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ENVIRONMENTAL EFFECTS ON MAINTENANCE COSTS FOR AIRCRAFT EQUIPMENT

AIR FORCE MATERIALS LABORATORY

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METALS BEHAVIOR BRANCH
METALS AND CERAMICS DIVISION

MAY 1976

TECHNICAL REPORT AFML-TR-76-31
FINAL REPORT FOR PERIOD NOVEMBER 1973 - JANUARY 1976

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AIR FORCE MATERIALS LABORATORY
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A series of mathematical models of the influence of environmental effects on maintenance costs was constructed using linear regression analysis. The equipment whose behavior were modeled were the KC-135 Doppler Radar and the F-4E engine starter. Models explaining more than 20% of the variation in maintenance cost as a result of weather factors were developed, where only the two most current month's weather was considered. Recommendations for further research using more sophisticated model development techniques are presented. A limited economic analysis of some life cycle cost implications of failure countermeasures for increased environmental resistance is given.

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FOREWORD

This report was prepared by Major Thomas K. Moore of the Structures Division, Directorate of Airframe Engineering, Aeronautical Systems Division ASD/ENFSS. It was submitted by the author on 12 January 1976 as a part of a cooperative inhouse research effort with the Air Force Materials Laboratory. The work was performed under Project 7351, "Metallic Materials for Air Force Weapon System Components", Task 735106, "Behavior of Metals", Inhouse Work Unit 735106B2, "Environmental Effects".

The report covers work conducted from November 1973 to January 1976. The research was conducted under the technical direction of Dr. Charles T. Lynch (AFML/LLN), Metals Behavior Branch, Metals and Ceramics Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

The author wishes to acknowledge the assistance of Professor Thomas H. Rockwell and Mr. Satish Desai of Ohio State University in formulating the problem, Mr. Desai for time series analysis statistical tests, Mr. Barry Brownstein of the Air Force Propulsion Laboratory for computer and computational problems, Mr. Jim Bias of the Oklahoma City Air Logistics Center for Air Force Logistics Command Maintenance Records, Captain Edward F. Kolczynski, ASD Staff Meteorology Office for weather data, and Lt. Dwight E. Collins of the Air Force Systems Command Commander's Working Group on Life Cycle Cost for reviewing the draft report.

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SECTION I
PROBLEM DEFINITION

The Air Force experiences significant cost in equipment maintenance due to environmentally caused failures, as has been documented by Dantowitz, Hirschberger and Pravidlo.[1] These failures or malfunctions are caused by one or more environmental agents such as temperature, moisture, suspended particulate matter, salt, and chemical pollutants. Because of the limitations present in any maintenance data reporting system where detailed investigations of each failure are not feasible, the true cause of equipment failures may not be detected or reported, and causative factors may not be apparent. At present there is relatively little accurate information relating environmental conditions with the cost of environmentally caused maintenance. Thus, there is little incentive to provide increased or decreased environmental protection or to increase or decrease the countermeasures for these failures.

This study examined the correlations between several environmental and operational factors and maintenance costs as reported by the AFM 66-1 maintenance data reporting system. It is likely that at least part of the maintenance cost which is attributable to environmental effects could be avoided by the application of appropriate corrective measures. Examples of these countermeasures are given in other documents such as the report of the Systems/Equipment Acquisition Programs Subgroup of the Corrosion Panel of the Maintenance Posture Improvement Program.[2] Additional possible actions to reduce environmentally caused system degradation will be given in this report and recommendations for further study of environmentally caused failures will be given.

This effort was meant to be exploratory to determine whether further research in this area was warranted. Because of the constraints of time available for this study, the results must be regarded as preliminary

SECTION II
SYSTEM DESCRIPTION

Aerospace vehicle maintenance is necessitated by many causes; however, for the purposes of this discussion these causes will be classified into three major categories:

1. Environmental Factors
2. Operational Factors
3. Miscellaneous

The environmental factors are considered to be active primarily while the aircraft is on the ground. These factors include atmospheric pollution, wind, temperature, moisture (humidity and precipitation), proximity to salt water, and the presence of sand, dust, or other particulate matter. (See Figure 1) Since military aircraft in general are flown less than commercial aircraft, the role of environmental factors would be greater in causing failures in military systems than they would be in commerical aircraft. The operational factors are those conditions which the system is exposed to under field conditions. The parameters used to characterize these factors include the number of sorties per month, the airborne vibrations and loads experienced (not used in this study), the operating hours per month, the average sortie length, and other factors which were not included in this study but which might include loading spectrums, temperature, etc. Other miscellaneous factors which cause maintenance include faulty design, accidents and Technical Order compliance. While this list of causative factors is not exhaustive it gives a reasonable indication of the range of causes for aircraft maintenance.

