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INERTIAL GYRO LIFE-CYCLE COSTS — ANALYSIS AND MANAGEMENT

by

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Chapter 6

SUMMARY AND CONCLUSIONS

This chapter contains a summary of this thesis effort, the conclusions from this effort, and recommendations for future effort.

6.1 Summary of Thesis Effort

This thesis is an investigation of the engineering and economic aspects of inertial gyros. A gyro production system was hypothesized in which gyros were assembled, tested, installed in the inertial measurement unit, sent to the field, returned from the field after failure, removed from the IMU, failure-identification tested, disassembled, reassembled, etc. A mathematical model of the system was derived which included elapsed time, material costs, labor costs, equipment costs, and yield (whenever applicable) for each operation in the hypothetical system. The model simulates the time-sequential behavior of the stable, dynamic, nonlinear system exhibiting both transient and steady-state behavior to the applied inputs and disturbances. The model of the system was developed in a digital computer program format that is easily learned, understood and applied. Data for the operation of the system were obtained informally from various industry and government sources, as well as the author's own personal experience. Many changes were introduced into the model with the objective of locating and describing the relationship between various system parameters and the gyro life-cycle costs. It is hoped that the identification of the most cost-sensitive parameters and their cost impact will assist in decisions in R & D contract allotments.

The most important contributions of this thesis are believed to be the following:

(a) A stable, dynamic, nonlinear mathematical model describing a gyro production system has been derived.

(b) Use of a simple digital computer language suitable for modeling a wide variety of systems and especially recommended for life-cycle costing studies has been demonstrated.

(c) The IMU costs attributable to the gyro have been included in the gyro life-cycle cost (LCC).

(d) A unique set of cost data and other data required to obtain meaning-

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by

Peter J. Palmer

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ABSTRACT

The engineering and economic aspects of inertial gyro production, test, and repair are investigated using the concept of life-cycle cost. The single-degree-of-freedom inertial gyro is taken as the example, but the study can be easily applied to other types of gyros and other engineering devices.

The nonlinear mathematical model is derived in a digital computer program format. A unique set of basic cost data was obtained, mainly from industry, and used in determining the characteristics of the model. Those parameters of the model which indicate the greatest life-cycle cost sensitivities are investigated. Areas where the return in terms of lower life-cycle costs may be greater than the investment are identified.

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TABLE OF CONTENTS

Chapter Number		Page Number
1	INTRODUCTION.	1
	1.1 Background	1
	1.2 Scope of the Thesis.	3
	1.3 Summary of Contents	4
2	DESCRIPTIVE MODEL OF THE SYSTEM	7
	2.1 Introduction	7
	2.2 The System	8
	2.3 The Plant	8
	2.4 The Gyro Sector of the Plant	11
	2.5 The Inertial Measurement Unit Sector of the Plant.	13
	2.6 The Field Sector.	15
	2.7 The System Details.	15
3	A MATHEMATICAL MODEL OF THE SYSTEM.	17
	3.1 Introduction	17
	3.2 Input and Output	19
	3.3 Gyro Assembly	23
	3.4 Gyro Acceptance Test	24
	3.5 Gyro Disassembly	26
	3.6 Gyro Reassembly	27
	3.7 Gyro Failure Indentification Tests – Plant Failures	28
	3.8 Gyro Failure Identification Tests – Field Failures	28
	3.9 Inertial Measurement Unit (IMU) Assembly	29
	3.10 Inertial Measurement Unit Acceptance Tests	30
	3.11 Inertial Measurement Unit Disassembly-Plant Failures	31
	3.12 Inertial Measurement Unit - Waiting Stack for Field Failures	31
	3.13 Inertial Measurement Unit-Failure Verification Test.	32
	3.14 Inertial Measurement Unit Disassembly-Field Failures	32
	3.15 Field Inventory	33

Chapter Number			Page Number
	3.16	Costs	34
	3.17	Output: Printed and Graphic	41
4	THE DATA		43
	4.1	Introduction	43
	4.2	Elapsed Time	44
	4.3	Labor Costs	44
	4.4	Material Costs	46
	4.5	Tools and Equipment Costs	46
	4.6	Yield	46
	4.7	Parts Lost	46
	4.8	Summary	46
5	ANALYSIS OF RESULTS		47
	5.1	Introduction	47
	5.2	Gyro Acquisition Costs	47
	5.3	System Costs when All Failures are Eliminated	47
	5.4	Effects of Varying Gyro Acceptance-Test Yield	49
	5.5	Impact of Automation on Gyro Assembly	54
	5.6	Effects of Varying IMU Acceptance-Test Yield	54
	5.7	Effects of Changes in Gyro Acceptance Test	55
	5.8	Costs as a Function of Failure Rates in the Field	58
	5.9	Summary	61
6	SUMMARY AND CONCLUSIONS		75
	6.1	Summary of Thesis Effort	75
	6.2	Conclusions	76
	6.3	Recommendations for Future Effort	77
Appendix A		Program Codes, Line Numbers and Definitions	79
Appendix B		The Program	87
References			97

LIST OF ILLUSTRATIONS

Figure Number		Page Number
2.1	Block Diagram of the System	9
2.2	Simplified Block Diagram of the Plant	10
2.3	Block Diagram of the Gyro Sector of the Plant	12
2.4	Block Diagram of the Inertial Measurement Unit Sector of the Plant	14
2.5	Block Diagram of the Field Sector	15
2.6	Detailed Block Diagram of the System	16
3.1	Time Notation	18
3.2	IMU Field Inventory and Assembled Gyros Divided by 3 vs Time	21
4.1	Nominal Values of Data for the System	45
5.1	Inertial Measurement Units vs Time for Zero Failures and Unity Yields	48
5.2	Life-Cycle Costs and Cost per Day per IMU in the Field vs Gyro Acceptance-Test Yield	52
5.3	Gyro Labor, Parts and Materials, and IMU Labor Subcosts vs. Gyro Acceptance-Test Yield	53
5.4	Life-Cycle Cost and Cost per Day per IMU in the Field vs IMU Acceptance-Test Yield	56
5.5	Gyro Labor, Parts and Materials, and IMU Labor Subcost vs IMU Acceptance-Test Yield	57
5.6	Inertial Measurement Units vs Time for IMU Failure Rates of 0.5/yr and 0.05/yr.	59
5.7	Life-Cycle Cost and Cost per Day-per-IMU in the Field vs IMU Failure Rate	60
5.8	Gyro Labor, Parts and Materials, and IMU Labor Subcosts vs IMU Failure Rate	62
5.9	Results of Reference Run	64
5.10	Results of Reference Run	65
5.11	Results of Reference Run	66
5.12	Results of Reference Run	67
5.13	Results of Reference Run	68

Figure Number		Page Number
5.14	Results of Reference Run	69
5.15	Results of Reference Run	70
5.16	Results of Reference Run	71
5.17	Results of Reference Run	72
5.18	Results of Reference Run	73

Chapter 1

INTRODUCTION

Emphasis in the past few years on the total-package-procurement concept by both the government and industry suggested that part of this concept, life-cycle costing (LCC), be applied in an engineering and economic study of the inertial gyro. Recent papers [12], [10], [11], [29], [30], [31] plus discussions with colleagues engaged in the research, development, production, and repair engineering of inertial gyros reinforced that idea. Thus the requirement of a thesis became the opportunity to investigate a subject of considerable personal interest.

1.1 Background

In the late 1940's and during the 1950's, the Department of Defense (DOD) instituted large-scale programs to develop major weapons systems. Substantial amounts of research, development, and production were involved, all with tight schedules. It became apparent that, under the cost-plus-fixed-fee contracts, hardware deliveries were late, anticipated quality did not materialize, and costs far exceeded the original budgets. An analysis of the escalation in costs revealed that on the average the final costs were three times the original cost estimates made at the R & D phase.[21] Several reasons were advanced for these discrepancies such as poor program definition and the fact that, since the R & D contractor had to compete for the production phase of the program, he tended to "buy-in" at the R & D phase in order to gain the advantage in the production contract award and recoup his losses on the R & D phase.

About 1960, DOD attempted to reduce costs by greater use of incentive-type contracts in which rewards were extended for good performance and penalties were imposed for poor performance. These actions, although beneficial, did not result in the intended or expected cost reductions. The government needed a contracting methodology which would result in a favorable price not only in the R & D phase or in the production phase, but in all phases of a program.

In 1964, the Air Force publicly announced what has become known as the Total Package Procurement Concept (TPPC).[21] This is an overall procurement procedure which includes program definition, incentives, life-cycle costing,

fixed prices, free competition and a commitment to production. Thus TPPC includes research, development, production, training, installation, spares, support equipment, maintenance, and field services. In other words, one contract in place of many. Because of its all-inclusive nature, TPPC has also been described by the following phrases: "bundle-bidding", "cradle-to-grave", "womb-to-tomb", and "single-threat".

This thesis is concerned with that part of the Total Package Procurement Concept called life-cycle costs. The term life-cycle costing was first disseminated widely in 1965 in a report for the DOD titled, "Life Cycle Costing in Equipment Procurement," by the Logistics Management Institute.[40] The report observed that operating and maintenance costs, as well as purchase price, can vary significantly among various suppliers' items produced to the same specifications. The conclusion was that techniques could be devised to allow the purchaser to measure and predict equipment costs with sufficient accuracy to warrant their use in evaluating bidders.

In any study such as this, the most difficult decision concerns which items to include in the life-cycle costs. The literature contains examples of check-lists with over eighty items[5] to aid in life-cycle costing. In the general case, the following categories are suggested:

(1) research and development
(2) initial acquisition (production)
(3) installation
(4) training and technical manuals
(5) operation
(6) spares
(7) repair and modification
(8) field services
(9) disposal

One survey of life-cycle costing practices in industry (nondefense industry) was recently conducted for DOD.[37] The major finding of the survey was that all industrial firms visited use the life-cycle costing concept in company operations and base their cost estimates on their own historical data. Industry includes cost items not usually included in government cost studies, such as taxes, revenue, advertising costs, market analyses, and cost of equipment down-time.

The life-cycle cost, or "cost-of-ownership", concept was applied to the selection of aircraft inertial systems in 1968.[31] Life-cycle costing, also called failure-free warranty, has been the basis of a U.S. Navy contract with Lear Siegler Inc.[28] This warranty assures that gyro platforms will operate 3000 hours or five years (whichever occurs first) for a fixed predetermined cost, or the company

will repair them at no extra cost to the Navy. The merits of this concept as seen by Lear Siegler[32] are:

- provides an enforceable guarantee with minimum exceptions
- provides for practical definitions of failure criteria
- increases operational readiness due to contractor incentives to reduce failure rates
- reduces logistics costs by
  - eliminating spare parts procurement
  - eliminating repair depot tooling and personnel
- guarantees budget control

How the total package procurement concept will fare in the future is difficult to evaluate, but one part of it—life-cycle costing—is here to stay.

1.2 Scope of the Thesis

The overall objective of this thesis research is to find the relationships between various parameters of the gyro production system and the total life-cycle costs. In particular, it is desired to determine which parameters have the greatest effect on the life-cycle cost so that research and development efforts can be concentrated in these areas. Before such efforts can begin, it is necessary to have an estimate, or estimates, of how much money can be saved by improving these selected sensitive parameters and their effects on costs. Everyone - at least all engineers - seems to be convinced that reliability plays a very important part in life-cycle cost. There is no doubt about this. Yet the questions remain, such as, How important are they? Compared to what? Also, statements such as "Test equipment is too expensive" have been made many times. Again, the reply should be, "Too expensive compared to what?"

The approach to this research is to propose that a field inventory of 1000 inertial measurement units (IMU's), of an advanced design and with a performance at least 10 to 20 times improved over current practice, be required within a period of five years. Also, that this inventory would be maintained at its level of 1000 IMU's for the following ten years. The thesis is concerned with modeling and studying this hypothetical gyro program over its entire life cycle, beginning with the manufacturing process in the plant. It is assumed that the research and development phases of the program have been completed so that the gyro has been fully qualified to meet the performance specifications. The manufacturing process includes gyro acceptance test, IMU assembly, IMU acceptance test, and all phases of gyro repair including the factory rejects and the rejects from the field. For the purposes of this thesis, only the gyro effort is considered; although it is recognized that the IMU contains accelerometers, electronics modules, etc. It is assumed that the

number of 1000 IMU's includes spares. It is assumed that the spares are apportioned among the various customers and that the spares are on stand-by, that is with gyro wheels running full time, as are all the other systems. Thus for convenience of this study, calendar time and wheel-running time are coincident. The inertial measurement units are automatically recalibrated periodically; and, if a failure is indicated, they are returned to the factory. The IMU's in the field, which include three gyros in each IMU, are assemed to be a required stable inventory which should not be decreased. The cost of nonoperational IMU's, the cost of operation of the IMU's in the field, the cost of transportation of the IMU's from the factory to the field, and the cost of returning the failed IMU's to the factory are not considered here in order to simplify the modeling. Each operation in the factory is described by the elapsed time, the material cost, the labor costs, and the tools and equipment costs.

The objectives of this thesis are summarized as follows:

1. Devise a model for the inertial gyro life-cycle costs concerned only with the areas of assembly, test, installation and test in the IMU, and repair.
2. Develop a mathematical model suitable for use on a digital computer, understandable to the engineering, business, and other communities, yet sufficiently complex to permit expansion in whole or in part.
3. Obtain cost data consistent with the proposed model.
4. Exercise the model to more fully understand its behavior.
5. Find the most sensitive parameters in terms of life-cycle cost as an indication of the areas in which research and development efforts are needed.
6. Point out those areas where the savings in the life-cycle cost could be greater than the investment.

1.3 Summary of Contents

The remaining chapters of this work are briefly summarized below. Each summary attempts to outline the content of the chapter for the interested reader.

Chapter 2 - Descriptive Model of the System

The overall system consisting of a manufacturing plant and a field inventory is described as an information feedback system with the management decisions in the feedback loop. The system processes and their interrelationships are described with the aid of block diagrams. The gyro sector of the plant is described by considering the gyro assembly, acceptance tests, disassembly, and reassembly areas. The gyro failure-identification test areas are also included in the gyro sector of the plant. The inertial measurement unit sector includes the IMU assembly, the IMU acceptance test, and IMU disassembly area, the IMU failure-verification test

area and IMU disassembly area. The field sector is simply the field inventory.

Chapter 3 - A Mathematical Model of the Plant

In this chapter, a mathematical model of the plant is developed in the DYNAMO[17] language. The motivations for choosing this particular program language are developed and the equation-generating processes are presented in detail. The equations are derived by plant sector in order that they may be easily referenced to Chapter 2.

Chapter 4 - The Data

The data for the model were obtained from the author's personal experience, his colleagues involved in research and development, his colleagues involved in the production of gyros, accelerometers, and inertial navigation and guidance systems of all types, and his colleagues involved in repair engineering of inertial systems, gyros and accelerometers. Estimates of elapsed time, material cost, labor costs, and costs of tools and equipment were obtained for each manufacturing process necessary for the proposed model. It was originally intended to use several sets of data in the model simulation. However, as the data were obtained in the course of the research, the spread in the data seemed to be negligible for the purposes of the thesis. Therefore, one set of data has been converged upon.

Chapter 5 - Analysis

In this chapter, the life-cycle costs as a function of several parameters are determined. The dynamics of the model are discussed. The main emphasis is on the quasi-static results of the manipulations of the model. The effects of changes in yields, reliabilities and other parameters are presented in detail.

Chapter 6 - Summary and Conclusions

This chapter contains a summary of the results of the thesis effort, the conclusions from the thesis effort, and recommendations for future work.

Appendix A

The computer program code words are defined and referenced to the program line number.

Appendix B

This appendix is a copy of the computer program.

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Chapter 2

DESCRIPTIVE MODEL OF THE SYSTEM

2.1 Introduction

In this chapter a verbal model, or descriptive model, of the hypothetical gyro-IMU production system is presented in conjunction with several block diagrams. In the next chapter, a mathematical model of the system is derived in order that the system may be precisely manipulated.

Particularly in recent years, models have become widely accepted as a means for studying complex phenomena.* The model simulates the real system so that the behavior of the real system can be studied (at a greatly reduced cost), not only over normal ranges of inputs and disturbances, but also over ranges that may seldom be encountered in practice. However, model construction in many areas requires drastic simplification of the real world in order that the model may be studied at all. On the other hand, too much simplification can result in a model that is not meaningful. The model is correct to the extent that the perception of the situation is correct. It is significant here that the author has had direct contact with the areas being modeled for a number of years.

In this study no attempt has been made to include the production interruptions due to:

(a) human nature, i.e., weekends, holidays, labor strikes, etc.

(b) mother nature, i.e., weather, etc.

(c) "Murphy's Law", i.e., if anything can go wrong, it will.

The model to be described in this chapter includes a plant where single-degree-of-freedom inertial gyroscopes[46] are assembled, tested, installed in inertial measurement units (IMU's), tested, sent to the field for operation, and repaired after return from the field. These IMU's are part of an inertial navigation or guidance system which usually includes a computer, displays, control, power supplies, etc.

*Models are used in many areas such as the physical sciences, engineering,[8],[33] industrial management,[17],[25],[39] ecology,[23] operations research (also called management science)[45] and urban dynamics.[18]

The model simulates the time-sequential behavior of the stable, dynamic, nonlinear system exhibiting both transient and steady-state behavior to the inputs and disturbances applied in this study. The nonlinearities are due to the constraints on the system such as those imposed by the available test equipment and the waiting-stack control function.

2.2 The System

It is proposed that a requirement exists for an inventory of 1000 inertial measurement units of an advanced design to be operational in the field within a period of five years. The life-cycle costs of this system are studied to find the cost relationships between various parameters of the system. The overall system is described by the block diagram shown in Fig. 2.1. The plant is the factory or production unit of the system. The field is the area outside the plant where the hardware output of the plant is being operated by one or by many customers. The hardware inflows to the plant are:

(a) new sets of gyro parts which are in kit form ready for assembly

(b) make-up parts to replace the rejected parts of the failed gyros

(c) failed IMU's returning from the field

The hardware outflows from the plant are:

(a) parts lost in the initial assembly

(b) inertial measurement units to the field

The plant is controlled by management decisions based on information feedback from the field and from the plant. Specific actions can be taken by comparing the desired inventory in the field with the actual inventory in the field.

Each operation in the plant is characterized (where applicable) by the elapsed time for the operation, the cost of the material required for the operation, the cost of the labor required for the operation, and the yield (see Chapter 4 for additional information).

The detailed block diagram presented in Fig. 2.6 describes the entire system and the connections between each of the main operations in terms of hardware flow.

2.3 The Plant

The block diagram of the plant is given in Fig. 2.2. New sets of parts are assembled in the gyro assembly area, where some small percentage of the parts are lost due to various reasons, such as mishandling, errors in initial dimensions, etc. The assembled gyros are tested in the gyro acceptance test area. The gyros

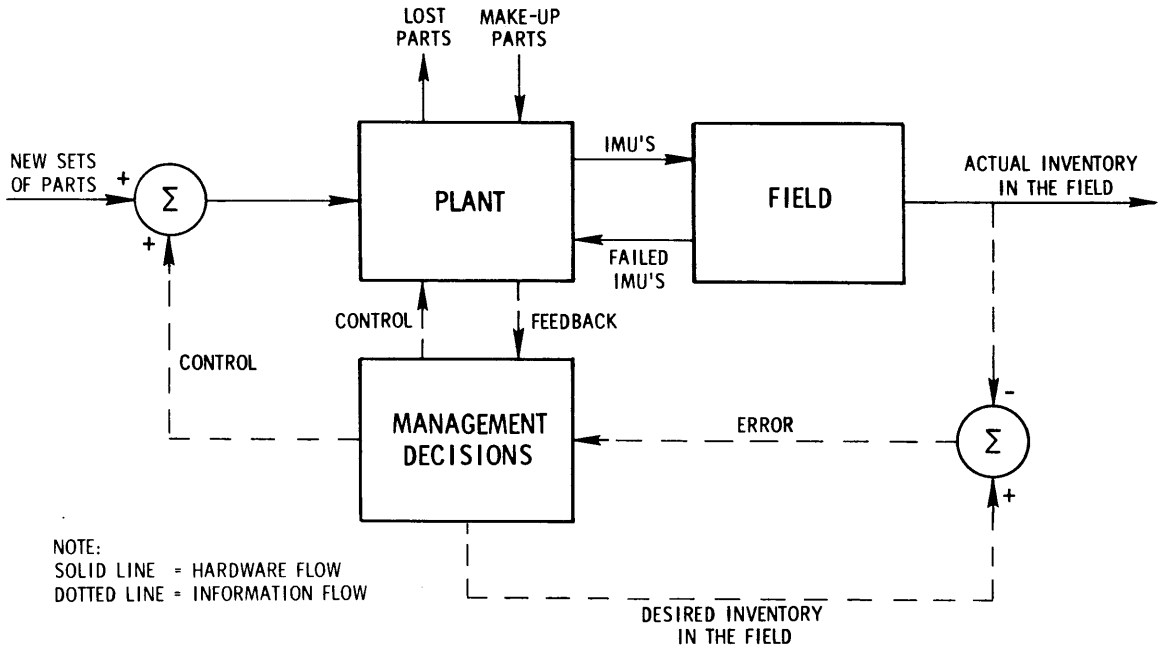

Figure 2.1 Block diagram of the system.

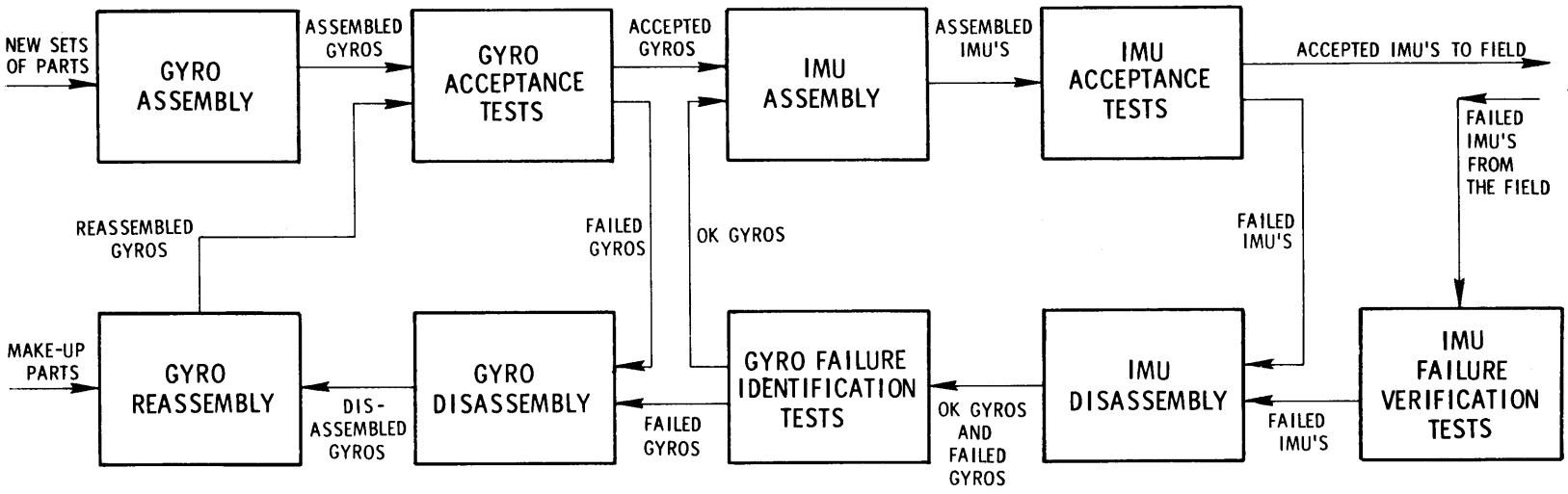

Figure 2.2 Simplified block diagram of the plant.

which are not accepted are disassembled, the rejected parts replaced, and the gyro is reassembled. After reassembly, the gyro is returned to the acceptance test area. The gyros which are accepted are assembled into inertial measurement units, along with the accelerometers which are produced in another part of the plant, but outside of the system being considered here.

The IMU's which are not accepted due to a gyro failure are disassembled and the gyros are removed. The gyros are subjected to failure-identification tests to determine the nature and extent of the failure. The identified failed gyros are disassembled. The gyros which pass the failure-identification tests and are "good" gyros, by definition, are returned to IMU assembly.

The IMU's which pass the IMU acceptance tests are delivered to the customer for operation in the field. It is assumed that the IMU's and the gyros are operational at all times or at least a sufficiently high percentage of the time, so that calendar time and gyro wheel running time are coincident. The inertial measurement units are assumed to be automatically calibrated at periodic intervals. A failure indication returns the IMU to the plant where it is subjected to failure-verification tests. It is assumed that all failures are verified and each IMU failure is due to the failure of one gyro.

2.4 The Gyro Sector of the Plant

All the strictly gyro operations are conducted in the gyro sector of the plant, which is shown in the block diagram in Fig. 2.3. The expansion of the diagram from Fig. 2.2 to Fig. 2.3 reveals the block labeled "gyro waiting" where gyros are held in an inventory or stack until they can be acceptance tested. The acceptance-test capacity is a management decision and is one of the nonlinearities built into the model. It is assumed that all gyros are subjected to the same tests and the rejected gyros are divided into three failure categories. Category 1 includes all failures located outside the gyro main housing and are generally assumed to be electronics failures, wiring opens and shorts, thermal control package malfunctions, preamplifiers, components of normalizing packages, etc. Category 2 includes all failures located between the main housing and the float, and assumed to be leaks through the main housing, flotation fluid contamination, bias changes, etc. Category 3 includes all failures located within the gyro float and requiring disassembly of the float, i.e., leaks in the float, spin-axis bearing malfunction, etc.

The gyros rejected at the IMU acceptance tests are tested to identify the failures and the failure modes. The gyros are sorted into "good", category 1, category 2, or category 3. The IMU is a complex electromechanical assembly

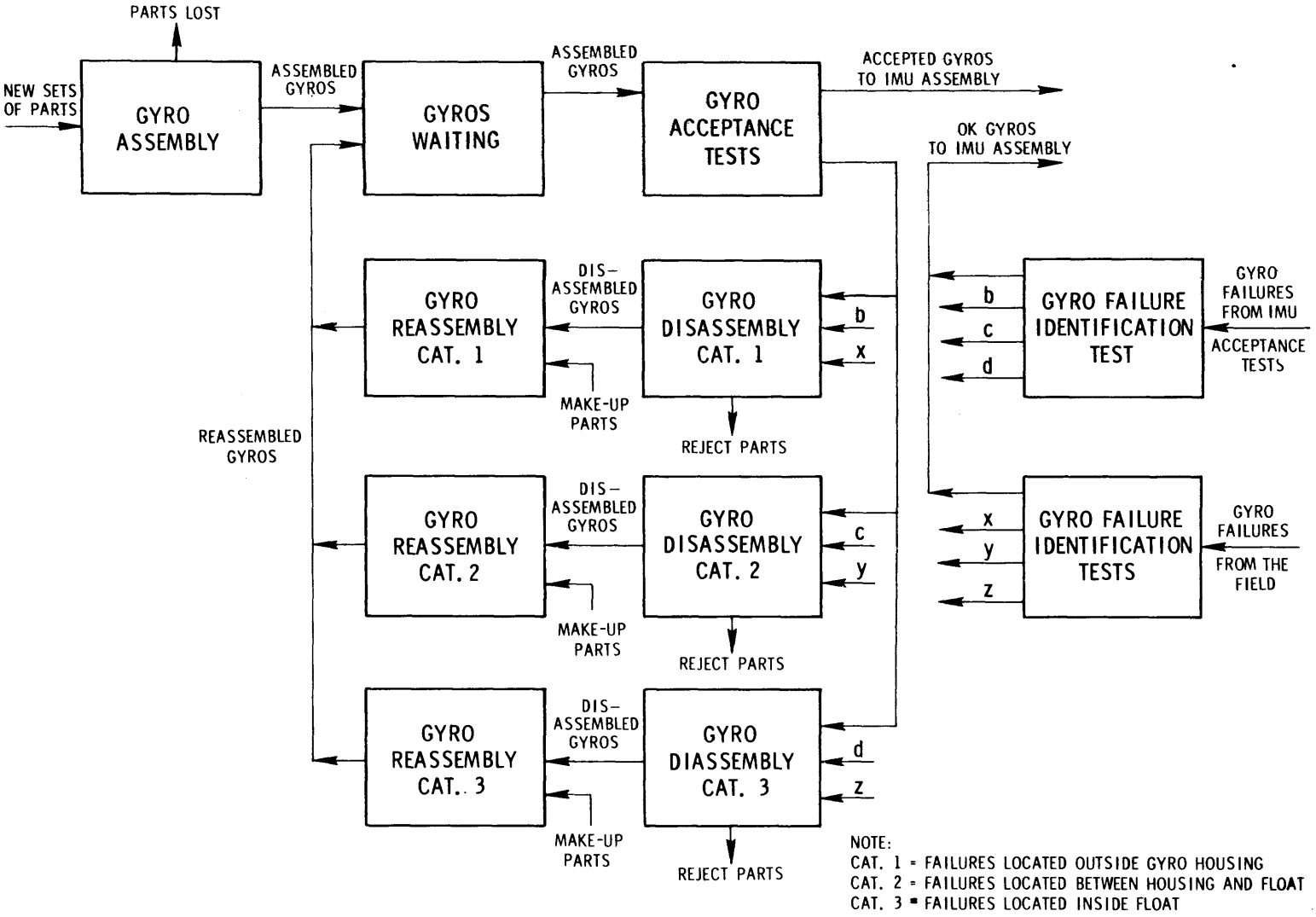

Figure 2.3 Block diagram of the gyro sector of the plant.

and specific identification of a component failure within the IMU is usually difficult and time consuming. The gyros from the IMU's rejected in the field are also subjected to failure-identification tests and sorted into their respective categories as shown in Figure 2.3.

It should be noted that the three inputs to the gyro disassembly area do not have the same failure distributions among the three categories.

The following references are suggested for the theoretical and engineering aspects of gyro design, assembly, test, and repair, (2) (19) (20) (26) (33) (35) (36) (41) (46).

