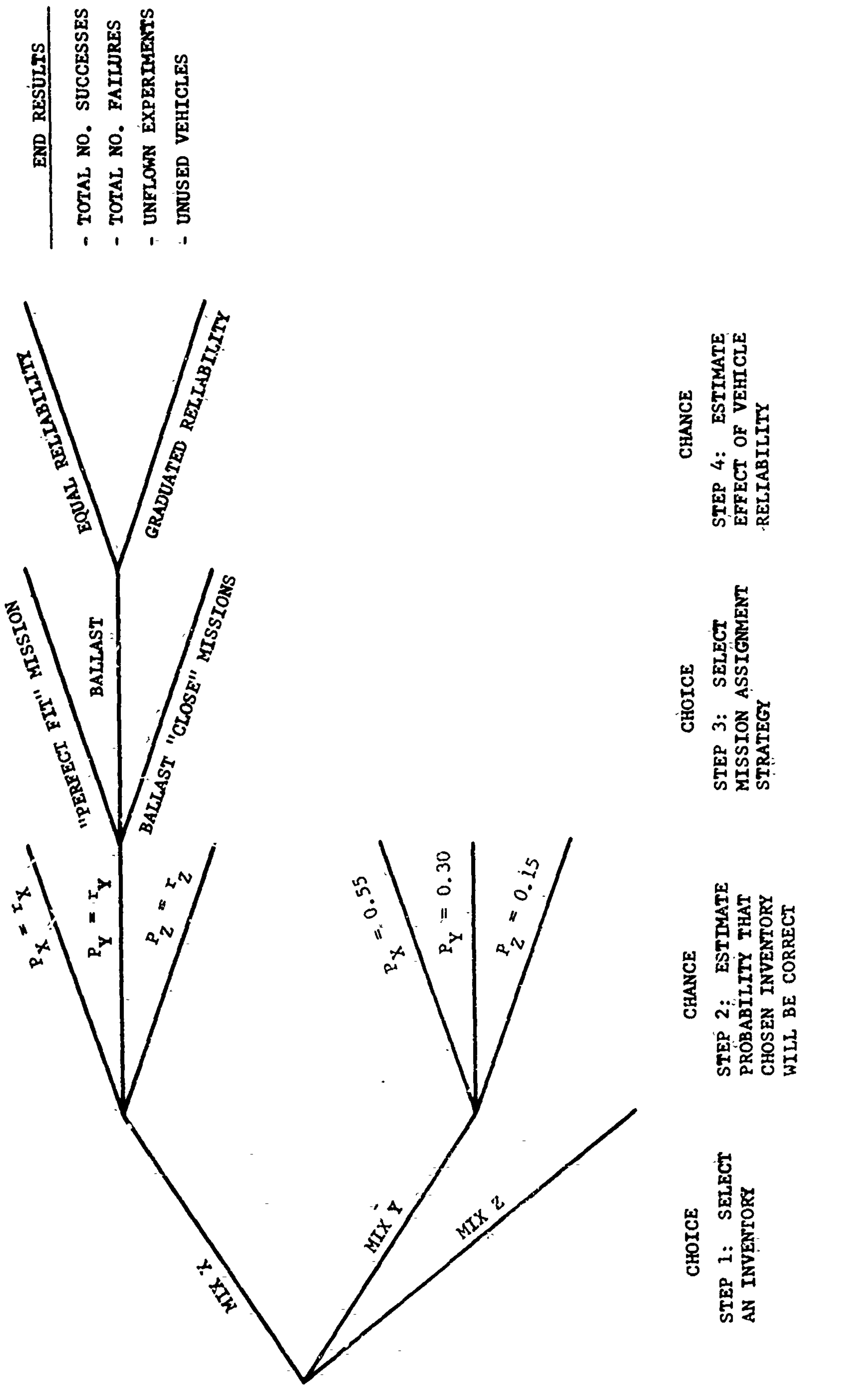

Figure 10. TYPICAL INVENTORY OPTIMIZATION DECISION TREE

result in a set of consequences which follow every set of branches. Referring to Figure 10 the typical decision tree for the inventory problem could be as follows:

Step 1 - (CHOICE): Select an Inventory

In a hypothetical problem we could begin by selecting three sounding rocket invetory mixes labeled as X, Y and Z in the illustration. The only constraint on Mixes X, Y and Z is that the cost of each branch is equal to the "S" dollars budgeted for the inventory.

Step 2 - (CHANCE): Estimate the Probability that the Chosen Inventory will be Correct.

To each branch of the decision tree we now attach another set of branches consisting of estimated probabilities that the particular course of action taken in Step 1 is the correct one. r_X represents the probability that Mix X will actually reflect the mission requirements as they arise, after the inventory has been purchased. r_Y and r_Z represent the probability that those respective mixes turn out to be the right ones. The only restriction on r_X, r_Y and r_Z is that they sum to 1.0. It can, of course, be argued that neither Mix X, Y or Z will represent the mission requirements as they actually turn out; however, if the mixes are carefully chosen the final requirements will at least closely resemble one of the selected inventories.

In assigning probabilities that the mixes are correct, it should be possible to use as a guide budgetary plans of AFCRL which form the basis for the sounding rocket purchases over the years. Then, these could be compared to the missions actually flown in those years, and reliability estimates on the accuracy of the pre-purchase predictions could be so obtained.