This system can be modeled as shown in Figure 2. New parts are installed

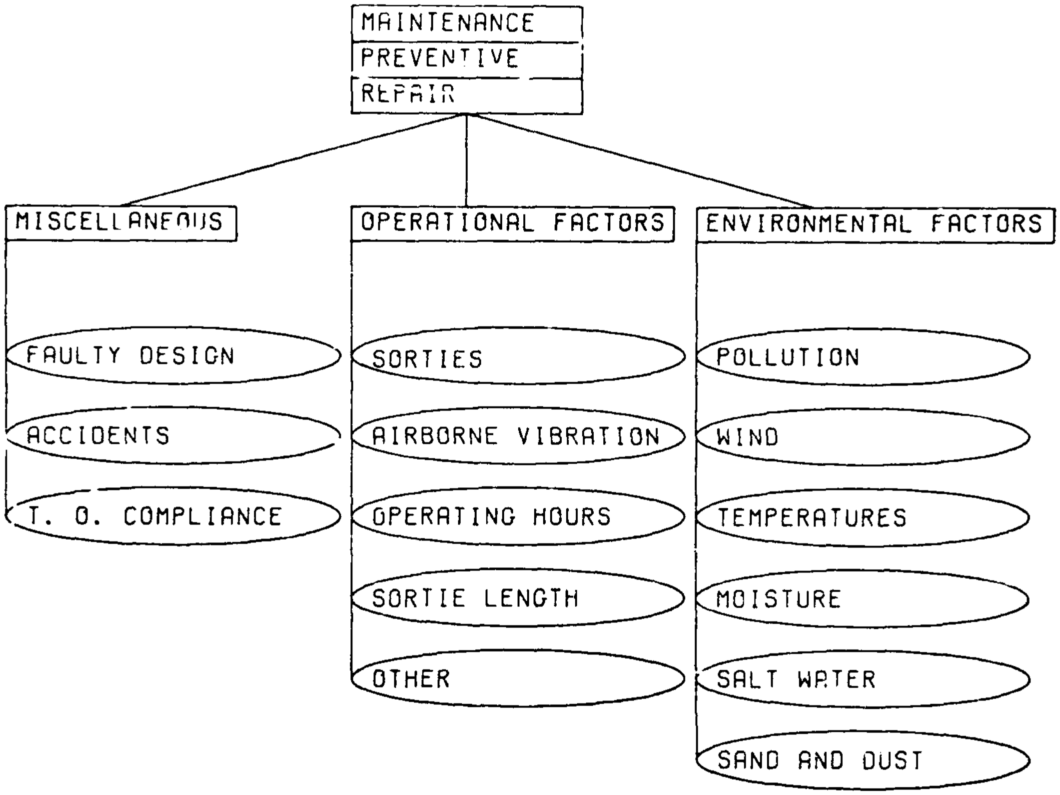

Figure 1. Causes of Aircraft Maintenance

either in new equipment or in equipment which is already in use. These installed parts then interact with and are subjected to operational, environmental and miscellaneous factors until failures occur. When failures occur, a decision must be made if the part is repairable. If it is not it is salvaged through the redistribution and marketing activities at the various facilities. If the part is repairable then there is interaction with support personnel (both base and depot level as applicable to the particular failure and to the supply system) and the replacement or repair is accomplished. In addition, when a failure occurs information is obtained which may be used in developing countermeasures to prevent the recurrence of the failure. This information may be used in repair or in the design of new components having similar functions.