2.5 The Inertial Measurement Unit Sector of the Plant

The inertial measurement unit operations are conducted in the IMU sector of the plant, which is shown in the block digaram in Fig. 2.4. In this case, the expansion from Fig. 2.2 to Fig. 2.4 reveals two waiting stacks, an IMU waiting stack, and a failed-IMU waiting stack. It is assumed that each failed IMU contains one failed gyro and two "good" gyros. The size of the IMU waiting stack at any given time is zero since the capacity of the IMU acceptance test equipment is always sufficient (by assumption). The size of the failed IMU waiting stack is a nonlinear function of the number of field-failed IMU's at a given time and the difference between the actual IMU inventory in the field and the desired inventory in the field (see section 3.12).

One might ask whether or not the costs of the IMU operations are included in the gyro life cycle cost or LCC. Partial costs of the IMU operations should be charged to the gyro (as they are in this study) for costing studies. The design of the gyro influences the cost of the IMU assembly and disassembly in the following ways: basic inertial system mechanization and design, mechanical fit, mechanical alignment and securing, and electrical connections. For the IMU assembly operation, only a portion of the cost is charged to the gyro since the accelerometers and other gear are also assembled.

The gyro portion of the IMU acceptance test is charged to the gyro. This cost accrues from the gyro alignment, calibration, drift specification verification, etc., which are accomplished in the IMU rather than at the gyro component level. These operations may seem, at first glance, to be repetitions of the gyro acceptance test. However, due to differences, at times, in the mechanical, thermal, and electrical environments between gyro test and IMU, some duplication may be unavoidable. Such environmental differences are more obvious in the R & D phase of a program where all manner of hardware and software changes are common occurrences. The model used in this thesis allows the investigation of trade-offs between gyro testing at the component level and at the IMU level. It should be noted that when a gyro fails during IMU acceptance test, the entire cost of the IMU

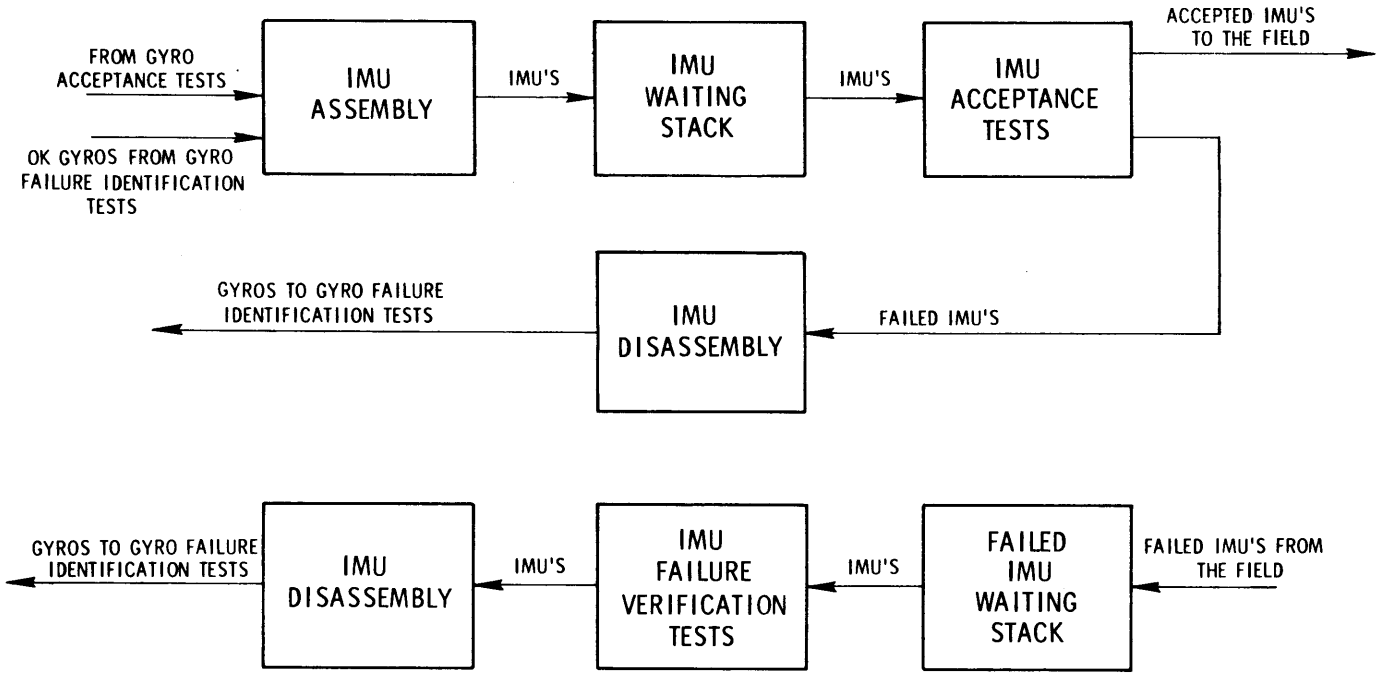

Figure 2.4 Block diagram of the inertial measurement unit sector of the plant.

assembly, acceptance test, and disassembly should be charged to the gyro since all these operations must be repeated. Under the assumption of one failed gyro per failed IMU, the entire cost of the IMU disassembly operation is included in the gyro cost. Thus, the IMU operations have a considerable importance on the gyro cost. This method of costing can be used to investigate the changes in yield at the IMU acceptance test level. It also emphasizes the impact of IMU design on the gyro cost since complex IMU assembly, diassembly and test operations increase the LCC of the gyro. Hopefully, these interacting engineering and cost relationships tend to maintain close relationships between the gyro and the IMU groups.

References (6), (13), (16), and (34) are suggested for additional background.

2.6 The Field Sector

The field acts as an inventory of IMU's in full-time operational status (see Fig. 2.5). Periodic automatic calibration reduces the operational costs (which are not included in this study), but does not eliminate them. The field operation is characterized by gyro failure rates per year for each of the failure categories 1, 2, and 3. The IMU has failed when the failure indicators emit a signal. The unit is then removed from the field and returned to the plant for repair. It is assumed that every failure is verified at the plant, although in actual practice such is not the case. It is also assumed that each IMU failure contains only one gyro failure (this seems to be a reasonable assumption and generally follows actual practice).

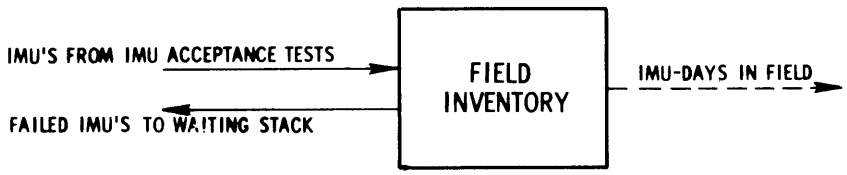

Figure 2.5 Block diagram of the field sector.

2.7 The System Details

The entire system is presented in Figure 2.6 where the connections between each of the main operations is indicated. The figure is a composite of the previous three figures. The flow of assembled gyros is from left to right through the processes indicated at the top of the figure to the field. The flow of rejected gyros is from the field through failure-identification, disassembly and reassembly.

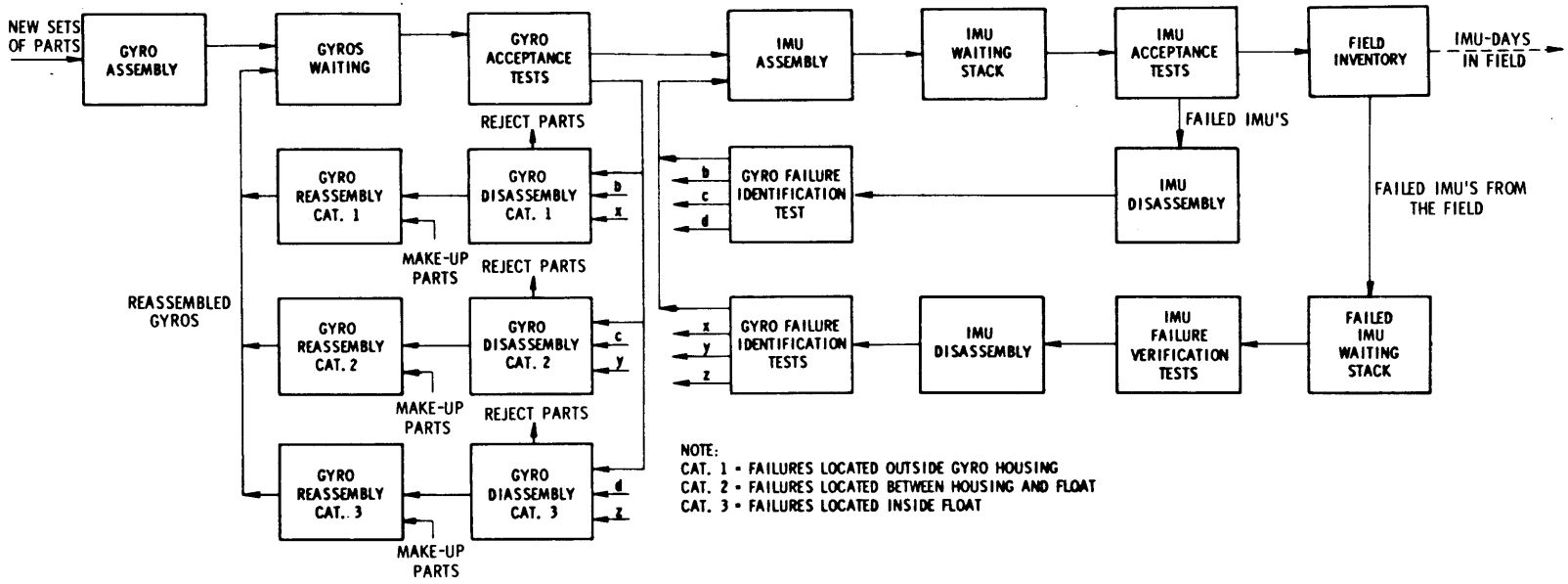

Figure 2.6 Detailed block diagram of the system.

Chapter 3

A MATHEMATIC MODEL OF THE SYSTEM

3.1 Introduction

In the previous chapter, the description of the gyro and IMU production and repair system is given and the general model developed. In this chapter, a mathematical model of the plant is presented in the DYNAMO language.[17][38] This program language can be easily learned and understood by individuals from all phases of the scientific, engineering, and business world.

A complex mathematical model of the production and repair of inertial gyros is developed in sectors. These sectors are the gyro sector, the inertial measurement (IMU) sector, and the field sector. Each sector can be expanded and studied separately. The entire model can be expanded by including many other aspects in economics, personnel practices, the cost of money, inventory control, production control, etc., without saturating the the compiler. An analytical approach could have been taken, in the form of a single long equation relating the cost functions in quadratic form (if available), then, by partial differentiation various cost sensitivities could be obtained, but the solution of the equation would be nonlinear, complex, and cumbersome. DYNAMO permits the mathematical modeling to be accomplished in a series of algebraic equations where each variable in the equation is given a code name chosen by the modeler. This process is convenient for a complex model which can be easily modified and expanded and yet permits clarity of expression.

The equation system used here is suitable for the simulation of many types of information feedback systems such as ecologic, economic, or industrial.[17][18][23][39]

DYNAMO is a special-purpose compiler for translating the mathematical model of a system into digital computer machine language. This compiler consists of machine language instructions that guide the checking, model simulation, output data print-out and output data plotting. With a large computer memory, DYNAMO can accept a dynamic model of some 1500 variables. The complier generates special functions such as steps, ramps, delays, smoothing functions, maximum and minimum functions, etc., which are useful in model construction and exercise. The advantages of DYNAMO over a general purpose compiler are taken from Ref. (38):

- the language is easily understood--the time notation aids in understanding the order of computation
- the language is easy to learn
- ingenuity, which is such an important part in the use of most computer languages, is not involved in most DYNAMO formulations--models of the same situation formulated by different users will be quite similar and easily compared
- the output includes graphic results as well as printed results
- all forms of the output can be specified easily
- automatic extensive error-checking simplifies the problem of obtaining a meaningful model

The computer calculates the results by moving through time in discrete steps and calculating all the variables at each step. The procedure is indicated graphically in Fig. 3.1. The time for which the present calculations are being made is labelled TIME K. The previous time at which the calculations were made is labelled TIME J, and the future time is labelled TIME L. The length of the intervals is DT, the delta time or solution time, and is the iteration time used in solving the zero-order and first order difference equations.[24] After calculating all the variables for time K

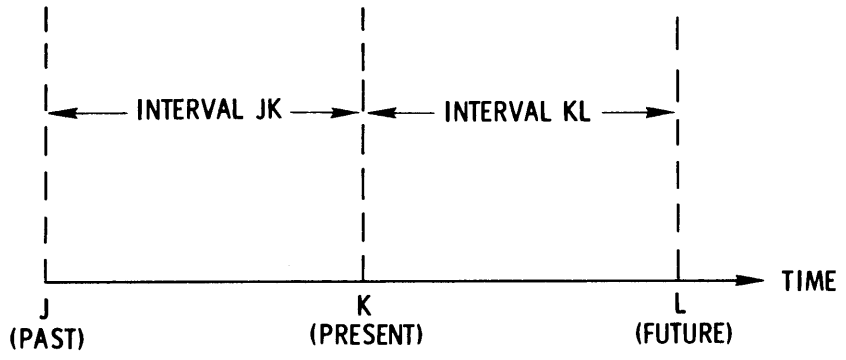

Figure 3.1 Time notation.

and the interval KL, the computer is moved forward one step and the process is repeated by relating the variables that were associated with the TIME K to the TIME J.

Three basic types of variables are used in the compiler:

A level equation (denoted by the letter L) is an accumulation within the system of a variable such as gyros, IMU's, etc., and is the time integral of a flow rate.

A rate equation (denoted by the letter R) represents a flow, between levels of the system, of a variable such as gyros, IMU's, information, etc.

An auxiliary equation (denoted by the letter A) is a variable introduced to simplify the algebraic complexity of the rate equations. Thus, they can be eliminated by substitution into the rate equations.

In addition, there are constants denoted by the letter C and initial conditions denoted by the letter N.

The order of the computations is as follows:

(a) levels at TIME K based on quantities from TIME J and JK interval

(b) auxiliaries based on levels and auxiliaries computed earlier at TIME K and on rates JK

(c) rates based on levels and auxiliaries from K and other rates from JK

The equations need not be written in order since the compiler will automatically sort the equations into the proper sequence. Each code name in the program will be defined the first time it appears in the equations, except where codes are used so infrequently that repetition seems advisable. For quick reference, an alphabetical listing of each code name accompanied by its definition and program line number is given in Appendix A. A copy of the program is given in Appendix B.

3.2 Input and Output

New parts are purchased from an outside supplier in large lots. The parts are delivered to the factory in sets, each set containing all the parts required to assemble one gyro. The production rate, which is a management decision, is increased linearly to three gyros per day by the end of one-and-one-half years,* remains constant at three gyros per day up to three-and-one-half years, decreases linearly to 2.1 gyros per day at four years and decreases linearly to zero at four-and-one-half years after the start of the program. The total number of gyro parts sets started is 3618 (with a parts loss rate in assembly of 8%, only about 3300 gyros are actually constructed from new parts).

* One year is assumed to consist of 360 days.

The desired initiation of assembly of gyros is shown in Fig. 3.2 and is described in the program by the following equation:

DINAS.K = TABHL(DSTART, TIME.K)/180,0,14,1) (11-A)
(all table functions and constants are management decisions)

where

DINAS = desired initiation of assembly at time K

TABHL = table from which values can be interpolated by the compiler (the HL indicates that the number of starts may exceed the high and low limits of the provided range)

DSTART = name of table of desired starts of new gyro sets

DSTART* = 0/1/2/3/3/3/3/3/2.1/0/0/0/0/0/0 = table of desired starts (12-C)
(an asterisk following a code word denotes a numerical tabulation)

TIME = time in days at time K

0, 14, = lowest and highest value in the time range in half-years of the desired starts of new gyro sets

1 = increment in table is in half-years

The desired inventory in the field (in inertial measurement units or IMU's) is given by:

DINFLD.K = TABHL(DFIELD, (TIME.K)/360, 0, 6, 1) (17-A)

where

DINFLD.K = desired inventory in the field (in IMU's) at time K

TABHL = table (see previous Eq.)

DFIELD = table of desired inventory

DFIELD* = 1/60/300/650/900/1000/1000* (20-C)

The number of gyros assembled is shown as a function of time in Fig. 3.2, along with the desired inventory in the field. The desired inventory in the field was chosen to lag the gyros being assembled by a time interval greater than the factory pipeline delay.

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* The value 650 in the DFIELD tabulation was originally intended to be 600. However, since this program typing error had essentially no effect on the results, it is shown as the original value in Fig. 3.2 and elsewhere.

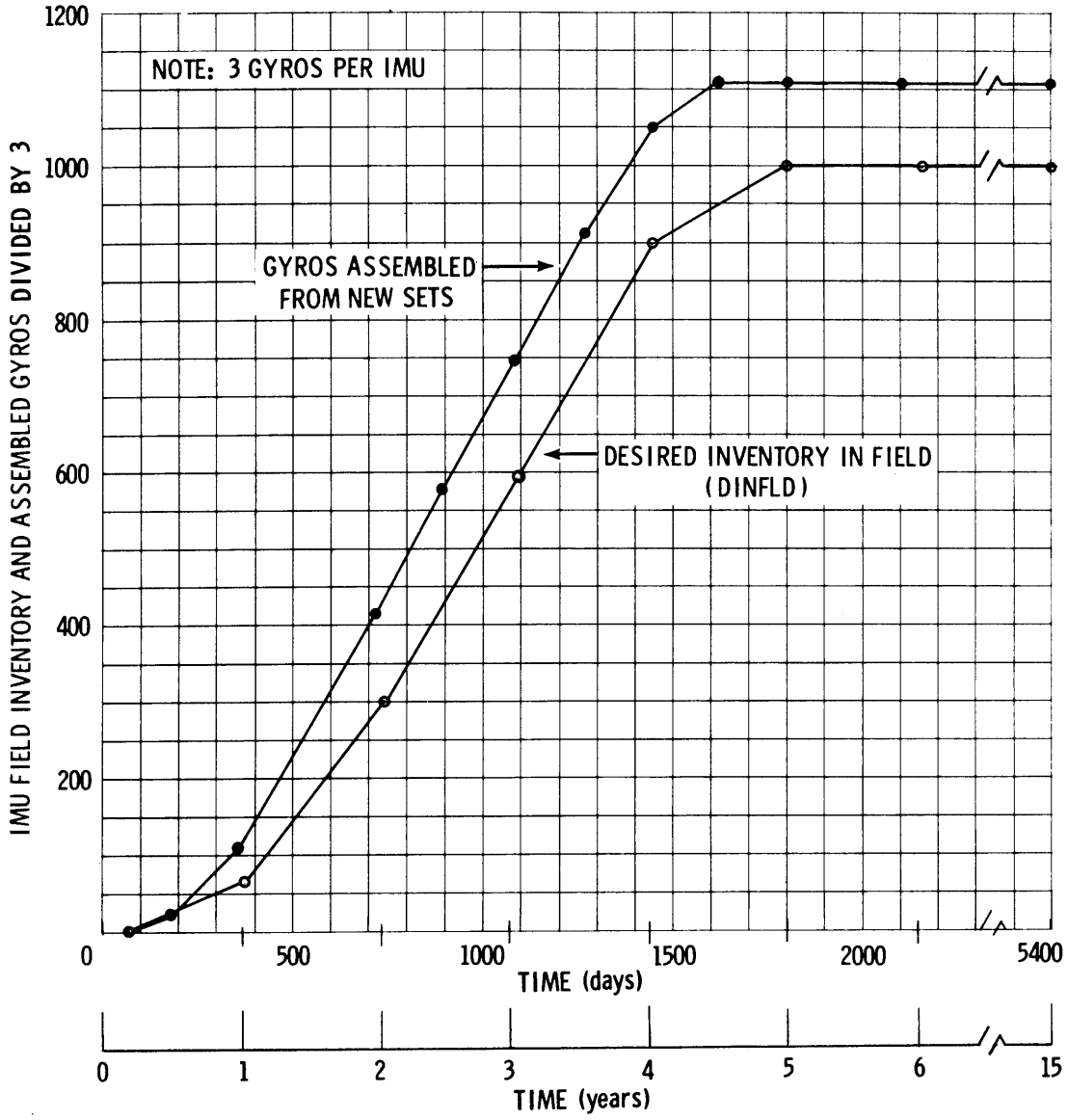

Figure 3.2 IMU field inventory and assembled gyros divided by 3 vs time.

The discrepancy between the desired inventory in the field and the actual inventory in the field generates the error rate.

$$ERROR.KL = DINFLD.K - FIELD.K \qquad (21\text{-}R)$$

The average value of the error at the present time is

$$AERROR.K = AERROR.J + (DT)(1/TSMTH)(ERROR.JK - AERROR.J) \qquad (22\text{-}L)$$

$$DT = \text{delta time} = \text{solution interval} = 1 \text{ day} \qquad (480\text{-}C)$$

$$TSMTH = \text{exponential smoothing time constant}^{(17)} = 30 \text{ days} \qquad (24\text{-}C)$$

The average error can be used to generate the correction signal to initiate new production of gyros when the actual inventory in the field decreases below the desired inventory in the field.

$$CORREC.K = AERROR.K * 3 * GAIN \qquad (28\text{-}A)$$

$$3 = \text{conversion factor from IMU's to gyros}$$

$$GAIN = \text{gain of the correction factor} = 0 \text{ (this is a management decision)} \qquad (29\text{-}C)$$

It is assumed that the production rate is being increased as fast as management finds possible, and is given by the table of desired starts of new gyro sets. The parameters affecting the buildup of the production rate in terms of preparation of the factory buildings and facilities, obtaining equipment, obtaining gyro parts, etc., are not considered here, but should be added for a more complete study. Since it is impossible to make a correction before the production reaches a steady-state value, the true correction starts after eighteen months. Note that an initial over-production of gyros cannot be reduced by a negative correction, i. e., by returning gyros for credit.

$$TCORREC.K = CLIP(CORREC.K, 0, TIME.K/360, 1.5) \qquad (32\text{-}A)$$

$$TCORREC = \text{true correction in gyros}$$

$$CLIP = \text{limiting function so that}$$

$$TCORREC.K = CORREC.K \quad \text{if } TIME.K/360 \geq 1.5$$

$$TCORREC.K = 0 \quad \text{if } TIME.K/360 < 1.5$$

3.3 Gyro Assembly

The gyro assembly rate of new sets of parts is the maximum value of the desired initiation of assembly plus the true correction.

NEWSETS.KL = MAX(DINAS.K + TCORREC.K,0) (35-R)

The total accumulated value of the new sets of parts started in gyro assembly is:

ACNEW.K = ACNEW.J + (DT)(NEWSETS.JK) (37-L)

The level of gyros in assembly is:

GYROAS.K = GYROAS.J + (DT)(NEWSETS.JK - ASSGYG.JK - ASSGYB.JK) (45-L)

where

ASSGYG = assembly rate of "good" gyros

ASSGYB = assembly rate of "bad" gyros

The equations are written in this manner to express the fact that some average percentage of the parts is lost in the assembly process for a number of reasons; damage, subassemblies which must be taken apart, etc.

The assembly rate of "good" gyros is:

ASSGYG.KL = DELAY3(NEWSETS.JK, TASGYRO)*(1-LSSRT) (50-R)

where

DELAY3 = third-order exponential delay;* intended to simulate the pipeline delay due to the assembly time (a pure transportation or pipeline delay represented by an infinite order exponential delay is not available in the DYNAMO compiler at present)

TASGYRO = time to assemble gyros in days = 30 (51-C)

* = multiplication

LSSRT = loss rate in assembling new sets = 8% (53-C)

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* three, cascaded, single-order, exponentials decreasing with time

The assembly rate of "bad" gyros which represents the parts lost is given by:

ASSGYB.KL = DELAY3(NEWSETS.JK, TASGYRO)*(LSSRT) (52-R)

3.4 Gyro Acceptance Test

The testing of inertial gyros requires an investment in test equipment which, although a small percentage of the total program cost, is not insignificant. The capacity of the test area is a management decision which is based upon the evaluation of many factors such as the level of the desired inventory in the field as a function of time, the expected yields in the factory, the expected failure rates for gyros in the field, the number of gyros kept waiting for test if the capacity is too small, etc. The inputs to the waiting area for gyro acceptance test area are the newly assembled gyros (ASSGYG) and the reassembled gyros. The failed gyros are segregated into three categories (described in section 2.4).

INFLOW.KL = ASSGYG.JK + GARCAT1.JK + GARCAT2.JK
+ GARCAT3.JK (61-R)

where

INFLOW = total rate of gyros flowing into the acceptance test waiting area

GARCAT1 = rate of reassembled gyros (cat. 1) flowing out of reassembly area

GARCAT2 = rate of reassembled gyros (cat. 2) flowing out of reassembly area

GARCAT3 = rate of reassembled gyros (cat. 3) flowing out of reassembly area

The level of the gyros waiting for test is:

GYROW.K = GYROW.J+(DT)(INFLOW.JK - GYROTT.JK) (62-L)

where

GYROW = gyros waiting for test

DT = delta time or solution interval = 1 day

GYROTT = rate of gyros moved from the waiting area into the acceptance-test area

The level of gyros in the acceptance-test area at any given time is equal to the level at the previous time plus the inflow over the previous period minus the outflow over the previous period.

$$GYROAT.K = GYROAT.J + (DT)(GYROTT.JK - GYACC.JK - GYNACC.JK) \qquad (75\text{-}L)$$

where

GYROAT = level of gyros in acceptance-test area

GYACC = rate of gyros accepted

GYNACC = rate of gyros not accepted

The rate at which gyros are moved into the acceptance-test area is determined by the number of equivalent test stations and the capacity of each equivalent test station.

$$GYROTT.KL = MIN(TCAP*CAPYLD, GYROW.K) \qquad (79\text{-}R)$$

where

TCAP = number of equivalent test stations = 25

CAPYLD = capacity of each equivalent test station = 0 .2 gyro/day

MIN = minimum function

GYROTT.KL = TCAP*CAPYLD if TCAP*CAPYLD < GYROW.K

GYROTT.KL = GYROW.K if TCAP*CAPYLD ≧ GYROW.K

The rate of gyros leaving the acceptance-test area is dependent upon the rate of gyros entering the acceptance-test area and the time required for performing the acceptance tests.

$$GYACC.KL = DELAY3(GYROTT, TGYAT)*YIELD \qquad (83\text{-}R)$$

$$GYNACC.KL = DELAY3(GYROTT, TGYAT)*(1 - YIELD) \qquad (86\text{-}R)$$

where

GYNACC = rate of accepted gyros leaving the acceptance-test area

GYNACC = rate of nonaccepted gyros leaving the acceptance-test area

TGYAT = time required for gyro acceptance test = 25 days

YIELD = fraction of gyros accepted at acceptance test = 0 .7 for reference run

3.5 Gyro Disassembly

Failed gyros are divided into three categories (described in section 2.4) and in each category there are gyros rejected from the original acceptance test, gyros rejected from IMU test, and gyros rejected due to failure in the field. Only the equations pertaining to the category 1 gyro disassembly sector will be given here, since the equations for categories 2 and 3 are identical (the numerical values in the equations are, of course, different). In the disassembly sector, the gyros are disassembled, the failed or rejected parts are disposed of, and the acceptable parts are processed to be ready for reassembly.

The inflow to the category 1 gyro disassembly area is:

$$INCAT1.KL = GYNACC.JK * FCTR1 + SDGCAT1.JK + FFCAT1.JK \quad (103\text{-}R)$$

where

INCAT1 = gyro input rate to the disassembly area - category 1

FCTR1 = fraction of gyros not accepted from the original acceptance test which are category 1 failures

$$FCTR1 = 0.3 \quad (111\text{-}C)$$

$$FCTR2 = 0.6 \quad (138\text{-}C)$$

$$FCTR3 = 0.1 \quad (167\text{-}C)$$

SDGCAT1 = rate of rejected gyros original IMU acceptance test - category 1

FFCAT1 = rate of rejected gyros from IMU's which failed in the field - category 1

The level of gyros in the gyro disassembly area (cat. 1) at any given time is equal to the previous level increased by the inflow rate and the disassembly time.

$$GDCAT1.K = GDCAT1.J + (DT)(INCAT1.JK - GDRCAT1.JK) \quad (108\text{-}L)$$

where

GDCAT1 = level of gyros in the category 1 gyro disassembly area

GDRCAT1 = rate of disassembled gyros leaving the category 1 disassembly area

The outflow rate from the gyro disassembly area is dependent upon the inflow rate and the disassembly time.

GDRACT1.KL = DELAY3 (INCAT1.JK, TDCAT1) (114-R)

where

TDCAT1 = time to disassemble category 1 rejects in days

NOTE: For category 1 only, TDCAT1 is so short that it is assumed:

GDRACT1.KL = INCAT1.JK

TDCAT2 = 7 days (142-C)

TDCAT3 = 10 days (170-C)

The total level of gyros in the disassembly area for all three categories is:

TLGDIS.K = GDCAT1.K + GDCAT2.K + GDCAT3.K (182.A)

The total disassembly rate for all three categories is:

RCDIS.K = GDRCAT1.JK + GDRCAT2.JK + GDRCAT3.JK (186-R)

3.6 Gyro Reassembly

The parts from the disassembly sector, plus purchased make-up parts, are assembled into complete gyros. As in the previous sector, only the equations pertaining to category 1 will be given here. The level of gyros in the gyro reassembly area at any given time is equal to the previous value of the level increased by the inflow and decreased by the outflow.

GACAT1.K = GACAT1.J + (DT)(GDRCAT1.JK - GARCAT1.JK) (117-L)

where

GACAT1 = level of gyros in reassembly - category 1

The gyro reassembly rate (the outflow) is dependent upon the disassembly rate and the reassembly time.

GARCAT1.KL = DELAY3(GDRCAT1.JK, TASC1) (120-R)

where

TASC1 = time to reassemble gyros - category 1 = 9 days (121-C)

TASC2 = 15 days (151-C)

TASC3 = 30 days (177-C)

The total level of gyros in the reassembly area for all three categories is:

TLGREAS.K = GACAT1.K + GACAT2.K + GACAT3.K (183-A)

The total reassembly rate for all three categories is:

RCRAS.K = GARCAT1.JK + GARCAT2.JK + GARCAT3.JK (187-A)

3.7 Gyro Failure-Identification Tests - Plant Failures

The gyro rejects from the IMU disassembly area are sorted into the three failure categories in the gyro failure-identification test area. Only the equations pertaining to the category 1 failures will be given here, since the equations for the other two categories are identical.

