INERTIAL GYRO LIFE-CYCLE COSTS —
ANALYSIS AND MANAGEMENT

by

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(1950)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF
SCIENCE
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June, 1970

Signature of Author

Department of Aeronautics and Astronautics
June, 1970

Certified by

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Chairman, Departmental Committee
on Graduate Students

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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-
This thesis was prepared under DSR Project 52-30621, sponsored by the Air Force Avionics Laboratory, Air Force Systems Command, United States Air Force, through Contract F33615-68-C-1155, Task No. 510201, with the Massachusetts Institute of Technology.

The publication of this thesis does not constitute approval by the Charles Stark Draper Laboratory or the Air Force of the findings or the conclusions contained therein. It is published only for the exchange and stimulation of ideas.
INERTIAL GYRO LIFE-CYCLE COSTS—
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by

Peter J. Palmer

Submitted to the Department of Aeronautics and Astronautics in June 1970 in partial fulfillment of the requirements for the degree of Master of Science.

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.
ACKNOWLEDGMENT

The author gratefully acknowledges the support of the Charles Stark Draper Laboratory in this thesis study.

The author wishes to express his appreciation to Professor Walter Wrigley, Educational Director of the Charles Stark Draper Laboratory and faculty advisor, for his counsel and encouragement throughout the Master's study program. He also wishes to thank his supervisor, Mr. William G. Denhard, Associate Director of the Charles Stark Draper Laboratory, for providing the opportunity to conduct the research reported in this thesis. Special thanks go to Mr. Richard Wright, Research Assistant at the Alfred P. Sloan School of Management for his assistance with the computer program.

Many thanks are due Mrs. Catherine Breen for her perseverance and skill in typing the manuscript. The author also wishes to express his gratitude to the Technical Publications Group for their assistance with the artwork and the publication.

To his dear wife, Jeanne, go very special thanks in appreciation of her cheerful patience and encouragement throughout the Master's program.

Many other individuals -- in his family, at MIT, in industry, and in government service--deserve mention. The author regrets that space and time prevent him for recognizing each and every one.
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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. 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 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. 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. Life-cycle costing, also called failure-free warranty, has been the basis of a U.S. Navy contract with Lear Siegler Inc. 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, industrial management, ecology, operations research (also called management science) and urban dynamics.
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 gyro's 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 gyro's are removed. The gyro's are subjected to failure-identification tests to
determine the nature and extent of the failure. The identified failed gyro's are
disassembled. The gyro's which pass the failure-identification tests and are "good"
gyro's, 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 gyro's 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 gyro's
are held in an inventory or stack until they can be acceptance tested. The accep-
tance-test capacity is a management decision and is one of the nonlinearities built
into the model. It is assumed that all gyro's are subjected to the same tests and
the rejected gyro's 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 gyro's rejected at the IMU acceptance tests are tested to identify the
failures and the failure modes. The gyro's are sorted into "good", category 1,
category 2, or category 3. The IMU is a complex electromechanical assembly
NOTE:

CAT. 1

FAILURES LOCATED OUTSIDE GYRO HOUSING

FAILURES LOCATED BETWEEN HOUSING AND FLOAT

FAILURES LOCATED INSIDE FLOAT

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

NOTE:
CAT. 1 - FAILURES LOCATED OUTSIDE GYRO HOUSING
CAT. 2 - FAILURES LOCATED BETWEEN HOUSING AND FLOAT
CAT. 3 - FAILURES LOCATED INSIDE FLOAT
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 diagram 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, disassembly 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.](image)

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. 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. 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 compiler 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. 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:

\[ \text{DINAS} \cdot K = \text{TABHL}(\text{DSTART}, \text{TIME} \cdot K)/180,0,14,1 \]  
(11-A)

where

\[ \text{DINAS} = \text{desired initiation of assembly at time } K \]

\[ \text{TABHL} = \text{table from which values can be interpolated by the compiler} \]

\[ \text{(the HL indicates that the number of starts may exceed the high and low limits of the provided range)} \]

\[ \text{DSTART} = \text{name of table of desired starts of new gyro sets} \]

\[ \text{DSTART}^* = 0/1/2/3/3/3/3/3/2.1/0/0/0/0/0/0/0/0/0 = \text{table of desired starts} \]  
(12-C)

\[ \text{(an asterisk following a code word denotes a numerical tabulation)} \]

\[ \text{TIME} = \text{time in days at time } K \]

\[ 0,14, = \text{lowest and highest value in the time range in half-years of the desired starts of new gyro sets} \]

\[ 1 = \text{increment in table is in half-years} \]

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

\[ \text{DINFLD} \cdot K = \text{TABHL}(\text{DFIELD}, (\text{TIME} \cdot K)/360,0,6,1) \]  
(17-A)

where

\[ \text{DINFLD} \cdot K = \text{desired inventory in the field (in IMU's) at time } K \]

\[ \text{TABHL} = \text{table (see previous Eq.)} \]

\[ \text{DFIELD} = \text{table of desired inventory} \]

\[ \text{DFIELD}^* = 1/60/300/650/900/1000/1000^* \]  
(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.

* 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.

\[ \text{ERROR.KL} = \text{DINFLD.K} - \text{FIELD.K} \quad (21-R) \]

The average value of the error at the present time is

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

Here:
- \( \text{DT} \) = delta time = solution interval = 1 day (480-C)
- \( \text{TSMTH} \) = exponential smoothing time constant (17) = 30 days (24-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.

\[ \text{CORREC.K} = \text{AERROR.K} \times 3 \times \text{GAIN} \quad (28-A) \]

Here:
- 3 = conversion factor from IMU's to gyros
- \( \text{GAIN} \) = gain of the correction factor = 0 (this is a management decision) (29-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.

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

Here:
- \( \text{CLIP} \) = limiting function so that
  - \( \text{TCORREC.K} = \text{CORREC.K} \) if \( \text{TIME.K}/360 \geq 1.5 \)
  - \( \text{TCORREC.K} = 0 \) if \( \text{TIME.K}/360 < 1.5 \)
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.

\[
\text{NEWSETS} \cdot KL = \text{MAX} (\text{DINAS} \cdot K + \text{TCORREC} \cdot K, 0) \quad (35-R)
\]

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

\[
\text{ACNEW} \cdot K = \text{ACNEW} \cdot J + (DT) \cdot (\text{NEWSETS} \cdot JK) \quad (37-L)
\]

The level of gyros in assembly is:

\[
\text{GYROAS} \cdot K = \text{GYROAS} \cdot J + (DT) \cdot (\text{NEWSETS} \cdot JK - \text{ASSGYG} \cdot JK - \text{ASSGYB} \cdot JK) \quad (45-L)
\]

where

\[
\text{ASSGYG} = \text{assembly rate of "good" gyros}
\]

\[
\text{ASSGYB} = \text{assembly rate of "bad" gyros}
\]

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:

\[
\text{ASSGYG} \cdot KL = \text{DELAY3} (\text{NEWSETS} \cdot JK, \text{TASGYRO}) \cdot (1 - \text{LSSRT}) \quad (50-R)
\]

where

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

\[
\text{TASGYRO} = \text{time to assemble gyros in days} = 30 \quad (51-C)
\]

\[
* = \text{multiplication}
\]

\[
\text{LSSRT} = \text{loss rate in assembling new sets} = 8% \quad (53-C)
\]

\* three, cascaded, single-order, exponentials decreasing with time
The assembly rate of "bad" gyros which represents the parts lost is given by:

\[
ASSGYB. KL = \text{DELAY3(NEWSETS. JK, TASGYRO)} \times (LSSRT) \tag{52-R}
\]

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).

\[
\text{INFLOW. KL} = \text{ASSGYG. JK} + \text{GARCAT1. JK} + \text{GARCAT2. JK} \\
+ \text{GARCAT3. JK} \tag{61-R}
\]

where

- \( \text{INFLOW} \) = total rate of gyros flowing into the acceptance test waiting area
- \( \text{GARCAT1} \) = rate of reassembled gyros (cat. 1) flowing out of reassembly area
- \( \text{GARCAT2} \) = rate of reassembled gyros (cat. 2) flowing out of reassembly area
- \( \text{GARCAT3} \) = rate of reassembled gyros (cat. 3) flowing out of reassembly area

The level of the gyros waiting for test is:

\[
\text{GYROW. K} = \text{GYROW. J + (DT)(INFLOW. JK - GYROTT. JK)} \tag{62-L}
\]

where

- \( \text{GYROW} \) = gyros waiting for test
- \( \text{DT} \) = delta time or solution interval = 1 day
- \( \text{GYROTT} \) = 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.

