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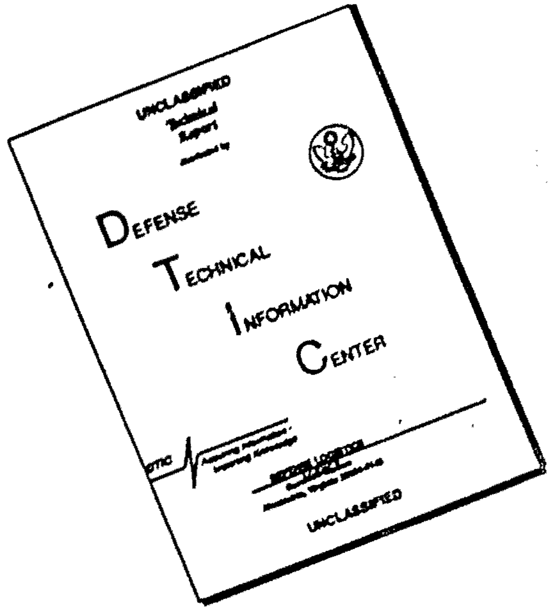

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Solution to the problem of estimating the probability that a given electronic malfunction will be corrected within a given time is addressed through compatible, complementary techniques. One technique compounds Fleet derived job factor success probability data to yield a probability of malfunction correction success. The complementary technique, based on computer simulation methods, yields the anticipated time for malfunction correction. The two techniques were applied to two different operational Navy systems. The results are presented and discussed in the context of technique reliability, utility, discriminating power, and reasonableness of obtained results.

14 KEY WORDS	LINK A		LINK B		LINK C	
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FOREWORD

This study was directed by the Human Factors Engineering Division at the Naval Air Development Center, Warminster, Pennsylvania, under Contract N63369-71-C-0014.

This contract is a part of the overall effort in support of advanced development objective (ADO) 43-13X; Human Factors Engineering Technology, which calls for the development of "reliability simulation models and analysis which permit the inclusion of the human variance term in reliability prediction and evaluation."

ABSTRACT

Solution to the problem of estimating the probability that a given electronic malfunction will be corrected within a given time is addressed through compatible, complementary techniques. One technique compounds Fleet derived job factor success probability data to yield a probability of malfunction correction success. The complementary technique, based on computer simulation methods, yields the anticipated time for malfunction correction. The two techniques were applied to two different operational Navy systems. The results are presented and discussed in the context of technique reliability, utility, discriminating power, and reasonableness of obtained results.

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At Applied Psychological Services, W. Rick Leahy programmed the data for computer simulation and Douglas H. Macpherson and Janet L. Siegel assisted with the data reduction and analysis.

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CHAPTER I

INTRODUCTION

Techniques and methods for predicting equipment reliability, in terms of mean time to failure, have become an integral part of the engineering armamentorium. However, parallel methods pertaining to human reliability (the probability of successful performance) have not evolved. Yet, total system reliability determinations are somewhat incomplete when the human aspect is ignored. Total system reliability is viewed as some function of both equipment and technician reliability. Since techniques for determining equipment reliability are available, Applied Psychological Services, Inc., in the past few years, has addressed itself to the problem of developing techniques for determining technician reliability.

A technique for determining the reliability of the human component in a system must, if it is to be useful, incorporate several different concepts and characteristics. First, the technique should yield a numerical estimate of predicted reliability. Second, the predicted human reliability estimate should be amenable to compounding with an equipment reliability estimate so as to provide a total system reliability estimate. This requirement indicates that the human reliability statement should be expressed as a probability.

Third, the human reliability predictive technique should be able to yield not only a total system or task reliability statement, but also statements of why a given human reliability determination is high or low. Since an equipment designer is interested in learning the areas in which his system is weak, an overall human reliability numeric represents a necessary, but not sufficient, index. The human reliability index should provide statements of task subsequence reliability, as well as a total sequence, reliability estimate. In hardware reliability, the counterparts for subsequences and total sequences are subsystems and systems.

Fourth, the technique must be applicable early in the system development cycle. If the required human reliability prediction fails to become available until late in the design cycle, the cost impact of any indicated design change could be excessive.

A fifth requirement involves technique practicality. Practicality infers cost minimization as well as ease of application. A technique which can be employed by a minimally trained analyst is held to be more practical than one which implies excessive mathematical or other sophistication. Similarly, a technique which is compatible with hand calculational or desk calculator methods is considered to be more practical than one which rests on the availability of high speed digital computers.

Sixth, the technique must be applicable to a wide variety of systems, i.e., the technique must possess generality. A technique which is too broadly based will tend to lose veridicality for any specific situation. On the other hand, a technique which is highly specific will possess high relevance for the given situation, but may drastically miss the mark when applied to other situations. For maximum utility, a technique is sought which optimizes applicability and veridicality.

Seventh, the technique should be fully compatible with specified end products that emerge from human factors analyses, currently performed during system development. Moreover, the technique should impose few analytic requirements other than those imposed by actual technique application. More specifically, if task or operational sequence data are required by the technique, the data requirements should be directly based on information which is customarily made available during the equipment developmental cycle.

Eighth, the technique should be valid. Validity in the present sense means predictive validity as well as content and construct validity. Validity, in the present context, also relates to the mathematical procedures which are involved and to the reasonableness of the mathematical assumptions.

Ninth, the technique should be psychometrically reliable. Different users should obtain the same numeric when applying the technique to the same system. Additionally, the same user should obtain the same numeric when applying the technique to the same system, on different occasions.

Finally, the human reliability technique should yield a statement of the time it will take a technician to complete a given task, as well as the probability of satisfactory task completion.

Overall Logic and Event Flow

Our overall logic for the development of a technician reliability determination technique rests on two approaches: (1) a deterministic method for calculating the probability that an average maintenance technician will successfully accomplish the sequence of acts required for malfunction correction, and (2) a stochastic, digital simulation method for predicting the time that it will take to accomplish the correction.