Step 3 - (CHOICE): Select a Mission Assignment Strategy

At the end of Step 2 we have a series of consequences: If Mix X was selected but the requirements actually fit Mix Y, then the consequences may be that there will be more vehicles than missions, more missions than vehicles, or the wrong missions for the vehicles on hand. A strategy must then be adopted to handle the situation.

Three strategy options are postulated on the decision tree. The first of these, that "perfect fit" missions will be flown, would indicate a method in which Type B missions would be flown only on Type B vehicles. If there is an excess of Type C vehicles (which by our earlier assumptions can handle Type B missions) those vehicles would not be used.

The second choice is to ballast all possible missions; if there were an excess of Type B missions and an excess of Type D vehicles, the latter will be ballasted to handle the excess Type B missions.

The third choice is a compromise in which only "close" vehicles are ballasted to satisfy unfulfilled mission requirements. For example, Type C could be ballasted to accomplish Type B, but Type D would not be ballasted to handle Type B. This is a fairly believable approach to the problem since it may very well be that the higher performing Type D sounding rocket would be too expensive to "waste" on a Type B mission.

Step 4 - (CHANCE): Estimate the Effects of Vehicle Reliability

Having made the decision how to fly the various vehicles, we would now take into account the effect of reliability of the different vehicles types on the success of the missions. One approach is to consider the reliability of all vehicles as equal. Another approach is to assign a specific reliability to each vehicle type in either a functional relationship or an arbitrary manner.

4. End Product

The end results at each branch of the decision tree would be the total number of successes, the vehicle failures, the number of unflown experiments and the number of unused vehicles.

Each course of action could then be compared to every other set of choices. If cost were the overall criterion of the optimization problem, then dollar figures would then have to be associated with each success, failure, unflown experiment, and unused vehicle.

By this approach it may turn out that a particular course of action in selecting an inventory--when combined with a set of mission assignment rules--will produce the best results in the face of the uncertainties in mission requirements and vehicle reliability. A number of additional benefits may arise. For instance, it may be that vehicle reliability is not really a strong factor in influencing the overall successes of the inventory purchase. The value of ballasting vehicles could also be determined as a worthwhile (or worthless) course of action.

5. Commentary

The decision tree shown in Figure 10 is by no means complete, nor are all the possible choices outlined. It could be much more complex if more than three possible inventory mixes are postulated. Even in the relatively simple example illustrated, there are over 50 possible paths through the tree. The complexity of the tree rapidly increases as more branches are added.

Nor need we stop there: Since there will, at the end of the calendar year, be some unflown experiments and unused vehicles, decision trees for successive years could be tacked on to each other. Thus, unflown experiments and unused vehicles resulting at the end of Year 1 could influence the mixes selected in Year 2. The leftovers at the end of Year 2 would further influence the decisions at the end of Year 3. The complexity and sophistication of the decision tree is thus more a function of the patience and computing power of the investigator the problem itself.

D. Cost Effectiveness of the Development of a New Sounding Rocket Vehicle

New vehicle development in the sounding rocket field has not been notably successful. Many attempts have been abandoned after vehicle design, rocket motor development, and even flight testing. Unfortunately, there have been relatively few successes. For example, only 48% of the 53 sounding rocket programs identified in Reference 4 have had ten or more flights; 33% have had 20 or more, and 18% have had 50 or more total flights (Figure 11).

If we consider a new sounding rocket vehicle to be successful when it has completed a total of 50 or more flights, then less than 20% of all vehicle development programs have been successful.

Historical hindsight, therefore, shows that many sounding rocket development programs either did not get off the ground at all or made only a few flights before they were abandoned. The fact that this is true of the definite majority of programs lends impetus to our search for a means to prevent the unnecessary financial and human expenditures wasted in an unsuccessful development program.

1. What Makes a New Sounding Rocket Vehicle Successful?

A new sounding rocket may be considered successful if, after its introduction, its use rate shows a steady initial growth and its range of application is steadily diversified. Growth in utilization is an indicator of success because it implies satisfactory performance of the new vehicle. Diversification of its application is another required success factor because it indicates that the sponsoring customer or agency is not the only one who is using the vehicle.

The requirement of diversification also eliminates the vehicles designed for highly specialized one-shot applications such as weapons testing where the particular vehicle may never be heard from again when the test series is over. In several such programs a good number

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Reference 4: APPLICATION OF ADVANCED SOLID AND HYBRID MOTORS TO SOUNDING ROCKETS: Space General Corporation; July 1966.