SDGCAT1.KL = DELAY3 (SFCTR1*IMUDISR.JK, TVCAT1) (247-R)

where

SFCTR1 = fraction of failed gyros from failed IMU's (plant rejects)

SFCTR 1 = 0.25 (260-C)

SFCTR 2 = 0.50 (261-C)

SFCTR 3 = 0.25 (262-C)

TVCAT1 = time to verify category 1 gyro failures = 7 days (253-C)

TVCAT2 = 8 days (254-C)

TVCAT3 = 8 days (255-C)

The "good" gyros from the IMU disassembly area are sent to the gyro acceptance-test area.

GOODSF.KL = DELAY3 (SGOK*IMUDISR.JK, TVGOOD) (250-R)

where

SGOK = two "good" gyros in each rejected IMU by assumption (258-C)

TVGOOD = time to verify "good" gyro from IMU rejections = 7 days (256-C)

3.8 Gyro Failure-Identification Tests - Field Failures

The outflow from the IMU disassembly area are delivered to the gyro failure-identification test area where the gyros are tested to determine their repair category. The outflow from the gyro failure-identification test area is equal to the inflow delayed by the time required to perform the tests.

FFCAT1.KL = DELAY3(DFFCAT1.JK, TVCAT1) (353-R)

where

FFCAT1 = verified gyro field-failures - category 1

TVCAT1 = time required to verify failures - category 1

The "good" gyros, of which there are two per failed IMU (by assumption), are delivered to the IMU assembly area. The delay in these "good" gyros is equal to the category 3 delay.

$$GOODFF.KL = 2*DELAY3(DFFCAT1.JK + DFFCAT2.JK + DFFCAT3.JK, TVCAT3) \quad (356\text{-R})$$

where

GOODFF = rate of good gyros from IMU field failures

3.9 Inertial Measurement Unit (IMU) Assembly and Waiting Stack

The level of the gyros in the IMU assembly area is composed of three inputs less one output (a) the rate of gyros accepted at gyro acceptance test, (b) the rate of "good" gyros from the IMU's rejected at IMU acceptance test, (c) the rate of "good" gyros from the IMU's rejected in the field, and (d) the output.

$$IMUASS.K = IMUASS.J + (DT)(GYACC.JK + GOODSF.JK + GOODFF.JK - GINIMU) \quad (194\text{-L})$$

where

IMUASS = level of gyros in the IMU assembly area

GOODSF = rate of "good" gyros from IMU factory failures

GOODFF = rate of "good" gyros from IMU field failures

GINIMU = rate of gyros in assembled IMU's to the wait-stack for IMU acceptance testing

The flow rate of gyros out of the IMU assembly area and into the waiting area is dependent upon the gyro input rates to the IMU assembly area and the time required to assemble an IMU

$$GINIMU.KL = DELAY3(GYACC.JK + GOODSF.JK + GOODFF.JK, TASIMU) \quad (197\text{-R})$$

where

TASIMU = time to assemble an IMU in days = 7 (198-C)

The flow rate of IMU's to the waiting area is one-third the flow rate of the gyros into the waiting area. The equation which converts dimensions from gyros to IMU's is

$$IMUWAIT.KL = GINIMU.JK/3 \quad (204\text{-R})$$

3.10 Inertial Measurement Unit Acceptance Tests

The level of IMU's in the waiting area (waiting for IMU acceptance test) is equal to the previous level increased by the inflow and decreased by the outflow over the previous period.

IMUWT.K = IMUWT.J + DT(IMUWAIT.JK - IMUTTST.JK) (202-L)

where

IMUWT = level of IMU's waiting for IMU test

IMUTTST = rate of IMU's to the IMU acceptance-test area

The IMU's waiting to be tested are moved into the IMU acceptance-test area when test equipment capacity is available. The level of IMU's in the IMU acceptance-test area is equal to the previous level increased by the inflow and decreased by the outflow over the previous period.

IMUTTA.K = IMUTTA.J + (DT)(IMUTTST.JK - IMUACC.JK - IMUNACC.JK) (210-L)

where

IMUTTA = level of IMU's in the IMU acceptance-test area

IMUACC = rate of IMU's which passed acceptance tests

IMUNACC = rate of IMU's which did not pass acceptance tests

In general, the capacity of the IMU acceptance-test area will be limited in a manner similar to that of the gyro acceptance-test area

IMUTTST.KL = MIN(IMUWT.K, CAPAC) (216-R)

CAPAC = capacity IMU acceptance test area in IMU's = 10 (217-C)

(management policy is not an issue here since CAPAC is sufficient for all modes of the system by assumption)

The rate of IMU's leaving the IMU acceptance-test area is dependent upon the rate of IMU's entering the acceptance-test area and time required for performing the acceptance tests

IMUACC.KL = DELAY3(IMUTTST.JK, TTIMU)*IMUYLD

IMUNACC.KL = DELAY3(IMUTTST.JK, TTIMU)*(1-IMUYLD) (220-R)

where

TTIMU = time required to test IMU's = 12 days (221-C)

IMUYLD = fraction of IMU's which passed IMU acceptance tests = 0.9 (224-C)

3.11 Inertial Measurement Unit Disassembly - Plant Failures

The IMU's which do not pass the IMU acceptance tests are disassembled, the gyros are removed and sent to gyro failure-identification. It is assumed that all failures are verified and identified. It is also assumed that each rejected IMU contains two "good" gyros and one failed gyro.

The IMU level in the IMU disassembly area is

$$IMUDIS.K = IMUDIS.J + (DT)(IMUNACC.JK - IMUDISR.JK) \qquad (235\text{-}L)$$

where

IMUDIS = IMU level in disassembly area

IMUDISR = IMU disassembly rate

The IMU disassembly rate which is the flow rate out the disassembly area is

$$IMUDISR.KL = DELAY3(IMUNACC.JK, TDISS) \qquad (238\text{-}R)$$

where

TDISS = time required to disassemble IMU's = 7 days (239-C)

3.12 Inertial Measurement Units - Waiting Stack for Field Failures

When IMU's fail in the field, they are returned to the factory and added to the waiting stack. If the gyros from these IMU's are not needed to maintain the desired inventory in the field (if for example the gyro failure rate decreased with time), these failed IMU's would remain in the waiting stack until the gyros are needed. The fraction of today's field failures to the waiting stack is given by

$$RATIO.K = TABHL(FSTACK, FIELD.K/DINFLD.K, .9, 1.05, .05) \qquad (309\text{-}A)$$

where

RATIO = ratio of field failed IMU's to the waiting stack vs field failed IMU's to the IMU failure-verification test

FSTACK* = table for stack field failures = 1.5/1.1/1.0/0 (310-C)

When the actual inventory in the field (FIELD) is greater than the desired inventory in the field (DINFLD) (say 1.05 times), then RATIO = 0.5 and 50% of today's failed IMU's returning from the field are held in the waiting stack and the other 50% continue on to IMU failure-verification test. When FIELD is equal to DINFLD, RATIO = 1 and all of today's failed IMU's continue on to IMU failure-verification test. When FIELD is less than DINFLD (say 0.95 time), then RATIO = 1.10 and all of today's failed IMU's plus a number of failed IMU's from the waiting stack equal to 10% of today's failed IMU's are sent to IMU failure-verification test. These actions are management policy and constitute another nonlinearity in the system.

The field-failed IMU's constitute the inflow to the waiting stack and the IMU's to IMU failure-verification test constitute the outflow. It is assumed that all failures will be verified at the factory although the failure category has not been established from information from the field.

The level of failed IMU's which contains a category 1 failure are

STKCAT1.K = STKCAT1.J + (DT)(FECAT1.JK - CAT1REP.JK) (314-L)

where

STKCAT1 = IMU field failures in stack - category 1

FECAT1 = IMU field failure rate - category 1

CAT1REP = rate of IMU field failures from waiting stack - category 1

The outflows from the waiting stack are fractions of the present IMU failures in the field, but cannot exceed the IMU's waiting.

CAT1REP.KL = MIN(STKCAT1.K, RATIO.K * FECAT1.JK) (324-R)

where

MIN = minimum function

CAT1REP.KL = STKCAT1.K if STKCAT1.K < RATIO*FECAT1.JK

CAT1REP.KL = RATIO.K*FECAT1.JK if STKCAT1.K ≥ RATIO*FECAT1.JK

3.13 Inertial Measurement Unit - Failure-Verification Test

The failed IMU's are delivered to the IMU field-failure verification-test area. The outflow is equal to the inflow delayed by the time required to conduct the tests.

VFECAT1.KL = DELAY3(CAT1REP.JK, TVER) (335-R)

where

VFECAT1 = IMU verified field failures which contain a category 1 gyro failure

TVER = time required for IMU failure-verification test = 9 days (338-C)

3.14 Inertial Measurement Unit Disassembly - Field Failures

The outflow from the IMU disassembly area is equal to the inflow delayed by the time required for IMU disassembly. The inflow to the IMU disassembly area is the outflow from the IMU failure-verification test area.

DFFCAT1.KL = DELAY3(VFECAT1.JK, TDISS) (347-R)

where

DFFCAT1 = gyro field-failure rate from IMU disassembly-category 1

TDISS = time required to disassemble IMU's = 7 days (239-C)

3.15 Field Inventory

The outflow from the IMU acceptance test area of the gyros which passed the tests is the inflow to the field inventory. The outflow from the field inventory is the total number of IMU failures in the field. The IMU level in the field inventory is

FIELD.K = FIELD.J + (DT)(IMUACC.JK - TOTBRK.JK) (270-L)

where

FIELD = actual IMU inventory in the field

TOTBRK = total failure rate of IMU's in the field

The total accumulated age of the IMU's in the field inventory is calculated by

AVAGET.K = AVAGET.J + (DT)(FIELD.J - TOTBRK.JK*AVAGE.J)(276-L)

where

AVAGE = average age of the IMU's in the field inventory

The average age of the IMU's in the field is calculated by

AVAGE.K = AVAGET.K/(MAX(FIELD.K, 1)) (279-A)

where

MAX = maximum function and is used to avoid division by zero

FIELD.K = FIELD.K if FIELD > 1

FIELD.K = 1

The IMU failures in the field can be assumed to be a function of the average time in the field, or chronological time, or both. For this purpose, the switch function is particularly useful for testing decision rules by means of reruns. Both decision rules are included in the program and the appropriate one is chosen by the switch function.[38]

TIMEVAR.K = (S*AVAGE.K + (1-S)*TIME.K)/360 (291-A)

where

TIMEVAR = time variation for IMU's in the field in years

S = switch function (290-C)

S = 1 for average time in the field

S = 0 for chronological time

The failure rates per year for IMU's in the field for category 1 are governed by a table function T1*. As noted previously, only the equations pertinent to category 1 are presented here.

PFECAT1.K = TABHL(T1, TIMEVAR.K, 0, 14, 1) (292-A)

where

PFECAT1 = field failure rates per year

TABHL = table from which values can be interpolated by the compiler (the HL indicates that the numbers in the table may exceed the high and low limits of the provided range)

T1 = name of the table of failure rates as a function of age in the field

T1* = actual table of failure rates for entire 15 years of the program for category 1

T1* = .10/.10/.10/.10/.10/.10/.10/.10/.10/.10/.10/.10/.10/.10/.10 (293-C)

T2* = .20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20 (296-C)

T3* = .20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20 (299-C)

TIMEVAR = time variation for IMU's in the field in years is the independent variable in the table

0, 14 = lowest and highest value in the time range in years

1 = increment in the table is in years

The actual number of failures per day in category 1 is given by

FECAT1.KL = FIELD*PFECAT1.K/360 (302-R)

The total IMU failure rate in the field is the sum of the category, 1, 2 and 3 failure rates

TOTBRK.KL = FECAT1.JK + FECAT2.JK + FECAT3.JK (328-R)

The total inventory of failed IMU's in the waiting stack at time K is the sum of the failed IMU's in each category

TFFWAIT.K = STKCAT1.K + STKCAT2.K + STKCAT3.K (331-A)

3.16 Costs

In this section of the program, the subcosts as rates in dollars per unit time (day) and as accumulated costs in dollars are calculated.

(a) Cost of parts purchased and parts lost in the assembly of the new sets of gyro parts

RSUBT1.KL = NEWSETS.JK*(COMPCT + AMLOST) (363-R)

where

RSUBT1 = component purchase and lost-material cost rate

COMPCT = component parts cost per gyro - new sets = 7500 (366-C)

AMLOST = average cost of material lost during assembly per gyro
= 500 (367-C)

SUBT1.K = SUBT1.J + (DT)(RSUBT1.JK) (364-L)

where

SUBT1 = subtotal cost of component purchase and parts lost in assembly

(b) Labor costs to assemble new sets of parts

RSUBT12.KL = NEWSETS.JK*NASLCST (370-R)

where

RSUBT12 = assembly labor cost rate for new sets

NEWSETS = actual new sets of parts

NASLCST = assembly labor cost per gyro using new sets of parts
= 5000 (373-C)

SUBT12.K = SUBT12.J + (DT)(RSUBT12.JK) (371-L)

where

SUBT12 = subtotal cost of gyro assembly labor - new sets

(c) Gyro disassembly labor costs

RSUBT3.KL = GDRCAT1.JK*DCAT1 + GDRCAT1.JK*DCAT2 + GDRCAT2*DCAT3 (377-R)

where

RSUBT3 = disassembly labor cost rate

GDRCAT1 = disassembly rate - category 1

GDRCAT2 = disassembly rate - category 2

GDRCAT3 = disassembly rate - category 3

DCAT1 = disassembly labor cost per gyro - category 1 = 100 (380-C)

DCAT2 = disassembly labor cost per gyro - category 2 = 500 (381-C)

DCAT3 = disassembly labor cost per gyro - category 3 = 1200 (382-C)

SUBT3.K = SUBT3.J + (DT)(RSUBT3.JK) (378-L)

where

SUBT3 = subtotal cost of gyro disassembly labor

(d) Gyro reassembly material costs

RGRMAT.KL = GARCAT1.JK*RMCAT1 + GARCAT2.JK*RMCAT2 + GARCAT3.JK *RMCAT3 (378-R)

where

RGRMAT = reassembly material cost rate

GARCAT1,2,3 = reassembly rate - categories 1,2,3

RMCAT1,2,3 = reassembly material cost per gyro - categories 1,2,3
= 400, 1000, 2800 (390-C)(391-C)(392-C)

GRMAT.K = GRMAT.J + (DT)(RGRMAT.JK) (380-L)

where

GRMAT = subtotal cost of gyro reassembly material

(e) Gyro reassembly labor cost

RGRLAB.KL = GARCAT1.JK*RCAT1 + GARCAT2.JK*RCAT2 + GARCAT3.JK *RCAT3 (394-R)

where

RGRLAB = reassembly labor cost rate

RCAT1,2,3 = reassembly labor cost per gyro - categories 1,2,3
= 600, 2000, 4000 (397-C)(398-C)(399-C)

GRLAB.K = GRLAB.J + (DT)(RGRLAB.JK) (395-L)

where

GRLAB = subtotal cost of gyro reassembly labor

NOTE: SUBT4.K = GRMAT.K + GRLAB.K

where

SUBT4 = subtotal cost of gyro reassembly (labor and material)

(f) Failure identification test labor costs for gyros which failed in the IMU acceptance-test

RSUBT5.KL = SDGCAT1.JK*GFVCAT1 + SDGCAT2.JK*GFVCAT2 + SDGCAT3.JK *GFVCAT3 (403-R)

where

RSUBT5 = failure-identification test labor cost rate for gyros which failed in the IMU acceptance test

SDGCAT1, 2, 3 = rate of gyros from IMU disassembly-categories 1, 2, 3

GFVCAT1, 2, 3 = gyro failure-identification test labor cost per gyro = 300, 700, 1000 (406-C)(407-C)(408-C)

SUBT5.K = SUBT5.J + (DT)(RSUBT5.JK) (404-L)

where

SUBT5 = subtotal cost of failure-identification test labor costs for gyros which failed IMU acceptance test

(g) Gyro acceptance test labor cost

RSUBT6.KL = (GYACC.JK + GYNACC.JK)*GACTC (411-R)

where

RSUBT6 = gyro acceptance test labor cost rate

GACTC = gyro acceptance test labor cost per gyro = 2000 (414-C)

SUBT6.K = SUBT6.J + (DT)(RSUBT6.JK) (412-L)

where

SUBT6 = subtotal cost of gyro acceptance test labor

(h) IMU disassembly cost - failures from IMU acceptance test

RSUBT10.KL = IMUDISR.JK*CIMUDIS (417-R)

where

RSUBT10 = IMU disassembly labor cost rate

IMUDISR = IMU disassembly rate

CIMUDIS = IMU disassembly cost per IMU = 200 (420-C)

SUBT10.K = SUBT10.J + (DT)(RSUBT10.JK) (418-L)

where

SUBT10 = subtotal cost of IMU disassembly labor - failures from IMU IMU acceptance test

(i) IMU field failure identification test cost

RSUBT2.KL = TIMUV*(VFECAT1.JK + VFECAT2.JK + VFECAT3.JK) (423-R)

where

RSUBT2 = IMU field failure-identification test labor cost rate

VFECAT1,2,3 = gyro field failure rate from IMU failure-identification test

TIMUV = IMU field failure-identification test labor cost per IMU = 400 (426-C)

SUBT2.K = SUBT2.J + (DT)(RSUBT2.JK) (424-L)

where

SUBT2 = subtotal cost of IMU field failure-identification test labor

(j) IMU field failure disassembly labor cost

RSUBT11.KL = (DFFCAT1.JK + DFFCAT2.JK + DFFCAT3.JK)*CIMUDIS (429-R)

where

RSUBT11 = IMU field failure disassembly cost rate

DFFCAT1,2,3 = gyro field failure rate from IMU disassembly-categories 1,2,3

CIMUDIS = IMU disassembly cost per IMU = 200 (420-C)

SUBT11.K = SUBT11.J + (DT)(RSUBT11.JK) (430-L)

where

SUBT11 = gyro field failure-identification labor cost rate

(k) Failure-identification test labor costs for gyros which failed in the field

RSUBT7.KL = FECAT1.JK*GFVCAT1 + FECAT2.JK*GFVCAT2
+ FECAT3.JK*GFVCAT3 (433-R)

where

RSUBT7 = gyro field failure-identification labor cost rate

FECAT1,2,3 = gyro failure rate in the field - categories 1,2,3

GFVCAT1,2,3 = gyro failure-identification test labor cost per gyro - categories 1,2,3
= 300, 700, 1000 (406-C)(407-C)(408-C)

$$SUBT7.K = SUBT7.J + (DT)(RSUBT7.JK) \quad (434\text{-}L)$$

where

SUBT7 = subtotal cost of gyro field failure-identification test labor

(l) IMU acceptance test cost

$$RSUBT8.KL = (IMUACC.JK + IMUNACC.JK)*STCOST) \quad (438\text{-}R)$$

where

RSUBT8 = IMU acceptance test labor cost rate

IMUACC = accepted IMU rate

IMUNACC = not accepted IMU rate

STCOST = IMU acceptance test labor cost per acceptance test
= 2000 (441-C)

$$SUBT8.K = SUBT8.J + (DT)(RSUBT8.JK) \quad (439\text{-}L)$$

where

SUBT8 = subtotal cost of IMU acceptance test labor

(m) IMU assembly cost

$$RSUBT9.KL = IMUWAIT.JK*IMUASSC \quad (444\text{-}R)$$

where

RSUBT9 = IMU assembly labor cost rate

IMUWAIT = rate of IMU's to waiting stack

IMUASSC = IMU assembly labor cost per IMU = 300 (447-C)

$$SUBT9.K = SUBT9.J + (DT)(RSUBT9.JK) \quad (445\text{-}L)$$

where

SUBT9 = subtotal cost of IMU assembly labor

(n) Total cost counter

```
P1.KL = RSUBT1.JK + RSUBT2.JK + RSUBT3.JK + RGRLAB.JK
                                  + RGRMAT.JK + RSUBT5.JK   (450-R)

P2.KL = RSUBT6.JK + RSUBT7.JK + RSUBT8.JK + RSUBT9.JK
                                  + RSUBT10.JK + RSUBT11.JK (451-R)

P3.KL = RSUBT12.JK                                          (452-R)

COST.K = COST.J + (DT)(P1.JK + P2.JK + P3.JK)               (453-L)
```

where

COST = total accumulated cost = life-cycle cost

RSUBT1 = new sets purchased and lost-material cost rate

RSUBT2 = IMU field failure-identification test labor cost rate

RSUBT3 = disassembly labor cost rate

RGLAB = reassembly labor cost rate

RGMAT = reassembly material cost rate

RSUBT5 = gyro (IMU acceptance test) failure-identification test labor cost rate

RSUBT6 = gyro acceptance test labor cost rate

RSUBT7 = gyro field failure-identification labor cost rate

RSUBT8 = IMU acceptance test labor cost rate

RSUBT9 = IMU assembly labor cost rate

RSUBT10 = IMU disassembly labor cost rate

RSUBT11 = IMU field failure disassembly cost rate

RSUBT12 = assembly (new sets) labor cost rate

and the initial value of the COST (of tools and equipment) is given by:

```
COST = TCAP*TCCOST + OTHER                                  (454-N)
```

where

TCAP = capacity of gyro acceptance-test area

TCCOST = cost per unit gyro test capacity = 300,000 (455-C)

OTHER = cost of other tools and equipment = 1,042,000 (458-C)

In order to calculate the cost per IMU per day in the field, a counter for days in the field is required.

$$DAYINF.K = DAYINF.J + (DT)(RFIELD) \qquad (461\text{-}L)$$

$$RFIELD.KL = MIN(FIELD.K, MAXFLD) \qquad (462\text{-}R)$$

where

DAYINF = IMU-days in the field

RFIELD = rate of accumulation of days in the field in IMU-days

FIELD = actual inventory of IMU's in the field

MAXFLD = maximum desired number of IMU's in the field = 1050 (463-C)

Note that if more than a specified number of IMU's (1050 in this problem) is delivered to the field, the manufacturer is not compensated for this extra production and it is not included in the program life-cycle costs. The cost per day is:

$$CPERDY.K = COST.K/(DAYINF.K + 1) \qquad (469\text{-}A)$$

where

CPERDY = cost per IMU per day in the field

COST = total cost of the program

(DAYINF.K + 1) = number of IMU-days in the field plus 1 (where the one additional day starts the problem and avoids a division by zero until one IMU is actually delivered to the field)

3.17 Output: Printed and Graphic

The output sector requires four constants:

$$LENGTH = 5400 \qquad (478\text{-}C)$$

$$DT = 1 \qquad (479\text{-}C)$$

$$PRTPER = 180 \qquad (480\text{-}C)$$

$$PLTPER = 180 \qquad (481\text{-}C)$$

The length of the program is 5400 days (15 years). The solution interval is one day. The print period is 180 days and the plot period is 180 days. The following information is printed and plotted:

```
PRINT  1) COST/2) DAYINF/3) CPERDY (0.3)/4)FIELD/5) GYROW/6) IMUWAIT/7) TFFWAIT
PRINT  1) NEWSETS/2)ACNFW/3) DINAS/4) TCORREC/5) CORREC/6)GYRCAS/7) AVAGE
PRINT  1) SUBT1/2) SUBT12/3) GRMAT/4) GRLAB/5) SUBT2/6) SUBT3/7) SUBT4/8) RATIO
PRINT  1) SUBT5/2) SUBT6/3) SUBT7/4) SUBT8/5) SUBT9/6) SUBT10/7) SUBT11
PLOT   FIELD=F/FECAT1=1,FECAT2=2,FFCAT3=3/TFFWAIT=W/AVAGE=A
PLOT   COST=$/SUBT1=1,SUBT12=*,SUBT2=2,SUBT3=3/SUBT4=4,SUBT5=5,SUBT6=6
PLOT   COST=$/SUBT7=7,SUBT8=8,SUBT9=9,SUBT10=0,SUBT11=1,GRLAB=L,GRMAT=M
PRINT  1) VFECAT1/2) VFECAT2/3) VFECAT3/4) INFLOW/5) GYROTT/6) COST/7) GYROW
PLOT   DINAS=I/DINFLD=F/ERROR=E/CORREC=C/NEWSETS=N/RCDIS=D,RCRAS=A
PLOT   GYROAS=G/TIGDIS=D/TLGREAS=R/GYROAT=T/IMUASS=S/IMUDIS=A/IMUTTA=B
PLOT   IMUACC=A,IMUNACC=N/GYACC=1,GYNACC=2/ASSGYG=G,ASSGYB=B
```

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Chapter 4

THE DATA

4.1 Introduction

In the previous two chapters, a descriptive model and a mathematical model of the system nave been presented. The descriptive model is used to present concepts, and the mathematical model is used to make controlled experiments on the model, that is, controlled within the limits of the assumptions which circumscribe the model. If a new system were being designed, for which there were no historical data, then it would be necessary to make assumptions about the range of the variables in the model. The model could be exercised to determine the most sensitive parameters and to study the influence of changes in policy on the system behavior.

In this study it was decided to obtain the best data available from several sources, witnin the constraints of allowable time and funding, because of the author's involvement with many aspects of inertial gyro technology. The data used in this study are the result of informal* contributions from several sources: from tne author's experience as an engineer engaged in research and development of inertial instruments for many years, and with considerable experience in liaison work with government and industry; discussions witn colleagues also involved in R & D in inertial gyros, accelerometers, and inertial guidance and navigation systems; discussions with colleagues involved in the production of hardware for the inertial market; and discussions with colleagues involved in repair engineering.

The costs have been assumed to be (a) variable cost of labor and material proportional to the rate of manufacture and repair, and (b) fixed costs proportional to plant capacity as determined by management decision. The fixed costs are not necessarily proportional to the ma imum rate of manufacturing and repair since the test equipment capacity imposes a limit on the maximum output rate. The costs are greater to manufacture a given quantity of items if the manufacturing rate fluctuates than if it is constant. This is due to factors personnel hiring costs, training costs, layoff costs, etc. Such variable costs,

* Except in one case where actual cost data for a special precision gyro program was obtained through the courtest of Mr. D. N. Ferguson, Vice President and General Manager, and Mr. W. Merritt, Program Manager, Northrup Nortronics, Precision Products Department, Norwood, Massachusetts.

which are some function of the manufacturing rate, are not included in this study.

Estimates of elapsed time, material costs, labor costs, and costs of tools and equipment, plus yield figures where applicable, were obtained for each process in the model. It was originally intended to use several sets of data to compare operations in various plants but since the actual cost data are proprietary, and since the cost estimates obtained in the course of the research seemed to converge to numbers with reasonable spreads, a weighted (by the author) average set of data has been used. No one reader will agree with all the data, but it is felt that a consistent set has been obtained, even when the reader may disagree with the absolute levels. The data used in this study are given Fig. 4.1 and discussed in the following sections.

4.2 Elapsed Time

Since the hypothetical problem posed as a vehicle for this study included the starting of an inertial gyro production and repair facility (plant), an important consideration in the dynamic behavior of the plant is the accumulation of the time lags in each operation. Elapsed time is not directly related to labor cost since no information is given as to the numbers of people working in each operation for what period of time. The elapsed time to produce a new gyro in a qualified IMU ready for operation in the field is about 75 days. The elapsed time for a category 3 field failure to be returned to the field is about 110 days. Now, the accuracy of the computer solution is a function of the iteration time or solution time interval (DT) compared to the shortest process time in the system. It is shown in Ref. 18 that the iteration time should be less than one-sixth the length of the shortest process time where pipeline delays are modeled by three first-order exponentials in series (see section 3.3). The original data contain delays as short as three days which would require a solution interval of less than one-half day. In order to reduce the costs of the computer time required for this study, it was decided to increase the original 3-day and 4-day delays to 7-day and 8-day delays, respectively. These changes* are expected to result in insignificant effects on the system performance for this study.

4.3 Labor Costs

Labor costs are a large percentage of the LCC of the inertial gyro. The labor costs in dollars per gyro , or per operation on the gyro, are given in the second column of Fig. 4.1. These costs are based on an hourly rate of approximately $17.50/hour and include overhead, data analysis, engineering time, etc.

*Gyro disassembly elapsed time for category 2, and gyro-failure-identification-test elapsed time for categories 1, 2, and 3 and "good".

Operation	elapsed time in days	labor cost in dollars	material cost in dollars/gyro	tools and equipment for 5 gyros/day	yield
gyro assembly (new sets)*	30	5000	7000	$1,042,000	
gyro reassembly - cat. 1	9	600	400		
cat. 2	15	2000	1000		
cat. 3	30	4000	2800		
gyro disassembly - cat. 1	NA	100	NA		
cat. 2	7	500	NA		
cat. 3	10	1200	NA		
gyro failure - identification tests - cat. 1	7	300	NA		
cat. 2	8	700	NA		
cat. 3	8	1000	NA		
"good"	7	1000	NA	$1,042,000	
gyro acceptance tests	25	2000	NA	7.5×10^6	0.7
IMU assembly (gyro portion)	7	300	NA	NA	
IMU disassembly	7	200	NA	NA	
IMU failure-verification tests (gyro portion)	12	400	NA	NA	
IMU acceptance tests (gyro portion)	12	2000	NA	NA	0.9

NA = not applicable

* parts-loss rate in assembly of new sets is 8%

Fig. 4.1. Nominal values of data for the system.

4.4 Material Costs

The material costs in dollars are given in Fig. 4.1. The set of parts required to assemble one gyro is $7000 and represents estimates based on lots of 200 to 500 sets of parts, where the main structural material is beryllium.

4.5 Tools and Equipment Costs

The costs of tools and equipment are given in two amounts of dollars in Fig. 4.1 sufficient for a given production rate. The estimated value for the costs of tools and equipment required for all assembly operations is given in one lump sum and was not to be considered a constraint in this study. The cost of the gyro acceptance-test equipment is given separately, since it is a constraint in this study.

4.6 Yield

The two significant yields for the gyro are the gyro acceptance-test yield and the IMU acceptance-test yield which are given in Fig. 4.1 as 0.7 and 0.9, respectively. These are intended to reflect average yields for a long-term program, since it is well known that yields can vary significantly from month to month.