Figure 1 presents the overall flow of events leading to and included in the present effort. The heavy lines in Figure 1 enclose those steps which were completed prior to the present study and on which the present study attempted to build. The logic on which the deterministic calculation is based calls for a multidimensional scaling analysis to yield the factors (in the factor analytic sense) involved in electronic maintenance. Having isolated these factors, technician reliability was determined on each of the factors. In the present context, technician reliability refers to an estimate of the probability that an "average" maintenance technician will perform each factor, isolated in the multidimensional scaling analysis, satisfactorily when the factor is involved in a malfunction correction. Since a malfunction correction involves several of the factors, the next step involved the development of a method for compounding technician reliability on each factor in such a way that a numeric would result which expressed the probability of a maintenance technician satisfactorily performing in combination those factors involved in any given malfunction correction. The technique was then applied to a sample of malfunctions, all representative of malfunction corrections in the Navy.

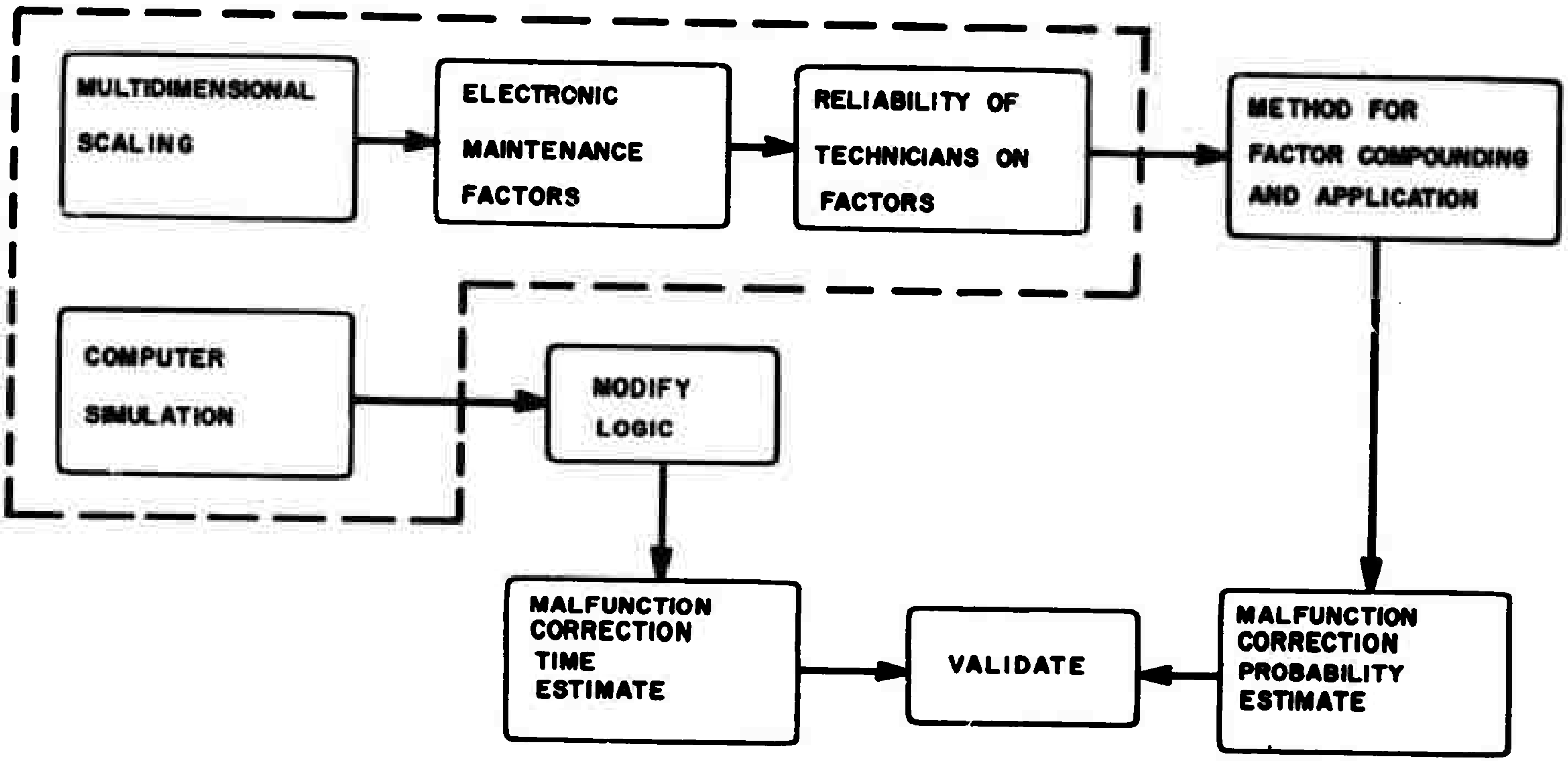

Figure 1. Flow of events in maintenance technician reliability program.

A computer simulation model was previously developed which has shown considerable promise for predicting operator performance in man/machine systems. The model, which has become known as the Siegel-Wolf simulation model, has been fully described elsewhere (Siegel & Wolf, 1969) and is used, in the present context, for predicting malfunction correction time. For the purpose of employing this model in a manner which possesses maximum synergism with the technician factor reliability data employed in the deterministic calculation, certain modifications were implemented in the logic of the model. These modifications were implemented through a preprocessing technique. This preprocessing serves to enable the model to act on the same technician factor reliability data employed in the deterministic calculation. The advantage of the preprocessing technique is that it leaves the internal logic of the model, and accordingly, the model's validity, unchanged. The end result is a prediction of time to complete the malfunction correction in a manner that is entirely compatible with the deterministic calculation of the probability of satisfactory malfunction correction.

The details and rationale for each of the steps completed earlier are presented in subsequent sections of Chapter I of this report. Subsequent chapters describe the tasks completed in the first year of the current program of work toward the establishment of a human reliability predictive technique for application in maintainability prediction situations.

Multidimensional Scaling

Multidimensional scaling analysis is a comparatively recent technique for defining or structuring an unordered universe. The technique has a history of test and application in a variety of contexts, including work on attitudes (Messick, 1954, 1956a; Abelson, 1954), personality (Jackson, Messick, & Solley, 1957), jobs (Reeb, 1959), facial expression (Abelson, 1962), civil defense (Smith & Siegel, 1967), and display evaluation (Silver, Landis, & Jones, 1965).

