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EXTENDING THE LIFETIME OF OPERATIONAL SYSTEMS THROUGH CORROSION TRACKING AND PREDICTION

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Corrosion tracking using the USAF Maintenance Data Collection System was extended to the B-52 fleet, another system of large but elderly aircraft in USAF inventory. This and a study of the C-141A fleet show that MDCS data, together with PACER LIME environmental severity ratings, could provide a basis for optimizing corrosion maintenance, extending operational life of the systems and minimizing overall costs. MDCS is seriously defective, however, and these benefits can not be realized with current data. Changes in USAF maintenance

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) policy, essentially the adoption of reliability-centered, phased inspections, also have produced a different MDCS. These changes are not suitable to the unique problems of corrosion, although the new system may be an improvement with respect to other maintenance requirements.

FOREWORD

This report summarizes several persons' effort, in addition to that of the authors. Mr. Richard Balbierz and Mr. Ted Kozan, of the Boeing Military Airplane Company, contributed to developing the airplane special inspection, and Mr. Kozan participated in analyzing the results. We have had continuing cooperation and encouragement from many people in USAF, particularly Dr. C.T. Lynch, former Project Engineer but now with the Office of Naval Research, Mr. F. W. Vahldiek, AFWAL/MLLN, Project Engineer, Dr. Harris Burte, Chief Scientist, AFWAL, and LCL G. Cooke, AFLC/LOE. The DCM's and their staffs at the special inspection airbases also provided valuable assistance. We gratefully acknowledge their interest and assistance in this project.

Portions of the Report are from the doctoral dissertations of R. Suter and N. Samsami.

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I. INTRODUCTION

Routinely-collected and well-documented maintenance records can be used to model and to predict airplane corrosion maintenance requirements, and thus provide an input to maintenance "packages" and scheduling decisions by Maintenance Review Boards. It is shown in this study that the USAF Maintenance Data Collection System (MDCS, formerly AFM 66-1 (1)) provided the records needed for this purpose, but recent changes to the system apparently have deleted this capability. The objectives of this study were to identify and to quantify factors in the AFM 66-1 data, and operational information which are effective for tracking corrosion in individual airplanes and in a collective fleet. From these factors and quantitative MDCS data a "probability of need" model for corrosion maintenance can be developed. Earlier studies had identified inadequacies in MDCS data, thus it also was an objective to gather maintenance data from other sources for comparison. This study supports a twenty-year-plus effort of USAF Strategic Air Command and AF Logistics Command to control corrosion costs and to minimize the impact on operational readiness of airplane systems.

Corrosion tracking and prediction, as developed earlier in a study of the C-141A fleet (2), is extended to the B-52 fleet, another large, but older aircraft system, as a basis for comparing maintenance, manpower, and materials costs vs force-effectiveness and operational life. If it can be demonstrated that predictive methods are applicable equally to both C-141A and B-52 systems --despite differences in age, mission, and structures --then one can apply the methods with confidence to all large aircraft systems. It is likely that smaller airplanes could be treated as well. In-service operational data, repair/maintenance histories, materials information, weather, airbase factors, and other relevant information are the basis of the study, and the primary source was the existing MDCS as received by AFLC and stored with minor alterations. Additional data were obtained from

(a) MDCS data from the Boeing Military Airplane Company, who serve as a duplicate archival facility to USAF; presumably their data are identical to that stored by AFLC; Boeing processes this data for its own purposes, but the data they store is as-received from USAF;

(b) the airbase-level computer systems, which provide the input to MDCS, and are the raw data as-entered into local computers;

(c) Monthly Maintenance Reports prepared from semi-raw, locally processed airbase-level data and published under RCS: SAC LGM (M 7902);

(d) a Special Inspection Request (SIR).

Except for item (d), these are merely different files of the same information. In addition, several airbases were visited by the Principal Investigators with the Project Engineer to inspect airplanes and to evaluate potential effects of airbase management on the maintenance data, including review of raw, noncomputerized data and interviews with maintenance personnel.

The Program was divided into four phases. In Phase I aircraft series and airbases were selected for more detailed study. Although several B-52 airplane series were manufactured, only the D, G, and H series remained in service. (As the study ended, the D airplanes were scheduled for retirement.) The 79 still-flying D's had been rebuilt recently, hence their corrosion problems might be atypical, but South Pacific area deployment quickly had cancelled this advantage. Although initial attention was focused on the G and/or H series, AFLC, SAC, and Boeing personnel urged inclusion of the D-series because of these unique characteristics --newly rebuilt and Pacific service --as well as subjective opinions that it was in worse condition corrosion-wise, hence a source of useful information, particularly with respect to corrosion protection systems which had been added to the aircraft at the time they were rebuilt. Consequently, closely-tracked airplanes and airbases represented all three series.

In Phase II a comprehensive data base was to be constructed from the alternate data sources. This task proved to be impossible for several reasons: (1) It was difficult to obtain materials specifically requested from the appropriate sources, and, when delivered, often it was done with considerable reluctance; (2) useful information --even the existence thereof --was never volunteered; (3) even when USAF agencies endeavored to cooperate, the results showed clearly that their hearts really were not in it. But, the most compelling reason was that data from different sources which described the same events were not comparable. Because of inherent defects in MDCS, a better data base was needed for corrosion tracking. The most important defects have been corrected by recent changes in the system, partly in response to our earlier recommendations. The fact that presumably identical data from different sources could not be compared, however, suggests that MDCS remains seriously flawed. It represents the best system available, however, from which to describe the condition of an aircraft fleet and its maintenance needs, provided recent changes in maintenance practices and data recording have not cancelled its utility. Unfortunately, we fear that this may be the case.

Phase III consisted of statistical analyses to evaluate data quality and to determine whether changes to MDCS might produce improvements. As noted, modifications to the data system consistent with earlier recommendations have been made, and more changes are in progress. Since analyses in this report were based on the older, unmodified system, the results are not applicable to the "new" MDCS, hence it is pointless to suggest further changes. The analyses of Phase III assessed, as far as possible, variations in maintenance repair rates from one airbase to another. Also addressed were questions of materials variations with a view to impacting PDM package decisions on the basis of material type compared with similar materials installed in inaccessible locations. Finally, statistical methods were applied to the problem of ACI aircraft selection, because it is clear that USAF resources could have been used more effectively.

Phase IV included a study of the effects of reliability-centered maintenance (RCM, also known as MSG-2*) procedures on corrosion repair costs. RCM was adopted subsequent to the C-141A study and during the maintenance time-frame of this study. USAF adopted RCM logic concurrently with a change from periodic inspections to isochronal phase inspections. Thus was lost the essential factor for a corrosion prediction equation, viz., the time coefficient for corrosion damage. Analyses reported here show that these policy changes were contemporary with some effects on corrosion maintenance costs, but it was not clear whether there was a cause-effect relation. A comparison of corrosion costs with environmental factors (PACER LIME) suggested that semiquantitative relations between them could be used effectively as inputs to the RCM logic.

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* After the report by the Air Transport Association's second Maintenance Steering Group.

II. BACKGROUND

A. CORROSION MAINTENANCE

Corrosion and fatigue of metal structures are major causes of reliability deterioration in aircraft. Corrosion damage can be detected and often corrected during routine inspections scheduled at intervals when several factors are optimized, including

--repairability,

--cost,

--operational requirements, and

--availability of maintenance resources.

The repairability question asks whether restoring the unit to serviceable condition can be effected at a favorable cost compared with the replacement cost. In the case of military airplanes, this question generally is answered on the basis of other considerations, not the least of them being political. One must assume that a given airplane system, such as the B-52, will not be replaced in the foreseeable future, hence repairs must be programmed so that required minimum levels of operational readiness and reliability exist in the fleet. Since the difficult question (i.e., repair vs. replace) has been answered in the political arena, only two easy questions remain:

1. At what points in the airplane's service life can the several levels of maintenance be effected most economically?

2. What queueing priority should be established considering the fleet size, individual airplane service environment (which may be modified to optimize maintenance), and the scope of available maintenance resources?

This study addresses the first question: given the service of the airplane and its operational environment, how can one compute the optimum time for the various levels of corrosion maintenance? "Level of maintenance", by analogy, compares with changing the oil in one's auto vs. overhauling the engine. The optimum time for maintenance should be easily predictable from service history --even by means of on-board computers --for both autos and airplanes if it is assumed that need for repair is proportional to "wearout", which in turn is proportional to service. Often this is true, but it is not true for corrosion except where it can be established that service is a simple linear function of calendar time.

When the damage state can not be predicted from service, the maintenance schedule adopted is either "isochronal" (fixed flying hour intervals) or "periodic" (fixed calendar intervals), when part or all of an airplane receives "Inspection, Repair as Necessary (IRAN)", which is approximately equivalent to "Retirement for Cause" (RFC). Currently, USAF aircraft are under a complex mixture of isochronal-and periodic-scheduled corrosion maintenance, which is based on "Reliability-Centered Maintenance (RCM)" logic (3). The scheduling system which immediately preceded the current plan essentially was periodic.

This may be contrasted with the "Group-Replacement" (GR) policy adopted where large numbers of identical components are used in identical service environments, and all units are replaced when a preselected fraction of components exhibits a critical state of failure, e.g., burnout of light bulbs, or detection of a fatigue crack of specified length in a turbine disc. An advantage of RFC vs. GR is replacement costs are minimized in the former, whereas the latter minimizes labor costs and system downtime. When parts are cheap and labor/downtime costs are high, GR is preferred, but increasing component costs shift the balance toward RFC. Obviously other factors enter the equation, e.g., how serious are the consequences of component failure? Such questions are addressed in RCM logic.

B. FORECASTING MODELS

An aircraft structure may be corroded at one or more locations. Failure of the structure may occur when the extent of corrosion at one point reaches a critical damage state. Corrosion initiates at randomly-distributed points of high Gibb's free energy, hence initiation is a random process, which depends on the metal and its environment; the progress of corrosion, once initiated, obeys the laws of chemical kinetics. Both initiation and propagation are predictable in terms of well-developed mathematical models which can be fitted to a corrosion problem by empirically establishing values for their several parameters using data collected in a corrosion monitoring program. This empirical data will describe as a function of time the onset of corrosion, its extent, the corrodibility of metals in question, and the severity of environmental corrosiveness. Thus the extent of an airplane's corrosion damage, y, at time t in a constant environment described by parameters x_i may be expressed as

[1] $$y(t,x_i) = P(t,x_i)\ f(t,x_i),$$

where $P(t,x_i)$ = probability function that corrosion will start, and

$f(t,x_i)$ = kinetic function of time and variables; generally the time dependence = at^N, where a and N are constants related to the environment.

The problem is simply to fit empirical data to appropriate models.

An airplane's service history is a discrete set of events and environmental conditions (e.g., flying hours by mission type, time spent at various airbases, weather at those airbases.) Corrosion damage, measured as manhours required to repair a component at time t may be expressed as a function of the time t_i spent in each event or condition x_i, e.g.,

[2] $$y'(t,x_i) = a_0 + a_i x_i + a_{ij} x_i x_j + a_{ijk} x_i x_j x_k \ldots$$

using the customary notation for summation. Both a_i and x_i are not necessarily simple factors, however, since each might be a complicated function of time and a specific environmental factor. Cross terms represent synergistic interactions between environmental factors, e. g., between salt and moisture. The a_i are risk "coefficients" for each factor or combination of factors. Thus maintenance could be scheduled for system or subsystem when $y(t,x_i)$ reaches a predetermined value for some critical component or for the entire airplane, hence based upon need for repair. One requires only the analytical form of Equation [2].

Such relations are available for specific environments, where all factors relating to corrosion are known and constant. For example, corrosion of cathodically polarized metals follows the relation (4)

[3] $$I_a = I_c[10^{-P/\beta_c} - 10^{P/\beta_a}],$$

where

I_a = applied current density,

I_c = corrosion rate expressed as current density,

β_a = anodic Tafel ("beta") constant,

β_c = cathodic Tafel ("beta") constant,

P = overpotential, or difference between open-circuit (corrosion) potential and the polarized potential.

Hence corrosion rates are readily calculated from laboratory and field measurements. (5)

Even in more complex environments, such as field test sites, empirical equations can be developed for a specific alloy. Weight gain data, ΔW for commercial low-alloy steels exposed at an industrial test site in northwest Indiana were found (6) to fit the equation

[4] $\Delta W = Kt^N$,

where K and N are empirical constants. Similar relations should exist between aircraft operational histories ("environment") and corrosion maintenance records, hence cost and repair frequency should be predictable from environmental factors.

A deterministic corrosion life/cost prediction model would predict the state of damage under the worst case of environmental exposure. Computed corrosion rates then would calculate when inspection would detect a preselected population of components which have suffered a preselected extent of damage. At that inspection, components are RFC or IRAN according to the optimum cost equation. Inasmuch as corrosion generally is not critical to safety of flight, there will be considerable latitude in selecting population and damage extent, as contrasted with fatigue cracking. Consequently, costs of RFC/IRAN are more significant in optimizing inspection intervals than is the extent of damage *per se*.

C. ENVIRONMENT

There is no established relation between corrosion damage and service environment. It is well-known that some environments are more corrosive to metals than others, but, until recently, such differences were treated with no more sophistication than to describe the environment as " "rural", "urban", "marine", or "industrial". Widespread monitoring of weather factors, coupled with the advent of atmospheric pollutant concentration studies, however, have made possible a more comprehensive approach to the corrosive environment problem. Although "environments" are better described (at least in principle), a *useful* measure of corrosion damage which may be related to the environment is not yet available. In an earlier study (7), we showed how ambient data can be used to provide a versatile, more accurate, and semi-quantitative description of environmental corrosivity. Moreover, we developed a specific corrosion severity index system for alloys and corrosion protection systems used in modern airframe construction, a system which has been used extensively by USAF. A deficiency of this method is the lack of environmental data for specific sites of interest, since available data may have been measured at remote sites as far as 25 miles away, while steep gradients of environmental factors may span distances as small as 1 km.

D. MAINTENANCE DATA AND ITS POTENTIAL VALUE IN CORROSION PREDICTION

Corrosion damage in a fleet usually is estimated based on the results of routine inspections of all aircraft units and in-depth inspections of a few selected airplanes. Inspection data report corrosion damage at critical locations, unit serial number, qualitative extent of damage as the repair cost (manhours plus parts), and relevant utilization data. A library of such data can be a rich source for operations research studies aimed at optimizing systems maintenance. For many years, USAF has maintained such a library under the Maintenance Data Collection System, (MDCS, AFM 66-1 (1)). This computerized, coded data system is used extensively and effectively for overall systems management and control. In principle it is sufficiently detailed to provide a wealth of data about the service performance of specific materials and components. Fleetwide application of a component could be tracked in the maintenance records to constitute a large scale service test, but the analyst has no control over the test or the maintenance actions reports that will constitute the data base. Like time series in economics and social sciences, one can only observe, hence the data are said to be non-experimental.

One might track, for example, fastener-related maintenance actions by the appropriate failure and repair codes as well as codes which identify locations on wing skins, fuselage, etc. Coupled with field-level and depot-level inspections by experienced corrosion engineers to determine true failure modes, the specific areas to be tracked can be selected on a given aircraft type. Repair and failure data then are obtained which provide relevant service performance information. There are several difficulties: (1) A well defined failure criterion for corrosion does not exist; (2) maintenance actions may result from failure during operation but more likely they result from observations made during inspections, and the inspection interval becomes important, as well as the subjective view of the inspector that a part has failed and needs repair; (3) the environment varies internally and externally to the aircraft --the latter can be tracked fairly well, and the former is helped by the statistical averaging of numerous actions. It follows that any part or component analyzed should constitute a corrosion "hot-spot" which can be defined in terms of a given number of maintenance actions related to corrosion that occur in a given period of time per aircraft.

Changes in performance of alloys as replaced in older aircraft can be tracked. The lack of control or ability to obtain first hand reports on how the data system was inputted, however, or to determine what were acceptable and unacceptable degrees of corrosion damage make this of doubtful value. Much of the information on damage levels and peculiarities in reporting are handled adequately by on-site field/depot inspections for current aircraft studies. This corrective or calibrating action is naturally eliminated in the historical analysis.

It is possible to install new systems or parts on airplanes and track their performance, but this is of little value. It provides limited information on a few aircraft in consequently limited environments. Also, one must wait five to ten years to obtain adequate information, and during that time the tracking system will break down because of the frequency of transfer of aircraft and maintenance people. Moreover, "test" systems are subject to well-intentioned interference by field personnel, and thus test validity is compromised. (Paint systems are a good example.)

Under a previous contract (2), Michigan State University analyzed corrosion maintenance of the C-141A fleet to determine whether corrosion-costs prediction from this data was feasible. Repair costs were found to be (a) linearly-cumulative over long time intervals, (b) independent of flying hours and mission type, and (c) variable with environment. It was possible to track and predict maintenance costs from the routinely-collected MDCS data. Moreover, significant cost savings were realized from the analysis because a quantitative basis was established for extending Programed Depot Maintenance (PDM) intervals from 36 to 48 months. The C-141A system, however, like most others, still is maintained on fixed-interval PDM cycles, and major overhaul is not based on analysis of exposure and operational requirements. Although the present USAF Maintenance Data Collection System may not provide quite the sort of data required, it provides sufficiently rich data that it is worthwhile to adapt, if possible, the modeling requirements to the available data base.

III. THE USAF MAINTENANCE DATA COLLECTION SYSTEM (MDCS)

USAF extensively documents maintenance actions which correct failures or modify airplanes. Routine service, e.g., washing, cleaning, and touch-up painting, was documented in less detail until recently. "MDCS is the primary source for AF reliability and maintainability data; basic understanding of its objectives, uses and limitations is essential to R & M [Reliability and Maintainability] users. The system was designed primarily as a base level production credit and management information system. Objectives are to provide [field-level] maintenance managers with information about production accomplished by the assigned maintenance personnel; to identify the equipment on which work was accomplished, why it was required, and the action required to do the job. The MDC system identifies maintenance requirements and problem areas so that appropriate management action can be taken to effectively support [sic], and meet the established operational requirements.
In addition, [i.e., an afterthought] the system is designed to provide data to AFLC for maintenance engineering and logistics management."(8) [Emphasis added.]

"...MDC does not stand for time accounting system (TAS) [but] stands for maintenance data collection. ... [A TAS] keeps track of all manhours and how they were utilized. [MDCS] identifies where, when, what, and how maintenance production resources are utilized."(9)

A. INSPECTIONS

A maintenance action is initiated by a Discrepancy Report, which usually --particularly in the case of corrosion --is generated in the course of a scheduled inspection. Authorized maintenance and inspection programs currently in effect for B-52D airplanes* are listed in Table 1 (10).

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*H and G series inspection programs are not available, but presumably are the same.

TABLE 1.

CURRENT MAINTENANCE/INSPECTION PROGRAMS

ORGANIZATIONAL LEVEL	
	INTERVAL
PREFLIGHT	DAILY
BETWEEN FLIGHT	DAILY
END OF DAY BASIC POSTFLIGHT	DAILY
SATELLITE PREFLIGHT-POSTFLIGHT	DAILY
COMBINED PREFLIGHT-POSTFLIGHT	DAILY
PHASED INSPECTION	200 HOUR
DEPOT LEVEL	
PROGRAMED DEPOT MAINTENANCE (PDM)	48 MONTHS
ANALYTICAL CONDITION INSPECTION (ACI)	CONJUNCTION WITH PDM
AIRGRAFT STRUCTURAL INTEGRITY PROGRAM (ASIP)	CONTINUOUS

In addition to the scheduled inspections listed in Table 1, there are several other special inspections. Each discrepancy report carries a "When Discovered" designator to indicate the type of inspection in effect; there are more than two dozen such designators. The maintenance action is recorded and the information then is entered into the local computer system. Portions of the data are forwarded to HQ AFLC. Data not forwarded are retained for a limited time interval and are accessible via the Base Level Inquiry System (BLIS). Base level data are used to compile Monthly Maintenance Reports.

"Permanent" records are the edited base-level data sent daily (8) to HQ AFLC where some additional information is added. Because of space constraints, permanent records do not contain all information originally recorded. Permanent records are the only source from which nonrecent maintenance can be reconstructed, although recent data are available from several sources. These records, however, are filtered and it is useful to compare the original record structure with the permanent record contents to see what can be deduced.

The events which culminate in a permanent record are:

(1) A component fails or deteriorates beyond tolerance;

(2) the failure or deterioration is noted at inspection, or in service, and

(3) is reported as a discrepancy; a maintenance action and documentation are initiated;

(4) maintenance is completed and recorded;

(5) recorded information is entered into the base computer;

(6) edited information from selected records is forwarded to HQ AFLC.

Each of these events is associated with a probability $P_i(t)$ that it will occur as described at time t, and the probability that an accurate record exists in any archival file which describes a given corrosion failure is the product

$$[5] \qquad P_R(t) = \prod_{i=1}^{6} P_i(t).$$

To these must be added a seventh probability, viz.,

(7) that the set of these records, or any desired subset, can be retrieved.

The questions of probabilities are considered extensively in current logic, and are discussed elsewhere in this report. We note here that in our view P_4, P_5, P_6, and especially P_7 are much more significant than P_1, P_2, and P_3.

B. MDCS DATA AND USAF PROCESSING

MDCS (T.O. 00-20-2) (1) details the maintenance information recorded alpha-numerically. Codes are listed in AF Manual 300-4 Volume XII (11) and reproduced for specific systems in the appropriate "Work Unit Code Manual", e. g., TO B-52-06 (12). AFTO forms 349 and 350 are source documents for MDCS, and there are two recording procedures: on-equipment and off-equipment. The former refers to complete end items, e.g., aircraft, removed engines, etc., and includes support general tasks and other maintenance actions. The latter refers to in-shop maintenance on items removed from complete end items. Rules are established for documenting the variety of situations in these two general cases, but loosely, form 349 is used for on-equipment and 350 for off-equipment maintenance. The former form is reproduced in Figures 1 and 2.

The primary categories of work recorded on AFTO 349 are Job Control Number, Workcenter, ID number, time, and further data related to the specific action at hand. For off-equipment work on removed components, primary entries are required which identify Federal Supply Class and Part Number. Additional

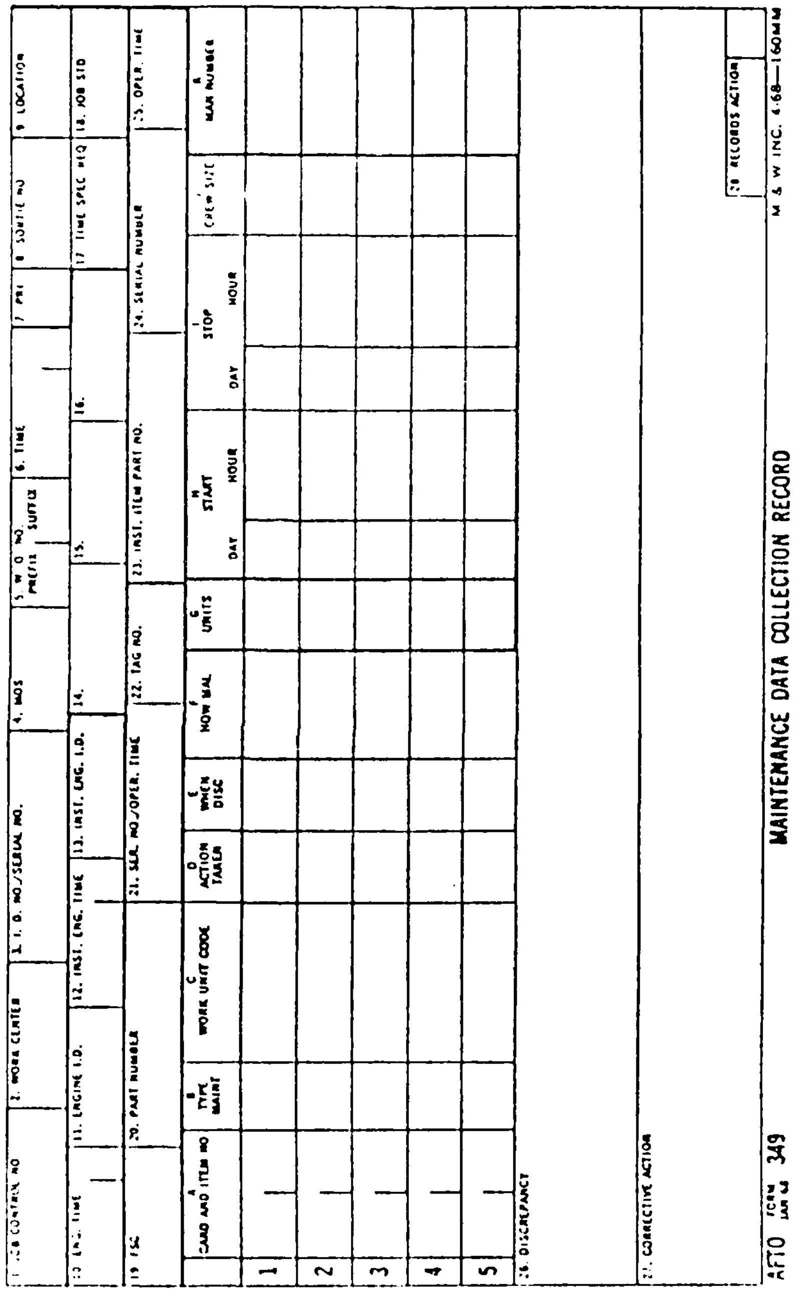


Figure 1. USAF AFTO Form 349 Maintenance Data Collection Record (Obverse).

29 PARTS REPLACED DURING REPAIR

LINE NUMBER	A FSC	B PART NUMBER	C WORK UNIT CODE	D REF. SYMBOL	E HOW MAL	F QTY

30. CONTINUATION FROM BLOCK ____________

Figure 2. USAF AFTO Form 349 Maintenance Data Collection Record (reverse).

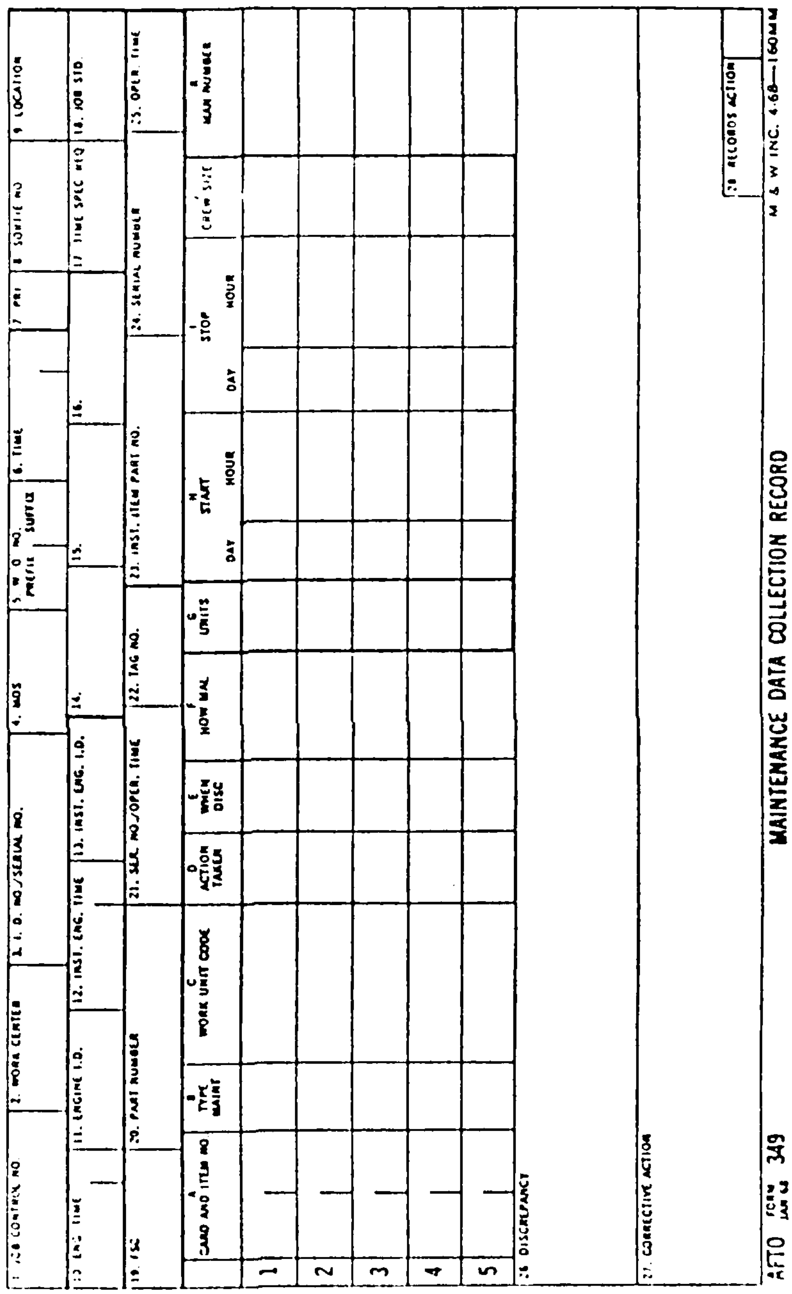


Figure 1. USAF AFTO Form 349 Maintenance Data Collection Record (Obverse).

29 PARTS REPLACED DURING REPAIR

LINE NUMBER	A FSC	B PART NUMBER	C WORK UNIT CODE	D REF. SYMBOL	E HOW MAL	F QTY

30. CONTINUATION FROM BLOCK ______

Figure 2. USAF AFTO Form 349 Maintenance Data Collection Record (reverse).

information also is available, e.g., Off-equipment maintenance (or shop repair), which is recorded on AFTO 350. Our main interest is in structural corrosion, however, for which Off-equipment records are very rarely relevant.

The following material includes quotations from USAF TO 00-20-2 with discussions to indicate relevance to the present problem.

> "a. The Work Unit Code consists of five characters and identifies the system, subsystem and component on which maintenance is effected. A few work-unit codes identify tasks of a general nature, e.g., equipment servicing, cleaning, and are called "Support General" codes." [Emphasis added.]