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

where

- \( \text{GYROAT} \) = level of gyros in acceptance-test area
- \( \text{GYACC} \) = rate of gyros accepted
- \( \text{GYNACC} \) = 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.

\[ \text{GYROTT}. KL = \text{MIN}(\text{TCAP} \times \text{CAPYLD}, \text{GYROW}. K) \] (79-R)

where

- \( \text{TCAP} \) = number of equivalent test stations = 25
- \( \text{CAPYLD} \) = capacity of each equivalent test station = 0.2 gyro/day
- \( \text{MIN} \) = minimum function

\[ \text{GYROTT}. KL = \text{TCAP} \times \text{CAPYLD} \text{ if } \text{TCAP} \times \text{CAPYLD} < \text{GYROW}. K \]
\[ \text{GYROTT}. KL = \text{GYROW}. K \text{ if } \text{TCAP} \times \text{CAPYLD} \geq \text{GYROW}. K \]

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.

\[ \text{GYACC}. KL = \text{DELAY3}(\text{GYROTT}, \text{TGYAT}) \times \text{YIELD} \] (83-R)
\[ \text{GYNACC}. KL = \text{DELAY3}(\text{GYROTT}, \text{TGYAT}) \times (1 - \text{YIELD}) \] (86-R)

where

- \( \text{GYNACC} \) = rate of accepted gyros leaving the acceptance-test area
- \( \text{GYNACC} \) = rate of nonaccepted gyros leaving the acceptance-test area
- \( \text{TGYAT} \) = time required for gyro acceptance test = 25 days
- \( \text{YIELD} \) = 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:

\[
\text{INCAT1.KL} = \text{GYNACC.JK} \times \text{FCTR1} + \text{SDGCAT1.JK} + \text{FFCAT1.JK}
\]

where:

- \( \text{INCAT1} \) = gyro input rate to the disassembly area - category 1
- \( \text{FCTR1} \) = fraction of gyros not accepted from the original acceptance test which are category 1 failures
  - \( \text{FCTR1} = 0.3 \)
  - \( \text{FCTR2} = 0.6 \)
  - \( \text{FCTR3} = 0.1 \)
- \( \text{SDGCAT1} \) = rate of rejected gyros original IMU acceptance test - category 1
- \( \text{FFCAT1} \) = 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.

\[
\text{GDCAT1.K} = \text{GDCAT1.J} + (\text{DT})(\text{INCAT1.JK} - \text{GDRCAT1.JK})
\]

where:

- \( \text{GDCAT1} \) = level of gyros in the category 1 gyro disassembly area
- \( \text{GDRCAT1} \) = 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.
\[ GDRACT1.\, KL = \text{DELAY3 (INCAT1.\, JK, TDCAT1)} \] (114-R)

where

\[ \text{TDCAT1} = \text{time to disassemble category 1 rejects in days} \]

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

\[ GDRACT1.\, KL = INCAT1.\, JK \]

\[ TDCAT2 = 7 \text{ days} \] (142-C)

\[ TDCAT3 = 10 \text{ days} \] (170-C)

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

\[ TLGDIS.\, K = GD Cat1.\, K + GD Cat2.\, K + GD Cat3.\, K \] (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

\[ GACAT1 = \text{level of gyros in reassembly - category 1} \]

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

\[ GARCAT1.\, KL = \text{DELAY3(GDRCAT1.\, JK, TASC1)} \] (120-R)

where

\[ TASC1 = \text{time to reassemble gyros - category 1} = 9 \text{ days} \] (121-C)

\[ TASC2 = 15 \text{ days} \] (151-C)

\[ TASC3 = 30 \text{ days} \] (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)
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.

\[
\text{SDGCAT1.KL} = \text{DELAY3} (\text{SFCTR1} \cdot \text{IMUDISR.JK}, \text{TVCAT1})
\]  

where

\[
\begin{align*}
\text{SFCTR1} & = \text{fraction of failed gyros from failed IMU's (plant rejects)} \\
\text{SFCTR 1} & = 0.25 \\
\text{SFCTR 2} & = 0.50 \\
\text{SFCTR 3} & = 0.25 \\
\text{TVCAT1} & = \text{time to verify category 1 gyro failures} = 7 \text{ days} \\
\text{TVCAT2} & = 8 \text{ days} \\
\text{TVCAT3} & = 8 \text{ days}
\end{align*}
\]

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

\[
\text{GOODSF.KL} = \text{DELAY3} (\text{SGOK} \cdot \text{IMUDISR.JK}, \text{TVGOOD})
\]

where

\[
\begin{align*}
\text{SGOK} & = \text{two "good" gyros in each rejected IMU by assumption} \\
\text{TVGOOD} & = \text{time to verify "good" gyro from IMU rejections} = 7 \text{ days}
\end{align*}
\]

The total reassembly rate for all three categories is:

\[
\text{RCRAS.K} = \text{GARCAT1.JK} + \text{GARCAT2.JK} + \text{GARCAT3.JK}
\]  

(187-A)

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.

\[
\text{FFCAT1.KL} = \text{DELAY3}(\text{DFFCAT1.JK}, \text{TVCAT1})
\]

where

\[
\begin{align*}
\text{FFCAT1} & = \text{verified gyro field-failures - category 1} \\
\text{TVCAT1} & = \text{time required to verify failures - category 1}
\end{align*}
\]
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.

\[ \text{GOODFF}_{KL} = 2 \times \text{DELAY3} (\text{DFFCAT1}_{JK} + \text{DFFCAT2}_{JK} + \text{DFFCAT3}_{JK}, \text{TVCAT3}) \]  

(356-R)

where

\begin{align*}
\text{GOODFF} & = \text{rate of good gyros from IMU field failures} \\
\text{GOODSF} & = \text{rate of "good" gyros from IMU factory failures} \\
\text{GOODFF} & = \text{rate of "good" gyros from IMU field failures} \\
\text{GINIMU} & = \text{rate of gyro's in assembled IMU's to the wait-stack for IMU acceptance testing} \\
\text{TASIMU} & = \text{time to assemble an IMU in days} = 7
\end{align*}

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" gyro's from the IMU's rejected in the field, and (d) the output.

\[ \text{IMUASS}_{K} = \text{IMUASS}_{J} + (\Delta t)(\text{GYACC}_{JK} + \text{GOODSF}_{JK} + \text{GOODFF}_{JK} - \text{GINIMU}) \]  

(194-L)

where

\begin{align*}
\text{IMUASS} & = \text{level of gyros in the IMU assembly area} \\
\text{GOODSF} & = \text{rate of "good" gyros from IMU factory failures} \\
\text{GOODFF} & = \text{rate of "good" gyros from IMU field failures} \\
\text{GINIMU} & = \text{rate of gyro's in assembled IMU's to the wait-stack for IMU acceptance testing}
\end{align*}

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

\[ \text{GINIMU}_{KL} = \text{DELAY3} (\text{GYACC}_{JK} + \text{GOODSF}_{JK} + \text{GOODFF}_{JK}, \text{TASIMU}) \]  

(197-R)

where

\[ \text{TASIMU} = \text{time to assemble an IMU in days} = 7 \]  

(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

\[ \text{IMUWAIT}_{KL} = \frac{\text{GINIMU}_{JK}}{3} \]  

(204-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.

\[ IMUWT\_K = IMUWT\_J + DT(IMUWAIT\_JK - IMUTTST\_JK) \] (203-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

\[ IMUTTST\_KL = \text{MIN}(IMUWT\_K, \text{CAPAC}) \] (216-R)

\[ \text{CAPAC} = \text{capacity IMU acceptance test area in IMU's} = 10 \] (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

\[ \text{IMUACC}\_KL = \text{DELAY3}(IMUTTST\_JK, \text{TTIMU})\#\text{IMUYLD} \]
\[ \text{IMUNACC}\_KL = \text{DELAY3}(IMUTTST\_JK, \text{TTIMU})\#(1-\text{IMUYLD}) \] (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

\[ IMUDIS, K = IMUDIS, J + (DT)(IMUNACC, JK - IMUDISR, JK) \]  

