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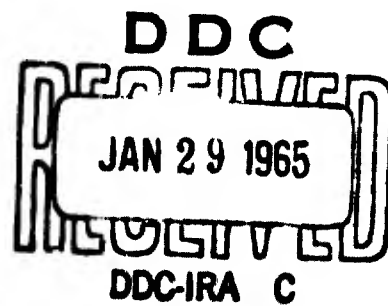
A FACTOR ANALYTIC APPROACH TO HUMAN ENGINEERING ANALYSIS AND PREDICTION OF SYSTEM MAINTAINABILITY

DONALD A. TOPMILLER, PhD

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**A FACTOR ANALYTIC APPROACH TO HUMAN ENGINEERING
ANALYSIS AND PREDICTION OF SYSTEM MAINTAINABILITY**

DONALD A. TOPMILLER, PhD

FOREWORD

This study was performed as a dissertation requirement for a Doctor of Philosophy degree in Psychology at Ohio State University. The United States Air Force is gratefully acknowledged for supporting the research contained in this report. The report was prepared in the Maintenance Design Branch, Human Engineering Division, Behavioral Sciences Laboratory, Aerospace Medical Research Laboratories, as part of Project 7184, "Human Performance in Advanced Systems," and Task 718406, "The Development of Human Engineering Maintainability Design Criteria." This report covers research performed between January 1964 and June 1964.

My gratitude is extended to Professor Robert J. Wherry whose support and advice was invaluable throughout the course of this study. Also my appreciation is conveyed to Captain Austin W. Kibler for his excellent technical and editorial suggestions. Mr. Edwin L. Godfrey deserves recognition for his assistance in programing many of the statistical computations used throughout this study.

This technical report has been reviewed and is approved.

WALTER F. GREYER PhD
Technical Director
Behavioral Sciences Laboratory

ABSTRACT

The study is introduced by reviewing previous attempts to quantify and predict systems maintainability. A theoretical formulation is outlined which treats the measurement and prediction of system maintainability as a "components-of-variance" model. The sources of variance are identified as: inter and intra man (personnel and social variables); machine (weight, volume, reliability, etc.) and man-machine interaction (human engineering design criteria). A restricted case of the formulation was investigated empirically in an attempt to predict maintainability of a sample of Air Force equipment from a questionnaire evaluation of the human engineering design features. The questionnaire contained 114 items concerning "desirable" human engineering maintainability design features. Ninety maintenance technicians completed the questionnaire on 90 subassemblies of three major weapon systems (B-52, GAM-77 and KC-135). Criterion data were developed from AFM 66-1 Maintenance Data Reporting System. Questionnaire responses, factor-analyzed by the Wherry-Winer Method, yielded eight orthogonal (independent) maintainability design factors. On the basis of the obtained factor loadings, seven of the original eight factors were selected as the most potent predictors. Several regression analyses were performed using different assumptions concerning both heterogeneity of sampled equipment and questionnaire scale stability. Coefficients of determination ranged from .27 to .47 depending on the assumptions made. Generally it was found that predictive efficiency increased and factor validity patterns changed when equipment was classified to make more homogeneous sets.

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SECTION I

INTRODUCTION

SYSTEMS HUMAN ENGINEERING MEASUREMENT AND PREDICTION

Briggs (ref 2) defines a system as "an assemblage of components (both man and machine) each with assigned functions, intercoupled so as to obtain a particular goal or goals." Systematic treatment of systems human engineering requires a conceptual model within which it is possible to broach such questions of system measurement and prediction as: Do human engineering design principles which have been developed as a result of laboratory research using nonoperational personnel as subjects in a well controlled laboratory environment investigating one, two or at best three independent variables at a time, provide useful data for predicting system performance as measured by some overall system criterion? That is, does man-machine performance variance, as influenced by incorporating or failing to incorporate human engineering design features into weapon system design, account for a significant portion of the variance of an overall system criterion?

Besides human engineering design (man-machine interactive variance), there are two major contributors to overall systems criterion variance; namely (1) inter and intra human variation such as individual differences and variations in aptitudes and skills, motivation, morale, group versus individual performance, strength, sensory acuity, etc, and (2) variance in the engineering parametric characteristics and requirements such as weight, volume, speed, reliability, tolerances to stress, etc. Also, as in any measurement system, a certain amount of error variance will remain due to sampling error and lack of metric sensitivity.

Christensen (ref 3) isolates systems criterion definition as one of the major systems engineering problem areas. Another systems-oriented engineering psychologist Muckler (ref 7), states:

"The ultimate objective of any man-machine system is to achieve some desired system output. The effectiveness of any element of the system, whether machine or man, must finally be judged in terms of the contribution of the element to the total system output. An obvious design objective, therefore, is that the elements of the system be designed to make maximum positive contribution without compromising other elements."

In terms of the above outlined components-of-variance conceptual approach, man-machine variations should be conceived of and treated as independent from the other major variance contributors.

Systems criterion variation can be viewed as both ultimate and proximal. Some functional formulations of ultimate systems criteria are as follows:¹

$$E_o = (P) \cdot (D) \quad (1)$$

where: E_o = Operational Effectiveness
 P = Performance
 D = Dependability

$$D = R + M \quad (2)$$

where: D = Dependability
 R = Reliability
 M = Maintainability

$$E_M = \frac{M}{C_M} \quad (3)$$

where: E_M = Maintenance Effectiveness
 M = Maintainability
 C_M = Cost of achieving a given maintainability level during development and in-field support.

These formulations are necessarily gross and presently defy precise quantification. To date, the additive or multiplicative nature of some of these relationships have yet to be defined. However, Air Force management is concerned about defining and eventually quantifying these ultimate systems criteria.

Since ultimate criteria are not presently accessible or perhaps even definable for research purposes, systems criteria are necessarily limited to those that are more proximal and most readily accessible. Since the purpose of this investigation is to examine the contribution of human engineering design (man-machine interactive variance) to quantifiable systems criteria, the interdisciplinary technology of maintainability has been chosen because of its importance to the Air Force and because there are provisions for convenient access to intermediate systems criteria.

The Air Force currently employs an organizational and field maintenance data reporting system (ref 1) to serve as a maintenance management guide for all operational bases. This reporting system provides a source of proximal systems maintainability criteria in the form of mean-time-to-repair, maintenance task times, etc.

Which of these criteria measures one wishes to attempt to predict depends to a large measure on what definition is accepted for systems maintainability. Cooper and Rigby (ref 10), for example, report that there are at least twenty-seven definitions and measures of maintainability. Most of these definitions either explicitly or implicitly include those measures that are currently being reported by operational

1. Formulations are a result of personal communication with Dr. J. W. Altman from American Institute for Research.

organizations of the Air Force. Generally, however, it has been agreed that maintainability is an aspect of equipment design that makes it possible to maintain equipment quicker, with less effort and cost, and with fewer mistakes, than would otherwise be possible. This generally agreed upon description of maintainability affirms that both machine variance (equipment design) and human performance variance (task times, effort and accuracy) are interactive determinants of systems maintainability. This notion permits compatibility with the general systems formulation outlined earlier.

Maintainability Measurement and Prediction

The first attempt at quantifying maintainability was performed by Munger and Willis (ref 8) for the Army Signal Corps. The purpose of their study was to develop a technique for measuring, during its development cycle, the maintainability of electronic equipment. To quote the authors, "A quantitative measure of maintainability must, therefore, take into account the maintenance design features possessed by an equipment and the effect that these features have upon maintenance in the context of normal field maintenance facilities." The procedure resulted in a maintainability index which yielded scores in what the authors define as "five maintenance consequence areas." Scores were also derived for each of nine intuitively developed design factors.

The Munger and Willis study resulted in a first approximation to a comprehensive, objective, and detailed procedure for making a quantitative evaluation of equipment maintainability during its development cycle. The research tools used in this approach were systems analyses and applied testing theory, both of which have general applicability. However, to again quote the authors, "empirical relationships between the index and operational effectiveness have not yet been established." This indicates that the technique was not predictive in nature, but merely permitted comparative evaluation of the human engineering maintainability design of different items of equipment. Further, the class of equipment on which the procedure was developed was restricted to radio, wire, and such miscellaneous equipment as radar, power supplies and test equipment, none of which was treated as a unified system with overall systems mission requirements (systems criteria).

Retterer et al (ref 9) at Radio Corporation of America (RCA) performed a study to develop a procedure to identify, measure, and improve the factors that affect the maintainability of electronic equipment. A further objective was to formulate a prediction technique for quantitatively specifying, predicting, testing, and demonstrating the maintainability of new systems and equipment.

Early in the program, RCA established the basic hypothesis that maintenance time is a function of three major parameters: design, personnel, and support. Each contributes to the maintenance time required to restore an equipment to satisfactory operating condition. Although these parameters may be intuitively

treated as independent, a degree of empirical interdependence exists. The major problem, then, was to find a quantitative relationship that expressed these parameters in terms of maintenance time.

After reviewing the requirements for a prediction scheme, the authors believed time to be the most appropriate criteria metric to which the parameters could be reduced and by which a quantitative maintainability numeric could be expressed. The reasons for this selection were that (1) time is universally meaningful, expresses the various aspects of maintenance understood by both operational and developmental agencies, and is a measurable quantity; and (2) time is a true measure of the influence of maintainability on operation capability.

Criterion data in the form of maintenance repair times were collected at the part level of maintenance by using a stop-watch and recording to the nearest 10th of a minute the times required for the performance of each of eight major elements for each maintenance task. These elements include (1) assembly and disassembly, (2) test and measurement, (3) removal and replacement, (4) check-out, (5) cleaning and lubrication, (6) obtaining materials, (7) preparing reports, and (8) contingency items. Predictor data were obtained by applying checklists to the maintainability design of the equipment as well as the existing maintenance environment as it influenced personnel and support factors. These data were recorded for each maintenance task. Empirically relating checklist scores to maintenance task times, through the use of regression analysis, provided a basis for a prediction formula.

The study by Retterer et al resulted in a number of useful findings. First, it was determined that the checklist scores were normally distributed; however, maintenance time was distributed log normally. Hence, all maintenance times were normalized through a log transformation. The regression analysis employed resulted in a prediction formula of the form:

$$\log M_{e_{\tau}} = 3.54651 - 0.2512A - 0.3055B - 0.0193C$$

where: $M_{e_{\tau}}$ = Mean Expected Repair Time

A = Design Features Score

B = Design Dictates Facilities Score

C = Design Dictates Skill Score

The total prediction yielded a multiple correlation coefficient of 0.74. Although other intuitively developed prediction factors of personnel and support were also used as predictors, they did not account for a significant portion of repair-time variance.

The design subfactors (A, B, and C) in the prediction formula were not identified as human engineering design criteria per se; however, on close examination they do represent identification of an interaction component of the structural formulation presented previously. This tends to support the hypothesis that the degree of inclusion of human engineering design principles in overall systems design accounts for a significant portion of proximal systems criteria variance and, moreover, that the design predictors are more effective than inter- or intra-human variability as shown by the small regressor weight for checklist C in the equation.

Schafer, Bensen and Clausen (ref 11) developed a technique to measure the maintainability of existing equipment and to predict maintainability from information available during the design phase of development. The criteria chosen for prediction were maintenance time, defined as the total number of man-hours of direct labor expended in unscheduled maintenance action, and maintenance load which is partially dependent on equipment reliability. If data on equipment failure rates are available maintenance time can be readily converted to a maintenance load index.

The investigators developed a procedure in this study for predicting the number of man-hours required to carry out an unscheduled maintenance action. This procedure involved 23 steps which included (1) identifying and analyzing malfunction symptoms, (2) identifying the suspected malfunctioning component of each symptom, (3) determining replacement times, (4) determining the time to prepare, test, align, and cleanup each component and the whole system, (5) calculating the mean maintenance time for each symptom and subsystem, and (6) calculating the mean maintenance time for the whole system. These times were based on standard times for the performance of basic task elements.

Partial validation of this method of maintenance-time prediction was made by using subsystems of the F-106 aircraft on the manufacturer's flight line and comparing predicted times and estimated times for the various maintenance tasks. A sample of 58 equipment items (components) of the F-106 was chosen to represent a wide range of difficulty in the maintenance tasks.

The estimated times for all tasks were obtained from flight line mechanics most familiar with the jobs. These estimated times were used as maintenance-time-prediction criteria. Standard times for the elements of the maintenance replacement tasks were obtained by timing Convair Corporation flight line mechanics during the F-106 maintenance operations.

The predicted maintenance task times for the 58 equipment items were computed by summing the standard times for all elements required for each maintenance replacement task involved. The regression of these predicted replacement times, Y, on estimated times, X, was computed and the following regression equation resulted:

$$Y = 0.233 + 0.4228X$$

Solving for X yields

$$X = 2.26Y - 0.52$$

It can be seen from the regression equation that the predicted time, Y, was an underestimation of estimated times, X, by experienced flight line mechanics. Analysis of variance demonstrated this regression to be significant beyond $P = .01$. The regression accounted for 83% of the sum of squares, thus permitting a valid prediction.

Preparation, test, alignment, and cleanup time steps, like replacement steps, were broken down into elements. The elements cover most of the actions, except replacement, occurring in maintenance tasks. The standard times for these elements were obtained by timing the mechanics. Technical order reference time and waiting time were not included, but were estimated by the maintenance analyst. To predict the preparation, test, alignment, and cleanup element times, the task elements to be performed were listed, classified and counted. These counts were then multiplied by the appropriate standard times and the products summed. This technique was carried out for a sample of 88 procedural steps in the maintenance of subsystems of the F-106. The following regression equation for these subtasks was:

$$Y = 0.023 + 0.894X$$

The previously discussed investigations all suffer from several major deficiencies. First, no attempt was made to perform these studies within a theoretical man-machine systems framework. Such a framework is necessary if any significant achievement is to be made in furthering human engineering design criteria research. That is, if no attempt is made to identify underlying system design dimensions which are critical in their influence on overall system performance, laboratory research performed to develop human engineering design criteria will suffer from lack of significance in application at the systems level. In the past 5 to 8 years concerted effort has been devoted to the development of human engineering design criteria guides, most of which were the result of the consolidation of laboratory and field research data. Also, considerable energy has been expended on the part of various military and civilian research and development agencies to convert these data into documentation with official status in terms of being contractually binding on prime contractors responsible for the development of weapon and space systems. Air Force Mil-Std-803 (ref 6) was developed as such a document, resulting from an extensive review and culling of human engineering design principles contained in many of the above referenced guides. It thus appears that any systems prediction technique should first attempt to isolate systems factors which are comprised of these design principles.