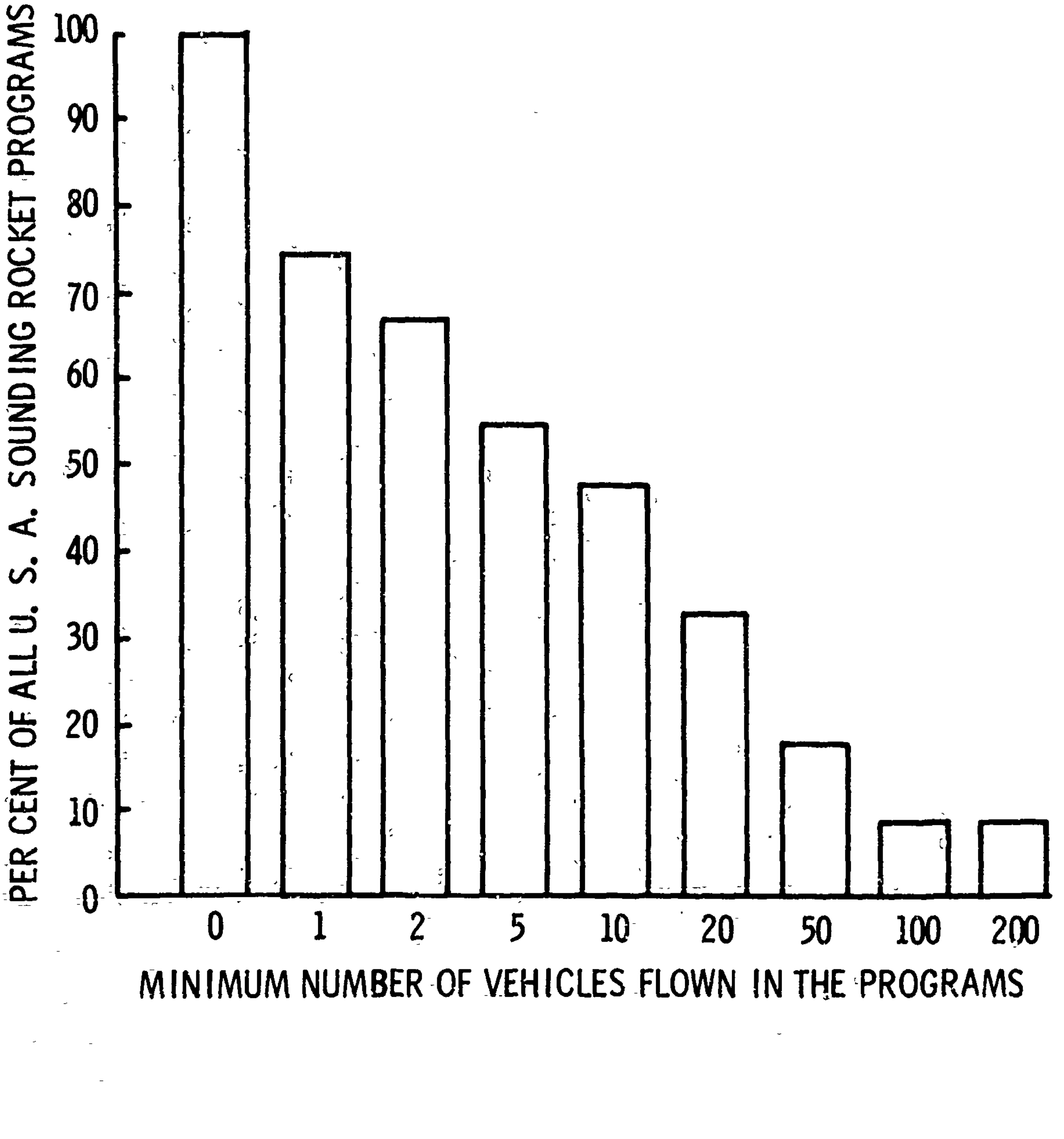

Figure 11. THE DISTRIBUTION OF MINIMUM NUMBER OF VEHICLES FLOWN

of vehicles were flown, for example the Deacon-Arrow, the Viper-Arrow, the Asp, and the Nike-Asp. However, none of these vehicles proved to be attractive to the scientific sounding rocket community and were dropped after a brief but spectacular career. The first indicator, steady growth rate, also rules out one-shot programs from being deemed successful since their growth rate is initially rapid, but ceases when the original application is over.

Another criterion of success of a new development is when the new system begins to supplant an existing well-established vehicle by taking away some of the latter's missions. Here it is important to differentiate between two types of competition between a new and an established vehicle, direct substitution and improved replacement. Direct substitution implies that the new vehicle competes Pound-for-Pound and Mile-for-Mile with an existing sounding rocket. If the new vehicle can reach higher altitudes or carry larger payloads (or both) than the established sounding rocket it is considered an improved replacement.

Without performance advantages a newly developed vehicle apparently stands little chance of becoming successful; an established vehicle has the considerable advantages of entrenchment which include a demonstrated flight history, an established reliability record, analytical support and user acceptance, the last being a psychological factor of no small importance.

If the new vehicle, as a direct substitute for an established sounding rocket, has a significant price advantage (on a unit cost basis) even that will not weigh heavily in its favor; its lack of demonstrated reliability usually outweighs its price advantage. Furthermore, realistically speaking, development costs are rising, making it highly unlikely that a new vehicle can be less expensive than an existing, proven, sounding rocket.

There is, however, one possible exception by which a newly developed sounding rocket can directly supplant an existing vehicle: that is if the existing vehicle has a poor reliability record, or consists of motors that no longer are available. In these cases, a new vehicle stands a considerably better chance of success. Even the threat of "no more motors" need sometimes not be taken too seriously. A classic example of this is the Nike, a component of practically every multi-stage sounding rocket in use in the United States today. There have been numerous "no more Nikes" panics in past years, but the demand has been steady enough so that the supply has continued unabated.

To be successful then, a newly developed vehicle must offer performance advantages over an existing sounding rocket or must be able to open a new area of the atmosphere to sounding rocket exploration. We can identify a vehicle as being successful by the steady growth of its use rate after its introduction, and the diversification of its application from that for which it was originally developed.

2. The Effect of Requirements on New Vehicle Development

Future requirements can provide the stimulus for the development of new vehicles. This is because requirement predictions can serve as indicators of areas in which substantial growth can be anticipated and, thereby, point out the performance regime for which a new sounding rocket should be developed.

To make these requirement predictions one could use the same techniques outlined in Section III.A.2.b. These consist of parabolic curve-fits of sounding rocket utilization histories in different apogee altitude/payload weight regions to form the basis for an extrapolation into future years.