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

\[ IMUDISR, KL = \text{DELAY3(IMUNACC, JK, TDISS)} \]  

where

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

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

\[ \text{RATIO}, K = \text{TABHL(FSTACK, FIELD, K/DINFLD, K, .9, 1.05, .05)} \]  

where

- \( \text{RATIO} \) = ratio of field failed IMU's to the waiting stack vs field failed IMU's to the IMU failure-verification test
- \( \text{FSTACK}^* \) = table for stack field failures = 1.5/1.1/1.0/0

When the actual inventory in the field (FIELD) is greater than the desired inventory in the field (DINFLD) (say 1.05 times), then \( \text{RATIO} = 0.5 \) 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, \( \text{RATIO} = 1 \) 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 \( \text{RATIO} = 1.10 \) 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

\[ STKCAT1.K = STKCAT1.J + (DT)(FECAT1.JK - CAT1REP.JK) \]  \hspace{1cm} (314-L)

where

\[ STKCAT1 = \text{IMU field failures in stack - category 1} \]
\[ FECAT1 = \text{IMU field failure rate - category 1} \]
\[ CAT1REP = \text{rate of IMU field failures from waiting stack - category 1} \]

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

\[ CAT1REP.KL = \text{MIN}(STKCAT1.K, RATIO.K \times FECAT1.JK) \]  \hspace{1cm} (324-R)

where

\[ \text{MIN} = \text{minimum function} \]
\[ CAT1REP.KL = STKCAT1.K \text{ if } STKCAT1.K < RATIO \times FECAT1.JK \]
\[ CAT1REP.KL = RATIO.K \times FECAT1.JK \text{ if } STKCAT1.K \geq RATIO \times FECAT1.JK \]

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.

\[ VFECAT1.KL = \text{DELAY3}(CAT1REP.JK, TVER) \]  \hspace{1cm} (335-R)

where

\[ VFECAT1 = \text{IMU verified field failures which contain a category 1 gyro failure} \]
\[ TVER = \text{time required for IMU failure-verification test} = 9 \text{ days} \]  \hspace{1cm} (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.

\[ DFFCAT1.KL = \text{DELAY3}(VFECAT1.JK, TDISS) \]  \hspace{1cm} (347-R)
where
\[ DFFCAT1 = \text{gyro field-failure rate from IMU disassembly-category 1} \]
\[ TDISS = \text{time required to disassemble IMU's} = 7 \text{ days} \]  \hspace{1cm} (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

\[ \text{FIELD.K} = \text{FIELD.J} + (DT)(\text{IMUACC.JK} - \text{TOTBRK.JK}) \]  \hspace{1cm} (270-L)

where
\[ \text{FIELD.} = \text{actual IMU inventory in the field} \]
\[ \text{TOTBRK} = \text{total failure rate of IMU's in the field} \]

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

\[ \text{AVAGET.K} = \text{AVAGET.J} + (DT)(\text{FIELD.J} - \text{TOTBRK.JK}*\text{AVAGE.J})(276-L) \]

where
\[ \text{AVAGE} = \text{average age of the IMU's in the field inventory} \]

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

\[ \text{AVAGE.K} = \text{AVAGET.K}/(\text{MAX}(\text{FIELD.K}, 1)) \]  \hspace{1cm} (279-A)

where
\[ \text{MAX} = \text{maximum function and is used to avoid division by zero} \]
\[ \text{FIELD.K} = \text{FIELD.K} \text{ if FIELD} > 1 \]
\[ \text{FIELD.K} = 1 \]

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)

\[ \text{TIMEVAR.K} = (S*\text{AVAGE.K} + (1-S)*\text{TIME.K})/360 \]  \hspace{1cm} (291-A)

where
\[ \text{TIMEVAR} = \text{time variation for IMU's in the field in years} \]
\[ S = \text{switch function} \]
\[ S = 1 \text{ for average time in the field} \]
\[ S = 0 \text{ for chronological time} \]
The failure rates per year for IMU's in the field for category 1 are governed by a table function \( T_1^* \). As noted previously, only the equations pertinent to category 1 are presented here.

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

where

\[
PFECAT1 = \text{field failure rates per year}
\]

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

\[
T1 = \text{name of the table of failure rates as a function of age in the field}
\]

\[
T1^* = \text{actual table of failure rates for entire 15 years of the program for category 1}
\]

\[
T1^* = .10/.10/.10/.10/.10/.10/.10/.10/.10/.10/.10/.10 (293-C)
\]

\[
\]

\[
\]

\[
TIMEVAR = \text{time variation for IMU's in the field in years is the independent variable in the table}
\]

\[
0, 14 = \text{lowest and highest value in the time range in years}
\]

\[
1 = \text{increment in the table is in years}
\]

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

\[
FECAT1.KL = FIELD^*PFECAT1.K/360 \quad (302-R)
\]

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

\[
TOTBRK.KL = FECAT1.JK + FECAT2.JK + FECAT3.JK \quad (328-R)
\]

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

\[
\]

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

\[ \text{RSUBT1}.KL = \text{NEWSETS}.JK*(\text{COMPCT} + \text{AMLOST}) \]  

where

\[ \text{RSUBT1} = \text{component purchase and lost-material cost rate} \]
\[ \text{COMPCT} = \text{component parts cost per gyro - new sets} = 7500 \]  
\[ \text{AMLOST} = \text{average cost of material lost during assembly per gyro} = 500 \]

\[ \text{SUBT1}.K = \text{SUBT1}.J + (\text{DT})(\text{RSUBT1}.JK) \]

(b) Labor costs to assemble new sets of parts

\[ \text{RSUBT12}.KL = \text{NEWSETS}.JK*\text{NASLCST} \]

where

\[ \text{RSUBT12} = \text{assembly labor cost rate for new sets} \]
\[ \text{NEWSETS} = \text{actual new sets of parts} \]
\[ \text{NASLCST} = \text{assembly labor cost per gyro using new sets of parts} = 5000 \]

\[ \text{SUBT12}.K = \text{SUBT12}.J + (\text{DT})(\text{RSUBT12}.JK) \]

(c) Gyro disassembly labor costs

\[ \text{RSUBT3}.KL = \text{GDRCAT1}.JK*\text{DCAT1} + \text{GDRCAT1}.JK*\text{DCAT2} + \text{GDRCAT2}.JK*\text{DCAT3} \]

where

\[ \text{RSUBT3} = \text{disassembly labor cost rate} \]
\[ \text{GDRCAT1} = \text{disassembly rate - category 1} \]
\[ \text{GDRCAT2} = \text{disassembly rate - category 2} \]
\[ \text{GDRCAT3} = \text{disassembly rate - category 3} \]
\[ \text{DCAT1} = \text{disassembly labor cost per gyro - category 1} = 100 \]
DCAT2 = disassembly labor cost per gyro - category 2 = 500 \hspace{1cm} (381-C)
DCAT3 = disassembly labor cost per gyro - category 3 = 1200 \hspace{1cm} (382-C)

\[
\text{SUBT3.K} = \text{SUBT3.J} + (DT)(\text{RSUBT3.JK}) \hspace{1cm} (378-L)
\]

where

\[
\text{SUBT3} = \text{subtotal cost of gyro disassembly labor}
\]

(d) \textbf{Gyro reassembly material costs}

\[
\text{RGRMAT.KL} = \text{GARCAT1.JK*RMCAT1} + \text{GARCAT2.JK*RMCAT2} + \text{GARCAT3.JK*RMCAT3} \hspace{1cm} (378-R)
\]

where

\[
\text{RGRMAT} = \text{reassembly material cost rate}
\]
\[
\text{GARCAT1,2,3} = \text{reassembly rate - categories 1,2,3}
\]
\[
\text{RMCAT1,2,3} = \text{reassembly material cost per gyro - categories 1,2,3}
\hspace{1cm} = 400, 1000, 2800 \hspace{1cm} (390-C)(391-C)(392-C)
\]

\[
\text{GRMAT.K} = \text{GRMAT.J} + (DT)(\text{RGRMAT.JK}) \hspace{1cm} (380-L)
\]

where

\[
\text{GRMAT} = \text{subtotal cost of gyro reassembly material}
\]