Originally developed by Richardson (1938), multidimensional scaling represents an expansion of factor analysis to qualitative domains. Gullicksen (1961), in summing up his feelings about the value of multidimensional scaling, said that it:

> ...is a rather powerful technique for investigating a wide array of situations. The basic experimental question is a very simple one. Despite a superficial appearance of difficulty and unreasonableness, one can get consistent answers and can come up with rather interesting conclusions--some of which verify the results of unidimensional scaling and others which go beyond (p. 17).

The basic logic of multidimensional scaling may be stated as follows. If similarity estimates among a variety of stimuli in a set can be assumed to be measures of the "psychological distances" between the stimuli in Euclidean space, the analytical problem becomes the determination of the number of axes in that space and the projection of the stimuli on these axes. Factor analytic methods represent the final stage of a multidimensional scaling analysis and, as in factor analysis, the result is a statement of the minimum number of dimensions (factors) which can be employed to describe the set of stimuli. The scale loadings of the stimuli on each dimension, or factor, enable the analyst to attach meaning to and so to name the dimensions.

The major difference between multidimensional scaling and unidimensional scaling is that in the typical unidimensional experiment the dimensions or scales are presented to judges whose task is to order the stimuli on the dimensions defined by the experimenter. Conversely, there are no such a priori definitions made in the multidimensional scaling experiment. Rather, the purpose of the analysis is to discover the characteristics of and the number of underlying dimensions in the empirical data.

In areas where the variables are complex and the dimensions unknown or doubtful, it is appropriate to delineate the variables through multidimensional scaling analysis, rather than to establish the dimensions arbitrarily. Evidence of the validity of the multidimensional method has been cited, especially in research where dimensions are well established. Messick, in his studies on color, concluded that "since multidimensional scaling procedures yielded structures which correlated highly with the revised Munsell system, it would now seem reasonable to apply these procedures for purposes of exploration and discovery in areas of unknown dimensionality" (1956c, p. 374).

To obtain the dimensionality of the job of the electronic maintenance technician, Siegel and Schultz (1963) performed a multidimensional scaling analysis of the job of Naval technicians concerned with electronic maintenance. The consensus of Fleet personnel interviewed indicated that the job of the technician was best described by some 29 different tasks. Examples of tasks were: "using schematics for complex circuits... " and "troubleshooting/isolating malfunctions in avionic equipments." The 29 tasks constituted the stimuli and both supervisory and line personnel constituted the sample who provided the basic inter-stimulus distance estimates for the analysis. Sixty-five subjects distributed over 14 separate maintenance units were involved. The corrected matrix of scale values was factor analyzed by the principal components method with rotation according to the equamax criterion (Saunders, 1962). Nine factors emerged. These factors were named: Electro-cognition (EC), Electro-repair (ER), Instruction (I), Electro-safety (ES), Personnel Relationships (PR), Electronic Circuit Analysis (ECA), Equipment Operation (EO), Using Reference Materials (URM), and Equipment Inspection (EI). These factors are fully defined in Table 1.

Table 1

Definition of Factors

1. Electro-cognition	This factor is associated with any routine mental activity involved in the troubleshooting acts. It includes the mental formulation of simple hypotheses regarding the cause of a malfunction, the mental synthesis of elementary cause-effect relationships, logical thinking of a routine nature, and the integration of test results with pretest hypotheses. Simple sequential tests do not involve electro-cognition. For example, continuity tests would not involve this category. This is a "how to make it work" factor as opposed to electronic circuit analysis, which is a "why it doesn't work" factor. Tasks which might involve electro-cognition are: 1. making logic changes in a data processing unit 2. comparing an output waveform to a manualized form 3. observing fault lights and inferring module to be replaced
2. Electro-repair	This factor includes the motor and manipulative aspects of physically repairing a component which has failed. It does not include module or component replacement but does include module or component repair. Examples of tasks including electro-repair are: 1. replacing a broken solder joint 2. adjusting the contacts on a relay
3. Instruction	This factor involves teaching others how to inspect, repair, operate, or maintain electronic equipments. Examples of tasks involving this factor are: 1. instructing another technician on how to use test equipment 2. instructing a subordinate on how to perform a test or repair act 3. instructing an operator on how to work an equipment

Table 1 (cont.)

4. Electro-safety	This factor involves implementation of special safety procedures so as to minimize personnel hazard during a repair or so as to minimize the possibility of additional equipment damage. An example task involving this factor is: 1. observing high voltage protection instructions on equipment
5. Personnel Relationships	This factor includes the management and supervisory aspects of maintenance organization functions. Examples of tasks involving this factor are: 1. supervising the operation/inspection/maintenance of an electronic equipment 2. assigning personnel to an electronic repair 3. developing a repair schedule
6. Electronic Circuit Analysis	This factor is purely mental in nature. It includes the application of electronic principles to the correction of a fault. Electronic principles include the selection and use of circuit formulae and the application of the results of calculations, the application of principles of electrical/electronic functions, and the like. This factor is different from the electro-cognition factor in that electro-cognition is almost directly effect-cause related, whereas electronic circuit analysis involves more sophisticated consideration of intervening processes. For example, if in the case of a faulty output, the technician can decide that either module A, B, or C is malfunctioning and that he can complete the repair by sequential replacement of modules until the correct output is obtained, then the factor involved is electro-cognition. On the other hand, if the technician must perform a test on each of A, B, and C and then apply Ohm's Law to determine the faulty module, then electronic circuit analysis is involved. Electronic circuit analysis might also be involved in certain aspects of failure reporting. Examples of electronic circuit analysis are:

Table 1 (cont.)

	1. determining why an oscillator yields an improper frequency response 2. determining why the time delay of a timing circuit is too long 3. determining why a power supply goes into an overvoltage shutdown mode
7. Equipment Operation	This factor involves the operation or exercise of prime equipment and electrical and electronics test equipment. Examples of this factor are: 1. employing repaired equipment 2. using an oscilloscope
8. Using Reference Materials	This factor includes the use of supporting documentation. The use of schematics and block diagrams is included under either electro-cognition or electronics circuit analysis.
9. Equipment Inspection	This factor includes inspections of electronic equipment, including those inspections and examinations required after performing a correction or repair to the equipment.