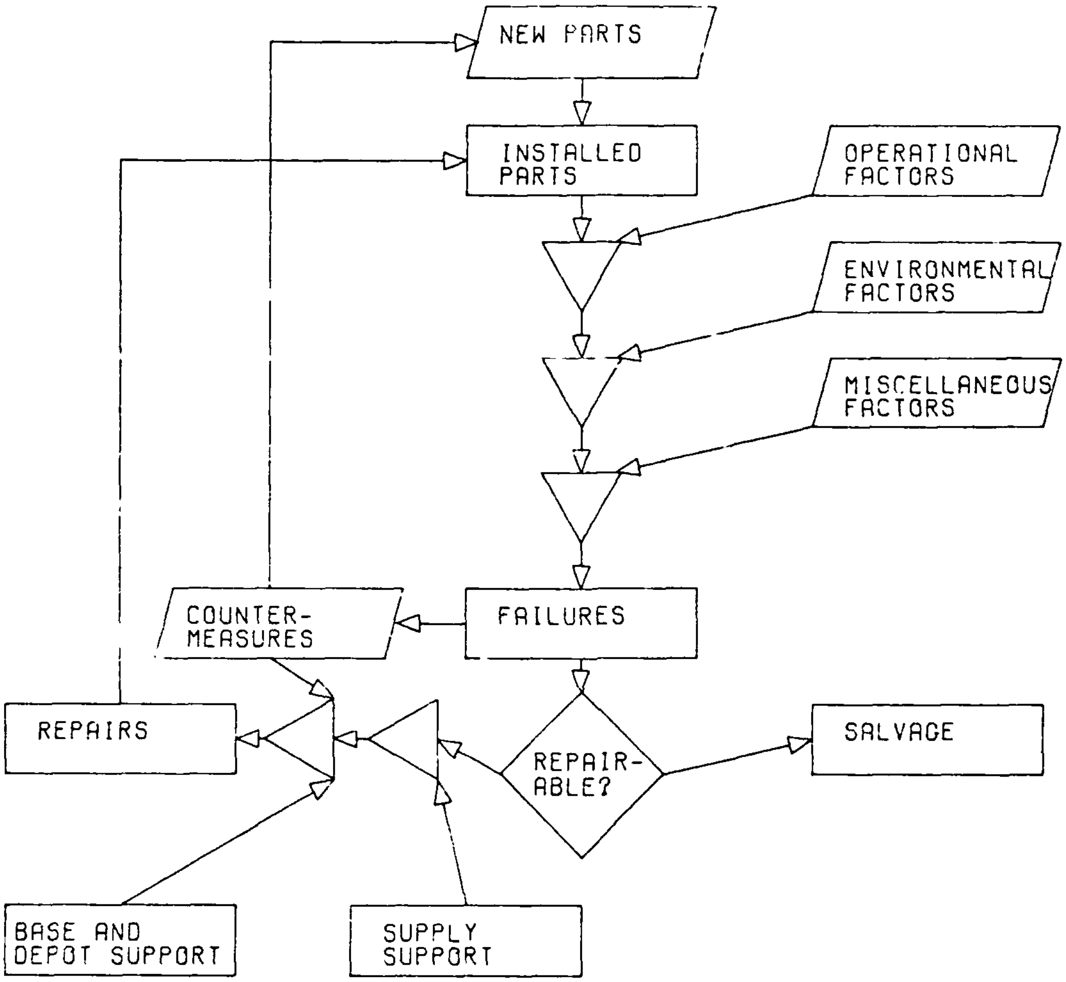

Figure 2. System Description

SECTION III

MODEL DEVELOPMENT

In order to evaluate the environmental effect on maintenance costs within the time available for this project it was decided to limit the study to two types of equipment. The criteria used for selecting the subject equipments were: 1) A relatively high contribution to the maintenance cost of the aircraft in which they are installed; 2) A reasonable likelihood that if the equipment malfunctions it would be repaired prior to the next flight rather than being allowed to remain inoperative for extended periods of time; 3) The equipment should be installed on a relatively large number of aircraft which are based in a wide variety of climatic conditions; 4) The equipments should differ from each other significantly, that is if one were primarily electronic the other should be primarily mechanical; and one should be of relatively new design while the other should be relatively older.

Air Force Logistics Command IROS data was reviewed for a number of candidate equipments, and the doppler radar on the KC-135 was selected as an example of a relatively old electronic equipment, while the engine starter on the F-4E was picked as the relatively new mechanical unit.

This section describes the development of a mathematical relationship between the maintenance costs and various factors influencing the maintenance costs. The model development can be viewed as consisting of:

Identification of Variables

Data Collection

Model Modification

1. IDENTIFICATION OF VARIABLES

At the beginning of the model development phase, a list of independent variables and response variables was prepared. This list is shown in Figure 3. Early inquiries into the availability of data led to the specific items represented on this list, and even with this preliminary screening some of the variables proved unobtainable. Some justification for inclusion of the variables shown was reinforced following personal interviews with maintenance personnel, and review of summarized maintenance actions reports(3) for the two selected equipments.

Personal Interviews

Personal interviews were conducted with some of the maintenance supervisors and technicians of the 17th Avionics Maintenance Squadron, (SAC), Wright-Patterson AFB, Ohio. The individuals interviewed were technicians responsible for the repair of KC-135 doppler radars and the technician's supervisors. The primary purpose of the interviews was to gain further insight into the doppler malfunctions and the required maintenance actions, and to determine if other factors, beyond those shown in Figure 3 should be included in the model. The following questions formed the basis of the personal interviews:

1. Have you observed any pattern to the failures in the equipment resulting from any of the following factors?

    a. Temperature
    b. Humidity, rain or snow
    c. Sand or dust
    d. Vibration or shock
    e. Proximity to salt water as in Southest Asian bases

2. Is there a lag between any of the above (if a pattern was noted) and the failures?

DEPENDENT VARIABLES

1. Maintenance Costs
   a. Man-Hour Costs
   b. Replacement Part Costs*
2. Downtime Costs*

INDEPENDENT VARIABLES

1. Number of aircraft
2. Number of flying hours in a month
3. Number of landings in a month
4. Distance from base to nearest body of salt water
5. Percent time wind blows from direction of salt water
6. Mean monthly temperature
7. Average maximum daily temperature
8. Average minimum daily temperature
9. Absolute maximum temperature for month
10. Absolute minimum temperature for month
11. Percent time relative humidity exceeds 50%
12. Percent time relative himidity exceeds 70%
13. Percent time relative humidity exceeds 80%
14. Percent time relative humidity exceeds 90%
15. Percent time sand or dust obscuration present
16. Number of freezing precipitation events
17. Number of hail events
18. Number of days with rain in a month
19. Number of days with snow in a month
20. Number of rain events in a month
21. Number of snow events in a month*
22. Pollution*

* These variables were not obtained or used in the model.