4.7 Parts Lost

During the assembly of any precision electromechanical device, such as inertial gyros, parts are lost due to mishandling, mistakes in inspection, and everyday errors. This value of the parts lost in the assembly of new sets of gyro parts is an average of 8%.

The cost of the parts lost in the reassembly process is included in the cost of the make-up parts.

4.8 Summary

The costs described in this chapter have been taken as constants over the entire 15-year program being studied here. In actual practice, these costs are variables as a function of time as a result of new union contracts, the cost of money, modifications, repair and updating of all tools and equipment, and changes in the original gyro design.

Chapter 5

ANALYSIS OF RESULTS

5.1 Introduction

In the previous chapters the model of an inertial gyro production and repair plant has been devised, and the basic data has been collected. In this chapter the results of exercising the model by changing parameters and combinations of parameters are presented and analyzed.

5.2 Gyro Acquisition Costs

Before exercising the entire model of the system, establishment of basic costs is needed, against which the costs of other system configurations can be compared. In particular, a common set of basic costs are those associated with the acquisition costs of a given number of new gyros. In the computer program this can be accomplished by setting the capacity of the IMU test area to zero (CAPAC = 0) and the IMU assembly labor cost to zero (IMUASSC = 0) so that the gyros that are produced remain in the IMU waiting stack. (See Chapter 2 for block diagrams of the system.) In determining the acquisition cost, the gyro acceptance test yield was set at 0.7. Of the rejects, 30% are assumed to be category 1 (FCTR1 = 0.3), 60% are assumed to be category 2 (FECTR2 = 0.6), and 10% are assumed to be category 3 (FECTR3 = 0.1). Since there are no failures from the field, equipment constraint is not a factor at a gyro yield of 0.7. The results show that the total acquisition cost is approximately $69.7 million, of which 12% is the cost of the tools and equipment, 44% is the cost of the parts and materials, and 44% is the cost of the labor. Since 3300 gyros were built, the cost of each gyro is about $21,000.

5.3 System Costs when All Failures are Eliminated

The minimum possible life-cycle cost for the system under consideration would result if the gyro and IMU acceptance test yields are unity (YIELD = IMUYLD = 1.0) and no failures occur in the field (T1 = T2 = T3 = 0). The resulting hardware build-up is shown in Fig. 5.1. The time lag between the gyros-to-assembly (minus the parts lost in assembly) and the IMU's in the field is the 75-day pipeline delay, or transportation lag,* in the plant. Since the gyro input between

* Also called "dead time" in control systems.[8]

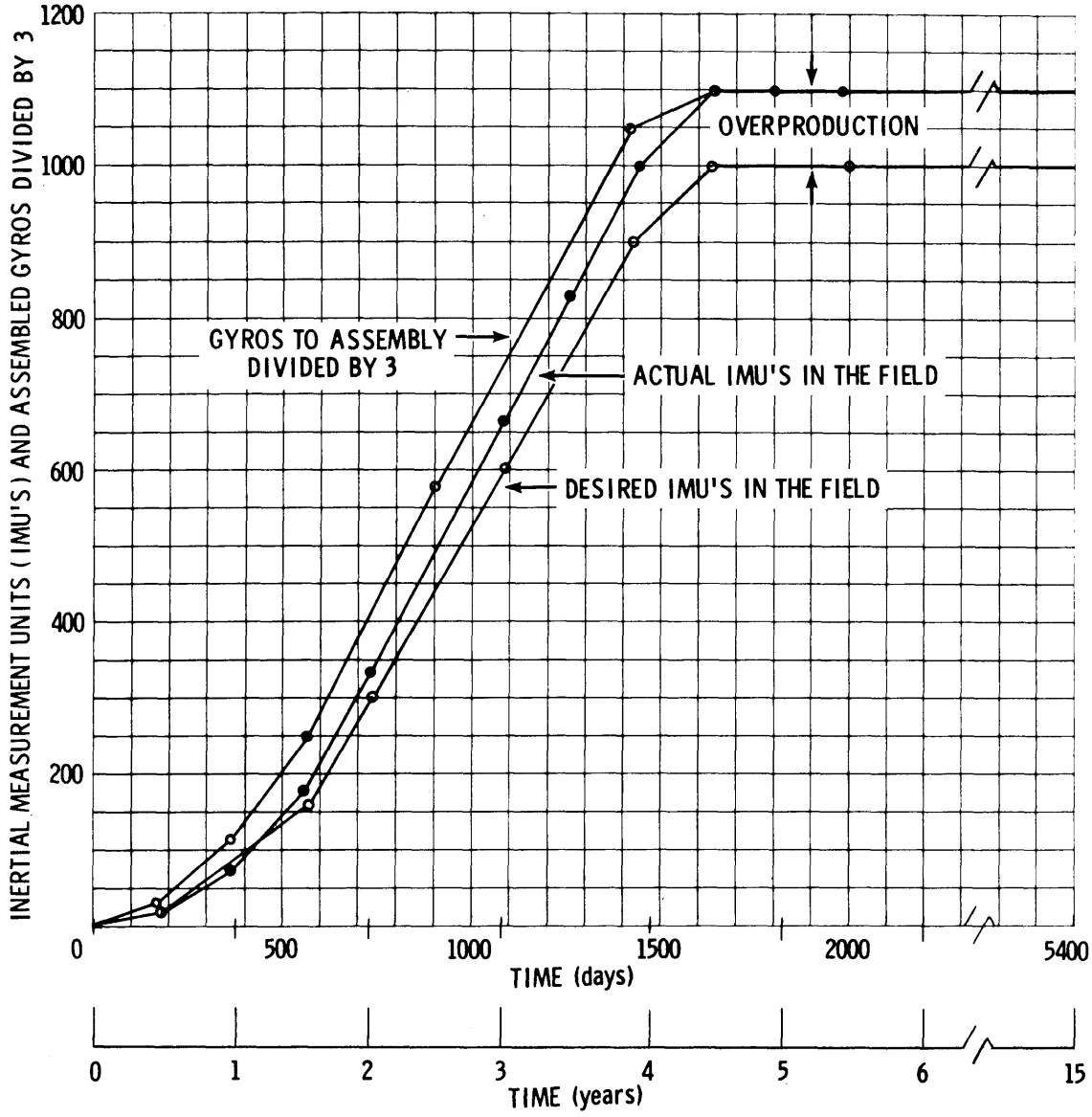

Figure 5.1 Inertial measurement units vs time for zero failures and unity yields.

540 days and 1440 days is nearly three gyros per day, or one IMU per day, the pipeline contains 75 IMU's (225 gyros). The build-up of IMU's in the field is leading the desired IMU's in the field since there are no failures.

The life-cycle cost (LCC) is approximately $64.8 million, of which 13% is the cost of the tools and equipment, 45% is the cost of the parts and materials, and 42% is the cost of the labor. The management decision in this case is to build all the originally planned gyros (since they had no foreknowledge of the zero failures in the future) so that the field inventory becomes 1100 IMU's. There is a contractual clause built into the program that IMU over production (above 1050 IMU's)* does not result in additional IMU days-in-the-field credit. The total number of IMU days-in-the-field is 4.71×10^6, and the cost per day per IMU (3 gyros) in the field is $13.74. The cost for 3000 gyros in the field (in 1000 IMU's) over about a 10-year period is about $21,600 per gyro.

5.4 Effects of Varying Gyro Acceptance Test Yield

The first set of results reported in this section were obtained with all constants as noted in Chapters 3 and 4, and called the reference run. It should be noted that 0.7 yield for the gyro acceptance test reveals that 30 of each 100 gyros are rejected, while 0.9 yield for the IMU acceptance test yield reveals that one in each ten IMU's, or one in each 30 gyros, is rejected (three gyros per IMU). The fractions of gyros not accepted at the gyro acceptance test are set at 0.3, 0.6, and 0.1 for categories 1, 2, and 3, respectively. Such a distribution of failures at this stage of the production cycle is justified on historical grounds[1] that the largest fraction of rejects is due to float-to-housing problems (category 2), probably mainly flotation fluid contamination. The smallest fraction is due to spin-axis bearing problems (category 3) with the category 2 rejections lying between the other two. The fractions of gyros rejected at the IMU acceptance test are set at 0.25, 0.5, and 0.25 for categories 1, 2, and 3, respectively. Again, the fraction of category 2 failure is set at a greater value than the other two categories, since float-to-case problems in the single-degree-of-freedom instrument are probably the most difficult testing problem.

The uniform probability density function was chosen to describe the IMU failure rates in the field for reasons of simplicity. Other probability distribution functions can be used if desired.[4] The IMU failures in the field are described by constant failure rates per year. For the reference run, the failure rates are 0.1/yr, 0.2/yr, and 0.2/yr for categories 1, 2, and 3, respectively. The total failure rate is 0.5/yr indicating that one-half of the IMU's in the field fail each year. Of the gyros returned from the field in the failed IMU's, one-third are failed gyros

* See line 462 in the computer program shown in Appendix B.

and two-thirds are "good" gyros. Additional discussion of failure rates is given in Section 5.8. All other constants in the system are as given in Chapters 3 and 4.

A complete copy of the results of the computations for the reference run is given in the figures at the end of this chapter (since references to these data are made in other sections of the chapter). Figures 5.9 through 5.12 are copies of the printed computer output, and Figs. 5.13 through 5.18 are copies of the graphic computer output. The computer outputs for other runs could not be included here due to lack of space.

The operation of the plant is completely described in dollars and in hardware flow by the information given in the figures. The life-cycle cost at any time (in days) in the program is given by COST. Several of the code names are nearly self-defining* (but once they have been defined, they are easily remembered), such as DAYINF = IMU days in field, CPERDY = cost per day, FIELD = number of IMU's in the field, GYROW = gyros waiting for gyro acceptance test, IMUWAIT = flow rate of IMU's to the wait stack (waiting for IMU acceptance test), TFFWAIT = IMU's waiting for repair, SUBTX = subtotal costs, VFECAT1 = IMU verified field failures, etc.

The costs (in dollars) of each operation as a function of time are given in both the printed computer output (Figs. 5.9 - 5.12) and the graphic computer output (Figs. 5.13 and 5.14). In Figs. 5.13 and 5.14, the life-cycle cost (COST) is plotted as a function of time as well as all the subtotal costs. The initial value of the life-cycle cost is the cost of the equipment for the plant. The final value of each subcost (cost of each operation) is given in the following tabulation:

Code Name	Description	$ x 10^6	%
SUBT1	cost of parts purchased and parts lost in new sets assembly	28.9	18.3
SUBT2	IMU field-failure identification test labor cost	2.4	1.5
SUBT3	gyro disassembly labor cost	6.6	4.2
GRLAB	gyro reassembly labor cost	24.5	15.6
GRMAT	gyro reassembly material cost	15.0	9.5
SUBT5	gyro plant failure identification test labor cost	0.5	0.3
SUBT6	gyro acceptance test labor cost	28.8	18.3
SUBT7	gyro field-failure identification test labor cost	4.5	2.9
SUBT8	IMU acceptance test labor cost	15.8	10.0

.... tabulation continued on next page ...

* All the code names are defined in Appendix A.

..... tabulation continued ...

Code Name	Description	$ x 10^6	%
SUBT9	IMU assembly labor cost	2.4	1.5
SUBT10	IMU disassembly labor cost - plant failures	0.2	0.1
SUBT11	IMU disassembly labor cost - field failures	1.2	0.8
SUBT12	gyro assembly labor cost - new sets	18.1	11.5
OTHER	tools and equipment	8.5	5.4
COST	life-cycle cost (LCC)	$157.5	100.0

A summary of the above costs can be presented as follows:

	$ x 10^6	%
parts and material	43.9	27.9
tools and equipment	8.5	5.4
labor	105.1	66.7
Total	$157.5	100.0

Note that two-thirds of the LCC of the program is composed of labor costs. Further analysis of the labor cost reveals that 53% is gyro labor cost and 13% is IMU labor cost (gyro portion of the total IMU labor cost). Labor costs are also treated in the next section. The cost for 3000 gyros in the field for about 10 years is nearly $52,500.

The effects of a changing gyro acceptance-test yield on (a) the life-cycle cost and cost per day are shown in Fig. 5.2, and (b) the gyro labor, parts, and materials, and IMU labor subcosts are shown in Fig. 5.3. The labor cost vs yield has the largest derivative and the largest second derivative with increasing yield.

The dynamic behavior of the system for the reference run, where the gyro acceptance-test yield is set at 0.7, can be described as follows. After an initial transient, the IMU inventory in the field (see FIELD in Fig. 5.15) reaches 900 IMU's at 1440 days. At this time, the number of gyros waiting for acceptance test (GYROW) has reached 111 since the production of new sets plus the reassembled gyros have saturated the test equipment for gyro acceptance test. The production rate of new sets is reduced between 1440 and 1620 days, so the the GYROW is reduced to nearly zero. However, by this time the actual IMU inventory in the field (FIELD) is larger

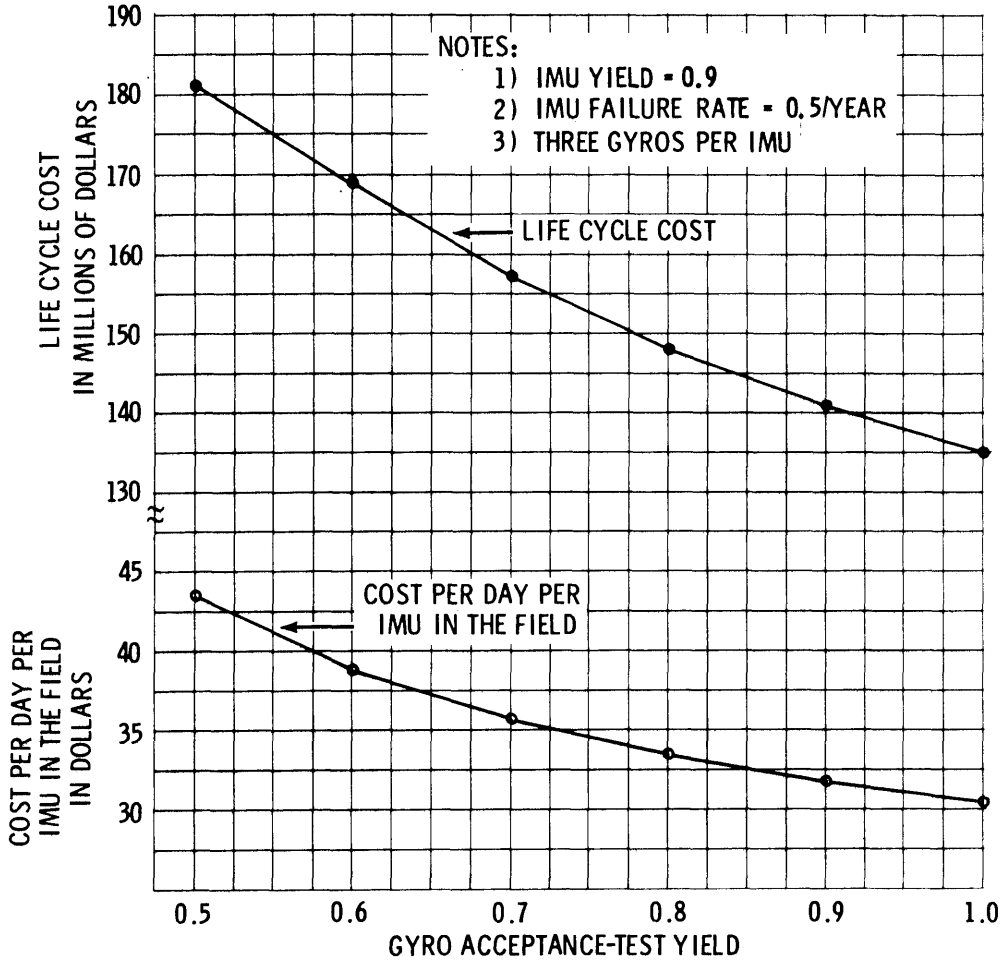

Figure 5.2 Life-cycle cost and cost per day per IMU in the field vs gyro acceptance-test yield.

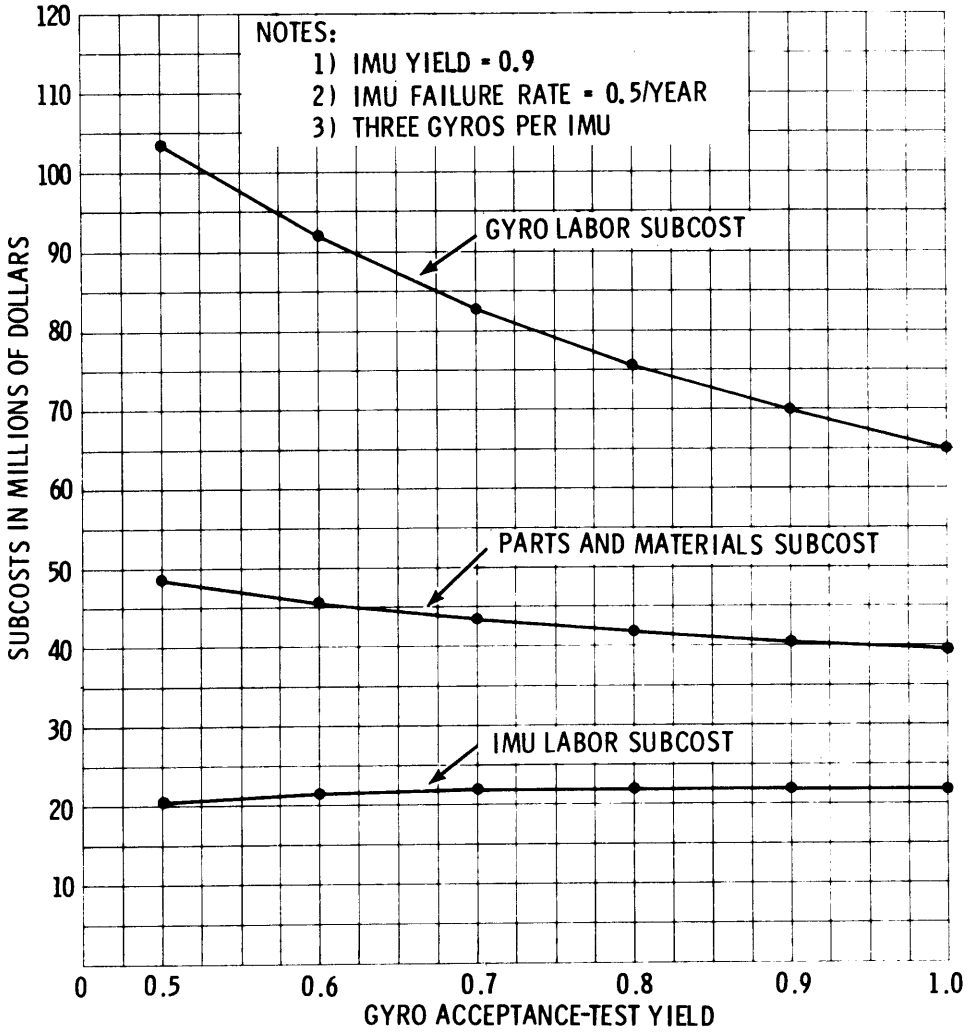

Figure 5.3 Gyro labor, parts and materials, and IMU labor subcosts vs gyro acceptance-test yield.

than the desired IMU inventory in the field (DINFLD) and the nonlinear control at the failed IMU waiting stack switches all the incoming failed IMU's into the waiting stack. The result is that the FIELD actually decreases so that at 1800 days there are fewer IMU's in the field (about ten) than there were at 1620 days (see ERROR in Fig. 5. 16). Because of the particular choice of the nonlinear control at the waiting stack (see Section 3. 12), the actual inventory in the field reaches the desired inventory in the field in an exponential-like manner. Thus, the management of the plant does not actually meet one of their objectives, which was to maintain an inventory of 1000 IMU's in the field beginning five years after the start of production.

The dynamic behavior of the system is quite sensitive to changes in the gyro acceptance test yield. When the YIELD decreases from 0. 7 to 0. 6, GYROW increases to a maximum of over 750 gyros at 1440 days, after which it slowly returns to zero. This is explained by the gyro acceptance test equipment constraint limit. These are intolerable situations for production, especially the latter case where 44% of the final production total is waiting for test. Management did not foresee the lower yields.

5. 5 The Impact of Automation on Gyro Assembly

In the previous section it was noted that two-thirds of the LCC of the program is composed of labor costs. Gyro assembly and reassembly labor costs account for 27% of the LCC. An estimate is made that two million dollars invested in the development of automatic machinery for assembling gyros will more than return its investment. It is proposed that the use of this automation will improve the gyro acceptance test yield from 0. 7 to 0. 8 by changing the failure distribution. At YIELD = 0. 7, failures in categories 1, 2, and 3 of 0. 3, 0. 6, and 0. 1, respectively, mean that of every 100 gyros there are nine category 1 failures, 18 category 2 failures, and three category 3 failures. At YIELD = 0. 8, of every 100 gyros it is estimated there are only eight category 2 failures and no change in categories 1 and 3. This is the result of the automation in reducing the contamination added to the gyro during assembly, filling with flotation fluid, etc.

The results are that the LCC is reduced from $157 million to $149 million, or an $8 million savings - - the savings are greater than the investment.

5. 6 Effects of Varying IMU Acceptance Test Yield

If the gyro acceptance test program were perfect, only gyros which did not meet the specified performance levels would be rejected and only those which did meet the specified performance levels would be accepted. In actual practice, the gyro acceptance tests fall short of this perfection, and some "bad" gyros pass acceptance tests and are rejected in the IMU acceptance tests. It might be argued that gyro deterioration between gyro acceptance test and IMU acceptance test could

occur, but since the time interval is so short compared to the expected life of the gyro, such an occurrence is rare. Thus, it is important to investigate the effects of changes in IMU acceptance test yield. This is simply accomplished in the computer program by changing the value of the IMU acceptance test yield (IMUYLD) to the desired values.

The LCC and the cost per day per IMU in the field is presented in Fig. 5.4, and the major subcosts in Fig. 5.5 as a function of the IMU acceptance test yield. IMU acceptance test yields of 0.5, 0.7, and 0.9 indicate that 17%, 10%, and 3.3% of the gyros accepted at the gyro acceptance test level were, in fact, rejects. Investments must be made in improving the gyro acceptance tests if a low IMU acceptance test yield is to be improved.* As can be seen from Fig. 5.4, over the range studied a 10% change in IMU acceptance test yield is worth about $16 million, or an average change of about 10% in the life-cycle costs.

5.7 Effects of Changes in Gyro Acceptance Test Effort

One of the many advantages of the model development in this thesis is that trade-offs between gyro operations and IMU operations can be explored and the changes in LCC analyzed. The specific example explored in this section is related to a comment made earlier, that some gyro testing and calibration is required at the IMU level because of gyro environmental differences between gyro and IMU acceptance testing. This suggests the reduction of the gyro acceptance test effort and an increase in the IMU acceptance test effort. The example chosen here is to reduce the gyro acceptance test to one-half of its former level by (a) reducing the gyro acceptance test time (TGYAT) from 25 days to 12 days, the gyro acceptance test labor cost (GACTC) from $2000 to $1000, the gyros per day capacity of each test unit (CAPYLD) from 0.2 to 0.4, and (b) increasing the gyro yield (YIELD) from 0.70 to 0.75, the elapsed time for IMU acceptance test (TTIMU) from 12 days to 18 days, the IMU acceptance test cost (STCOST) from $2000 to $3000, and the capacity of the IMU test area (CAPAC) from 10 to 18.

However, the IMU acceptance test yield drops to 0.25. This is explained as follows. When the YIELD = 0.7 and the IMUYLD = 0.9, 30 gyros of each 100 gyros were rejected at the gyro test level and 3.3 gyros of each 100 gyro were rejected at the IMU level. When the YIELD = 0.75, only 25 out of each 100 gyros are rejected at the gyro test level, and an additional five reject gyros are allowed to reach the IMU test level. When 8.3 gyros of each 100 gyros, or one in twelve, are rejected at the IMU level, the IMUYLD drops to one-fourth, since there are three gyros in each IMU. The results of this change are compared with the standard run reported in Section 5.4.

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* It is assumed that no specification incompatibilities exist between the gyro and the IMU acceptance tests.

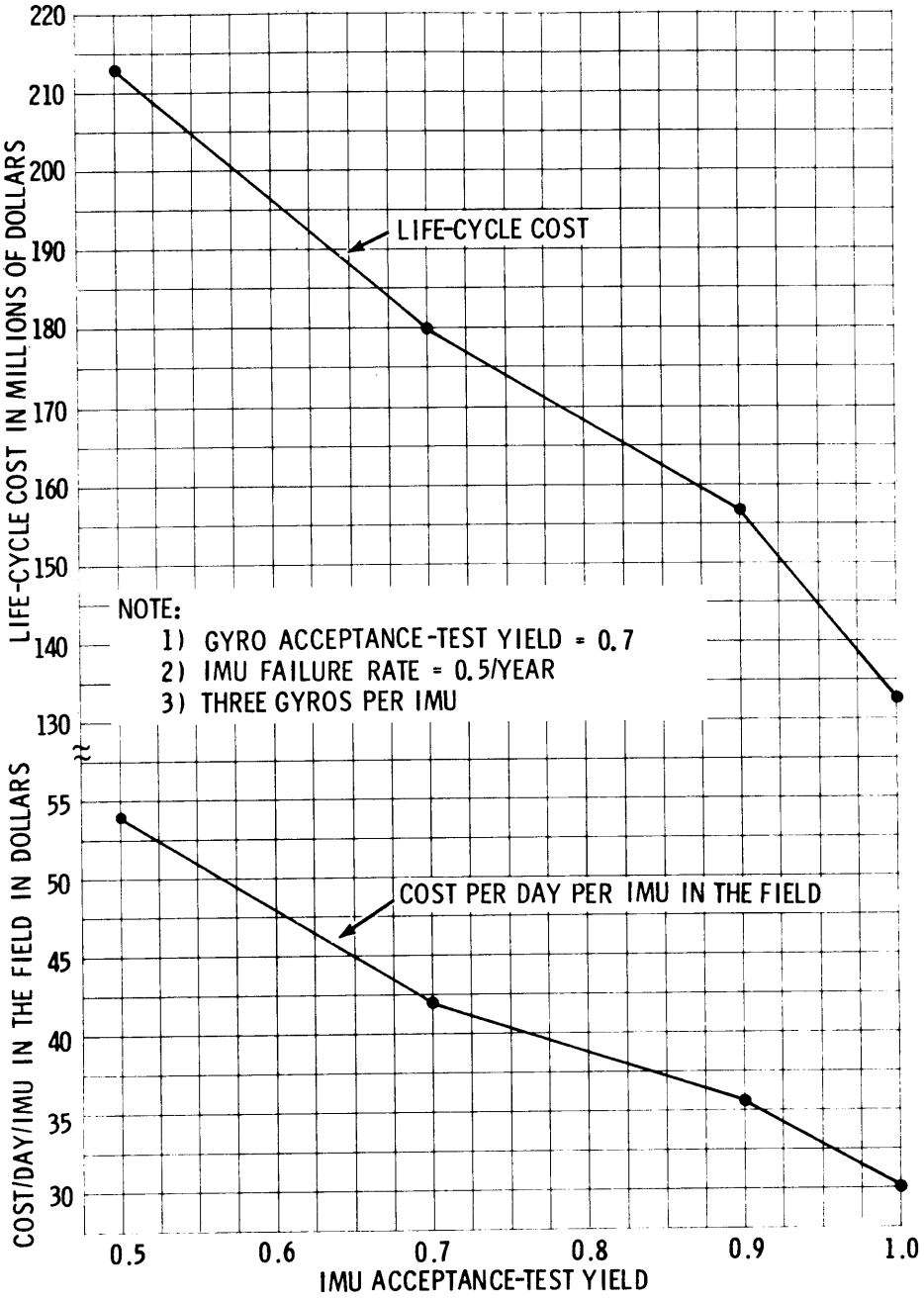

Figure 5.4 Life-cycle cost and cost per day per IMU in the field vs IMU acceptance-test yield.

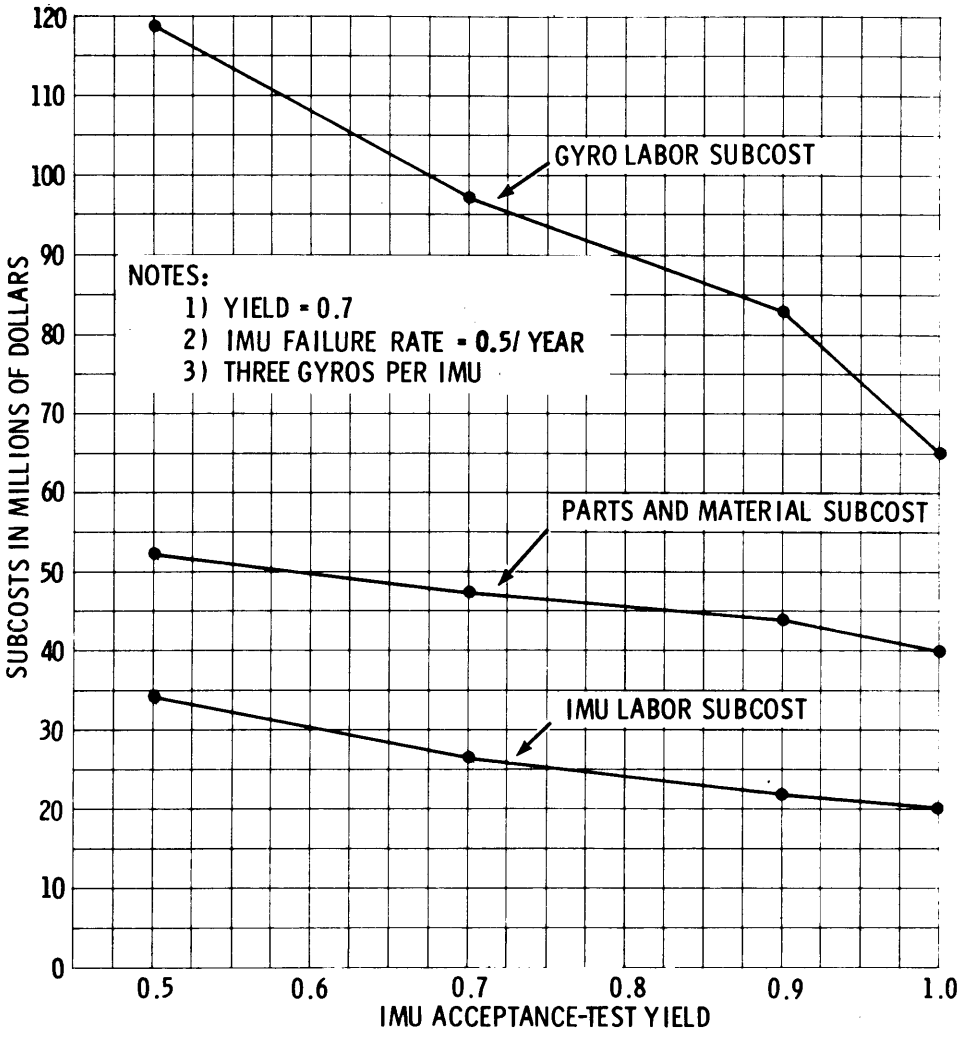

Figure 5.5 Gyro labor, parts and materials, and IMU labor subcosts vs IMU acceptance-test yield.