Reliability of Maintenance Technicians on Each Factor

The factorial based, empirically derived taxonomy described above provides a basis for describing electronic maintenance tasks. It provided a structure which is manageable and relatively unencumbered. As such, the technique was used in studies in which the ability of Naval technicians to perform the functions subsumed by the factors was examined. In order to obtain evaluations of the Naval technician's ability on each factor, a scheme was developed which was drawn from the work of Whitlock (1963). Whitlock investigated the relationship between observation and performance evaluation and pointed out that: (1) performance evaluation represents a response to observations of performance, (2) observations associated with performance evaluation are observations of performance specimens, and (3) observations of performance specimens can be remembered over reasonable rating periods and reported accurately at the end of the rating period. A reasonable rating period for Whitlock was up to six months in duration.

Whitlock defined a performance specimen as "an incident of relevant performance which is uncommonly effective or uncommonly ineffective [1963, p. 15]." Regarding the definition of uncommon performances, Siegel and Pfeiffer (1966b) pointed out that this definition, in a sense, represents an adaptation of Flanagan's critical incident technique (cf., Flanagan, J. C. The critical incident technique, Psychological Bulletin, 1954, 51, 327-358.) Recall of such incidents will depend on the time interval between the event and the rating and, in part, on who does the reporting.

Siegel and Pfeiffer examined, in the Naval situation, the relationship between peer ranking of personnel proficiency and peer estimates of job proficiency. Peer estimates of job proficiency were determined, through the magnitude estimate method of the number of uncommonly effective and uncommonly ineffective performances over the immediately preceding four month period. The correlation coefficient obtained between these two sets of data was .73. The researchers commented that since peer rankings are consistently found to be one of the most useful indicators of personnel proficiency, the correlation of .73 suggests that the judgments of uncommonly effective and uncommonly ineffective performances possess merit for the same purposes.

Siegel and Pfeiffer (1966b) employed the above described factor analytically determined job activities and obtained, for each activity, magnitude estimates of the number of uncommonly effective and uncommonly ineffective performances relative to a short prior period for avionic personnel. Two Fleet electronic maintenance objectives were involved: "readiness"* and "performance."** The technicians were both ratees and raters. Each technician rated the other nine in the group. Three Naval rates were involved: aviation electronics technician, aviation fire control man, and aviation electrician's mate. A ratio of uncommonly effective (UE) performances divided by the sum of uncommonly effective plus uncommonly ineffective (UI) performances ($\Sigma UE/\Sigma UE + \Sigma UI$) was used as the performance index. This index yields a value which varies between 0.00 and 1.00. The researchers, in their discussion of this index, claimed that it normalizes across the opportunity to perform. The resultant data tended to support the use of the ratio, in that emergent differences were in the anticipated direction. Specifically, in the case of the two squadrons involved, one of the two squadrons possessed technicians who were considerably more experienced than the other. The ability of the technique to differentiate in this manner was considered as evidence supporting its discriminating power. Additional significant differences were indicated between technicians and between job activities. Although there was no a priori basis for predicting the direction of these differences, Siegel and Pfeiffer argued that these results also supported a contention in favor of the discriminating power of the technique. Siegel and Pfeiffer concluded that: (1) magnitude estimates of uncommonly effective and ineffective performances yielded useful data which could form the basis for a personnel subsystem reliability index, (2) the ratio of the sum of uncommonly effective performances to the sum of the uncommonly effective plus uncommonly ineffective performances yields an index which distinguishes in the anticipated direction, and (3) the obtained avionic personnel subsystem index could be utilized for posttraining performance appraisal, personnel placement, and squadron evaluative purposes.

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*Readiness: Completion of any given mission in minimum time with an appropriate level of accuracy and reliability.

**Performance: To maintain self, subordinate personnel, equipment, and systems in a state of readiness consistent with Fleet requirements.

Siegel and Pfeiffer (1966a) also provided basic information regarding the nature and characteristics of the underlying scale when magnitude estimates are employed to collect performance related data. The investigators concluded that the method yields a scale in which standard deviations do not increase with mean values (metathetic scale). These data again suggest the utility of the magnitude estimate method for collecting data relative to job performance.

Siegel and Federman (1970) employed the same factor analytically derived maintenance job dimensions and the same approach (magnitude estimates of uncommonly effective and uncommonly ineffective performances)to obtain data on a Fleet sample of 533 technicians. The technicians represented the following ratings: electrician's mate (EM), electronics technician (ET), fire control technician (FT), interior communications electrician (IC), radarman (RD), radioman (RM), sonar technician (ST), and torpedoman's mate (TM). The data were based on the following destroyers: USS Roan, USS Dyess, USS Sperry, USS Basilone, USS Ingraham, USS Page, USS Fiske, USS Eaton, USS Cony, USS Hank, and USS Conway. These destroyers were based at Philadelphia and Newport.

The data obtained on these technicians were treated in the same manner ($\Sigma UE/\Sigma UE + \Sigma UI$) as in the Siegel and Pfeiffer (1966b) study. The data were analyzed separately for each rate by pay grade, ship, and squadron.

Several of Siegel and Federman's conclusions were that: (1) a statistically significant difference existed among the electronics ratings, (2) no significant difference was found among the three squdrons, (3) the job activities differed significantly among themselves, and (4) there were no significant differences among the 11 ships sampled. Since there were no significant differences among ships and squadrons, the data were combined across ships and squadrons. Figure 2 presents the combined data for the individual ratings on each job activity.