Not all AFTO information is included in permanent records, and, moreover, certain categories of data are not included at all. The Work Unit Code determines whether a record form remains a temporary base-level record or becomes a permanent record. It also determines whether information must be entered in certain blocks on the form. Support general codes are costs only and, presumably, have only base level significance. As such labor relates to "corrosion," two codes are relevant, viz., 02000 Washing, cleaning, corrosion prevention treatment and decontamination; and 09000 Shop support functions, fabrications, [prevarications?] painting etc. When support general work unit codes are used, line items need not be completed on the AFTO form; the information is retained at base level only and not forwarded to HQ AFLC. Consequently, there can be an extensive volume of corrosion-related repair activity covered by the support general WUC's, and thus is never seen nor reviewed by AFLC HQ personnel, nor will it appear in the permanent records. It is accounted for, however, as part of maintenance costs and summarized in the Monthly Maintenance Reports.* Flexibility is [and should be] allowed to decide whether a maintenance action is Support General --corrosion treatment -- or not. Unfortunately, the use of such codes varies from one airbase to

* We have pointed this problem out in the past; partly in response, maintenance organizations have been advised to use Support General WUC's sparingly and with caution when repairs may be corrosion related.

another, thus another factor in the corrosion equation is lost through the use of the support general WUC's.

> "The first two characters of the (non-support general) work unit codes are standard system codes which identify functional systems, e.g., flight control systems. The third and fourth characters identify subsystems or major assemblies. The fifth character normally identifies repairable items, although there are exceptions for critical non-repairable parts.
>
> "All failed parts replaced during repair do not require assignment of work unit codes because these parts are recorded in blocks 29 of AFTO form 349 using the Federal Supply Classification (FSC) and part number.
>
> "Work unit codes are designed as quick reference numbers to identify system, subsystem, and component relationships within an item. This provides a standard method of sorting data and of summarizing different levels of detail that is not possible through any other numbering procedure applicable to all types of equipment. Work-unit codes provide the capability to utilize data in maintenance or engineering programs by multiple systems, or components within each weapon or support system or by end item of equipment. This capability is also used to assess corrective actions. Thus combined with the equipment classification codes, a highly flexible and informative data-retrieval capability is available, and is utilized at all levels of management. [Emphasis added; cf. p. 14]
>
> "The work unit code, in combination with an action-taken code, is used to describe a 'unit of work.' An entry of one or more units completed must also be made in the Units Block of the data collection form to record a completed action. An example of a unit of work would be removal and replacement of an antenna. It would be documented with a work unit code for the antenna, with an action taken code for removed and replaced, and a unit count of one. By using additional codes to identify the end item, type of maintenance being accomplished, when the maintenance requirement was discovered, how the item failed, and the time expended in accomplishing the work, the production credit system also provides information essential for maintenance and logistics management."

A list of "hot spots" (i.e., corrosion-prone areas") can be developed from analysis of repair activity, but such areas can be described only in general terms because the WUC --despite its wealth of detail --does not refer to hardware-sized components. Moreover, Work-unit codes are not related directly to size or complexity of the zone, hence a large volume of repair activity for a specific code may result from an excessive failure rate, or merely because the code refers to a large number of similar components, e.g., fasteners.

"b. Job Control Number (JCN) is a 7-character code (reduced to 6 by HQ AFLC) used to control and identify maintenance actions. The first three characters are the Julian date on which the JCN is assigned --in most cases the same day maintenance is effected. The last four characters identify the job and normally are a daily or monthly sequence number. JCN's are used to tie together all data, both on-equipment and off-equipment, relating to correction of a discrepancy or modification. JCN's are assigned in four basic categories: Equipment discrepancies; Time Compliance Technical Orders (TCTO) and time change requirements; inspections; and Support General work other than inspection."

For our purposes, only the first and third categories are significant. In the case of equipment discrepancies, the JCN is important in their control, identification, and analysis.

"c. The Work Center Code identifies the organization unit that performed the maintenance."

In the case of aircraft, it was the unfortunate practice (until 1981) to replace this information with the codes of the Organizational Maintenance Squadron, i.e., the "owning" work center, before forwarding the records to HQ. Thus it is not possible to determine who performed the maintenance. This is a long-standing practice and no USAF personnel remember why it was adopted; as of June 1981, it has been discontinued and subsequent records contain the "Performing" Work Center codes (13).

"d. The Type Maintenance Code is a single character, to identify the type of work accomplished, e.g., scheduled or unscheduled maintenance."

Essentially, this code describes aircraft status at the time of maintenance, and whether the discrepancy was anticipated for scheduled inspection.

"e. The Action-Taken Code is a single character to identify the specific maintenance action effected, e.g., removal and replacement of a component."

"f. The When-Discovered Code, a single character, identifies the operational status of the airplane at the time the discrepancy was discovered."

g. How-Malfunction Codes "are designed to identify the nature of the defect not the cause of the discrepancy." The number of such codes "is maintained at a minimum to simplify reporting." [They number more than 200.]

The distinction between the "nature of the defect" vs. the "cause of the discrepancy" is reasonably clear, but the interpretation of the former is ambiguous. It should be remembered that the repair person who enters this data, although highly skilled, has very limited technical sophistication. Consequently, a how malfunction code falls far short of a competent failure analysis, and how mal codes must be used with care. If one wishes to analyze corrosion-related maintenance, it is necessary to collect not only those records identified by corrosion how mal codes, but in addition those records with a variety of codes used when the corrosion factor was not recognized by the maintenance personnel. Among the more controversial codes, but also the most often misused, is HM 190, cracked. Without question, there are serious difficulties associated with using how mal codes as a hind-sight failure analysis diagnostic.

> "h. Units Entries identify completed maintenance actions, or actions in progress but not completed, or actions in which a work center participated but was not assigned primary responsibility for completion of a maintenance action."

An entry of one or more indicates the number of times that the action taken was performed. An entry of zero, however, may be made for at least four different reasons: (1) The work centers identified in block 2 did not have primary responsibility for completing the action; or (2) the action stopped prior to completion or was deferred more than 15 minutes; or (3) there was change of crew size or category of labor; or (4) the unit was reported against a different category of labor. Consequently, although non-zero entries are unambiguous, zero entries are uncertain since there is no way to determine why the record was closed.

C. PERMANENT DATA

Several comments have been made in preceding sections about changes made to original data before they reach the status of permanent record. The final form and contents of these records will be compared with the record format for the permanent "on-equipment" records shown in Table 2 for data in the 1975-80 time period. Data may be provided in a slightly different format, but the information is essentially the same. Most items have been explained, but some merit further comment.

Location, a four character code, identifies the airbase where maintenance was effected, and "Command" indicates operational authority of the the airplane. "Card Code" indicates which of several tape formats apply for a specific record. The tape format used in this study was the "A" (On Equipment) format. Information in columns 81-84 is added by HQ AFLC: "System Manager Air Materials Area" identifies responsibility for management of the system; "Type Equipment" groups different equipment classification codes into similar equipment, e. g., aircraft and engines; "Record" identifies the data record and relates it to specific record formats, e.g., "On-Equipment, Aircraft"; "Type How Malfunction" categorizes How-Mal codes to identify and separate failure information from other malfunctions and maintenance actions.

There are redundancies in the permanent records. "Mission-Design", "Command", "System Manager AMA," and "Type Equipment" are the same for all C-141A or all B-52 airplanes. The "Command" changes when an airplane enters depot maintenance, but there is a corresponding change in location codes, hence depot command code (F) provides the same information as the depot location code. The record date is given twice, and (practically) a third time in the "Job Control Number". Type of "How Malfunction" seems to be a duplication. These redundancies exist probably because MDCS was devised in an era of primitive computers.

For reconstruction of maintenance actions, the following items are of potential use:

TABLE 2. MDCS TAPE RECORD FORMAT B-52X AIRPLANES

Column	Contents		Example
1-7	Mission-Design-Series		XXB052G
8-11	Blank		XXXX
12-19	Serial Number		59000162
20-24	Time (usually blank)		XXXXX
25-29	Work Center		23100
30	Type Maintenance		Y
31-33	Standard Reporting Designator		ABN
34	Year (1 digit code; e.g., 1978=8)		8
35-37	Julian Calendar Day		119
38	Component Position Number		X
39-43	Work Unit Code		11AAE
44	Action Taken		V
45	When Discovered		M
46-48	How Malfunctioned		190
49-50	Units		01
51-54	Start Time [a]		1430
55-58	Stop Time, or Manhours, in tenths[a]		0025
59	Crew Size		2
60-63	Airbase Code		AWUB
64-65	Command		05
66-68	Tag Number		XXX
69-71	Day	Job Control Number	312
72-75	Sequence Number		6400
76-79	ID Number (last 4 digits)		0162
80	Record Type		A
81	Type How Mal		Blank
82	Type Equipment		Blank
83-89	Mission-Design-Series/End Article Designator		XXB052G
90	Record Mark		X

[a] Records may list Start-time and Stop-time in the Manhours field with crew size. Where this information has been converted to manhours, the Start-time field should be blank.

Record date

Serial number

Type maintenance

Work-unit code

Action taken

When discovered

How malfunction

Units

Labor manhours	Some files list start/stop time crew size; whereas in others, this has been converted to manhours. Each file must be inspected to determine which is the case

Location.

The Job Control Number might be of interest, since one might retrieve all maintenance actions related to a particular record. This was not of practical significance, however, because large numbers of records are generated under the same JCN during certain inspections, e. g., Phase Inspections. Although these actions are related to one another from a management standpoint, they are not related with respect to cause of failure. Accordingly, it should be possible to answer the journalist's questions: Who, what, where, why, how, when, except that records prior to 1981 do not answer the question of "who".

IV. B-52 FLEET AND SERVICE ENVIRONMENT

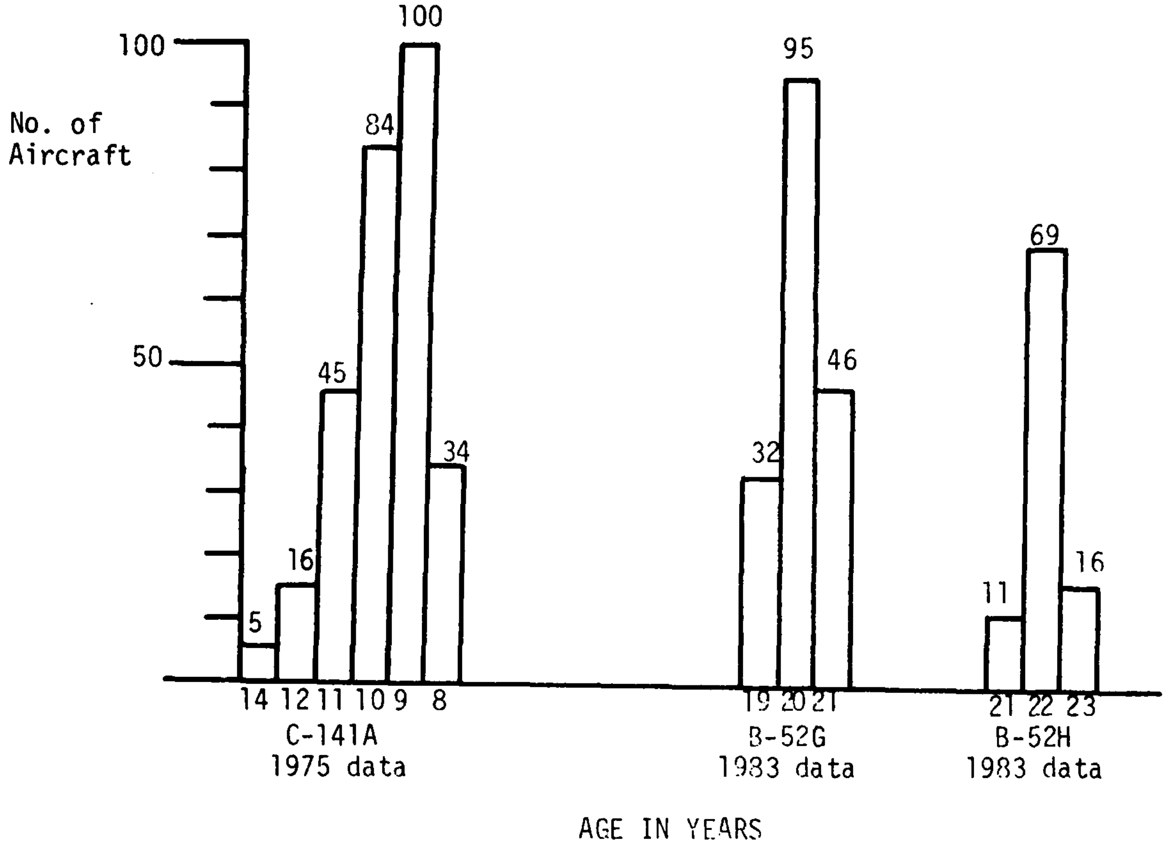
A. THE B-52 FLEET

The B-52 bomber has been a primary weapons delivery system of the USAF Strategic Air Command for more than 25 years. Eight series of the airplane were built, but only the D, G, and H series were still in service, and the D-units were scheduled for retirement within two years. The remaining chronologically-older D series, however, were in fact the newest B-52 airplanes, having been rebuilt and modified extensively under Engineering Change Proposal 1581 (ECP 1581, code-named PACER PLANK), completed in 1977 (14). Data relating to inventories, flying hour utilization, and chronological age of these three B-52 series are shown in Table 3 together with similar data for the C-141A fleet (2).

B. AIR BASE ASSIGNMENTS

The four MDS are distributed among 24 different airbases of widely differing environments. In general, B-52 airplanes are traded infrequently from one airbase to another. There were major transfers of airplanes in the time period 1975 to 1980, but these were related to the closing of certain airbases and re-alignments of commands. Occasionally, transfers were effected when an airplane entered PDM but moved to another airbase on output, from modification fly-in programs, and to keep units at required strengths. Modifications currently in progress on about half of the the D-series and all the G-series airplanes, however, would upset completely the prior stability of airbase assignments (15). All parties know in advance which airplanes are to be transferred to another airbase, and which will remain at a given airbase for the next one to four years.

There is a special corrosion problem in the D-series airplanes, because they were rotated routinely to Andersen AFB, Guam in order to spread the corrosion damage of that severe environment over the fleet. Initially,



		C-141A 1975 data	B-52D 1983 data	B-52G 1983 data	B-52H 1983 data
Flying Hours	High	24,000	15,514	13,493	12,382
	Average	15,343	13,726	8,819	7,402
	Low	5,000	12,512	3,269	2,482

Table 3. Age and Flying Hour Comparison C-414A and B-52X.

following the PACER PLANK modification, airplanes were stationed at Guam for 18 months, but in 1977, the assignment period was reduced to 12 months with 6 airplanes transferring to Andersen from Carswell and four each from March and Dyess (15). Similar policies have been in effect with respect to the excessive wear and tear of training airbases.

Generally, one wing (nominally 16 airplanes, but from 14 to 19 in practice) is assigned to each airbase, but three airbases (Carswell, Barksdale, and Ellsworth) had two wings each. Castle AFB is a training base for G-and H-series airplanes, and may exhibit anomalous repair histories, as was the case of the C-141A airplanes assigned to Altus AFB (2).

B-52 airplanes received only organizational- and depot-level maintenance; Programed Depot Maintenance is performed at Tinker AFB, Oklahoma City (G-series) and Kelly AFB, San Antonio (D- and H-series).

C. ENVIRONMENTS

The PACER LIME program (7) classifies environmental corrosion severity according to the nature and intensity of ambient corrosive factors. These include environmental constituents, e.g., sea salt, sulfur dioxide, and weather factors. Three algorithms rate environmental severity with respect to corrosion damage to alloys and corrosion protection systems from the ambient level or concentration of several parameters compared with a set of Working Environmental Corrosion Severity Standards (WECS). The WECS were established from the extreme and median values observed in the continental US. If a parameter exceeds the WECS level, it is rated corrosive, whereas a lower value is rated noncorrosive. The WECS environmental parameters listed in decreasing order of significance for corrosion are (a) proximity to airborne salt source, e.g., seacoast, (b) moisture as humidity or rainfall, and (c) atmospheric pollutants, including particulates, SO_2, photochemical oxidants as O_3, and nitrogen oxides, NO_X. In evaluating environmental risk to corrosion protection systems (e. g., paint), the intensity of solar radiation also is considered.

There are questions about the relative weighting of these factors in the algorithms. High humidity and high rainfall are considered equivalent, but this is a minor point, since these factors generally are parallel. Atmospheric pollutants are weighed equally, but evidence that oxidants or "particulates" are as corrosive as SO_2 is less than compelling. The corrosive effects of salts, SO_2, and moisture, especially in concert, are well established. The algorithms could be revised so as to de-emphasize some factors by raising the threshhold values.

There are three PACER LIME algorithms for each environment which: (1) establish washing intervals, (2) establish repainting intervals, and (3) predict the relative extent of corrosion damage. For evaluating corrosion maintenance histories on the B-52 fleets, only the repaint and corrosion damage algorithms are of interest. Each rates an environment as AA, A, B, or C in descending order of severity; a numerical 4, 3, 2, 1 scale is equivalent. Since there are two sets of WECS, one more restrictive than the second, two sets of environmental recommendations result and an environment would be rated twice, e.g., A-B, B-C, etc. Usually, these ratings are converted to the equivalent numerical rating, as a sum of the two values, i.e., A-B = 5. Ratings listed in Appendix A result from available data from several sources. Unfortunately, data collected by airbase weather services, by Environmental Protection Agencies, air quality monitoring stations, and others, may not reflect the actual airplane environment at a given airbase because monitoring stations might be at some distance. Accordingly, airbase ratings are tentative, subject to better data and knowledge concerning local corrosive factors, such as acid rainfall or nearby pollutant sources. Nevertheless, these are the best available ratings for airbase environmental corrosion severity at this time.

B-52 airbases are listed in Appendix A together with geographical location, B-52 MDS, the average number of assigned airplanes*, and the PACER LIME ratings. The D-series airbases are somewhat homogeneous geographically --with the exception of Andersen --being located in the Southwest U.S. Carswell and Dyess both are in Texas, about 200 miles apart, and March AFB, near Los Angeles, is in a (God-forsaken) near-desert environment similar to that of Texas. Of the H-series airbases, three are located in Northern Plains states within 300 miles of one another, and K. I. Sawyer AFB, in the (beautiful) forested Upper Peninsula of Michigan near Lake Superior, has a similar climate. Castle AFB is in northern California and is somewhat different (as are all things Californian). G-series airplanes are based in widely different environments, but among the ten airbases, there are apparently similar subsets. Four (Barksdale, Blytheville, Robins, and Seymour-Johnson) are in the Southeast U. S. --two in the Mississippi valley and two in the Piedmont east coast. Four (Fairchild, Griffiss, Loring, and Wurtsmith), although widely separated, share a northern environment and similar climate. Castle and Mather, both in north-central California close to one another, might be expected to have similar environments, but also suffer the California syndrome. When environmental severity (PACER LIME) is considered, however, there are significant differences among these apparently similar locations.

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*Assigned airplanes are an average of the quarterly possessed aircraft for the period 1978-1979; one or two non-operational (CRESTED DOVE) airplanes may be included.

V. B-52 CORROSION MAINTENANCE DATA

A. DATA BASE AND OVERVIEW

"Complete" permanent maintenance histories of B-52 aircraft were provided for the time intervals 1975-1981, but not as one entire set, thus overlapping record sets were provided. These records were assumed to be complete and to represent all data which had been delivered to HQ AFLC within the respective time periods. Both organizational- and depot-level maintenance were included. Nearly fifty reels of computer tape were edited to yield smaller files of corrosion-related maintenance. This was accomplished by removing selected records from the main files. The criteria for creating these subfiles were:

a. Airbase codes where B-52 series D, G, and H were stationed;

b. How malfunction codes 117, 170, 190, 230, 520, 605, 617, 622, 667, 846, 865, and 878;

c. Action taken codes V and Z.

Only records bearing the "A" format were used. Subsequent to selection, the records were sorted into separate files by Mission-Design-Series, airbase, and airplane serial number.

As in the C-141A study, there is some room for discussion as to whether the codes selected (or possibly others) are related to corrosion. Clearly, the specific corrosion codes (170, 667, Z) are relevant. Further, delamination (846) and deterioration (117) are related to environmental conditions; the results show that this assumption has validity. Since protective coatings and sealants are intended to prevent corrosion, their failure (code 865) will indicate a precorrosion condition. Dirty code (230) and cleaning code (V) may be borderline. It was our intention to include not only the obvious corrosion codes, but also those which contribute to environmental degradation and those which might be used in error (cf. p. 11.) The inclusion of code 190 Cracked has been questioned. Opinions vary between one extreme, considering most crack failures to result from fatigue only, to the opposite view considering most cracks to be corrosion accelerated. We subscribe to the latter view, i.e., all metal crack growth rates are accelerated by environmental conditions to varying degrees, hence are corrosion related.

The corrosion failure and repair manhours for the B-52 fleet for 1Q 78 -3Q 79 are listed in Tables 4-6. These data represent all corrosion related records extracted from complete AFM 66-1 Maintenance Histories for the corresponding time period exactly as supplied to us by HQ AFLC. The corrosion records are further subdivided into Organizational-level, depot-level, and How Malfunction code. Since these records represent repair histories on a variable number of airplanes, both in field and at depot, the numbers are not directly comparable, but highlight the scope of the study. The numbers are reduced to a per-airplane basis in Tables 7-9, from which more meaningful comparisons may be made. Records for the D models represent nearly 30,000 failures and 104,000 manhours; for G models, nearly 66,000 repairs and more than 200,000 manhours; and for the H models, more than 36,000 repairs and nearly 100,000 manhours over the 1-3/4 year time period. The following observations are made from Tables 7-9.

D-model How Malfunction codes show larger repair costs at field level than at depot. In some cases, the difference is not large, e.g., code 865, but in others it is more than an order of magnitude, e.g., code 230. The largest category is code 190, where nearly 700 manhours per airplane were spent in the field, but only 50 at depot. The next largest is code 170 with 250 in the field vs. 105 manhours per airplane at depot.

G-model data reveal a different pattern. There is less corrosion repair work done overall, with about 1/3 as much in the field but 90% at depot as on the D-models. The largest item is code 190, the total being about the same as

TABLE 4. B-52D ORGANIZATIONAL- AND DEPOT-LEVEL CORROSION MAINTENANCE BY HOW MALFUNCTION CODE, 1Q 1978 - 3Q 1979.

	Field		Depot	
How-Mal	Failures	Manhours	Failures	Manhours
117	1478	2976	61	86
170	9060	19719	1478	3142
190	11803	54875	302	1494
230	3825	10304	34	284
667	753	3282	106	206
846	999	7705	18	34
865	50	143	7	40

TABLE 5. B-52G ORGANIZATIONAL- AND DEPOT-LEVEL CORROSION MAINTENANCE BY HOW MALFUNCTION CODE, 1Q 1978 - 3Q 1979.

	Field		Depot	
How-Mal	Failures	Manhours	Failures	Manhours
117	2684	7259	5943	10936
170	6363	13370	983	6238
190	24589	96798	5142	21007
230	14074	25150	66	92
667	265	1187	290	2361
846	2376	13068	2941	14121
865	131	300	8	33

TABLE 6. B-52H ORGANIZATIONAL- AND DEPOT-LEVEL CORROSION MAINTENANCE BY HOW MALFUNCTION CODE, 1Q 1978 - 3Q 1979.

	Field		Depot	
How Mal	Failures	Manhours	Failures	Manhours
117	2796	5047	618	1322
170	2317	5048	1210	4446
190	12464	40596	3190	11720
230	11376	14328	24	156
667	71	296	512	5792
846	747	3774	883	5797
865	237	262	3	4

TABLE 7. COMPARISON OF B-52D ORGANIZATIONAL- AND DEPOT-LEVEL CORROSION MAINTENANCE COSTS BY HOW MALFUNCTION CODE, 1Q 1978 - 3Q 1979, MANHOURS PER AIRPLANE.

How Mal Code	Field	Depot
117	37.6	2.9
170	250.	105.
190	695.	49.8
230	130.	9.5
667	41.5	6.9
846	97.5	1.1
865	1.8	1.3

TABLE 8. COMPARISON OF B-52G ORGANIZATIONAL- AND DEPOT-LEVEL CORROSION MAINTENANCE COSTS BY HOW MALFUNCTION CODE, 1Q 1978 - 3Q 1979, MANHOURS PER AIRPLANE.

How Mal Code	Field	Depot
117	43	156
170	79.1	89.1
190	573	300
230	149	1.3
667	7.1	33.7
846	77.3	202
865	1.8	0.5

TABLE 9. COMPARISON OF B-52H ORGANIZATIONAL- AND DEPOT-LEVEL CORROSION MAINTENANCE COSTS BY HOW MALFUNCTION CODE, 1Q 1978 - 3Q 1979, MANHOURS PER AIRPLANE.

How Mal Code	Field	Depot
117	52.6	42.6
170	52.6	143
190	423	378
230	149	5.0
667	3.1	187
846	39.3	187
865	2.7	0.1

for the D-models. Depot-level, however, consumes more than six times as much as on the G-models. Code 230 on G airplanes is about the same as for the D-models, but much smaller at depot. Code 667 has a small effort at field level but a larger effort at depot. Code 846 shows a large amount of depot work, where the D's are a small labor consumer. Field delamination work on G's is about the same as on D's. Code 865 work also is minimal on G's. There is an occcasional reversal of the relative size of depot vs field effort on G airplanes.

H-model airplanes show substantial repairs for cracked codes at both depot and field level, closely matching the G-series. Deteriorated is about the same in the field as in the D-series, although effort at depot is small compared with that for the G airplanes. Corroded mild to moderate has a larger effort at depot than either G or D models, but the field effort on code 170 is smaller than G and significantly smaller than for D. D effort on code 230 is approximately the same as for H , G, and D models. Code 667 shows an effort at depot much larger than for either G or D airplanes. Delamination exhibits a pattern similar to that of the G models but somewhat larger at depot. Again, code 865 is negligible in the H's. In these models, there also is a reversal from the D with respect to the relative size of depot and field efforts.

B. COMPARISON OF B-52 AND C-141A MAINTENANCE DATA

The B-52 and the C-141A systems differ with respect to mission (cargo vs. bomber aircraft) as well as age (manufactured in the middle 1960's vs. the late 1950's). In addition, there are several series of B-52, whereas at the time of study, there was only one C-141 series. There is a wider variety of home airbase environments for the B-52 than for the C-141A, and a command difference, Military Airlift Command (MAC) vs. Strategic Air Command (SAC). All of these differences might be expected to impact maintenance data;

surprisingly, there is little evidence that they have done so.

In Table 10, the distribution of maintenance manhours among corrosion-related how malfunction codes for the two airplanes is compared. Both field and depot-level data are included as per cent of total manhours spent on selected codes. Thus 10% manhours for a given code means 10% of the set 117, 170, 190, 230, 667, 846, and 865 code total only; not included are other maintenance actions and how malfunction codes. Records for the C-141A are listed for two separate time periods, 1970-1974 and 1975-1976, whereas B-52 data listed span 1978-79 only. The two separate sets of data for the cargo airplane were obtained from different sources and thus may differ somewhat for that reason.

C-141A and B-52 airplanes are different in how malfuncton 190-cracked, 846-delaminated, and 865-coating, paint, sealant. In the case of 190, C-141A maintenance effort was approximately 35% of the corrosion-related effort, whereas for the B-52, it was about 54%. This difference may result from a difference in mission or design. Although the B-52 airplanes are older, the C-141's have accumulated many more flying hours. Typically, a B-52 had about 10,000 hours vs. about 30,0000 for the cargo airplane, as of 1980. The difference also may reflect the inclusion of cracking in the data base.

The difference in delamination and coating, etc., is more obscure. Delamination amounts to 15-20% of effort for C-141A's, but only 7-13% for the B-52. This difference may be related to construction. In the case of coating, sealant, there is a large difference: for the cargo airplane, 8-18% of effort is in this category, but it is negligible for the bomber.

Similarities are found between certain categories of effort, particularly 117-deteriorated, 170-mild to moderate corrosion, 230-dirty, and 667-severe corrosion. Differences in cracking may reflect mission or design differences, whereas delamination and coating/sealant problems may reflect construction

TABLE 10. DISTRIBUTION OF MAINTENANCE MANHOURS AMONG CORROSION-RELATED HOW MALFUNCTION CODES FOR C-141A AND B-52D, G, AND H AIRPLANES, PERCENT. BOTH FIELD- AND DEPOT-LEVEL DATA ARE INCLUDED.

	1970-74	1975-76		1978-79	
How Malfunction		C-141A*	B-52D	B-52G	B-52H
117	7.1	3.7	2.9	8.6	6.5
170	12.7	14.5	21.9	9.2	9.6
190	34.1	36.3	54.1	55.5	53.1
230	8.7	10.5	10.2	11.9	14.7
667	2.5	3.8	3.3	1.7	6.2
846	15.1	20.2	7.4	12.8	9.7
865	7.9	7.7	0.2	0.3	0.3

*Reference 2.

materials or design.

Considering the B-52 data separately, there is a similarity among series in the 190, 230, 846, and 865 codes, but they differ in 117, 170, and 667 codes. For example, code 117 costs for the B-52G were 8.6% of effort, whereas only 2.9% was spent on B-52D's. Code 170 on B-52D was nearly 22%, but less than 10% for G/H series. A reversal is seen for code 667, where the effort is 6, 3.3, and 1.7 % for H, D, and G, series, respectively. This parallels the D series where mild to moderate corrosion is significant, the H series where severe corrosion is large, and the G series with significant code 117 repairs. Considering the relative age of these airplanes (D series rebuilt 5 years ago, hence are the newest, the H series are 10 years old and the G series 12-13 years old), the data become interesting.

Failure rates are distinguished from manhours: Failure rates are represented by the number of reported repairs in a given time period, whereas manhours represent the labor, hence cost, for the same items. Comparing failure rates (Table 11), the picture differs from the previous cost picture: While Codes 117, 170, 230, and 667 are not much different, there is a significant difference between code 190, 846, and 865 for the cargo vs. the bomber airplanes. In the case of 190, the difference is smaller than for manhours. There is a difference between failure rate, but the difference is smaller, 33% vs. 42%. Code 846 differs by a factor of 3, 17% vs. 5%. Code 865 is 7-22% on the C-141A, but is negligible for the B-52.

C. ORGANIZATIONAL-LEVEL MAINTENANCE

1. MAINTENANCE EFFORT COMPARED WITH POSSESSION

In order to compare an airbase's maintenance effort with the number of its aircraft, one may assess the relative magnitudes of maintenance. Aircraft Possession Percent represents the fraction of the fleet for which a given

TABLE 11. DISTRIBUTION OF FAILURES AMONG CORROSION-RELATED HOW MALFUNCTION CODES FOR C-141A AND B-52D, G, AND H AIRPLANES, PERCENT. BOTH ORGANIZATIONAL- AND DEPOT-LEVEL DATA ARE INCLUDED.