(e) \textbf{Gyro reassembly labor cost}

\[
\text{RGRLAB.KL} = \text{GARCAT1.JK*RCAT1} + \text{GARCAT2.JK*RCAT2} + \text{GARCAT3.JK*RCAT3} \hspace{1cm} (394-R)
\]

where

\[
\text{RGRLAB} = \text{reassembly labor cost rate}
\]
\[
\text{RCAT1,2,3} = \text{reassembly labor cost per gyro - categories 1,2,3}
\hspace{1cm} = 600, 2000, 4000 \hspace{1cm} (397-C)(398-C)(399-C)
\]

\[
\text{GRLAB.K} = \text{GRLAB.J} + (DT)(\text{RGRLAB.JK}) \hspace{1cm} (395-L)
\]

where

\[
\text{GRLAB} = \text{subtotal cost of gyro reassembly labor}
\]

\text{NOTE: SUBT4.K} = \text{GRMAT.K} + \text{GRLAB.K}
where

\[ \text{SUBT4} = \text{subtotal cost of gyro reassembly (labor and material)} \]

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

\[ R\text{SUBT5. KL} = SD\text{GCaT1. JK} \cdot GF\text{VCaT1} + SD\text{GCaT2. JK} \cdot GF\text{VCaT2} + SD\text{GCaT3. JK} \cdot GF\text{VCaT3} \]  
\[ \text{ (403-R)} \]

where

\[ R\text{SUBT5} = \text{failure-identification test labor cost rate for gyros which failed in the IMU acceptance test} \]

\[ SD\text{GCaT1, 2, 3} = \text{rate of gyros from IMU disassembly-categories 1, 2, 3} \]

\[ GF\text{VCaT1, 2, 3} = \text{gyro failure-identification test labor cost per gyro} \]

\[ = 300, 700, 1000 \]  
\[ \text{ (406-C)(407-C)(408-C)} \]

\[ \text{SUBT5. K} = \text{SUBT5. J} + (DT)(R\text{SUBT5. JK}) \]  
\[ \text{ (404-L)} \]

(g) Gyro acceptance test labor cost

\[ R\text{SUBT6. KL} = (G\text{YACC. JK} + G\text{YNACC. JK}) \cdot G\text{ACTC} \]  
\[ \text{ (411-R)} \]

where

\[ R\text{SUBT6} = \text{gyro acceptance test labor cost rate} \]

\[ G\text{ACTC} = \text{gyro acceptance test labor cost per gyro} = 2000 \]  
\[ \text{ (414-C)} \]

\[ \text{ (412-L)} \]

where

\[ \text{SUBT6} = \text{subtotal cost of gyro acceptance test labor} \]

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

\[ R\text{SUBT10. KL} = I\text{MUDISR. JK} \cdot C\text{IMUDIS} \]  
\[ \text{ (417-R)} \]

where

\[ R\text{SUBT10} = \text{IMU disassembly labor cost rate} \]
IMUDISR = IMU disassembly rate
CIMUDIS = IMU disassembly cost per IMU = 200

\[ \text{SUBT10.} \text{K} = \text{SUBT10.} \text{J} + (DT)(\text{RSUBT10.} \text{JK}) \] (418-L)

where

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

(i) **IMU field failure identification test cost**

\[ \text{RSUBT2.} \text{KL} = \text{TIMUV} \times (\text{VFECAT1.} \text{JK} + \text{VFECAT2.} \text{JK} + \text{VFECAT3.} \text{JK}) \] (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

\[ \text{SUBT2.} \text{K} = \text{SUBT2.} \text{J} + (DT)(\text{RSUBT2.} \text{JK}) \] (424-L)

where

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

(j) **IMU field failure disassembly labor cost**

\[ \text{RSUBT11.} \text{KL} = (\text{DFFCAT1.} \text{JK} + \text{DFFCAT2.} \text{JK} + \text{DFFCAT3.} \text{JK}) \times \text{CIMUDIS} \] (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

\[ \text{SUBT11.} \text{K} = \text{SUBT11.} \text{J} + (DT)(\text{RSUBT11.} \text{JK}) \] (430-L)

where

SUBT11 = gyro field failure-identification labor cost rate

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

\[ \text{RSUBT7.} \text{KL} = \text{FECAT1.} \text{JK} \times \text{GFVCAT1} + \text{FECAT2.} \text{JK} \times \text{GFVCAT2} + \text{FECAT3.} \text{JK} \times \text{GFVCAT3} \] (433-R)
where

\[ \text{RSUBT7} = \text{gyro field failure-identification labor cost rate} \]
\[ \text{FECAT1,2,3} = \text{gyro failure rate in the field - categories 1,2,3} \]
\[ \text{GFVCAT1,2,3} = \text{gyro failure-identification test labor cost per gyro - categories 1,2,3} \]
\[ = 300, 700, 1000 \]

\[ \text{SUBT7} = \text{subtotal cost of gyro field failure-identification test labor} \]

(1) **IMU acceptance test cost**

\[ \text{RSUBT8. KL} = (\text{IMUACC. JK} + \text{IMUNACC. JK}) \times \text{STCOST} \]  
where

\[ \text{RSUBT8} = \text{IMU acceptance test labor cost rate} \]
\[ \text{IMUACC} = \text{accepted IMU rate} \]
\[ \text{IMUNACC} = \text{not accepted IMU rate} \]
\[ \text{STCOST} = \text{IMU acceptance test labor cost per acceptance test} \]
\[ = 2000 \]

\[ \text{SUBT8. K} = \text{SUBT8. J} + (\text{DT})(\text{RSUBT8. JK}) \]

where

\[ \text{SUBT8} = \text{subtotal cost of IMU acceptance test labor} \]

(m) **IMU assembly cost**

\[ \text{RSUBT9. KL} = \text{IMUWAIT. JK} \times \text{IMUASSC} \]  
where

\[ \text{RSUBT9} = \text{IMU assembly labor cost rate} \]
\[ \text{IMUWAIT} = \text{rate of IMU's to waiting stack} \]
\[ \text{IMUASSC} = \text{IMU assembly labor cost per IMU} = 300 \]

\[ \text{SUBT9. K} = \text{SUBT9. J} + (\text{DT})(\text{RSUBT9. JK}) \]

where

\[ \text{SUBT9} = \text{subtotal cost of IMU assembly labor} \]
(n) **Total cost counter**

\[ P1_{KL} = RSUBT1_{JK} + RSUBT2_{JK} + RSUBT3_{JK} + RGRLAB_{JK} + RGRMAT_{JK} + RSUBT5_{JK} \]

\[ P2_{KL} = RSUBT6_{JK} + RSUBT7_{JK} + RSUBT8_{JK} + RSUBT9_{JK} + RSUBT10_{JK} + RSUBT11_{JK} \]

\[ P3_{KL} = RSUBT12_{JK} \]

\[ COST_{K} = COST_{J} + (DT)(P1_{JK} + P2_{JK} + P3_{JK}) \]

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:

\[ COST = TCAP \times TCCOST + OTHER \]

where

- **TCAP** = capacity of gyro acceptance-test area
- **TCCOST** = cost per unit gyro test capacity = 300,000
- **OTHER** = cost of other tools and equipment = 1,042,000
In order to calculate the cost per IMU per day in the field, a counter for
days in the field is required.

\[
\text{DAYINF}.K = \text{DAYINF}.J + (DT)(\text{RFIELD}) \tag{461-L}
\]

\[
\text{RFIELD} . KL = \min (\text{FIELD} . K, \text{MAXFLD}) \tag{462-R}
\]

where

\[
\begin{align*}
\text{DAYINF} &= \text{IMU-days in the field} \\
\text{RFIELD} &= \text{rate of accumulation of days in the field in IMU-days} \\
\text{FIELD} &= \text{actual inventory of IMU's in the field} \\
\text{MAXFLD} &= \text{maximum desired number of IMU's in the field} = 1050 \tag{463-C}
\end{align*}
\]

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:

\[
\text{CPERDY}.K = \frac{\text{COST}.K}{(\text{DAYINF}.K + 1)} \tag{469-A}
\]

where

\[
\begin{align*}
\text{CPERDY} &= \text{cost per IMU per day in the field} \\
\text{COST} &= \text{total cost of the program} \\
(\text{DAYINF}.K + 1) &= \text{number of IMU-days in the field plus 1 (where the one}
\text{additional day starts the problem and avoids a division}
\text{by zero until one IMU is actually delivered to the field)}
\end{align*}
\]

3.17 Output: Printed and Graphic

The output sector requires four constants:

\[
\begin{align*}
\text{LENGTH} &= 5400 \tag{478-C} \\
\text{DT} &= 1 \tag{479-C} \\
\text{PRTPER} &= 180 \tag{480-C} \\
\text{PLTPER} &= 180 \tag{481-C}
\end{align*}
\]