3. Reliability of a Newly Developed Vehicle

The reliability of a newly developed vehicle has a tremendously important influence on the cost effectiveness of its development. A new vehicle may present a substantial cost advantage over a rocket in current use which may be completely nullified if the new rocket develops a poor reliability record. Furthermore, since a new vehicle rarely costs less than an existing type, the problem of reliability becomes a critical one. In considering the reliability of a newly developed rocket, we will look at two phases of the problem: (a) Reliability Growth and (b) Long Term Reliability.

a. Reliability Growth

To anticipate the reliability growth of a newly developed sounding rocket, we examine the following model:

Let r_n = Reliability of the "nth" launch

N = Number of major failure modes initially present in the design

p = Probability of occurrence of a single failure mode during any single flight

d = Probability that a failure mode will be detected and identified once it has occurred

n = Total number of flights.

Then, we made the following basic assumptions:

1. All failure modes have the same probability of occurrence, detection, and identification.
2. Operational policy is to correct all known failure modes by redesign and/or procedural changes.
3. There are no salvo launchings so that policy 2 may be applied to successive vehicles.
4. All failure modes are critical to all missions.
5. Corrective action initiated as a result of a failure does not introduce new failure modes.

Now consider a specific failure mode. The probability that this mode has not occurred, and been detected, after n flights is, $(1-pd)^n$.

The expected number of failure modes discovered, $\overline{X}$, is:

$$\overline{X} = N\left[1-(1-pd)^n\right] \tag{6}$$

The reliability of the "(n + 1)th" flight is, on an expected basis,

$$\overline{r}_{n+1} = (1-p)^{(N-\overline{X})}, \tag{7}$$

or $$\bar{r}_{n+1} = (1-p)^{N(1-pd)^n} \tag{8}$$

The variation of expected reliability with flight number is shown in Figure 12 for a case in which there are five failure modes ($\underline{N} = 5$), the probability of occurrence of any of the failure modes is 25% ($\underline{p} = 0.25$), and the detection probability of the failure modes varies from a low of 25% to a high of 99% ($\underline{d} = 0.25 - 0.99$).

The expected reliability increases rapidly as the failure mode detection probability goes from 25% - 75%, but less rapidly as $\underline{d}$ approaches 99%. This illustrates the importance of carrying a reasonable amount of diagnostic instrumentation on the first few flights if rapid reliability growth is desired.

The effect of the number of failure modes on reliability growth is illustrated in Figure 13 which shows reliability as a function of increasing $\underline{N}$, with $\underline{d}$ fixed at 0.75 and $\underline{p}$ at 0.25. As expected, vehicles with large numbers of failure modes have slower rates of reliability growth.

Another interesting aspect of the reliability growth problem is illustrated in Figure 14, where $\underline{N} = 5$, $d = 0.75$, $p = 0.25$ and 0.50. Here we see that a high probability of occurrence of a failure mode actually helps the reliability growth because the failures, occurring earlier, are corrected earlier.

After parametrically exploring the effect on reliability of detection probability, number of failure modes, and probability of occurrence, we attempted to fit the theoretical growth model to empirical data derived from actual sounding rocket experience. As a source of empirical data, we selected eight recent sounding rocket development programs and considered their history over their first five flights. Table VI gives the average reliability of this ensemble as a function of the number of flights.