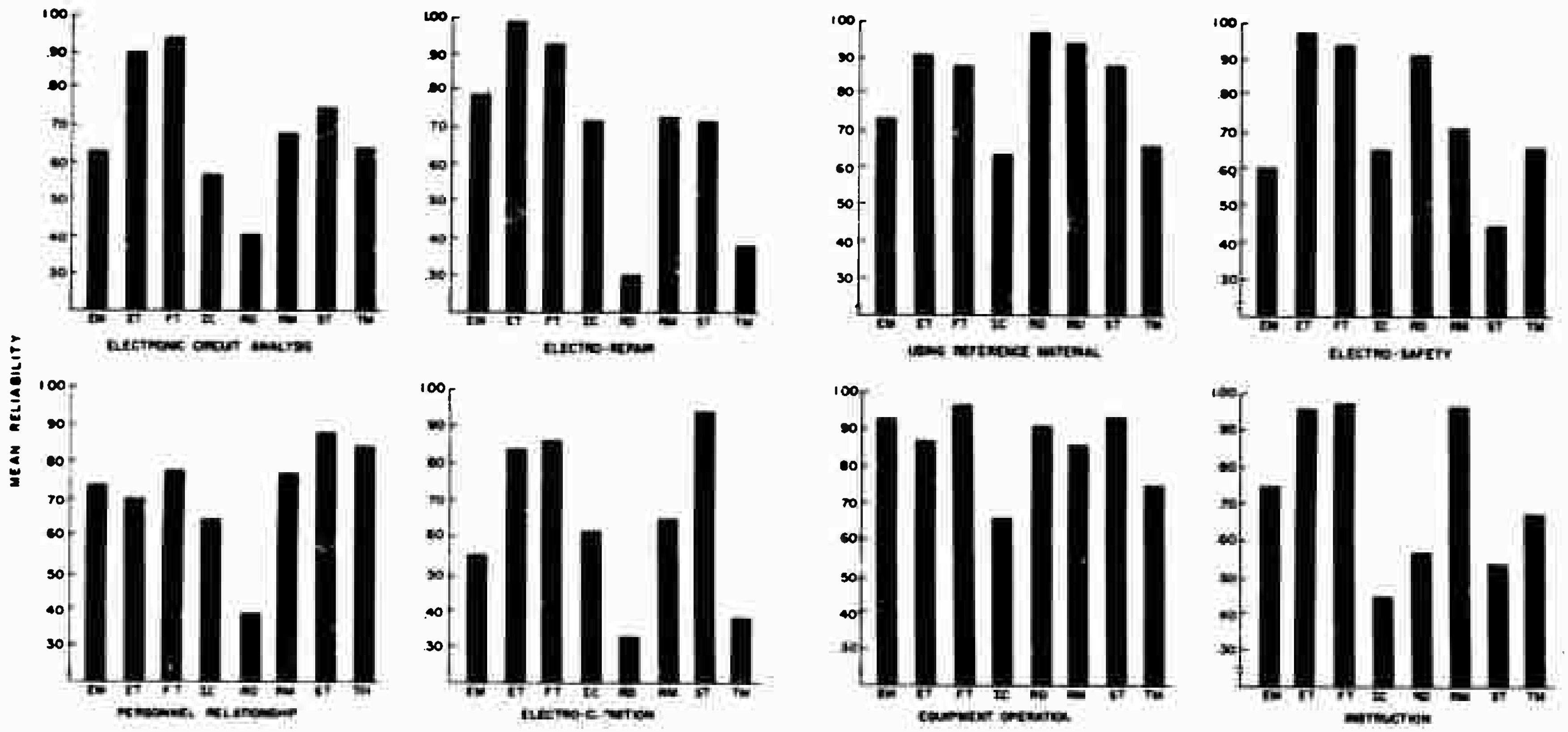

Figure 2. Mean personnel reliability values of technical ratings across squadrons on maintenance job activities.

If the position is taken that: (1) the estimates of unusually effective and unusually ineffective performance represent the tails of a distribution, (2) the remaining performances (viz., that are neither unusually effective or unusually ineffective) will distribute themselves equally over the central area of the distribution, and (3) performances above the mean of the distribution are satisfactory, whereas performance below the mean are unsatisfactory, then the numeric yielded by the ratio $\Sigma UE/\Sigma UE + \Sigma UI$ can be held to represent the probability of satisfactory performance by a member of a given Naval rating on a given job factor. It is this set of probability numbers which forms the basic data for the present study.

Method for Compounding

Several different job activities and persons may be involved in the performance of a task. Task performance, to be successful, may require the successful performance of all involved job activities by all persons or the successful performance of some particular combination of job activities. The probability of successful performance will be increased when several persons are assigned to the same task, i.e., when they perform a job activity in parallel with each other. In addition, the probability of successful performance will be increased if a technician is permitted to repeat the performance or one aspect of the performance.

Siegel and Miehle (1967) presented methods for determining overall probability of successful task accomplishment when the probability of accomplishing each of the elements of the task is known. The methods suggested are reviewed below. The methods were developed to exploit the job factors isolated in the multidimensional scaling studies, as well as the personnel reliability data on each factor as collected originally by Siegel and Pfeiffer and later by Siegel and Federman.

Let:

s = satisfactory task performance

r_{mn} = satisfactory performance of job activity m by technician n

R_{mn} = reliability of technician n on activity m

$P_r[r_{mn}]$ = probability that statement r_{mn} is true.

Thus $P_r[r_{mn}] = R_{mn}$ and $P_r[s]$ = reliability of task performance.

Suppose performance of a task involves technician b on three job factors: 3, 4, and 6 and technician g on three factors: 3, 5, and 8. Both technicians perform factor 3. The condition for satisfactory task performance is:

$$s \rightleftharpoons (r_{3b} \vee r_{3g}) \wedge r_{4b} \wedge r_{6b} \wedge r_{5g} \wedge r_{8g}$$

$\vee$ is a symbol for inclusive <u>or</u> (inclusive disjunction)

$\wedge$ is a symbol for <u>and</u> (conjunction)

$\rightleftharpoons$ is a symbol for "is equivalent to."

We are not limited to an "and" and "or" logic. Statements could conceivably be connected by conditional or biconditional symbols. These in turn can be expressed in items of "and," "or," and negation. The negation of r_{ij} is r'_{ij}

If all activities must be performed satisfactorily, the condition is expressed by joining all statements by "conjunction" ($\wedge$), $s \rightleftharpoons r_{1a} \wedge r_{2a}$. This might be called a <u>series</u> task.

$$P_r[s] = P_r[r_{1a} \wedge r_{2a}] = P_r[r_{1a} | r_{2a}] \, P_r[r_{2a}]$$

$P_r[r_{1a}|r_{2a}]$ is a conditional probability which is read "the probability of r_{1a}, given r_{2a}." It is the probability that r_{1a} is true under the condition of r_{2a} being true. When the truth of r_{1a} is independent of the truth of r_{2a}, we say that r_{1a} and r_{2a} are independent statements. In this case, $P_r[s] = P_r[r_{1a}]P_r[r_{2a}]$.