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:

\[
\begin{align*}
\text{PRINT} &\quad 1) \text{COST} / 2) \text{DAYINF} / 3) \text{CPERDY} / (0.3)/ 4) \text{FIELD} / 5) \text{GYROW} / 6) \text{IMUWAIT} / 7) \text{TFFWAIT} \\
\text{PRINT} &\quad 1) \text{NEWSETS} / 2) \text{ACNPW} / 3) \text{DINAS} / 4) \text{TCORREC} / 5) \text{CORREC} / 6) \text{GYRCAS} / 7) \text{AVAGE} \\
\text{PRINT} &\quad 1) \text{SUBT1} / 2) \text{SUBT2} / 3) \text{GRMAT} / 4) \text{GRLAB} / 5) \text{SUBT3} / 6) \text{SUBT4} / 7) \text{SUBT5} / 8) \text{RATIO} \\
\text{PRINT} &\quad 1) \text{SUBT5} / 2) \text{SUBT6} / 3) \text{SUBT7} / 4) \text{SUBT8} / 5) \text{SUBT9} / 6) \text{SUBT10} / 7) \text{SUBT11} \\
\text{PLOT} &\quad \text{FIELD} = F / \text{FCAT1} = 1, \text{FCAT2} = 2, \text{FCAT3} = 3, \text{TFFWAIT} = W / \text{AVAGE} = A \\
\text{PLOT} &\quad \text{COST} = $ / \text{SUBT1} = 1, \text{SUBT2} = *, \text{SUBT3} = 2, \text{SUBT4} = 4, \text{SUBT5} = 5, \text{SUBT6} = 6 \\
\text{PLOT} &\quad \text{COST} = $ / \text{SUBT7} = 7, \text{SUBT8} = 8, \text{SUBT9} = 9, \text{SUBT10} = 0, \text{SUBT11} = 1, \text{GRLAB} = L, \text{GRMAT} = M \\
\text{PRINT} &\quad 1) \text{VFECAT1} / 2) \text{VFECAT2} / 3) \text{VFECAT3} / 4) \text{INFLOW} / 5) \text{GYROTT} / 6) \text{COST} / 7) \text{GYROW} \\
\text{PLOT} &\quad \text{DINAS} = 1 / \text{DINFLD} = F / \text{ERROR} = E / \text{CORREC} = C / \text{NEWSETS} = N / \text{RCDIS} = D, \text{CRAS} = A \\
\text{PLOT} &\quad \text{GYROAS} = G / \text{TIGDIS} = D / \text{TGLGREAS} = R / \text{GYROAT} = T / \text{IMUASS} = S / \text{IMUDIS} = A / \text{IMUTTA} = B \\
\text{PLOT} &\quad \text{IMUACC} = A, \text{IMUNACC} = N / \text{GYACC} = 1, \text{GYNACC} = 2 / \text{ASSGYG} = G, \text{ASSGYB} = B
\end{align*}
\]

41
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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 have 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, within 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 the 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 with 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 maximum 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 courtes 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".
<table>
<thead>
<tr>
<th>Operation</th>
<th>elapsed time in days</th>
<th>labor cost in dollars</th>
<th>material cost in dollars/gyro</th>
<th>tools and equipment for 5 gyros/day yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>gyro assembly (new sets)*</td>
<td>30</td>
<td>5000</td>
<td>7000</td>
<td>$1,042,000</td>
</tr>
<tr>
<td>gyro reassembly</td>
<td>9</td>
<td>600</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>cat. 2</td>
<td>15</td>
<td>2000</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>cat. 3</td>
<td>30</td>
<td>4000</td>
<td>2800</td>
<td></td>
</tr>
<tr>
<td>gyro disassembly</td>
<td>NA</td>
<td>100</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>cat. 1</td>
<td>7</td>
<td>500</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>cat. 3</td>
<td>10</td>
<td>1200</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>gyro failure - identification tests - cat. 1</td>
<td>7</td>
<td>300</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>cat. 2</td>
<td>8</td>
<td>700</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>cat. 3</td>
<td>8</td>
<td>1000</td>
<td>NA</td>
<td>$1,042,000</td>
</tr>
<tr>
<td>&quot;good&quot;</td>
<td>7</td>
<td>1000</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>gyro acceptance tests</td>
<td>25</td>
<td>2000</td>
<td>NA</td>
<td>$7.5 \times 10^6 0.7</td>
</tr>
<tr>
<td>IMU assembly (gyro portion)</td>
<td>7</td>
<td>300</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>IMU disassembly</td>
<td>7</td>
<td>200</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>IMU failure-verification tests (gyro portion)</td>
<td>12</td>
<td>400</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>IMU acceptance tests (gyro portion)</td>
<td>12</td>
<td>2000</td>
<td>NA</td>
<td>0.9</td>
</tr>
</tbody>
</table>

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 (FCTR2 = 0.6), and 10% are assumed to be category 3 (FCTR3 = 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.
Inertial measurement units vs time for zero failures and unity yields.

Figure 5.1
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 $4.71 \times 10^6$, 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 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. 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:

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

* All the code names are defined in Appendix A.
A summary of the above costs can be presented as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>$ \times 10^6</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>parts and material</td>
<td>43.9</td>
<td>27.9</td>
</tr>
<tr>
<td>tools and equipment</td>
<td>8.5</td>
<td>5.4</td>
</tr>
<tr>
<td>labor</td>
<td>105.1</td>
<td>66.7</td>
</tr>
<tr>
<td>Total</td>
<td>$157.5</td>
<td>100.0</td>
</tr>
</tbody>
</table>

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.
NOTES:
1) IMU YIELD = 0.9
2) IMU FAILURE RATE = 0.5/YEAR
3) THREE GYROS PER IMU

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.

* 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.
NOTES:
1) YIELD = 0.7
2) IMU FAILURE RATE = 0.5/YEAR
3) THREE GYROS PER IMU

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

* 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, gyro reliability for an aircraft inertial navigator was estimated at 15,000 gyro operating hours between "unscheduled removals".

Another example can be cited 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. 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 $0.10 \times 10^6$ per percent for the gyro acceptance-test yield and $0.16 \times 10^6$ per percent for the IMU acceptance-test yield.
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.
## JRYO COST ANALYSIS

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Figure 5.9 Results of reference run - Page 1.
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| 28.941 | 18.038 | 12.814 | 1139.0 | 3457.9 | 17.641 |
| 288.12 | 18.872 | 2119.7 | 8.584 | 1293.4 | 85.61 | 575.7 |
| .27827 | .55613 | .55613 | 2.2075 | 2.2075 | 112.11 | 2.21 |

| 3240 | 115.61 | 2243.2 | 51.536 | 999.40 | 2.21 | 1.5444 | 4.556 | 1.0012 |
| 1.0000 | 3617.9 | .0000 | 0. | 0. | 0.02 | 670.09 |
| 28.941 | 13.088 | 8.858 | 14.619 | 1239.0 | 3702.3 | 22.019 |
| 306.48 | 19.264 | 2304.5 | 9.140 | 1239.0 | 3702.3 | 22.019 |
| .27795 | .55589 | .55589 | 2.2062 | 2.2062 | 115.61 | 2.21 |

| 3420 | 119.10 | 2423.0 | 49.153 | 999.54 | 2.21 | 1.5439 | 4.334 | 1.0007 |
| 1.0000 | 3617.9 | .0000 | 0. | 0. | 0.02 | 649.23 |
| 28.941 | 18.038 | 8.858 | 14.619 | 1238.9 | 3946.9 | 23.477 |
| 325.44 | 20.506 | 2484.4 | 9.695 | 1460.1 | 96.72 | 677.6 |
| .27784 | .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 |
| 1.0000 | 3617.9 | .0000 | 0. | 0. | 0.02 | 669.95 |
| 26.941 | 18.038 | 9.413 | 15.521 | 1438.3 | 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 | 999.45 | 2.20 | 1.5435 | 4.132 | 1.0003 |
| 1.0000 | 3617.9 | .0000 | 0. | 0. | 0.02 | 701.23 |
| 28.941 | 18.038 | 9.413 | 15.521 | 1538.7 | 4435.9 | 26.391 |
| 363.14 | 21.640 | 2858.1 | 10.807 | 1626.7 | 107.82 | 767.6 |
| .27782 | .55564 | .55564 | 2.2049 | 2.2049 | 126.99 | 2.20 |

| 3960 | 129.58 | 2962.5 | 43.740 | 999.70 | 2.20 | 1.5434 | 4.039 | 1.0002 |
| 1.0000 | 3617.9 | .0000 | 0. | 0. | 0.02 | 705.35 |
| 28.941 | 18.038 | 10.523 | 17.324 | 1638.6 | 4680.3 | 27.947 |
| 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.
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Figure 5.12 Results of reference run - Page 4.
Figure 5.13 Results of reference run - Page 5.
JRYO COST ANALYSIS

COST=$, SUBT1=1, SUBT2=2, SUBT3=3, SUBT4=4, SUBT5=5, SUBT6=6

Figure 5.14  Results of reference run - Page 6.
Figure 5.15 Results of reference run - Page 7.
Figure 5.16 Results of reference run - Page 9.
Figure 5.17 Results of reference run - Page 8.
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% ($70 \times 10^6$) 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 $15 \times 10^6$ 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 ($-0.3\% \text{ per } 1\%$) 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 ($-1\% \text{ per } 1\%$) 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.