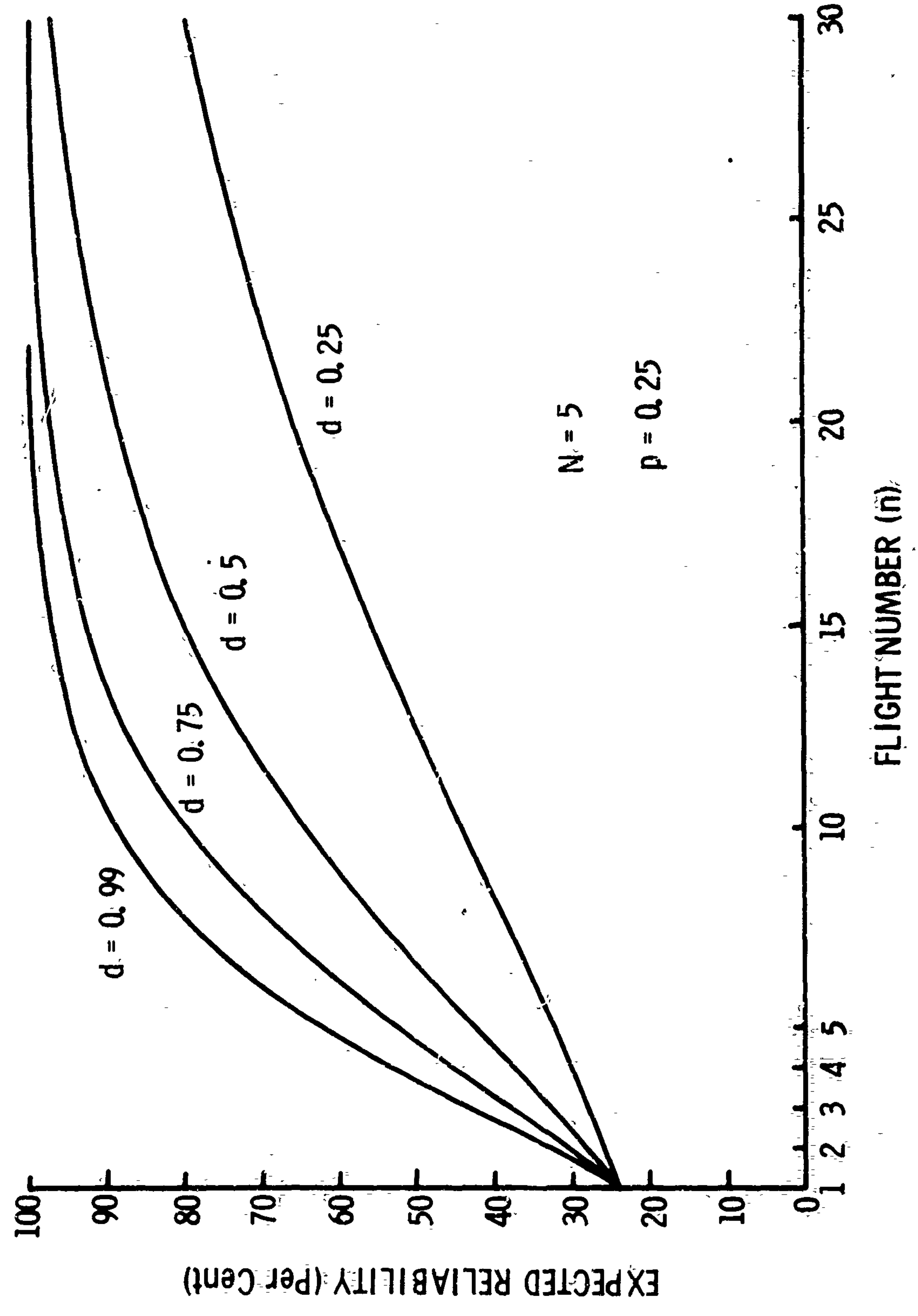

Figure 12.

THE EFFECT OF DETECTION PROBABILITY ON EXPECTED RELIABILITY

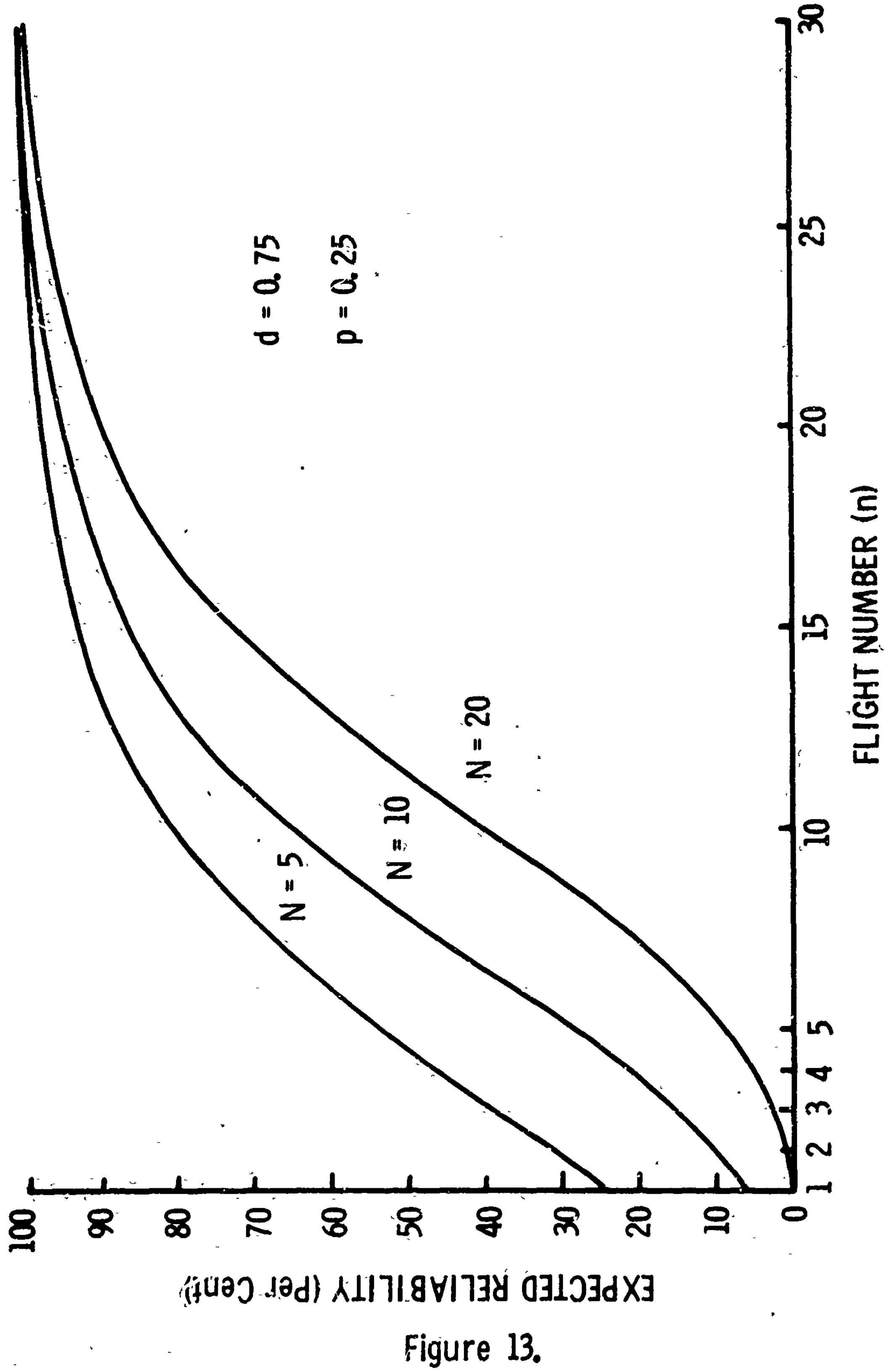

Figure 13.