N = 45

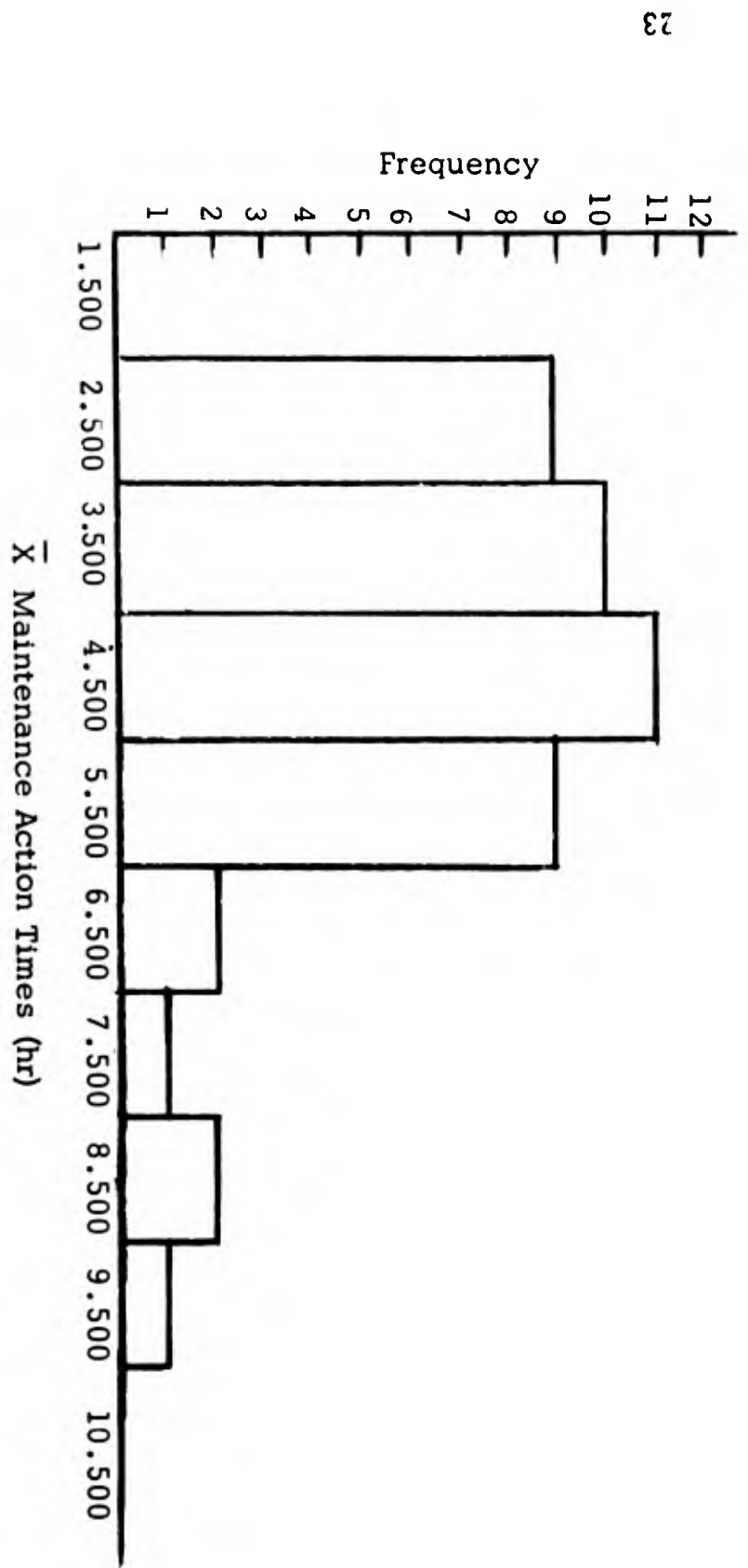


FIGURE 2. DISTRIBUTION OF ON-EQUIPMENT \bar{X} MAINTENANCE ACTION TIMES

N = 45

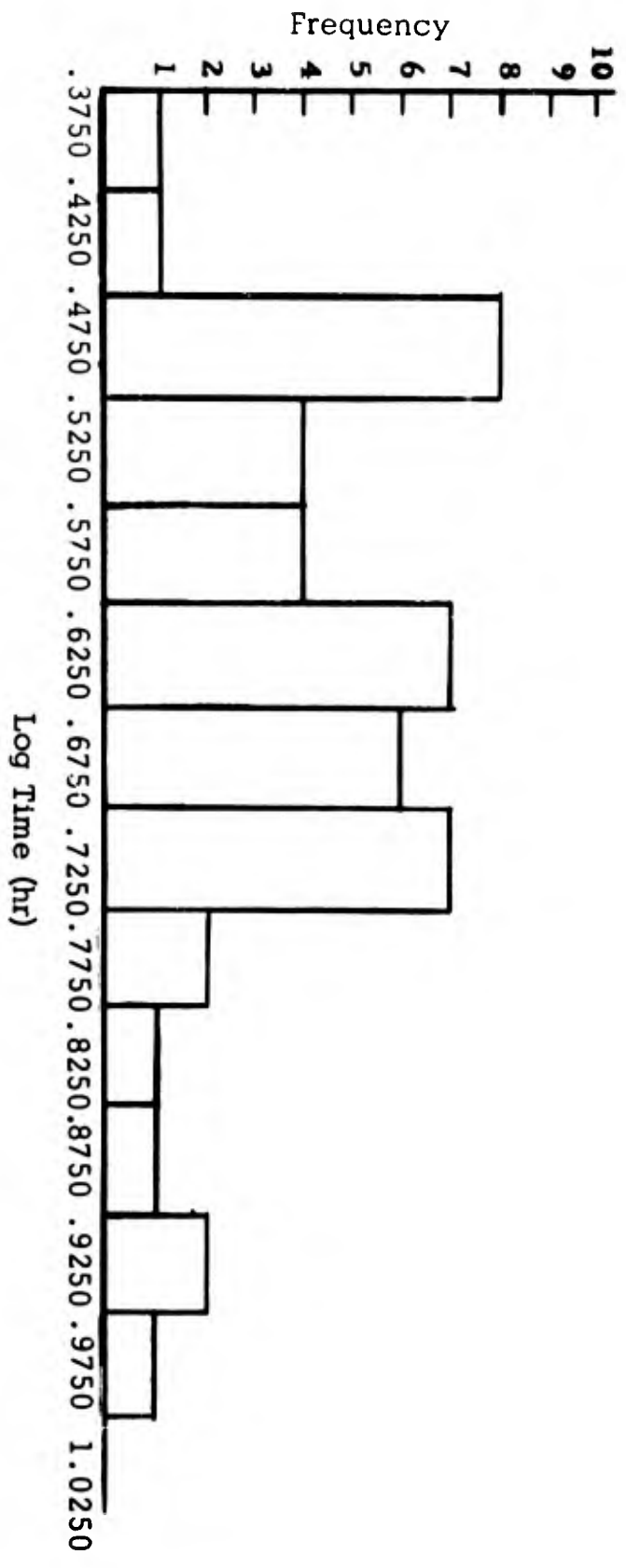


FIGURE 3. DISTRIBUTION OF ON-EQUIPMENT \bar{x} MAINTENANCE ACTION LOG TIMES

TABLE VI
INTERCORRELATIONS BETWEEN GUESSED SUBTESTS

	1	2	3	4	5	6	7	8
1	1.000	.659	.420	.594	.559	.535	.585	.460
2	.659	1.000	.439	.690	.575	.529	.674	.628
3	.420	.439	1.000	.582	.442	.529	.480	.547
4	.594	.690	.582	1.000	.561	.612	.600	.630
5	.559	.575	.442	.561	1.000	.484	.446	.549
6	.535	.529	.529	.612	.484	1.000	.500	.612
7	.585	.674	.480	.600	.446	.500	1.000	.447
8	.460	.628	.547	.630	.549	.612	.447	1.000
Σ	4.812	5.194	4.439	5.269	4.616	4.801	4.732	4.873
\bar{X} Score	76.833	51.422	36.822	43.211	48.278	40.322	40.311	33.067
σ Score	12.820	8.549	5.805	6.968	7.969	7.832	8.060	5.651

TABLE VII

WHERRY-DOOLITTLE LINEAR DEPENDENCY CHECK

	1	2	3	4	5	6	7	8	Sum Check	Test #
a1	—	—	—	—	—	—	—	—	—	—
b1	.420	.439	1.000	.582	.442	.529	.480	.547	4.439	3
c1	-.420	-.439	-1.000	-.582	-.442	-.529	-.480	-.547	-4.439	
a2	1.000	.659	.420	.594	.559	.535	.585	.460	4.812	1
b2	.824	.475	—	.350	.373	.313	.383	.230	2.948	
c2	-1.000	-.576	—	-.425	-.453	-.380	-.465	-.279	-3.577	
a3	.460	.628	.547	.630	.549	.612	.447	1.000	4.873	8
b3	—	.255	—	.214	.203	.236	.077	.637	1.622	
c3	—	-.400	—	-.336	-.319	-.371	-.121	-1.000	-2.547	
a4	.585	.674	.480	.600	.446	.500	1.000	.447	4.732	7
b4	—	.211	—	.132	.036	.071	.583	—	1.033	
c4	—	-.362	—	-.226	-.062	-.122	-1.000	—	-1.772	
a5	.559	.575	.442	.561	1.000	.484	.446	.549	4.616	5
b5	—	.072	—	.069	.569	.029	—	—	.738	
c5	—	-.127	—	-.121	-1.000	-.051	—	—	-1.297	
a6	.535	.529	.529	.612	.484	1.000	.500	.612	4.801	6
b6	—	-.009	—	.072	—	.504	—	—	.567	
c6	—	.018	—	-.143	—	-1.000	—	—	-1.125	
a7	.594	.690	.582	1.000	.561	.612	.600	.630	5.269	2
b7	—	.089	—	.392	—	—	—	—	.481	
c7	—	-.219	—	-1.000	—	—	—	—	-1.227	

TABLE VIII

WHERRY-DOOLITTLE Z TABLE - LINEAR DEPENDENCY CHECK^a

	1	2	3	4	5	6	7	8
Z ₁	1.000	1.000	<u>1.000</u>	1.000	1.000	1.000	1.000	1.000
Z ₂	<u>.824</u>	.807	0	.661	.805	.720	.770	.701
Z ₃	0	.533	---	.512	.636	.601	.592	<u>.637</u>
Z ₄	---	.431	---	.440	.571	.513	<u>.583</u>	0
Z ₅	---	.355	---	.410	<u>.569</u>	.505	0	---
Z ₆	---	.346	---	.402	0	<u>.504</u>	---	---
Z ₇	---	.347	---	<u>.392</u>	---	0	---	---
Z ₈	---	<u>.327</u>	---	0	---	---	---	---

^a Subtests selected in the order underlined

TABLE IX

OBLIQUE FACTOR LOADINGS

	A ₃	B ₁	C ₈	D ₇	E ₅	F ₆	G ₄	H ₂
ST ₁	.420	1.000	.460	.585	.559	.535	.594	.659
ST ₂	.439	.659	.628	.674	.575	.529	.690	1.000
ST ₃	1.000	.420	.547	.480	.442	.529	.582	.439
ST ₄	.582	.594	.630	.600	.561	.612	1.000	.690
ST ₅	.442	.559	.549	.446	1.000	.484	.561	.575
ST ₆	.529	.535	.612	.500	.484	1.000	.612	.529
ST ₇	.480	.585	.447	1.000	.446	.500	.600	.674
ST ₈	.547	.460	1.000	.447	.549	.612	.630	.628

TABLE X
 WHERRY DOOLITTLE WITH HORIZONTAL EXTENSION

	A ₃	B ₁	C ₈	D ₇	E ₅	F ₆	G ₄	H ₂	I	II	III	IV	V	VI	VII	VIII	Sum Check
A ₁	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	
B ₁	1.000	.420	.547	.480	.442	.529	.582	.439	-1.000	0	0	0	0	0	0	0	3.439
C ₁	-1.000	-.420	-.547	-.480	-.442	-.529	-.582	-.439	1.000	0	0	0	0	0	0	0	-3.439
A ₂	.420	1.000	.460	.585	.559	.535	.594	.659	0	-1.000	0	0	0	0	0	0	3.812
B ₂		.824	.230	.383	.373	.313	.350	.475	.420	-1.000	0	0	0	0	0	0	2.368
C ₂		-1.000	-.279	-.465	-.453	-.380	-.425	-.577	-.510	1.214	0	0	0	0	0	0	-2.875
A ₃	.547	.460	1.000	.447	.549	.612	.630	.628	0	0	-1.000	0	0	0	0	0	3.873
B ₃			.637	.077	.203	.236	.214	.255	.430	.279	-1.000	0	0	0	0	0	1.331
C ₃			-1.000	-.121	-.319	-.371	-.336	-.400	-.675	-.438	1.570	0	0	0	0	0	-2.090
A ₄	.480	.585	.447	1.000	.446	.500	.600	.674	0	0	0	-1.000	0	0	0	0	3.732
B ₄				.583	.036	.071	.132	.211	.233	.431	.121	-1.000	0	0	0	0	.819
C ₄				-1.000	-.062	-.122	-.226	-.362	-.400	-.739	-.208	1.715	0	0	0	0	-1.404
A ₅	.442	.559	.549	.446	1.000	.484	.561	.575	0	0	0	0	-1.000	0	0	0	3.616
B ₅					.569	.029	.069	.072	.101	.337	.311	.062	-1.000	0	0	0	.550
C ₅					-1.000	-.051	-.121	-.127	-.177	-.592	-.546	-.109	1.757	0	0	0	-.966
A ₆	.529	.535	.612	.500	.484	1.000	.612	.529	0	0	0	0	0	-1.000	0	0	3.801
P ₆						.504	.072	-.009	.176	.206	.340	.119	.051	-1.000	0	0	.459
C ₆						-1.000	-.143	.018	-.349	-.409	-.675	-.236	.101	1.984	0	0	-.911
A ₇	.582	.594	.630	.600	.561	.612	1.000	.690	0	0	0	0	0	0	-1.000	0	4.269
B ₇							.392	.089	.169	.164	.222	.201	.114	.143	-1.000	0	.494
C ₇							-1.000	-.227	-.431	-.418	-.566	-.513	-.291	-.365	2.551	0	-1.260
A ₈	.439	.659	.628	.674	.575	.529	.690	1.000	0	0	0	0	0	0	0	-1.000	4.194
B ₈								.326	-.107	.233	.269	.310	.102	-.050	.227	-1.000	.310
C ₈								-1.000	.328	-.715	-.825	-.951	-.313	.153	-.696	3.067	-.952

Table IX contains the oblique factor loadings of subtests on factors. Since all of the original guessed subtests were retained, the resulting factor matrix is a square. Normally on the basis of the Z table criterion, one or more of the subtests would be eliminated and the resulting factor matrix would be rectangular.

To obtain orthogonal factor structure of all loadings of the 114 variables on the 8 factors, the oblique subtest loadings must be transformed by computing an extended Doolittle (table X) and a transformation matrix (table XI). This transformation matrix is then multiplied against the original variable-subtest centroid projections to yield an estimate of orthogonal factor loadings, r_{iK} . Or in matrix algebra terms:

$$ID = T$$

where: I is the inverse matrix developed by using the rows (R) of the extended Doolittle (table X) as columns of the I matrix.

D is the diagonal matrix developed by using the square root of the leading (A) row entries in the Doolittle as the diagonal entries.

The oblique factor matrix (table IX) is multiplied by the transformation matrix to yield the orthogonal loadings or $VT = F$.

where: V is the oblique factor matrix.

F is the orthogonal factor matrix.

The resulting r_{iK} matrix (F) was then rotated through five cycles according to Varimax Criterion (ref 5) to produce the final factor structure presented in table XII.