How Malfunction	C-141A*		B-52D	B-52G	B-52H
	1970-74	1975-76		1978-79	
117	4.6	3.8	5.1	13.3	9.4
170	20.7	15.0	35.2	11.1	9.7
190	35.4	29.2	40.4	45.1	42.9
230	13.9	16.7	12.9	21.5	31.3
667	0.9	1.5	2.9	0.9	1.6
846	16.1	19.3	3.4	8.1	4.5
865	7.0	11.8	0.2	0.2	0.7

*Reference 2

TABLE 12. CORROSION-RELATED MAINTENANCE COSTS COMPARED WITH OWNERSHIP, BOTH AS PERCENT, FOR B-52D AIRPLANES 1978-79 (ORGANIZATIONAL-LEVEL ONLY).

Airbase	Per Cent Airplanes	Per Cent Manhours	Ratio
Andersen	16.5	22.5	1.36
Carswell	42.4	47.1	1.11
Dyess	20	13.8	0.69
March	21.2	16.5	0.78

airbase is responsible, whereas Per Cent of Maintenance reflects the actual airbase contribution. Thus the comparison shows whether an airbase was meeting more or less than its share of responsibility based only on the number of "resident" airplanes. Obviously, for many reasons, some residents may be more demanding than others, while some "caretakers" are more generous than others.

This comparison is shown in Tables 12-14, which list the per cent of airplanes possessed together with the per cent of fleet maintenance manhours for each airbase. A third column lists the ratio of the second column entry to the first. A ratio greater than or less than one suggests a correspondingly larger or smaller corrosion maintenance effort than what was required merely by the number of airplanes to be serviced. An airbase with a larger effort may have experienced more serious corrosion problems because of a more severe environment; more maintenance personnel were available; greater emphasis was placed on corrosion by airbase management; more corrosion maintenance was reported; or records may be more nearly complete. Comparisons must be made with caution: for example, one or two stations with high or low efforts would cause some other airbase to appear excessive in the opposite direction.

Nevertheless, Andersen, Carswell, Blytheville, Castle, Griffiss, and Loring were found to be high in relative maintenance effort, while Dyess, Barksdale, Fairchild, Robins, Grand Forks, and Minot were low. The remaining airbases performed corrosion maintenance at levels approximately matching their responsibility.

2. ORGANIZATIONAL-LEVEL MAINTENANCE BY HOW MALFUNCTION CODE

Corrosion-related labor costs are listed in Tables 15-17 by airbase and by work unit code as manhours per airplane. Discussion here is confined to observations of relative values.

TABLE 13. CORROSION-RELATED MAINTENANCE COSTS COMPARED WITH OWNERSHIP, BOTH AS PER CENT, FOR B-52G AIRPLANES, 1978-1979 (ORGANIZATIONAL-LEVEL ONLY.)

Airbase	Per Cent Airplanes	Per Cent Manhours	Ratio
Barksdale	18.2	12.2	0.67
Blytheville	9.4	10.6	1.13
Castle	8.8	16.9	1.92
Fairchild	9.4	6.9	0.73
Griffiss	9.4	11.6	1.23
Loring	8.8	11.1	1.26
Mather	8.8	7.3	0.83
Robins	8.8	6.3	0.72
Seymour-Johnson	8.8	7.5	0.85
Wurtsmith	9.4	9.4	1.0

TABLE 14. CORROSION-RELATED MAINTENANCE COSTS COMPARED WITH OWNERSHIP, BOTH AS PER CENT, FOR B-52H AIRPLANES, 1978-79 (ORGANIZATIONAL-LEVEL ONLY.)

Airbase	Per Cent Airplanes	Per Cent Manhours	Ratio
Castle	9.0	18.1	2.0
Ellsworth	32.6	33.7	1.03
Grand Forks	18.0	13.1	0.73
K. I. Sawyer	21.3	23.3	1.08
Minot	19.1	12.0	0.63

TABLE 15. CORROSION-RELATED LABOR COSTS, B-52D AIRPLANES, 1978-79, BY AIRBASE AND WORK UNIT CODE, MANHOURS PER AIRPLANE.

	Work Unit Code					
Airbase	117	170	190	230	667	867
Andersen	49.6	476	761	157	91.9	55.4
Carswell	30.9	227	731	129	27.8	149
Dyess	37.1	60.6	519	87.9	34.1	62.8
March	30.0	214	504	110	23.1	26.7

TABLE 16. CORROSION-RELATED LABOR COSTS, B-52G AIRPLANES, 1978-79, BY AIRBASE AND WORK UNIT CODE, MANHOURS PER AIRPLANE.

	Work Unit Code					
Airbase	117	170	190	230	667	846
Barksdale	26.7	27.8	451	68.5	4.5	79.0
Blytheville	28.1	187	504	336	4.5	53.6
Castle	63.9	68.9	1337	315	23.3	90.4
Fairchild	20.4	52.4	420	117	12.8	42.8
Griffiss	96.5	78.8	679	144	3.8	216
Loring	32.6	91.3	757	237	10.2	112
Mather	101	44.2	517	88.3	5.6	66.9
Robins	26.7	30.2	483	127	5.6	37.9
Seymour-Johnson	43.8	31.8	644	79.4	6.8	39.6
Wurtsmith	36.8	271	488	96.0	1.9	83.0

TABLE 17. CORROSION-RELATED LABOR COSTS, B-52H AIRPLANES, 1978-79, BY AIRBASE AND WORK UNIT CODE, MANHOURS PER AIRPLANE.

	Work Unit Code					
Airbase	117	170	190	230	667	846
Castle	73.3	66.5	1067	266	2.2	44.8
Ellsworth	111	32.9	446	194	2.0	28.4
Grand Forks	15.0	20.9	322.	167	2.2	44.8
K. I. Sawyer	31.7	160	423	195	4.7	39.9
Minot	24.1	10.8	349	71.5	3.1	36.1

D-series airbases, Table 15, do not show excessive maintenance in code 117, with the exception of Andersen. Code 170 shows widely differing values ranging from 61 to nearly 500 manhours per airplane. Andersen is the largest consumer of manhours in this category, and Dyess is the smallest. Code 190 shows a narrow range of values between 500 and 700 manhours per airplane. Code 230 also is not remarkable, with most bases between 100 and 150 manhours per airplane. Code 667 shows little difference except for the fairly large value at Andersen, about three times higher than the other three bases. Finally, code 846 shows Carswell having the high value at 149 manhours per airplane; Dyess and Andersen are approximately equal and March has a low value of 27 manhours per airplane.

For B-52G airplanes, Table 16, code 117 has Mather, Griffiss, and Castle high compared with the other bases, which have values about the same as in Table 14 for D series. Code 170 shows Blytheville and Wurtsmith anomalously high compared with other bases. These two appear to be comparable with Carswell and March. Other bases in the G-series, however, have values comparable with that of Dyess. For code 190, there is only one high value, viz., Castle with more than three times the value of the lowest base in the group. All others are closely grouped in manhours spent on cracking repairs. The Castle value may be explainable because it is the training base for G- and H-series airplanes, hence its repair record reflects the wear-and-tear of training missions. Code 230 exhibits a range of values from a low of 69 to a high of 315 with no apparent pattern. Code 667 has uniformly low values, with the exception of Castle (high) and Wurtsmith (low). This may be related to the use of code 170 at Wurtsmith. Code 846 shows Griffiss to be high, but the rest are comparable. On-site inspections at the airbases revealed some possible patterns in attitude of personnel which may explain high useage of code 846 at Griffiss.

For the H-model airplanes, Table 17, code 117 has a high value for Ellsworth and a somewhat high value for Castle. Code 170 shows K.I. Sawyer to be high, but the rest are more-or-less comparable. Code 170 is a bit low for Minot. Code 190 again shows Castle with more than twice that of any other airbase in this category, which again may be related to its training mission. Code 230 shows Minot to be somewhat low compared with the others which are comparable with one another. Code 667 is used almost negligibly at H-model airbases, and code 846 shows about the same values for all airbases.

3. CUMULATIVE MAINTENANCE

A useful tool for tracking maintenance efforts is a graphic display of cumulative corrosion failures and cumulative corrosion maintenance manhours vs. calendar time by individual airplane serial number. Such charts reveal day-to-day maintenance on the airplane and major events such as alert duty, transfer to another airbase, depot maintenance, and phased inspections. Certain kinds of faulty data also are frequently apparent, e.g., data "gaps". Such gaps appear as flat spots on the charts, but can be identified with certainty only if comparisons are made with other airplanes and airbases. These charts were prepared in the C-141A study and were found to provide insight into maintenance practices, hence also have been prepared for all operational B-52 airplanes in USAF inventory. Samples are reproduced in Figures 3-5. As was true for the C-141A system, organizational maintenance in the B-52 system is linearly cumulative over long time periods, and the slope of field-level maintenance thus measures the maintenance rate as either manhours per month or failures per month. In Figures 3-5 these values are indicated together with other relevant information. A consistent maintenance rate is apparent over several years for each airbase, both before and after depot maintenance. Thus, one may be confident that the rate of field

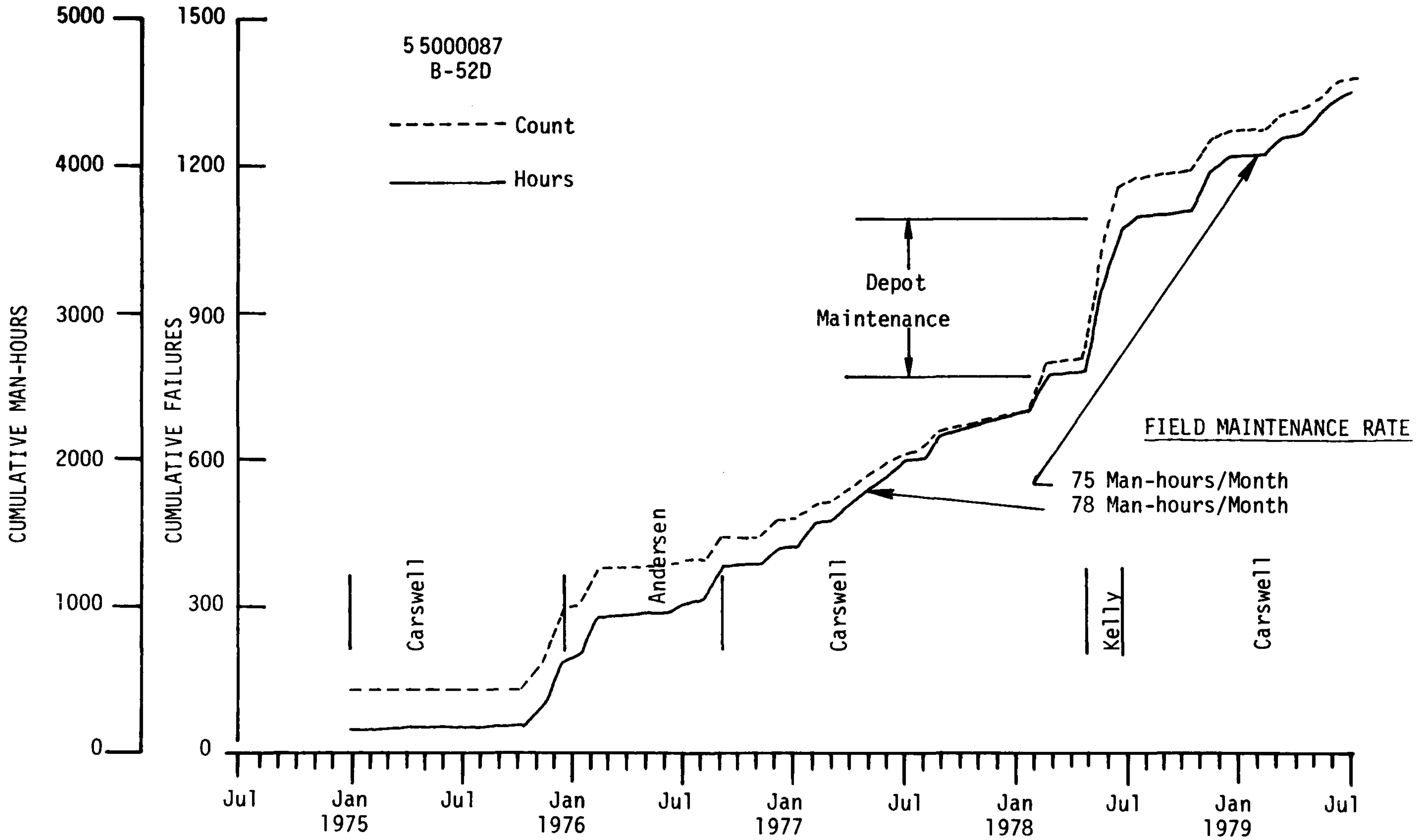

Figure 3. CUMULATIVE CORROSION MAINTENANCE ON B-52D AIRPLANE SERIAL NUMBER 55000087, 1975-1979.

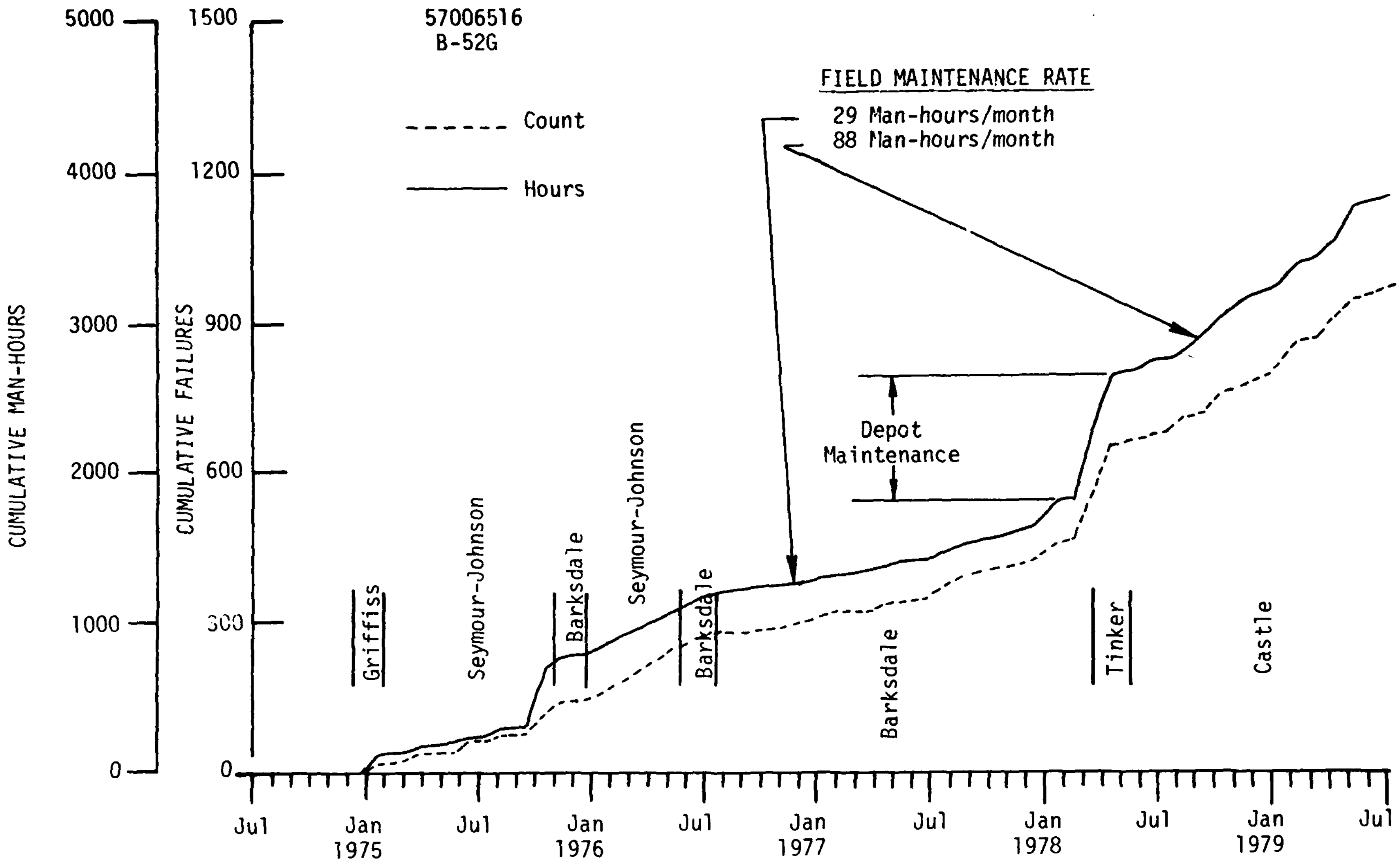

Figure 4. CUMULATIVE ORGANIZATIONAL-LEVEL MAINTENANCE ON B-52G AIRPLANE SERIAL NUMBER 57006516, 1975-1979.

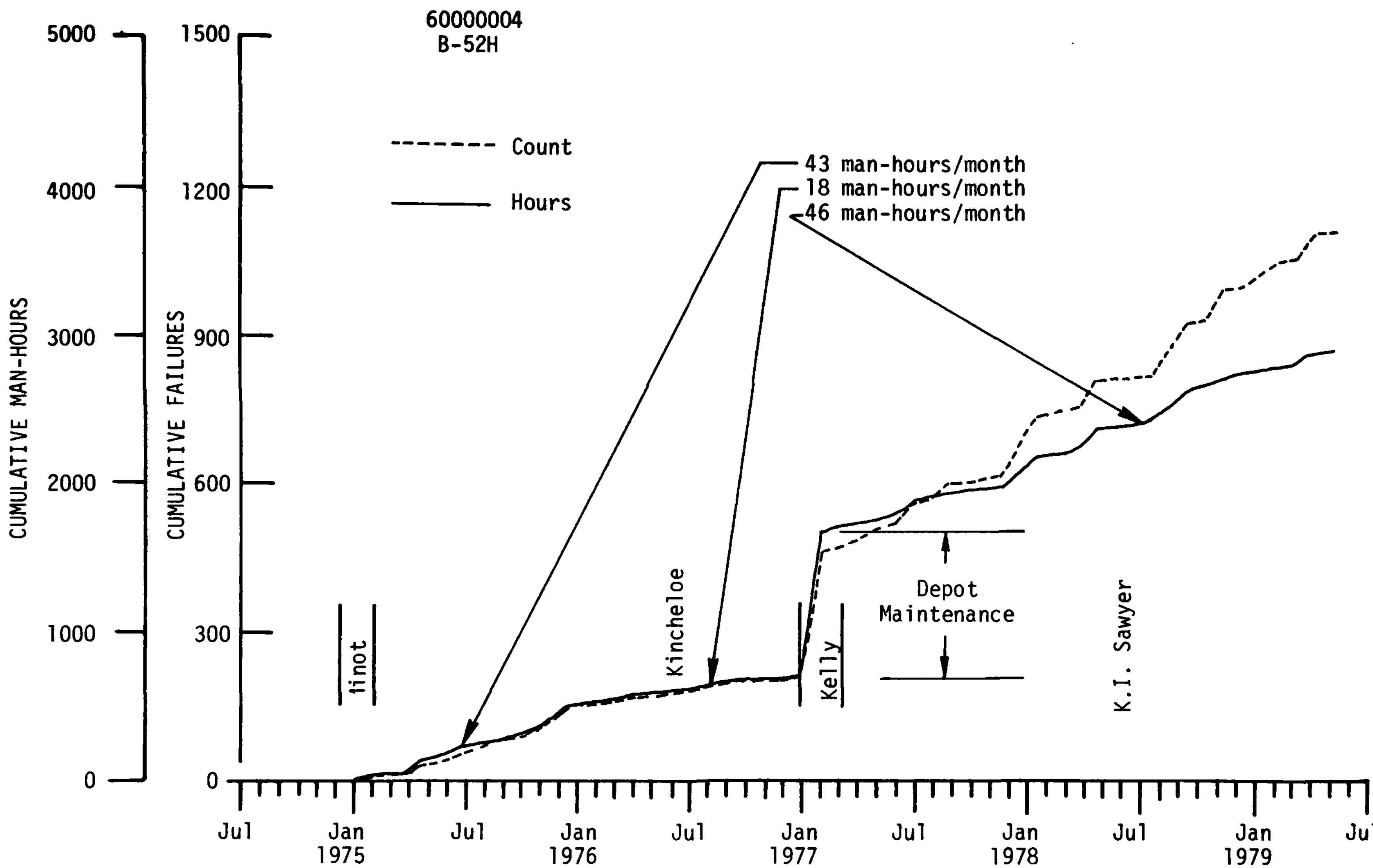

Figure 5. CUMULATIVE CORROSION MAINTENANCE ON B-52H AIRPLANE SERIAL NUMBER 60000004, 1975-1979.

maintenance for a given airbase is a constant regardless of what factors may drive it. This rate reflects environmental corrosivity and other factors which determine the amount of effort .

A second method of determining field maintenance rates is to determine the total effort by aircraft serial number from AFM 66-1 data and compare this with the time period the airplane was assigned to that airbase, i.e., total manhours divided by possessed months.

4. STATISTICAL DISTRIBUTION OF FIELD MAINTENANCE

The statistical distribution of corrosion maintenance data was determined for field maintenance rates measured by both slopes of cumulative maintenance vs. time and total maintenance divided by possessed months for each airbase. The data were plotted as monthly manhours per airplane by serial number against the per cent of total population for each airbase, as in Figures 6 and 7 for B-52D and -H systems. Similar data plotted for the G-series are comparable, but are not reproduced because the number of similar airbases yields too complex a graphical presentation. The data are summarized, however, in tabular form together with those of the D-and H-series. Figures 6 and 7 are charts of the data obtained by dividing total manhours by possessed months. Plots of slopes from cumulative maintenance vs. time are similar but are not reproduced.

The results closely parallel those of the C-141A system in that the data are distributed essentially normally. From these charts one can deduce three types of information: (a) the data are more-or-less normal, (b) a mean value, and (c) the standard deviation. These data are collected in Tables 18-20 for all series. Results are shown both for values obtained from the cumulative maintenance vs. time charts as well as the total effort vs. possessed months values. Again as in the case of the C-141A, there is a striking difference from one airbase to another. In the case of the D-models, monthly manhours

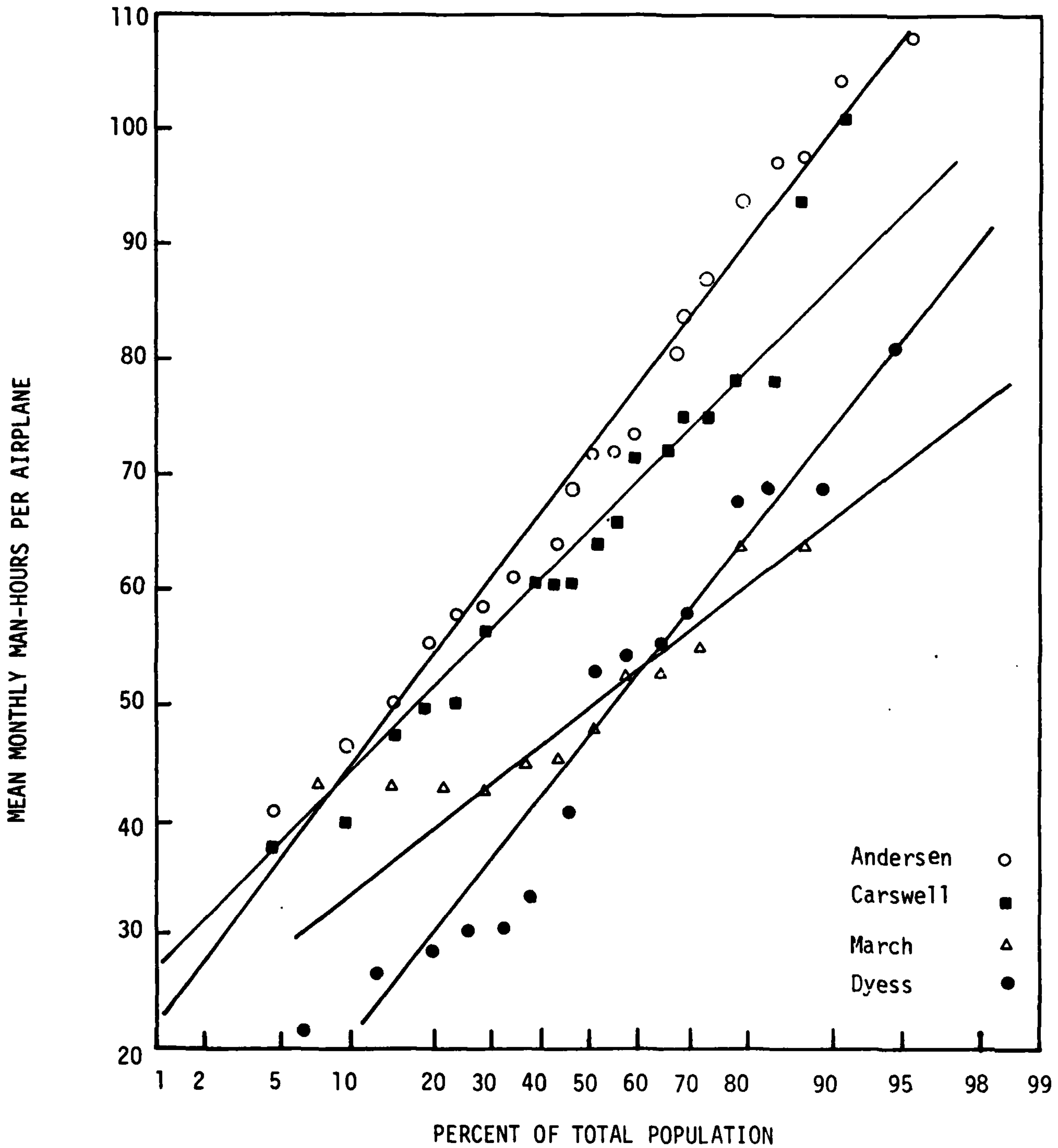

Figure 6. B-52D ORGANIZATIONAL-LEVEL CORROSION MAINTENANCE TO INDIVIDUAL AIRPLANES, 1Q78-3Q79.

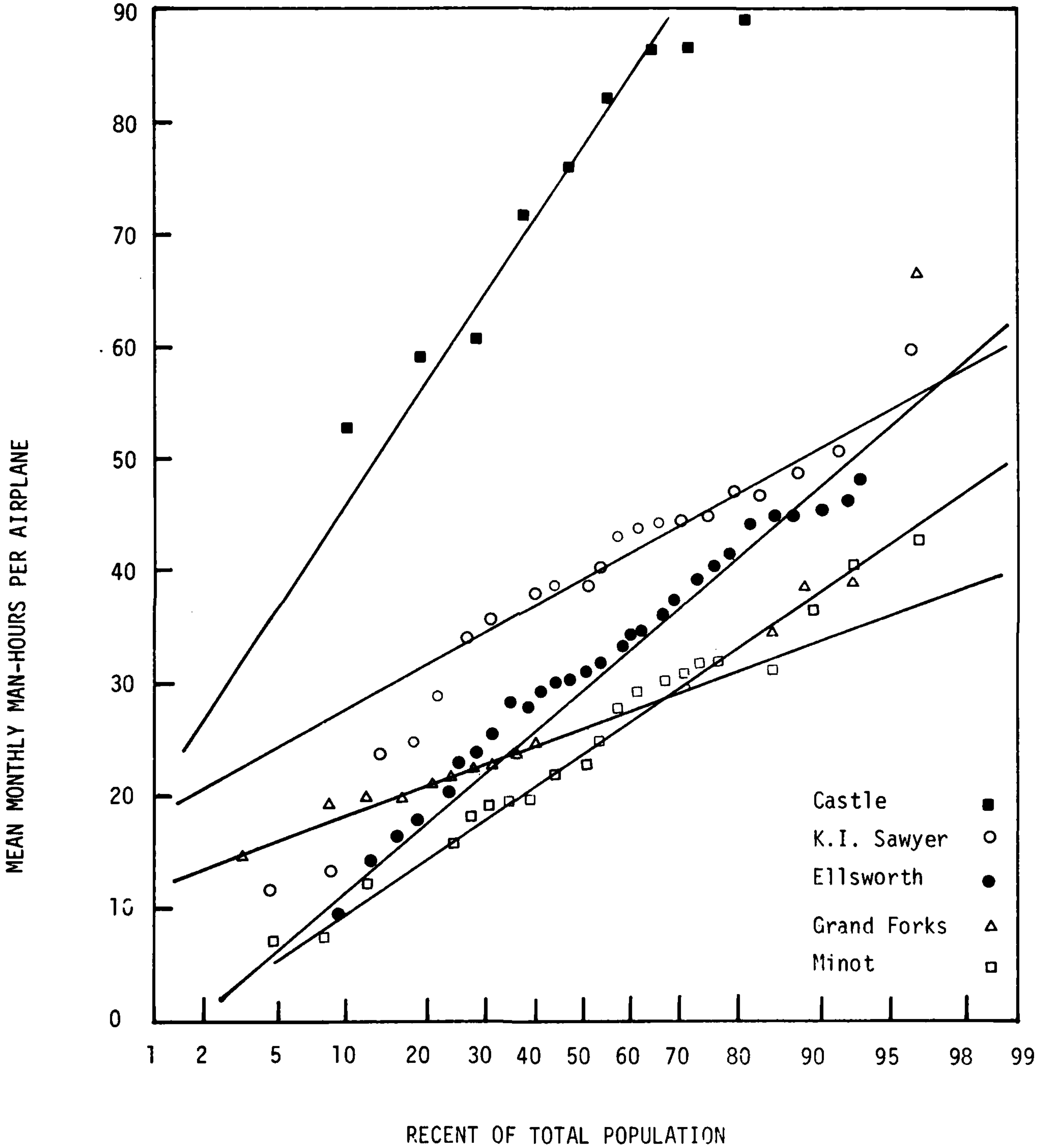

Figure 7. B-52H ORGANIZATIONAL-LEVEL CORROSION MAINTENANCE TO INDIVIDUAL AIRPLANES, 1Q78-3Q79.

TABLE 18. B52D ORGANIZATIONAL-LEVEL CORROSION MAINTENANCE, MEAN MONTHLY MANHOURS PER AIRPLANE, 1Q 1978 - 3Q 1979.[a, b]

Airbase	Cumulative Effort		Mean Monthly Effort	
Andersen	73	(22)	107	(53)
Carswell	66	(16)	62	(22)
Dyess	48	(21)	40	(19)
March	50	(13)	47	(10)

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a See text.
b Parenthetic values are standard deviation.