Figure 3. Preliminary Variables

3. Do you know of any part of the maintenance data reporting system which would tend to influence the data in any way?

4. Is labor cost a significant portion of the total maintenance cost for this equipment?

The following comments are based primarily on the interviews and a review of several maintenance Technical Orders and the associated equipment.

The AN/APN-81 Doppler Radar was designed in the mid-1950s. It was produced by General Precision Laboratories. Last production for KC-135 use was in approximately 1964. Shortages of spare parts and test equipment were noted by all interviewees. Spare parts are increasingly difficult to obtain. The equipment consists of 8 major assemblies and 38 subassemblies. Each of these has separate Work Unit Codes (WUCs) under which maintenance actions are recorded. Most of the equipment is in tightly closed containers inside the pressurized portion of the aircraft; however the Receiver-transmitter unit and the antenna are not within the pressurized compartment.

The following are comments on environmental sensitivities which the maintenance personnel noted:

1. The heat exchangers on the units tend to clog in dusty environments.

2. The components having moving parts freeze up or jam in cold weather. It is suspected that the grease used to lubricate these parts is of too high viscosity.

3. The system normally operates at a temperature of about 56°C. During cold weather the magnetron in the Receiver-Transmitter unit may require as much as a 30 minute warm-up, however the system timer allows full system use in 5 minutes. A local procedure change at one base whereby the transmitter was not operated for 30 minutes after turn-on in cold weather resulted in fewer failures.

4. Capacitors in all components fail more often in hot weather than in cold weather.

5. Flexible waveguides failed (split) significantly more often in hot humid weather than during other climatic conditions.

6. Electron tubes are particularly sensitive to low temperatures and vibration.

7. Corrosion was noted in several areas, particularly where soldering flux had been left on the area soldered.

8. Snowstorms can result in snow being packed against the aircraft in such a way that as the snow melts water can be forced into the system.

9. Bases differ significantly in test equipment availability, supply support, flight-line transportation support, and maintenance manning.

10. Cold weather significantly increases the amount of time required to accomplish almost all maintenance activities.

The maintenance personnel expresses the opinion that there might be about a 5 month cycle to maintenance activity. A serial correlation test was run on the maintenance cost data from several bases; however, there was not sufficient serial correlation to warrant rejecting the null hypothesis.

It was felt that in general the maintenance data from field organizations was reasonably accurately reported, and that while there was undoubtedly some error in the data provided by various bases that this could probably be considered as system noise, and that the errors due to inaccurate field reporting would be less than the differences in maintenance times caused by differences in supply support, test equipment availability, and flight-line transportation support. Further discussions with maintenance analysis personnel in Headquarters Air Force Logistics Command confirmed comparatively low error rate for field data; however, for depot level maintenance no assurances of accuracy were given, and it was suggested that data from depot level maintenance be ignored for this study. This suggestion was taken, and only field maintenance actions were considered.

There was also consensus that the major portion of the cost associated with the repair of malfunctions to these equipments was labor costs, with replacement parts being estimated at less than 10% the total maintenance costs.

Analysis of Summarized Maintenance Actions Reports

The summarized Maintenance Actions for Selected Work Unit Codes Reports were analyzed, and the causes of maintenance traced, when possible, to be variables listed in Figure 3. Figure 4 shows one such fault analysis for a subassembly (72EBE Lobe Switch Assembly) of the KC-135 Doppler Radar.

A preliminary screening of the independent variables was accomplished based on the information gained from the personal interviews and a review of the maintenance actions reports. A second screening was accomplished when it became apparent that certain data, such as pollution information, and replacement parts cost was not available.

2. DATA COLLECTION

Data on the response and independent variables was collected from several sources. Mr. J. Bias, a statistician from Oklahoma City Air Logistics Center was able to write a computer program, using the Air Force Logistics Command CREATE system which was able to extract man-hours charged against each of the Work Unit Codes of interest at each Air Force Base on a monthly basis from the master records maintained at Logistics Command Headquarters. These master records are based on the activities recorded by each maintenance technician on an AFTO Form 349. These forms are converted into computer compatible key-punch records and are then preserved on magnetic tape by the Air Force Logistics Command for use in its operations. These records are normally preserved for one year in a form which is readily accessible. For this the calender year 1973 was the time base selected. For converting the

MOST COMMON FAILURES	POSSIBLE CAUSES	RELATED VARIABLES
Fluctuates	Water in System	Rain, Snow, Humidity
	Dirt in System	Sand, Dust
	Vibration, Fatigue	Flying Time Number of Landings
	Temperature Cycling	Temperatures
Broken	Vibration	Flying Time Number of Landings
	Temperature Cycling	Temperatures
Stuck or Jammed	Vibration	Flying Time Number of Landings
No Output	---	---
Internal Failure	---	---
Lock-on Malfunction	---	---
Excessive Ground Speed	-	---
Deteriorated	Chemical Attack Corrosion Material Deficiency Dirt Abrasion Temperature Cycling	Pollution Humidity, Temperature -- Sand and Dust Temperatures
Intermittent	Water in System	Rain, Snow Humidity

Figure 4. Analysis of Summarized Maintenance Actions Report: WUC 72EBE Lobe Switch Assembly (The most common failures from the report are given, possible causes and related variables are listed)

man-hour information extracted by the computer program to costs the maintenance man-hour costs given in Air Force Manual 66-18 were used.