Let $s \rightleftharpoons r_{2a} \wedge r_{3d} \wedge r_{6a}$

$$P_r[s] = P_r[r_{2a} \wedge r_{3d} \wedge r_{6d}]$$

$$= P_r[r_{2a}|r_{3d} \wedge r_{6a}]P_r[r_{3d}|r_{6a}]P_r[r_{6a}].$$

If all statements are independent, this reduces to:

$$P_r[s] = P_r[r_{2a}]P_r[r_{3d}]P_r[r_{6a}].$$

If the satisfactory performance of one or the other factor (or both) is required for the satisfactory performance of the task, then the task is called a parallel task. The satisfactory performance of parallel tasks is expressed as:

$$s \rightleftharpoons r_{3e} \vee r_{7e}.$$

In this case, job factors 3 and 7 are involved and the task is performed by technician e.

When the same job factor is performed by two technicians and acceptable performance of either technician will constitute acceptable performance for the team, the condition is expressed as:

$$s \rightleftharpoons r_{3a} \vee r_{3c}.$$

This condition is also referred to as a parallel performance. Here, job factor 3 is performed by technicians a and c.

$$P_r[s] = P_r[r_{3a} \vee r_{3c}] = P_r[(r'_{3a} \wedge r'_{3c})'] = 1 - P_r[r'_{3a} \wedge r'_{3c}]$$

$$= 1 - P_r[r'_{3a} | r'_{3c}] P_r[r'_{3c}]$$

$$= 1 - (1 - P_r[r_{3a} | r'_{3c}])(1 - P_r[r_{3c})$$

If the statements are independent, then:

$$P_r[s] = 1 - (1 - P_r[r_{3a}])(1 - P_r[r_{3c}]).$$

Let $s \rightleftharpoons r_{1b} \vee r_{1c} \vee r_{1g}$.

$$P_r[s] = P_r[r_{1b} \vee r_{1c} \vee r_{1g}] = 1 - P_r[r'_{1b} \wedge r'_{1c} \wedge r'_{1g}]$$

$$= 1 - P_r[r'_{1b} | r'_{1c} \wedge r'_{1g}] P_r[r'_{1c} | r'_{1g}] P_r[r'_{1b}]$$

$$= 1 - (1 - P_r[r_{1b} | r'_{1c} \wedge r'_{1g}])(1 - P_r[r_{1c} | r'_{1g}])(1 - P_r[r_{1g}].$$

For independent statements, this reduces to:

$$P_r[s] = 1 - (1 - P_r[r_{1b}])(1 - P_r[r_{1c}])(1 - P_r[r_{1g}]).$$

Both the series and parallel formulas can be extended to larger numbers of activities or performers. These formulas can be written in many different forms if conditional probabilities are involved.

Example 1. Assume that Task A is performed by technician c and that job factors 1, 3, 4, 7, and 9 are involved. Performance will be considered satisfactory if, and only if, either (or both) factors 1 or 7 are performed satisfactorily, either (or both factors 3 and 9 are performed satisfactorily, and factor 4 is performed satisfactorily. This is symbolized by:

$$s \rightleftharpoons (r_{1c} \vee r_{7c}) \wedge (r_{3c} \vee r_{9c}) \wedge r_{4c}{}^{*}$$

$$P_r[s] = P_r[(r_{1c} \vee r_{7c}) | (r_{3c} \vee r_{9c}) \wedge r_{4c}] \, P_r[(r_{3c} \vee r_{9c}) | r_{4c}] \, P_r[r_{4c}].$$

The first two probability expressions would require further expansion to remove the expression $r_{1c} \vee r_{7c}$ in the first term and the expression $r_{3c} \vee r_{9c}$ in the second term. This would produce a very complicated appearing expression, still containing conditional probabilities, for $P_r[s]$. However, it can be argued that such expansion is not warranted.

In the study of systems reliability, it is generally assumed that the proper operation of one component does not depend on the proper operation of another. This assumption does not always hold. For example, suppose that two beams are used to support a weight. If one beam fails, the whole weight is then placed on the other which will now possess a greater probability of failure, although each beam was designed to hold the whole weight. This is the "domino effect."

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*This expression might be read as follows: this maintenance task will be successfully performed if either electro-cognition or equipment operation is completed successfully, and either an instruction or an equipment inspection is performed acceptably and safety precautions are observed throughout. All activities are performed by technician c.

For independence to hold, a failure of one component must not influence the operation of another. If there is a cause for failure of one component, that cause should not operate on the other components. If, for satisfactory overall performance, all components must operate properly, then when one fails, the whole system fails. In this case, it is irrelevant whether other components also fail as a result of the failure of the first component. Here, the reliability value of interest is the conditional probability of proper functioning, given that all other components function properly. Usually a component is tested in isolation, and it is assumed that when combined with other components its reliability will not be influenced. Otherwise, each component would have to be assigned as many reliability values as there are systems in which it is used.

This consideration may also hold for persons on a job factor. If reliabilities were not independent, then a single value such as r_{2b} would be useful only if technician b worked on job factor all by himself. If technician b performed several job activities or worked with other technicians, then his reliability would be determined on a particular task under a variety of "given conditions." Overall task reliability would then be determined directly rather than on the basis of the component reliabilities.