TABLE 19. B-52G ORGANIZATIONAL-LEVEL CORROSION MAINTENANCE, MEAN MONTHLY MANHOURS PER AIRPLANE. 1Q 1978 - 3Q 1979. [a, b]

Airbase	Cumulative Effort	Mean Monthly Effort
Barksdale	31 (8)	30 (10)
Blytheville	54 (24)	86 (33)
Castle	91 (20)	81 (19)
Fairchild	40 (14)	35 (18)
Griffiss	61 (15)	56 (26)
Loring	58 (15)	55 (24)
Mather	39 (8)	38 (9)
Robins	36 (8)	36 (6)
Seymour-Johnson	43 (12)	39 (19)
Wurtsmith	44 (12)	45 (17)

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[a] See text.
[b] Parenthetic values are standard deviation.

TABLE 20. B-52H ORGANIZATIONAL-LEVEL CORROSION MAINTENANCE, MEAN MONTHLY MANHOURS PER AIRPLANE, 1Q 1978-3Q 1979. [a, b]

Airbase	Cumulative Effort		Mean Monthly Effort	
Castle	74	(27)	78	(25)
Ellsworth	40	(14)	30	(14)
Grand Forks	30	(5)	26	(6)
K. I. Sawyer	46	(13)	39	(9)
Minot	30	(10)	24	(11)

[a] See text.
[b] Parenthetic values are standard deviation.

per airplane range from 40 to more than 100 for the four airbases. In the case of the G-series, they range from 30 to more than 85 manhours per month, and for H -airplanes, from 24 to 78.

5. COMPARISON WITH ENVIRONMENT

A preliminary comparison of monthly corrosion maintenance manhours per airplane with environmental corrosion severity indices obtained from PACER LIME is shown in Figures 8-10. Results for D-series airplanes show excellent linear correlation with environmental severity ratings. In the case of G-series airplanes, the agreement is not good, probably because there are unknown factors in the corrosion equation. There are similarities, however: Seymour-Johnson, Robins, and Barksdale are similar both in geography and maintenance, yet Blytheville is anomalous, having a similar environment but a much higher rate of corrosion maintenance. The Castle effort also is high, probably reflecting the training-mission-induced cracking repairs. Griffiss is high in corrosion maintenance, related to delamination problems and possibly corrosion caused by acid rain, also not included in the corrosion severity algorithms. No obvious explanation comes to mind for the high values at Loring, except possibly the acid rain question.

The H-series results show good agreement for Ellsworth, Minot, and Grand Forks, which have similar environments. Castle is high, again reflecting training mission damage. K. I. Sawyer may not be indexed properly with its environment, which may be more severe than reflected in the PACER LIME results.

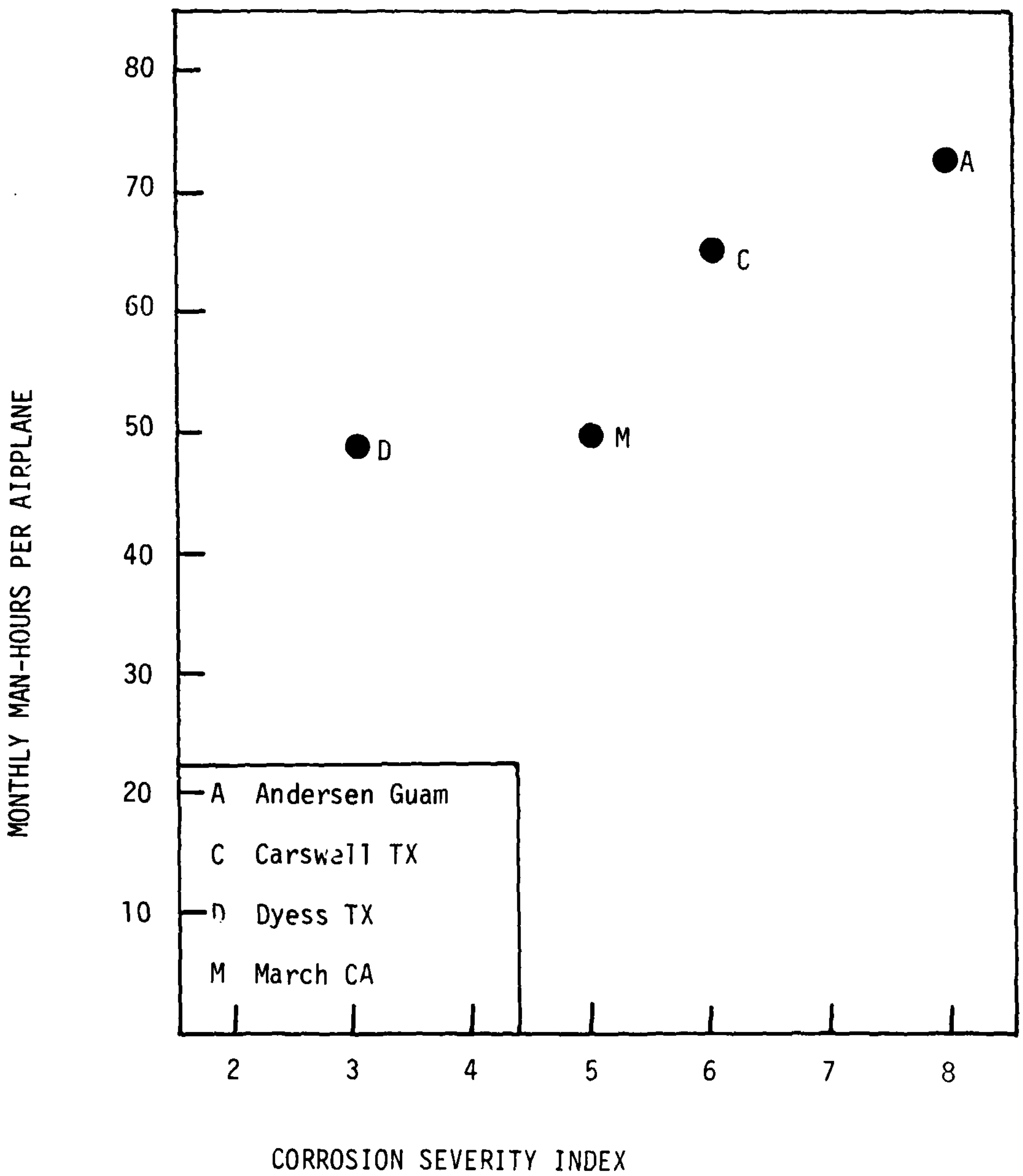

Figure 8. B-52D ORGANIZATIONAL-LEVEL CORROSION MAINTENANCE COMPARED WITH ENVIRONMENTAL RATINGS, 1 078-30 79

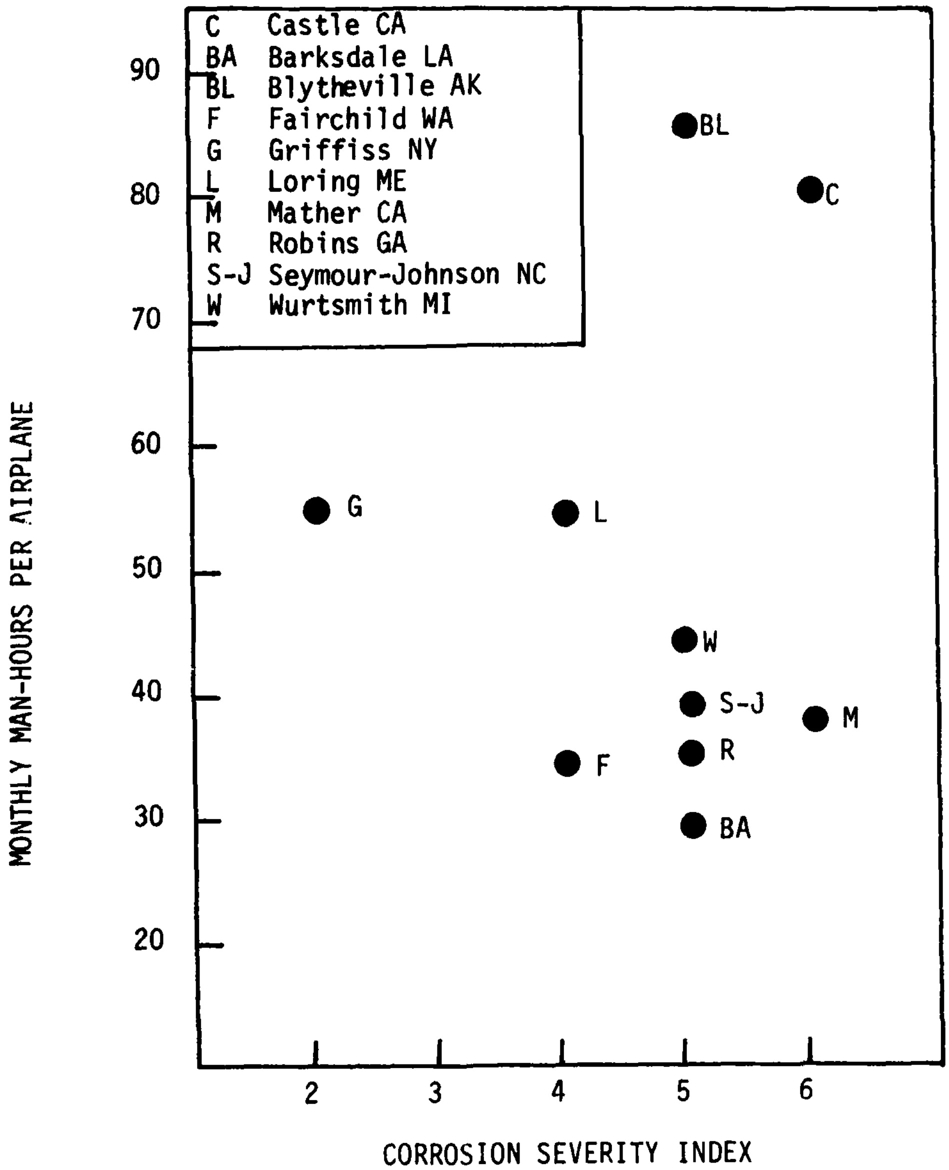

Figure 9. B-52G ORGANIZATIONAL-LEVEL CORROSION MAINTENANCE COMPARED WITH ENVIRONMENTAL RATINGS, 1Q78-3Q79.

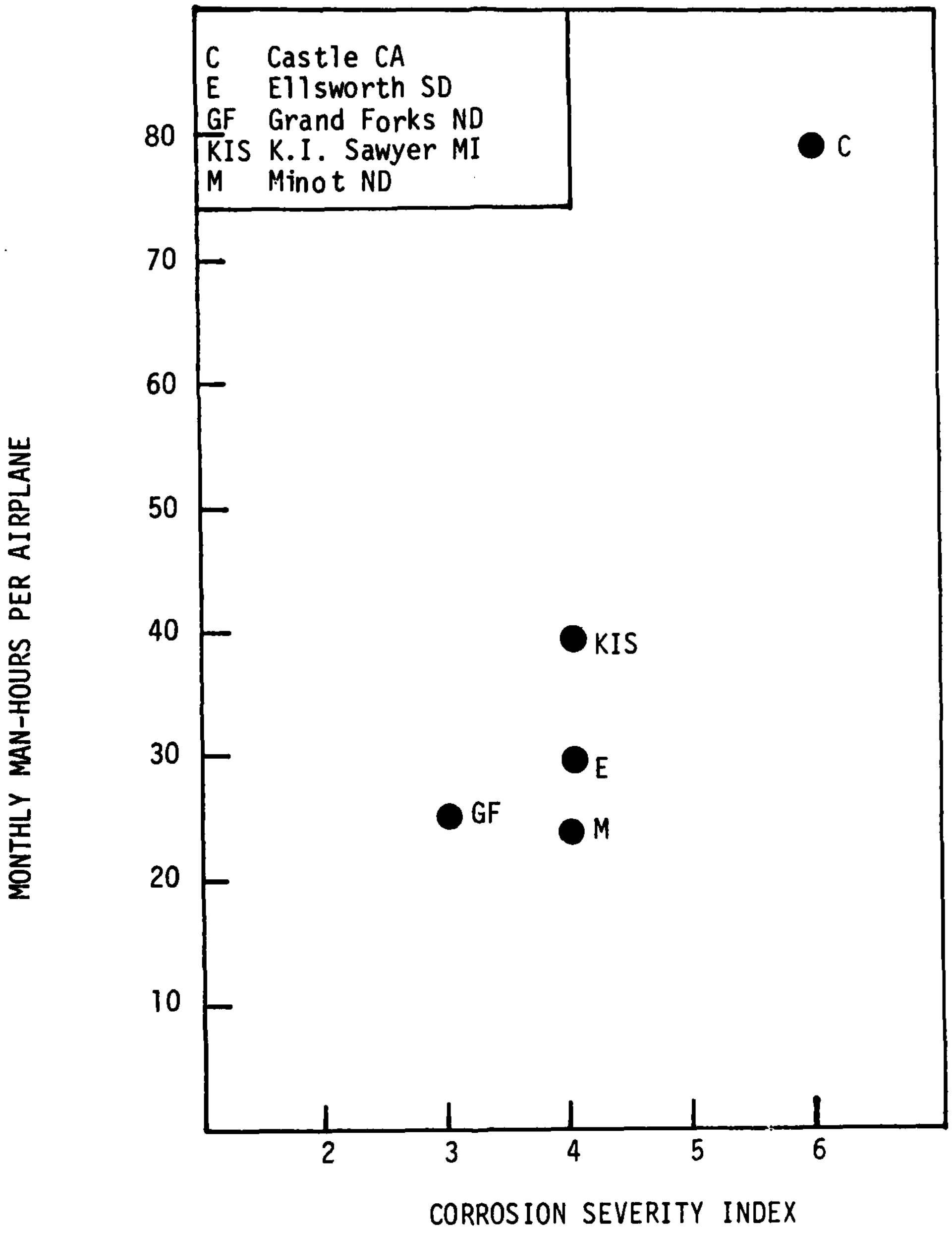

Figure 10. B-52H ORGANIZATIONAL-LEVEL CORROSION MAINTENANCE COMPARED WITH ENVIRONMENTAL RATINGS, 1Q78-3Q79.

D. THE WORKCENTER IDENTIFICATION PROBLEM

Replacement of "performing" work center codes with "owning" work center codes has proved somewhat annoying because many opportunities for data correlation have been short-circuited. Nevertheless, it has been possible to describe several characteristics of USAF maintenance from comparisons of MDCS data with that from alternate sources.

Certain organizational units, or "service shops," have primary responsibility for specific classes of maintenance, e.g., there is a Corrosion Control Shop at each airbase. It might be assumed that most, if not all maintenance work in such a class could be attributed to the appropriate specialty shop. As it turns out, this probably is not correct, but before it can be dismissed, one should estimate the validity of the assumption.

Consider first the relation between maintenance "customers" and a specialty service shop. The latter may be either

(1) a monopoly, where customers must be served by this shop, or

(2) competitive, where other shops offer the same services, more-or-less efficiently at higher-or-lower cost, and the customer may choose from them to suit his needs.

USAF maintenance shops are depot- or organizational-level, and a set of specialty units exists at each level. Depot facilities, as an aggregate of specialty and general shops, usually are a monopoly for PDM. In special cases a contractor, e.g., the airframe manufacturer as in the case of ECP 1581 PACER PLANK, may provide PDM services simultaneously with a major modification. Generally, however, USAF depots enjoy monopoly status with no competition for that maintenance business. The "package" of services to be performed is subject to annual bargaining _via_ the Maintenance Review Board process, wherein the depot seeks to maximize the package while operating commands seek to minimize the cost.

The situation is more complex at field level. Organizational-level maintenance is the responsibility of the airbase Deputy Commander for Maintenance (DCM), whose operations are divided into several major categories including Organizational Maintenance Squadron (OMS), Avionics Maintenance Squadron (AMS), Munitions Maintenance Squadron (MMS), and others; only OMS and FMS are relevant here. Essentially, OMS personnel are "employed" by the military wing which "owns" and operates a given set of airplanes, whereas, FMS personnel are maintenance specialists, more-or-less "on-call" to serve the needs of the owners, hence they comprise a set of quasi-monopoly specialty repair shops.

The term "quasi-monopoly" means that these are not "union" shops. (We would prefer that they were!) If, in a union shop, a pipe-fitter discovers a defect requiring a welding repair, a weldor must be summoned to perform the task. In a non-union shop, the pipe-fitter would repair the weld and continue fitting pipes; a weldor would be called in only if the repair were beyond the pipe-fitter's non-specialized skills. USAF maintenance shops follow non-union practices, hence, without work center identification codes, one cannot determine whether a corrosion repair was effected by a Corrosion Control shop specialist or by a pipe-fitter.*

*As noted, "performing" Work Center codes previously were replaced routinely with the "owning" Work Center code--for no obvious reason, but one which must have appeared sensible at the time of adoption. This practice has been discontinued in accordance with our recommendations from earlier studies. Unfortunately, this change does not help here--all Carswell MDCS corrosion (170, 667) records, for example, bear WC code 22110 (Bomber Flight Line OMS).

Consider further whether the shop is overstaffed or understaffed.

(1) If it is overstaffed, then some maintenance personnel sit about waiting for work--not necessarily an undesirable situation --and the sum of actual hours worked on specific jobs will be less than the total available personnel hours. On one hand, this means workers are paid for nonproductive time, but, on the other hand, customers can receive service as needed, and work done will be related directly to need.

(2) If the shop is understaffed, there will be a customer queue and pressure to create (or defection to) competitive shops. There will be no idle personnel and hours worked will be credited to a specific work order. Actual work done will not necessarily be related to work need, and, hence, to failure rate or damage rate. Instead, the work done will reflect the system used to prioritize work requests.

It might be expected that most How Mal 170/667 and/or Action Taken maintenance would have been effected by the Corrosion Control shop. Since a non-union shop policy is in effect, non-specialized personnel also are authorized to use these codes. These personnel might be assigned to

-21--OMS Flight Line

-311-FMS Fabrication

-312-FMS Metal Processing

-313-FMS Structural Repair

-314-Corrosion Control.

Representative data (from Carswell AFB) for these work centers are listed in Table 21 for comparison with corrosion-related MDCS data. "Available" and "documented" man-hours are listed. The former values are computed from

TABLE 21. WORK CENTER PRODUCTIVITY, CARSWELL AFB, THIRD CALENDAR QUARTER 1980 [a]

Work Center	Available Man-hours	Documented Man-hours	Ratio
-211-OMS Bomber Flight Line	64178	27244	2.35
-311-FMS Fabrication	4015	2770	1.45
-312-FMS Metal Processing	2460	2128	1.16
-313-FMS Structural Repair	14907	11155	1.34
-314-FMS Corrosion Control	4886	3028	1.61

B-52D corrosion-related man-hours [b]

AFM 66-1	380
D056B	246

[a] "Monthly Maintenance Summary," September 1980, Carswell AFB, TX, p.60.

[b] See text.

twenty-one eight-hour days per month multiplied by the available maintenance personnel, excluding supervisors and vacation days. For example, 23140-Corrosion Control in September 1980 had nine personnel (plus five supervisors) assigned to its roster, yielding approximately 1500 available man-hours; the monthly maintenance report lists 1332 man-hours, with the descrepancy probably attributable to vacation time. "Documented" man-hours represent work time accounted for on AFTO 349, 350, etc., thus were computerized and are part of the MDC system.

Available man-hours of course are larger than documented man-hours, and the difference between the values represents non-productive time categories such as transit to work site, "on-call", and others. The ratio available/documented will reflect the significance of such categories, being close to one for mostly in-shop work and significantly larger than one for on-equipment work.

Nevertheless, it may be concluded that all maintenance shops listed in Table 21 were overstaffed, partly in order to provide service on an as-needed basis. Consequently, it may be assumed that work performed is related to need, and not related to an assigned priority.

Documented corrosion-related B-52 man-hours--i.e., those which find their way into AFM 66-1 permanent records of one sort or another--also are listed in Table 21. They are almost negligible compared with any of the maintenance service shop's credits, even Corrosion Control. Specifically, MDCS man-hours (from AFLC) for the same time period, On-Equipment B-52D, How Mal 170 or 667, work unit codes 11A through 11P, number 380. From D056B, they number 246. Regardless of the source, they are fewer than 10% of the documented man-hours tallied by the Carswell analysis section for the Corrosion Control shop.

The Corrosion Control shop also is responsible for maintenance on the resident KC-135 wing(s). Data from BLIS suggests that the KC-135 system requires about 25% of the corrosion maintenance on B-52 systems. Consequently, if one assumes that MDCS corrosion-related on equipment man-hours were entirely the product of the Corrosion Control shop, it would account for perhaps one quarter of their documented effort.

Data discussed here are from a single airbase, but material from other airbases is comparable. Consequently, we conclude that the 314--Corrosion Control shops are quasi-monopoly, non-union, overstaffed specialty shops. Their monopoly status is quite weak in that their efforts are less than half --even as low as 10%-- of the total corrosion maintenance effort for sampled B-52 airbases. Moreover, the "specialty" in corrosion is equally weak, since only a fraction of their documented effort is found to be corrosion-related work on aircraft.

The rest of their effort either is documented as support general or undocumented.

These observations are not intended to disparage the Corrosion Control shops' efforts or management's methods of accounting for them. The conclusions relate only to the questions of corrosion maintenance logistics as previously outlined.

VI. MAJOR AIRCRAFT INSPECTION PROGRAMS: ACI, PDM

A. THE ANALYTICAL CONDITION INSPECTION PROGRAM

The Analytical Condition Inspection (ACI) Program (AFLCR 66-28) provides for special inspections over and above normal inspection requirements. Usually, these are accomplished concurrently with PDM on a "representative" number of aircraft in order to predict the condition of airplanes in the balance of the fleet. An ACI is "in-depth" in order to discover hidden defects and to accumulate data for engineering evaluation relative to flight safety, PDM cycles and work requirements, structural condition, and inspection intervals. The airplane sample for ACI is selected on the basis of chronological age, time since last PDM, operational environment, cumulative flying hours, and other factors which suggest that an airplane may have problems not indicated by AFM 66-1 data, Material Deficiency Reports, or other sources. Thus, the total number of aircraft and specific serial numbers to receive ACI are determined by considering aircraft configuration, mission, operational environment, calendar age, and flying hours; Lead the Force (LTF) and Controlled Interval Extension (CIE) programs also are considered as ACI candidates. The number of ACI aircraft is based upon the inventory size and the confidence level desired in the results to indicate the fleet condition.

As applied in practice to the B-52 fleet, these well-considered principles have produced the following results. First, neither CIE nor LTF programs are in effect currently for the B-52 systems. In fact, operational practices apparently are intended to prolong the service lifetime of the entire fleet for as long as possible, hence "high flyers" are allowed to rest whilst the pack catches up. Second, all airplanes are on a 48-month PDM interval and, since ACI's are concurrent with PDM, they also will occur at that interval. With the exception of occasional "test bed" units, mission differences will not be significant, if, for no other reason, simply because the airplanes do not fly much. Calendar age no longer is relevant. Configurations have been somewhat different between the three series in the past, and certainly such differences will be accentuated as ALCM deployment and avionics MODS proceed. Within each series, however, no important differences will exist with respect to the above factors. Consequently, operational environment is the only useful basis for selecting a "representative" sample.

The number of B-52 airplanes selected for ACI for several years has been fixed at ten each for the 79 D, 173 G, and 96 H airplanes, thus, the statistical confidence level will be somewhat higher for D-series and lower for G-series fleets. Serial number selection has been variable. In one year, the first ten units scheduled for PDM were picked; another year they were the alternate ten; yet another year they were sprinkled among the list. Perhaps the PDM schedule itself was prepared on the basis of the ACI criteria: each unit, however, managed to enter PDM at the specified 48 months, give or take a few weeks. Finally, the operational environment criterion--based on the inaccurate and superseded "Interim PACER LIME" (16,17), ratings--seem to have had no real impact on the selection process: For example, in some years nearly the entire ACI sample was drawn from a single airbase.

B. THE IMPACT OF PDM, ACI, AND RCM PROGRAMS ON FIELD MAINTENANCE

Organizational-level data have been compared for time intervals before and after depot maintenance for FY 1978 and 1979 PDM programs. The results show some curious effects of PDM and ACI efforts, but also suggest an improvement in the selection of ACI airplanes.

Field level data for FY 1978 and FY 1979 were calculated as man-hours per calendar quarter for the time period before and after depot maintenance. Airplanes which had spent less than six months at either the source or recipient airbase were excluded in order to eliminate short residence interval fluctuations, because airplanes often receive no corrosion maintenance over intervals of several months, especially when on alert status. The available data for each airplane MDS then were plotted on probability paper for the respective fiscal year program, Figs. 11-14, on which ACI units are designated with a different symbol. These latter are shown separately for G-series airplanes in Figs. 15-16, where the before and after values are connected by a line.

Before/after FY 78 PDM G-series data reveal no dramatic differences, although maintenance effort after is somewhat lower. The FY 79 program, however, was followed by substantially higher field data, e.g., the mean value is about 50% higher. Comparing ACI airplane data yields similar results, slightly lower maintenance following 1978 PDM, and significantly higher after 1979. H-series data show, if anything, a reversal of this pattern.

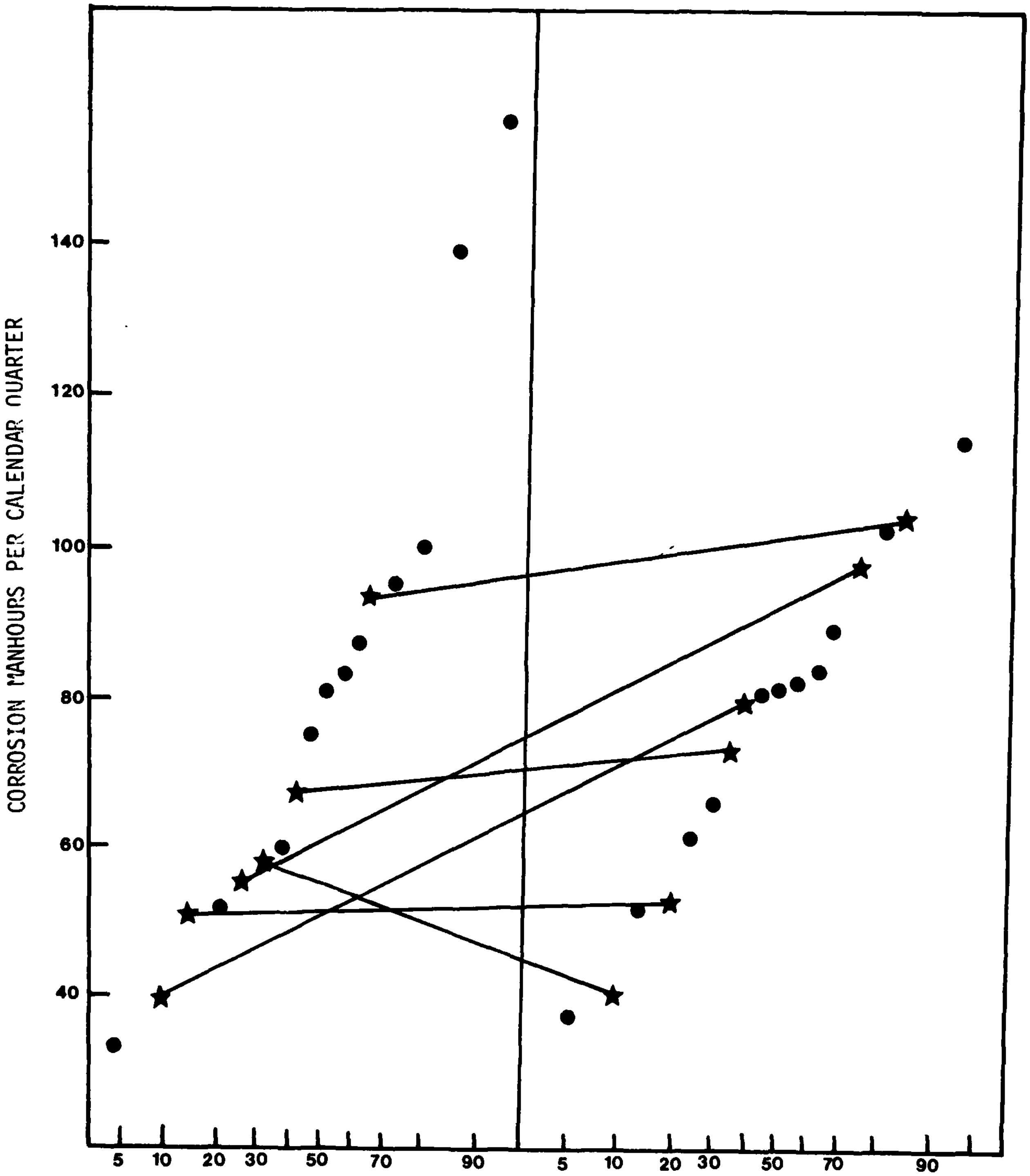

FIGURE 11. ORGANIZATIONAL-LEVEL B-52H CORROSION MAINTENANCE BEFORE AND AFTER PDM IN FY 78. STARRED VALUES ARE ACI UNITS, AND LINES CONNECT SAME AIRPLANE.