Monthly data from 14 F-4 bases and from 35 KC-135 bases was extracted. The expected wide range of climatic conditions was found with bases in Alaska, Iceland, Northern Europe, Southeast Asia, Guam and the continental United States included.

Flying time and landing information was extracted from other Air Force Logistics Command reports; however, this was done manually, since for the relatively small number of records to be screened, the development of an automated extraction system could not be justified.

Information on replacement part costs was initially thought to be available; however, further investigation revealed that this information was to be incorporated into the Advanced Logistics System and would not be available until that system was essentially fully operational.

Information on environmental vairables was obtained with the assistance of the Aeronautical Systems Division Staff Meteorologist from the Air Weather Service's Environmental Technical Applications Center, Ashville, North Carolina.[4] It was presented in both printed and punch card format, giving monthly summaries for each of the bases of interest for an 18 month time period. The time period included the year for which maintenance costs had been extracted.

The weather information was derived from magnetic tape records which had been made of the weather reported hourly, or more frequently, at the airfields of interest. In general, this data was considered reliable with a few exceptions. For example, the amount of snowfall reported was termed "useless" and unreliable.[4] It was possible, however, to extract most of the weather information desired from these reports.

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3. MODEL MODIFICATIONS

The data accumulated for use in modeling was assembled in the CDC 6600 computer at Wright-Patterson AFB in a random access file, then sorted to match the various inputs of data for each base and each month to form a consistent ordered file, suitable for input into the regression analysis program which was used.

A stepwise linear multiple regression analysis computer program BMD02R,[(5)] was used for the analysis of the assembled data. While Davis and Wood[(6)] have shown inaccuracies in some programs in the determination of regression coefficients, BMD02R was checked on a sample problem from Davis and Wood[(6)] and accurate coefficients to four decimals were obtained. It is believed that the trends indicated by analysis using BMD02R would be found by other, more sophisticated analysis techniques.

For all computations performed the maintenance man-hour cost was used as the dependent variable. Underlying the model used were the following assumptions:

1. Total maintenance costs for these systems are highly correlated with the maintenance man-hour costs.
2. The effects of mechanical vibration, shock, and number of hours the systems were actually used were adequately defined by the parameters:
    a. Number of flight hours per base per month
    b. Number of aircraft at a given base per month
    c. Number of takeoffs per month (Johnson and Reel noted "... much maintenance is associated with the number of aircraft take-offs and landings.", in their maintainability/reliability study.)[7]
3. The proportion of maintenance cost attributed to miscellaneous sources such as bad reporting, faulty design, and other such sources is the same for all observation points.
4. Since the cost of preventive maintenance and the cost of malfunctions are inseparable, they are assumed included in the maintenance man-hour costs.

5. Age of the aircraft has little effect on the maintenance costs. In an earlier study, maintenance man-hours per flight hour were found to be independent of the age of the aircraft after a relatively short (9-12 months) initial "breaking-in" period.[7]

The regression model development is summarized in the following sequential activities: (See Figure 5)

1. Raw Data: The initial regression model was developed using the assembled raw data for each type of equipment. The analysis was accomplished assuming the current months cost was determined by the current month's weather and operations.

2. Transgenerations: Examination of the residuals indicated that the logarithms of certain independent variables and interactions between certain variables would fit the data better than the variable itself. The BMD family of computer programs uses the term transgeneration for these operations, and this usage is continued here. A number of different runs were made in testing several forms of several of the variables.

3. Aggregation: Because of the likelihood to correlations between previous month's weather and current maintenance costs, several runs were made in which the previous month's weather was included in determining the current month's maintenance costs. Because of the complexity of the problem and the limitations of the regression analysis program, only one previous month's weather was included in the problem.