The LCC and the cost per day per IMU in the field rises from $157 million and $35.79 to $308 million and $85.98, respectively. This result demonstrates, rather severely, the importance of testing components and subassemblies at the lowest possible level. Whenever a failed component is allowed to proceed along the production line into another assembly, the IMU for example, it gathers costs as it proceeds. When it is finally revealed as a failed component, all the costs for assembly testing and disassembly of the IMU are lost since all these operations must be repeated.

5.8 Costs as a Function of Failure Rates in the Field

Previous sections in this chapter have explored the effects on the life-cycle costs as a function of gyro and IMU yields and other parameters. This section is devoted to an investigation of life-cycle costs as a function of IMU failure rates in the field (assuming, as before, that the IMU failures are due to a single gyro failure in each IMU failure). [14]

The system build-up as a function of time is presented in Fig. 5.6. The initial gyro assembly (divided by three to obtain equivalent IMU's) and the IMU's in the field for IMU failure rates of both 0.05/yr and 0.5/yr are shown. With an average IMU failure rate of 0.05/yr, the number of IMU's in the field at any given time exceeds the desired inventory in the field until the value of 1000 IMU's is reached. The number of failed IMU's in the failed IMU waiting stack slowly increases with time to about 100 IMU's after the new gyro production is completed and the plant becomes nearly empty. As the IMU failure rate increases to 0.5/yr the actual IMU inventory in the field at any given time indicates a lengthening transportation time compared to the gyros assembled. At 1600 days, the transportation time is nearly 300 days, and there exists a growing stack of failed IMU's waiting for repair (see Section 5.4).

The LCC and the cost per day per IMU are presented in Fig. 5.7 as a function of the IMU failure rate per year.* At the high failure rates, the costs decrease drastically as the failure rate decreases. The LCC at a failure rate of 1/yr is $225 million, while the LCC at a failure rate of 0.5/yr is $157 million, a decrease of almost $70 million or over 30% of the LCC. For those cases where the failure rate is greater than 1/yr, a halving of the failure rate would result in an even more drastic decrease in the LCC.

For the case where the IMU failure rate (uniform probability density function) is 100% per year, the gyro failure rate is 33%/yr (assuming one failed gyro per failed IMU). The average gyro operates in the field for two years, or

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* Constant failure rates have been assumed for the IMU inventory in the field. [4]

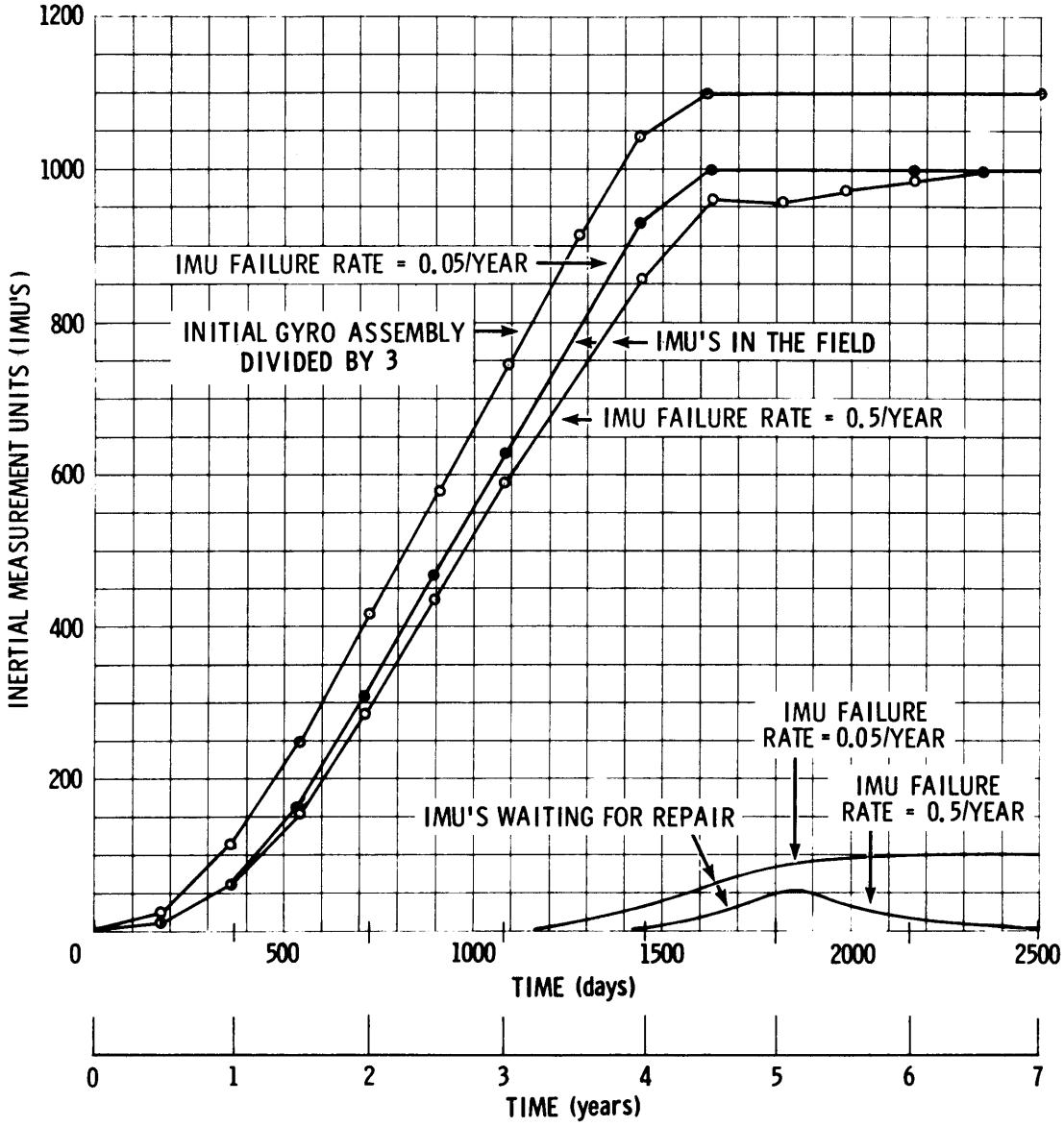

Figure 5.6 Inertial measurement units vs time for IMU failure rates of 0.5/yr and 0.05/yr.

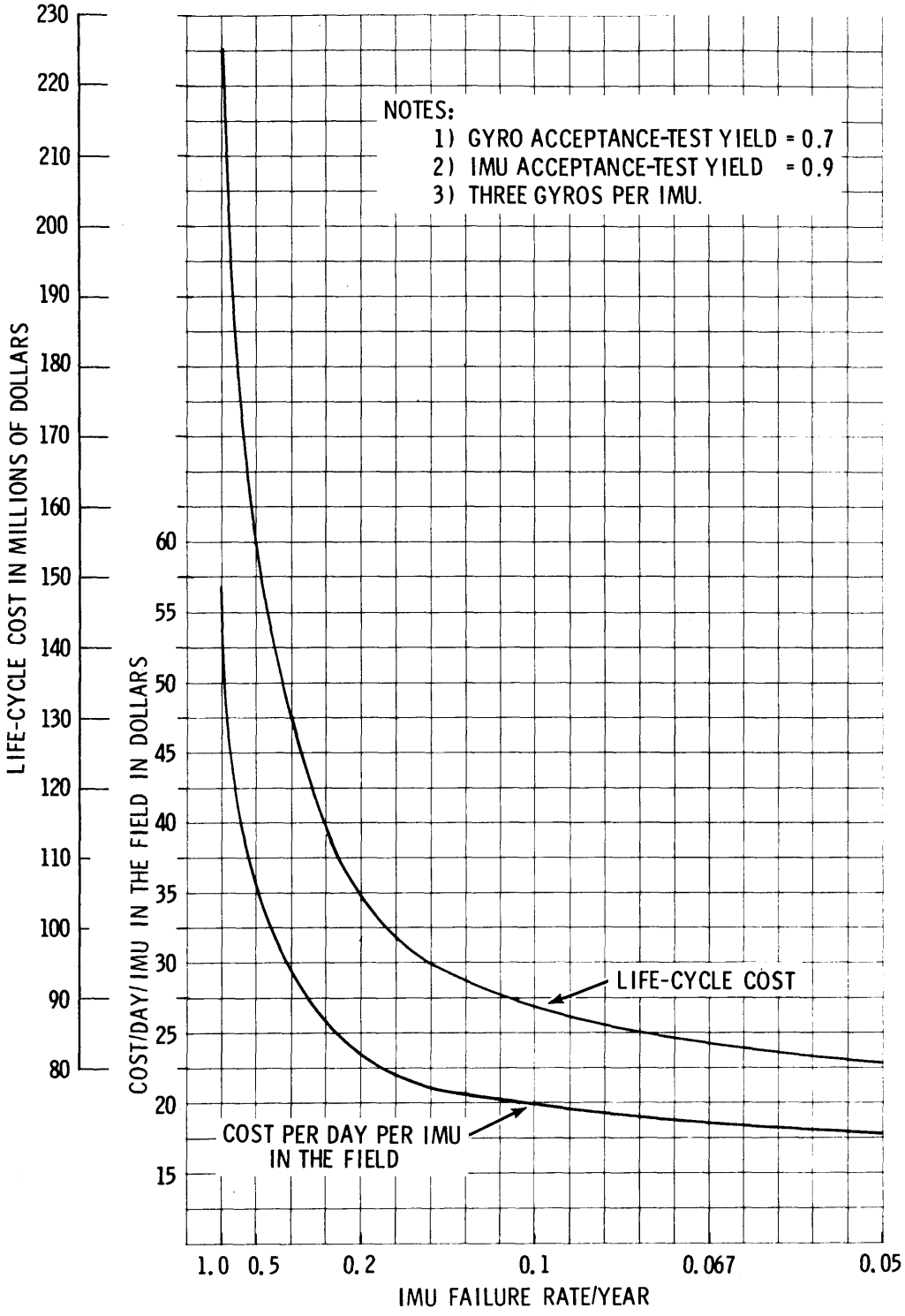

Figure 5.7 Life-cycle cost and cost per day per IMU in the field vs IMU failure rate.

about 17,000 hours. As recently as a year ago,[44] gyro reliability for an aircraft inertial navigator was estimated at 15,000 gyro operating hours between "unscheduled removals".

Another example can be cited[11] concerning a relatively small sample of gyros built by the Instrumentation Laboratory for a back-up system. These gyros were built in 1962 and were still in service in September 1969 with no noticeable change in performance, having accumulated over 30,000 operating hours and over 35,000 nonoperating hours.

The problem is that failure models have not been devised which will permit analytical reliability prediction. Extensive data accumulation and effective data evaluation are required. Thus, reliability is not a direct measurement but an estimated figure reported with a calculated confidence factor.[4] It is important that reliability be placed on an analytical basis for, as greater and greater reliability is required, the risk of making an engineering design change to improve performance or any other parameter increases rapidly.

The major subcosts are given in Fig. 5.8 as a function of IMU failure rate. The largest reductions in costs occur at the high failure rates where many rebuilds occur over the life cycle of the program.

5.9 Summary

The usual approach in the past to defining the "cost of a gyro" has been to quote the acquisition cost at the point where the gyro is delivered for IMU installation. For the plant considered here, the acquisition cost is $21,000 per gyro based on the data given in Chapter 4 (with gyro acceptance-test yield = 0.7). When the costs of gyro installation into the IMU, acceptance testing in the IMU (with yield = 0.9), disassembly of the IMU if a gyro failure occurs, and gyro failure identification tests are included, the gyro cost is increased to about $23,000 per gyro. On a life-cycle cost basis, the cost to the program when the yields are unity, the failures are zero, and only 3000 gyros are assembled, is $21,600 per gyro.

For the reference run, the life-cycle cost is about $52,500 per gyro where 67% of the LCC is labor cost and 27% of the LCC is gyro assembly and reassembly labor cost. These percentages should receive a significant amount of attention from management. An illustration of the possible impact of gyro assembly automation to improve the gyro acceptance-test yield was explored in Section 5.5 with a resulting indication that the savings would be greater than the investment.

The effects of variations in gyro acceptance-test yield and IMU acceptance-test yield result in changes in LCC which are almost linear with changes in yield (Sections 5.4 and 5.6). The partial derivatives are nearly $0.10 x 10 per percent for the gyro acceptance-test yield and $0.16 x 10^6 per percent for the IMU acceptance-

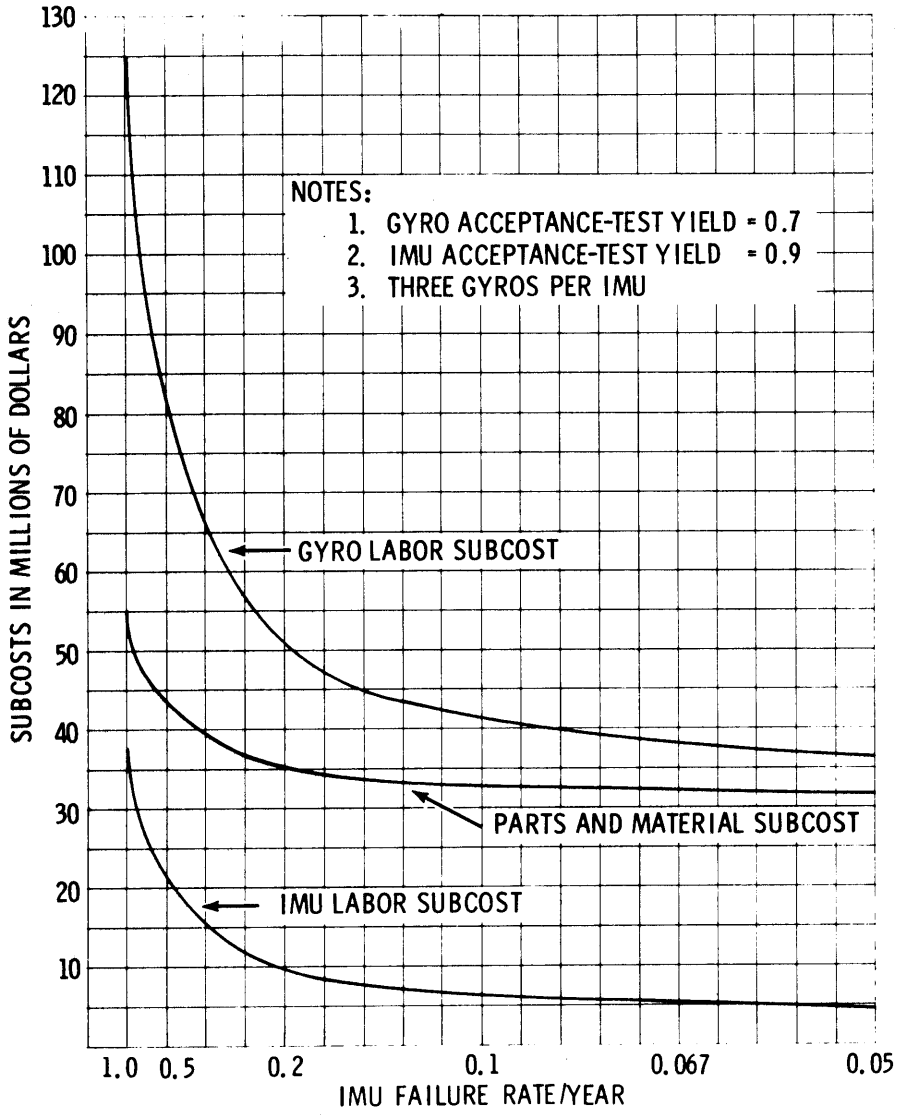

Figure 5.8 Gyro labor, parts and materials, and IMU labor subcosts vs IMU failure rate.

test yield over the ranges of yield from 0.5 to 1.0. It is important to note that an improvement in gyro acceptance test yield (due to better gyro design and assembly practices) has a "snowballing" effect on the program costs since both gyro costs and IMU costs are reduced (based on the assumption of one failed gyro per failed IMU). Although not included in this study, each time a gyro fails the IMU test the entire cost of the IMU acceptance test and other IMU operations should be charged to the gyro since these operations must then be essentially repeated. These ideas are explored in Section 5.7 where the gyro acceptance-test effort was contracted and the IMU test effort was expanded. The life-cycle costs rose rather sharply, illustrating the importance of testing at the lowest possible level.

In Section 5.8, the effects of gyro failure rates on the life-cycle costs are studied. It is shown that the life-cycle costs are extremely sensitive to changes in failure rates at the high failure rates. For example, the LCC is reduced 30% when the failure rate is reduced from 100% per year to 50% per year.

The costs of the system and the dynamics are a function of the pipeline delay in the plant which varies from 75 days for new sets to 110 days for a category 3 failure from the field, the gyro acceptance-test equipment constraint which can result in significant numbers of IMU's waiting for repair early in the program, the gyro acceptance-test yield, the IMU acceptance-test yield, the gyro failure rates in the field, and other factors such as the IMU test equipment constraint, the gains and filtering times in management decisions, etc., which were not included in this thesis.

PAGE 1 JRYO COST ANALYSIS

TIME	COST	DAYINF	CPERDY	FIELD	GYROW	IMUWAIT	TFEWAIT	RATIO
	NEWSETS	ACNEW	DINAS	TCORREC	CORREC	GYROAS	AVAGE	
	SUBT1	SUBT12	GRMAT	GRLAB	SUBT2	SUBT3	SUBT4	
	SUBT5	SUBT6	SUBT7	SUBT8	SUBT9	SUBT10	SUBT11	
	VFECAT1	VFECAT2	VFECAT3	INFLOW	GYROTT	COST	GYROW	
- - - - - - - -								
E+00	E+06	E+03	E+00	E+00	E+00	E+00	E+00	E+00
	E+00	E+00	E+00	E+00	E+00	E+00	E+00	
	E+06	E+06	E+06	E+06	E+03	E+03	E+06	
	E+03	E+06	E+03	E+06	E+03	E+03	E+03	
	E+00	E+00	E+00	E+00	E+00	E+06	E+00	
- - - - - - - -								
.0	8.54	.0	8542.T	.00	.00	.0000	.000	1.5000
	.0000	.0	.0000	0.	0.	.000	.00	
	.000	.000	.000	.000	.0	.0	.000	
	.00	.000	.0	.000	.0	.00	.0	
	.00000	.00000	.00000	.0000	.0000	8.54	.00	
- - - - - - - -								
180.	9.81	.2	43.94T	6.36	.95	.1755	.009	1.5000
	1.0000	89.5	1.0000	0.	0.	26.666	33.73	
	.708	.443	.009	.015	.1	5.5	.024	
	.35	.088	.2	.015	2.8	.13	.0	
	.00144	.00287	.00287	.9550	.9476	9.81	.95	
- - - - - - - -								
360.	14.21	4.9	2924.X	53.61	2.36	.5578	.074	1.5000
	2.0000	359.0	2.0000	0.	0.	56.665	82.66	
	2.956	1.785	.086	.152	2.4	44.7	.238	
	3.98	.605	4.9	.133	22.0	1.26	1.1	
	.01380	.02761	.02761	2.3663	2.3581	14.21	2.36	
- - - - - - - -								
540.	22.01	22.4	981.0X	150.54	3.88	1.0204	.208	1.5000
	3.0000	808.5	3.0000	0.	0.	86.665	128.51	
	6.444	4.027	.272	.477	11.6	134.2	.748	
	12.58	1.645	22.9	.401	64.1	3.88	5.5	
	.03996	.07992	.07992	3.8935	3.8847	22.01	3.88	
- - - - - - - -								
720.	32.13	61.7	520.7X	291.00	4.57	1.3846	.403	1.0600
	3.0000	1348.5	3.0000	0.	0.	90.001	172.94	
	10.764	6.727	.586	1.019	32.5	280.7	1.605	
	26.77	3.161	63.1	.833	130.4	8.14	15.7	
	.07854	.15708	.15708	4.5758	4.5738	32.13	4.57	
- - - - - - - -								
900.	42.89	127.4	336.6X	440.44	4.91	1.6188	.611	1.2820
	3.0000	1888.5	3.0000	0.	0.	90.007	222.33	
	15.084	9.427	.996	1.720	68.1	468.1	2.715	
	44.56	4.850	130.5	1.368	211.4	13.45	33.2	
	.12004	.24007	.24007	4.9118	4.9100	42.89	4.91	
- - - - - - - -								
1080.	54.15	220.1	246.1X	588.68	18.77	1.8056	.816	1.4547
	3.0000	2428.5	3.0000	0.	0.	90.012	269.74	
	19.404	12.127	1.487	2.552	118.7	691.0	4.039	
	65.10	6.639	225.6	1.982	304.3	19.57	58.2	
	.16130	.32259	.32259	5.1934	5.0000	54.15	18.77	
- - - - - - - -								

Figure 5.9 Results of reference run - Page 1.

PAGE 2 JRYO COST ANALYSIS

TIME	COST	DAYINF	CPERDY	FIELD	GYROW	IMUWAIT	TFFWAIT	RATIO
	NEWSETS	ACNEW	DINAS	TCORREC	CORREC	GYROAS	AVAGE	
	SUBT1	SUBT12	GRMAT	GRLAB	SUBT2	SUBT3	SUBT4	
	SUBT5	SUBT6	SUBT7	SUBT8	SUBT9	SUBT10	SUBT11	
	VFECAT1	VFECAT2	VFECAT3	INFLOW	GYROTT	COST	GYROW	
1260.	65.73	338.5	194.2X	726.53	72.71	1.9447	1.008	1.2003
	3.0000	2968.5	3.0000	0.	0.	90.018	315.25	
	23.724	14.827	2.044	3.489	183.7	941.9	5.533	
	87.61	8.439	347.2	2.653	405.6	26.26	90.4	
	.15977	.39954	.39954	5.4041	5.0000	65.73	72.71	
1440.	76.56	480.8	159.2X	853.06	111.67	2.0723	1.184	1.1172
	2.1000	3427.9	2.1000	0.	0.	66.021	357.26	
	27.405	17.129	2.659	4.516	261.9	1217.7	7.175	
	111.76	10.239	493.3	3.373	514.0	33.44	129.3	
	.23509	.47017	.47017	4.9121	5.0000	76.56	111.67	
1620.	84.16	644.9	130.5X	968.70	3.26	1.9523	16.012	.6063
	.0000	3617.9	.0000	0.	0.	7.022	395.40	
	28.941	18.088	3.326	5.626	348.4	1514.6	8.952	
	137.42	12.029	661.8	4.136	628.5	41.06	172.9	
	.17721	.35441	.35441	3.2410	3.2613	84.16	3.26	
1800.	87.45	819.5	106.7X	959.61	2.09	1.4963	46.937	1.0809
	.0000	3617.9	.0000	0.	0.	.022	471.78	
	28.941	18.088	3.820	6.437	430.7	1727.3	10.257	
	155.66	12.872	841.2	4.656	704.2	46.35	213.4	
	.28677	.57354	.57354	2.0975	2.0944	87.45	2.09	
1980.	90.97	993.0	91.607	971.34	2.27	1.5882	29.758	1.0573
	.0000	3617.9	.0000	0.	0.	.022	521.18	
	28.941	18.088	4.382	7.350	534.1	1976.9	11.732	
	174.47	13.661	1019.6	5.217	788.8	51.95	265.0	
	.28544	.57087	.57087	2.2699	2.2699	90.97	2.27	
2160.	94.54	1169.0	80.876	983.24	2.25	1.5734	18.884	1.0335
	.0000	3617.9	.0000	0.	0.	.022	559.42	
	28.941	18.088	4.952	8.275	636.2	2227.3	13.226	
	193.71	14.476	1200.4	5.787	874.2	57.65	316.1	
	.28238	.56476	.56476	2.2496	2.2498	94.54	2.25	
2340.	98.08	1346.6	72.840	990.41	2.23	1.5610	12.544	1.0192
	.0000	3617.9	.0000	0.	0.	.022	591.30	
	28.941	18.088	5.516	9.191	737.5	2475.4	14.706	
	212.76	15.283	1382.9	6.351	958.8	63.30	366.8	
	.28045	.56091	.56091	2.2312	2.2313	98.08	2.23	
2520.	101.60	1525.1	66.620	994.54	2.22	1.5535	8.904	1.0109
	.0000	3617.9	.0000	0.	0.	.022	617.59	
	28.941	18.088	6.076	10.101	838.3	2721.9	16.176	
	231.69	16.085	1566.5	6.912	1042.9	68.90	417.2	
	.27932	.55863	.55863	2.2199	2.2200	101.60	2.22	

Figure 5.10 Results of reference run - Page 2.

TIME	COST NEWSETS SUBT1 SUBT5 VFECAT1	DAYINF ACNEW SUBT12 SUBT6 VFECAT2	CPERDY DINAS GRMAT SUBT7 VFECAT3	FIELD TCORREC GRLAB SUBT8 INFLOW	GYROW CORREC SUBT2 SUBT9 GYROTT	IMUWAIT GYROAS SUBT3 SUBT10 COST	TFEWAIT AVAGE SUBT4 SUBT11 GYROW	RATIO
2700.	105.11	1704.3	61.676	996.89	2.21	1.5491	6.826	1.0062
	.0000	3617.9	.0000	0.	0.	.022	638.95	
	28.941	18.088	6.634	11.007	938.7	2967.6	17.641	
	250.54	16.883	1750.6	7.470	1126.5	74.48	467.4	
	.27866	.55731	.55731	2.2134	2.2134	105.11	2.21	
2880.	108.61	1833.8	57.658	998.23	2.21	1.5466	5.640	1.0035
	.0000	3617.9	.0000	0.	0.	.022	656.13	
	28.941	18.088	7.191	11.911	1038.9	3212.8	19.102	
	269.34	17.678	1935.1	8.027	1210.0	80.05	517.5	
	.27828	.55656	.55656	2.2096	2.2096	108.61	2.21	
3060.	112.11	2063.4	54.333	999.98	2.21	1.5451	4.960	1.0020
	.0000	3617.9	.0000	0.	0.	.022	669.82	
	28.941	18.088	7.747	12.814	1139.0	3457.6	20.561	
	288.12	18.472	2119.7	8.584	1293.4	85.61	567.5	
	.27807	.55613	.55613	2.2075	2.2075	112.11	2.21	
3240.	115.61	2243.2	51.536	999.40	2.21	1.5443	4.566	1.0012
	.0000	3617.9	.0000	0.	0.	.022	680.68	
	28.941	18.088	8.302	13.717	1239.0	3702.3	22.019	
	306.98	19.264	2304.5	9.140	1376.7	91.16	617.6	
	.27795	.55589	.55589	2.2062	2.2062	115.61	2.21	
3420.	119.10	2423.0	49.153	999.64	2.21	1.5439	4.334	1.0007
	.0000	3617.9	.0000	0.	0.	.022	689.23	
	28.941	18.088	8.858	14.619	1338.9	3946.9	23.477	
	325.64	20.056	2489.4	9.695	1460.1	96.72	667.6	
	.27788	.55576	.55576	2.2056	2.2056	119.10	2.21	
3600.	122.59	2602.9	47.100	999.78	2.21	1.5436	4.193	1.0004
	.0000	3617.9	.0000	0.	0.	.022	695.95	
	28.941	18.088	9.413	15.521	1438.8	4191.4	24.934	
	344.39	20.848	2674.2	10.251	1543.4	102.27	717.6	
	.27784	.55568	.55568	2.2052	2.2052	122.59	2.21	
3780.	126.09	2782.7	45.311	999.85	2.20	1.5435	4.102	1.0003
	.0000	3617.9	.0000	0.	0.	.022	701.23	
	28.941	18.088	9.968	16.423	1538.7	4435.9	26.391	
	363.14	21.640	2859.1	10.807	1626.7	107.82	767.6	
	.27782	.55564	.55564	2.2049	2.2049	126.09	2.20	
3960.	129.58	2962.5	43.740	999.90	2.20	1.5434	4.039	1.0002
	.0000	3617.9	.0000	0.	0.	.022	705.35	
	28.941	18.088	10.523	17.324	1638.6	4680.3	27.847	
	381.88	22.432	3043.9	11.362	1710.1	113.37	817.6	
	.27781	.55561	.55561	2.2048	2.2048	129.58	2.20	

Figure 5.11 Results of reference run - Page 3.