* 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. Little, if anything, has been done in the application of optimal control theory. 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

<table>
<thead>
<tr>
<th>Code</th>
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<th>Definition</th>
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<td>*</td>
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<td>----</td>
<td>multiplication</td>
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<tr>
<td>A</td>
<td></td>
<td>A</td>
<td>auxiliary equation—a component equation of a rate equation</td>
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<td>ACNEW</td>
<td>37</td>
<td>L</td>
<td>accumulated new sets of gyro parts started</td>
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<td>average error in the inventory in the field equal to the previous error + (delta time) (1/smoothing time) (error rate minus the average error)</td>
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<td>C</td>
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<td>C</td>
<td>constant</td>
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<td>gyros per day capacity per gyro test unit</td>
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<td>CPERDY</td>
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<td>cost per day in field per IMU</td>
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†A = auxiliary, C = constant, L = level, N = initial value, R = rate (Ref. 17)
A correction which equals the average error times the gain times three

days in field in IMU's (3 gyros per IMU)
initial value of days in field in IMU's
disassembly labor cost per gyro-category 1
disassembly labor cost per gyro-category 2
disassembly labor cost per gyro-category 3
third order delay
table of desired inventory in field in IMU's as a function of time
gyro field-failure rate from IMU disassembly-category 1
gyro field-failure rate from IMU disassembly-category 2
gyro field-failure rate from IMU disassembly-category 3
desired initiation of assembly
desired inventory in the field in IMU's
desired starts of new gyro sets (tabulation)
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 in inventory in field in IMU's equals desired inventory in field minus actual inventory in field
fraction not accepted from original test-category 1
fraction not accepted from original test-category 2
fraction not accepted from original test-category 3
field failures per day in gyros (one gyro per IMU)-category 1
field failures per day in gyros (one gyro per IMU)-category 2
field failures per day in gyros (one gyro per IMU)-category 3
rate of gyro field failures verified-category 1
rate of gyro field failures verified-category 2
rate of gyro field failures verified-category 3
actual inventory of IMU's in the field
initial value of IMU's in the field
table for stacking field failures
gyro's in reassembly-category 1
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<td>initial value of gyros in IMU assembly</td>
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APPENDIX B

THE PROGRAM
NOTE: PETTER PALMER  MARCH 197C
NOTE: PETCO010
NOTE: PETCO020
NOTE: PETCO030
NOTE: PETCO040
NOTE: PETCO050
NOTE: PETCO060
NOTE: PETCO080
NOTE: PETCO090
NOTE: PETCO100
NOTE: PETCO110
NOTE: PETCO120
NOTE: PETCO130
NOTE: PETCO140
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NOTE: PETCO480
NOTE: PETCO490
NOTE: PETCO500
NOTE: PETCO510
NOTE: PETCO520
NOTE: PETCO530
NOTE: PETCO540
NOTE: PETCO550

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NOTE THERE MAY BE BACKLOG FOR TESTING
NOTE TESTING REQUIRES LARGE INVESTMENT PER CAPACITY
NOTE TWO INPUTS TO LEVEL- NEWLY ASSEMBLED GYROS (ASSGY) AND RETURNS
NOTE FROM GYROS REASSEMBLY CATEG 1, 2, 3 (GARCAT1, GARCAT2, GARCAT3)
NOTE OUTFLOW IS GYROS MOVED INTO GYRO TEST AREA
L GYROW.K=GYRCW.J*(ET) (INFLOW.JK-GYRCTT.JK) GYROS WAITING FOR TEST
N GYRO=0 INITIAL VALUE GYROS WAITING FOR TEST
NOTE
NOTE GYRO ACCEPTANCE TEST
NOTE TCAP IS TESTING CAPACITY OF GYFC
NOTE NUMBER OF GYROS THAT CAN FIT IN AREA AT ANY TIME
NOTE NUMBER OF CAPACITY UNITS (100K) EACH GOOD FCR 6 GYROS A MONTH
NOTE GYROS IN TEST AREA INCREASED BY GYROS MOVED TO TEST (GYRCTT)
NOTE DECREASED BY GYROS TESTED AND ACCEPTED (GYNACC)
NOTE AND BY GYROS TESTED AND NOT ACCEPTED (GYNACC)
NOTE GYROAT=0 INITIAL VALUE GYROS IN TEST AREA
NOTE WILL MOVE AS MANY AS POSSIBLE OF WAITING GYRCS TO TESTING AREA
R GYBOAT.K=MAX(TCAP*CAPYLD,GYBCW.K) GYRCS TO TESTING AREA
C CAPYLD=.2 6 GYROS/MONTH CAP PER CAPACITY UNIT-.2/DAY
NOTE GYRO TEST ACCEPTS OR REJECTS GYRCS
R GYACC.KI=DELA13(GYRCTT.K,GYAT)*YIELD
C YIELD=.7 FRACTION GYROS ACCEPTED
R GYNACC.KI=DELA13(GYBOAT.K,GYAT)* (1-YIELD) NOT ACCEPTED.
NOTE GYROS DISASSEMBLY SECTOR
NOTE GYROS FALL INTO 3 CATEGORIES
NOTE IN EACH CATEGORY THERE ARE REJECTED GYRCS FROM THE ORIGINAL
NOTE GYRO TEST, REJECTED GYRCS FROM IMU TEST, AND REJECTED
NOTE GYROS FROM FIELD FAILURES
NOTE CATEGORY 1 OUTSIDE MAIN HOUSING
NOTE GYROS IN DISASSEMBLY CATEGORY 1
NOTE THREE SOURCES
NOTE GYROS NOT ACCEPTED FROM GYRO TEST ARE DIVIDED BETWEEN
R INCAT1.KL=GYNACC.JK*FCTR1+SDGCAT1.JK+FFCAT1.JK INFLOW TO DIS. CAT1
NOTE GYACC*FCTR1 RECM ORIG GYRO TEST
NOTE SDGCAT1 FROM IMU TEST FAILURES (CAT1)
NOTE PFCAT1 FROM FIELD FAILURES
N DCAT1=0 INITIAL VALUE
C FCTR1=.3 FRACTION NOT ACCEPTED FROM OBG TEST TO CAT 1
NOTE
NOTE RATE OF DISASSEMBLY CAT1
R GRCAT1.K=INCAT1.JK - SMALL DECEY IN DISASS CAT1
NOTE
NOTE GYRO RF-ASSEMBLY CATEGORY 1
N GACAT1=0 INITIAL VALUE GYRO REASSEMBLY CATEGORY 1
NOTE
NOTE GYRO REASSEMBLY RATE CATEGORY 1
R GRCAT1.KI=DELAY3(GRCAT1.JK,TASC1) GYRO REASSEMBLY CAT 1
C TASC1=9 TIME TO BE ASSEMBLE CATEGORY 1 GYRO FAILURE
NOTE
NOTE
NOTE CATEG 2 MAIN HOUSING TO FLOAT
NOTE
NOTE GYROS IN DISASSEMBLY CATEGORY 2
NOTE INFLOW AGAIN HAS THREE COMPONENTS
NOTE SEE DESCRIPTION FOR CATEGORY 1 ABOVE
R INCAT2.KL=GYNACC.JK*FCTR2+SDGCAT2.JK+FFCAT2.JK
NOTE
NOTE GYNACC*FCTR2 FROM ORIGINAL GYRO TEST NO ACCEPT
NOTE
NOTE SDGCAT2 FROM IMU TEST FAILURES
NOTE
NOTE)
NOTE FFCAT2 FROM FIELD FAILURES
NOTE
NOTE GYROS IN DISASSEMBLY CATEGORY 2
L GDRCAT2.K=GDCAT2.JK+ (DT) (INCAT2.JK-GRCAT2.JK)
N GDCAT2=0 INITIAL VALUE GYROS IN DISASSEMBLY CATEGORY 2
NOTE
C FCTR2=.6 FRACTION ORIGN. GYRO ACC. REJECTS TO CATEG 2
NOTE
NOTE GYRO DISASSEMBLY RATE CATEGORY 2
R GRCAT2.KL=INCAT2.JK-TASC2) GYRO DISAS RATE CATEG2
C TASC2=7 TIME TO DISASSEMBLY CATEG 2 GYRO FAILURES
NOTE
NOTE
NOTE CATEG 2 REASSEMBLY LEVEL
NOTE GYROS IN REASSEMBLY CATEGORY 2
L GACAT2.K=GACAT2.JK* (DT) (GDRCAT2.JK-GARCAT2.JK)
N GACAT2=0 INITIAL VALUE GYROS IN REASSEMBLY CATEGORY 2
NOTE
NOTE GYRO REASSEMBLY RATE CATEGORY 2
R GARCAT2.KI=DELAY3(GRCAT2.JK,TASC2) REASSEMBLY RATE CAT 2
C TASC2=15 TIME TO RE-ASSEMBLY CATEGORY 2
NOTE
NOTE
NOTE CATEG 3 INSIDE FLOAT
NOTE
NOTE GYROS IN DISASSEMBLY CATEGORY 3
NOTE THREE SOURCES - SEE DESCRIPTION FOR CATEGORY 1 ABOVE
NOTE
NOTE TOTAL INFLOW TO GYRO DISASSEMBLY CATEGORY 3
R INCAT3.KL=GYNACC.JK*FCTR3+SDGCAT3.JK+FFCAT3.JK
NOTE
NOTE GYNACC*FCTR3 FROM ORIGINAL GYRO TEST REJECTS
NOTE SDGCAT3 FROM IMU TEST FAILURES
NOTE
NOTE FFCAT3 FROM FIELD TEST FAILURES
NOTE