4. Outliers Removed: Examining the data showed that bases which had less than seven of either type aircraft frequently had non-representative missions and costs did not tend to fit the patterns seen in other bases. For example, the aircraft might be test aircraft, or used in other than their primary designed role or receiving unusual modifications or maintenance. Removing these outliers

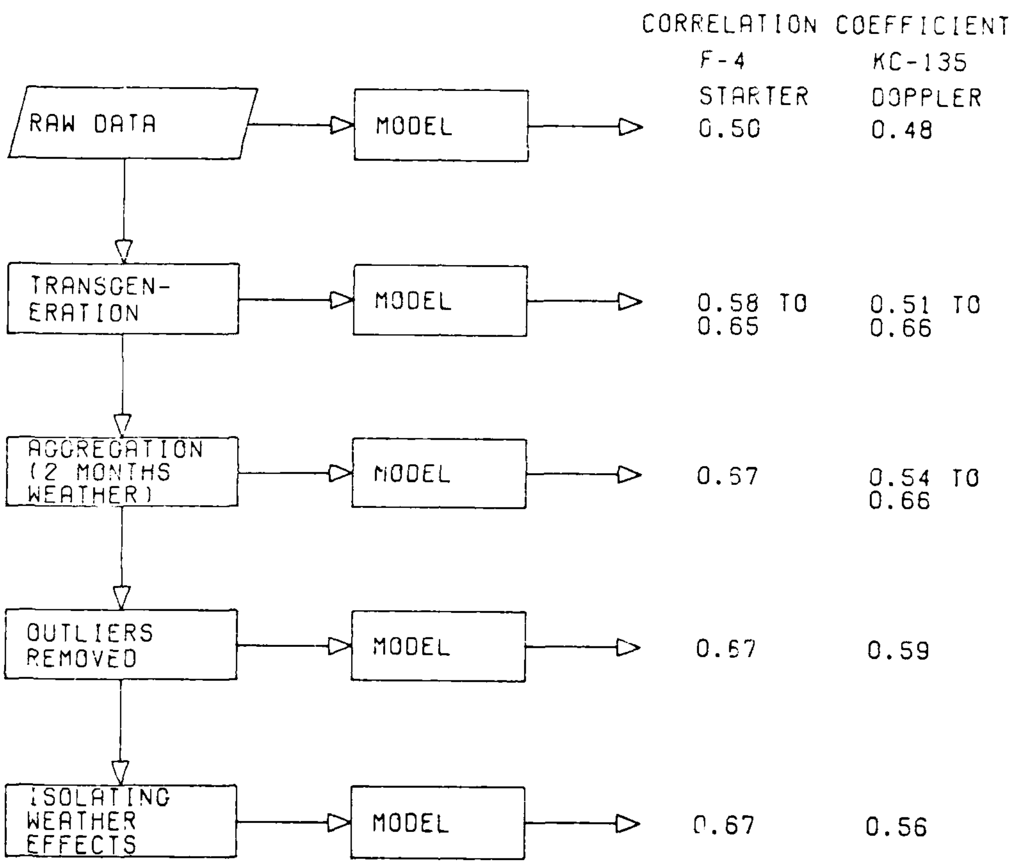

Figure 5. Model Performance

increased the correlation coefficient "r" by 0.05 for the KC-135 data from what seemed to be the most reasonable equation developed under the trans-generations section.

At this point the regression equations explained approximately 60% of the total maintenance costs; however, this included contributions from both operational and environmental data. To isolate the environmental effects additional runs were made without the operational data.

5. Isolating Weather Effects: The additional runs which were made without the operational factors showed a slight decrease in the correlation coefficient, as was expected; however, the decrease was not as great as expected. The influence coefficients of the regression equations changed somewhat, and no major decrease in regression equation fit was noted.

Up to this point the regression equation obtained was less that acceptable for several reasons. The final equation did not explain more than 80% of the variation in maintenance costs ($r^2 > 0.80$), a goal which had been established at the beginning of the study. Several coefficients did not seem to have the values to be expected from the forms of the underlying failure mechanisms. The number of variables was a large number which required considerable computer capacity for manipulation. There was also a need for a better outlier test and for greater traceability of depot data to give a more complete picture of the maintenance costs which were caused by weather.

On the other hand, there was sufficient evidence to conclude that environmental factors do have a significant influence on maintenance costs. The environmental variables which have the greatest significance in the regression equations are also variables mentioned by maintenance personnel as probably having some effect. The need for, and direction of, further research is also indicated.

SECTION IV

ENVIRONMENTAL FACTORS IN EQUIPMENT DETERIORATION

Much additional work needs to be done before a model is available which would allow the prediction of the effect of the environment on equipment deterioration. However, some conclusions can be drawn at this time.

1. It appears possible to construct a model which will give useful information for predicting failures or degradation based on the environment to which the system is exposed.

2. Environmental factors accounted for more than 20% of the maintenance costs of the equipment which was examined in this study. While the analyses of the two equipments showed that the coefficients of the regression equations differed, several of the same factors entered both regression equations at very high significance levels. These factors included absolute monthly temperatures, humidity and precipitation, and sand and dust.