Assuming independence, i.e., that success or failure of one job activity does not affect the probability of success or failure of another job factor, the formula simplifies to:

$$P[s] = P_r[r_{1c} \wedge r_{7c}]\, P_r[r_{3c} \wedge r_{9c}]\, P_r[r_{4c}]$$

$$P_r[s] = \{1 - (1 - P_r[r_{1c}])(1 - P_r[r_{7c}])\}\{1 - (1 - P_r[r_{3c}])(1 - P_r[r_{9c}])\}P_r[r_{4c}].$$

If the reliabilities ($\Sigma UE / \Sigma UE + \Sigma UI$ values) for technician c on job factors 1, 3, 4, 7, and 9 are .88, .82, .88, .82, and .89, respectively, then the overall probability of successful task performance is:

$$P_r[s] = \{1 - (1 - .88)(1 - .82)\}\{1 - (1 - .82)(1 - .89)\}.88$$

$$= \{1 - (.12)(.18)\}\{1 - (.18)(.11)\}.88$$

$$= \{1 - .0216\}\{1 - .0198)\}.88$$

$$= .845.$$

Example 2. Assume that Task B involves technician j who performs job factors 1, 2, 5, 7, and technician e, who performs job factor 6. Both technicians work on job activities 3, 4, and 8.

$$s \rightleftharpoons r_{1j} \wedge r_{2j} \wedge r_{5j} \wedge r_{7j} \wedge r_{6e} \wedge (r_{3j} \vee r_{3e}) \wedge (r_{4j} \vee r_{4e}) \wedge (r_{8j} \vee r_{8e}).$$

$$P_r[s] = P_r[r_{1j}]\, P_r[r_{2j}]\, P_r[r_{5j}]\, P_r[r_{7j}]\, P_r[r_{6e}]$$

$$\{1 - (1 - P_r[r_{3j}])(1 - P_r[r_{3e}])\}\, \{1 - (1 - P_r[r_{4j}])(1 - P_r[r_{4e}])\}$$

$$\{1 - (1 - P_r[r_{8j}])(1 - P_r[r_{8e}]\}$$

$$P_r[s] = (.82)(.79)(.91)(.77)(.86)\ \{1 - (1 - .81)(1 - .76)\}$$

$$\{1 - (1 - .87)(1 - .80)\}\ \{1 - (1 - .88)(1 - .75)\}$$

$$= (.82)(.79)(.91)(.77)(.86)\ \{1 - (.19)(.24)\}$$

$$\{1 - (.13)(.2)\ 1 - (.12)(.25)\}$$

$$= (.82)(.79)(.91)(.77)(.86)(1 - .0456)(1 - .026)(1 - .03)$$

$$= (.82)(.79)(.91)(.77)(.86)(.9544)(.974)(.97)$$

$$= .352.$$

Job Activity Repetition

It is often possible to improve the unsatisfactory performance on a job by repeating a process or by calling on another technician. However, in order for reliability to be affected by the repetition of a job activity, the realization of the unsatisfactory performance must come prior to the completion of the entire task. Otherwise, the entire job performance may be considered unsatisfactory. The repetition of job activities is equivalent to parallel operations which yield reliability factors of: $1 - (1 - R)(1 - R) = 1 - (1 - 2R + R^2) = 2R - R^2 = R(2 - R)$, instead of R itself. Thus, if $R = .8$, the new reliability factor is: $.8(2 - .8) = .8(1.2) = .96$.

The expected number of attempts, E, is a function of the maximum number (n) of attempts permissible or the number of attempts necessary to give a specified resultant reliability.

$$E_n = \frac{1 - (1 - R)^n}{R}$$

where n is the maximum permissible number of trials.

In the limiting case, as n increases indefinitely, E approaches $1/R$. Thus, if $R = .8$, E approaches 1.25. This means that, if many trials are allowed, or equivalently, if the required reliability must be close to 1, then for $R = .8$ the average increase in number of trials is not more than 25 per cent. For $R = .6$, E approaches 1.67.

Let R_n equal the reliability attained by allowing up to n trials:

$$R_n = R + R(1 - R) + R(1 - R)^2 + \ldots + R(1 - R)^{n-1}$$

$$= 1 - (1 - R)^n.$$

This formula also applies when n technicians work in parallel on the same job activity.

Computer Simulation

The computational technique described above in association with the Fleet data of the Siegel and Federman (1970) study provides a method for estimating the probability that a maintenance technician will satisfactorily perform a given task. The question of how long it will take the maintenance technician to complete the repair task is now considered. For this purpose, the present program relies on a computer simulation technique. The specific computer simulation involved is the model known as the Siegel-Wolf man-machine simulation model (Siegel & Wolf, 1969).

Computer simulation has had a wide and varied background of utilization. It has been used to investigate investment behavior in the stock market, plant flow, and social behavior. It has also been used to test a number of military systems, from the man-machine interactive point of view. Digital computer simulation, made possible by the advent of the high-speed digital computer, possesses at least the following attributes and advantages:

- allows consideration of the idiosyncratic and variable aspects of human performance
- often costs less than physical simulation
- allows hypothetical procedures and systems to be tested
- facilitates the consideration of myriad variables in interaction

Over the years, the Siegel-Wolf model* has been successively revised, improved, and validated. Initially prepared to simulate the actions of a single operator, the model was later expanded to allow simulation of a two-operator man-machine system. New variables were added and computational routines modified and updated as the model matured. Similarly, the model has been continuously updated in terms of more modern computing equipment and in terms of more symbolic programming languages. Prepared originally for the IBM 650 computer system using the SOAP programming technique, the model was later programmed in AUTOCODER, and more recently, it was prepared in FORTRAN IV.

The Siegel-Wolf model has been documented in professional journals, addresses to professional associations, and technical reports. The most up-to-date description of the technique is found in Siegel and Wolf (1969). Other documentation is summarized in Tables 2 and 3. Additional documentation, expansion, and elaboration of the technique has been produced by the Boeing Company, Honeywell, the General Electric Company, Autonetics, the Naval Air Development Center, and the Aerospace Medical Research Laboratory of the Wright-Patterson Air Force Base.

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*The word "model" as used here is defined as a logical mathematical representation of a concept, system, or operation programmed for solution on a high-speed digital computer (Martin, 1968). As such, digital simulation models are distinct from replication (analogy) and formulation (mathematical) models.