TIME	COST	DAYINF	CPERDY	FIELD	GYROW	IMUWAIT	TFFWAIT	RATIO
	NEWSETS	ACNEW	DINAS	TCORREC	CORREC	GYROAS	AVAGE	
	SUBT1	SUBT12	GRMAT	GRLAB	SUBT2	SUBT3	SUBT4	
	SUBT5	SUBT6	SUBT7	SUBT8	SUBT9	SUBT10	SUBT11	
	VFECAT1	VFECAT2	VFECAT3	INFLOW	GYROTT	COST	GYROW	
4140.	133.07	3142.3	42.349	999.92	2.20	1.5433	3.995	1.0002
	.0000	3617.9	.0000	0.	0.	.022	703.57	
	28.941	18.088	11.078	18.226	1738.5	4924.8	29.304	
	400.63	23.224	3228.8	11.918	1793.4	118.91	867.6	
	.27780	.55560	.55560	2.2048	2.2048	133.07	2.20	
4320.	136.56	3322.1	41.107	999.92	2.20	1.5433	3.954	1.0002
	.0000	3617.9	.0000	0.	0.	.022	711.10	
	28.941	18.088	11.633	19.127	1838.4	5169.2	30.760	
	419.37	24.016	3413.7	12.473	1976.6	124.46	917.6	
	.27780	.55560	.55560	2.2048	2.2048	136.56	2.20	
4500.	140.05	3502.0	39.993	999.92	2.20	1.5433	3.913	1.0002
	.0000	3617.9	.0000	0.	0.	.022	713.06	
	28.941	18.088	12.189	20.028	1938.3	5413.6	32.217	
	438.11	24.808	3598.5	13.029	1959.7	130.00	967.6	
	.27780	.55560	.55560	2.2048	2.2048	140.05	2.20	
4680.	143.54	3681.8	38.988	999.92	2.20	1.5433	3.871	1.0002
	.0000	3617.9	.0000	0.	0.	.022	714.59	
	28.941	18.088	12.744	20.930	2038.2	5658.1	33.673	
	456.85	25.600	3783.4	13.584	2042.9	135.55	1017.6	
	.27780	.55560	.55560	2.2048	2.2048	143.54	2.20	
4960.	147.04	3861.6	38.076	999.92	2.20	1.5433	3.830	1.0002
	.0000	3617.9	.0000	0.	0.	.022	715.79	
	28.941	18.088	13.299	21.831	2138.1	5902.5	35.130	
	475.60	26.392	3968.2	14.140	2126.1	141.10	1067.5	
	.27780	.55560	.55560	2.2048	2.2048	147.04	2.20	
5040.	150.53	4041.4	37.246	999.92	2.20	1.5433	3.789	1.0002
	.0000	3617.9	.0000	0.	0.	.022	716.71	
	28.941	18.088	13.854	22.733	2238.0	6147.0	36.587	
	494.34	27.184	4153.1	14.695	2209.2	146.64	1117.4	
	.27780	.55560	.55560	2.2048	2.2048	150.53	2.20	
5220.	154.02	4221.2	36.486	999.92	2.20	1.5433	3.748	1.0002
	.0000	3617.9	.0000	0.	0.	.022	717.44	
	28.941	18.088	14.409	23.634	2337.9	6391.4	38.043	
	513.08	27.976	4338.0	15.251	2292.4	152.19	1167.3	
	.27780	.55560	.55560	2.2048	2.2048	154.02	2.20	
5400.	157.51	4401.1	35.788	999.92	2.20	1.5433	3.707	1.0002
	.0000	3617.9	.0000	0.	0.	.022	718.00	
	28.941	18.088	14.964	24.536	2437.8	6635.8	39.500	
	531.82	28.768	4522.8	15.806	2375.5	157.74	1217.1	
	.27780	**.55560**	**.55560**	**2.2048**	**2.2048**	**157.51**	**2.20**	

Figure 5.12 Results of reference run - Page 4.

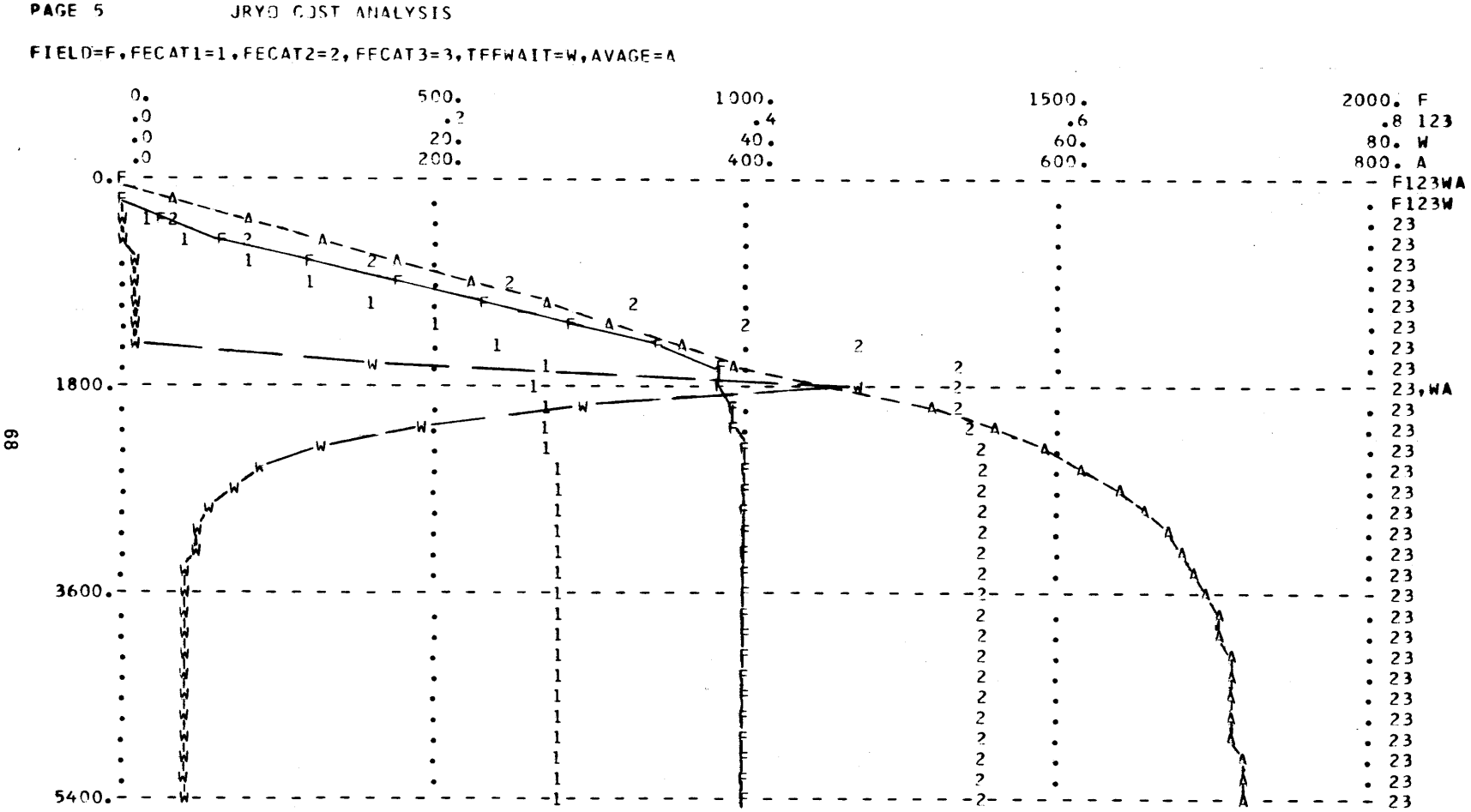

Figure 5.13 Results of reference run - Page 5.

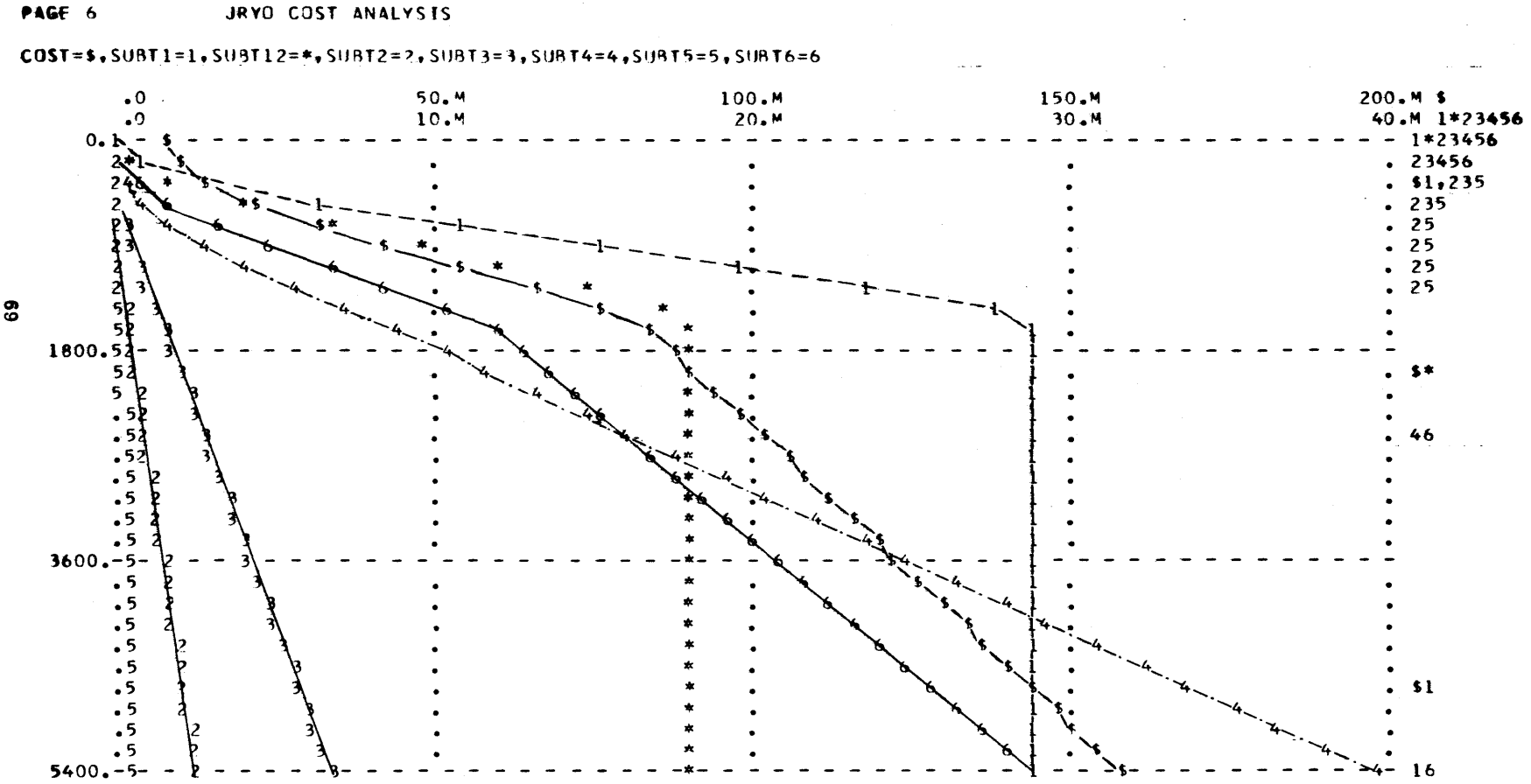

Figure 5.14 Results of reference run - Page 6.

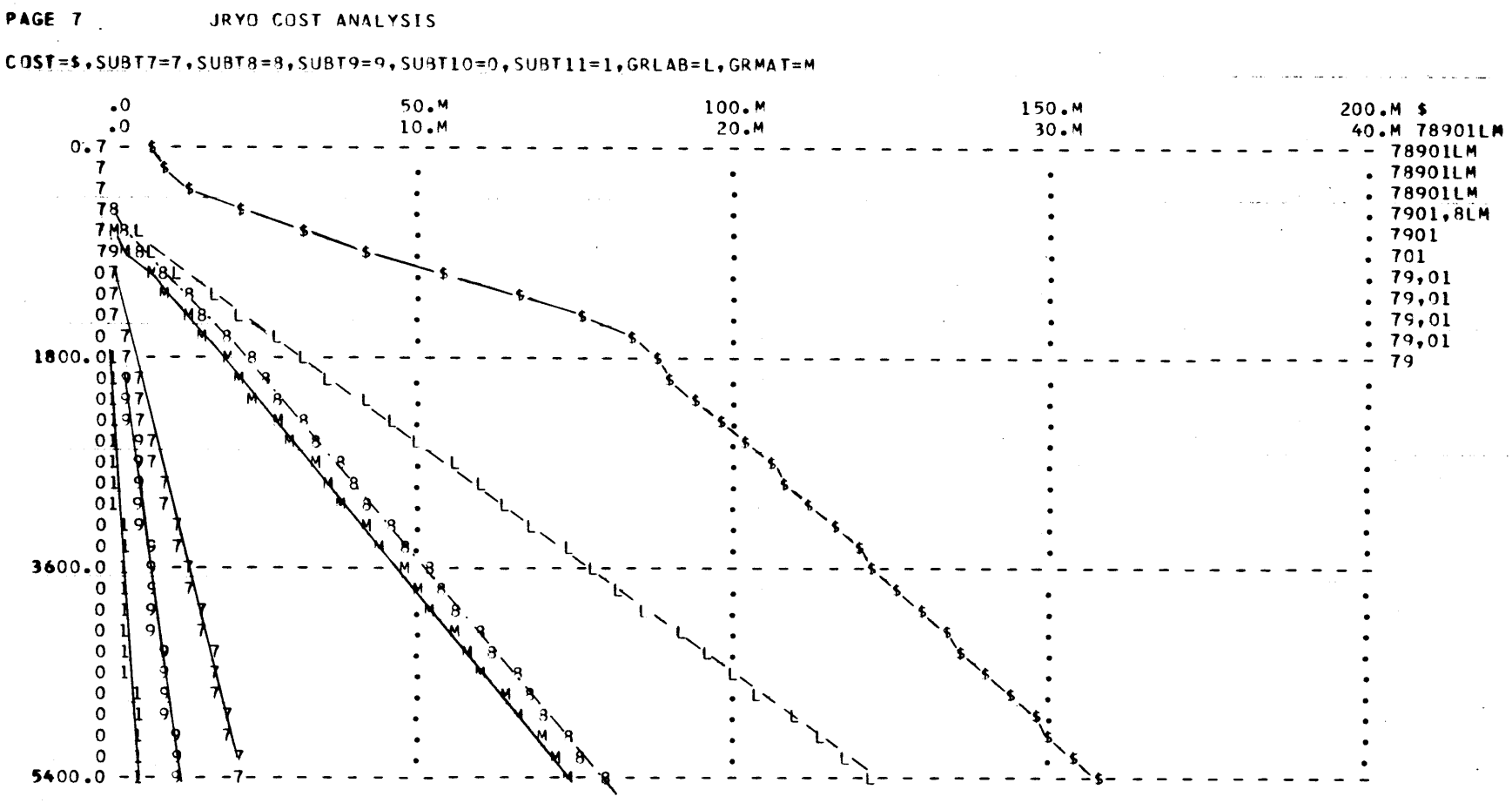

Figure 5.15 Results of reference run - Page 7.

JRYO COST ANALYSIS

GYROAS=G,TLGDIS=D,TLGREAS=R,GYROAT=T,IMUASS=S,IMUDIS=A,IMUTTA=B

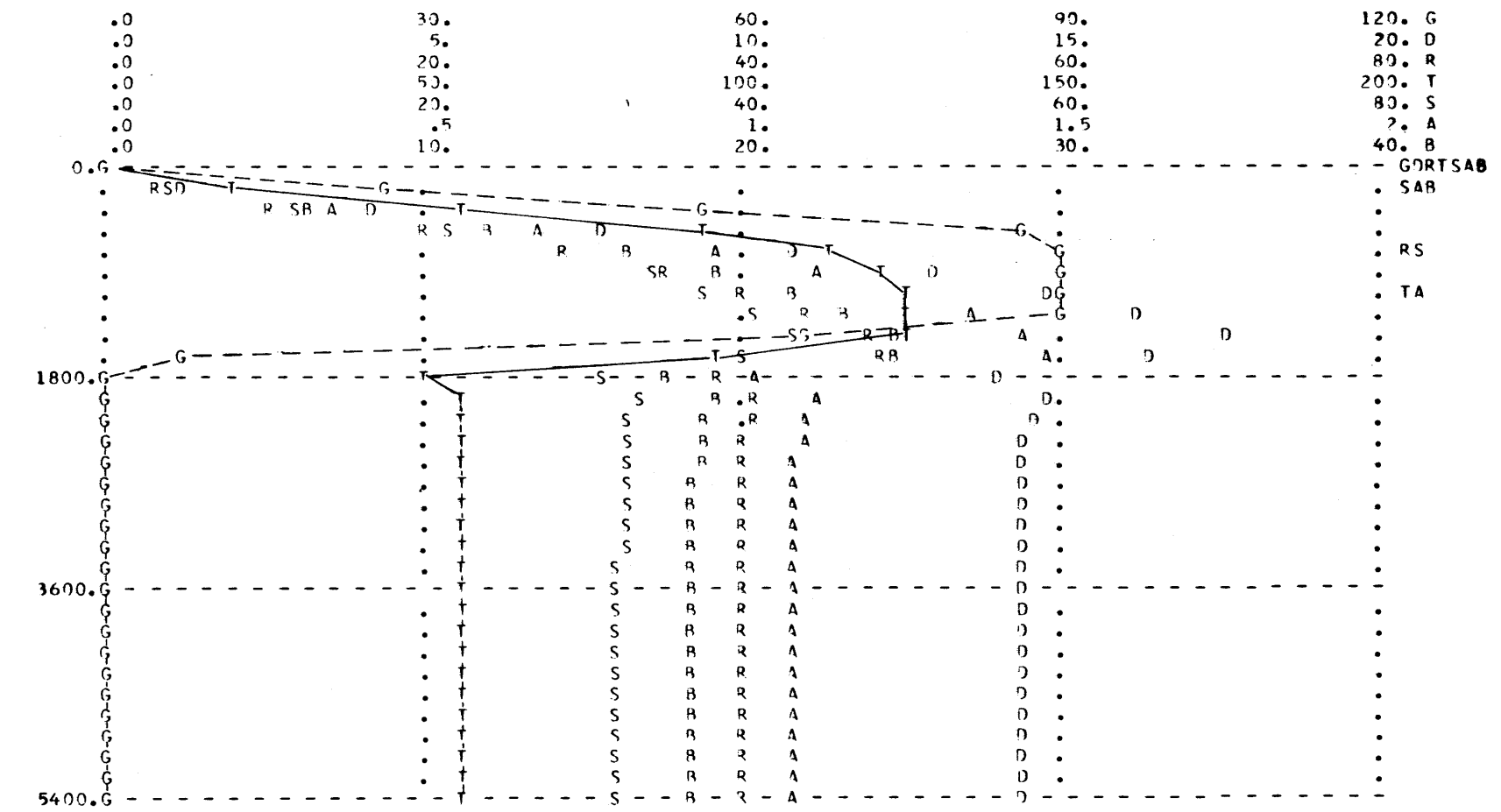

Figure 5.16 Results of reference run - Page 9.

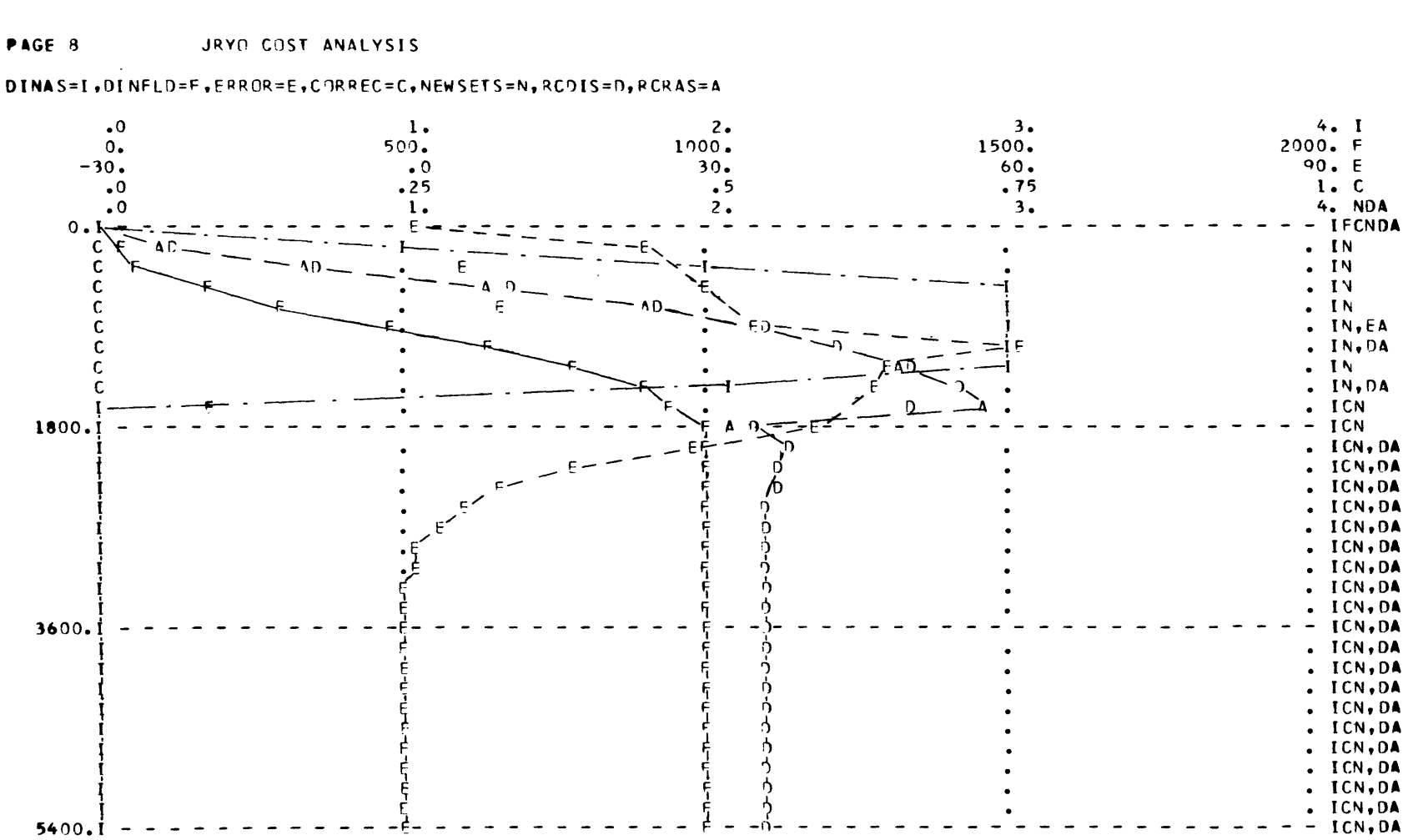

Figure 5.17 Results of reference run - Page 8.

CRYO COST ANALYSIS

IMUACC=A, IMUNACC=N, GYACC=1, GYNACC=2, ASSGYG=G, ASSGYB=B

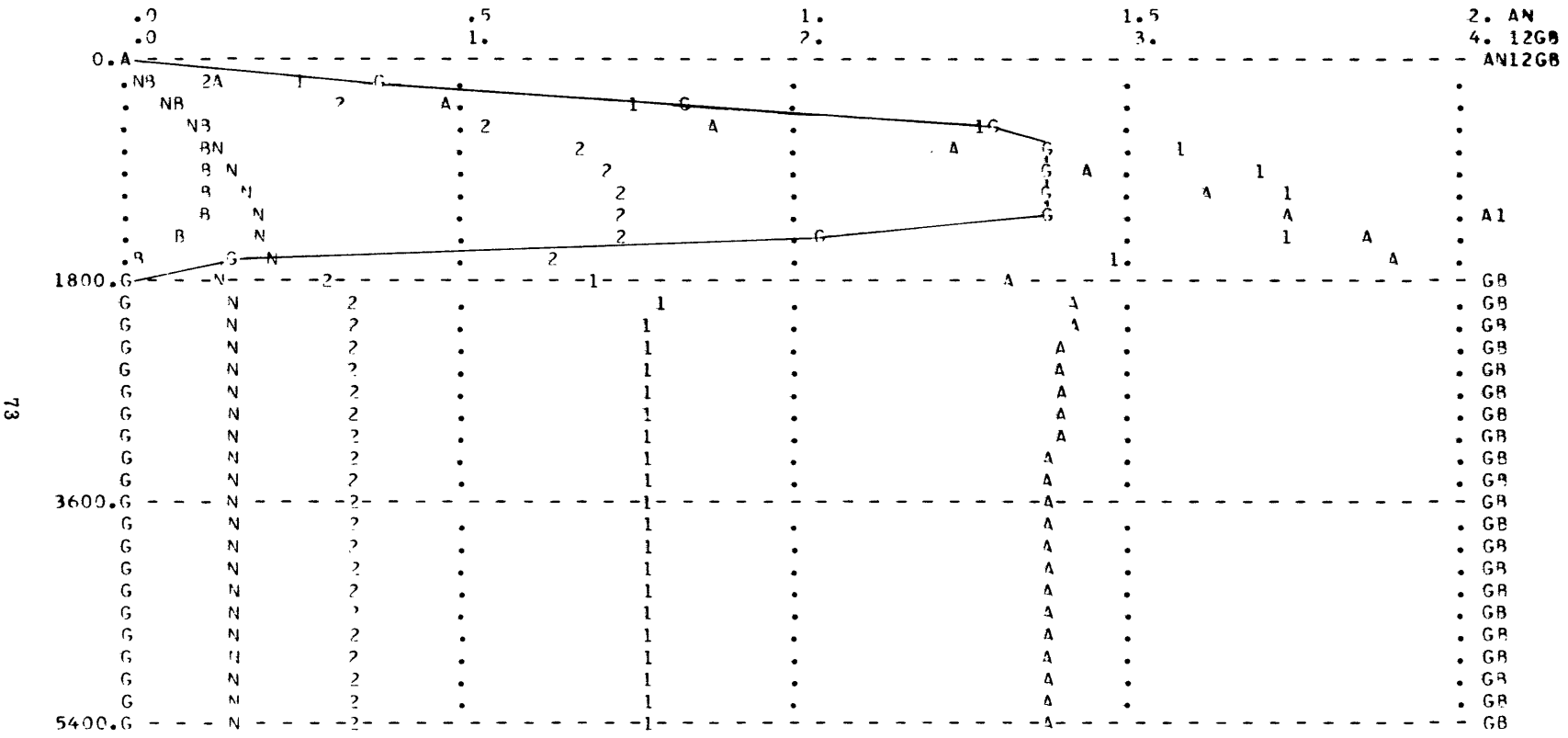

Figure 5.18 Results of reference run - Page 10.

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Chapter 6

SUMMARY AND CONCLUSIONS

This chapter contains a summary of this thesis effort, the conclusions from this effort, and recommendations for future effort.

6.1 Summary of Thesis Effort

This thesis is an investigation of the engineering and economic aspects of inertial gyros. A gyro production system was hypothesized in which gyros were assembled, tested, installed in the inertial measurement unit, sent to the field, returned from the field after failure, removed from the IMU, failure-identification tested, disassembled, reassembled, etc. A mathematical model of the system was derived which included elapsed time, material costs, labor costs, equipment costs, and yield (whenever applicable) for each operation in the hypothetical system. The model simulates the time-sequential behavior of the stable, dynamic, nonlinear system exhibiting both transient and steady-state behavior to the applied inputs and disturbances. The model of the system was developed in a digital computer program format that is easily learned, understood and applied. Data for the operation of the system were obtained informally from various industry and government sources, as well as the author's own personal experience. Many changes were introduced into the model with the objective of locating and describing the relationship between various system parameters and the gyro life-cycle costs. It is hoped that the identification of the most cost-sensitive parameters and their cost impact will assist in decisions in R & D contract allotments.

The most important contributions of this thesis are believed to be the following:

(a) A stable, dynamic, nonlinear mathematical model describing a gyro production system has been derived.

(b) Use of a simple digital computer language suitable for modeling a wide variety of systems and especially recommended for life-cycle costing studies has been demonstrated.

(c) The IMU costs attributable to the gyro have been included in the gyro life-cycle cost (LCC).

(d) A unique set of cost data and other data required to obtain meaning-

ful results from the study have been obtained and used.

(e) Additional insights into the effects of variations in program subcosts, gyro acceptance-test yields, IMU acceptance-test yields, gyro failure rates in the field, specific gyro failure rates at gyro acceptance test, etc., have been obtained.

(f) The basic model is applicable to LCC studies of the inertial-grade accelerometer and other complex engineering devices which cannot be repaired in the field. This model can be effectively expanded to accommodate a large number of additions and variations.

6.2 Conclusions

Until recent years, very few physical devices, if any, were returned to the factory (or a depot) for repairs. Those devices which are returned for repair are too complex to be serviced in the field. Such is the case for the inertial gyro. The concepts and approaches used here have shown themselves to be especially applicable to the engineering and economic aspects of inertial gyro assembly, testing, repair, reassembly, etc. This thesis has directed attention to a different model for gyro LCC which includes IMU costs attributable to the gyro; has substantiated some theories about gyro life-cycle costs; and has established a basic method and model for further research.

The specific conclusions obtained from analysis of the results are the following:

(1) The life-cycle cost is extremely sensitive to the IMU failure rates. The LCC decreases 30% ($70 x 10^6) for the reference run when the IMU failure rate decreases from 100%/yr to 50%/yr. Estimating that the R & D contract for a new gyro would require $15 x 10^6 over a period of three years, significant savings could accrue by increasing the R & D budget purchase reliability as well as size, weight and performance. The system is also sensitive to increases in failure rates during the initial production and during later times if the failure rate exceeds the maximum production rate.

(2) The partial derivative of the LCC as a function of the gyro acceptance-test yield is nearly a constant (negative constant) over the range studied (-0.3% per 1%) for the reference run.

(3) The partial derivative of the LCC as a function of the IMU acceptance-test yield is nearly a constant (negative constant) over the range studies (-1% per 1%) for the reference run.

(4) The labor cost is two-thirds of the LCC for the reference run.

(5) The total gyro assembly labor cost is 27% of the life-cycle cost for the reference run. The use of automation in gyro assembly could

pay for itself many times over in a large program.

(6) The gyro test equipment is about 5% of the LCC for the reference run and yet is a major factor in the program because it applies a constraint to the production, and because improper test equipment (and test methods) will pass "bad" gyros, thus increasing the LCC.

(7) Testing must be accomplished at the lowest possible level of assembly.

6.3 Recommendations for Future Effort

There are several areas in which future effort should be applied. Many of these efforts will result in savings greater than the investment.

(1) The R & D budget in a program should be increased to buy reliability and maintainability as well as size, weight and performance.

(2) Gyro acceptance test specifications should be stringent. Gyro failures at gyro acceptance test are less costly than gyro failures at IMU acceptance test or in the field.

(3) Gyro acceptance-test methodology should be improved to reduce the number of "bad" gyros which pass the gyro acceptance tests.

(4) The gyro assembly process should be automated in whole or in part.

(5) The model (simulation) developed in this thesis should be exploited to analyze additional specific alternatives in the management of a program.