TABLE XI
TRANSFORMATION MATRIX

	I	II	III	IV	V	VI	VII	VIII
A ₃	1.000	-.463	-.539	-.306	-.133	-.248	-.270	.187
B ₁		1.101	-.350	-.565	-.446	-.290	-.262	-.408
C ₈			1.253	-.159	-.412	-.479	-.354	-.471
D ₇				1.310	-.082	-.168	-.321	-.543
E ₅					1.325	-.072	-.182	-.179
F ₆						1.409	-.228	.087
G ₄							1.597	-.397
H ₂								1.751

TABLE XII

 ROTATED FACTOR MATRIX^a
 (FACTOR LOADINGS)

Decimal points are omitted

Questionnaire Item No.	I	II	III	IV	V	VI	VII	VIII
1	27	<u>52*</u>	03	05	16	16	03	20
2	<u>41*</u>	21	08	-20	-03	-03	-00	-26
3	18	18	03	02	-05	04	<u>30*</u>	01
4	<u>32*</u>	22	01	-01	19	04	04	10
5	21	<u>31*</u>	07	15	13	24	12	27
6	-02	16	01	04	-03	28	09	<u>32*</u>
7	-04	03	-11	14	<u>46*</u>	14	-06	-11
8	-03	02	-03	14	04	<u>62*</u>	10	11
9	<u>38*</u>	04	09	18	04	24	15	27
10	22	03	-00	19*	19	-08	11	<u>32</u>
11	06	<u>46*</u>	-12	18	26	18	17	25
12	15	<u>27*</u>	07	-07	26	01	07	14
13	12	<u>44*</u>	01	-21	03	-18	-02	12
14	17	<u>40*</u>	05	-23	-06	-06	04	00
15	13	02	09	02	10	-15	<u>60*</u>	12
16	<u>33*</u>	-06	15	27	00	-19	07	18
17	17	<u>47*</u>	12	17	23	24	26	29
18	<u>47*</u>	06	25	02	06	05	07	06
19	<u>26*</u>	-13	29	22	06	27	29	<u>29</u>
20	<u>32</u>	09	17	03	01	29	<u>27*</u>	11
21	06	04	17	07	-19	01	36	<u>48*</u>
22	04	06	03	-16	<u>43*</u>	04	-09	31
23	03	<u>63*</u>	03	17	28	03	08	27
24	-06	<u>45*</u>	-01	20	05	11	17	-07
25	-13	<u>45*</u>	-01	02	-12	-12	-12	-17
26	<u>44*</u>	-19	-17	07	-06	09	-05	-20
27	<u>43</u>	-06	00	14	-01	23	09*	-02
28	<u>40*</u>	03	-00	13	14	05	03	10

^aThose loadings that are underlined represent the highest positive loading for that questionnaire item (design feature) across all factors. The asterisks identify those items that were initially guessed to belong to that factor. The final predictor-factors were constructed by selecting those items that loaded the highest on a given factor.

TABLE XII -- Continued

Questionnaire Item No.	I	II	III	IV	V	VI	VII	VIII
29	17	10	02	15	05	25	08	<u>38</u> *
30	11*	-19	-01	-02	01	<u>37</u>	07	04
31	11	20	02	-11	<u>50</u> *	-10	-08	09
32	15	08	27	16	17	<u>57</u> *	-13	19
33	16	18	18	-03	33	<u>56</u> *	02	10
34	14	13	-09	<u>62</u> *	04	-02	08	-10
35	07	<u>52</u> *	06	19	-03	26	07	09
36	-04	<u>30</u> *	17	27	06	-01	-06	00
37	-08	15*	-12	-01	-05	04	<u>36</u>	31
38	06	-00	<u>28</u> *	27	-02	13	-04	09
39	-09	-16	-04	-05	22	25	02	<u>30</u> *
40	-11	-01	08*	00	-11	-06	<u>23</u>	22
41	16	26	20	31	00	<u>47</u> *	-11	11
42	02	22*	11	03	13	<u>31</u>	-09	01
43	25	32	11	12	<u>46</u> *	10	-18	00
44	10	37	09	11	11	<u>47</u> *	-09	-17
45	-01	03	15	-01	05	<u>33</u> *	-06	06
46	14	03	-12	<u>42</u> *	03	11	-09	07
47	05	21*	-00	03	14	15	<u>25</u>	04
48	16	<u>35</u> *	16	-04	24	04	10	-01
49	00	04	-05	11	08	12	05	<u>49</u> *
50	08	05	-01	22	23	21	<u>28</u> *	26
51	20	13	-01	19	10	19	10	<u>26</u> *
52	<u>54</u> *	-04	09	01	01	10	-01	-08
53	<u>22</u>	18	08	00	11*	06	-08	-10
54	-04	28	03	<u>37</u> *	07	17	-01	08
55	03	12	<u>59</u> *	03	12	19	-01	05
56	34	21	22	-03	12	<u>37</u> *	-04	10
57	21	17	23	12	<u>37</u> *	08	-08	24
58	17	04	12	<u>59</u> *	03	10	16	21
59	10	<u>53</u> *	11	34	28	03	19	24
60	-12	<u>40</u> *	-01	-02	08	-07	11	08
61	06	18	09	02	19	02	00	<u>40</u> *
62	-04	21	-09	38	07	24	<u>43</u> *	08
63	02	-05	11*	<u>25</u>	02	-13	13	07
64	<u>31</u>	08*	-01	07	-03	06	10	26
65	29*	33	12	08	-01	<u>35</u>	-13	11
66	01	18	04	<u>26</u> *	22	10	02	02
67	10	11	<u>61</u> *	-01	17	31	19	-01

TABLE XII-- Continued

Questionnaire Item No.	I	II	III	IV	V	VI	VII	VIII
68	10	15	12	17	13	<u>73*</u>	06	-10
69	01	-07	11	24	<u>60*</u>	17	11	15
70	12	09	14	37*	-06	07	12	<u>39</u>
71	12	13	-11	15	09	<u>33*</u>	13	08
72	-08	-05	-10	15	-01	<u>52</u>	13	31*
73	06	17	10	02	19	-07	07	<u>59*</u>
74	11	26*	00	24	-01	22	13	<u>35</u>
75	15	19	10	-19	<u>44*</u>	01	-01	25
76	11	04	13	12	27	20	<u>45*</u>	16
77	21	04	06	19	33	<u>36</u>	26*	01
78	13	12	-00	<u>56*</u>	14	30	-10	13
79	21	-01	<u>33*</u>	07	28	12	12	22
80	03	-17	-01	25	25*	03	21	<u>30</u>
81	-10	09	14	13	27	03	08	<u>47*</u>
82	-06	03	-01	<u>53*</u>	-04	19	16	38
83	-07	<u>43*</u>	01	16	24	19	08	23
84	21	19	10	17	15	23	08	<u>40*</u>
85	-20	04	00	-00	14	22	<u>36*</u>	33
86	20	05	<u>48*</u>	-00	25	10	29	11
87	18	-03	19	-03	16	<u>30*</u>	19	15
88	-05	18	04	14	12	<u>47</u>	27*	01
89	-14	-06	-03	<u>47*</u>	37	16	05	06
90	04	05	16	03	<u>52*</u>	08	11	-03
91	17	17	<u>53*</u>	-04	21	25	14	-03
92	05	<u>29</u>	03	25*	-04	28	01	18
93	06	24	36	-02	15	-06	<u>38</u>	15*
94	-08	<u>39*</u>	02	13	02	19	02	14
95	01	06	07	20	05	<u>24</u>	23*	16
96	-07	-05	05	-05	19	20	<u>29*</u>	23
97	05	-04	04	-04	08	<u>65*</u>	05	-00

TABLE XII-- Continued

Questionnaire Item No.	I	II	III	IV	V	VI	VII	VIII
98	17	25	10	<u>34</u> *	06	05	04	16
99	-03	08	01	25	01	03	-03	<u>31</u> *
100	04	00	09	<u>38</u> *	-09	09	09	32
101	01	20	11	-01	<u>36</u>	13	16	29*
102	10	<u>30</u> *	13	19	-11	24	05	08
103	02	17*	02	09	12	24	10	<u>34</u>
104	<u>26</u> *	11	10	15	25	-16	12	24
105	31	02	18	07	14	04	<u>39</u> *	08
106	03	10	22*	<u>29</u>	15	-02	01	18
107	07	-05	29	24	-01	21	02	<u>32</u> *
108	23	02	31	22	08	<u>58</u> *	-02	21
109	-09	03	29	26	17	02	14	<u>44</u> *
110	12	14	12	11	<u>44</u> *	23	22	-08
111	-16	16	17	17	<u>40</u> *	08	22	05
112	15	-09	22*	01	-15	<u>32</u>	09	10
113	17	03	13	04	<u>34</u> *	07	20	20
114	-06	-05	09	18	<u>51</u> *	07	26	18

Factor I was originally guessed subtest No. 3 and retained its same basic identity as Maintenance Safety. Items 20, 27, 53, and 64 were added to this factor by virtue of their relatively high loadings. Items 19, 30, and 65 were eliminated from Factor I and rotated onto other factors. The following items, in order of the magnitude of their loadings, now constitute Factor I:

<u>Loading</u>		<u>Item No.</u>
.54	Are there any cables attached to the front of cabinets where they could be "bumped" by passing equipment or personnel?	52
.47	Do units in excess of 45 pounds but less than 90 pounds have provision for two-man lift where lifting height is not in excess of 5 feet?	18
.44	Are there any equipment units presumably designed for one-man manipulation that are too large or too heavy to be conveniently lifted, carried, pulled, pushed or manually turned?	26
.43	Are components so arranged in a given compartment that one type of specialist must wait for another type of specialist to remove his part before the first technician can get to his part?	27
.41	Do access doors to high voltage areas have provisions for automatically shutting off power (safety interlocks on door etc)?	2
.40	Are there any lines routed such that the failure to securely clamp them in place would allow the lines to droop and be struck by moving parts?	28
.38	Are all access covers that are not completely removable, self-supporting in the open position?	9

<u>Loading</u>		<u>Item No.</u>
.33	Are cables or lines attached to units that can be partially removed (chassis on slide racks), attached so the unit can be replaced conveniently without damaging the cable or interfering with the securing of the unit?	16
.32	Are controls and displays that are used for maintenance or calibration only and that are not necessary to actual operation, kept distinct from operation controls?	20
.32	Are cables routed so they cannot be pinched by doors, lids, etc and so they will not be stepped on or used as hand holds?	4
.31	Do labels identifying control handles appear on the handle as well as the panel since the panel may be removed during maintenance?	64
.26	Are access openings free of sharp edges or projections that constitute a safety hazard?	104
.22	Where screwdriver adjustments must be made blind, are either mechanical guides provided or the screws mounted so that the screwdriver will not fall out of line?	53

Factor II, initially identified as guessed subtest No. 1, emerged as Maintenance Information and principally contains high loading items concerned with the design of prime and support equipment informational display features, ie, labeling, coding, and quantitative and qualitative display systems. Although item 92 has the highest loading on Factor II and has been so assigned, it also loads almost as high on two other factors. This is the only item which Factor II gained. Items 37, 42, 47, 64, 74, and 103 were initially classified as belonging to this subtest but now have their highest loadings on other factors. The following items now constitute Factor II:

<u>Loading</u>		<u>Item No.</u>
.63	Do display labels provide full identifying information?	23

<u>Loading</u>		<u>Item No.</u>
.53	Do display labels appear on every item that you must recognize, read or manipulate?	59
.52	Do display and control labels clearly indicate their functional relationship? Displays should be labeled by functional quantity rather than operational characteristics (ie, gal., psi, ohms, etc).	35
.52	Are access points individually labeled?	1
.47	Are the functions of each control clearly labeled?	17
.46	Are display labels imprinted, embossed, or attached so that they will not be lost, mutilated, or become otherwise unreadable?	11
.45	Are displays and controls labeled to correspond to notations found in system diagrams, in T.O.'s etc?	24
.45	Does (do) access(s) have labels indicating what auxiliary equipment is needed for service, checking, etc, at this point?	25
.44	Does (do) the access(s) have labels that tell what can be reached through this point?	13
.43	Are appropriate labels used for each test point?	83
.40	Are parts that require access from two or more openings properly marked to indicate this requirement?	14
.40	Do access covers have permanent part numbers marked on the cover?	60
.39	On component covers, are there display labels that provide relevant information concerning electrical, pneumatic, or hydraulic characteristics of the part?	94

<u>Loading</u>		<u>Item No.</u>
.35	Are all potted parts labeled with current, voltage, impedance, terminal information, etc?	48
.31	Are displays and their associated controls clearly labeled to show their relationship?	5
.30	Are color codes or other symbolic coding schemes used for identifying test points or tracing wire or lines easily identifiable under all illumination conditions?	36
.30	Are electrical terminals clearly marked + or - ?	102
.29	Are U-lugs rather than O-lugs used for clamping?	92
.27	Do display labels for each termination have the same code symbol as the wire or line attached to it?	12

Factor III, originally subtest number 8 which contained unassigned miscellaneous items now is identified as Handling for Removal and Replacement. Only six of the original ten items were acquired. To make this Factor a reliable predictor, would probably require additional items, and, in turn, a sampling of the new item field. No new items were added and items 40, 63, 106, and 112 now load on other factors. The following items now make up Factor III:

<u>Loading</u>		<u>Item No.</u>
.61	Are handles and grasp areas so located that at least 2 inches of clearance from obstructions is provided for handling?	67
.59	Are units designed to be removed and replaced provided with handles or other suitable provisions for grasping, handling and carrying?	55
.53	Are handles and grasp areas located so that at least 2 inches of clearance from obstructions is provided for handling?	91

<u>Loading</u>		<u>Item No.</u>
.48	Are cables routed so they need not be bent or unbent sharply when being connected or disconnected?	86
.28	In your judgment was the equipment designed to consider all environmental conditions (cold weather, darkness, etc) under which it was to be maintained?	38
.33	For removal units which have irregular, fragile, or awkward extension, such as cables, wave guides, hoses, etc; are these extensions easily removable before the unit is handled?	79

Factor IV was identified as Fasteners and Tools and was originally guessed subtest No. 7. Items 63 and 106 were acquired by this factor which also load highly on other factors. Items 10, 70, and 92 now load on other factors. The following items now comprise Factor IV:

<u>Loading</u>		<u>Item No.</u>
.62	Are fasteners standardized to minimize the number of tools required?	34
.59	Are access cover fasteners of the captive type?	58
.56	Are mounting bolts semipermanently captive (preferably with snap on collars)?	78
.53	Are finger operated fasteners used wherever feasible?	82
.47	Are identical screw and bolt heads used to enable various panels and components to be removed and installed with one type of tool?	89
.42	Are tool operated screws, of the type that can be operated by several tools (screw-driver, wrench, or pliers)?	46

Secondly, previous research has been limited to predicting maintainability for certain restricted classes of equipment. Munger and Willis (ref 8) used only ground equipment in their sample. Retterer et al (ref 9) limited their equipment to ground electronic systems, and Schafer, Benson and Clausen (ref 11) only sampled maintenance tasks on the F-106. No single study sampled equipment across several different weapon systems. Since different design approaches are used in packaging, environmental conditioning, etc, based upon the operational employment of the equipment, sampling must be across different classes of equipment. Narrow sampling of equipment is restrictive in the degree of generalization that can be made of any predictive scheme.