3. There is some evidence in examining the maintenance data that there may exist an autocorrelation of lag one in the maintenance costs. The regression equations frequently showed opposite signs for the influence of the current month's weather and the previous months weather (for the same parameter). In addition, there does appear to be a sawtooth pattern to the monthly maintenance costs for almost all bases. (See Figure 6)

4. The absence of pollution information is perhaps one of the major weaknesses of this study. In comparing the maintenance cost information displayed in Figure 6 there is a major difference in maintenance cost per aircraft for the KC-135 doppler radar at Wright-Patterson and Rickenbacker Air Force Bases. It is believed significant that Wright-Patterson is down-wind, under

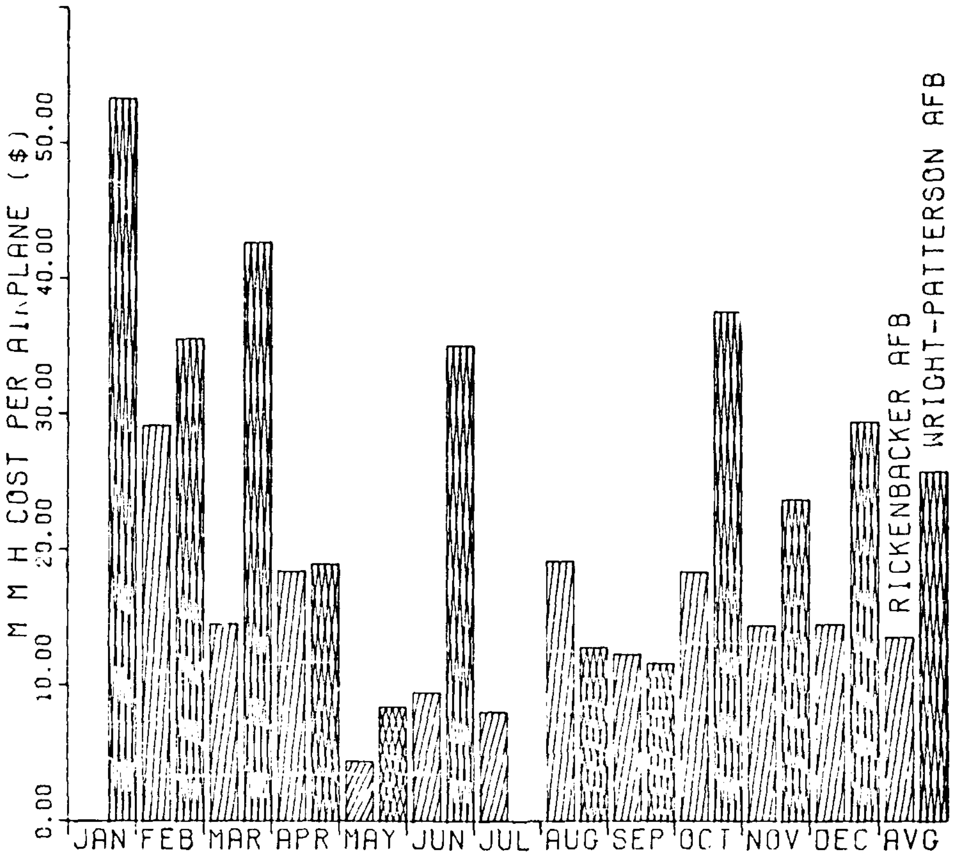

Figure 6. Monthly Maintenance Man-Hour Cost on the KC-135 Doppler Radar at Two Bases

prevailing wind conditions, from the Cincinnati-Middletown-Dayton industrial complex and receives considerable fallout from air pollution sources in this region. In contrast there are no major industrial pollution sources up-wind from and near Rickenbacker Air Force Base.

In general it would appear that better environmental protection would be warranted on equipment of the types studied. Unfortunately, this sort of protection is frequently expensive and add to an existing system; however, in the design of new equipment it is comparatively easier to obtain. While a thorough life cycle cost analysis may be required to justify the increased initial investment in any particular case, it is also prudent to look for specification changes in general documents such as finish specifications where improved protection can be added to have a favorable impact on numerous systems which will be procured in the future using these general specifications.

There are some measures which can be taken at relatively low cost to improve the corrosion resistance of systems, and since corrosion is one of the major forms of environmental degradation, this effort would serve to reduce maintenance costs. The actions which would have a favorable impact would include:

1. Increased use of water displacing compounds. These materials can act as a temporary protection for equipment to isolate it from water.

2. Use of corrosion inhibitors around corrosion-prone areas of aircraft, such as galleys, crew relief facilities, and bilges, could significantly reduce the chemical activity causing major maintenance expenses in these areas.

3. The addition of corrosion inhibitors to aircraft wash water could serve to increase the effectiveness of aircraft washing as a corrosion control procedure. This would be even more effective and affordable, if the washing process were automated to make it less labor intensive and if washing could then be done more frequently.

4. Corrosion inhibitors should be considered as an addition to insulating materials. These materials can serve to trap water and hold it in areas which are sensitive to corrosion. The addition of corrosion inhibitors to the materials which trap water could radically reduce the deleterious effect of the entrapped water.

In addition to aircraft system failures, there are other failures in the lite ature which occurred while the equipment was either in storage,[8] or in use in a controlled environment.[9] Reduced maintenance costs could result from prediction techniques which would indicate a systems expected storage life or its expected life, if the system were exposed to a given environment.