THE EFFECT OF NUMBER OF FAILURE MODES ON EXPECTED RELIABILITY

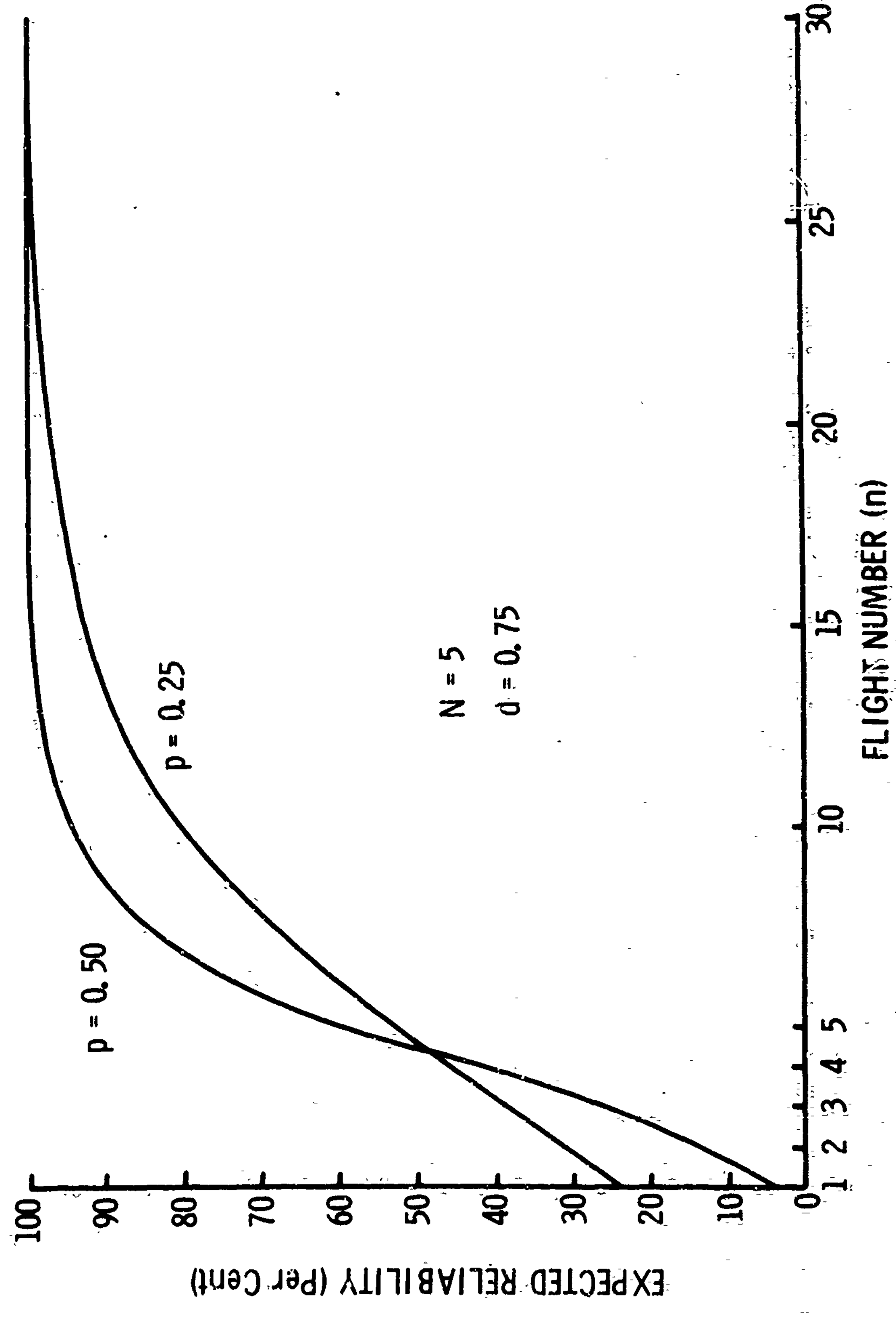

Figure 14.

THE EFFECT OF FAILURE MODE PROBABILITY ON EXPECTED RELIABILITY

TABLE VI

RELIABILITY GROWTH

Vehicle Type / Flight Number	1	2	3	4	5
ALFA	X	X	X	X	✓
BRAVO	X	✓	✓	✓	X
CHARLIE	X	X	X	X	X
DELTA	X	X	✓	X	✓
ECHO	X	X	✓	*	*
FOX	X	X	X	✓	✓
GOLF	✓	✓	X	✓	✓
HOTEL	X	X	X	✓	✓
Average Reliability	0.13	0.25	0.38	0.57	0.71

✓ - Vehicle Success; X - Vehicle Failure; * - Not Yet Flown

VEHICLE FAILURE: Vehicle either did not meet design objectives and/or alterations to design or operational procedures were required for succeeding launches. All other vehicles were considered successful.

Close agreement was found between the empirical data and the theoretical model when $\underline{N}$ was assumed to be 5, $\underline{p}$ was 0.50, and $\underline{d}$ was 0.90 (Figure 15). We found that no other variation of the equation parameters $\underline{N}$, $\underline{d}$, and $\underline{p}$, resulted in such close correlation.