Thirdly, none of the studies used criterion data currently being collected as a matter of course for management or research and development purposes. To develop a practical procedure for government in-house application, the technique must utilize the criterion data currently available. With the exception of the Munger and Willis approach, past techniques required the use of maintenance task demonstrations and the directly observed task time associated with those demonstrations as their criterion. Because the crucial period in the development process for making design decisions regarding modifications in the equipment to enhance maintainability is before fabrication has started, the prediction method must utilize preliminary design data.

The following sections describe a combined factor analytic-multiple correlation analysis technique for predicting man-machine performance variance at the systems criteria level for maintenance operations. This investigation presumes to overcome most of the major inadequacies in previous research as outlined above.

SECTION II

PROCEDURE

PREDICTOR INSTRUMENT DEVELOPMENT AND ADMINISTRATION

The first step in this study was to review all existing human engineering maintainability design criteria published in official documentation and research publications. From these sources, specific questionnaire items were developed, each item reflecting a "recommended" human engineering design feature. One hundred and seventeen were so selected.

In an attempt to determine how well each item measured equipment maintainability the preliminary questionnaire was administered to a maintenance group at Bunker Hill Air Force Base, which had the responsibility for organizational maintenance of the B-58 flight control system. It was believed that this system most nearly possessed all classes of subassemblies (eg, electronic, mechanical, hydraulic, etc), and thereby permitted a fairly representative sampling of different types of equipment. Eighteen subassemblies (equipment items) were evaluated by the questionnaire. Inspection of the raw data responses indicated that several questionnaire items were useless in measuring. Thus several of the items were rewritten, certain items were eliminated from the questionnaire, and the response alternatives were expanded from 3 to 5. One hundred and fourteen items were selected for inclusion in the final version of the questionnaire. In the revised questionnaire, the five alternatives to all items were these: (1) The feature is clearly a design characteristic of the equipment, (2) the feature is reflected in the design of the equipment to a great extent, (3) the feature is not applicable to the equipment, (4) the feature is reflected in the design of the equipment to a small extent, and (5) the feature is not possessed by the equipment. The final questionnaire form is included as Appendix I.

To provide sampling of various classes of equipment and to sample different maintenance practices and procedures in the field, questionnaires were applied to three different weapon systems (B-52, GAM-77, and KC-135) at two operational Air Force installations (Strategic Air Command (SAC) Bases at Wright-Patterson Air Force Base and Lockbourne Air Force Base). Weapon Systems by Air Force Base are listed in Table I.

Such a sampling procedure is not intended to be completely random nor in any sense truly stratified; however, it does partially overcome objections to previous research outlined in Section I, since it cuts across various equipment classes (electrical, mechanical, and hydraulic), weapon system classes (bomber, missile, and tanker), and various maintenance practices.

Operational requirements at the SAC bases did not permit briefing each technician on the proper application of the questionnaire to a given item of equipment. In lieu of individual briefings, maintenance supervisors were briefed during one of their normally scheduled training periods. These supervisors were first given a general background on the need and requirements for the research program in which they were participating, and then presented specific instructions on how to have their technicians complete the questionnaire. Supervisors were requested to select technicians under their control who were familiar with certain items of equipment. The equipment items were to be identifiable to the subassembly level by work-unit code. Each technician was to complete the questionnaire on only that subassembly with which he was most familiar. Maintenance actions for both on-equipment (on aircraft) and off-equipment (shop) were considered in completing the questionnaire and so identified. Tables II through IV list the individual items of equipment evaluated by the questionnaire by common name, technical order designation and associated Air Force Specialty Code (AFSC) of the technician performing the evaluation.

This general method was adhered to at both SAC Bases with one exception. To obtain an estimate of rater (technician) reliability, ten items of equipment were selected for questionnaire evaluation by ten pairs of technicians, each pair evaluating the same item of equipment independently. Again, operational exigencies precluded utilizing this reliability check for all rater technicians and for all items of equipment.

TABLE I

WEAPONS SYSTEMS BY STRATEGIC AIR COMMAND ORGANIZATION

B-52 (Bomber)	GAM-77 (Missile)	KC-135 (Tanker)
17th Bomber Wing, WPAFB, Ohio	17th Bomber Wing, WPAFB, Ohio	17th Bomber Wing, WPAFB, Ohio
		301st Bomber Wing, Lockbourne AFB, Columbus, Ohio

TABLE II
B-52 EQUIPMENT ITEMS

Name	Technical Order Designation	Squadron and AFSC
Engine Pressure Ratio Transducer	1 B-52D-2-6	FMS 422X0
Fuel Flow Transmitter (Type J-7)	1 B-52D-2-6	FMS 422X0
Altimeter Drive Assembly	1 B-52B-2-3	FMS 421X2
Air Research Air Conditioning Unit	1 B-52B-2-3 1 B-52E-06-41-000	FMS 422X2
Converter Liquid Oxygen	1 B-52B-2-3 1 B-52E-07-47000	FMS 42251
Air Cycling Machine	1 B-52B-2-3 1 B-52E-06 41 ACB	FMS 42251
Hydraulic Power Pack Assembly	1 B-52B-2-14	FMS 421X2
B-52 Landing Gear System	1 B-52B-2-10	FMS 421X2
Flight Controls (Spoiler and Airbrake System)	14000 1 B-52B-2-11	FMS 421X2
Displacement Gyro	1 C-135(K) A-2-9 1 B-52D-2-6	FMS 422X0
AN/ARC-65 Radio Set	12 R2-2ARC 65-2	A&E 30150
Evaluator, Fire Control System AN/APH-2	33D5-12-58-1	A&E 32350G
Evaluator Operator AN/AWQ-2	33D5-12-58-11	A&E 32350G
MD-9 Fire Control System	1 B52B-2-29 11 F1-A3A-12	A&E 32350G

TABLE II-- Continued

Name	Technical Order Designation	Squadron and AFSC
Bombing/Navigation System ASB-4A	1 B52E-2-26	A&E 32170K
Bombing/Navigation System ASB-4A (Advance Capability Radar)	1 B52E-2-26 11 B31-3-3-2	A&E 32170K
Bombing/ Navigation System MADREC AJM14	1 B52E-2-37	A&E 32150K
AN/APR-9 Radar Set	12P3-2APR9-12	A&E 30133B
AN/APR-14 Radar Set	12P3-2APR-14-2	A&E 30153B
AN/ALT-6B Jamming Transmitter	12P3-2ALT 6-42	A&E 30153B
AN/ALR-18 Receiver, Counter- measures	12P3-2ALR 18-2	A&E 30133B
AN/ALT-13 Transmitter, Counter- measures	12P3-2ALT-13	A&E 30153B
AN/ALT-16 Transmitter, Counter- measures	12P3-2ALT-16	A&E 30153B
AN/APS 54 Range Radar	12P6-2APS-54	A&E 30153B
AN/ALT-15 Transmitter, Counter- measures	12P3-2ALT-15	A&E 30153B
MA-2 (A-14) Auto Pilot	5 A 4-2-3-3	A&E 32570Z
N-1 Compass System	5N-1-2-6-1	A&E 32570Z
A J A-1 True Heading	5-N-1-2-3-2	A&E 32570Z
MD-1 Auto Astro Compass	5-N-3-2-3-22	A&E 32570Z

TABLE II-- Continued

Name	Technical Order Designation	Squadron and AFSC
Radio Set AN/ARN-21C	12 R5-2ARN 21-42	A&E 30171B
Radio Receiving Set AN/ARN-14	12 R5-7ARN-14-12	A&E 30171B
Radio Receiving Set AN/ARN-31	12 R5-2ARN-31-2	A&E 30151B
Radio Receiving Set AN/ARN-32	12 R5-2ARN-32-2	A&E 30151B
Transponder Set (IFF) AN/APX-25	12 P4-2APX-25-2	A&E 30171B
Radio Beacon AN/APN-69	12 P5-2APN-69-2	A&E 30171B

TABLE III

GAM-77 EQUIPMENT ITEMS

Name	Technical Order Designation	Squadron and AFSC
Stable Platform	21-GAM 77-2-7	AMMS 31553Q
Motor Generator Drive	21-GAM 77-2-5	AMMS 44370Z
Transmitter	21-GAM 77A-2-6	AMMS 31573Q
Combined Systems Run	21-GAM 77A-WS-6-1-SP	AMMS 31553Q
GAM 77A Post Flight Inspection	21-GAM 77-WC-6-1-PO	AMMS 44350Z
GAM Periodic Inspection	21-GAM 77-WC-6-1-PE	AMMS 44350Z
Converter-Monitor	21 GAM-77-2-4	AMMS 44350Z
Missile Pylon Simulator	1 B-52C-2-35	AMMS 31553Q
Astrotracker	21 GAM 77-2-7	AMMS 31553Q
Computer	21 GAM 77-2-7	AMMS 31573Q
KE-900 Package Console	33X2-3-4-22	AMMS 31572S
Missile Handling Trailer	MDE 3458	AMMS 44370Z
Under Wing Checkout	1 B-52C-2-35	AMMS 31553Q
Missile Rigging Fixture	MDE 4448-5	AMMS 44370Z

TABLE III-- Continued

Name	Technical Order Designation	Squadron and AFSC
Carriage & Shackle Assembly	44 472-00015	AMMS 31553S
Fixture Assembly - Package	MDE 4447-305	AMMS 31553S
Propulsion Checkout Console	MDE 4441-27	AMMS 44370Z
Auto, Checkout Test Console, Flight Control and OSS # 2	MDE 4440-7	AMMS 31553S
Bomber Checkout Console	MDC 4453-305	AMMS 31553S
C247 Bomber Checkout Console	31X2-3-4-32-1	AMMS 31552S
Digital Amplifier	1 B-52C-2-35	AMMS 31X3-Q
Console, Missile Package	ST. # 4935-768-3262	AMMS 17575173
Auto-navigator Checkout Console	T.O. 21 GAM 77-06-2	AMMS 31551Q
Turner Programmer	11G1-3-6-12	AMMS 31552S
Helmick F/C Console	31X2-3-4-42	AMMS 31552S
Helmick Amplifier	11G1-36-12	AMMS 31552S
Stable Platform	21-GAM-77-06-2 11G2-10-2-2-2	AMMS 31551Q
Flight Control Alignment Console	21-GAM-77-06-2 31X2-3-23-1	AMMS 31551Q
Electronic Computer	11G6-3-4-3	AMMS 31551Q

TABLE III-- Continued

Name	Technical Order Designation	Squadron and AFSC
Air Data & Surface Control Unit	11G7-2-8-3	AMMS 31571Q
Radar Altimeter Alignment Test Set	33D9-42-9-1	AMMS 31551Q
Power Supply Assembly	11G9-2-2-3	AMMS 31551Q
Terrain Computer	11G1-3-11-3	AMMS 31551Q
C2-39A-B Computer	31X2-3-10-1 11G 2-10-2-2-3	AMMS 31571Q
Verdan, Digital Computer	11G 6-2-2-3 T.O. 21 GAM 77-06-2	AMMS 31551Q
Platform Amplifier Assembly	11G 2-10-2-2-2 21 GAM 77-06-2	AMMS 31571Q
Tie in Converter	1 B52 C-2-35	AMMS 31553Q
Sensing Inst. (GAM 72)	11G 1-3-6-12	AMMS 31552S
Air Data Unit	21 GAM 77A-2-6	AMMS 31573Q
Hydraulic Test Stand	35 M-5-3-6-1	AMMS 44370Z

TABLE IV
KC-135 EQUIPMENT ITEMS

Name	Technical Order Designation	Squadron and AFSC
Automatic Direction Finder AN/ARA-25	12R2-2ARA-25-2	A&E 30150
Inter-Phone AN/AIC-10	12R2-AIC-10-2	A&E 30150
AN/ARC-34 Radio Set	12R2-2ARC-34-2	A&E 30170
AN/ARC-58 Radio Set	12R2-2ARC-58-2	A&E 30170
Compass System J-4	5N-1-2-10-2	A&E 32570Z
MC-1 Automatic Pilot System	5N-1-2-22-1	A&E 32570Z
Radio Set AN/ARN-21C	12R5-2ARN-21-42	A&E 30171B
Radio Receiving Set AN/ARN-14	12R5-2ARN-14-12	A&E 30171B
Radio Receiver AN/ARN-31	12R5-2ARN-31-2	A&E 30151B
Radio Receiver Set AN/APN-32	12R5-2ARN-32-2	A&E 30151B
Transponder Set (IFF) AN/APX-25	12P4-2APX-25-2	A&E 30171B
Radar Beacon AN/APN-69	12P5-2APN-69-2	A&E 30171B
Navigation Compass AN/ASN-7	5N-1-3-4-2	A&E 30171B
Radar Set AN/APN-81	12P5-2APN-81-2	A&E 30171B

TABLE IV-- Continued

Name	Technical Order Designation	Squadron and AFSC
Radar Altimeter SCR 718	12P5-3SCR 718-22	A&E 30171B
Radar Set (Doppler) AN/APN-59	12P5-2APN 59-12	A&E 30171B

Systems Criterion Selection

As was explained in Section I, any man-machine systems level prediction requires that the criterion to be predicted vary at the systems level. In addition, such criterion data must be proximal in that they are accessible through normal reporting media. With these requirements defined it was decided to use maintenance data reported through AFM 66-1 (ref 1). These data are reported worldwide. Only the last six-month reporting period was used for data reduction. Partial reduction and analysis was performed by the appropriate Air Material Area (AMA), and reported through the Data Analysis Section of Air Force Logistics Command (AFLC) to the author. Two report products were so received:

a. Off-equipment maintenance (primarily shop maintenance) - Product No. AFLC-D056B-2. This product provides information on the maintenance actions, man-hours, aborts or mission failure for the past six months as each work-unit code (alpha-numeric code identifying equipment to the replaceable module level) included in the master record for a complete end-piece of equipment (aircraft, GAM, GAR, missile, aerospace ground equipment, trainer or simulator, ground communications--electronic equipment, special weapons and special purpose vehicles).

Upon receipt of these data from AFLC further data reduction was performed to determine their general suitability as a criterion. IBM machine sorts were made, summing all maintenance action times across classes of actions (repair, repair and replace, adjust, remove, etc). Since all items of equipment evaluated by the questionnaire were classified at the subassembly level, the IBM sorts of maintenance action times were made on the basis of the first two alphas and the first numeric of the five alpha-numeric code. By dividing the total time by frequency of failure, the IBM sort permitted determination of average shop maintenance task times for the equipment item. Subsequently, only sixteen of the original ninety equipment items could be assigned a quantitative criterion value in terms of mean-maintenance-action times. It was decided not to use these data as a criterion, due to the extremely small sample size.

b. On-equipment maintenance (primarily on aircraft or missile maintenance) - Product No. AFLC-D056B-3. This product provides six months of data by how-malfunctioned and action-taken codes on specific work-unit codes in an endpiece of equipment (aircraft, GAM, GAR, missile, aerospace ground equipment, trainer or simulator, ground communications--electronic equipment, special weapons and special purpose vehicles).

These criterion data were found to be in directly useable form as received from AFLC. To obtain mean on-equipment maintenance action times, times were summed across all how-malfunctioned codes and maintenance-action-taken codes (approximately twenty types of maintenance actions) for each identifiable sub-assembly, and then divided by the frequency of failure of that item. Assuming no biased reporting of these raw data in the field and assuming errorless data reduction, both of which may be somewhat tenuous, criterion measurement should be reliable, since the minimum number of observations per mean was 10 and the maximum in excess of 2000. Unequal observations per mean was a result of the natural sampling process used. The absolute number of observations for each sub-assembly was purely a function of the equipment reliability of that item. Therefore, by using the ratio of total maintenance man-hours to equipment failure frequency, estimates of average maintenance task times were obtained. Using this procedure criterion, data were available on 45 of the original 90 items of equipment. The prediction analysis was made using this criterion only. However, the factor analysis was made on all ninety questionnaires.