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N GECAT3=0 INITIAL VALUE GYROS IN DISSASSEMBLY CATEGORY 3
C FCTR3=.1 FRACTION OF GYROS REJECTS GFC ACC TEST TO CAT 3
NOTE
R GERCAT3,KL=DELAY3,GECAT3.JK=TDCAT3 DIS. RATE PCG CATEGORY 3
C TDCAT3=10 TIME TO DISSASSEMBLY CATEGORY 3
NOTE
NOTE GYROS IN DISSASSEMBLY CATEGORY 3
L GACAT3,J=GACAT3,J+GECAT3,J GYROS TEST
C GACAT3=0 INITIAL VALUE
NOTE
F GERCAT3,KL=DELAY3,GECAT3.JK=GACAT3.JK REASSEMBLY CAT 3
C TASC3=30 TIME TO REASSEMBLY CATEGORY 3
NOTE
NOTE SUPPLEMENTARY EQUATIONS FOR OUTPUT
NOTE
NOTE TOTAL GYROS IN DISSASSEMBLY -- OUTPUT VARIABLE
NOTE
NOTE TOTAL DISSASSEMBLY AND REASSEMBLY RATES
A RCIS.K=GERCAT1.JK+GERCAT2.JK+GERCAT3.JK
A RCRAS.K=GACAT1.JK+GACAT2.JK+GACAT3.JK
NOTE
NOTE GYROS IN IMU ASSEMBLY
NOTE ACCEPTABLE GYROS FROM GYR ACCEPTANCE TEST (GYACC)
NOTE PLUS ANY GOOD GYROS FROM IMU TEST FAILURE DISSASSEMBLY (GCDSEF)
NOTE PLUS ANY GOOD GYROS FROM IMU TEST FAILURE DISSASSEMBLY (GOODF)
NOTE ARE FABRICATED INTO IMUS-- ФЕАСЕМЕЛЬ DELAY IS 3 GYROS IN IMUS
L IMUASS.K=IMUASS.J+3 (IT) (GYACC.JK+GOODSF.JK+GOODF.JK+GINMU.JK) GYROS IN IMU
N IMUASS=0 INITIAL VALUE
NOTE
R GINIMU.KL=DELAY3,GYACC.JK+GOODSF.JK+GOODF.JK+GINMU.J, TASIIMU) GYROS INTO IMU
C TASIIMU=7 TIME TO ASSEMBLE GYROS INTO IMU
NOTE
NOTE STACK FOR IMU ACCEPTANCE TESTS
NOTE MUST EXPRESS INFLOW IN TERMS OF IMUS-- 3 GYROS/IMU
L IMUWT.K=IMUWT.JK+DT) IMU WAITING, JK-IMUTST.JK) IMUS WAITING
N IMMWT=0 INITIAL VALUE IMUS WAITING FOR IMUS TEST
R IMUWAIT.KL=GINIMU.JK/3 IMUS TO WAIT STACK-- 3 GYROS FED IMU
NOTE
NOTE IMUS IN TEST AREA
NOTE MOVES IN IMUS WAITING TO BE TESTED, INFLOW IS OK IMUS
NOTE (IMUACC) AND REJECTED IMUS (IMUNACC)
L IMUTST.K=IMUTST.JK+4 (IT) IMUTST.JK-IMUACC.JK-IMUNACC.JK) IMUS IN TEST
R IMUTST=0 INITIAL VALUE IMUS IN TEST AREA
NOTE
NOTE WILL PCFV INTO TEST AREA AS MANY IMUS AS POSSIBLE
NOTE BUT THERE MAY BE A CAPITAL/CAPACITY CONSTRAINT
NOTE CAPAC IS CAPACITY OF TEST AREA
F IMUTST.K=MIN(IMUWT.K,CAFC) IMUS TO TEST AREA RATE
C CAPAC=10 CAPACITY OF IMUS TEST AREA IN IMUS
NOTE
NOTE OUTPUT OF IMUS TEST IS ACCEPT, IMUS AND REJECTED IMUS
F IMUACC.K=DELAY3,IMUTST.JK,TTIMU)*IMUACC ACCEPTED IMUS

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C TITMU=12 TIME TC TEST IMUS
B IMUNACC.KL=DELAY3(IMUTST.JK,TITMU)*(1-IMUYLD)
NOTE
C IMUYLD=.9 IMU TEST YIELD RATIO--GOOD IMUS
NOTE
NOTE IMU TEST REJECTS ARE DISASSEMBLED (REMEMBER 3 GYROS/IMU)
NOTE AND SEPARATED INTO FAILURE CATEGORIES 1, 2, 3 FOR GYRO DISASSEMBLY
NOTE
NOTE IMUS DISASSEMBLY
NOTE
NOTE INFLOW IS NOT ACCEPTED IMUS FROM IMU TEST
NOTE
NOTE INFLOW IS IMU DISASSEMBLY RATE
NOTE
L IMUCIS.K=IMUCIS.J*(1-TM) (IMUNACC.JK-IMUDISR.JK)
N IMUDIS=0 INITIAL VALUE IMU DISASSEMBLY
NOTE
R IMUDISR.KL=DELAY3(IMUNACC.JK,TVDIS) IMU DISASS RATE
C TVDIS=7 TIME TO DISASSEMBLE IMUS
NOTE
NOTE Sort CATEGORIES
NOTE IMU DISASSEMBLIES DIVIDED TO GYRO FAILURE TYPES
NOTE AFTER GYRO FAILURE VERIFICATION DELAY
NOTE FACTORS SFCAT1, SFCAT2, SFCAT3 SORT IMU FAILURES
NOTE INTO APPROPRIATE GYRO FAILURE CATEGORIES
NOTE
L SIGCAT1.KL=DELAY3(SFCAT1,IMUDISR.JK,TVCAT1) CAT1 BAD GYROS
R SIGCAT2.KL=DELAY3(SFCAT2,IMUDISR.JK,TVCAT2) CAT2 BAD GYROS
R SIGCAT3.KL=DELAY3(SFCAT3,IMUDISR.JK,TVCAT3) CAT3 BAD GYROS
R GOOGSF.KL=DELAY3(IMUDISR.JK,TVGOOD) GOOD GYROS FICT IMU FAIL
NOTE
NOTE DELAY TIMES FOR GYRO VERIFICATION
C TVCAT1=7 TIME VERIF. CAT1 GYRO FAILURE
C TVCAT2=8 TIME VERIF. CAT2 GYRO FAILURE
C TVCAT3=8 TIME VERIF. CAT3 GYRO FAILURE
C TVGOOD=7 TIME VERIF. GOOD GYRO IS IMU FAILURE
NOTE
C SFCTR1=.25 TWO GOOD GYROS IN EVERY IMU BY ASSUMPTION
NOTE CATEGORIES FAILURE PERCENTAGES FROM IMU TEST REJECTS
C SFCTR2=.6
C SFCTR3=.25
NOTE THE SORT FACTORS SHOULD ADD TO 3 NUMBER OF GYROS/IMU
NOTE
NOTE FIELD INVENTORY
NOTE
NOTE INFLOW IS ACCEPTED IMUS FROM IMUS TEST
NOTE OUTFLOW IS FIELD BREAKDOWNS--TC1BBF,JK
L FIELD.K=FIELD.J*(1-TM) (IMUNACC.JK-TC1BBF.JK) FIELD INVENTORY
N FIELD=0 INITIAL VALUE FIELD
NOTE
NOTE WILL NEED MEASURE OF AVERAGE AGE OF IMUS IN FIELD TO
NOTE ESTIMATE BREAKDOWN PROBABILITIES
NOTE RUNNING TOTAL ACCUMULATED AGE IN FIELD