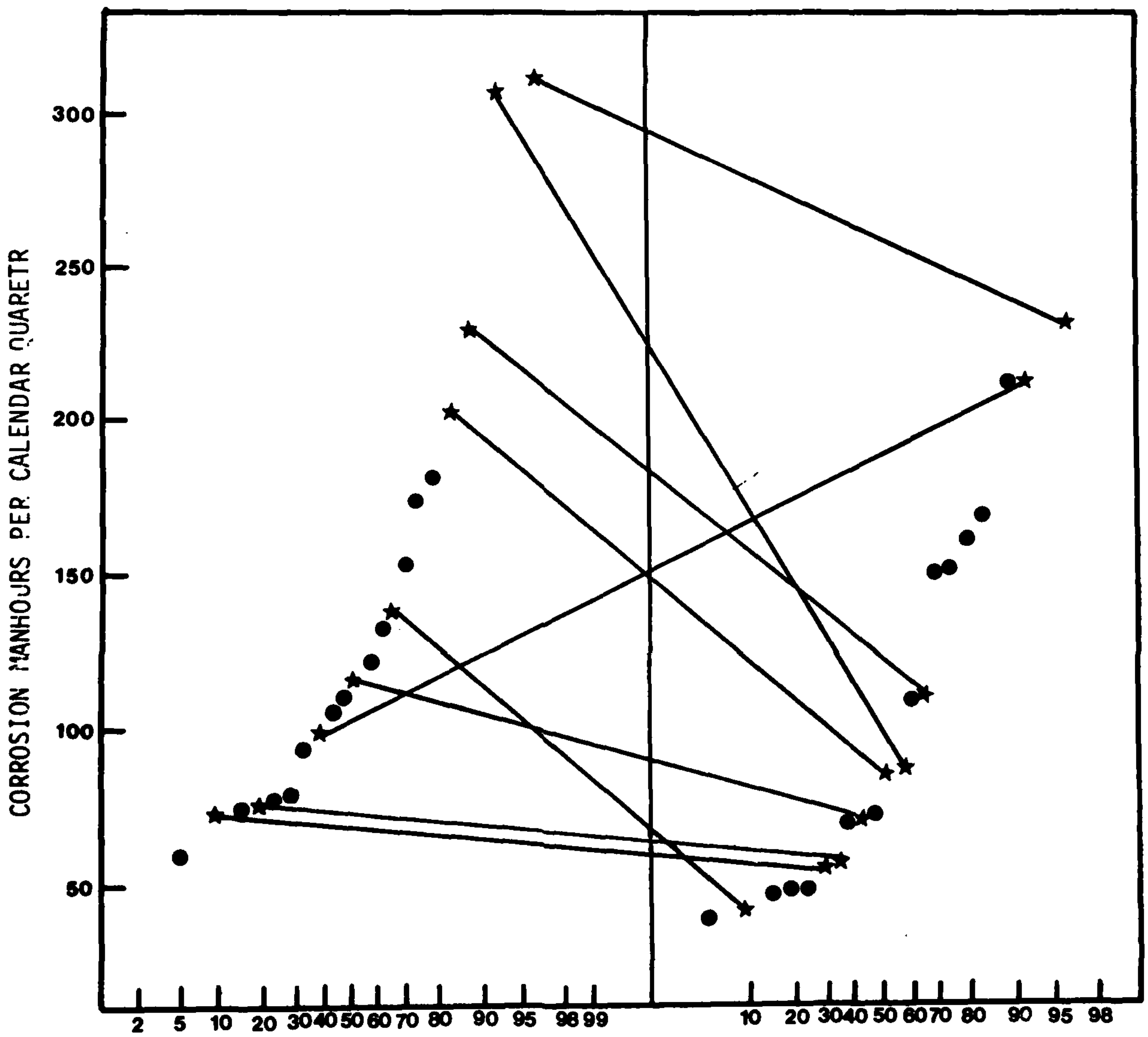

FIGURE 12. ORGANIZATIONAL-LEVEL B-52H CORROSION MAINTENANCE BEFORE AND AFTER PDM IN FY 79. STARRED VALUES ARE ACI UNITS, AND LINES CONNECT SAME AIRPLANE.

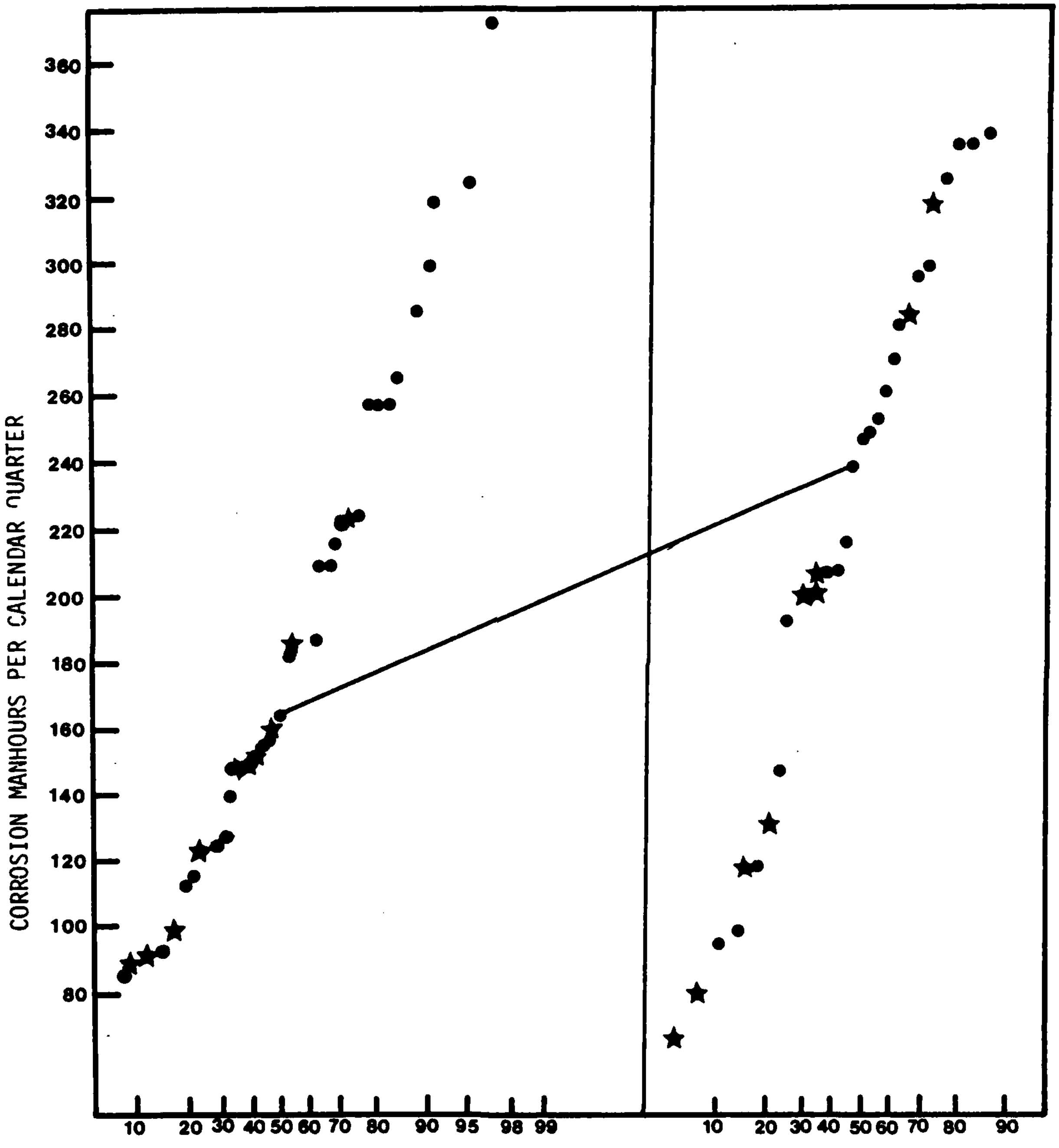

FIGURE 13. ORGANIZATIONAL-LEVEL B-52G CORROSION MAINTENANCE BEFORE AND AFTER PDM IN FY 78. STARRED VALUES ARE ACI UNITS, AND LINE CONNECTS THE MEANS.

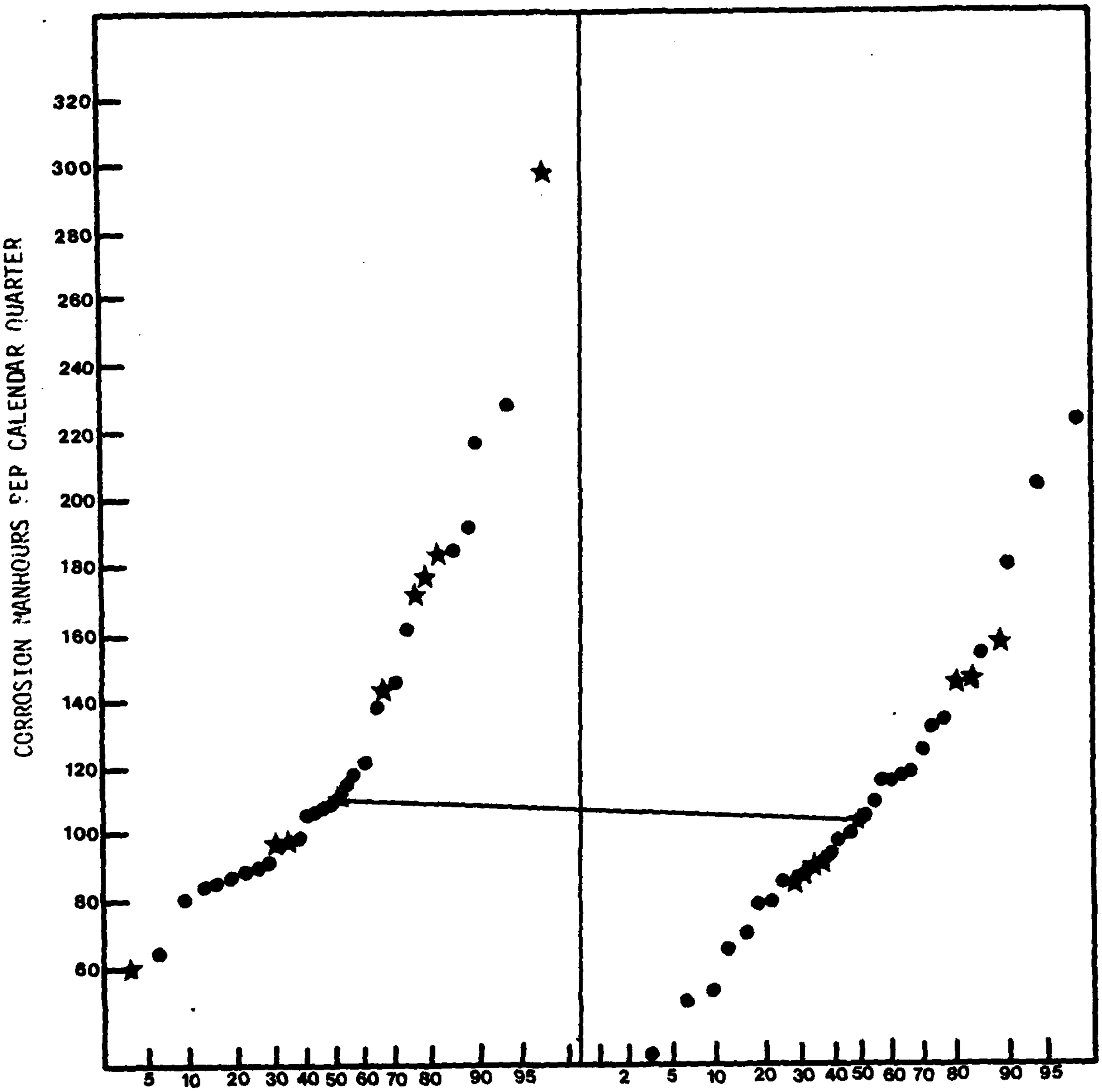

FIGURE 14. ORGANIZATIONAL-LEVEL B-52G CORROSION MAINTENANCE BEFORE AND AFTER PDM IN FY 79. STARRED VALUES ARE ACI UNITS, AND LINE CONNECTS THE MEANS.

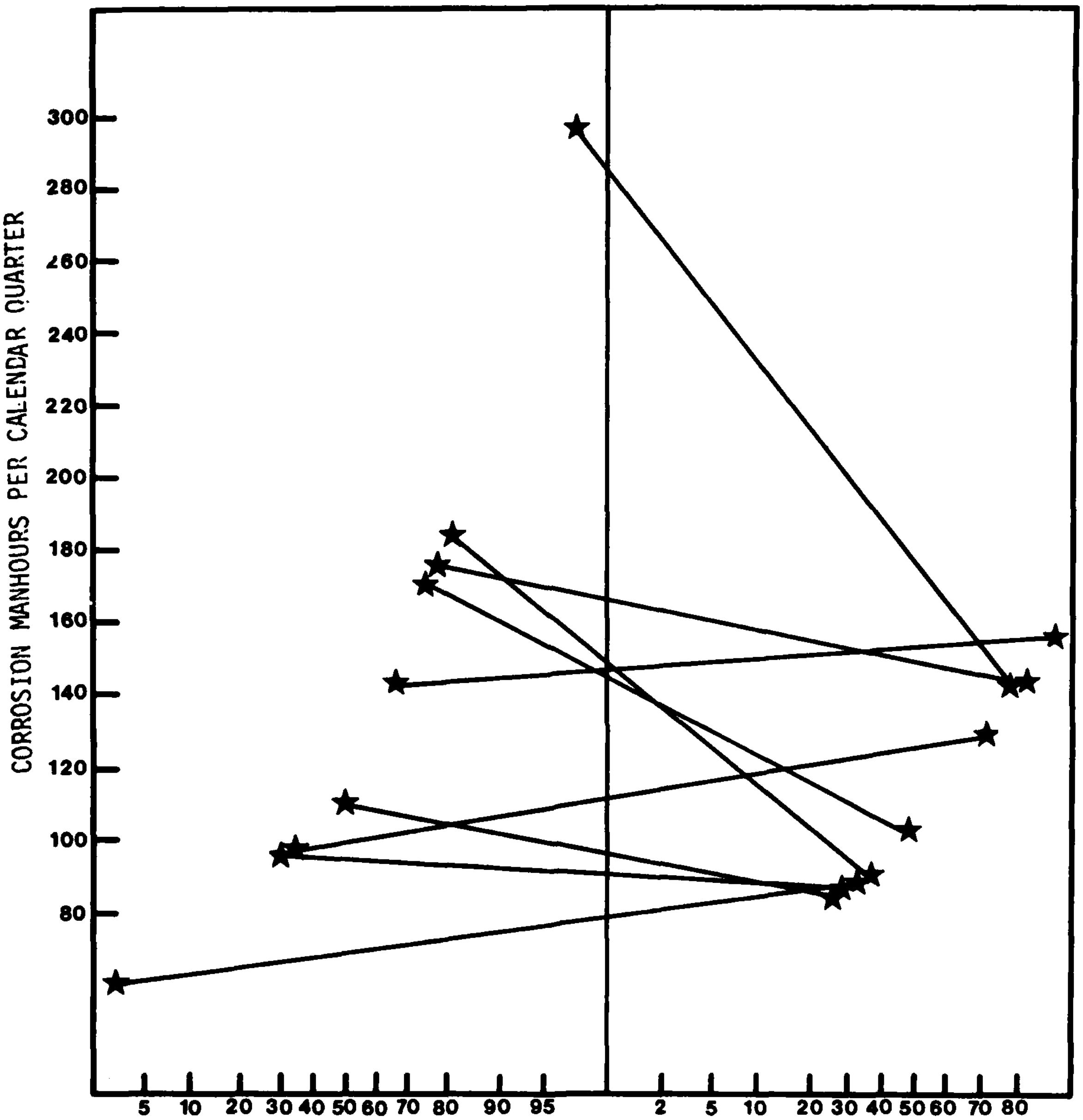

FIGURE 15- ORGANIZATIONAL-LEVEL B-52G CORROSION MAINTENANCE BEFORE AND AFTER PDM FOR ACI AIRPLANES IN FY 79.

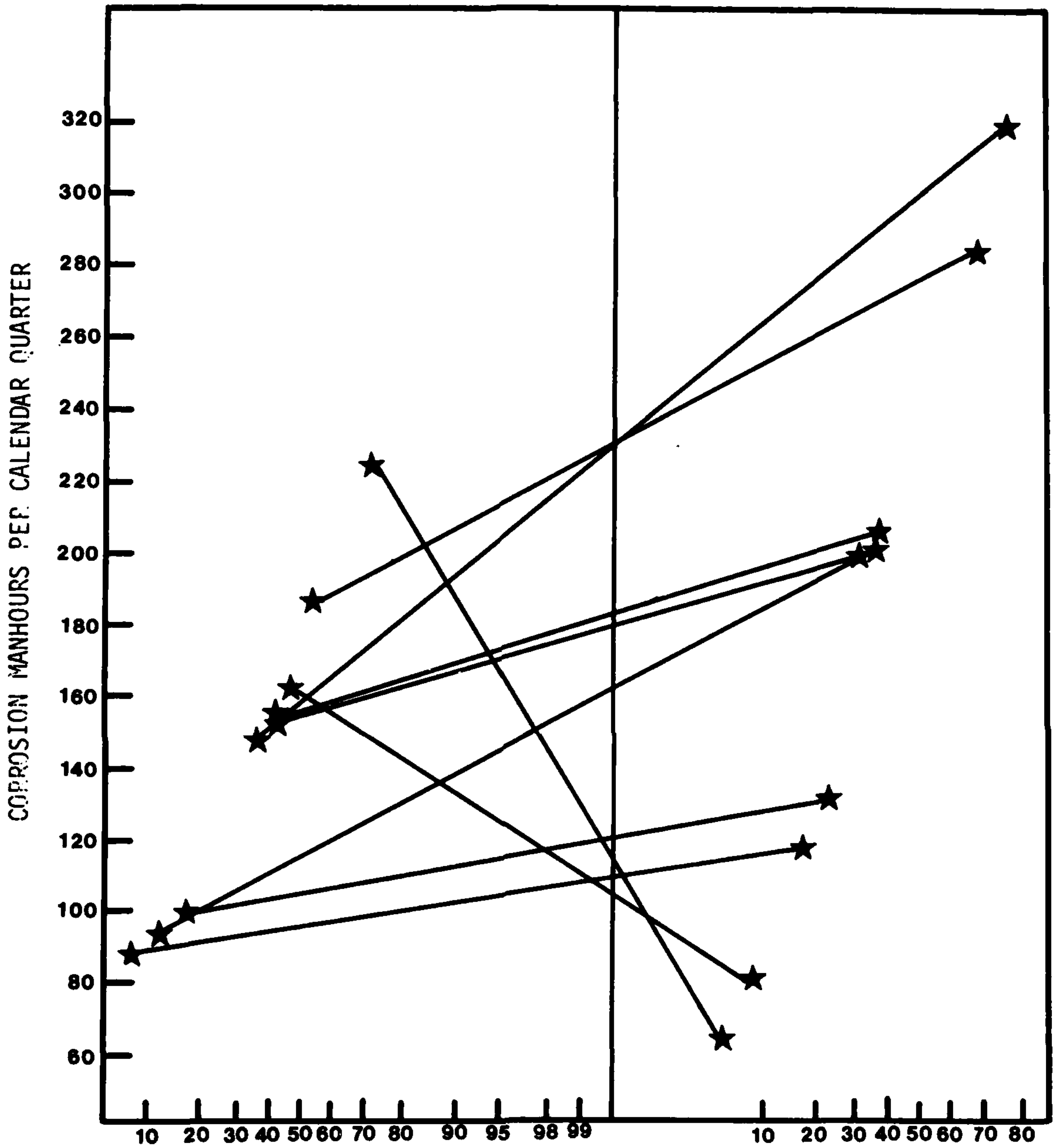

FIGURE 16-ORGANIZATIONAL-LEVEL B-52G CORROSION MAINTENANCE BEFORE AND AFTER PDM FOR ACI AIRPLANES IN FY 78.

Assignment to a recipient airbase different from the source obviously can significantly affect the data. In these two years, 15 out of 80 G's and 10 out of 40 H's were returned from PDM to the source airbase; in FY 79, 21 of 22 D's went "home". The total airbase environment together with the airplane's history, of course, determines the level of corrosion maintenance effort. These samples are too small, however, to produce useful results, particularly in view of the confused situation in the G MDS. More light could have been put on the question if required data and documents had been provided as requested.

These results are of value in the problem of ACI airplane selection. Clearly PDM-input airplanes have received widely differing levels of corrosion maintenance during the preceeding four years. This information and the input airbase environment can be valuable tools in selecting that "representative" sample.

MDCS data prior to the adoption of RCM is fundamentally different from post-RCM data. Pre-RCM maintenance (non-TCTO) was a periodic IRAN program; under such logic, inspections were performed at fixed calendar intervals, and time-to-failure was a measureable event which depended only on the probability P_f that an inspected aircraft contained a given failure, and the probability P_d that the failure is detected. Post-RCM maintenance, on the other hand, is an isochronal combination of "hard-time" (TCTO) and "on-condition" (IRAN). Only "on-condition" maintenance can be described as a measureable event, but, under RCM logic, only selected components are inspected --adjacent damaged components are ignored unless they are included in the phase work deck at hand. Most significantly, however, RCM "on-condition" maintenance is a measureable event related to calendar time only if an airplane is flown about the same number of hours per calendar time period. This is the case with civilian airlines and, to some extent, military cargo airplanes. It definitely is not the case for military weapons carriers --specifically, B-52's --which may stand unused on armed alert for several months. There is a fundamental incompatibility between isochronal-phased RCM programs and corrosion to such airplane systems. To be sure, some things wear out only if you use them, but "rust [almost] never sleeps." Consequently, while corrosion is calendar-time dependent, isochronal flying hour maintenance is not calendar-time dependent in the B-52 systems. It follows that post-RCM MDCS data may not be useful for tracking or prediction of corrosion damage.

We turn now to a consideration of the limitations of inspection programs as they relate to statistical questions. Thereafter, we present a discussion of improved selection procedures which will provide a desired confidence level at lower cost to the ACI program.

C. PROBABILITIES*

A fundamental objective is the detection of corrosion/corrosion-cracks in a specific subsystem, but not necessarily the most critically corroded item. Once damage is discovered, one would investigate the corrosion problem and, if necessary, add an inspection/repair requirement for all airplanes in the fleet.

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* This material is adapted from Reference 3.

Corrosion and residual strength estimates evaluate a specific component, but corrosion detection in a fleet, C_D, is a function of a cumulative random series of corrosion occurrences and systematic inspections. If more inspections are performed and/or more corrosion is initiated on the specific component, the probability of finding a corroded item increases. The corrosion process itself, once initiated, is a monotonically increasing function of time. It is essential to relate the corrosion detection process to detection capability, which perhaps could be accomplished by utilizing the in-service maintenance data base.

The random detection of corrosion in a fleet is represented by "typical" detectibility characteristics derived from service data. This approach also can be used to establish service-demonstrated Damage Tolerance Ratings (DTR) which are used to derive minimum required DTR's on a comparative basis.

In addition to providing a comparative damage tolerance evaluation between similar details on various aircraft models, the system provides a simplified method of evaluating the effect of varying corrosion rates, inspection methods, improving accessibility, and the use of supplemental inspections. The probability of inspecting an airplane with damage, P_1, is a function of the level of inspection, the number of airplanes inspected, the position each inspected airplane holds relative to the operational lifetime, and the cumulative exposure to risk (cf. Equations [1] and [2], p.7).

The probability of inspecting the detail under consideration, P_2, is a function of the area or component under consideration at the specific level of inspection.

The probability of detecting the damage at a specific threshold, P_3, depends on the inspection method used (visual, NDE, etc.) the extent of damage, and the mental set of the inspector/inspectrix.

The probability of detecting at least one instance of damage at the specified threshold, P_s, is the product $P_1 \cdot P_2 \cdot P_3$. Or, if corrosion damage at the threshold level has occurred on one component of one airplane in the fleet, the probability of detecting it during a typical inspection is P_S.

For the corrosion propagation characteristics shown in Figures 17-18

L_D is the threshold of damage detection for a given inspection level and method of inspection;

L_C is the corrosion damage at which residual strength corresponds to minimum design strength (critical); and

T is the calendar time in which corrosion will propagate from L_D to L_C*. Corrosion damage at the time of inspection is necessarily random. A relation between the probability of detection and the extent of corrosion damage can be established from service experience for a large number of components. This data then can be used to integrate the corrosion propagation curves to derive equivalent values for probability of detection P_3 during time interval $\bar{T}$ (see Figures 17-18).

If $\bar{T}$ is the average interval between inspections, the frequency of inspections during damage detection interval T is $T/\bar{T}$. Therefore, for a given inspection level and inspection method, the probability that a single corroded component (the first) in the fleet in interval T is

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*This does not take account of L_U, the level of corrosion damage when repair can be effected instead of remove/replace, i.e., the optimum damage level for repair.

[6] $P_r = 1 - [1-P_S]^{T/\bar{T}}$.

It is known empirically, that when corrosion damage is detected in a specific component of an inspected airplane (say at ACI), additional inspections on other airplanes and/or similar components at another location usually will reveal comparable damage, provided the ACI sample was representative. As we have pointed out frequently, there is not a one-to-one correlation: A specified level of confidence must be known in order to assure that the critical damage level has been determined via the selective inspection.

Let ΔT be the mean time interval between corrosion-damage detection in the fleet for the same component/subsystem (which is a random variable.) If the first damage is detected at T_1, the second case should be detectable at $T_1+\Delta T$, and the third at $T_1+2\Delta T$, etc.

Thus in time period T, the interval available for detecting first damage, the second, and third will be $T-\Delta T$, $T-2\Delta T$, etc. From this, the frequency of fleet inspections during the corrosion period is $[T/\bar{T}]^{\gamma}$ where

[7] $\gamma = \sum_{n=1} [1-(n-1)\Delta T/\bar{T}]_{+}$

n = corrosion occurrence number,

+ = values > zero.

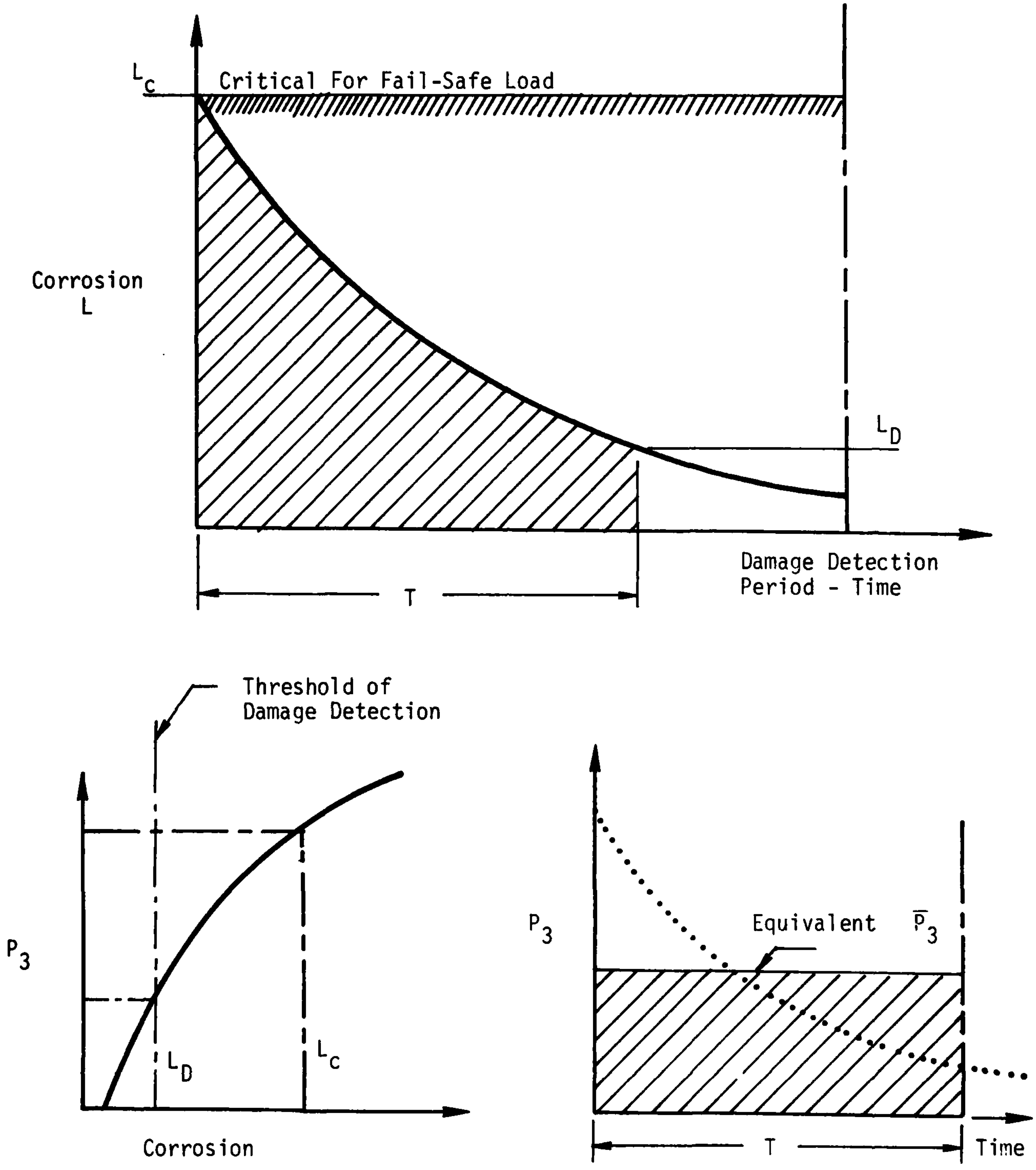
Consequently, for a given inspection method and level, the probability of detecting one threshold or critically-damaged corroded component in the time interval T is

[8] $P_d = 1-[1-P_S](T/\bar{T})^{\gamma}$, or

[9] $P_d = 1-[1-P_r]^{\gamma}$.

Considering all levels of inspection in a fleet, the cumulative probability of damage detection is

[10] $P_D = 1-[\prod_i (1-P_{d_i})]$,



P_3 = PROBABILITY OF DETECTING CORROSION DAMAGE AT A SPECIFIC THRESHOLD FOR A SPECIFIC INSPECTION LEVEL AND METHOD.

Figure 17. Corrosion Damage Detection vs Time.