(6) The application of the model developed in this thesis might usefully be studied by managers to obtain a clearer picture of their own production problems and production costs. Such clarification will reduce the LCC.*

Recommendations for further studies beyond this thesis are the following:

(1) Expand the model to include additional contractual provisions which affect the hardware system such as incentives for early delivery, penalties for late delivery, etc.

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* At this point, a quotation from Mason Haire, Professor of Management at the MIT Sloan School of Management, comes to mind, "Too many companies still reward executives for short-term profits. Very often a manager will not spend money on the future, and with luck he will be promoted out of his job before the future arrives. Some other guy has to live with his consequences."[22] Technology is not always the problem. We must interface with a real world full of people living on a day-to-day basis.

(2) Expand the model to include additional real constraints and costs due to personnel hiring, training, layoff, interruptions in the work schedule, test equipment breakdown, inventory cost, etc.

(3) Expand the section on gyro field failure to maintain a record of gyros which are returned to the plant for category 1 failure and for category 2 failure (assuming that a category 3 failure is repaired and returned to the field as a new gyro).

(4) Expand the failure sector of the model so that at least two failure distributions for each failure category can be included in the model at the same time. For example, especially in military programs a significant number of gyros are returned from the field for repair as a result of the steep slope of the learning curve at the beginning of a program. This is especially evident for the gas-bearing gyro where over-slewing results in characteristic spin-axis bearing damage.

(5) This study was specifically restricted to the consideration of IMU's which were sealed and unsealed only at the plant. The study could be applied to other inertial navigation and guidance systems where the gyro can be replaced in the field.

(6) There seems to be a revival of interest in the applications of control theory in the analysis of dynamic models outside of engineering.[9][27][43] Little, if anything, has been done in the application of optimal control theory.[3][7] The feasibility of applying these new techniques to the economic and industrial dynamics problems should be investigated.

APPENDIX A

PROGRAM CODES, LINE NUMBERS, AND DEFINITIONS

APPENDIX A

Program Codes, Line Numbers, and Definitions

Code	Line No.	Eqn.† Type	Definition
*		----	multiplication
A		A	auxiliary equation--a component equation of a rate equation
ACNEW	37	L	accumulated new sets of gyro parts started
ACNEW	38	N	initial value
AERROR	22	L	average error in the inventory in the field equal to the previous error +(delta time) (1/smoothing time) (error rate minus the average error)
AERROR	23	N	initial value
AMLOST	367	C	average cost of material lost during assembly per gyro
ASSGYB	52	R	rate of assembled gyros-bad
ASSGYG	50	R	rate of assembled gyros-good
AVAGE	279	A	average age of IMU's in the field in days
AVAGET	276	L	total accumulated age of IMU's in the field in days
AVAGET	277	N	initial value of total accumulated age of the IMU's in the field in days
C		C	constant
CAPAC	217	C	capacity of IMU test area in IMU's
CAPYLD	80	C	gyros per day capacity per gyro test unit
CAT1REP	324	R	IMU failure rate from waiting stack-category 1
CAT2REP	325	R	IMU failure rate from waiting stack-category 2
CAT3REP	326	R	IMU failure rate from waiting stack-category 3
CIMUDIS	420	C	IMU disassembly cost
COMPCT	366	C	component parts cost per gyro-new sets
COST	453	L	total accumulated cost of program in dollars
COST	454	N	initial value
CPERDY	469	A	cost per day in field per IMU

†A =auxiliary, C =constant, L =level, N =initial value, R =rate (Ref. 17)

Code	Line No.	Eqn. Type	Definition
CORREC	28	A	correction which equals the average error times the gain times three
DAYINF	460	L	days in field in IMU's (3 gyros per IMU)
DAYINF	461	N	initial value of days in field in IMU's
DCAT1	380	C	disassembly labor cost per gyro-category 1
DCAT2	381	C	disassembly labor cost per gyro-category 2
DCAT3	382	C	disassembly labor cost per gyro-category 3
DELAY3		—	third order delay
DFIELD	20	C	table of desired inventory in field in IMU's as a function of time
DFFCAT1	347	R	gyro field-failure rate from IMU disassembly-category 1
DFFCAT2	348	R	gyro field-failure rate from IMU disassembly-category 2
DFFCAT3	349	R	gyro field-failure rate from IMU disassembly-category 3
DINAS	11	A	desired initiation of assembly
DINFLD	17	A	desired inventory in the field in IMU's
DSTART	12	C	desired starts of new gyro sets (tabulation)
DT	479	C	delta time = solution time interval = 1 day (a) should be less than the length of the shortest first order delay and should be less than one-half of the delay (b) should be less than one-sixth the length of the shortest third-order delay
ERROR	21	R	error in inventory in field in IMU's equals desired inventory in field minus actual inventory in field
FCTR1	111	C	fraction not accepted from original test-category 1
FCTR2	138	C	fraction not accepted from original test-category 2
FCTR3	167	C	fraction not accepted from original test-category 3
FECAT1	302	R	field failures per day in gyros (one gyro per IMU)-category 1
FECAT2	303	R	field failures per day in gyros (one gyro per IMU)-category 2
FECAT3	304	R	field failures per day in gyros (one gryo per IMU)-category 3
FFCAT1	353	R	rate of gyro field failures verified-category 1
FFCAT2	354	R	rate of gyro field failures verified-category 2
FFCAT3	355	R	rate of gyro field failures verified-category 3
FIELD	270	L	actual inventory of IMU's in the field
FIELD	271	N	initial value of IMU's in the field
FSTACK	310	C	table for stacking field failures
GACAT1	117	L	gyros in reassembly-category 1

Code	Line No.	Eqn. Type	Definition
GACAT2	146	L	gyros in reassembly-category 2
GACAT3	173	L	gyros in reassembly-category 3
GACAT1	118	N	initial value of gyros in reassembly-categroy 1
GACAT2	147	N	initial value of gyros in reassembly-category 2
GACAT3	174	N	initial value of gyros in reassembly-category 3
GACTC	414	C	gyro acceptance test labor cost per gyro
GAIN	29	C	gain in the feedback loop
GARCAT1	120	R	rate of gyros reassembled-category 1
GARCAT2	150	R	rate of gyros reassembled-category 2
GARCAT3	176	R	rate of gyros reassembled-category 3
GDCAT1	108	L	gyros in disassembly-category 1
GDCAT2	135	L	gyros in disassembly-category 2
GDCAT3	165	L	gyros in disassembly-category 3
GDCAT1	109	N	initial value of gyros in disassembly-category 1
GDCAT2	136	N	initial value of gyros in disassembly-category 2
GDCAT3	166	N	initial value of gyros in disassembly-category 3
GDRCAT1	114	R	rate of gyros disassembled-category 1
GDRCAT2	141	R	rate of gyros disassembled-category 2
GDRCAT3	169	R	rate of gyros disassembled-category 3
GFVCAT1	406	C	gyro failure-identification test labor cost-category 1
GFVCAT2	407	C	gyro failure-identification test labor cost-category 2
GFVCAT3	408	C	gyro failure-identification test labor cost-category 3
GINIMU	197	R	rate of gyros into IMU
GOODFF	356	R	rate of good gyros from IMU field failures
GOODSF	250	R	rate of good gyros from IMU plant failures
GRLAB	395	L	total gyro reassembly labor cost
GRLAB	396	N	initial value
GRMAT	388	L	gyro reassembly material costs
GRMAT	389	N	initial value
GYACC	83	R	rate of gyros accepted
GYNACC	86	R	rate of gyros not accepted
GYROAS	45	L	gyros in assembly
GYROAS	46	N	initial value of gyros in assembly
GYROAT	75	L	gyros acceptance tested
GYROAT	76	N	initial value of gyros in test area
GYROTT	79	R	rate of gyros to test
GYROW	62	L	gyros waiting for test
GYROW	63	N	initial value of gyros waiting for test

Code	Line No.	Eqn. Type	Definition
IMUACC	220	R	accepted IMU rate
IMUASS	194	L	gyros in IMU assembly
IMUASS	195	N	initial value of gyros in IMU assembly
IMUASSC	447	C	IMU assembly labor cost
IMUDIS	235	L	IMU's in disassembly
IMUDIS	236	N	initial value of IMU's in disassembly
IMUDISR	238	R	IMU disassembly rate
IMUNACC	222	R	not accepted IMU rate
IMUTTA	210	L	IMU's in test area
IMUTTA	211	N	initial value of IMU's in test area
IMUTTEST	216	R	rate of IMU's to test area
IMUWAIT	204	R	rate of IMU's to wait stack for acceptance test
IMUWT	202	L	IMU's waiting for test
IMUWT	203	N	initial value of IMU's waiting for test
IMUYLD	224	C	IMU test yield ratio-good IMU's
INCAT1	103	R	gyro input rate to disassembly-category 1
INCAT2	129	R	gyro input rate to disassembly-category 2
INCAT3	160	R	gyro input rate to disassembly-category 3
INFLOW	61	R	gyro flow into GYROW
L		L	level equation: levels are the varying contents of the reservoirs
LENGTH	478	C	length of program in days-5400 days (15 years)
LSSRT	53	C	parts loss rate
MAXFLD	463	C	maximum desired IMU's in field
N		N	initial value of a level equation
NASLCST	373	C	assembly labor cost per gyro using new set of parts
NEWSETS	35	R	rate of actual new sets of parts for gyros
OTHER	458	C	other tools and equipment cost
P1	450	R	partial cost rate # 1
P2	451	R	partial cost rate # 2
P3	452	R	partial cost rate # 3
PFECAT1	292	A	probability of field failures (per year)-category 1
PFECAT2	295	A	probability of field failures (per year)-category 2
PFECAT3	298	A	probability of field failures (per year)-category 3
PLTPER	481	C	plot period
PRTPER	480	C	print period
R		R	rate equations define the rates of flow between the levels
RATIO	309	A	ratio of failures-to-stack vs failures-to-repair

Code	Line No.	Eqn. Type	Definition
RCAT1	397	C	gyro reassembly labor cost per gyro- category 1
RCAT2	398	C	gyro reassembly labor cost per gyro- category 2
RCAT3	399	C	gyro reassembly labor cost per gyro- category 3
RCDIS	186	A	total rate of gyros disassembled
RCRAS	187	A	total rate of gyros reassembled
RFIELD	462	R	RFIELD.KL=FIELD.K
RGRLAB	394	R	reassembly labor cost rate
RGRMAT	387	R	reassembly material cost rate
RMCAT1	390	C	gyro reassembly material cost per gyro-category 1
RMCAT2	391	C	gyro reassembly material cost per gyro-category 2
RMCAT3	392	C	gyro reassembly material cost per gyro-category 3
RSUBT1	363	R	component purchase and lost material cost rate
RSUBT2	423	R	IMU field failure verification test labor cost rate
RSUBT3	377	R	gyro disassembly labor cost rate
RSUBT5	403	R	gyro failure identification labor cost rate
RSUBT6	411	RΠ	gyro acceptance test labor cost rate
RSUBT7	433	R	gyro field failure identification labor cost rate
RSUBT8	438	R	IMU acceptance test labor cost rate
RSUBT9	444	R	IMU assembly labor cost rate
RSUBT10	417	R	IMU disassembly labor cost rate
RSUBT11	429	R	IMU field failure diassembly cost rate
RSUBT12	370	R	assembly labor cost rate for new sets
S	290	C	switch function
SDGCAT1	247	R	rate of gyros from IMU disassembly - category 1
SDGCAT2	248	R	rate of gyros from IMU disassembly - category 2
SDGCAT3	249	R	rate of gyros from IMU disassembly - category 3
SFCTR1	260	C	fraction of failed gyros from failed IMU's tests-category 1
SFCTR2	261	C	fraction of failed gyros from failed IMU's tests-category 2
SFCTR3	262	C	fraction of failed gyros from failed IMU's tests-category 3
SGOK	258	C	two good gyros in each failed IMU by assumption
STCOST	441	C	IMU acceptance test labor cost
STKCAT1	314	L	field failures in stack-category 1
STKCAT1	315	N	initial value
STKCAT2	316	L	field failures in stack-category 2
STKCAT2	317	N	initial value
STKCAT3	318	L	field failures in stack-category 3
STKCAT3	319	N	initial value

Code	Line No.	Eqn. Type	Definition
SUBT1	364	L	subtotal cost of component purchase and parts lost in new-sets assembly
SUBT1	365	N	initial subtotal cost
SUBT2	424	L	subtotal cost of IMU field-failure identification test labor
SUBT2	425	N	initial value
SUBT3	378	L	subtotal cost of gyro disassembly labor
SUBT3	379	N	initial value
SUBT4	400	A	subtotal cost of gyro reassembly for all three categories (labor plus material)
SUBT5	404	L	subtotal cost of gyro plant-failure identification test labor
SUBT5	405	N	initial value
SUBT6	412	L	subtotal cost of gyro acceptance test labor
SUBT6	413	N	initial value
SUBT7	434	L	subtotal cost of gyro field-failure identification labor
SUBT7	435	N	initial value
SUBT8	439	L	subtotal cost of IMU acceptance test labor
SUBT8	440	N	initial value
SUBT9	445	L	subtotal cost of IMU assembly labor
SUBT9	446	N	initial value
SUBT10	418	L	subtotal cost of IMU disassembly labor cost, plant-failures from IMU acceptance test
SUBT10	419	N	initial value
SUBT11	430	L	subtotal cost of IMU field-failure disassembly labor
SUBT11	431	N	initial value
SUBT12	371	L	subtotal cost of assembly labor-new sets
SUBT12	372	N	initial value
T1	293	C	probability of failure as a function of age in the field
T2	296	C	probability of failure as a function of age in the field
T3	299	C	probability of failure as a function of age in the field
TABHL	11		table
TASC1	121	C	time to reassemble gyros-category 1
TASC2	151	C	time to reassemble gyros-category 2
TASC3	177	C	time to reassemble gyros-category 3
TASGYRO	51	C	time to assemble gyros
TASIMU	198	C	time to assemble gyros into IMU

Code	Line No.	Eqn. Type	Definition
TCAP	69	C	capacity of gyro acceptance-test area
TCCOST	455	C	cost per unit of gyro test capacity
TCORREC	32	A	actual correction
TDCAT2	142	C	time to disassemble gyros-category 2
TDCAT3	170	C	time to disassemble gyros-category 3
TDISS	239	C	time to disassemble IMU's
TFFWAIT	331	A	total IMU's waiting for repair
TGYAT	84	C	time for gyro acceptance test
TIME	80	—	time is in days
TIMEVAR	291	A	time variation for IMU's in the field (in years)
TIMUV	426	C	cost per IMU field failure verification test
TLGDIS	182	A	total gyros disassembled level
TLGREAS	183	A	total gyros reassembled level
TOTBRK	328	R	total failure rate of IMU's in the field (one gyro per IMU)
TSMTH	24	C	exponential smoothing time constant for error in the field inventory in days
TTIMU	221	C	time to test IMU's
TVCAT1	253	C	time to verify category 1 gyros from disassembly
TVCAT2	254	C	time to verify category 2 gyros from disassembly
TVCAT3	255	C	time to verify category 3 gyros from disassembly
TVER	338	C	time to do IMU failure-verification test
TVGOOD	256	C	time to verify good gyro from IMU failure
VFECAT1	335	R	rate of IMU verified field failures-category 1
VFECAT2	336	R	rate of IMU verified field failures-category 2
VFECAT3	337	R	rate of IMU verified field failures-category 3
YIELD	85	C	fraction of gyros accepted at acceptance test

APPENDIX B

THE PROGRAM

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FILE: PETER1   DYNAMC   P1                MASSACHUSETTS INSTITUTE OF TECHNOLOGY

NOTE  PETER PALMER      MARCH 1970                                              PET00010
NOTE  GYRO CCST STUDY                                                           PET00020
NOTE                                                                            PET00030
NOTE                                                                            PET00040
NOTE                                                                            PET00050
NOTE  DESIRED INITIATION OF ASSEMBLY                                            PET00060
NOTE  SET BY SCHEDULE AT BEGINNING OF PROJECT                                   PET00070
NOTE  TIME IN DAYS THROUGHOUT THIS MODEL                                        PET00080
NOTE  IMPORTANT TO KEEP UNITS STRAIGHT                                          PET00090
NOTE  TIME/180 IS TIME IN HALF YEARS                                            PET00100
A  DINAS.K=TABHL(DSTART,(TIME.K)/180,0,14,1)                                    PET00110
C  DSTART*=0/1/2/3.0/3.0/3.0/3.0/3.0/2.1/0/0/0/0/0  TAB FOR DES STARTS          PET00120
NOTE  DESIRED STARTS PER DAY SPECIFIED AT 6 MONTHS INTERVALS                    PET00130
NOTE                                                                            PET00140
NOTE  CORRECTION FACTOR INDICATED-- DIFFERENCE BETWEEN ACTUAL FIELD INV.        PET00150
NOTE  AND SCHEDULED IN FIELD INVENTORY                                          PET00160
A  DINFLD.K=TABHL(DFIELD,(TIME.K)/360,0,6,1)                                    PET00170
NOTE  TIME/360 IS IN YEARS--TABLE SPECIFIES NUMBER OF UNITS DESIRED             PET00180
NOTE  IN FIELD INVENTORY                                                        PET00190
C  DFIELD*=1/60/300/650/900/1000/1000                                          PET00200
R  ERROR.KI=DINFLD.K-FIELD.K     DISCREPENCY BETWEEN DESIRED AND ACTUAL         PET00210
L  AERROR.K=AERROR.J+(DT)(1/TSMTH)(ERROR.JK-AERROR.J)  SMOOTHING EQUATIO        PET00220
N  AERROR=0                                                                     PET00230
C  TSMTH=30   SMOOTHING TIME FOR ERROR                                          PET00240
NOTE                                                                            PET00250
NOTE    CORRECTION SIGNAL TO DESIRED INITIATION OF NEW PRODUCTION               PET00260
NOTE      REMEMBER 3 GYROS PER IMU                                              PET00270
A  CORREC.K=AERROR.K*3*GAIN  CORRECTION FACTOR                                  PET00280
C  GAIN=.000   GAIN ON CORRECTION LOOP                                          PET00290
NOTE                                                                            PET00300
NOTE  IMPOSSIBLE TO MAKE CORRECTION BEFORE 1 1/2 YEARS                          PET00310
A  TCORREC.K=CLIP(CORREC.K,C,TIME.K/360,1.5)  ACTUAL CORRECTION                 PET00320
NOTE     STARTS AFTER EIGHTEEN MONTHS                                           PET00330
NOTE  TOTAL STARTS-- SCHEDULED STARTS PLUS CORRECTION FACTOR                    PET00340
R  NEWSETS.KL=MAX(DINAS.K+TCORREC.K,C)    STARTS    ACTUAL NE                 PET00350
NOTE  ACCUMULATED TOTAL NEW SETS STARTED                                        PET00360
L  ACNEW.K=ACNEW.J+(DT)(NEWSETS.JK)  NEW SETS OF GYROS                          PET00370
N  ACNEW=0   INITIAL VALUE ACCUMULATED NEW SETS GYROS STARTED                   PET00380
NOTE                                                                            PET00390
NOTE  GYROS IN ASSEMBLY-- IN PROCESS INVENTORY                                  PET00400
NOTE                                                                            PET00410
NOTE  INFLOW IS MANAGEMENT DECISION--INITIAL COMPONENTS TO                      PET00420
NOTE  ASSEMBLY.  OUTFLOW IS ASSEMBLED COMPONENTS AND REJECTED                   PET00430
NOTE  COMPONENTS--ASSEMBLED GYROS GOOD(ASSGYG) AND BAD(ASSGYB)                  PET00440
L  GYROAS.K=GYROAS.J+(DT)(NEWSETS.JK-ASSGYG.JK-ASSGYB.JK)                       PET00450
N  GYROAS=0  INITIAL VALUE GYROS IN ASSEMBLY                                    PET00460
NOTE                                                                            PET00470
NOTE  ASSEMBLED GYROS APPEAR AFTER A DELAY IN FABRICATION                       PET00480
NOTE  A FRACTION (LSSRT-LOSS RATE)  OF INPUT IS REJECTED                        PET00490
R  ASSGYG.KI=DELAY3(NEWSETS.JK,TASGYRO)*(1-LSSRT)  GOOD GYROS                   PET00500
C  TASGYRO=30   TIME TO  ASSEMBLY GYROS                                         PET00510
R  ASSGYB.KI=DELAY3(NEWSETS.JK,TASGYRO)*(LSSRT)  BAD GYROS                      PET00520
C  LSSRT=.08  PARTS LOSS RATE                                                   PET00530
NOTE                                                                            PET00540
NOTE  GYROS WAITING FOR ACCEPTANCE TEST                                         PET00550
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PAGE 001