Figure 15 thus indicates that 5 major failure modes are a realistic number to be expected in today's state of the art, and that the probability curve of 90% indicates that today's sounding rockets are well instrumented and closely observed, and that little guessing is necessary to determine the reasons for a vehicle's failure.

The record also shows that four to five flights are required before an experimenter has an even chance of success when he risks a payload on a new vehicle.

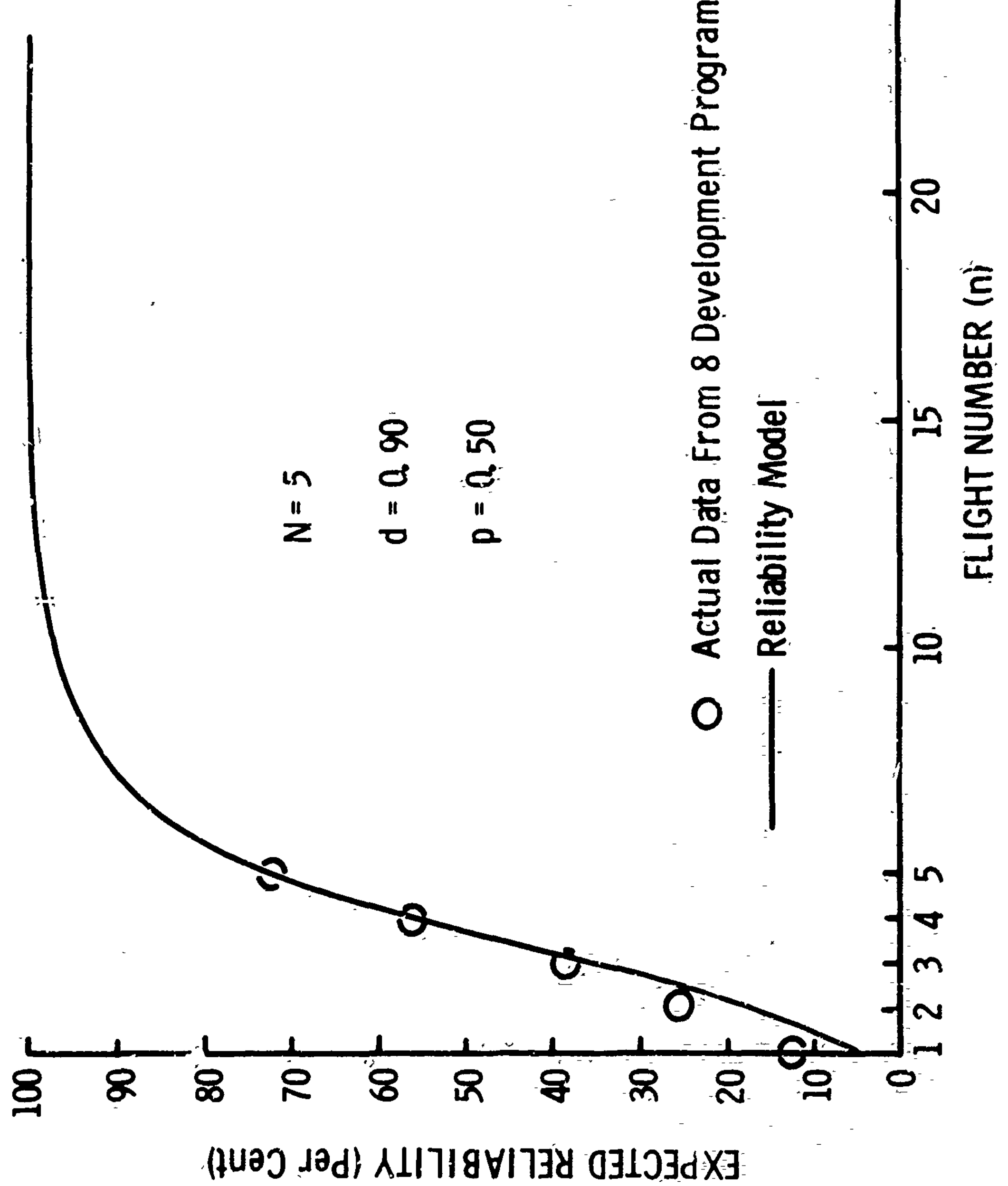

Figure 15.

CORRELATION OF THE RELIABILITY MODEL WITH ACTUAL FLIGHT DATA

b. Long-Term Reliability

Long-term reliability of a (new) vehicle is much more difficult to predict than short-term reliability growth. Experience has shown that, for successful sounding rockets, long-term vehicle reliability will range from a low of 75% to a high of nearly 95%. In terms of affecting the Figure of Merit of a particular vehicle inventory, this reliability range is significant. Therefore, the predicted reliability of a new vehicle will profoundly influence its cost effectiveness.

The theoretical model for reliability growth proposed in Section III.D.3.a. cannot be applied to predicting long-term reliability; the model indicates an expected reliability of practically 100% after only 15 flights. One reason for this phenomenon is that, usually after a very limited number of test/development firings, the vehicle is released for initial operational service. The operational payloads carry minimal diagnostic instrumentation, and are frequently launched under weather conditions which limit the usefulness of optical coverage. As a result, failure detection probabilities are considerably less than 90%. It is also true that some failure modes have an occurrence probability much less than 50%. It follows from this that the actual reliability curve breaks, and asymptotically approaches some terminal value. A first approximation to this situation is to use the curve of Figure 13 until the reliability has reached, say, 90%, and then assume that, thereafter, reliability is constant.