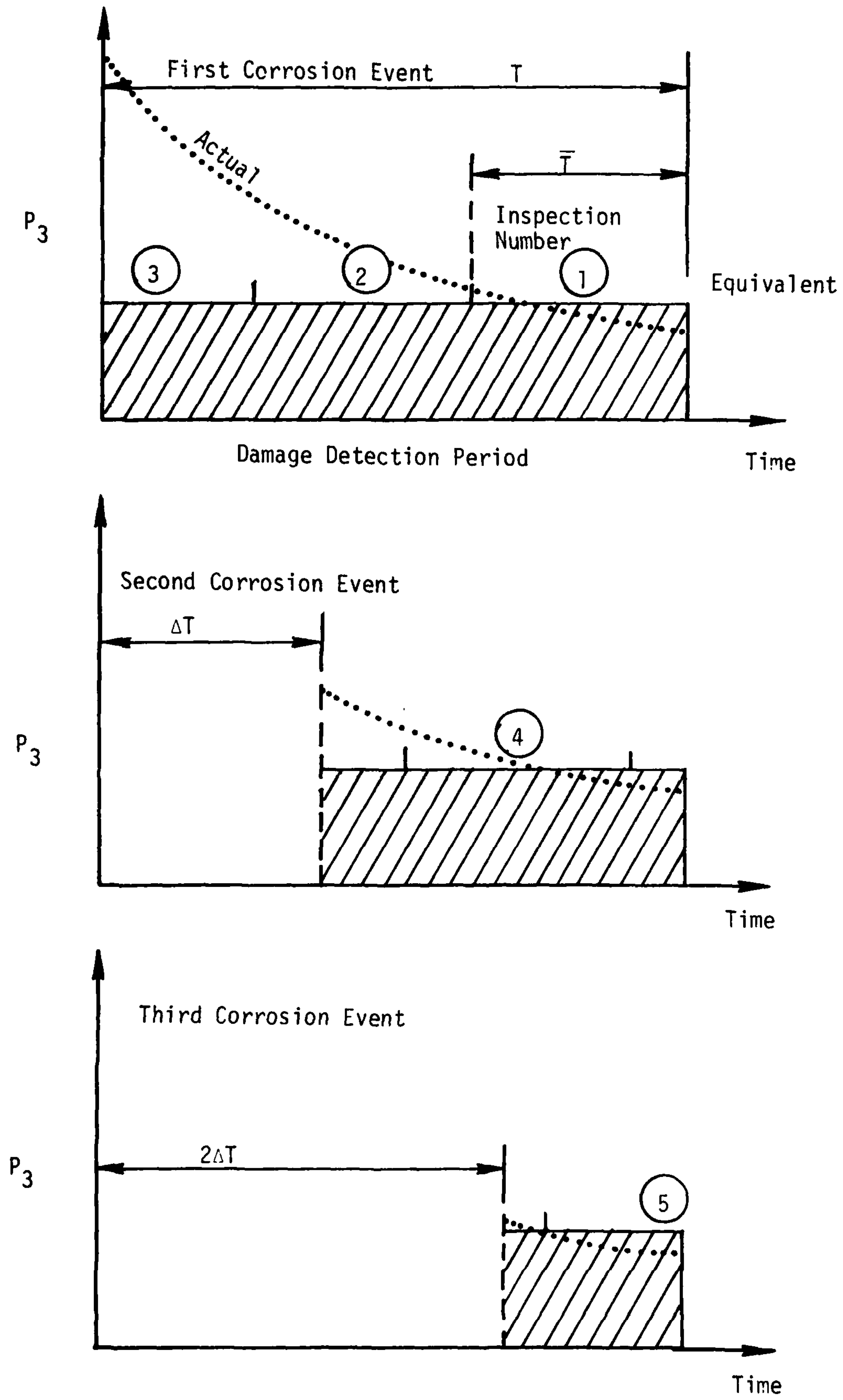


Figure 18. Sequential Corrosion Events and the Probability of Damage Detection.

where i is the applicable inspection level (cf. Table 1).

Although values of P_D may be close (0.999 vs. 0.998), the probabilities of not detecting a damaged component, given by $(1-P_D)$, 0.001 vs. 0.002, are widely different, hence the latter probability provides a better basis for comparison.

To provide a direct qualitative measure of design and/or maintenance planning actions, an equivalent number of 50/50 opportunities of detection may be used to define a Damage Tolerance Rating as follows.

[11] $DTR = \log(1-P_D)/\log 0.5$

[12] $P_D = 1-(1/2^{DTR})$.

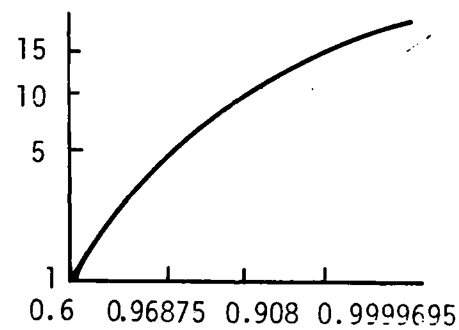


Figure 19. Damage Tolerance Rating vs Cumulative Probability of Damage Detection.

Required levels of DTR will be established by evaluating "acceptable" service corrosion using the same system. Therefore, a DTR is a comparative measure of damage detection opportunities in the fleet.

The required rating system standards are P_1, P_2, P_3, L_i, and ΔT. The data can be used with corrosion propagation data (kinetics) to derive DTR's. If a derived DTR is found to be unacceptable, compared with previous acceptable service experience, the required level can be obtained by

--improving detectability characteristics (accessibility, visibility, more sophisticated inspection methods),

--increased surveillance (inspections at a lower, more frequent level, special or supplemental inspections; inclusion of an item in ACI),

--extending corrosion propagation intervals *via* material/design/stress level changes.

The DTR data can be used with other maintenance requirements to provide a flexible structural inspection program for the MRRB process.

The DTR system is a comparative fleet system; therefore the variability of structural maintenance in the fleet should be monitored and controlled by concerted OMS/manufacturer action. A most essential prerequisite to such action is that the manufacturer must be supplied with complete and accurate maintenance data. It is doubtful that this is done currently (cf. Section VIII).

Inspection interval escalation reduces DTR. When the DTR level reaches the minimum level required, maintenance planning action is necessary. Alternative actions which can be considered are:

--Discontinue escalation,

--modify the basic maintenance plan for the detail,

--supplement the basic maintenance plan with "lead-the-force" inspections.

DTR EQUATION SUMMARY

P_1 = Probability of inspecting an airplane with damage

P_2 = Probability of inspecting detail considered

P_3 = Probability of detecting damage during inspection

$P_S = P_1 \cdot P_2 \cdot P_3$, single inspection, single corrosion event, single level

$P_r = 1-(1-P_S)^{N/\bar{N}}$, multiple inspections, single corrosion event, single level

$P_d = 1-(1-P_r)^{\gamma}$, multiple inspections, multiple corrosion events, single level

$P_D = 1-[1-\prod_{i=A}^{S}[1-P_{d_i}]]$, multiple inspections, multiple corrosion events, all levels

i = applicable inspection level (Table 1)

T = damage detection period, calendar time

$\bar{T}$ = inspection interval, calendar time

ΔT = spacing of corrosion occurrences in fleet, calendar time

$\gamma = \sum_{n=1} [1-(n-1)\Delta T/T]_+$, + = values > zero

DTR= $\sum[\log(1-P_d)/\log 0.5]$, or $[\log(1-P_D)/\log 0.5]$

D. CORROSION RELIABILITY FROM WEIBULL STATISTICS: ORGANIZATIONAL-LEVEL MAINTENANCE

Aircraft corrosion rates are not related to flying hours, but depend only on "environment". We have no exact time-based data for each component failure, hence our data could be considered insufficient to establish directly the life distribution of each component with a high degree of confidence. The only available data are the corrosion related man-hours of each airplane. These man-hours show the effort and amount of corrosion repair of each airplane which is related to the corrosion failure of components.

One may use the Weibull formula as a reliability prediction model for an airplane component. The condition on which the Weibull distribution depends is that the component failure F_E, occurred according to the Poisson distribution, i.e., the probability of exactly i equipment failures is

$$P = \frac{\mu^i e^{-\mu}}{i} \quad [13]$$

where $\mu = (\tau i/\beta)^\alpha$ is the mean of the distribution of component failures per unit time. The Poisson distribution is valid provided:

1. Equipment operates continuously;
2. a system is not turned off when a component fails;
3. the probability of failure of each component within the system is only a small fraction of the total system probability of failure.

Since "corrosion [almost] never sleeps", these conditions are satisfied. Therefore, the reliability of components should be predicted by the Weibull formula.

The actual magnitude of man-hours per month was plotted on Weibull probability paper Fig. 20. The slope of the straight line provides an estimate of $\frac{1}{\sigma}$ and that the line y = 0 give the x intercept as an estimate of μ. The slope is approximately 8.77, giving $\tilde{\sigma} = \frac{1}{8.77} = 0.114$. Also the value x = 0.023 corresponds to the value y = 0 and gave the estimate μ = 0.032. These can be converted to Weibull parameters

$$\tilde{\beta} \quad \frac{1}{\sigma} = 8.77 \qquad \bar{\alpha} = \exp(-\mu) = .97$$

The data of these calculations were obtained from those B-52G airplanes which underwent PDM in FY 1977. These airplanes transferred to Robins AFB after PDM and they have been stationed at that airbase approximately four years. These airplanes were chosen to examine and construct the model since they were released from PDM at the same time and it was assumed that most of the parts were repaired or new.

E. ACI SAMPLE SIZE

The lifetime to corrosion failure of a new structural detail in a fleet of aircraft can be represented by a two-parameter Weibull distribution with characteristic life β and shape as α

[14] $R(\tau) = e^{-(\tau/\beta)^{\alpha}}$

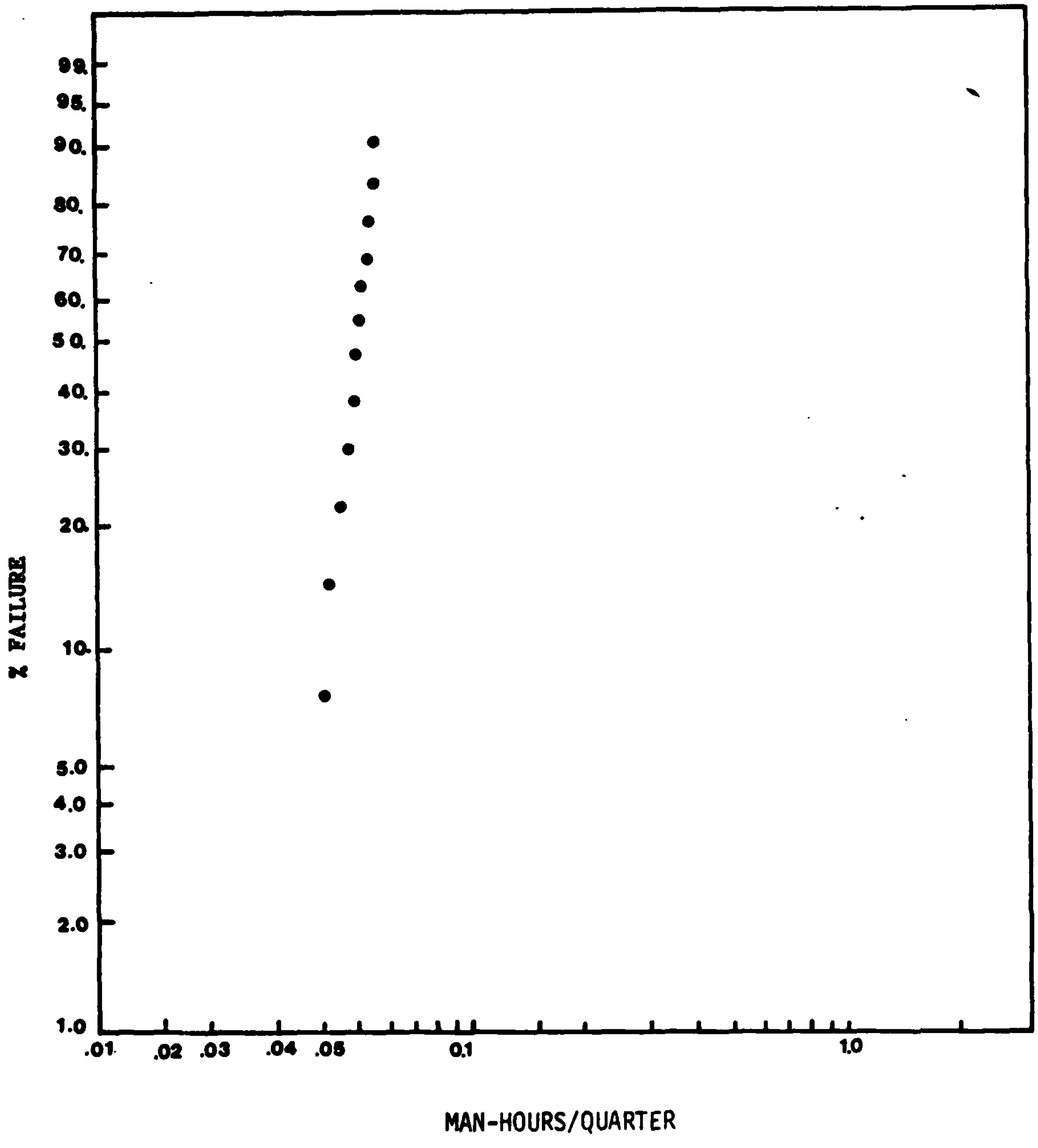


FIGURE 20. WEIBULL PROBABILITY PLOT OF CORROSION MAN-HOURS PER CALENDAR QUARTER AFTER PDM IN FY 1977

The characteristic life is the time period at the end of which the greatest concentration of corrosion will occur in a given population, α is a scale parameter which shifts the distribution along the horizontal time axis but does not alter its shape. In a set of objects exposed to the same corrosive environment, the order of first occurrence of corrosion damage is random. In a more severe environment, first occurrences will appear at shorter time intervals than in milder environments, i.e., the distribution shifts to left or right depending on the severity of the environment. Consequently, supplemental inspections of fleet leader aircraft (i.e., those exposed to severe environments for longest time periods) should give the greatest benefit for damage detection. Requirements for supplemental leader inspections generally will be governed by the additional required level of damage-detectability, which depends directly on P_1 and P_2. Values of P_2 depend on the extent of corrosion as well as the inspection method used, and will correspond to the values used during scheduled maintenance with the same inspection method. For a supplemental (ACI) inspection, P_1 is a function of the number of aircraft and the time period of exposure to a corrosive environment, all other factors being equal. The probability of including at least one damaged aircraft in an ACI sample of size n is given by the equation

[15] $$P_n = 1 - [\prod_{i=1}^{n} R(\tau_i)], \text{ where}$$

$R(\tau_i)$ = reliability of an arbitrary detail,

$= \exp[-(\tau_i/\beta)^{\alpha}]$

n = number of sample airplanes

i = airplane number

N_i = repair man-hours for i-th airplane

β = characteristic life parameter

α = Weibull shape parameter.

If it may be assumed that damage has occurred, and the entire fleet is inspected, the value of P_n is one. Consequently, the normalized probability that an ACI sample of n airplanes includes at least one or more airplanes with corrosion damage to a specific component is given by:

$$[16] \quad P_1 = P_n/P_{n_T} = \{1-[\prod_{i=1}^{n} R(\tau_i)]\}/\{1-[\prod_{i=1}^{n_T} R(\tau_i)]\},$$

where n_T is the total number of aircraft in the fleet. If P_i for each aircraft and P_{n_T} for the fleet are known, the desired level of P_1 is achieved by selecting a sufficient number of aircraft for inspection. Since the highest value of τ/β yields the maximum P_1 values, inspecting fleet leader aircraft gives the minimum number of aircraft to be inspected. For some models it may be more convenient to spread the supplemental inspections to some percentage of a larger fleet leader sample. Corresponding values of P_1 can be derived by considering the average of a series of random selection of aircraft from the fleet leader sample size. When specific aircraft are included in the sample, the value of P_1 can be determined in a tabulated form for each aircraft.

In order to apply this method to B-52G aircraft, first one must determine the fleet size. The number of aircraft at each airbase varies slightly, hence it is difficult to observe the effect of airbase environment on each airplane. Therefore, airplanes were selected which were stationed continuously at one airbase for seven or eight calendar quarters, yielding seventy-one airplanes. The quarterly corrosion maintenance man-hours of each airplane, normalized by mean quarterly man-hours of that base, were plotted on Weibull probability paper Fig. 21. The data fit a straight line well and show no evidence that they are not represented by a Weibull distribution. Graphical estimates of μ and σ and related parameters $\beta=1/\sigma$ and $\alpha = \exp(-\mu)$ in the Weibull survivor function $S(t) = \exp[-(\alpha\tau)^{\beta}]$, can be obtained. The slope of the straight line was approximately 4.5, giving $\tilde{\sigma} = 1/4.5 = .022$. In addition the value of x = 0.4. corresponds to Y = 0, yielding the estimate $\tilde{\mu} = 0.4$. These can be converted into estimates for the Weibull parameters

$$\beta = 1/\tilde{\sigma} = 4.5 \quad \text{and} \quad \alpha = \exp(-\tilde{\mu}) = 0.67.$$

In order to compute the minimum number of fleet leader aircraft required to achieve $P_1 = .95$ confidence in knowing the Weibull parameter α and β, one calculates

$$[17] \quad P_{n_T} = 1-\{\prod_{i=1}^{n} R(\tau_i)\} \quad \text{or} \quad P_{n_T} = 1-\{\prod_{i=1}^{n} \exp-(\tau_i/\beta)^{\alpha}\} .$$

The value of P_{n_T} became approximately 1, therefore, there is no need to normalize the P_n's. Using equation [16] the cumulative value of P_1 is shown for the fleet leader aircraft in Table 22. The result shows that eight B-52G ACI aircraft are needed to achieve a P_1 value .95.

Table 22. Cumulative P_1 Values for Fleet Leader Aircraft.

Number	Airbase	Amount of Quarterly man-hours	Reliability R(N)	Probability P_1
1	Wurtsmith	1.85	.6199	.38
2	Fairchild	1.8	.6266	.61
3	Fairchild	1.6	.6545	.74
4	Mather	1.54	.6632	.83
5	Seymour-Johnson	1.5	.669	.88
6	Barksdale	1.42	.68	.92
7	Griffiss	1.4	.684	.94
8	Griffiss	1.39	.686	.95
9	Barksdale	1.37	.689	.97
10	Loring	1.33	.695	.98

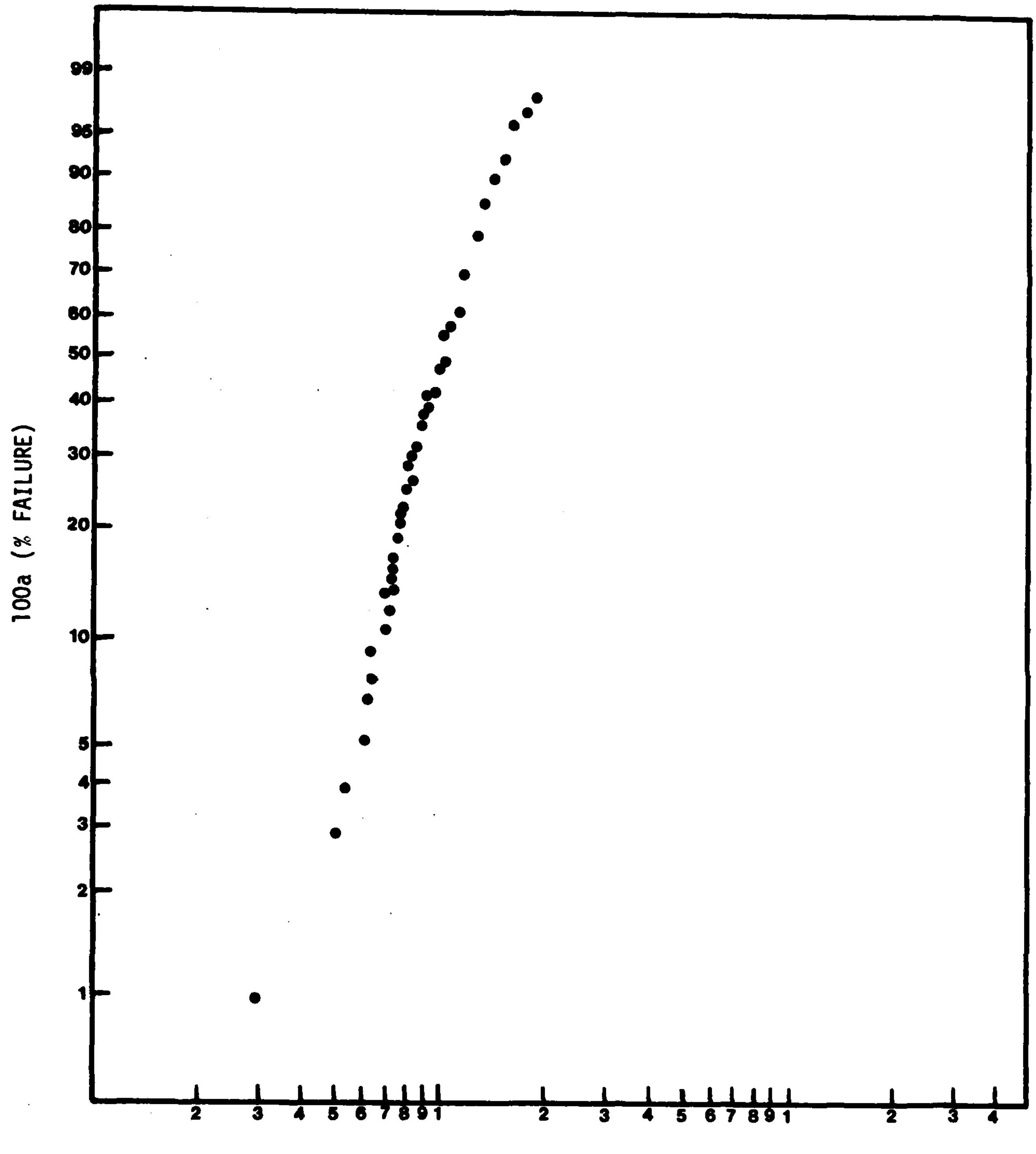


FIGURE 21. WEIBULL PROBABILITY PLOT OF CORROSION MAN-HOURS PER CALENDAR QUARTER

Secondly, it is possible to determine the minimum number of fleet leader aircraft which must be inspected to achieve the required level of P_1 if no airbase is to inspect more than one airplane. The same procedure is used as in the first case omitting the airplanes which exceed an airbase quota of one airplane. The cumulative value of P_1 is shown in Table 23, from which it is seen that eight airbases must be sampled, including Wurtsmith, Fairchild, Mather, Seymour-Johnson, Barksdale, Griffiss, Loring, and Blytheville.

VII. ESTIMATING MAINTENANCE INTERVALS AND MAGNITUDE, AND DETERMINING ENVIRONMENTAL AND EFFICIENCY PARAMETERS.

A. PROBLEM STATEMENT

The basic problem in aircraft corrosion maintenance is to determine optimum inspection intervals based upon need rather than the current isochronal phase and periodic policy. Standard objectives of statistical quality control are to

(a) detect changes in product performance,

(b) identify assignable changes in product performance, and

(c) adjust maintenance procedures in order to maintain the desired operational readiness/reliability level.

Maintenance data in the format produced here provide a basis for time series analysis of corrosion maintenance to determine:

(a) the amount of corrosion attributable to environmental factors as well as to maintenance policy,

(b) the time relations between components repaired/replaced, man-hours cost, and the various MDCS codes, and

(c) the optimum maintenance policy, hence cost reductions.

Table 23. Cumulative P_1 Values for Fleet Leader Aircraft when One Aircraft is Inspected per Airbase.

Number	Airbase	Amount of Quarterly Man-hours	Reliability R(N)	Probability P_1
1	Wurtsmith	1.85	.6199	.38
2	Fairchild	1.8	.6266	.61
3	Mather	1.54	.6632	.74
4	Seymour-Johnson	1.5	.669	.82
5	Barksdale	1.42	.68	.88
6	Griffiss	1.4	.684	.91
7	Loring	1.37	.689	.944
8	Blytheville	1.33	.695	.95

First, however, one must deal with difficult theoretical and practical questions. Although considerable statistical literature exists, application to our data is not straightforward.

B. CONSTRUCTING STOCHASTIC PROCESS MODELS OF CORROSION MAINTENANCE

A component is repaired or replaced subsequent to one of a variety of aircraft inspections. The time from the start of the data file to the time of the first, second, etc. repair/replacement is noted. Each time period is a stochastic (i.e., time dependent) random variable. The distribution of time intervals can be modelled using various assumptions about the underlying processes which generate the failure.

If there are n aircraft at an airbase for the same time interval, all suffering the same maintenance effort and environment, then for a given work element, there will be n independent identically distributed stochastic processes. Such processes are analyzed by Renewal Theory. (19)

If multiple components are replaced/repaired, the renewal process is said to be compound. In this case, the time intervals between failures as well as the number of repairs form random variable sets (see Note 1 for details).

If a given component is replaced or otherwise restored to as-new condition, failure is related directly to the length of service in the given environment. Together with assumptions of non-overlapping intervals and independence of failure, this will result in a Poisson distribution of failures and a gamma distribution of times to failure. It is expected that maintenance policies will interfere with these assumptions.

There are many environmental factors acting on various subsystems. Initial analysis should be confined to single subsystems, rather than to the aircraft as a whole. As many Work Unit Codes (hereafter WUCs) on the SIR forms as possible were included, initially those with more than 500 corrosion related maintenance man-hours of effort. A tentative list of these can be found in Note 2.

A disccussion of the Environmental Factors is not given here but an extensive discussion can be found in Reference 7.

C. VARIOUS STATISTICAL PROPERTIES OF INTEREST

1. Definitions (20). Let w(t) be a stochastic process function of t,

a. Mean, $\overline{w} = \frac{1}{N}\sum_{n=1}^{N} w_n$, where n is the number of observations of w(t),

b. Variance, $s_w{}^2 = c_0 = \frac{1}{N}\sum_{n=1}^{N}(w_n-\overline{w})^2$.

c. Covariance, $\gamma_k = \mathrm{cov}[w_n, w_{n+k}] = E[(w_n-\overline{w})(w_{n+k}-\overline{w})]$, $k=0,1,2,\ldots k_1$.

d. Autocovariance, $c_k = \frac{1}{N}\sum_{n=1}^{n-k}(w_n-\overline{w})(w_{n+k}-\overline{w})$, $k=0,1,2,\ldots k$.

e. Autocorrelation function, $r_k = c_k/c_0$.

f. Partial autocorrelation function,

$$\phi_{jj} = \begin{bmatrix} r_1 & m=1 \\ \cdot & \cdot \\ \cdot & \cdot \\ \cdot & \cdot \\ \dfrac{r_1 - \sum_{m=1}^{m-1} \hat{\phi}_{m-1} {}^* r_{m-j}}{1 - \sum_{j-1}^{m-1} \hat{\phi}_{m-1,} {}^* r_j}, & m = 2,3,..,M. \end{bmatrix}$$

The partial autocorrelation function describes auto regressive process* in terms of an arbitrary number, 'p' non-zero functions of autocorrelations; e.g.,

[18] $P_j = \phi_{k1} P_{j-1} + \ldots + \phi_{k(k-1)} P_{j-k}$, j-1,2,...,k

The P_j then are determined iteratively beginning with P_1. Determining the partial auto-correlation functions is analogous to determining the number of independent variables in a multiple regression.

From these initial descriptive statistics other descriptive statistics can be generated. These also can be obtained (20) and would include the following:

1. estimates of seasonal and nonseasonal autoregressive parameters,
2. moving average parameters,
3. overall constant terms,
4. white noise variance,
5. least squares residuals,
6. standard errors of estimates,
7. covariance matrix of estimates,
8. residual autocorrelations,
9. various Chi-square statistics,
10. input-output cross correlation functions,
11. impulse response function estimates, and

*Auto regressive processes are those in which the current values of the process are determined from previous values of the process and a random noise component.

Not only would such statistics provide an exhaustive description of the maintenance process over time but also would provide insight into the various underlying parameters governing the corrosion process. Once these determinations are effected, the IMSL routines may be used again to forecast failure rates and required repair efforts. Should these predictions be proved accurate by subsequent data, the tools available to the Air Force for the control and optimization of the maintenance process would be greatly increased.

2. Initial data analysis that might be considered.

We might start with the following list of variables and examine relationships among them. The WUCs are listed in Note 2. For each of those work unit codes we would want the repair man-hours per quarter, over all quarters. For each WUC, How Mal Code (HMC), and Action Taken Code (ATC), one would compute the statistical prameters listed above as well as the cross-correlation matrices. An initial list of ATCs would include the following

code	explanation*
V	clean
Z	corrosion repair
F	repair, not minor
G	repair, replacement, minor
R	remove and replace
S	remove and reinstall
H	equipment check, no repair required

For an initial list of HMCs

code	explanation*
105	loose fasteners, bolts, nuts, etc.
106	missing fasteners, bolts, nuts, etc,
117	deteriorated
170	corroded, mild
190	cracked
230	dirty
667	corrosion, severe
846	delaminated

*Approximately equivalent to -6 descriptions. cf. Ref. 12.

A cross-correlation matrix might be prepared for HMC 170 vs. WUC 11BWC, which could be examined for serial dependence, and whether the dependency is linear/nonlinear with time, the effects of corrosion and/or maintenance efforts. How the latter might be determined is outlined in the next section.

D. MODELS

The model sketched below illustrates what could be done and is without any particular justification. Other models, based on time dependent Poisson processes, Weibull, and other probability distributions, could be built and tested.

One might test the proposition that the rate of corrosion maintenance, Z(t), is an additive function of maintenance support level, relative humidity, salt concentration in the air, and an error term. One could assume further that the first and the last terms are stationary time processes while the middle terms are linearly time dependent processes, thus:

[19] $Z(t) = M(t) + H(t) + S(t) + E(t),$

where

$H(t) = A \cdot t + B$, and

$S(t) = C \cdot t + D.$

Given the stationarity of the 1st and last terms, one could, for the limiting process, set

$M(t) = \mu_m$

$E(t) = \mu_e$

with covariance matrices $C[M_{t+h}, M_h] = \gamma(h)$, which is the autocovariance function. The values of the covariance function depend only on the time interval 'h'.

Before considering various models, examination of the initial descriptive statistics should give insight into the various processes. If there were positive, or negative serial correlations, for example, the process would be nonstationary. Tests such as the Kolgomorgov-Smirnov, Wald, Durbin, etc., could be run to determine possible underlying probability models. Various estimation procedures such as least squares, maximum likelihood, etc. could be used to determine parameter estimates.

Underlying these models, however, are various assumptions which do not conform to the known facts about the corrosion/maintenance processes. Modification and removal of these underlying (and simplifying assumptions) would complicate considerably the models, but such modification will allow determination of the relative contributions of environmental factors and of maintenance efforts.

Renewal processes usually are taken as a norm against which deviations generated by environmental and/or maintenance factors may be measured. These processes thus are dependent on more than a time parameter; in particular, they are dependent on corrosion generated wear and maintenance effort. The assumptions underlying Poisson renewal processes are typically violated by these latter parameters. Renewal theory based Poisson processes assumes

(i) the length of the intervals is independent,

(ii) the events occur in non-overlapping intervals, and

(iii) the rate parameter is a simple exponential of time-to-failure.

There are many ways that corrosion rates may affect the distribution of failure times. A model which could be used to distinguish the efficiency of the maintenance process from the rate of corrosion might be as follows. The time to the first corrosion repair should be longer than the times to subsequent repairs because once corrosion is initiated, it is difficult to remove completely. Once such a site is developed corrosion may spread more rapidly. To maintain the unit in serviceable condition a sequence of repairs and/or cleanings would have to be introduced at shorter intervals. The less thorough the repair, the shorter should be the subsequent intervals. If the maintenance effort were high, but in a severe environment, one might expect a relatively short initial failure interval, but relatively longer, and more stable, subsequent passage times.*

Although it takes little effort to generate such models, considerable care must be put into the analysis of underlying assumptions to insure that those models which are developed for testing justify the effort.