SECTION V

COMMENTS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This study achieved one of its major objectives by showing that there are significant correlations between weather and other environmental phenomena and maintenance costs. The relatively unsophisticated regression analysis techniques which were used are probably not the appropriate mathematical tool to develop the models which are needed to effectively predict environmentally caused deterioration. The short time period of the maintenance data studied, along with the limitations of the regression analysis program used do not adequately reflect the long term nature of the failure phenomena. In addition, the absence of pollution data, which may be quite significant for certain failure mechanisms, reduces the usefulness of this study.

An initial program to more conclusively prove the utility of the concept of failure prediction based on environmental factors would be an appropriate laboratory effort. One possible method of accomplishing this would be to collect the complete maintenance history of one aircraft type, then by tracking the basing history of the individual aircraft, and with the weather history from the appropriate locations an adequate data base for study would exist. One promising research approach would be the use of more advanced computer techniques which utilize adaptive control, or learning networks technology to see whether failure-causing patterns could be identified. If this technique yielded useful results, then the cost of extending it to all Air Force systems should be assessed. This assessment should consider the benefits which the prediction information would yield against the cost of obtaining the information, much as has been done with the Aircraft Structural Integrity Program.

For the initial study a trainer aircraft, such as the T-37, T-38 or T-41, where only a limited number of bases would be involved, would be the easiest aircraft system to analyze. However, since the study would require extensive co-operation with the Air Logistics Center, the aircraft chosen should be the one for which the Air Force Logistics Command most needs the predictive information.

In addition to labor costs and spare part costs, the Air Force experiences what might be termed "Downtime Costs" when an aircraft is grounded for maintenance. Although this downtime cost is difficult to measure, the downtime itself serves as an indicator of the cost. The downtime is the amount of clock time required to repair a malfunction. This is also referred to as Elapsed Maintenance Time (EMT). EMT measures the amount of time that maintenance and support facilities are used in the repair of an equipment. Economic evaluation of a proposed countermeasure to provide increased environmental protection should include the downtime cost consideration.

Considerable work is needed in characterizing and analyzing the economics of failure countermeasures. One simplified analysis for evaluation of the economic feasibility of a countermeasure is suggested below.

For the equipment under consideration let

C_M = Labor (MMH) cost for one year

C_P = Spare part cost for one year

C_B = Base and depot support cost attributable to the equipment maintenance for one year

Assuming the final model indicates that p% of the MMH cost are attributable to the environmental factors,

$$\text{Environmental component of MMH cost} = p \times C_M \quad (1)$$

In the absence of other information we will assume that C_P and C_B are directly proportional to C_M. Therefore,

$$E_i = \text{Total annual environmental failure cost} = p\ (C_M+C_P+C_B) \qquad (2)$$

The next step is to estimate the remaining life cycle cost. Let

N = Years of equipment life remaining

Then, the Net Present Value of a series of annual environmental cost

$$= \sum_{i=1}^{N} \frac{E_i}{(1+r)^{i-1}} \qquad (3)$$

where r denotes the annual discount rate.

If the proposed countermeasure costs C dollars for design, development, testing, evaluation, incorporation into future production, and retrofitting the design change into past production, and if the reduction in maintenance costs due to the countermeasure is expected to be k%, then the anticipated net costs due to application of the proposed countermeasure

$$= C + \sum_{i=1}^{N} \frac{(1-k)xE_i}{(1+r)^{i-1}} \qquad (4)$$

the adoption of the proposed countermeasure will depend on the trade-off between current cost, represented by Equation (3), plus the intangible downtime cost and the anticipated cost resulting from the countermeasure, represented by Equation (4).

If, as a result of environmental malfunctions, missions have to be aborted, the cost of aborts should also be included in the above considerations. Although the abort cost is intangible, a part of it can be estimated by summing the crew hour costs, equipment costs, and support costs expended in preparation and execution of the aborted mission.

A major current difficulty is estimating accurately the quantity p, % of maintenance costs attributable to environmentally caused failures, and the quantity k, the reduction in maintenance costs resulting from the application of a countermeasure. Sensitivity analysis on these quantities would permit better insight into the uncertainty of the problem.

SECTION VI

SUMMARY

In the current era of restricted military budgets, it is essential that all available resources be used in the most effective manner possible. In order to better schedule depot maintenance actions on aircraft, techniques for predicting damage or deterioration of systems, subsystems or components to be made available for routine use within the Air Force Logistics Command are needed. Some techniques for tracking and predicting fatigue damage to aircraft structure are available and are being used; however, similar tracking and prediction techniques are not available to provide forecasting of corrosion damage.

This study was undertaken to identify the major factors contributing to environmentally induced equipment maintenance. Multiple linear regression analysis was used to correlate maintenance costs with various environmental and non-environmental factors. Variations in environmental conditions were shown to cause at least 20% of the maintenance costs, and more sophisticated non-linear techniques might indicate an even stronger environmental influence on maintenance costs. Several key environmental factors are identified in this study, and recommendations for refinement and extension of the study are included.

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