For the present the effect of long-term reliability on the cost effectiveness of a new development can be evaluated on an iterative basis. As a first step, we will assume a long-term reliability that is an average of the best and worst available in today's successful sounding rockets. If the resulting Figure of Merit calculations show that this reliability level is sufficient to give a new vehicle a cost effectiveness advantage, then we can assume its development to be economically worthwhile. If an extremely high reliability, such as 90% - 95%, is required of a new vehicle before it becomes worthwhile to develop it, then we must re-evaluate its cost effectiveness on the basis of a higher development program cost that would be required to achieve that reliability.

In some cases in which the development of a new vehicle is economically sensible only if the configuration possesses a high long-term reliability, large development costs may be justifiable. The best such justification would be a large predicted utilization for a vehicle with its performance characteristics. In this case, high development program costs will be readily absorbed by the large utilization rate.

E. A Typical Approach To Computing the Cost Effectiveness of a Sounding Rocket Vehicle Development Program

Using the criteria developed in the analysis, it is possible to make predictions about the economic consequences of developing a new rocket. The key step in this calculation is the formulation of a set of ground rules for the development program, in operation's research terminology--a scenario. For example, a typical scenario might read as follows:

> "We will consider a five-year time span in which the effect of developing a new vehicle, Type F, on the AFNA inventory will be evaluated. Based on the performance of available rockets and the strong predicted requirement growth in the 40 - 140 pounds to 60 - 160 miles area, the Type F performance specification is taken to be 120 pounds to 70 miles ranging to 60 pounds to 110 miles. Preliminary calculations indicate that such a rocket will have a development cost of $260,000 and its unit production cost will be $6,500. Development time, including the flight of two fully instrumented test articles, is estimated to be two years. Design reliability is predicted to approach 88%, assuming the first eight or ten operational payloads are at least partially instrumented for rocket problem detection."

At first, it might appear that all that remains to determine the cost effectiveness of Type F is to enter it in a new set of trial mixes and, based on the idea of maximizing the Figure of Merit, compute the number of Type F which could be used each year in the AFNA inventory. This cannot be done because, as yet, there is no accounting for amortization of development costs. There are many ways of doing this. For example, the development cost might be spread evenly over the first 189 rockets sold. Or, spread evenly over all rockets sold within 48 months of program go-ahead date, etc.

We must, therefore, consider which of such amortization schedules will be applied. This cannot be done until the scenario is amended by adding a statement about the financial (or other) goals of the sponsoring organization. Once this is done, the optimum amortization program for Type F may be determined.

Once a statement of organization goals has been formulated, a first "trial" amortization program may be attempted. In the present scenario, suppose that development costs must be written off over the first two years of operational service, and for ease of accounting, the development burden is to be taken as constant over a time of one year. Then we may write that:

$$D_2 + D_3 = \$260{,}000,$$

$$C_2 = \$6{,}500 + \frac{D_2}{n_2},$$

$$C_3 = \$6{,}500 + \frac{D_3}{n_3},$$

$$\text{and} \quad C_n = \$6{,}500 \text{ thereafter.}$$

where D_2, D_3 = Development costs to be written off in Years 2 and 3. (The development starts at the beginning of Year 0.)

n_2, n_3 = Number of Type F required in the optimum mixes in Years 2 and 3, assuming that numerical values for D_2 and D_3 have been fixed.

C_2, C_3 = Unit prices for Type F in Years 2 and 3.

As a first guess, we might take, say,

D_2 = \$140,000, and

D_3 = \$120,000

Now trial mixes may be arranged, and an iterative solution for n_2 and n_3 for the optimum mixes found. This process may be repeated for different numerical values of D_2 and D_3 until that combination which most closely satisfies the organizational goals is found.

The output of the above procedure is some number; the total vehicles required during the next five years, which relates the effect of adopting the policy, "develop Type F", to the sponsoring organization's goals. By doing the same for Type G, H, etc., one can arrive at vehicle specifications and a preliminary design for the most desirable development investment.

IV. CONCLUSIONS

The purpose of the work described in this report was to study analytical methods that could be used to improve the cost effectiveness of sounding rocket procurement. Based on the results achieved in this effort, we conclude that:

1. Sounding rocket inventory optimization is feasible and can produce substantial savings.
2. Short-term predictions of sounding rocket requirements are most valid in performance regimes where a utilization history is well established.
3. It is difficult to predict requirements in performance regimes in which little or no utilization history exists.
4. Based on conclusions 2 and 3 above it is difficult to forecast the cost effectiveness of a newly developed sounding rocket vehicle and the question of cost effectiveness of a new vehicle development is left largely unanswered.

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13. ABSTRACT

Analytical methods, that could be used to make scientific sounding rocket procurement and utilization more economically effective, are described. A Figure of Merit comparator, on which sounding rocket procurement and vehicle development decisions can be based, is proposed. The cost optimization of combinations of sounding rocket types for a user agency's vehicle inventory, selected on the basis of the Figure of Merit, is demonstrated. It is shown that optimum combinations of vehicle types can produce significant savings in the overall costs of a sounding rocket inventory.

Techniques for predicting mission requirements are discussed, and one of these, polynomial extrapolations of actual utilization histories, is applied to historical utilization data from AFCRL and NASA/GSFC. More sophisticated statistical prediction techniques are examined for their applicability to this problem.

Bayesian decision theory is discussed in its potential application to inventory optimization.

Methods of estimating the cost effectiveness of a proposed sounding rocket vehicle development program are examined. Considerations of success criteria, projected mission requirements, and reliability growth, are included in the guidelines for the cost effectiveness evaluation.

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