Of course, measures designed to separate maintenance effort from corrosion rate damage can be generated by other means. For example, Semi-Markov processes could be used. Markov processes are used to determine, among other things, the transition probabilities between states of a system; as repaired, not repaired. A semi-Markov Process does the same, except that duration in a particular state also has a probability density function. In effect, it is a Markov process with a built-in probabilistic delay function. The character of that delay and the rate of transition to other states could

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*We could examine ratios ρ_i of time intervals and compare the results for the various bases in n-by-n table form (see Note 3).

corrosion rate

maintenance effort		
	$\rho 1$	$\rho 2$
	$\rho 3$	$\rho 4$

be used to generate parameter estimates. Similarly, time dependent Poisson processes, and variants of Weibull functions also, in principle, could be used, and, under some conditions, spectral density functions.

E. NOTES

NOTE 1. Definitions, and Models of Stochastic Renewal Processes.

A simple renewal Poisson process is defined as follows:

Assume that W(t), the waiting times between events (parts repair/replacement), are distributed exponentially with the same parameter λ. Let N(t) be the counting process defined as

$$[20] \quad N(t) = \begin{cases} 0 & \text{if } 0<t<W_1 \\ 1 & \text{if } W_1<t<W_1+W_2 \\ 2 & \text{if } W1+W_1<t<W_1+W_2+W_3 \\ \vdots & \end{cases}$$

The N(t) is a Poisson process, the W(t) are Gamma distributed. The increment of N(t) in $(0,t_1)$ is Z_1. Continuing

$$[21] \quad \begin{aligned} Z_1 &= N(t_1) \\ Z_2 &= N(t_2) - N(t_1) \\ &\vdots \\ Z_n &= N(t_n) - N(t_{n-1}) \end{aligned}$$

The Z_i are also mutually independent Poisson distributed random variables, with parameters λt_1, $\lambda(t_2-t_1),\ldots, \lambda(t_n-t_{n-1})$

Graphically the situation is

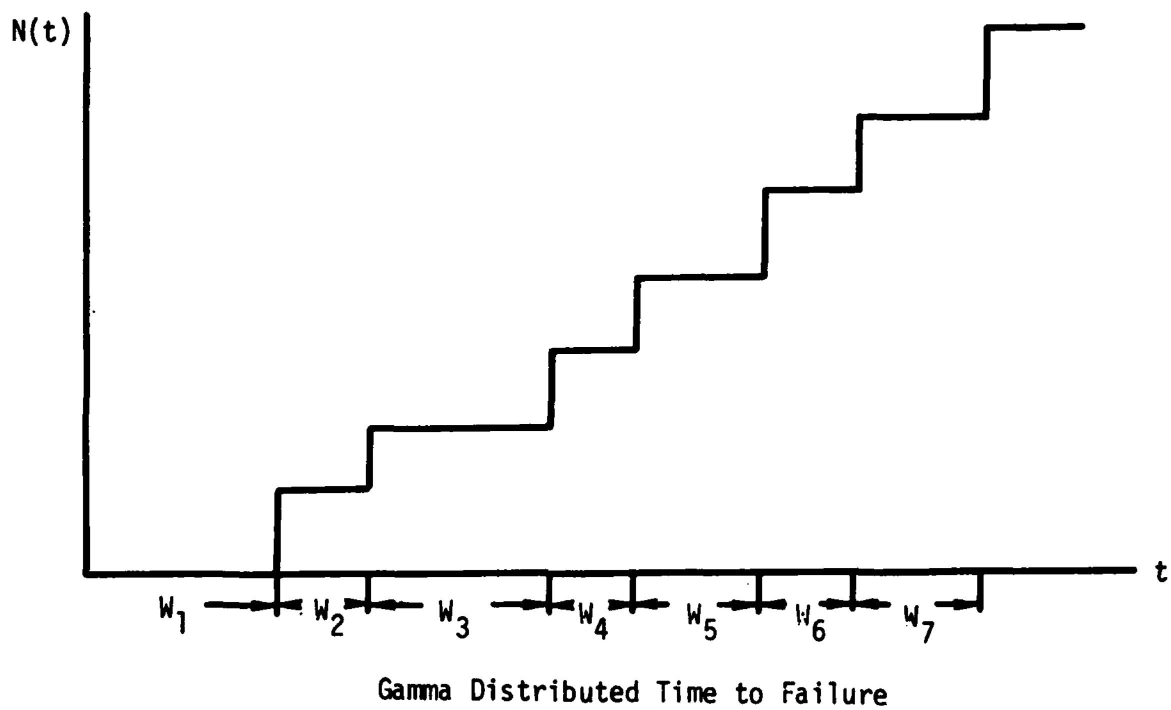

Figure 22. Hypothetical Distribution of Part Failures, N(t), for a Sample Poisson Distribution.

A compound Poisson Process is the same except that instead of having single jumps at times $t_1, t_2, \ldots, t_n$ the increments are random amounts. Let X_i be the size of the 'i'th increment. Then in place of N(t), we will have the random variable Y(t). The waiting times W(t) are exponentially distributed, each with some parameter λ. Then

$$[22] \quad Y(t) = \begin{cases} 0 & 0<t<W_1 \\ X_1 & W_1<t<W_2 \\ X_1+X_2 & W_2<t<W_3 \\ X_1+X_2+X_3 & W_3<t<W_4 \end{cases}$$

Graphically we would have

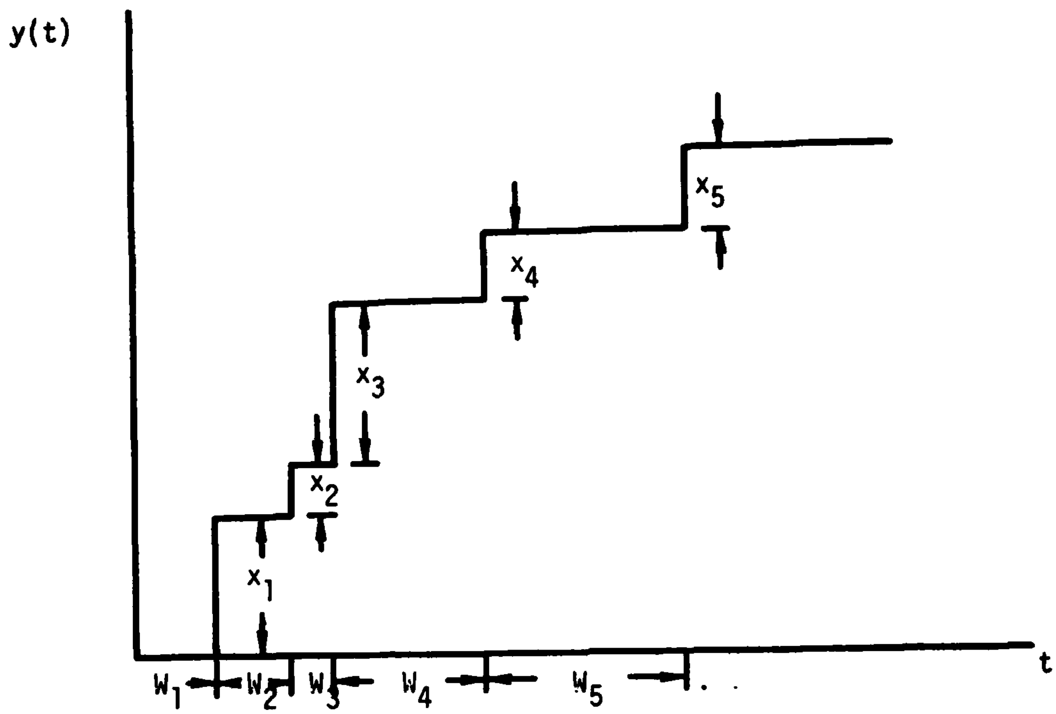

Fig 23. Hypothetical Distribution of Parts Failures, N(t), as a Compound Poisson Process.

As suggested previously, the combination of environmentally induced corrosion and levels of maintenance effort will distort the corrosion rates from that of a compound Poisson Process. Specifically, the rate parameters will become time dependent. Where this occurs we have a semi-Markov Renewal process, the methamatics of which can quickly become intractable. However, applications of Generalized Linear Programming, Linear Complementary Programming problems can be made to these problems and then be solved analytically. An outline of such a procedure is supplied in Note 4.

NOTE 2. Table 24-Work Unit Codes with 500 or more man-hours on B-52G Airplane Fleet, 1975-79. [a]

11000	14AEA
11ADA	14AJC
11AEK	14AKA
11AEL	14B99
11AHC	14CEF
11AUG	14EK6
11AVP	14EHA
11AVQ	
11AVO	23AAA
	23000
11B99	23BAX
11BEA	23ECB
11DEA	23EQA
11BED	23HAL
11BET	23HQP
11BGF, K,L	23HAK,P,Q
11BKD, NC	23JAA,D
*11BWB,C,E,G,M,P,M,N,T,U,V,W,Y,X,Z,XR,ZB,ZG	23JAD,H
11BW1,2,5,6,7	23KQJ
11D99	23MAC
11DAO	23LRA
*11DCJ,R,S,T	23NQH
*11DLE	42BB2
*11EAA	42DFB
11EAD	42FBB
11EBB	42DGA
11EMA	46000
	46A99
11FAA	46DOA,AT
11FHG	46FBA,DA,FA,DO
11FLH	46GAH,BA
11JA6	73FAO
11JAO	74KCA
11KOO	74KDA
11K99	
11K	
11KAC,E	
11KCH	
11LOO	
11LAC	
11MDB	
11MDF,E,G	
11MNA	
11RAA	
11GAA	
12GAA	

[a] An asterisk indicates WUC's used in the Special Inspection Request.

NOTE 3. A possible mechanism to distinguish maintenance efforts from effects of different corrosive environments

Variables:

(a) maintenance effort, measured by man-hours per WUC, or groups of WUCs

(b) number of WUCs (repairs) per period.

Define a set of states in a Markov chain by the different values which may be taken by the ratio of a/b, = (maintenance hours)/(# of WUCs) an initial, simple, Markov transition matrix could then be defined as

maintenance effort

corrosion	high	low
mild	P_{11}	P_{12}
severe	P_{21}	P_{22}

The P_{ij} measure transition between states. A variety of properties may be associated with Markov chains and could be used to make inferences concerning interactions between levels of maintenance effort and the corrosion severity of the environment.

Consider the transition probabilities between states, P_{ij}. The distribution of entities between states may be characterized by several statistical properties. Among these are stationarity, duration in a state, first passage times out of a state, and subsequent passage time out. By comparing these properties one may characterize the interactions of environment and maintenance effort. One might suppose, for example, that transitions out of state 1 (characterized by high maintenance, mild corrosion) would be rather low and tend toward a constant distribution over time.

If, however, an aircraft were transferred to a base characterized by low maintenance effort and high environmental severity, one would expect a time dependent probability transition rate to be observed and, the mean distribution of aircraft in a deteriorated state will increase, rather than move towards a limiting value.

The corrosion/maintenance process could be modelled by a variety of Markov and Semi-Markov Renewal models. Unfortunately, such models quickly lead to intractable mathematics. If these models are formulated as generalized linear programs however, they can be solved by a variety of methods (18,24). The development of such models, although showing considerable promise, would require much work before they could be turned into efficient management tools. This is especially true where bias in the data must be extracted first.

NOTE 4. Markov chain analysis of aircraft maintenance conditions and relation to measures of corrosion repair.

There are several questions:

a. The extent to which moves between states are random or deterministic.

b. If the moves are deterministic, description of the overall process can be determined more efficiently by probabilistic methods as Markov Chains.

The question of efficiency usually hinges on the amount of computation required. The deterministic models which must account for the complete history of an aircraft and all air bases is hopelessly inefficient. In such cases probabilistic approximations are preferred.

c. The relation of flight status to corrosion. This relationship would include

(i) relations between time in different flight states and transitions between them to corrosion levels of components.

Possible measures would include:

(a) ratio of flying hours to repair man-hours tracked over time;

(b) ratios of Action Taken Codes repair to remove and replace, again tracked over time;

(c) flying hours vs upper surface paint damage,

(ii) specify a different set of states to characterize the numbers of repairs for a given part system per time period, and the types of repairs which occur.

d. Use parts (i) and (ii) of c to generate two or more time series which may be examined for time-related dependency. This examination may be handled via the Box-Jenkins methods. With these tools one may specify the overtime nature of the relation between corrosion rates and duration at a base and relation to flight hours, which determine inspection time of the corrosion process and thus the corrections to the corrosion conditions viewed. The problem is one of stochastic control. In particular, one may determine which relations may be characterized as a Markov process, semi-Markov, deterministic, or other probabilistic arguments. Once these determinations are made, various models may be tested and their parameters estimated thus providing measures of corrosion repair effectiveness.

From such models policy recommendations can be made.

For the B-52 Aircraft the corresponding states in a Markov Chain might include:

1. Alert
2. PDM
3. Flight Line
4. In Use
5. Preparation for Flight
6. Washing
7. Phased Inspection
8. New Airplane (transferred from another base)
9. Lost Airplane (transfers to another base)

Our concern is not so much with the status of a given aircraft at any moment but rather the distribution of aircraft in these states. The use of Markov Chains, or other statistical devices is more efficient to determine the status of aircraft at any time than attempting to determine all of the factors affecting the status of aircraft and then aggregating over all aircraft to determine their distribution over the various states.

NOTE 5. Problems of creating complex causal models in reliability/ aircraft maintenance engineering.

A. The Problem

A major problem in reliability engineering is the separation of maintenance operations from environmental effects on the overall corrosion and repair rates. Inferences must be made from a set of observations whose underlying mechanisms may be quite different and which may vary in time. From these observations, one would like to discern the effects each mechanism has on the observable record of failures and repairs. Models which can analytically handle these problems have been outlined in schematic form and can yield qualitative results (22). Quantitative results can be obtained for simple exponential probability density and renewal functions. Should more complex probability models be assumed, as the Weibull distribution, time-dependent Poisson, or other nonstationary distributions, the resulting mathematics become intractable. Solutions can be found in special cases with the use of numerical methods. Virtually all of the approaches tried to date attempt to effect solutions with generating functions, LaPlace transforms, and various approximations techniques (23). Alternatively, efficient computational algorithms can be generated using mathematical programming methods. In the case to be considered here, Linear Complementary Programming appears to be appropriate (23).

B. Dilemma Summary

(1) It is not possible to observe underlying causes directly, nor interaction of causes, (e.g., failure rates caused by corrosion rates, or imperfect maintenance, or both), nor their interactions over time.

(2) Models which incorporate all the relevant assumptions are too difficult to solve analytically.

The programming methods outlined below should provide a way out of the dilemma, thus not only resolving the immediate problem, but also providing an alternative formulation applicable to a wide variety of reliability engineering problems.

C. Potentially useful properties of the Semi-Markov and renewal process which could be used to make inferences about underlying causal mechanisms would include, but are not limited to

(1) degree of process stationarity,

(2) duration in a state (which may be defined in terms of number of repairs per time period, the distribution of waiting times between repairs, the number of man-hours per repair),

(3) the number of transitions between states,

(4) the ratio of first passage to subsequent passage times, and

(5) the renewal densities.

Examples of use.

These properties can be used to make inferences concerning the relative efficiency of maintenance operations at different bases and the severity of corrosion. Consider renewal densities. When these are defined for various states in terms of the number of repairs, man-hours per repair, times between repairs, a great deal could be said about maintenance operations, the rates at which various states are approached or left.

D. Relations between linear complementary programs and semi-Markov and renewal models.

The renewal model is a 'one' state semi-Markov Model and thus a special case of semi-Markov models.

The general form of the renewal equation is (21)

$$[23]\quad h(t) = a\cdot f(t) + a \int_0^t h(t-u)\cdot f(u)du$$

where

$h(t)$ = the renewal density function, 'h' may be a scalar, a vector, or a matrix. (The same hold for the remaining entries).

a = the probability of transition from one state to another.

$f(t)$ = the probability of remaining in a state for a time 'u' such that $u<t$.

The general form of the Linear Complementary Program is (23)

[24] $w - Mz = q(t)$

where

w = a vector of slack variables

M = a matrix of transition probabilities, M is equivalent to 'a' above and is set to $M = \left[\begin{array}{c|c} A & 0 \\ \hline 0 & I \end{array}\right]$

A = the matrix of elements a_{ij}

I = the identity matrix

$z = \begin{bmatrix} a \cdot f(t) \\ 1 \end{bmatrix}$, a vector of holding time probabilities

$q(u) = \begin{bmatrix} h(u) \\ 1 \end{bmatrix}$, the system is solved for $h(u)$.

The '1' vector insures that we are dealing a convex set. Problems of this type can be solved parametrically for a wide class of functions dependent on time, 't'. A set of computationally efficient computer codes has been implemented to solve optimal control problems as generalized linear programs and can be adapted to solve semi-Markov renewal models as Linear Complementary programs. (24)

Equation [24] will have a solution only if $h(u)$ can be expressed as a non-negative linear combination of (eigen) vectors. This is exactly the condition that is required of a renewal density function.

If h(u) represents a stationary process the solution procedures are relatively straightforward. If the process is non-stationary the LCP can be solved parametricaly by methods already developed in another context. (20)

In summary, the use of complementary programming methods makes it possible to develop workable analytic models and to relate them systematically to models which may be estimated from the data base. No longer will such models have to serve as crude approximations limited to relatively short time intervals.

F. Problems of data analysis of U.S. Air Force corrosion data.

A persistent problem has been the separation of relevant information from noise and distortion caused by recording and reporting procedures. The problem is more complex than simply extracting a signal from noisy data, where one could form assumptions about the quality of the 'noise'. One could assume the worst possible characteristics of the 'noise', that it has infinite variance, is unpredictable, and has a zero mean. This technique, employed frequently by stochastic control theorists, makes 'nature' a 'rational' opponent in a zero-sum game. Thus certain statements can be made about the system in question.

This is not possible with USAF maintenance data because air bases have their own standards both for the repairs and in the classification. It is a system in which there is noise, together with two signals, one for the corrosive environment and one for the reporting of maintenance. Efforts to extract the former have been frustrated by an inability to deal with the latter. The problem is not insoluble, but standard statistical procedures and modeling techniques are inadequate to the task.

One method of dealing with the idiosyncrasies of the reporting system is to model that system via mathematical discriminant functions. Problems cast in this manner can be solved as problems in mathematical programming. One such technique being developed formulates the problem of reporting accuracy as a 0-1 nonlinear integer programming problem.

Once a procedure is in place which allows estimates of reporting bias, the corrosion process remains to be modelled. The process is inherently complex and not readily amenable to standard statistical methods, especially where large quantities of data are involved. For example, there is reason to believe that the corrosion process may be modelled as a sequence of Markovian and time dependent Markovian processes. Repairs under such conditions may be modelled as a renewal process. However, there is little reason to suppose that the renewal densities follow a simple exponential process. Rather, they are Weibull, or some other complex non-exponential function. In such cases, it is not possible to achieve analytic solutions. Numerical methods must be used. These have computational difficulties, are expensive, and achieve only local optima. Such renewal problems could be formulated, however as a sequence of Complementary Linear Programs (i.e., linear programs without objective functions). Further, they could be aggregated into a large scale optimization problem which could be solved over an arbitrary time period as a Generalized Linear Program.

In summary, the Air Force data base contains considerable promise for the analysis of corrosion problems. But to realize that promise new tools must be developed and tested. Until such problems are addressed, the Air Force will not be able to exploit fully its data base as a management tool.

VIII. THE MAINTENANCE DATA COLLECTION SYSTEM: RELIABILITY AND INTEGRITY

A. PROBLEM

AFM 66-1 data has been the basis for many reliability and maintainability studies in the open literature (2, 25-31). All of them have been cynical to some extent about data quality, reflecting a wide range of opinion within USAF. In some cases, allowances were made for assumed data faults by discarding one data subset or another on the basis of more-or-less arbitrary criteria; but in the end, data were accepted at face value. In no case have the results been sufficient to inspire confidence in MDCS, and data quality has been a handy scape-goat.

Nevertheless, this data is used widely: within USAF as an engineering management tool; and elsewhere by many DOD contractors for design, development, and R and M activities. It is USAF policy to make data from certain management information systems available to contractors as defined in AFSC/AFLCR 174-1 "Feedback to Contractors of Data from Certain Automatic Data Processing Systems."[8] Maintenance and operational data, from AFM 66-1 and AFM 65-110, respectively, are major ingredients. There also exists the "Government Industry Data Exchange Program (GIDEP)," a cooperative program to make maximum use of existing knowledge via exchange of technical data related to research, design, development, production, and operational phases in the life cycle of systems. Numerous DOD and federal agencies, as well as Canadian DOD and industries, participate in GIDEP. One element of GIDEP is the Reliability-Maintainability Data Bank (RMDB) which contains failure rate/mode and replacement-rate data on parts and components based on field performance information and/or reliability tests of equipment, subsystems, and systems.

The bank also contains reports on theories, methods, techniques, and procedures related to reliability and maintainability practices. Another is the Failure Experience Data Bank (FEDB) which contains objective failure information.

Few MDCS users rely on original data, but use instead one or more of AFLC-processed summaries. Any faults in the raw or semiprocessed data of course will be present in such "products" together with errors and biases introduced in the production processes. In view of nearly universal doubts about the validity of AFM 66-1 data in any form, one must feel uneasy about decisions based on it. Such decisions, however, are not of little import.

Accordingly, an objective of this program was to assess more quantitatively the reliability of MDCS data and, if possible, to provide a basis for "reliability calibration" factors. Our approach was to collect maintenance data from several sources at different levels in the processing heirarchy, compare them, and identify error sources where possible. These data sources included:

- raw data in the form of AFTO forms, and
- interviews with maintenance personnel;
- airbase-level computerized AFM 66-1 data, and
- airbase produced "Monthly Maintenance Summaries";
- AFM 66-1 data from AFLC;
- AFM 66-1 data from Boeing Military Airplane Company, who store data presumably identical to that of AFLC, but which has been processed via Seattle;
- and a Special Inspection Request from airbase maintenance personnel, supplemented with personal inspections of airplanes by the Principal Investigators.

There exist other useful sources of maintenance-related information, some of which could be obtained (albeit with difficulty), e.g., "Maintenance Requirements Review Board" reports, repair manuals; others could be had at no price despite "USAF policy." The available materials were studied in more-or-less useable form and each has provided insight into the questions about AFM 66-1 data.

B. DATA SOURCES

1. Raw data exist at airbase level for a limited time in the form of AFTO 349 and similar forms. These forms, from 314-Corrosion Control Shop, were inspected by the Principal Investigator at each airbase visited during implementation of the Special Inspection Request (q.v.). The objective was to determine approximately the relative useage of Support General codes where appropriate corrosion-related WUC's should have been used. (Often the SIR team found themselves involved in informal training seminars explaining the use of these codes.)

2. "Interviews" with maintenance personnel is not sufficently descriptive of the in-depth relationships developed. Much was learned concerning "attitude" as well as technical problems. Attitude has much impact on AFM 66-1 data. It is not meant to imply that these are anything but well-trained, skilled, dedicated people. The data, nevertheless, are impacted.

3. Computerized airbase-level data are available via the Base Level Inquiry System (BLIS). After the personnel and raw forms, these records are the closest to the event and are the closest computer records. Computer operator and key punch errors are the only problems at this level, and are

estimated to be _ca_ 5%(see, for example, Ref. 9.). All data elements entered are included, expecially the Support General data. Each airbase from the SIR was asked to provide BLIS reports for CY 1980 according to a specified format. Enough reports were received in useable form for comparison purposes.

4. Monthly Maintenance Summaries. Maintenance reports or summaries are published monthly by the DCM at each airbase and are prepared from airbase-level computer data. These documents are intended to support the primary purpose of MDCS (cf. p. 13), and also to serve a significant role in disseminating information locally to maintenance personnel, and of maintaining morale _via_ gold stars and "Attaboys." By their nature, they necessarily are self serving. Nevertheless, these reports are a useful source for comparative information and they have the advantage of being chronologically and physically close to the events.

These reports contain information concerning status and inventory of aircraft, manning levels of work centers by rated level of skill, and much information related to the impact of maintenance on aircraft operational readiness and airbase performance. Unfortunately, they contain little specific information about airplanes by serial number, and there is little uniformity in the documents from one airbase to another.

For the purpose of this project, it was requested that the MMR's be provided from each airbase included in the Special Inspection Request from March 1980 through the end of FY 1981.

5. MDCS data were described earlier (p. 31ff).

6. Boeing MDCS data are received from AFLC via Seattle. Each processing stage provides opportunity for error, ranging from computer operator errors to program "bugs," and including the fact that each subsequent processor may not understand what has been done to the data. Each processing stage prepares the data for use at that stage. Each subsequent user may assume falsely that delivered data are identical to the original, when in fact the copy is an edited version. An impartial editor/editrix does not exist. Consequently, the Boeing data are at least twice-filtered, first by AFLC, then by Boeing-Seattle, and possibly a third time by Boeing-Wichita.

7. The D056 System. Most of the maintenance-generated data are submitted to HQ AFLC and processed in the D056 Product Performance System. This system prepares from the data "output reports" which contain Reliability and Maintainability factors within established computer programs, and also provides interfacing systems with source data. Some interfacing data systems also "output" reports containing R and M factors appropriate for their purposes. (Presumably, the Boeing system is such an interfacing system.) Figures 24 through 26 trace the data flow from point of origin through the D056 major system process and to interfacing systems. D056 output reports are presented in terms of variables thought to be useful to AFLC. These output reports are prepared in several formats, e. g., to detail maintenance actions for selected Work Unit Codes. Some reports are relevant to this study:

(a) Maintenance Actions, Man-hours and Aborts by Work Unit Codes, RCS: LOG-LOE(AR)7170, provides six months of selected information by month on every reportable WUC.