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NOTE    THERE MAY BE BACKLOG FOR TESTING                                    PET00560
NOTE      TESTING REQUIRES LARGE  INVESTMENT PER CAPACITY                   PET00570
NOTE    TWO INPUTS TO LEVEL- NEWLY ASSEMBLED GYROS (ASSGYG) AND RETURNS     PET00580
NOTE      FROM GYROS REASSEMELY CATEG 1,2,3 (GARCAT1, GARCAT2,GARCAT3)      PET00590
NOTE  OUTFLOW IS GYROS MOVED INTO GYRO TEST AREA                            PET00600
R  INFLOW.KL=ASSGYG.JK+GARCAT1.JK+GARCAT2.JK+GARCAT3.JK  TOTAL INFLOW       PET00610
L  GYROW.K=GYROW.J+(DT)(INFLOW.JK-GYROTT.JK)  GYROS WAITING FOR TEST        PET00620
N  GYROW=0  INITIAL VALUE GYROS WAITING FOR TEST                            PET00630
NOTE                                                                        PET00640
NOTE  GYRO ACCEPTANCE TEST                                                  PET00650
NOTE                                                                        PET00660
NOTE  TCAP IS TESTING CAPACITY OF GYRO ACCEPT TEST AREA                     PET00670
NOTE       NUMBER OF GYROS THAT CAN FIT IN AREA AT ANY TIME                 PET00680
C  TCAP=25      TESTING CAPACITY  IN GYRO TEST AREA                         PET00690
NOTE  NUMBER OF CAPACITY UNITS (300K) EACH GOOD FOR 6 GYROS A MONTH         PET00700
NOTE                                                                        PET00710
NOTE  GYROS IN TEST AREA INCREASED BY GYROS MOVED TO TEST (GYROTT)          PET00720
NOTE       DECREASED BY GYROS TESTED AND ACCEPTED (GYACC)                   PET00730
NOTE        AND BY GYROS TESTED AND NOT ACCEPTED (GYNACC)                   PET00740
L  GYROAT.K=GYROAT.J+(DT)(GYROTT.JK-GYACC.JK-GYNACC.JK)                     PET00750
N  GYROAT=0   INITIAL VALUE GYROS IN TEST AREA                              PET00760
NOTE                                                                        PET00770
NOTE  WILL MOVE AS MANY AS POSSIBLE OF WAITING GYROS TO TESTING AREA        PET00780
R  GYROTT.KL=MIN(TCAP*CAPYLL,GYROW.K)  GYROS TO TESTING AREA                PET00790
C  CAPYLL=.2   6 GYROS/MONTH CAP PER CAPACITY UNIT-.2/DAY                   PET00800
NOTE                                                                        PET00810
NOTE  ACCEPTANCE TEST ACCEPTS OR REJECTS GYROS                              PET00820
R  GYACC.KL=DELAY3(GYROTT.JK,TGYAT)*YIELD                                   PET00830
C  TGYAT=25  TIME FOR GYRO ACC. TEST                                        PET00840
C  YIELD=.7  FRACTION GYROS ACCEPTED                                        PET00850
R  GYNACC.KL=DELAY3(GYROTT.JK,TGYAT)*(1-YIELD)  NOT ACCEP.                 PET00860
NOTE                                                                        PET00870
NOTE                                                                        PET00880
NOTE                                                                        PET00890
NOTE  GYRO DISASSEMBLY SECTOR                                               PET00900
NOTE  REJECTED GYROS FALL INTO 3 CATEGORIES                                 PET00910
NOTE                                                                        PET00920
NOTE                                                                        PET00930
NOTE  IN EACH CATEGORY THERE ARE REJECTED GYROS FROM THE ORIGINAL           PET00940
NOTE       GYRO TEST , REJECTED GYROS FROM IMU  TEST, AND REJECTED          PET00950
NOTE        GYROS FROM FIELD FAILURES                                       PET00960
NOTE                                                                        PET00970
NOTE  CATEGORY 1  OUTSIDE MAIN HOUSING                                      PET00980
NOTE                                                                        PET00990
NOTE  GYROS IN DISASSEMBLY CATEGORY 1                                       PET01000
NOTE      THREE SOURCES                                                     PET01010
NOTE      GYROS NOT ACCEPTED FROM GYRO TEST ARE DIVIDED BETWEEN             PET01020
R  INCAT1.KL=GYNACC.JK*FCTR1+SDGCAT1.JK+FFCAT1.JK  INFLOW TO DIS. CAT1      PET01030
NOTE      GYNACC*FCTR1 FROM ORIGINAL GYRO TEST                              PET01040
NOTE       SDGCAT1 FROM IMU  TEST FAILURES (CAT1)                           PET01050
NOTE       FFCAT1    FROM FIELD FAILURES                                    PET01060
NOTE                                                                        PET01070
L  GDCAT1.K=GDCAT1.J+(DT)(INCAT1.JK-GDRCAT1.JK) CAT1 DISASSEMBLY            PET01080
N  GDCAT1=0   INITIAL VALUE                                                 PET01090
NOTE                                                                        PET01100
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C  FCTR1=.3  FRACTION NOT ACCEPTED FROM ORIG TEST TO CAT 1                PET01110
NOTE                                                                     PETC1120
NOTE     RATE OF DISASSEMBLY CAT1                                        PET01130
R  GDRCAT1.KL=INCAT1.JK    SMALL DELAY IN DISASS CAT1                    PET01140
NOTE                                                                     PET01150
NOTE  GYRO RE-ASSEMBLY CATEGORY 1                                        PET01160
L  GACAT1.K=GACAT1.J+(DT)(GDRCAT1.JK-GARCAT1.JK)                         PETC1170
N  GACAT1=0  INITIAL VALUE GYRO REASSEMBLY CATEGORY 1                    PET01180
NOTE  GYRO REASSEMBLY RATE CATEGORY 1                                    PET01190
R  GARCAT1.KL=DELAY3(GDRCAT1.JK,TASC1) GYRO REASSEMBLY CAT 1             PETC1200
C  TASC1=9   TIME TO RE ASSEMBLE CATEGORY 1 GYRO FAILURE                 PET01210
NOTE                                                                     PET01220
NOTE                                                                     PET01230
NOTE  CATEGORY 2  MAIN HOUSING TO FLOAT                                  PET01240
NOTE                                                                     PETC1250
NOTE  GYROS IN DISASSEMBLY CATEGORY 2                                    PET01260
NOTE  INFLOW AGAIN HAS THREE COMPONENTS                                  PETC1270
NOTE  SEE DESCRIPTION FOR CATEGORY 1 ABOVE                               PET01280
R  INCAT2.KL=GYNACC.JK*FCTR2+SDGCAT2.JK+FFCAT2.JK                        PET01290
NOTE      GYNACC*FCTR2  FROM ORIGINAL GYRO TEST NO ACCEPT                PET01300
NOTE       SDGCAT2  FROM IMU  TEST FAILURES                              PET01310
NOTE       FFCAT2 FROM FIELD FAILURES                                    PETC1320
NOTE                                                                     PETC1330
NOTE  GYROS IN DISASSEMBLY CATEGORY 2                                    PET01340
L  GDCAT2.K=GDCAT2.J+(DT)(INCAT2.JK-GDRCAT2.JK)                          PETC1350
N  GDCAT2=0  INITIAL VALUE GYROS IN DISASSEMBLY CATEGORY 2               PET01360
NOTE                                                                     PETC1370
C  FCTR2=.6  FRACTION ORIGN. GYRO ACC. REJECTS TO CATEG 2                PETC1380
NOTE                                                                     PET01390
NOTE  GYRO DISASSEMBLY RATE CATEGORY 2                                   PETC1400
R  GDRCAT2.KL=DELAY3(INCAT2.JK,TDCAT2) GYRO DISAS RATE CATEG2            PET01410
C  TDCAT2=7  TIME TO DISASSEMBLY CATEG 2 GYRO FAILURES                   PETC1420
NOTE                                                                     PETC1430
NOTE  CAT 2 REASSEMBLY LEVEL                                             PET01440
NOTE  GYROS IN REASSEMBLY CATEGORY 2                                     PETC1450
L  GACAT2.K=GACAT2.J+(DT)(GDRCAT2.JK-GARCAT2.JK)                         PETC1460
N  GACAT2=0  INITIAL VALUE  GYROS IN REASSEMBLY CATEGORY 2               PET01470
NOTE                                                                     PET01480
NOTE  GYRO REASSEMBLY RATE CATEGORY 2                                    PET01490
R  GARCAT2.KI=DELAY3(GDRCAT2.JK,TASC2)  REASSEMBLY RATE CAT 2            PET01500
C  TASC2=15  TIME TO RE-ASSEMBLE CATEGORY 2                              PETC1510
NOTE                                                                     PET01520
NOTE                                                                     PET01530
NOTE  CATEGORY 3  INSIDE FLOAT                                           PETC1540
NOTE                                                                     PET01550
NOTE  GYROS IN DISASSEMBLY CATEGORY 3                                    PET01560
NOTE  THREE SOURCES-- SEE DESCRIPTION FOR CATEGORY 1 ABOVE               PET01570
NOTE                                                                     PETC1580
NOTE  TOTAL INFLOW TO GYRO DISASSEMBLY CATEGORY 3                        PETC1590
R  INCAT3.KL=GYNACC.JK*FCTR3+SDGCAT3.JK+FFCAT3.JK                        PET01600
NOTE        GYNACC*FCTR3 FROM ORIGINAL GYRO TEST REJECTS                 PET01610
NOTE  SDGCAT3 FROM IMU  TEST FAILURES                                    PET01620
NOTE  FFCAT3  FROM FIELD TEST FAILURES                                   PET01630
NOTE                                                                     PET01640
L  GDCAT3.K=GDCAT3.J+(DT)(INCAT3.JK-GDRCAT3.JK)  GYROS IN DISASM CAT3    PETC1650
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N  GDCAT3=0  INITIAL VALUE GYROS IN DISSASSEMBLY CATEGORY 3                    PET01660
C  FCTR3=.1  FRACTION OBIG REJECTS GYRO ACC TEST TO CAT 3                     PET01670
NOTE                                                                          PET01680
R  GDRCAT3.KL=DELAY3(INCAT3.JK,TDCAT3) DIS. RATE FOR CATEGORY 3               PET01690
C  TDCAT3=10  TIME TO DISASSEMBLE CATEGORY 3                                  PET01700
NOTE                                                                          PET01710
NOTE  GYROS IN REASSEMBLY CATEGORY 3                                          PET01720
L  GACAT3.K=GACAT3.J+(DT)(GDRCAT3.JK-GARCAT3.JK)                              PET01730
N  GACAT3=0  INITIAL VALUE                                                    PET01740
NOTE                                                                          PET01750
R  GARCAT3.KL=DELAY3(GDRCAT3.JK,TASC3)  REASSEMBLY CAT 3                      PET01760
C  TASC3=30  TIME TO BE ASSEMBLE CATEGORY 3                                   PET01770
NOTE                                                                          PET01780
NOTE  SUPPLEMENTARY EQUATIONS FOR OUTPUT                                      PET01790
NOTE                                                                          PET01800
NOTE  TOTAL GYROS IN DISASSEMBLY -- OUTPUT VARIABLE                           PET01810
A  TIGDIS.K=GDCAT1.K+GDCAT2.K+GDCAT3.K  TOTAL GYROS IN DISASS                 PET01820
A  TLGREAS.K=GACAT1.K+GACAT2.K+GACAT3.K  TOTAL GYROS IN REASSEM               PET01830
NOTE                                                                          PET01840
NOTE  TOTAL DISSASSEMBLY AND REASSEMBLY RATES                                 PET01850
A  RCDIS.K=GDRCAT1.JK+GDRCAT2.JK+GDRCAT3.JK                                   PET01860
A  RCRAS.K=GARCAT1.JK+GARCAT2.JK+GARCAT3.JK                                   PET01870
NOTE                                                                          PET01880
NOTE  GYROS IN IMU  ASSEMBLY                                                  PET01890
NOTE  ACCEPTABLE GYROS FROM GYRO ACCEPTANCE TEST (GYACC)                      PET01900
NOTE  PLUS ANY GOOD GYROS FROM IMU  TEST FAILURE DISASSEMBLY (GCODSF)         PET01910
NOTE  PLUS ANY GOOD GYROS FROM FIELD FAILURE DISASSEMBLY (GOODFF)             PET01920
NOTE  ARE FABRICATED INTO IMUS-- PROCESS DELAY IS GYROS IN IMUS               PET01930
L  IMUASS.K=IMUASS.J+(DT)(GYACC.JK+GCODSF.JK+GCODFF.JK-GINIMU.JK)             PET01940
N  IMUASS=0 INITIAL VALUE                                                     PET01950
NOTE                                                                          PET01960
R  GINIMU.KL=DELAY3(GYACC.JK+GOODSF.JK+GCODFF.JK,TASIMU)  GYROS INTO IMU      PET01970
C  TASIMU=7  TIME TO ASSEMBLE GYROS INTO IMUS                                 PET01980
NOTE                                                                          PET01990
NOTE  STACK FOR IMU  ACCEPTANCE TESTS                                         PET02000
NOTE  MUST EXPRESS INFLOW IN TERMS OF IMUS - 3 GYROS/IMU                      PET02010
L  IMUWT.K=IMUWT.J+(DT)(IMUWAIT.JK-IMUTTST.JK) IMUS WAITING                   PET02020
N  IMUWT=0  INITIAL VALUE IMUS WAITING FOR IMUS TEST                          PET02030
R  IMUWAIT.KL=GINIMU.JK/3  IMUS TO WAIT STACK-- 3 GYROS PER IMU               PET02040
NOTE                                                                          PET02050
NOTE                                                                          PET02060
NOTE  IMUS IN TEST AREA                                                       PET02070
NOTE  MOVE IN IMUS WAITING TO BE TESTED. OUTFLOW IS OK IMUS                   PET02080
NOTE  (IMUACC) AND REJECTED IMUS (IMUNACC)                                    PET02090
L  IMUTTA.K=IMUTTA.J+(DT)(IMUTTST.JK-IMUACC.JK-IMUNACC.JK) IMU IN TEST        PET02100
N  IMUTTA=0  INITIAL VALUE IMUS IN TEST AREA                                  PET02110
NOTE                                                                          PET02120
NOTE  WILL MOVE INTO TEST AREA AS MANY IMUS AS POSSIBLE                       PET02130
NOTE  BUT THERE MAY BE A CAPITAL/CAPACITY CONSTRAINT                          PET02140
NOTE  CAPAC IS CAPACITY OF TEST AREA                                          PET02150
R  IMUTTST.KL=MIN(IMUWT.K,CAPAC)  IMUS TO TEST AREA RATE                      PET02160
C  CAPAC=10  CAPACITY OF IMUS TEST AREA IN IMUS                               PET02170
NOTE                                                                          PET02180
NOTE  OUTPUT OF IMUS TEST IS ACCEPT. IMUS AND REJECTED IMUS                   PET02190
R  IMUACC.KL=DELAY3(IMUTTST.JK,TTIMU)*IMUYLD  ACCEPTED IMUS                   PET02200
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C  TTIMU=12  TIME TO TEST IMUS                                          PET02210
R  IMUNACC.KL=DELAY3(IMUTTST.JK,TTIMU)*(1-IMUYLD)                       PET02220
NOTE                                                                    PET02230
C  IMUYLD=.9   IMU  TEST YIELD RATIO--GOOD IMUS                         PET02240
NOTE                                                                    PET02250
NOTE                                                                    PET02260
NOTE  IMU  TEST REJECTS ARE DISASSEMBLED (REMEMBER 3 GYROS/IMU )        PET02270
NOTE  AND SEPARATED INTO  FAILURE CATEGORIES 1,2,3 FOR GYRO DISSASSEMBLYPET02280
NOTE                                                                    PET02290
NOTE                                                                    PET02300
NOTE  IMUS DISASSEMBLY                                                  PET02310
NOTE      INFLOW IS NOT ACCETPED IMUS FROM IMU  TEST                    PET02320
NOTE       OUTFLOW IS IMU  DISASSEMBLY RATE                             PET02330
NOTE                                                                    PET02340
L  IMUDIS.K=IMUDIS.J+(DT)(IMUNACC.JK-IMUDISR.JK)                        PET02350
N  IMUDIS=0  INITIAL VALUE IMU  DISASSEMELY                             PET02360
NOTE                                                                    PET02370
R  IMUDISR.KL=DELAY3(IMUNACC.JK,TDISS)  IMU  DISASS RATE                PET02380
C  TDISS=7    TIME TO DISASSEMBLE IMUS                                  PET02390
NOTE                                                                    PET02400
NOTE  SORT CATEGORIES                                                   PET02410
NOTE     IMU  DISSASSEMBLIES DIVIDED TO GYRO FAILURE TYPES              PET02420
NOTE     AFTER GYRO FAILURE VERIFICATION DELAY                          PET02430
NOTE     FACTORS SFCAT1, SFCAT2, SFCAT3 SORT IMU  FAILURES              PET02440
NOTE    INTO APPROPRIATE GYRO FAILURE CATEGORIES                        PET02450
NOTE                                                                    PET02460
R  SIGCAT1.KL=DELAY3(SFCTR1*IMUDISR.JK,TVCAT1)  CAT1 BAD GYROS          PET02470
R  SDGCAT2.KI=DELAY3(SFCTR2*IMUDISR.JK,TVCAT2)  CAT2 BAD GYROS          PET02480
R  SIGCAT3.KL=DELAY3(SFCTR3*IMUDISR.JK,TVCAT3)   CAT3 BAD GYROS         PET02490
R  GOODSF.KL=DELAY3(SGOK*IMUDISR.JK,TVGOOD)  GOOD GYROS FROM IMU  FAIL  PET02500
NOTE                                                                    PET02510
NOTE      DELAY TIMES FOR GYRO VERIFICATION                             PET02520
C  TVCAT1=7  TIME VERIF. CAT1 GYRO FAILURE                              PET02530
C  TVCAT2=8  TIME VERIF. CAT2 GYRO FAILURE                              PET02540
C  TVCAT3=8  TIME VERIF. CAT3 GYRO FAILURE                              PET02550
C  TVGOOD=7  TIME VERIF. GOOD GYRO IS IMU FAILURE                       PET02560
NOTE                                                                    PET02570
C  SGOK=2    TWO GOOD GYROS IN EVERY IMU  BY ASSUMPTION                 PET02580
NOTE    CATEGORY FAILURE PERCENTAGES FROM IMU  TEST REJECTS             PET02590
C  SFCTR1=.25                                                           PET02600
C  SFCTR2=.5                                                            PET02610
C  SFCTR3=.25                                                           PET02620
NOTE  THE SORT FACTORS SHOULD ADD TO 3  NUMBER OF GYROS/IMU             PET02630
NOTE                                                                    PET02640
NOTE                                                                    PET02650
NOTE  FIELD INVENTORY                                                   PET02660
NOTE                                                                    PET02670
NOTE  INFLOW IS ACCEPTED IMUS FROM IMUS TEST                            PET02680
NOTE  OUTFLOW IS FIELD BREAKDOWNS--TOTBRK.JK                            PET02690
L  FIELD.K=FIELD.J+(DT)(IMUACC.JK-TOTBRK.JK)  FIELD INVENTORY           PET02700
N  FIELD=0  INITIAL VALUE FIELD                                         PET02710
NOTE                                                                    PET02720
NOTE  WILL NEED MEASURE OF AVERAGE AGE OF IMUS IN FIELD TO              PET02730
NOTE       ESTIMATE BREAKDOWN PROBABILITIES                             PET02740
NOTE  RUNNING TOTAL ACCUMULATED AGE IN FIELD                            PET02750
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L  AVAGET.K=AVAGET.J+(DT)(FIELD.J-TOTBRK.JK*AVAGE.J)                    PET02760
N  AVAGET=0                                                            PET02770
NOTE                                                                   PET02780
A  AVAGE.K=AVAGET.K/(MAX(FIELD.K,1))  AVERAGE AGE IMUS IN FIELD        PET02790
NOTE     MAX FUNCTION TO AVOID DIVISION BY ZERO                        PET02800
NOTE                                                                   PET02810
NOTE  PROBABILITY OF FAILURE CALCULATIONS FOR THREE FAILURE CATEG.     PET02820
NOTE  AVAGE/360 IS AVERAGE AGE IN YEARS                                PET02830
NOTE                                                                   PET02840
NOTE  ****WARNING PROBAB EXPRESSED IN PERCENT PER YEAR                 PET02850
NOTE        MUST SCALE FOR DAILY RUN                                   PET02860
NOTE                                                                   PET02870
NOTE    BREAKDOWNS ASSUMED FUNCTION OF AVERAGE TIME UNIT IN FIELD      PET02880
NOTE       OR CHRONOLOGICAL TIME OF RUN, OR BOTH                       PET02890
C  S=1    SWITCH  =1 FOR AVERAGE TIME IN FIELD, =0 FOR CHRONOLOGY      PET02900
A  TIMEVAR.K=(S*AVAGE.K+(1-S)*TIME.K)/360  TIME IN YEARS                PET02910
A  PFECAT1.K=TABHL(T1,TIMEVAR.K,0,14,1) PROB CAT 1 FAIL                PET02920
C  T1*=.10/.10/.10/.10/.10/.10/.10/.10/.10/.10/.10/.10/.10/.10/.10     PET02930
NOTE                                                                   PET02940
A  PFECAT2.K=TABHL(T2,TIMEVAR.K,0,14,1) PROB CAT2 FAIL                 PET02950
C  T2*=.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20     PET02960
NOTE                                                                   PET02970
A  PFECAT3.K=TABHL(T3,TIMEVAR.K,0,14,1) PROB CAT3 FAIL                 PET02980
C  T3*=.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20/.20     PET02990
NOTE                                                                   PET03000
NOTE  ACTUAL NUMBER FAILURES BY CATEGORY                               PET03010
R  FECAT1.KL=FIELD.K*PFECAT1.K/360 CAT1 FAILURE RATE                   PET03020
R  FECAT2.KL=FIELD.K*PFECAT2.K/360 CAT2 FAILURE RATE                   PET03030
R  FECAT3.KL=FIELD.K*PFECAT3.K/360 CAT3 FAILURE RATE                   PET03040
NOTE                                                                   PET03050
NOTE  WE ALLOW STACKING OF FIELD FAILURE IMUS BEFORE REPAIR            PET03060
NOTE      IF MORE IMUS IN FIELD THAN DESIRED, PROBABLY WILL NOT REPAIR  PET03070
NOTE      FIRST GET PERCENT OF TODAYS FAILURES TO STACK AND TO REPAIR   PET03080
A  RATIO.K=TABEL(FSTACK,FIELD.K/DINFLD.K,.9,1.05,.05)                  PET03090
C  FSTACK*=1.5/1.1/1.0/0  TABLE FOR STACKING FIELD FAILURES            PET03100
NOTE                                                                   PET03110
NOTE  INVENTORIES OF FIELD FAILURE IMUS BY FAILURE TYPE                PET03120
NOTE     FAILURES FLOW INTO WAITING STACK, IMUS TO REPAIR FLOW OUT      PET03130
L  STKCAT1.K=STKCAT1.J+(DT)(FECAT1.JK-CAT1REP.JK)                      PET03140
N  STKCAT1=0                                                           PET03150
L  STKCAT2.K=STKCAT2.J+(DT)(FECAT2.JK-CAT2REP.JK)                      PET03160
N  STKCAT2=0                                                           PET03170
L  STKCAT3.K=STKCAT3.J+(DT)(FECAT3.JK-CAT3REP.JK)                      PET03180
N  STKCAT3=0                                                           PET03190
NOTE                                                                   PET03200
NOTE  THE OUTFLOWS FROM THEWAIT FOR REPAIR INVENTORIES                 PET03210
NOTE  ARE FRACTION OF TODAYS FAILURES (BUT NOT MORE THAN TOTAL WAITING) PET03220
NOTE                                                                   PET03230
R  CAT1REP.KL=MIN(STKCAT1.K,RATIO.K*FECAT1.JK) CAT1 FLD FAIL TO REPAIR PET03240
R  CAT2REP.KL=MIN(STKCAT2.K,RATIO.K*FECAT2.JK) CAT2 FLD FAIL TO REPAIR PET03250
R  CAT3REP.KL=MIN(STKCAT3.K,RATIO.K*FECAT3.JK) CAT3 FLD FAIL TO REPAIR PET03260
NOTE      TOTAL IMUS FAILING THIS PERIOD FROM FIELD INVENTORY          PET03270
R  TOTBRK.KL=FECAT1.JK+FECAT2.JK+FECAT3.JK  TOTAL FAILURE RATE         PET03280
NOTE                                                                   PET03290
NOTE  TOTAL IMUS WAITING FOR REPAIR                                    PET03300
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A  TFFWAIT.K=STKCAT1.K+STKCAT2.K+STKCAT3.K                              PET03310
NOTE                                                                    PET03320
NOTE      FIELD FAILURES ARE DISASSEMBLED AND GYROS SORTED INTO         PET03330
NOTE  IMU FAILURE VERIFICATION TESTS                                    PET03340
R  VFECAT1.KL=DELAY3(CAT1REP.JK,TVER) IMU VERIF. CATEG 1                PET03350
R  VFECAT2.KL=DELAY3(CAT2REP.JK,TVER)  IMU VERIF CATEG 2                PET03360
R  VFECAT3.KL=DELAY3(CAT3REP.JK,TVER)  IMU VERIF CATEG 3                PET03370
C  TVER=9    TIME TO DO IMU FAILURE IDENT TEST                          PET03380
NOTE                                                                    PET03390
NOTE     FIELD FAILURE IMU  DISASSEMBLY                                 PET03400
NOTE                                                                    PET03410
NOTE  VERIFIED FIELD IMU FAILURES ARE DISASSEMBLED AND SORTED           PET03420
NOTE      INTO GYRO FAILURE CATEGORIES                                  PET03430
NOTE                                                                    PET03440
NOTE        WE ASSUME ONLY ONE BAD GYRO PER FIELD IMU  FAILURE          PET03450
NOTE                                                                    PET03460
R  DFFCAT1.KL=DELAY3(VFECAT1.JK,TDISS)  CAT1 GYROS FROM FLD FAIL        PET03470
R  DFFCAT2.KL=DELAY3(VFECAT2.JK,TDISS)  CAT2 GYROS FROM FLD FAIL        PET03480
R  DFFCAT3.KL=DELAY3(VFECAT3.JK,TDISS)  CAT3 GYRO FIELD FAIL RATE       PET03490
NOTE                                                                    PET03500
NOTE  FINALLY, FIELD FAILURE GYROS ARE VERIFIED AS TO FAILURE CATEGORY  PET03510
NOTE      THESE GYROS WILL FLOW INTO GYRO DISASSEMBLY AREA              PET03520
R  FFCAT1.KL=DELAY3(DFFCAT1.JK,TVCAT1)  CATEG1 FAILED GYROS FROM FIELD  PET03530
R  FFCAT2.KL=DELAY3(DFFCAT2.JK,TVCAT2)  CATEG2 FAILED GYROS FROM FIELD  PET03540
R  FFCAT3.KL=DELAY3(DFFCAT3.JK,TVCAT3) CATEG3 FAILED GYROS FROM FIELD   PET03550
R  GCODFF.KL=2*DELAY3(DFFCAT1.JK+DFFCAT2.JK+DFFCAT3.JK,TVCAT3)          PET03560
NOTE  GOOD GYROS FROM FIELD IMU FAILURES--2 GOOD GYROS/IMU              PET03570
NOTE                                                                    PET03580
NOTE                                                                    PET03590
NOTE                                                                    PET03600
NOTE      COST SECTOR                                                   PET03610
NOTE  COMPONENT PURCHASE AND LOST MATERIAL COST                         PET03620
R  RSUBT1.KL=NEWSETS.JK*(COMPCT+AMLOST)                                 PET03630
L  SUBT1.K=SUBT1.J+(DT)(RSUBT1.JK)  ACCUM. SUBTOTAL 1                   PET03640
N  SUBT1=0 INITIAL VALUE                                                PET03650
C  COMPCT=7500  GYRO PARTS COST--NEW SETS OF PARTS                      PET03660
C  AMLOST=500   AVERAGE MATERIAL LOST DURING ASSEMBLY OF NEW SETS       PET03670
NOTE                                                                    PET03680
NOTE  COMPONENT LABOR FABRICATION COST                                  PET03690
R  RSUBT12.KL=NEWSETS.JK*NASLCST                                        PET03700
L  SUBT12.K=SUBT12.J+(DT)(RSUBT12.JK)  ACCUM SUBTOTAL 12                PET03710
N  SUBT12=0  INITIAL VALUE                                              PET03720
C  NASLCST=5000  ASSEMBLY LABOR COSTS NEW SETS                          PET03730
NOTE                                                                    PET03740
NOTE                                                                    PET03750
NOTE  GYRO DISASSEMBLY COSTS                                            PET03760
R  RSUBT3.KL=GDRCAT1.JK*DCAT1+GDRCAT2.JK*DCAT2+GDRCAT3.JK*DCAT3         PET03770
L  SUBT3.K=SUBT3.J+(DT)(RSUBT3.JK)  ACC SUBTOTAL 3                      PET03780
N  SUBT3=0  INITIAL VALUE                                               PET03790
C  DCAT1=100                                                            PET03800
C  DCAT2=500                                                            PET03810
C  DCAT3=1200                                                           PET03820
NOTE                                                                    PET03830
NOTE  GYRO REASSEMBLY COSTS                                             PET03840
NOTE  TWO KINDS REASSEMBLY COST--LABOR AND MATERIAL                     PET03850
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PAGE 007

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FILE: PETER1   DYNAMC   P1                MASSACHUSETTS INSTITUTE OF TECHNOLOGY

NOTE  REASSEMBLY   MATERIAL COSTS                                          PET03860
R  RGRMAT.KL=GARCAT1.JK*RMCAT1+GARCAT2.JK*RMCAT2+GARCAT3.JK*RMCAT3         PET03870
L  GRMAT.K=GRMAT.J+(DT)(RGRMAT.JK)    MAT SUB TOTAL                       PET03880
N  GRMAT=0                                                                PET03890
C  RMCAT1=400    MATERIAL COST CAT1                                       PET03900
C  RMCAT2=1000   MATERIAL COST CAT2                                       PET03910
C  RMCAT3=2800   MATERIAL COST CAT3                                       PET03920
NOTE  REASSEMBLY LABOR COST                                               PET03930
R  RGRLAB.KL=GARCAT1.JK*RCAT1+GARCAT2.JK*RCAT2+GARCAT3.JK*RCAT3           PET03940
L  GRLAB.K=GRLAB.J+(DT)(RGRLAB.JK)   LAB SUB TOTAL ACCUMULATED            PET03950
N  GRLAB=0                                                                PET03960
C  RCAT1=600   LABOR COST CAT1                                            PET03970
C  RCAT2=2000   LABOR COST CAT2                                           PET03980
C  RCAT3=4000   LABOR COST CAT3                                           PET03990
A  SUBT4.K=GRMAT.K+GRLAB.K                                                PET04000
NOTE                                                                      PET04010
NOTE  IMU  FAILURE DISASSEMBLY AND VERIFICAITON COST                      PET04020
R  RSUBT5.KL=SDGCAT1.JK*GFVCAT1+SDGCAT2.JK*GFVCAT2+SDGCAT3.JK*GFVCAT3     PET04030
L  SUBT5.K=SUBT5.J+(DT)(RSUBT5.JK)   ACCUM SUBT TOTAL 5                   PET04040
N  SUBT5=0                                                                PET04050
C  GFVCAT1=300                                                            PET04060
C  GFVCAT2=700                                                            PET04070
C  GFVCAT3=1000                                                           PET04080
NOTE                                                                      PET04090
NOTE  GYRO ACCEPTANCE TEST COST                                           PET04100
R  RSUBT6.KL=(GYACC.JK+GYNACC.JK)*GACTC                                   PET04110
L  SUBT6.K=SUBT6.J+(DT)(RSUBT6.JK)   ACC SUBTOTAL 6                       PET04120
N  SUBT6=0   INITIAL VALUE                                                PET04130
C  GACTC=2000    GYRO ACCEPTANCE TEST LABOR COST                          PET04140
NOTE                                                                      PET04150
NOTE  IMU  DISASEMBLY COST                                                PET04160
R  RSUBT10.KL=IMUDISR.JK*CIMUDIS                                          PET04170
L  SUBT10.K=SUBT10.J+(DT)(RSUBT10.JK)   ACCUM SUBTOTAL 10                 PET04180
N  SUBT10=0                                                               PET04190
C  CIMUDIS=200   COST OF IMU  DISASSEMBLY                                 PET04200
NOTE                                                                      PET04210
NOTE  IMU FIELD FAILURE VERIFICATION TEST COST                            PET04220
R  RSUBT2.KL=TIMUV*(VFFCAT1.JK+VFFCAT2.JK+VFFCAT3.JK)  IMU FIELD VER COSTPET04230
L  SUBT2.K=SUBT2.J+(DT)(RSUBT2.JK)    ACCUM SUBTOTAL 2                    PET04240
N  SUBT2=0                                                                PET04250
C  TIMUV=400   IMU FIELD FAILURE VERIFICATION COST                        PET04260
NOTE                                                                      PET04270
NOTE  FIELD IMU FAILURE DISASSEMBLY COST                                  PET04280
R  RSUBT11.KL=(DFFCAT1.JK+DFFCAT2.JK+DFFCAT3.JK)*CIMUDIS                  PET04290
L  SUBT11.K=SUBT11.J+(DT)(RSUBT11.JK)  ACCUM SUBTOTAL 11                  PET04300
N  SUBT11=0                                                               PET04310
NOTE  FIELD FAILURE DISASSEMBLY AND VERIFICATION COSTS                    PET04320
R  RSUBT7.KL=FECAT1.JK*GFVCAT1+FECAT2.JK*GFVCAT2+FECAT3.JK*GFVCAT3        PET04330
L  SUBT7.K=SUBT7.J+(DT)(RSUBT7.JK)   ACCUM SUBTOTAL 7                     PET04340
N  SUBT7=0                                                                PET04350
NOTE                                                                      PET04360
NOTE  IMU  ACCEPTANCE TEST                                                PET04370
R  RSUBT8.KL=(IMUACC.JK+IMUNACC.JK)*STCOST                                PET04380
L  SUBT8.K=SUBT8.J+(DT)(RSUBT8.JK)   ACCUM SUBTOTAL 8                     PET04390
N  SUBT8=0                                                                PET04400
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FILE: PETER1   DYNAMC   P1                    MASSACHUSETTS INSTITUTE OF TECHNOLOGY

C  STCOST=2000   IMU  ACCEPTANCE TEST COST/IMU                                  PET04410
NOTE                                                                           PET04420
NOTE  IMU  ASSEMBLY COST                                                       PET04430
R  RSUBT9.KL=IMUWAIT.JK*IMUASSC  NOTE IN NUMBER IMUS NOT GYROS                 PET04440
L  SUBT9.K=SUBT9.J+(DT)(RSUBT9.JK)  ACCUM SUBTOTAL 9                           PET04450
N  SUBT9=0                                                                     PET04460
C  IMUASSC=300     IMU  ASSEMBLY COST/IMU                                      PET04470
NOTE                                                                           PET04480
NOTE  TOTAL COST COUNTER                                                       PET04490
R  P1.KL=RSUBT1.JK+RSUBT2.JK+RSUBT3.JK+RGRLAB.JK+RGRMAT.JK+RSUBT5.JK           PET04500
R  P2.KL=RSUBT6.JK+RSUBT7.JK+RSUBT8.JK+RSUBT9.JK+RSUBT10.JK+RSUBT11.JK         PET04510
R  P3.KL=RSUBT12.JK                                                            PET04520
L  COST.K=COST.J+(DT)(P1.JK+P2.JK+P3.JK)  TOTAL ACCUM COST                     PET04530
N  COST=TCAP*TCCOST+OTHER  INITIAL COST --CAPITAL EXPEN.                       PET04540
C  TCCOST=300000  COST PER UNIT GYRO TEST CAPACITY                             PET04550
NOTE       TWO COMPONENTS--GYRO TEST CAP-TCAP*300000                           PET04560
NOTE      AND OTHER--OTHER CAPITAL                                             PET04570
C  OTHER=1042000   OTHER CAPITAL COST-NOT INCLUD GYRO TEST                     PET04580
NOTE                                                                           PET04590
NOTE  COUNTER FOR TOTAL USEFUL DAYS IN FIELD                                   PET04600
L  DAYINF.K=DAYINF.J+(DT)(RFIELD.JK)   DAYS IN FIELD                           PET04610
R  RFIELD.KL=MIN(FIELD.K,MAXFLD)  WILL ONLY COUNT TO MAX DES IN FIELD          PET04620
C  MAXFLD=1050     MAXIMUM DESIRED IMUS IN FIELD                               PET04630
NOTE          ANY MORE IMUS PRODUCED ARE NOT USED IN COST/DAY CALCUL.          PET04640
N  DAYINF=0   INITIAL DAYS IN FIELD                                            PET04650
NOTE                                                                           PET04660
NOTE  COSTS TO DAYS IN FIELD RATIO                                             PET04670
NOTE                                                                           PET04680
A  CPERDY.K=COST.K/(DAYINF.K+1.)  COSTS PER DAY IN FIELD                       PET04690
NOTE     THE (+1.)  IN (DAYINF.K+1.) ABOVE IS THERE TO PREVENT DIVISION        PET04700
NOTE    WHICH CONFUSES THE COMPUTER.  REMEMBER IT TAKES SOME TIME              PET04710
NOTE     TO GET ANY COMPLETED SYSTEMS INTO THE FIELD                           PET04720
NOTE                                                                           PET04730
NOTE                                                                           PET04740
NOTE  OUTPUT SECTION                                                           PET04750
NOTE  SPECIFICATION CARDS                                                      PET04760
NOTE                                                                           PET04770
C  LENGTH=5400                                                                PET04780
C  DT=1.                                                                       PET04790
C  PRTPER=180                                                                  PET04800
C  PLTPER=180                                                                  PET04810
NOTE                                                                           PET04820
PRINT 1)COST/2)DAYINF/3)CPERDY(0.3)/4)FIELD/5)GYROW/6)IMUWAIT/7)TFFWAIT        PET04830
PRINT 1)NEWSETS/2)ACNEW/3)DINAS/4)TCORREC/5)CORREC/6)GYRCAS/7)AVAGE            PET04840
PRINT 1)SUBT1/2)SUBT12/3)GRMAT/4)GRLAB/5)SUBT2/6)SUBT3/7)SUBT4/8)RATIO         PET04850
PRINT 1)SUBT5/2)SUBT6/3)SUBT7/4)SUBT8/5)SUBT9/6)SUBT10/7)SUBT11                PET04860
PLOT  FIELD=F/FECAT1=1,FECAT2=2,FECAT3=3/TFFWAIT=W/AVAGE=A                     PET04870
PLOT  COST=$/SUBT1=1,SUBT12=*,SUBT2=2,SUBT3=3/SUBT4=4,SUBT5=5,SUBT6=6         PET04880
PLOT  COST=$/SUBT7=7,SUBT8=8,SUBT9=9,SUBT10=0,SUBT11=1,GRLAB=L,GRMAT=M        PET04890
PRINT 1)VFECAT1/2)VFECAT2/3)VFECAT3/4)INFLOW/5)GYROTT/6)COST/7)GYROW           PET04900
PLOT  DINAS=I/DINFLD=F/ERROR=E/CORREC=C/NEWSETS=N/RCDIS=D,RCRAS=A              PET04910
PLOT  GYROAS=G/TIGDIS=D/TLGREAS=R/GYROAT=T/IMUASS=S/IMUDIS=A/IMUTTA=B          PET04920
PLOT  IMUACC=A,IMUNACC=N/GYACC=1,GYNACC=2/ASSGYG=G,ASSGYB=B                    PET04930
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PAGE 009

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