Analysis Procedure

To isolate independent predictors of on-equipment mean maintenance task times, a factor analysis method by Wherry-Winer (ref 14) was performed on the 114 questionnaire item responses on 90 separate items of equipment.

The Wherry-Winer method is essentially a multiple group centroid factor analysis, (ref 13), in which guessed subtests of items are treated as clusters of intercorrelations used in the multiple-group method. Three Engineering Psychologists, who were also expert in human engineering design requirements for maintainability, sorted the original 114 questionnaire items into 7 homogeneous groups. Items on which agreement could not be reached were assigned to an eighth category. Table V shows the initial expert sorts. Items are identified by their number in the original questionnaire (Appendix V).

Two assumptions must be met before proceeding with the Wherry-Winer method. First, it is necessary that the subtests be linearly independent. Secondly, if any of the guessed subtests contain ten or fewer items, the correlation between an item and the test of which it is a part would include the contribution of a specific factor, hence would constitute a spurious overestimation of the true correlation. This effect tends to be negligible if there are 10 or more items in each subtest. All subtests contained ten or more items, therefore, no correction was made. The test for linear independence was made by using the Z portion of the Wherry-Doolittle Test Selection Procedure, (ref 4), starting with the subtest having the lowest average intercorrelation with all other subtests and progressively adding subtests whose variances show the least overlap with the selected tests. A suggested point at which to eliminate subtests is when their unpredicted variance becomes less than twenty. In this case, the last subtest was selected with a Z table value of .327, hence all of the original guessed factors were retained (see table VIII).

A Fortran IBM 7094 program, developed by Sandia Corporation was used as a computational aid in performing the factor analysis. General instructions for using this program are included in Appendix II. Two major series of computations are performed by this program. First, from raw scores it computes the subtest intercorrelations (r_{KL}) as well as the item by subtest intercorrelations (r_{iK}). Since the program was developed for factoring forced choice rating scales, the rates (in this case equipment items) must be divided into best and worst categories. This categorization is based on a median split of the gross questionnaire score. Means and standard deviations for guessed subtest scores as well as item discrimination values are also provided. The second major computation is a matrix multiplication of the transformation matrix times the oblique item loadings to provide orthogonal item loadings. The orthogonal loadings obtained were rotated by a Varimax criterion (ref 5).

Finally, relatively independent predictors were recreated by selecting items which load high on only one factor. A new intercorrelation matrix between the newly developed predictor factors, including the criterion variable, was then computed. Multiple regression was performed on this new matrix.

TABLE V
 GUESSED SUBTESTS
 (QUESTIONNAIRE ITEMS)

Maintenance Displays	Accessibility	Safety	Workspace Configuration	Alignment & Keying	Control Design	Fasteners & Tools	Miscellaneous
1		2	3	7	8	10	38
5	21	4	15	22	32	34	40
11	29	9	20	31	33	46	55
12	39	16	27	43	41	54	63
13	49	18	50	53	44	58	67
14	51	19	62	57	45	66	79
17	61	26	76	69	56	70	86
23	72	28	77	75	68	78	91
24	73	30	85	80	71	82	106
25	81	52	88	90	87	89	112
35	84	65	95	110	97	92	
36	93	104	96	111	108	98	
37	99		105	113		100	
42	101			114			
47	107						
48	109						
59							
60							
64							
74							
83							
94							
102							
103							

SECTION III

RESULTS AND DISCUSSION

To estimate rater reliability, 10 pairs of technicians were required to rate 10 different items of equipment. Operational limitations did not permit having more than two raters evaluate the same item of equipment nor were more than ten items of equipment available for paired ratings. The between rater Pearson product moment correlations ranged from $r=.41$ to $r=.97$ with a median $r=.62$.

Figure 1 shows the frequency histogram of the distribution of overall scores on the questionnaires for all 90 items of equipment. The distribution is slightly negatively skewed due to curtailment of the upper end of the distribution. Since no further analysis was made on the overall scores, no attempt was made to normalize them through transformation.

Figure 2 displays the frequency distribution of on-equipment mean maintenance task times, in hours, for 45 items of equipment on which criterion data were available. This distribution appears log normally distributed. This finding is in agreement with other studies by Retterer et al (ref 9) and Schafer, Benson and Clausen (ref 11). It was, therefore, decided to perform a logarithmic (base 10) transformation on all mean maintenance task times for further analysis. Figure 3 contains the distribution of these transformed criterion data. Although somewhat more normal in terms of skewness, these scores now take on a slight bimodality. This bimodality may be either indicative of a truly heterogeneous population distribution of maintenance repair times or due solely to the small sample size ($N=45$). However, in accordance with the convention of previous studies, the log transformed scores were retained as the criterion distribution.

Tables VI through XI show intermediary results of the Wherry-Winer Factor Analysis. Table VI contains the guessed subtest intercorrelations along with their individual score means and standard deviations. The intercorrelation table of items with the subtests of which they were guessed to be a part are included in Appendix III. Discrimination indices of these items are included in Appendix IV.

Table VII and table VIII contain the Doolittle without horizontal extension and the Wherry Z table used in selecting the various subtests. Table VIII shows that subtests were selected in the order 3, 1, 8, 7, 5, 6, 4, and 2 where the numerals represent the initial identification of guessed subtests. This table also shows that approximately 32 % of the variance was remaining with the selection of the last test (guessed subtest #2). Normally, it is recommended that the selection of tests be stopped when the Z value is less than 20 (remaining error variance). However, since this point had not been reached, all of the initial guessed predictor subtests were retained at this phase.

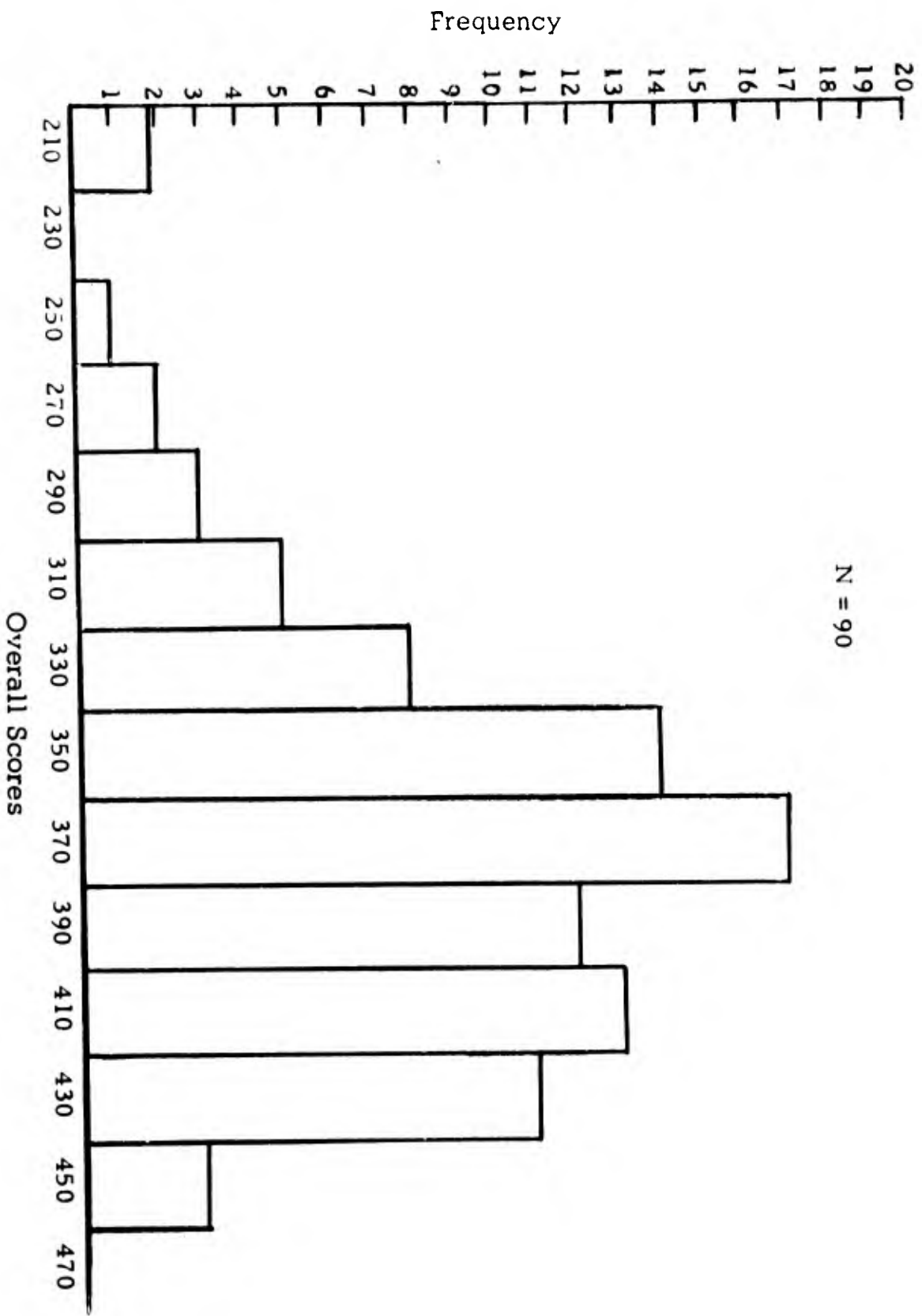


FIGURE 1. DISTRIBUTION OF QUESTIONNAIRE OVERALL SCORES

APPENDIX I

MAINTAINABILITY QUESTIONNAIRE

This questionnaire is a preliminary portion of a research project that ultimately will attempt to predict overall system maintainability from an evaluation of equipment design characteristics.

This is not a test to measure your knowledge of the equipment with which you work. However the assumption is made that, as a result of working with particular equipment and serious thought on your part about various design features, you will be able to answer all of the applicable questions. Answer each question by checking one of the five alternatives as follows:

1. The feature is clearly a design characteristic of the equipment.
2. The feature is reflected in the design of the equipment to a great extent.
3. The feature is not applicable to the equipment.
4. The feature is reflected in the design of the equipment to a small extent.
5. The feature is not possessed by the equipment.

If after serious consideration of a given question you determine it is not applicable to the equipment item on which you are answering the questions you may select the NA (not applicable) alternative No. 3.

For purposes of meaningful evaluation of the questionnaire responses you should select a major equipment item with which you are most familiar and is a functionally identifiable unit, and answer all the questions you can on this item only. Do not change the equipment item you are evaluating, midstream in the questionnaire.

Please provide the following information before answering any of the questions.

1. Rank _____.
2. AFSC _____.
3. Skill Level _____.

4. Number of months to the nearest whole month you have been working with the equipment item on which you are answering the questionnaire. _____

5. Major equipment item on which you are answering this questionnaire. Name _____

T.O. Designation _____

6. Work Unit Code _____

7. Number of technicians performing maintenance action _____

8. Training courses taken relevant to your present work. _____

There is room provided at the end of the questionnaire for any maintainability design characteristics which you believe may reduce maintenance time, facilitate maintenance operations and minimize safety hazards. Any ideas you may have which were not covered in the questionnaire will be greatly appreciated.

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
1. Are access points individually labeled?	_____	_____	_____	_____	_____
2. Do access doors to high voltage areas have provisions for automatically shutting off power (safety interlocks on door etc.)?	_____	_____	_____	_____	_____
3. When maintenance activities demand the collaboration of a team effort, are traffic flow and communication adequate?	_____	_____	_____	_____	_____
4. Are cables routed so they cannot be pinched by doors, lids, etc. and so they will not be stepped on or used as hand holds?	_____	_____	_____	_____	_____
5. Are displays and their associated controls clearly labeled to show their relationship?	_____	_____	_____	_____	_____
6. Is adequate clearance provided between switches and knobs to prevent inadvertent actuation, while allowing sufficient finger room for manipulation?	_____	_____	_____	_____	_____
7. Are guide pins or other means used on units and assemblies for alignment during mounting?	_____	_____	_____	_____	_____
8. Are pointer knobs designed so there is no possibility of mistaking which end of the knob is the pointing end?	_____	_____	_____	_____	_____
9. Are all access covers which are not completely removable, self-supporting in the open position?	_____	_____	_____	_____	_____
10. Are self-locking safety catches provided on connector plugs rather than safety wire?	_____	_____	_____	_____	_____
11. Are display labels imprinted, embossed, or attached in such a way they will not be lost, mutilated, or become otherwise unreadable?	_____	_____	_____	_____	_____

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
12. Do display labels for each termination have the same code symbol as the wire or line attached to it?	_____	_____	_____	_____	_____
13. Does (do) the access(s) have labels which tell what can be reached through this point?	_____	_____	_____	_____	_____
14. Are parts which require access from two or more openings properly marked to indicate this requirement?	_____	_____	_____	_____	_____
15. Generally is the equipment located such that awkward working positions are unnecessary?	_____	_____	_____	_____	_____
16. Are cables or lines attached to units which can be partially removed (chassis on slide racks), so attached so the unit can be replaced conveniently without damaging the cable or interfering with the securing of the unit?	_____	_____	_____	_____	_____
17. Are the functions of each control clearly labeled?	_____	_____	_____	_____	_____
18. Do units in excess of 45 but less than 90 pounds have provision for two man lift where lifting height is not in excess of five feet?	_____	_____	_____	_____	_____
19. Are limit stops provided on roll-out racks and drawers?	_____	_____	_____	_____	_____
20. Are controls and displays used for maintenance or calibration only, and which are not necessary to actual operation, kept distinct from operation controls?	_____	_____	_____	_____	_____
21. Are units placed so they are not in recesses, behind or under stress members, floor boards, seats, hoses, pipes, or other items which are difficult to move?	_____	_____	_____	_____	_____

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
22. Is the design such that it is physically impossible to reverse connections or terminals in same, or adjacent circuits?	_____	_____	_____	_____	_____
23. Do display labels provide full identifying information?	_____	_____	_____	_____	_____
24. Are displays and controls labeled so they correspond to notations found in system diagrams, in T.O.'s etc?	_____	_____	_____	_____	_____
25. Does (do) access(s) have labels indicating what auxiliary equipment is needed for service, checking, etc., at this point?	_____	_____	_____	_____	_____
26. Are there any equipment units presumably designed for one-man manipulation which are too large or too heavy to be conveniently lifted, carried, pulled, pushed or turned manually?	_____	_____	_____	_____	_____
27. Are components arranged such in a given compartment so that one type of specialist must wait for another type of specialist to remove his part before the first technician can get to his part?	_____	_____	_____	_____	_____
28. Are there any lines routed such that the failure to securely clamp them in place would allow the lines to droop and be struck by or interfere with other moving parts?	_____	_____	_____	_____	_____
29. Are all the throwaway assemblies or parts so located to be accessible without removal of other components?	_____	_____	_____	_____	_____
30. Do units over 90 pounds have provisions for mechanical or power lift?	_____	_____	_____	_____	_____