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NOTE AVERAGE AGE IN FIELD

NOTE MAX FUNCTION TO AVOID DIVISION BY ZERO

NOTE PROBABILITY OF FAILURE CALCULATIONS FOR THREE FAILURE CATEGORIES

NOTE AVERAGE/360 IS AVERAGE AGE IN YEARS

NOTE MUST SCALE FOR DAILY RUN

NOTE ACTUAL NUMBER FAILURES BY CATEGORY

NOTE FIRST GET PERCENT OF TODAY'S FAILURES TO STACK AND TO REPAIR

NOTE INVENTORIES OF FIELD FAILURE IMUS BY FAILURE TYPE

NOTE THE OUTFLOWS FROM THE WAIT FOR REPAIR INVENTORIES

NOTE ARE FRACTION OF TODAY'S FAILURES (BUT NOT MORE THAN TOTAL WAITING)

NOTE TOTAL IMUS WAITING FOR REPAIR
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NOTE REASSEMBLY MATERIAL COSTS
R RGRMAT.KL=GARCAT1.JK*RMCAT1+GARCAT2.JK*RMCAT2+GARCAT3.JK*RMCAT3
L GMAT.K=GRMAT.J*(DT) (RGRMAT.JK) MAT SUB TOTAL
N GRMAT=0
C RMCAT1=400 MATERIAL COST CAT1
C RMCAT2=1000 MATERIAL COST CAT2
C RMCAT3=2000 MATERIAL COST CAT3
NOTE REASSEMBLY LABOR COST
R RGRLAB.KL=GARCAT1.JK*RCAT1+GARCAT2.JK*RCAT2+GARCAT3.JK*RCAT3
L GFLAE.K=CLAE.J+(DT) (RGRLAE.JK) LAE SUB TOTAL
C RCAT1=600 LABOR COST CAT1
C RCAT2=2000 LABOR COST CAT2
C RCAT3=4000 LABOR COST CAT3
A SUBT4.K=GRMAT.K*RGRLAB.K
NOTE
NOTE IMU FAILURE DISASSEMBLY AND VERIFICATION COST
R RSUBT5.KL=SDGCAT1.JK*GFVCAT1+SDGCAT2.JK*GFVCAT2+SDGCAT3.JK*GFVCAT3
N SUBT5=0
C GFVCAT1=300
C GFVCAT2=700
C GFVCAT3=1000
NOTE
NOTE GYRO ACCEPTANCE TEST COST
R RSUBT6.KL=(GYACC.JK+GYNACC.JK)*GACTC
N SUBT6=0
C GACTC=2000
NOTE
NOTE IMU DISASSEMBLY COST
R RSUBT7.KL=IMUDISR.JK*CIMUDIS
N SUBT7=0
C CIMUDIS=200 COST OF IMU DISASSEMBLY
NOTE
NOTE IMU FIELD FAILURE VERIFICATION TEST COST
N SUBT8=0
NOTE
NOTE IMU ACCEPTANCE TEST
R RSUBT9.KL=(IMUACC.JK+IMUNACC.JK)*STCOST
N SUBT9=0
NOTE
NOTE FIELD IMU FAILURE DISASSEMBLY COST
R RSUBT10.KL=IMUDISF.JK*CIMUDISF
N SUBT10=0
C CIMUDISF=200 COST OF IMU DISASSEMBLY
NOTE
NOTE FIELD IMU FAILURE VERIFICATION TEST COST
R RSUBT11.KL=(FFCAT1.JK+FFCAT2.JK+FFCAT3.JK)
N SUBT11=0
NOTE
NOTE FIELD FAILURE DISASSEMBLY AND VERIFICATION COSTS
N SUBT12=0
NOTE
NOTE IMU ACCEPTANCE TEST
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C S1COST=2000 IMU ACCEPTANCE TEST CCST/IMU
NOTE
NOTE IMU ASSEMBLY CCST
R RSUET9,KL=IMUWAIT,JK*IMUASSC NOTE IN NUMBER IMUS NOT GYROS
L SUBT9,K=SUBT9,J+(IT) (RSUET9,JK) ACCUM SUETOTAL 9
NOTE
NOTE TOTAL COST COUNTER
R P1,KL=RSUBT1,JK+RSUET2,JK+RSUBT3,JK+RSUET4,JK+RSUET5,JK
R P2,KL=RSUBT6,JK+RSUET7,JK+RSUET8,JK+RSUET9,JK+RSUET10,JK+RSUBT11,JK
L COST,K=COST,J+(IT) (P1,JK+P2,JK) TOTAL ACCUM COST
NOTE
NOTE CCST/K=COST,J+(IT) (P1,JK+P2,JK+F3,JK)
TOTAL ACCUM COST
NOTE
NOTE TOTAL COST--CAPITAL EXPENSE.
R COST=CAP*CCST
NOTE
NOTE TWO COMPONENTS--GYRO TEST CAP=CCST30000
NOT INCLUDE GYRO TEST
NOTE
NOTE TOTAL COST--OTHER CAPITAL CCST
NOTE
NOTE NOTE COSTS TO DAYS IN FIELD PATTC
NOTE
NOTE CPERDY,K=CCST,K/(DAYINF,K+1.) CCSTS PER DAY IN FIELD
NOTE
NOTE WHICH CONFUSES THE COMPUTER. REMEMBER IT TAKES SOME TIME
NOTE
NOTE TO GET ANY COMPLETED SYSTEMS INTO THE FIELD
NOTE
NOTE
NOTE OUTPUT SECTION
NOTE SPECIFICATION CARES
NOTE
NOTE LENGTH=5400
C DT=1.
C PITPEP=180
C PIBUP=180
NOTE
PRINT 1) COST/2) DAYINF/3) CPERDY (1. J. 3/4) FIELD/5) GYRO/6) IMUWAIT/7) TFFWAIT
PRINT 1) NEWSETS/2) ACNF/3) DINAS/4) TCCORREC/5) CORREC/6) GYRAS/7) AVGAGE
PRINT 1) SUET1/2) SUBT1/3) GGMAT/4) GGLAP/5) SUBT2/6) SUBT3/7) SUBT4/8) QAORT
PRINT 1) SUET5/2) SUBT5/3) SUBT7/4) SUBT9/5) SUBT6/6) SUBT10/7) SUBT11
PRINT 1) VFECAT1/2) VFECAT2/3) VFECAT3/4) INFLOW/5) GYRATE/6) COST/7) GYROW
PRINT 1) DINAS=I/EINFLD=F/ERROR=E/CORREC=C/NEWSETS=N/SCDS=E/RERAS=A
PRINT 1) GYRAS=G/TIGEIS=C/LIGEIS=R/GYMAT=Y/IMUASS=S/IMUWAIT=A/IMUTTA=B
PRINT IMUACC=A,IMUNACC=B/GYACC=1,GYBACC=2/ASSGYG=G,ASSGYB=B
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