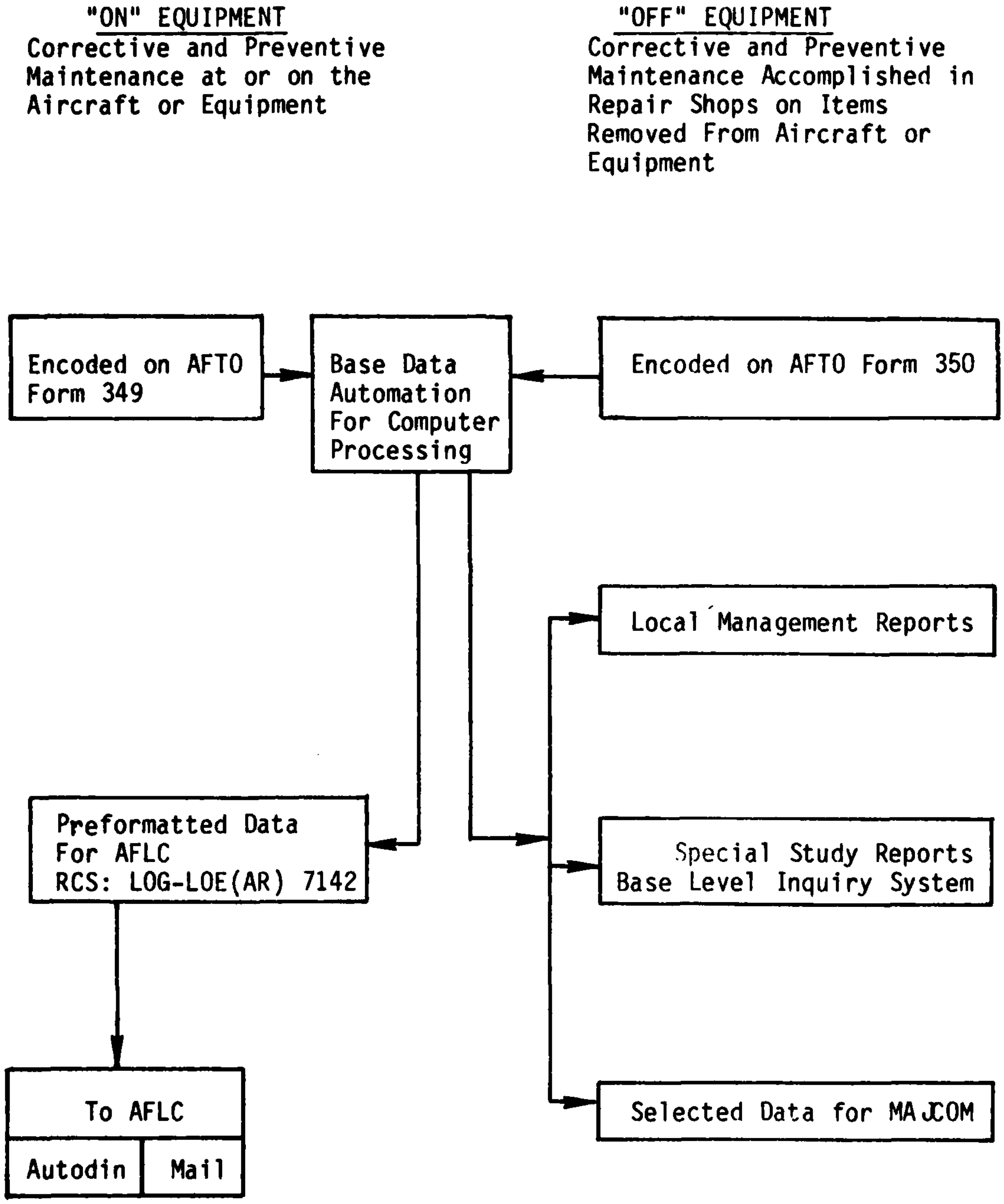

Figure 24-Maintenance Data Collection System Reporting at AF Bases

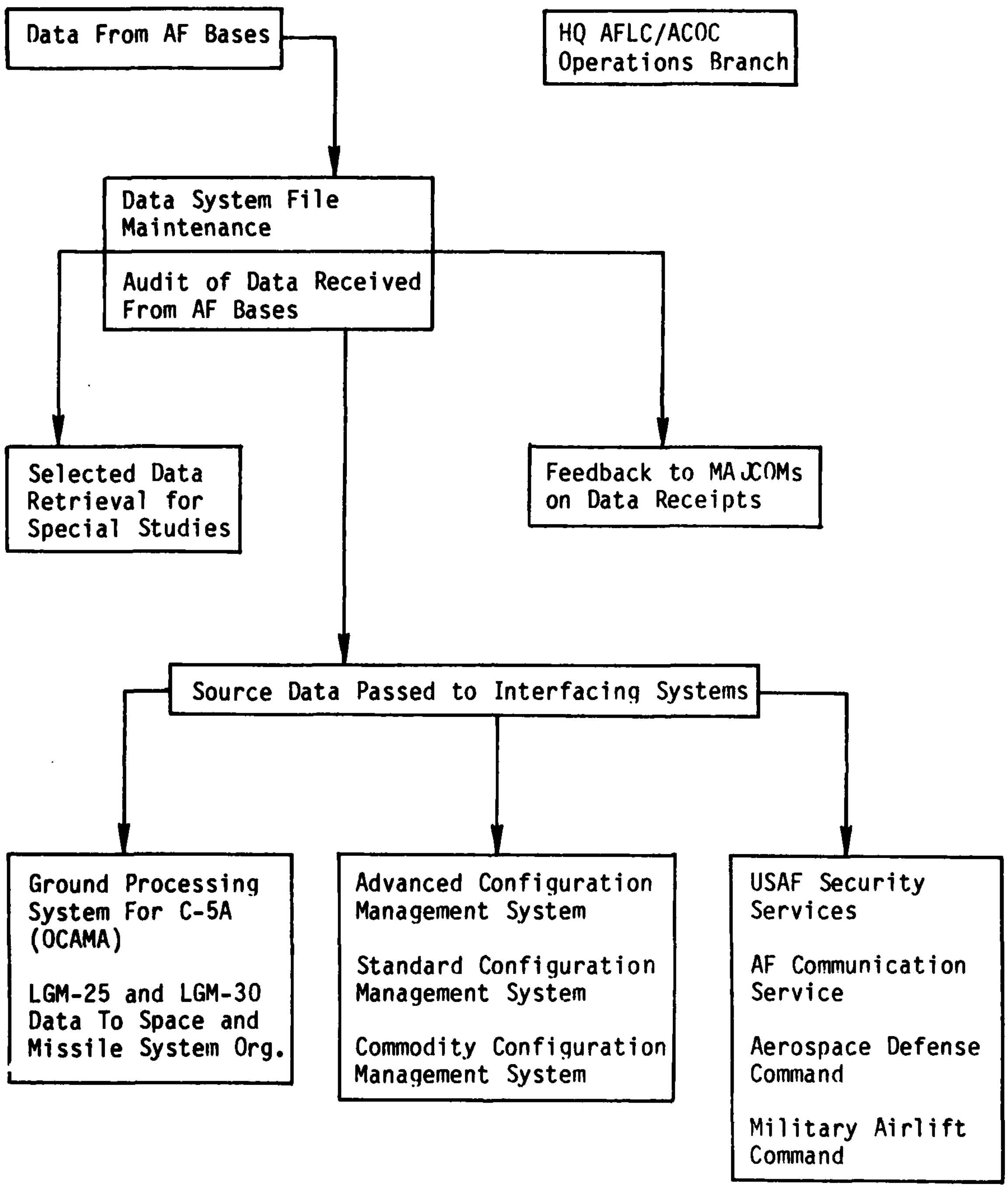

Figure 25-AFLC D056 Weekly Computer Processes

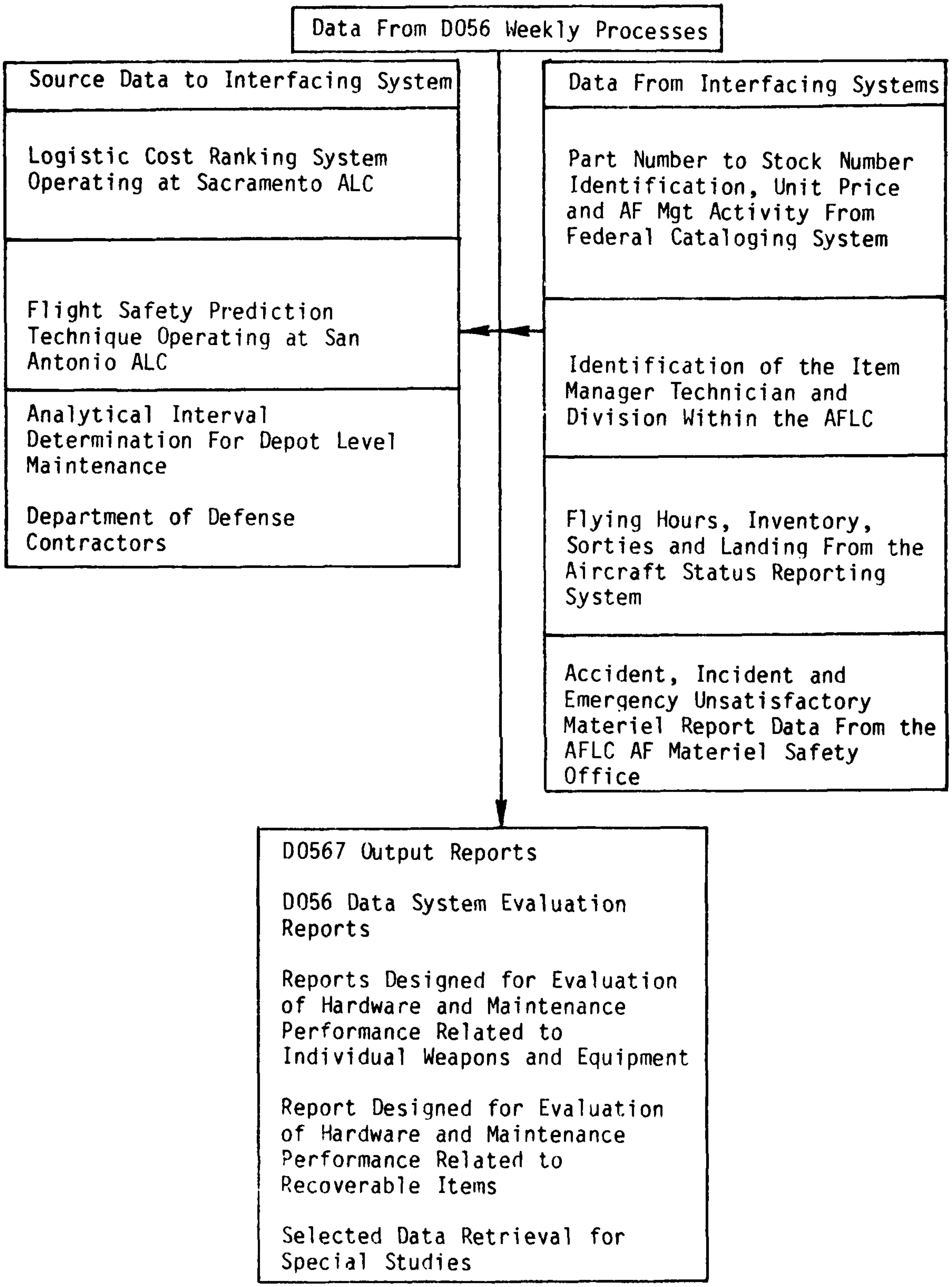

Figure 26-AFLC D056 Monthly Computer Processes

(b) Work Unit Code Corrosion Summary, RCS: LOG-LOE(AR)7179, provides three months of information on a weapon or equipment identifying work unit codes, units, man-hours and labor cost [by multiplying man-hours by a standard $ per man-hour figure]. The highest repair cost WUC's are rank ordered and displayed. This report is based on WUC's 170 and 667, thus neglect other corrosion related codes as outlined here.

(c) System, Subsystem Corrosion Summary, RCS: LOG-LOE(AR)7180, uses the same three months as (c) except the information is summarized to system/subsystem level and base location. For comparative purposes, we have extracted from AFM 66-1 records which conform to the same selection criteria of D056.

8. The Special Inspection Request developed for this study is discussed separately in a later section.

There are many opportunities for error at the data recording stage, partly because it is required that the maintenance expert must analyze the failure as well as chronicle it on an AFTO form. In view of the voluminous maintenance literature (1, 11, 12) and the limits of human commitment, this is too much to ask. Maintenance personnel frequently are reminded that recorded information must be valid, accurate, and reliable, to insure that "data describes [sic] actually what took place and that AFTO forms are documented according to the rules..." (1) Overall, our results suggest that there has been more care in fact at the recording stage than during subsequent processing.

Nevertheless, problems at the recording stage must be noted. Priorities as well as personality of the local DCM are reflected in personnel attitudes and the monthly published summaries. "Accuracy" of data reporting is interpreted to mean that one should use code combinations on AFTO forms which the computer will not reject, thus keeping the unit's "error rate" low. Once individuals learn "successful" code combinations, they use them habitually, regardless of whether the combination "accurately describes..." the maintenance action. Thus Action Taken Code G, "bits and pieces" consistently is used when TO-00-20-2 clearly (if circuitously) labels the useage incorrect. Base-level computers did not read TO-00-20-2 nor the corresponding -6 manual, hence do not recognize the code as an error. This problem has been pointed out earlier (2), but it is of greater significance than we had thought.

Other kinds of invalid data exist in the permanent files to show that airbase-level error detection is imperfect. For example, one finds records bearing WUC 11BVV charged to B-52D aircraft, or 11BDQ/BDR (the equivalent of 11BVV) charged to G-series airplanes; these are invalid combinations. The number of such errors is not small, unless compared with the overall MDCS system. Nevertheless, it is admittedly nit-picking to point them out.

Personnel attitudes also may directly influence actual maintenance performed. For example, all parties know well in advance an airplane is scheduled for PDM or ACI and whether it will be returned to the original airbase. A four fiscal-year average shows that less than 13% of G-series units are returned. Should an airplane nearing PDM receive special attention when the odds are eight to one that it will soon be someone else's problem?

Maintenance personnel universally believe that they send away "queens" and receive "dogs." The condition and maintenance records of "Crested Dove" airplanes suggest that one looks after one's own interests.

C. COMPARISON

AFM 66-1 data from BLIS, AFLC, and Boeing should be identical, except BLIS data contained Support General records. Summaries from them should match those of D056, assuming similar selection processes are used. Data comparisons which follow show, unfortunately, that the truth is otherwise. Further, it seems that everyone knows this, (but does not share the knowledge), yet presses on because "it is the best we have to work with." Perhaps one should turn else-where. We have prepared comparative statistics from these data sources for a few airbases where direct comparisons were possible.

Preliminary comparisons based on our standard analysis programs revealed large discrepancies between the sources. Careful review of the procedures used, to insure that the same questions were asked, followed by further analysis still resulted in wide variations. Finally, selected airplane serial numbers, compared on a day-by-day and record-by-record basis, showed that BLIS, AFLC-MDCS, and Boeing-MDCS are not comparable.

Examination showed first that AFLC records are redundant, for reasons unknown. Data records exist frequently in duplicate, triplicate, and higher. Most often copies lie adjacently in the files, but not always. The AFLC tapes carry no warning that such replication may exist. The copy records are identical in all details, thus cannot be keypunch errors, which, for the most part, are eliminated at airbase level; BLIS records do not contain them. It is possible that multiple copies are generated in order to indicate the existence of related Off-Equipment records, but it is not obvious what purpose would be served thereby.

In subsequent analysis, adjacent multiple records were removed, an easy process _via_ computers (others seem to have done it by eyeball (31)!) The problem seems impossible if duplicates are not adjacent.) Boeing reportedly (32) rejects _all_ copies of duplicate records, which seems to be unreasonable, because at least one record should be valid, judged from comparisons with BLIS data.

After duplicates were removed from AFLC files, they contained substantially less information than BLIS files. Boeing files were grossly deficient, perhaps as a result of their editing process noted above. Boeing has offered no explanation (32). Since the Boeing data were only a shadow of BLIS records, they were analyzed no further. AFLC uses their own files to compile the various D056 products. We extracted comparable data from AFLC-supplied tapes, both before and after removal of duplicates for comparison. The parable about blind men and the elephant comes to mind. Examples of these results are shown in Tables 25-28, which the reader is invited to study -but briefly!

Table 25. Comparison of Maintenance Data Files from March AFB, CY 1980. Records are How Mal 170 or 667 or Action Taken V or for BLIS, MDCS, and Boeing.

FIRST QUARTER 1980

	Man-hours			Records		
Serial Number	BLIS	MDCS [a]	Boeing	BLIS	MDCS [a]	Boeing
55-066	1	1	1	1	1	1
55-071	19	24	19	6	8	6
55-080	11	15	4	13	19	8
55-088	15	31		17	34	
55-104	30	53		29	54	
56-580	4	4	4	2	2	2
56-588	6	8		4	6	
56-612	37	73		32	62	
56-617	42	68		77	135	
56-629	4	4		3	3	
Man-hour totals	169	281	28			

DO 56 Man-hours 159

SECOND QUARTER 1980

	Man-hours			Records		
Serial Number	BLIS	MDCS [a]	Boeing	BLIS	MDCS [a]	Boeing
55-066	7	9	7	3	5	3
55-071	86	56	34	53	60	39
55-080	29		17	21		12
55-104	16	18		11	19	
55-111	28			22		
56-580	11	2	10	3	2	3
56-671	14	17		23	28	
56-694	6	6		4	4	
56-617	2			2		
56-629	2			2		
56-666	5	5		5	5	
56-694	6			4		
Man-hour totals	212	113	68			

D056 Man-hours 172

[a] Contains duplicate records. See text.

Table 26. Comparison of Maintenance Data Files From Carswell AFB, CY 1980.

For Ten (10) Airplanes	MAN-HOURS First Quarter 1980			Second Quarter 1980		
Serial Number	BLIS [a]	MDCS [b]	Boeing [b]	BLIS [a]	MDCS [b]	Boeing [b]
55-057	81	66	-	-	-	-
55-059	37	140	92	17	2	19
55-067	3	1	-	88	55	-
55-068	33	29	-	35	31	-
55-070	-	-	-	3	-	-
55-071	5	-	-	-	-	-
55-073	27	27	27	-	-	-
55-074	29	17	10	19	18	18
55-077	26	40	20	1	-	-
55-078	28	13	10	34	18	-
Totals All Serial Numbers (36)	659	710	243	576	623	153
D056 Man-hours		484			350	

[a] BLIS man-hours are Corrosion Control Shop -3140 only, and do not include Support General Codes. All are How Mal 170 or 667, WUC 11A-11P, thus should appear in D056.

[b] MDCS and Boeing records are How Mal 170 or 667, thus directly comparable with D056. MDCS duplicates removed.

Table 27. Comparison of Maintenance Data Files for B-52D Serial Number 55000077, CY 1981: Records Bearing How Mal Code 170 and Work Unit Code 11A to 11P. Carswell AFB.

Day	WUC	Hrs.	BLIS	MDCS	Boeing
050	11LA0	1.0	X	X	X
081	11ENJ	2.6		X	X
096	11L00	2.5	X	X	X
106	11ABE	2.0	X		
106	11AD0	1.5	X		
106	11BAX	5.0	X		
107	11DAG	3.0	X	X	
107	11EBB	1.0	X	X	
107	11EMG	1.0	X	X	
107	11FAR	1.5	X	X	

Table 28. Comparison of D056 RCS: LOG-LOE(AR) 7180 with MDCS Records Bearing How Mal 170 or 667 for Selected Airbases, CY 1980.

	1Q	2Q	3Q	4Q
Andersen				
MDCS	2351	1343	2000	1158
D056	1057	705	940	1011
Carswell				
MDCS	1113	890	380	191
D056	484	350	246	201
Castle				
MDCS	93	363	93	33
D056	57	118	55	22
Dyess				
MDCS	173	122	731	36
DD56	123	90	357	67
Ellsworth				
MDCS	57	3	7	0
D056	38	5	6	4
Fairchild				
MDCS	66	--	47	16
D056	22	15	18	18

AFLC-supplied data tapes were inconsistent from one to another in a chronological set. It was not possible to know whether the end of a tape contained complete data for the respective time period, or whether the start of the next tape filled in gaps without repetition. Thus comparisons were made between data from the middle of data files, yet they were discrepant. An on-line data filing system would benefit continuing MDCS users, but would have offerred no benefits to this study.

The results outlined here do call airbase-level reliability into question, but it is not possible to know to what extent. As noted, one must know what is the nature of data processing at each stage of middlemen. Ultimately, the analyst must ask:

Are the data in hand, from whatever source, a full deck? A stuffed deck? Were the data transferred accurately? When these are answered, one then can turn to questions relating to quality of the original data and relating to environmental effects. Unfortunately, there are no adequate answers to the first questions.

Questions about data transferral may be linked to the child's game "Go Fish," where one player asks another for a stated set of cards, which the latter may or may not possess. The second player complies as best he can, i.e., without conscious error or intentional deception, because such error or deception is detectable via internal relations among the cards in a deck. In the USAF maintenance data, however, the number of "decks" is not limited, and the relations among the cards, if any and at best, are complex. Consequently, there seems to be no test of consistency or test of completeness that can be applied to the data set in hand, hence any analysis of MDCS data--even those produced by USAF agencies--necessarily are suspect, and most of them are little better than a "shot in the dark." Finally, we conclude that the MDCS has serious and deep-seated defects.

D. A NOTE ON DATA COLLECTION

We cannot conclude without commenting on the difficulties of working with government agencies. Collecting information proved extremely difficult. Some sources provided unreliable information or in a wrong format. Other sources were merely uncooperative, some even deceptive; information never was volunteered. Problems of MDCS data need not be repeated, but it is clear that accurate information probably is not available. Obtaining information from the operational level proved equally hopeless, even though authorization came from the highest levels.

In one phase of the program, it was necessary to inspect airplanes directly. These are, after all, strategic weapons delivery systems, hence they contain classified subsystems. Appropriate security clearances were requested for processing by the Defense Industry Security Clearance Office (DISCO). DISCO either is inept, incompetent, intransigent, insincere, all, or worse.

IX. SPECIAL INSPECTION REQUEST

A. BACKGROUND

The C-141A study (2) had shown that MDCS was inherently, perhaps congenitally defective. Moreover, USAF D056 products do not describe corrosion in either sufficient or appropriate detail for the purposes of corrosion prediction. Defects in this system included the problem of Support General code useage, variability of airbase practices with respect to data codes, deliberate and inadvertant misuse of codes, ignorance on the part of personnel, the voluminous and poorly written TO manuals, and the general attitude of airmen toward the system. In addition to its failure to take account of these problems, D056 also gives insufficient consideration to variations from one airbase to another, thus masking environmental effects. Finally, corrosion probably is not the most important maintenance problem area in the view of D056.

As a partial correction, Boeing personnel suggested a one-time corrosion Special Inspection Request to obtain specific data on selected "hot spots" and thus provide an independent evaluation of aircraft condition. Since Boeing had not inspected some B-52 series for many years, they were especially interested to learn how specific corrosion protection systems had performed, and hoped to obtain information via the SIR. The use of SIR's was, for Boeing, a routine device with which they had much experience and their (albeit dated, cf. Ref 34) experience with corrosion on the B-52 airplanes should provide the keys needed for successful use of an SIR. Hence, with the guidance and active participation of Boeing, an SIR was developed for the D-series airplanes, and a slightly different version for the H/G-series.

The form and contents of the Special Inspection were discussed with AFLC, AFML, and SAC personnel at Robins, Wright-Patterson, and Tinker AFB's, respectively. It was decided to apply the SIR to D, G, and H series airplanes, with emphasis on the G's. Work Unit Codes were selected to represent areas considered to be corrosion "hot spots," but readily accessible and requiring no special tools for inspection. Instruction materials and report forms are reproduced together with a detailed discussion of the SIR in Reference 35, to which the interested reader is referred.

The SIR's were implemented at nine airbases (Table 29), at two of which Boeing personnel participated. Every effort was made to minimize the trouble of inspection and reporting, and to emphasize the importance of the effort. It was hoped that the matter would receive careful and serious attention.

TABLE 29 PARTICIPATING AIRBASES AND NUMBER OF AIRCRAFT SPECIAL INSPECTIONS.

Airbase [a]	By Project Personnel	By FMS Personnel
Barksdale (10 Sept 80)	5	96
Carswell (12 Sept 80)	8	72
Fairchild (19 Sept 80)	4	16
Griffiss (10 Oct 80)	5	1
K.I. Sawyer (31 Oct 80)	6	11
March (17 Sept 80)	5	0
Mather (15 Sept 80)	5	0
Robins [b]		0
Wurtsmith (21 Nov 80)	3	0

[a] Dates of on-site briefing in parentheses.
[b] No on-site visit by project personnel.

In fact, the response was far less than expected. Two air bases (where Boeing was represented at implementation) responded enthusiastically, two others provided a useful response (despite difficult climates for outdoor inspections); the rest were never heard from again (cf. Table 29). Such results, of course, are a disappointment, and it is tempting to reject the entire effort. Nevertheless, they were obtained at much cost, therefore are deserving of analysis to whatever extent possible. The SIR and report forms were designed for computer analysis, hence the results were keypunched as received into the MSU computer system.

B. PROBLEMS

There are problems with the SIR data. (1) incomplete data; (2) systematic bias; (3) inadequate size from March, Griffiss, Mather, and Wurtsmith.

1. Missing Data

Overall Work Unit Codes and airbases, for categories severity, amount affected and type, data missing amounts to 46%, but is as high as 80% for fasteners.

One individual provided most of the reports from each air base; other inspectors coded very few reports. There are no apparent differences in coding practices, however, suggesting uniformity of effort based on the instructions. The problem is summarized in Table 30.

Table 30. Missing SIR Data

Airbase	Percent Missing over all	Entries on the SIR form	
	Severity	Affected	Type
Sawyer	64%	66%	66%
Barksdale	%	%	%
Fairchild	23%	42%	42%
Griffiss	20%	20%	20%
Carswell	9%	61%	60%
average of the 5 airbases	37%	50%	50%

Percentages are defined as

$$\% \text{ missing} = \frac{\text{right missing} + \text{left missing}}{(\text{total \# of aircraft}) \text{ X}15^{*}}$$

*15 = the # of entries on the SIR form

2. SYSTEMATIC CODING BIAS

Several factors suggest that there is bias in the data coding or reporting procedures. At Barksdale, nearly all reports described one side of the aircraft for one month, and the opposite side was recorded the next month. Both sides should have been inspected at the same time. Where data were recorded for both sides, the SIR forms were not completely filled out.

Efforts to isolate sources of bias in data from other airbases were frustrated by the lack of reports as well as the inability to compare SIR reports with subsequent maintenance as documented in MDCS.

CONCLUSION

Because of these problems, the SIR data are of doubtful value. The small size will make inter-base comparisons difficult. Further, it is difficult to determine the extent or severity of potential sources of bias in the data collected. Unfortunately, there is no readily available method for locating these potential sources.

X. CONCLUSIONS AND RECOMMENDATIONS

The USAF Maintenance Data Collection System is in-place, has wide scope, and great potential value. The system, however is seriously flawed.

(1) It is excessively complex and begs for overhaul to relieve the pressures generated by this complexity.

(2) Objectives are ambiguous, i.e., does it serve operational-level or command/logistic-level purposes, or both? The system should be reviewed to clarify its purposes.

(3) Data processing at every stage, from initial recording forward, introduces its own opportunities for error, bias, loss, and superfluity. It is essential that methods be developed whereby data files can be tested for accuracy and completeness. Current data are seriously suspect, however, in the absence of such tests.

(4) Inconsistencies from one airbase to another, in data recording practices, monthly maintenance summaries, etc., should be eliminated (cf. point (2) above). Airbase-level material is worthless at command-levels if it is not comparable.

(5) Several constructive criticisms of MDCS, which have been communicated formally and informally to USAF under this and previous contracts by us, have been incorporated into the system. These, hopefully, will produce the required improvements.

(6) Adoption of Isochronal/Phased Inspections is a step backward with respect to corrosion control in systems where flying hours are not a linear function of calendar time. We recommend that a periodic corrosion inspection program be re-instituted, with intervals not less than mid-PDM.

(7) The "natural" environment, as reflected in the PACER LIME or similar environmental ratings, is useful to predict future maintenance requirements as well as to analyze previous repair experience. Reliable, on-site environmental parameters are required, however, as well as some modification to existing rating systems. The data themselves can suggest these changes, e.g., the acid rain question at Griffiss. Factors other than the environmental ones may be important to the rate of maintenance, e.g., operational -- training mission at Castle, Altus; Attitude -- Griffiss delamination; Mather anything; logistic -- Guam rotations impact receiving base; unknown -- effective, but not identified; e.g., Wurtsmith, Blytheville; morale and DCM personality -- Barksdale, Carswell, K. I. Sawyer as reflected in cooperation with SIR.

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APPENDIX A. USAF B-52 AIRBASES

Airbase: Andersen, Guam

Location: Guam Lat: 01335N Long: 14455E

MDS and Number on Station: B-52 D, 14

PACER LIME Ratings: Repaint -- ? Corrosion -- AA-AA/8

Comments: Corrosion rating estimated from proximity to surf.

Airbase: Barksdale, LA

Location: Bossier City, LA Lat: 03230N Long: 09340W

MDS and Number on Station: B-52 G, 29

PACER LIME Ratings: Repaint -- C-C/2 Corrosion -- A-B/5

Comments: Center City-commercial EPA station, 10 km west @ 03229N, 09343W.

Airbase: Blytheville, AK

Location: 4 mi NW of Blytheville Lat: 03558N Long: 08957W

MDS and Number on Station: B-52 G, 15

PACER LIME Ratings: Repaint -- C-C/2 Corrosion -- A-B/5

Comments: Center City-commercial EPA station, 6 km southeast @ 03556N, 08354W.

Airbase: Carswell, TX

Location: 7 mi NW of Fort Worth Lat: 03246N Long: 09725W

MDS and Number on Station: B-52 D, 36

PACER LIME Ratings: Repaint -- A-B/5 Corrosion -- A-A/6

Comments: Suburban-residential EPA station, 9 km northeast @ 03248N, 09721W.

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[a]Underlined airbases were included in the Special Inspection Request study.

Airbase: Castle, CA

Location: 8 mi NW of Merced   Lat: 03723N   Long: 12034W

MDS and Number on Station: B-52 G 14, H

PACER LIME Ratings: Repaint -- A-A/6   Corrosion -- A-A/6

Comments: Suburban-commercial EPA station, 13 km southeast @ 03718N, 12030W; training base

Airbase: Dyess, TX

Location: 2 mi WSW of Abilene   Lat: 03226N   Long: 09951W

MDS and Number on Station: B-52 D, 17

PACER LIME Ratings: Repaint -- B-C/3   Corrosion -- B-C/3

Comments: Suburban-residential EPA station, 10 km northeast @ 03227N, 09944W.

Airbase: Ellsworth, SD

Location: 11 mi ENE of Rapid City   Lat: 04408N   Long: 10306W

MDS and Number on Station: B-52 H, 29

PACER LIME Ratings: Repaint -- B-C/3   Corrosion -- B-B/4

Comments: Suburban-commercial EPA station 13 km southwest @ 04404N, 10315W.

Airbase: Fairchild, WA

Location: 12 mi WSW of Spokane   Lat: 04738N   Long: 11739W

MDS and Number on Station: B-52 G, 15

PACER LIME Ratings: Repaint -- A-A/6   Corrosion -- B-B/4

Comments: Suburban-residential EPA station 20 km northwest @ 04740N, 11725N.

Airbase: Grand Forks, ND

Location: 16 mi W of Grand Forks   Lat: 04757N   Long: 09724W

MDS and Number on Station: B-52 H, 6

PACER LIME Ratings: Repaint -- C-C/2   Corrosion -- B-C/3

Comments: Center City-commercial EPA station 128 km southeast @ 04652N, 09647W.

Airbase: Griffiss, NY

Location: 1 mi NE of Rome Lat: 04314N Long: 07524W

MDS and Number on Station: B-52 G, 15

PACER LIME Ratings: Repaint -- C-C/2 Corrosion -- C-C/2

Comments: Center City-commercial EPA station 4 km east @ 04313N, 07527W.

Airbase: K. I. Sawyer, MI

Location: 16 mi S of Marquette Lat: 04621N Long: 08724W

MDS and Number on Station: B-52 H, 19

PACER LIME Ratings: Repaint -- B-B/4 Corrosion -- B-B/4

Comments: Unknown EPA station 23 km north @ 04632N, 08723W.

Airbase: Loring, ME

Location: 4 mi NW of Limestone Lat: 04657N Long: 06753W

MDS and Number on Station: B-52 G, 14

PACER LIME Ratings: Repaint -- C-C/2 Corrosion -- B-B/4

Comments: Center City-commercial EPA station 31 km southwest @ 04641N, 06759W.

Airbase: March, CA

Location: 9 mi SE of Riverside Lat: 03354N Long: 11715W

MDS and Number on Station: B-52 D, 18

PACER LIME Ratings: Repaint -- A-B/5 Corrosion -- A-B/5

Comments: Center City-residential EPA station 17 km northwest @ 03354N, 11723N.

Airbase: Mather, CA

Location: 12 mi ENE of Sacramento   Lat: 03834N   Long: 12118W

MDS and Number on Station: B-52 G, 14

PACER LIME Ratings: Repaint -- A-A/6   Corrosion -- A-A/6

Comments: Center City-commercial EPA station 14 km west @ 03834N, 12129W.

Airbase: Minot, ND

Location: 13 mi N of Minot   Lat: 04825N   Long: 10121W

MDS and Number on Station: B-52 H, 17

PACER LIME Ratings: Repaint -- B-C/3   Corrosion -- B-B/4

Comments: Center City-commercial EPA station 22 km southeast @ 04815N, 10118W.

Airbase: Robins, GA

Location: at Warner Robins   Lat: 03250N   Long: 08338W

MDS and Number on Station: B-52 G, 14

PACER LIME Ratings: Repaint -- C-C/2   Corrosion -- A-B/5

Comments: Center City-residential EPA station 23 km north @ 03248N, 08338W.

Airbase: Seymour-Johnson, NC

Location: Lat: 03520N   Long: 07758W

MDS and Number on Station: B-52 G, 14

PACER LIME Ratings: Repaint -- C-C/2   Corrosion -- A-B/5

Comments: Center City-commercial EPA station 5 km north @ 03523N, 07759W.

Airbase: Wurtsmith, MI

Location: 1 mi NW of Oscoda   Lat: 04427N   Long: 08324W

MDS and Number on Station: B-52 G, 15

PACER LIME Ratings: Repaint -- C-C/2   Corrosion -- B-C/3

Comments: Unknown EPA station 68 km north @ 04504N, 08325W.

*USGPO: 1983-659-062-1133