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
31. Are all interchangeable units physically coded (keyed) so that it is impossible to insert a wrong unit?	—	—	—	—	—
32. Do the controls which are multi-position selectors have detent positions to prevent leaving the switch between detent positions?	—	—	—	—	—
33. Are controls which are meant to have continuous movement (not detented) actually have a small amount of smooth, even resistance?	—	—	—	—	—
34. Are fasteners standardized to minimize the number of tools required?	—	—	—	—	—
35. Do display and control labels clearly indicate their functional relationship? Displays should be labeled by functional quantity rather than operational characteristics (i.e., gal., psi, ohms etc.)	—	—	—	—	—
36. Are color codes or other symbolic coding schemes used for identifying test points or tracing wire or lines easily identifiable under all illumination conditions?	—	—	—	—	—
37. Does (do) the access(s) have labels which specify the frequency for maintenance either by calendar or operating time?	—	—	—	—	—
38. In your judgment was the equipment designed to consider all environmental conditions (cold weather, darkness, etc.) under which it was to be maintained?	—	—	—	—	—

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
39. Do miniaturized components as compared with nonminiaturized components tend to be mounted too close together for easy removal and replacement?	—	—	—	—	—
40. Are cables or lines which must be routed through walls or bulkheads so designed for easy installation and removal without necessity for cutting or splicing of lines?	—	—	—	—	—
41. Are controls so marked to indicate which direction to operate the control?	—	—	—	—	—
42. Are all units weighing 45 pounds or more prominently labeled with their weight?	—	—	—	—	—
43. Are units coded (labels, colors, etc.) to indicate the correct unit and its orientation for replacement?	—	—	—	—	—
44. Generally do controls appear on panels in the sequential order in which they are to be used?	—	—	—	—	—
45. Do controls which can be inadvertently displaced come to rest at the null point in case of power failure?	—	—	—	—	—
46. For tool operated screws, are they of the type which can be operated by several tools (screwdriver, wrench, or pliers)?	—	—	—	—	—
47. Is printed matter displayed upright from your normal viewing position?	—	—	—	—	—
48. Are all potted parts labeled with current, voltage, impedance, terminal information etc?	—	—	—	—	—

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
49. Do access openings used for frequent visual inspection have transparent or "quick opening" type covers?	_____	_____	_____	_____	_____
50. Can displays (dials, gages, GO-NO-GO indications etc.) be easily observed and/or read from a convenient working position?	_____	_____	_____	_____	_____
51. If components require "stacked" mounting to conserve space are the components with the highest failure rate located on top?	_____	_____	_____	_____	_____
52. Are there any cables attached to the front of cabinets where they could be "bumped" by passing equipment or personnel?	_____	_____	_____	_____	_____
53. Where screwdriver adjustments must be made blind, are either mechanical guides provided or the screws mounted so that the screwdriver will not fall out of line?	_____	_____	_____	_____	_____
54. Are there a greater number of fasteners (screws, bolts, clamps, etc.) on access panels than required to maintain structural integrity of the unit?	_____	_____	_____	_____	_____
55. Are units designed to be removed and replaced provided with handles or other suitable provisions for grasping, handling and carrying?	_____	_____	_____	_____	_____
56. When more than one control is used for adjusting a single (or interacting) function are the controls placed on the same panel?	_____	_____	_____	_____	_____
57. Are keyways for tubes and tube sockets suitably marked so you do not have to rely on "feel" to find the proper position?	_____	_____	_____	_____	_____

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	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
58. Are access cover fasteners of the captive type?	_____	_____	_____	_____	_____
59. Do display labels appear on every item which you must recognize, read or manipulate?	_____	_____	_____	_____	_____
60. Do access covers have permanent part numbers marked on the cover?	_____	_____	_____	_____	_____
61. Are access covers designed so it is obvious how they are to be opened or closed?	_____	_____	_____	_____	_____
62. Can controls (switches, knobs, etc.) be easily reached for operation from a convenient working position?	_____	_____	_____	_____	_____
63. Are all cables, liquid or pressure lines color coded and both ends tagged?	_____	_____	_____	_____	_____
64. Do labels identifying control handles appear on the handle as well as the panel since the panel may be removed during maintenance?	_____	_____	_____	_____	_____
65. Are internally mounted controls located away from dangerous voltages?	_____	_____	_____	_____	_____
66. Are combination-head mounting bolts with a deep internal slot (either single blade or phillips) arrangement and hex head used?	_____	_____	_____	_____	_____
67. Are handles and grasp areas so located that at least two inches of clearance from obstructions is provided for handling?	_____	_____	_____	_____	_____
68. Do controls which are intended to have a limited degree of motion have adequate mechanical stops to prevent damage?	_____	_____	_____	_____	_____

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
69. Are assembly parts designed with orienting seats, pins, etc., to save time getting parts in proper position for fastening?	_____	_____	_____	_____	_____
70. Are quick disconnect devices (fractional-turn, quick-snap action, press-fit, etc.) used wherever possible?	_____	_____	_____	_____	_____
71. For fixed procedure operation is the sequence of use of controls indicated by number?	_____	_____	_____	_____	_____
72. Are all lubrication points accessible?	_____	_____	_____	_____	_____
73. Are access openings designed so the technician can see what he is doing (clearance for hand only, obscures the thing the technician is working on)?	_____	_____	_____	_____	_____
74. Are maintenance displays located on the side normal for maintenance tasks of inspection, check-out, troubleshooting, removal and replacement?	_____	_____	_____	_____	_____
75. In order to prevent mismatching or interchanging connections is there some means of physical design to prevent this? (unique fastener or socket, routing of cables or lines so lengths vary, spreader blocks, etc.)	_____	_____	_____	_____	_____
76. Is there sufficient space to use test equipment and other tools required during checkout?	_____	_____	_____	_____	_____
77. Are externally mounted controls which must be operated without visual reference located in front rather than to the side or behind the operator?	_____	_____	_____	_____	_____
78. Are mounting bolts semi-permanently captive (preferably with snap on collars)?	_____	_____	_____	_____	_____

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
79. For removal units which have irregular, fragile, or awkward extensions, such as cables, wave guides, hoses, etc; are these extensions easily removable before the unit is handled?	---	---	---	---	---
80. Do covers or shields through which mounting screws must pass for attachment to the basic chassis of unit have large enough holes for passage of the screw or bolt without perfect alignment?	---	---	---	---	---
81. Are high failure rate components easily accessible for replacement?	---	---	---	---	---
82. Are finger operated fasteners used wherever feasible?	---	---	---	---	---
83. Are appropriate labels used for each test point?	---	---	---	---	---
84. Do access covers which remain attached to the basic equipment assigned such so they do not have to be held open or "dangle" in the way?	---	---	---	---	---
85. Are displays located so they can be observed without removal of other equipment or disassembly of any portion of the installation?	---	---	---	---	---
86. Are cables routed so they need not be bent or unbent sharply when being connected or disconnected?	---	---	---	---	---
87. Are sensitive adjustments located or guarded such to prevent inadvertently "bumping" them out of adjustment?	---	---	---	---	---

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
88. Are all controls located where they can be seen and operated from the normal working position - without disassembly or removal of any part of the installation?	_____	_____	_____	_____	_____
89. Are identical screw and bolt heads used to enable various panels and components to be removed and installed with one type of tool?	_____	_____	_____	_____	_____
90. Is the proper orientation of units within their respective case made obvious, either through design of the cases or by means of appropriate labels?	_____	_____	_____	_____	_____
91. Are handles and grasp areas located so that at least two inches of clearance from obstructions is provided for handling?	_____	_____	_____	_____	_____
92. Are U-lugs rather than O-lugs used for clamping purposes?	_____	_____	_____	_____	_____
93. Is there sufficient space between connectors so they can be grasped firmly for connecting and disconnecting?	_____	_____	_____	_____	_____
94. Are there display labels on component covers which provide relevant information concerning electrical, pneumatic or hydraulic characteristics of the part?	_____	_____	_____	_____	_____
95. Are access openings generally located at convenient working positions?	_____	_____	_____	_____	_____
96. When group activity demands the use of a central visual display are the lines of sight to the display blocked by poor arrangement of people or equipments?	_____	_____	_____	_____	_____

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
97. Are control knobs which only require resetting occasionally or in special cases, provided with a cover, seal or otherwise guarded against inadvertent actuation?	_____	_____	_____	_____	_____
98. Are field units and assemblies replaceable with nothing more than common hand tools?	_____	_____	_____	_____	_____
99. Are cases designed as lift off units rather than having the units lifted out of the cases?	_____	_____	_____	_____	_____
100. Do hinged doors or covers have captive quick-opening fasteners wherever possible?	_____	_____	_____	_____	_____
101. Are adjacent soldered connections located far enough apart so work on one connection does not compromise the integrity of adjacent connections?	_____	_____	_____	_____	_____
102. Are electrical terminals clearly marked + or - ?	_____	_____	_____	_____	_____
103. When selector switches have to be used with a cover panel off, are these duplicate switch position labels on the internal unit so you don't have to refer to the label on the case or cover panel?	_____	_____	_____	_____	_____
104. Are access openings free of sharp edges or projections which constitute a safety hazard?	_____	_____	_____	_____	_____
105. Are components located such that physical interference among technicians working on the same or adjacent areas is minimized?	_____	_____	_____	_____	_____
106. Are functionally similar units interchangeable between systems or subsystems?	_____	_____	_____	_____	_____

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
107. Are units which are frequently pulled out of their installed position for checking mounted on roll-out racks, slides or hinges?	-----	-----	-----	-----	-----
108. Are cranks designed and positioned with respect to the speed or load which they administer; that is, small cranks at elbow height for fast wrist action. light loads; large cranks oriented for full arm motion?	-----	-----	-----	-----	-----
109. Are bulkheads, brackets, other units etc., designed not to interfere with the removal or opening of covers of units within which work must be done?	-----	-----	-----	-----	-----
110. Are connector plugs designed so that pins cannot be damaged (aligning pins extend beyond electrical pins)?	-----	-----	-----	-----	-----
111. Are plugs, connectors and receptacles clearly marked to show proper position of keys for aligning pins for proper insertion position?	-----	-----	-----	-----	-----
112. Are exterior access doors on flight line equipment so large or heavy that they require more than one man to open and remove them?	-----	-----	-----	-----	-----
113. Are control linkage attachments designed such that reversed assembly is not physically possible?	-----	-----	-----	-----	-----
114. Are components or access covers designed so they can be easily oriented for fastening by providing alignment pins or grooves?	-----	-----	-----	-----	-----

APPENDIX II

INSTRUCTIONS FOR USE FOR WHERRY-WINER PROGRAM

1. This program was designed especially for use in constructing force-choice rating scales.
2. Check-List scales are administered to group, asking each respondent to rate Best and Worst man on a five point scale.
3. You must have an equal number of Best and Worst. Also all statements must be rated (we usually punch 3 for blanks).
4. Number the Worst from 0001 - 4999. Number the Best from 5001 -
5. In keypunching the data:

1-4	Man Number
5-6	Card Number (01, 02, etc.)
7-10	Blank
11-80	Data
6. Make table cards. The Wherry-Winer calls for the "arm-chairing" of factors. Set up table cards by placing "TABLE" in Cols. 1-5. In Cols. 6-8, the item number immediately following. Then from 9-30 use 2 column fields to designate categories. That is, the first statement is in category #1, the second statement in #2, the third in #3, etc. If you exhaust a category, just skip that category number.

Example: TABLE 001010203040501020305

In the above example, we have 5 categories. 001 tells us the statement number immediately following; then 01 says that the first statement is in the first category, etc. Notice that in the second series we have 03, 03; that is, we have exhausted category #4, continue along omitting that category.

You can place 36 statements by category to a card. Your second card would read: TABLE 037-----,
Your third: TABLE 073-----,
Your fourth: TABLE 109-----,

7. The first output results in Means, Standard Deviations, DI's computed via Snason's recommendations. Category inter r's, and statement to category r's.
8. Factor analyze the category to category matrix.

9. Solve Doolittle front and back solutions. (We do this by hand because you must exercise judgment whether or not to throw out a factor.)
10. Place beta weights in Factor Load cards.
11. We can only handle 7 sets of weights at a time. The first card in Columns 1-2, place the number of sets of Beta's you have-06,03,07; if over 7, say 10, then split them up. The first set would be 07, then the seven sets of Betas, then 03, and the last three sets of Betas.
12. Use the following format for punching in Betas: Use ten column fields - 10, 20, 30 - through Column 70.
13. Anywhere in the ten column field punch the beta weight, including sign and decimal. (You need not punch the plus sign.)

If you drop out a factor you must punch .00 in the appropriate 10 Column Field. If you have over 7 armchair factors, continue on to second card. When you have completed all armchair factors, begin new card for the next set of weights.

<u>Loading</u>		<u>Item No.</u>
.38	Do hinged doors or covers have captive quick-opening fasteners wherever possible?	100
.37	Are there a greater number of fasteners (screws, bolts, clamps, etc) on access panels than required to maintain structural integrity of the unit?	54
.34	Are field units and assemblies replaceable with nothing more than common handtools?	98
.29	Are functionally similar units interchangeable between systems or subsystems?	106
.26	Are combination-head mounting bolts with a deep internal slot (either single blade or phillips) arrangement and hex head used?	66
.25	Are all cables, liquid or pressure lines, color coded and both ends tagged?	63

Factor V was identified as Alignment and Keying Factor. Only one item (101) was gained by this factor. Two items (53 and 80) were now loaded on Factor I and VII respectively. Based on previous experience, the design features included in this factor are deemed most readily amenable to human engineering application since they rarely impose a significant cost trade-off against other design considerations. This is not so with most of the design features comprising the other factors. The following items now make up Factor V:

<u>Loading</u>		<u>Item No.</u>
.60	Are assembly parts designed with orienting seats, pins, etc, to save time getting parts in proper position for fastening?	69
.52	Is the proper orientation of units within their respective case made obvious, either through design of the cases or by means of appropriate labels?	90
.51	Are components or access covers designed so they can be easily oriented for fastening by providing alignment pins or grooves?	114

<u>Loading</u>		<u>Item No.</u>
.50	Are all interchangeable units physically coded (keyed) so that it is impossible to insert a wrong unit?	31
.46	Are units coded (labels, colors, etc) to indicate the correct unit and its orientation for replacement?	43
.46	Are guide pins or other means used on units and assemblies for alignment during mounting?	7
.44	Is there some means of physical design to prevent mismating or interchanging connections. (unique fastener or socket, routing of cables or lines so lengths vary, spreader blocks etc)	75
.44	Are connector plugs designed so that pins cannot be damaged (aligning pins extend beyond electrical pins)?	110
.43	Is the design such that it is physically impossible to reverse connections or terminals in same, or adjacent circuits?	22
.40	Are plugs, connectors and receptacles clearly marked to show proper position of keys for aligning pins for proper insertion position?	111
.37	Are keyways for tubes and tube sockets suitably marked so you do not have to rely on "feel" to find the proper position?	57
.36	Are adjacent soldered connections located far enough apart so work on one connection does not compromise the integrity of adjacent connections?	101
.34	Are control linkage attachments designed so that reversed assembly is not physically possible?	113

Factor VI was initially thought to be a control design factor, guessed subtest number 6, however, eight new items now load highly on this factor. The contribution of these new items allows the emergence of a factor now defined as Manual Control Layout. This factor, with the new items, appears to be one of the more potent factors in terms of the total number of items (20) loading highly on it. The following items now comprise this factor.

<u>Loading</u>		<u>Item No.</u>
.73	Do controls that are intended to have a limited degree of motion have adequate mechanical stops to prevent damage?	68
.65	Are control knobs that only require resetting occasionally or in special cases, provided with a cover, seal or otherwise guarded against inadvertent actuation?	97
.62	Are pointer knobs designed so there is no possibility of mistaking which end of the knob is the pointing end?	8
.58	Are cranks designed and positioned with respect to the speed or load which they administer; that is, small cranks at elbow height for fast wrist action, light loads; large cranks oriented for full arm motion?	108
.57	Do the controls that are multi-position selectors have detent positions to prevent leaving the switch between detent positions?	32
.56	Do controls that are meant to have continuous movement (not detended) actually possess small amount of smooth, even resistance?	33
.52	Are all lubrication points accessible?	72
.47	Are all controls located where they can be seen and operated from the normal working position--without disassembly or removal of any part of the installation?	88

<u>Loading</u>		<u>Item No.</u>
.47	Generally, do controls appear on panels in the sequential order in which they are to be used?	44
.47	Are controls so marked to indicate which direction to operate the control.	41
.37	When more than one control is used for adjusting a single (or interacting) function, are the controls placed on the same panel?	56
.37	Do units over 90 pounds have provisions for mechanical or power lift?	30
.36	Are externally mounted controls that must be operated without visual reference located in front rather than to the side or behind the operator?	77
.35	Are internally mounted controls located away from dangerous voltages?	65
.33	For fixed procedure operation is the sequence of use of controls indicated by number?	45
.32	Are exterior access doors on flight line equipment so large or heavy that they require more than one man to open and remove them?	112
.31	Are all units weighing 45 pounds or more prominently labeled with their weight?	42
.30	Are sensitive adjustments located or guarded such to prevent inadvertently "bumping" them out of adjustment?	87
.24	Are access openings generally located at convenient working positions?	95

This factor lost no items as a function of analysis or rotation.

Factor VII, originally guessed subtest No. 4, was defined as Workspace Configuration. Items 37, 47, and 93 are new to this factor and appear to contribute to its interpretability. Items 27, 77, 88, and 95, which were originally assigned to the subtest, now load on other factors. The following items now constitute Factor VII:

<u>Loading</u>		<u>Item No.</u>
.60	Generally is the equipment located such that awkward working positions are unnecessary?	15
.45	Is there sufficient space to use test equipment and other tools required during checkout?	76
.43	Can controls (switches, knobs, etc) be easily reached for operation from a convenient working position?	62
.39	Are components located such that physical interference among technicians working on the same or adjacent areas is minimized?	105
.38	Is there sufficient space between connectors so they can be grasped firmly for connecting and disconnecting?	93
.36	Does (do) the access(s) have labels which specify the frequency for maintenance either by calendar or operating time?	37
.36	Are displays located so they can be observed without removal of other equipment or disassembly of any portion of the installation?	85
.30	When maintenance activities demand the collaboration of a team effort, are traffic flow and communication adequate?	3
.29	When group activity demands the use of a central visual display are the lines of sight to the display blocked by poor arrangement of people or equipments?	96

<u>Loading</u>		<u>Item No.</u>
.28	Can displays (dials, gages, GO-NO-GO indications, etc) be easily observed and/or read from a convenient working position?	50
.25	Is printed matter displayed upright from your normal viewing position?	47
.23	Are cables or lines which must be routed through walls or bulkheads so designed for easy installation and removal without necessity for cutting or splicing of lines?	40

Factor VIII, defined as Accessibility, was originally guessed subtest No. 2 and contains the following items:

<u>Loading</u>		<u>Item No.</u>
.59	Are access openings designed so the technician can see what he is doing (clearance for hand only, obscures the thing the technician is working on)?	73
.49	Do access openings used for frequent visual inspection have transparent or "quick opening" type covers?	49
.48	Are units placed so they are not in recesses, behind or under stress members, floor boards, seats, hoses, pipes, or other items which are difficult to move?	21
.47	Are high failure rate components easily accessible for replacement?	81
.44	Are bulkheads, brackets, other units etc, designed not to interfere with the removal or opening of covers of units within which work must be done?	104
.40	Are access covers designed so it is obvious how they are to be opened or closed?	61

<u>Loading</u>		<u>Item No.</u>
.40	Do access covers that remain attached to the basic equipment assigned such so they do not have to be held open or "dangle" in the way?	84
.39	Are quick disconnect devices (Fractional-turn, quick-snap action, press-fit, etc) used wherever possible?	70
.38	Are all the throwaway assemblies or parts so located to be accessible without removal of other components?	29
.35	Are maintenance displays located on the side normal for maintenance tasks of inspection, checkout, troubleshooting, removal and replacement?	74
.34	When selector switches have to be used with a cover panel off, are there duplicate switch-position labels on the internal unit so you don't have to refer to the label on the case or cover panel?	103
.32	Are units that are frequently pulled out of their installed position for checking mounted on roll-out racks, slides or hinges?	107
.32	Is adequate clearance provided between switches and knobs to prevent inadvertent actuation, while allowing sufficient finger room for manipulation?	6
.32	Are self-locking safety catches provided on connector plugs rather than safety wire?	10
.31	Are cases designed as lift-off units rather than having the units lifted out of the cases?	99
.30	Do covers or shields through which mounting screws must pass for attachment to the basic chassis of unit have large enough holes for passage of the screw or bolt without perfect alignment?	80

<u>Loading</u>		<u>Item No.</u>
.30	Do miniaturized components as compared with nonminiaturized components tend to be mounted too close together for easy removal and replacement?	39
.29	Are limit stops provided on rollout racks and drawers?	19
.26	If components require "stacked" mounting to conserve space, are the components with the highest failure rate located on top?	51

Items 72, 93, 101, 107, and 109 no longer load on this factor. Accessibility has traditionally been thought to be one of the major contributors to maintenance action times. In the present study, however, this was not the case, as will be explained in the ensuing discussion of the regression analysis results.

Seven new Factor-Tests were rescored for use as predictors in multiple regression analyses. Intercorrelations between the newly constructed Factor-Predictors and with the mean maintenance action scores were computed. For prediction purposes, Factor III, Handling for Removal and Replacement, was eliminated since only six items now loaded on this factor. Instead, all six items were assigned to factors on which they loaded next highest. Table XIII contains the items selected for each of the seven Factor-Predictors.

Factor V, Manual Control Layout, correlated highest with the criterion $r = -.464^2$ compared to all other factors. Factor II, Maintenance Information and Factor IV, Alignment and Keying had the next greatest relationship to the criterion variable, $r = -.357$ and $r = -.356$ respectively. Factor III, Fasteners and Tools correlated $r = -.310$ with the criterion while all other factors related less than $r = .20$.

Since one of the objectives of the factor analytic portion of this study was to isolate those human engineering design dimensions which are most highly related to systems maintainability criteria, most consideration for future design criteria research should be devoted to manual control layout, alignment and keying, and maintenance information display systems. This conclusion is somewhat novel, in that workspace layout and accessibility have traditionally been thought to be

2. A negative relationship is in the proper direction since the better the human engineering design, the more one expects maintenance task times to decrease.

TABLE XIII
PREDICTOR FACTOR* ITEMS

	I	II	IV	V	VI	VII	VIII
Maintenance							
Safety							
	2	1	34	7	8	3	6
	4	5	38	22	30	15	10
	9	11	46	31	32	37	19
	16	12	54	43	33	40	21
	18	13	58	57	41	47	29
	20	14	63	69	42	50	39
	26	17	66	75	44	62	49
	27	23	78	90	45	76	51
	28	24	82	101	55	85	61
	52	25	89	110	56	86	70
	53	35	98	111	65	93	73
	64	36	100	113	67	96	74
	104	48	106	114	68	105	79
		59			71		80
		60			72		81
		83			77		84
		92			87		99
		94			88		103
		102			91		107
					95		109
					97		
					108		
					112		

*Factor III deleted.

the major areas where maintenance burden was most severe. The relatively high relationship of Factor III, Fasteners and Tools, to maintenance task times is partially in accordance with the findings of Schafer, Benson and Clausen (ref 11), where a simple fastener count proved to be one of the best predictors of maintenance time.

A multiple correlation coefficient $R = .523$ was obtained between the six predictor-factors and mean maintenance action times in log hours. This multiple R had a standard error of estimate of $.133$. Analysis of variance for multiple linear regression, which tests the ratio of the variance due to regression to the variance due to deviation about the regression line, was significant at $.10 > P > .05$. The measured vs. the predicted mean maintenance action times in log hours for each of the 45 items of equipment are shown in table XVI in Appendix V.

After the initial regression and validity analyses, two additional series of analyses were run.

First, previous research in maintainability prediction was criticized in section I on the basis of homogeneous sampling of equipments. Since this study had sampled across classes of equipment, it was possible to classify the 45 items of equipment into electronic and nonelectronic items with N s of 25 and 20 respectively. Factor Validities and Multiple R s are presented in the second two columns of table XIV. The first column contains the results of the initial analyses. There is a pronounced shift in factor validities between electronic and nonelectronic equipment. Whereas Factor VI, Manual Control Layout, has the highest validity for all equipment and electronic equipment, Factor V, Alignment and Keying, has the highest validity for nonelectronic equipment. With the exception of Factor VIII, Accessibility, and Factor IV, Fasteners and Tools, to a slight extent, all other validities increase for nonelectronic equipment. The multiple R also increases slightly over electronic equipment. It should be cautioned, however, that halving the sample size reduces the stability of both the Validity r s and Multiple R s reported. The rather large increases in Multiple R s for the smaller samples may be inflated by correlation with chance errors when N is reduced.

Secondly, originally response alternative No. 3 on the questionnaire was thought to be an indifference point on a scale from 1 to 5. However, the use of this alternative for nonapplicable responses could produce different validity patterns or different overall predictive efficiency, depending on whether or not these responses were included in the factor scores. To test this possibility, a series of analyses was made using the mean scores on all factors without response alternative No. 3. On the average, approximately three questionnaire items per factor were so eliminated. The results of these analyses are presented in the right-hand side of table XIV. No change in the Multiple R for all equipment was obtained, differing only by $.005$. This indicated that response alternative No. 3 truly represents an indifference point when prediction for all equipment is concerned. The validity

TABLE XIV

PREDICTOR FACTOR VALIDITIES

Factors	All Response Alternatives			Mean Responses Without Response Alternative #3		
	All Equipment N = 45	Electronic N = 25	Nonelectronic N = 20	All Equipment N = 45	Electronic N = 25	Nonelectronic N = 20
I Maintenance Safety	-.185	-.249	-.408	-.178	-.109	-.315
II Maintenance Information	-.357*	-.298	-.401	-.268	-.251	-.273
IV Fasteners and Tools	-.310*	-.353	-.324	-.234	-.348	-.114
V Alignment and Keying	-.356*	-.134	-.536**	-.288*	-.142	-.381
VI Manual Control Layout	-.464**	-.455*	-.481*	-.495**	-.519**	-.471*
VII Workspace Configuration	-.190	-.080	-.289	-.214	-.115	-.283
VIII Accessibility	-.190	-.186	-.061	-.181	-.208	-.038
R	.523*	.609*	.682*	.518*	.668*	.683*
R ²	.274	.371	.465	.269	.446	.467

Significance Values based on Wallace and Snedecor Tables (1931).

* = .05

** = .01

pattern remained approximately the same, with only Factor II and III reversing ordinal position. In comparing electronic vs nonelectronic equipment, the validity patterns shift slightly from those based on all response alternatives. In terms of prediction based on all equipment, very little effect is produced by eliminating response alternative number 3 from the analysis. A greater apparent effect is produced on the validities between equipment types, but this again could be due to unstable correlations when small samples are used.

At first, the coefficients of determination obtained in this study appear to be comparatively small explanations of criterion variance (27% - 47%), however, other interpretations appear warranted.

Customarily one assigns all unexplained variance to errors of measurement either in the predictors or the criterion variable. In this study, however, it was anticipated that there would be other systematic contributors to systems criterion variance beyond human engineering design (man-machine interaction variance). If the conceptual formulation outlined in section I truly represents reality, then man-variance (inter and intra human variations) and machine-variance (weight, volume, reliability, etc) also should account for systematic criterion variance. No attempt was made in this study to measure these other contributors. However, in the restricted case of maintainability prediction machine-variance should be minimal since the construction of the criterion variable (ie, mean maintenance action times were averaged across all how-malfunction codes).

Secondly, assuming machine-variance is minimal and both man-variance and man-machine variance are approximately equal contributors to systems maintainability criterion variance, coefficients of determination between .269 and .467 are not explaining all systematic man-machine variance possible and the remaining variance is due to error of measurement.

On the predictor side of the equation, error of measurement probably occurs because of the lack of high rater reliability. On the criterion side, error of measurement stems from lack of precision in reporting AFM 66-1 maintenance data. For example, the difference between predictive efficiency of this study compared to the Retterer et al (ref 9) study is at least partially due to the fact that in the latter effort, criterion data were obtained by actual stop watch timing of the maintenance tasks. Since economic limitations require that the Air Force use maintenance data reported from operational bases, the current AFM 66-1 reporting system should be modified so that more precise measurement of maintenance action times can be achieved. One major stride towards greater accuracy would be to report delay times (supply, transportation, queing, etc) encountered in maintenance activities. Presently, there are no provisions for reporting these times. Also, there are no provisions for reporting troubleshooting and fault isolation times. If these times could be partialled out as a criterion variable from overall maintenance action times, the maintenance information predictor-factor should relate higher with purer measures than found with the overall times used in this study.

Human errors in equipment operation and maintenance appear to be highly related to maintenance action times, since the more errors in performing a task the longer the task will take. Shapero et al, (ref 12) found that 20 per cent to 50 per cent of all missile equipment malfunction is attributable to human-initiated equipment failures due to poor human engineering design. The findings of this study indicating human engineering design dimensions account for approximately 27 to 47 per cent of systems criterion variation appears more than coincidental.

From the previous findings and discussions, several areas of follow-up research are indicated:

1. A limited scale validation program should be undertaken in which design engineers rate specific subassemblies of equipment using the predictor-factor questionnaire items. Higher rater reliability should result than obtained from operational technicians, since engineers generally have a more thorough acquaintance with the design details of the equipment.
2. Inter-intra personnel factor-predictors should be developed, so that they could be treated additively along with the human engineering factor-predictors in explaining more systematic variance of the conceptual formulation outlined in section I. The findings of such an effort would then allow ;more intelligent programming of personnel and human engineering research support to weapon system development programs.
3. Finally, an extensive research program should be undertaken to develop and measure criterion data currently being reported from operational commands. Not only should these data be reported as the basis for management and development engineering decisions but attention should also be given to psychological scaling of reporting media by the technician in terms of discriminability of action-taken and how-malfunction codes.

SECTION IV

CONCLUSIONS

A theoretical formulation was outlined which treats systems measurement and prediction as a components of variance model. The sources of variation are identified as: inter- and intra-man variation (personnel and social variables); machine variation (weight, volume, reliability, etc) and man-machine interaction variation (human engineering design criteria). A restricted case of the formulation was empirically investigated in an attempt to predict maintainability of sampled Air Force equipment from a questionnaire evaluation of human engineering design features.

A questionnaire was developed containing 114 items of "desirable" maintainability human engineering design features. Ninety maintenance technicians completed the questionnaire on 90 subassemblies in three major weapon systems (B-52, GAM-77, and KC-135). Questionnaire responses were factor analysed by the Wherry-Winer Method, yielding eight orthogonal maintainability design factors. On the basis of factor loadings, seven of the original eight factors were selected as the most potent prediction factors.

Criterion data were developed from the AFM 66-1 maintenance data reporting system. To obtain mean maintenance action times, 6 months of maintenance data were averaged across all how-malfunction codes and maintenance-action-taken codes. The resulting distribution of mean times on 45 subassemblies of equipment appeared log normally distributed and, consequently, were transformed to log hours (base 10) to permit further analysis.

Several series of regression analyses were performed using different sets of assumptions of heterogeneity of sampled equipment and questionnaire scale stability. Coefficients of determination ranged from .27 to .47 depending on which assumptions are made. Generally, when equipment was classified to make more homogeneous sets, predictive efficiency increased and factor validity patterns changed. When response alternative No. 3 was eliminated from the questionnaire scale, little effect was produced on predictive efficiency or factor validity patterns.

The coefficients of determination found were interpreted as being a partial explanation of maintainability criterion variance by human engineering design factors. Other possible interpretations were offered which appear compatible with the general theoretical formulations.

The following recommendations for future research were suggested on the basis of the findings of this study:

1. A validation program should be undertaken in which design engineers evaluate equipment on the basis of human engineering design factors.
2. Research should be designed in an attempt to incorporate personnel predictors along with human engineering predictors.
3. Efforts should be made to modify the current maintenance data reporting system to enable more precise and reliable criterion data collection.

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TABLE XV -- Continued

R (3-1), R (3-2) etc.	R (4-1), R (4-2) etc.	R (4-1), R (4-2) etc.	R (4-1), R (4-2) etc.	R (4-1), R (4-2) etc.	R (4-1), R (4-2) etc.	R (4-1), R (4-2) etc.	R (4-1), R (4-2) etc.	R (4-1), R (4-2) etc.	R (4-1), R (4-2) etc.	
1	.4052	.3017	.2322	.3692	.3953	.1268	.0385	.1629	.5166	.3243
11	.2515	.2377	.1001	.1362	.2250	.3791	.4242	.5205	.4739	.4534
21	.2160	.1313	.2317	.0644	-.1619	.3193	.4633	.4398	.3336	.1720
31	.1598	.3867	.3748	.2349	.2326	.0754	.0230	.1999	.0274	-.0358
41	.3707	.1394	.3699	.2329	.1029	.2090	.1603	.2581	.1488	.2778
51	.3365	.5033	.2369	.1234	.2236	.4680	.3824	.3834	.3453	-.0491
61	.1985	.1702	.0937	.3675	.4020	.1245	.3265	.3151	.2409	.3119
71	.2386	.1091	.2282	.2965	.2483	.3231	.3941	.3243	.3898	.1846
81	.1129	.1755	.1378	.2965	-.0032	.3989	.3241	.1615	.0591	.1806
91	.3612	.2103	.2359	.0642	.1828	.0813	.1911	.3120	.0939	.2012
101	.1997	.2330	.1989	.3593	.4246	.1908	.2673	.4744	.1631	.2982
111	.0559	.2456	.3210	.1558						
1	.3457	-.0014	.3027	.2307	.4371	.2803	.1285	.3999	.4463	.2902
11	.4493	.2285	-.0110	.0347	.4781	.1807	.5895	.2683	.5521	.4695
21	.3989	.1209	.3604	.2661	-.1765	.0166	.2936	.2480	.3733	.2157
31	.0836	.3641	.4423	.2440	.3213	.0940	.3230	.1638	.1887	.1509
41	.3308	.1605	.1913	.2420	.1379	.1387	.3435	.2465	.2581	.5026
51	.3601	.1577	.0692	.2325	.2205	.3138	.2695	.4400	.4853	.1100
61	.2190	.5625	.1415	.2637	.2317	.2093	.4172	.4622	.4153	.3561
71	.3520	.3850	.2779	.3972	.2058	.6005	.5409	.3149	.3768	.3548
81	.2988	.4049	.3425	.4325	.4267	.4619	.3958	.4830	.2885	.2911
91	.3806	.2817	.4142	.2116	.3907	.3720	.3263	.2847	.1477	.2793
101	.3809	.2622	.3478	.2789	.4758	.2088	.2892	.4551	.3518	.4480
111	.3557	.2407	.3896	.4333						

TABLE XV-- Continued

	R (5=1)	R (5=2)	etc.																	
1	.3755	.0041	.0630	.2950	.3529	.1288	.4059	.1802	.2566	.3061										
11	.4387	.3524	.1035	.0253	.1964	.1202	.4965	.2191	.2818	.2056										
21	.4455	.4454	.4819	.1721	-.1017	-.0823	.1129	.2455	.2435	.0581										
31	.4872	.3768	.5007	.1370	.1921	.1679	.0575	.1146	.2468	-.0366										
41	.2445	.2290	.5921	.2538	.1344	.1120	.2409	.3476	.2160	.3735										
51	.2660	.0977	.1702	.2076	.2860	.3103	.5102	.2430	.5140	.1440										
61	.5239	.2113	.0764	.1240	.1964	.2828	.3670	.3052	.6445	.1684										
71	.2042	.1313	.3586	.2147	.5055	.4178	.4574	.3106	.4337	.3179										
81	.4020	.1586	.3998	.3799	.2489	.4191	.2937	.2714	.4022	.5334										
91	.3866	.1459	.3123	.1718	.1986	.2680	.1772	.2382	.1243	.0838										
101	.4827	.0293	.2827	.3649	.2849	.2713	.1793	.3300	.3468	.5218										
111	-.640	-.0041	.4426	.5571																
	R (5=1)	R (5=2)	etc.																	
1	.3805	.0324	.1160	.1980	.4282	.3161	.1916	.5746	.3913	.0950										
11	.5519	.1711	-.0524	.0300	.0363	.0015	.4822	.2476	.4206	.4021										
21	.1057	.1510	.2881	.2121	-.0782	.0699	.3110	.2023	.3623	.3089										
31	.0745	.6178	.6795	.1248	.4049	.1392	.0445	.2503	.2251	-.0524										
41	.5161	.5802	.3477	.5559	.3447	.1910	.2216	.2183	.1874	.5225										
51	.5142	.2126	.1795	.2914	.1739	.5222	.3262	.2940	.3255	.0093										
61	.1744	.3163	-.0412	.1765	.4931	.2064	.4902	.7673	.3387	.2363										
71	.1583	.4654	.1212	.3516	.1902	.3311	.4785	.4497	.3254	.1208										
81	.1877	.2875	.3464	.4274	.2208	.3124	.3824	.4965	.2473	.2305										
91	.4548	.3769	.1433	.2830	.3044	.2215	.5871	.2411	.1220	.1969										
101	.2861	.3483	.3295	.0672	.2010	.1654	.3388	.7118	.1986	.3883										
111	.2203	.3277	.2372	.2172																

TABLE XV-- Continued

R (7-1)	R (8-2)	etc.	R (8-1)	R (8-2)	etc.
1	.3511	.1709	.1245	.1622	.4138
11	.4485	.2257	-.0564	-.0969	.1379
21	.2757	.0976	.4408	.2784	-.0279
31	.0406	.5945	.2555	.5424	.3738
41	.4805	.1600	.2848	.2390	.0958
51	.5800	.0835	.0650	.4434	.1521
61	.2482	.5029	.4210	.2455	.2872
71	.3004	.3437	.2988	.4661	.0697
81	.3481	.6347	.3823	.4528	.2035
91	.1422	.4041	.1595	.2841	.3315
101	.2126	.3175	.3232	.2989	.1330
111	.4782	.1182	.2306	.3231	.3632
R (8-1), R (8-2) etc.					
1	.2799	.0534	.1655	.1794	.3494
11	.2080	.2166	.0207	.0580	.2648
21	.3268	.1579	.2823	.1403	-.1056
31	.1242	.4351	.4531	.0923	.2595
41	.4116	.2177	.2846	.2595	.2229
51	.2400	.2112	.1362	.1974	.5946
61	.2464	.2238	.1534	.1641	.2924
71	.1453	.1161	.2833	.2653	.2543
81	.3209	.2742	.2505	.3849	.2218
91	.6320	.2237	.4768	.1700	.2756
101	.4316	.2704	.2469	.2685	.3814
111	.2425	.2974	.3438	.3548	.3230
R (8-1), R (8-2) etc.					
1	.0372	.1917	.2298	.3556	.1997
11	.4602	.2380	.3666	.5360	.3898
21	.1858	.1098	.1799	.2758	.1239
31	.0559	.2110	.3343	.1120	.1128
41	.1848	.0396	.2807	.1494	.2949
51	.4108	.4014	.3745	.4077	.0526
61	.6966	.1242	.3961	.3710	.5484
71	.3707	.4178	.2594	.5025	.2120
81	.3799	.6193	.3027	.1879	.5106
91	.2390	.2368	.2789	.1338	.2512
101	.4245	.3230	.5609	.4466	.3639

APPENDIX IV

TABLE XVI

DISCRIMINATION INDICES

Questionnaire Item No.	Questionnaire Item No.	Questionnaire Item No.	Questionnaire Item No.	Questionnaire Item No.	Questionnaire Item No.	Questionnaire Item No.			
1	30	26	16	51	14	76	24	101	34
2	28	27	32	52	16	77	24	102	28
3	16	28	18	53	8	78	34	103	16
4	14	29	32	54	22	79	24	104	14
5	28	30	6	55	36	80	24	105	38
6	22	31	22	56	26	81	32	106	26
7	30	32	36	57	24	82	28	107	30
8	20	33	34	58	28	83	22	108	24
9	20	34	20	59	42	84	28	109	30
10	24	35	30	60	14	85	26	110	32
11	32	36	26	61	24	86	32	111	36
12	26	37	10	62	30	87	14	112	18
13	14	38	26	63	16	88	28	113	16
14	14	39	10	64	10	89	26	114	34
15	32	40	10	65	18	90	18		
16	24	41	36	66	8	91	38		
17	40	42	22	67	44	92	22		
18	28	43	32	68	28	93	34		
19	22	44	40	69	30	94	20		
20	22	45	16	70	20	95	30		
21	34	46	14	71	18	96	18		
22	20	47	20	72	24	97	18		
23	30	48	24	73	22	98	14		
24	36	49	8	74	34	99	22		
25	38	50	26	75	20	100	24		

APPENDIX V

TABLE XVII

ACTUAL VS. PREDICTED MEAN MAINTENANCE
ACTION TIMES IN LOG HOURS

Equipment (Subassembly)	Actual Log Y	Predicted Log Y	Residual
1 Converter Liquid Oxygen	.66511	.79286	-.12775
2 MD-9 Fire Control System	.55955	.83771	-.27816
3 Hydraulic Power Pack Assembly	.99269	.75322	.23947
4 Electronic Computer	.88992	.78592	.10400
5 Fuel Flow Transmitter	.66511	.70795	-.04284
6 Altimeter Drive Assembly	.83461	.61121	.22340
7 Radar Set AN/APN-59	.71240	.70764	.00476
8 Transponder Set AN/APX-25	.58467	.60334	-.01867
9 GAM 77A Computer	.75861	.70087	.05774
10 Transponder Set	.60390	.60427	-.00037
11 GAM 77A Astrotracker	.75035	.71872	.03163
12 B-52 Landing Gear System	.63417	.60843	.02574
13 Radar Beacon AN/APN-69	.72395	.67040	.05355
14 Radio Set AN/ARN-21C	.60163	.71771	-.11608
15 Bomb Nav. System AN/ASB 4A (ACR)	.71037	.69034	.02003
16 MC-1 A/P System	.45969	.60811	-.14842
17 N-1 Compass System	.59195	.61159	-.01964
18 GAM-77 Stable Platform	.93080	.69573	.23507
19 Flight Controls (Spoiler and Airbrake System)	.50406	.60721	-.10315
20 Bomb Nav System AN/ASB 4A	.71037	.65282	.05755
21 Navigational Computer AN/ASN-7	.71366	.62270	.09096
22 Air Data and Surface Control Unit	.66276	.70786	-.04510
23 MA-2 Auto Pilot	.64187	.61852	.02335
24 GAM-77A Motor Generator Drive	.92054	.63854	.28200

TABLE XVII --Continued

Equipment (Subassembly)	Actual Log Y	Predicted Log Y	Residual
25 APS 54 Range Radar	.45803	.58159	-.12356
26 MD-1 Automatic Astro Compass	.71012	.62653	.08359
27 GAM-77A Air Data Unit	.66276	.67755	-.01479
28 ALT-13 Countermeasure Transmitter	.52840	.61200	-.08360
29 AN/ALR-18 Receiver Counter- measures	.52504	.56623	-.04119
30 AN/AIC-10 Interphone System	.38668	.63281	-.24613
31 AN/APP-9 Repeater	.45939	.51990	-.06051
32 APR-14 Detection Radar	.47085	.51396	-.04311
33 AJA-1 True Heading Indicator	.62469	.60210	.02259
34 AN/APH-2 Evaluator, Fire Control System	.62459	.59909	.02550
35 AN/ALT-16 Countermeasure Transmitter	.46746	.57752	-.11006
36 AN/ALT-15 Countermeasure Transmitter	.55157	.58765	-.03608
37 GAM-77A Converter-Monitor	.53832	.60614	-.06782
38 J-4 Compass System	.47026	.59804	-.12778
39 Automatic Checkout Test Console, Flight Control and OSS#2	.77815	.62348	.15467
40 Engine Pressure Ratio Transducer	.63417	.56630	.06787
41 Terrain Computer	.69897	.55968	.13929
42 Power Supply Assembly	.47567	.56441	-.08874
43 AJM14V Tester	.42846	.56056	-.13210
44 ALT-6B Jamming Transmitter	.48087	.51105	-.03018
45 AN/ARC-65 Communication Radar	.69592	.53286	.16306

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13 ABSTRACT The study is introduced by reviewing previous attempts to quantify and predict systems maintainability. A theoretical formulation is outlined which treats the measurement and prediction of system maintainability as a "components-of-variance" model. The sources of variance are identified as: inter and intra man (personnel and social variables); machine (weight, volume, reliability, etc.) and man-machine interaction (human engineering design criteria). A restricted case of the formulation was investigated empirically in an attempt to predict maintainability of a sample of Air Force equipment from a questionnaire evaluation of the human engineering design features. The questionnaire contained 114 items concerning "desirable" human engineering maintainability design features. Ninety maintenance technicians completed the questionnaire on 90 subassemblies of three major weapon systems (B-52, GAM-77, and KC-135). Criterion data were developed from AFM 66-1 Maintenance Data Reporting System. Questionnaire responses, factor-analyzed by the Wherry-Winer Method, yielded eight orthogonal (independent) maintainability design factors. On the basis of the obtained factor loadings, seven of the original eight factors were selected as the most potent predictors. Several regression analyses were performed using different assumptions concerning both heterogeneity of sampled equipment and questionnaire scale stability. Coefficients of determination ranged from .27 to .47 depending on the assumptions made. Generally predictive efficiency increased and factor validity patterns changed when equipment was classified to make more homogeneous sets.		

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