Table 2

Summary of Reports on Man-Machine Simulation

Item	Title	Authors	Date	No. of Men Simulated	Sponsor	Computer and Location	Task Simulated	Type of Report
1	Development of a Digital Computer Technique for Evaluating the Operator Loading in Man-Machine Systems	Arthur I. Siegel J. Jay Wolf	May 1958	1	ONR	--	--	Preliminary project report
2	*A Description of a Model and the Results of Its First Application	Arthur I. Siegel J. Jay Wolf	Feb. 1959	1	ONR	IBM 650 NADC	Carrier landing	Formal project report
3	*Application of a Previously Derived Model to the Launching of an Air-to-Air Missile	Arthur I. Siegel J. Jay Wolf	June 1959	1	ONR	IBM 650 Westinghouse	Air-to-air missile launching	Formal project report
4	*Description of a Model to Simulate a System Manned by Two Operators	Arthur I. Siegel J. Jay Wolf	Jan. 1960	2	ONR	--	--	Interim project report
5	A Technique for Evaluating Man-Machine System Designs	Arthur I. Siegel J. Jay Wolf	Jan. 1961	1	ONR	IBM 650	Two above	Journal article Human Factors, Vol. 3, No. 1
6	*A Model for Digital Simulation of One and Two-Operator Man-Machine Systems	Arthur I. Siegel J. Jay Wolf Kenneth Crain	March 1961	2	ONR	IBM 705 USN ASO	In-flight refueling	Formal project report
7	*A Further Application of a "Model" for Digital Simulation of One or Two-Operator Man-Machine Systems	Arthur I. Siegel J. Jay Wolf	June 1961	2	ONR	IBM 705 III USN ASO	Air-to-air intercept	Formal project report
8	Computer Simulation of Man's Performance in Man-Machine Systems	Arthur I. Siegel	June 1961	2	ONR	--	--	Naval Research Reviews article
9	A Simulation Study of Selected Preliminary Descent-to-Earth Sequences for Apollo	Arthur I. Siegel J. Jay Wolf	Sept. 1961	1 (2 man model)	GE	IBM 705 III USN ASO	Astronaut decent	Final report
10	*Evaluation of a One or a Two-Operator System Evaluative Model Through a Controlled Laboratory Test	Arthur I. Siegel J. Jay Wolf R. T. Sorenson	July 1962	2	ONR	IBM 705 III USN ASO	Synthetic man-machine task (model railway system)	Formal project report
11	*A Discontinuous Analytic Model for Simulating Apollo Vehicle Operator Actions and Information Exchange	Arthur I. Siegel J. Jay Wolf Robert Ollman	Sept. 1962	2	M-H	--	--	Final report
12	*A Model for Digital Simulation of Two-Operator Man-Machine Systems	Arthur I. Siegel J. Jay Wolf	Oct. 1962	2	ONR	IBM 705 III USN ASO	In-flight refueling and air-to-air intercept	Journal article Ergonomics, Vol. 5, No. 4
13	*Modification and Further Evaluation of a Digital Man-Machine Simulation Model	Arthur I. Siegel J. Jay Wolf	July 1963	1 (2 man model)	ONR	IBM 705 III Curtiss	Air-to-air missile launching	Formal project report

Item	Title	Authors	Date	No. of Men Simulated	Sponsor	Computer and Location	Task Simulated	Type of Report
14	*Further Test and Evaluation of a Man-Machine Simulation Model	Arthur I. Siegel J. Jay Wolf R. S. Lanterman	Oct. 1963	2	ONR	IBM 705 III Curtiss	Synthetic man-machine task (model railway system)	Formal project report
15	Computer Simulation of Man-Machine Systems	Arthur I. Siegel J. Jay Wolf	1963	2	--	--	--	Chapter in <u>Unusual Environments and Human Behavior</u>, Free Press of Glencoe
16	Application of a Digital Computer Simulation Technique to Maintenance of a Sonar System (CONFIDENTIAL)	Arthur I. Siegel M. A. Fischl	April 1967	2	NSSC ONR	IBM 7094 G. E. Valley Forge	Sonar maintenance	Project PAIR report
17	Verification of a Digital Technique for Sonar Operation Simulation	Arthur I. Siegel D. H. Macpherson	May 1967	1	NSSC ONR	IBM 7094 G. E. Valley Forge	Sonar operation	Project PAIR report
18	Application of a Digital Machine Simulation Model during the Development of the PAIR System (CONFIDENTIAL)	Arthur I. Siegel M. A. Fischl	Aug. 1967	2	NSSC ONR	IBM 7094 G. E. Valley Forge	Sonar operation	Project PAIR report
19	Recent Revisions to the Digital Simulation Model for Simulating Two-Operator Man-Machine Interaction	Arthur I. Siegel J. Jay Wolf	Nov. 1967	2	NSSC ONR	IBM 7094 G. E. Valley Forge	Sonar operation	Project PAIR report
20	Prediction of Individual and Crew Performance by Computer Simulation	Arthur I. Siegel	Jan. 1967	2	ONR	IBM 7094 G. E. Valley Forge	Various	Symposium on human performance quantification in systems effectiveness
21	Computer Simulation Savior; Sanctuary, or Silliness?	Arthur I. Siegel J. Jay Wolf	Nov. 1968	2	ONR	IBM 7094 G. E. Valley Forge	Various	Symposium on applied models of man-machine systems effectiveness
22	Man-Machine Simulation Models	Arthur I. Siegel J. Jay Wolf	1969	2	--	Various	Various	Book
23	Operator Training Requirements through Digital Computer Simulation (CONFIDENTIAL)	M. A. Fischl J. Jay Wolf Arthur I. Siegel	Dec. 1969	2	NSSC	G. E. 635 G. E. Valley Forge	Sonar operation	Project PAIR report
24	Digital Model Modification for On-Line Simulation and Further Extensions of Operator Loading Treatment	Arthur I. Siegel J. Jay Wolf Wm. Miehle	July 1969	--	WPAFB	--	--	Project MISS report
25	Vulnerability/Survivability Estimation through Computer Simulation: I. Program Logic, Task Analysis, and Initial Simulation for the F-106 Aircraft (CONFIDENTIAL)	W.R. Leahy J. Jay Wolf Arthur I. Siegel	Dec. 1969	1	WPAFB	G. E. 635 G. E. Valley Forge	1	Project BATH report

* Common major title: Techniques for Evaluating Operator Loading in Man-Machine Systems

Table 3

Summary of Addresses on Man-Machine Simulation

	Date	Audience	Author/Presenter	Title
1	1959	Eastern Psychological Association	Arthur I. Siegel J. Jay Wolf	Development and application of a method for predicting operator loading in man-machine systems
2	1959	American Psychological Association	Arthur I. Siegel J. Jay Wolf	A psychological-mathematical model for comparing and predicting operator overloading in man-machine systems
3	1960	8th Human Engineering Conference	Arthur I. Siegel	The use of mathematical and computer models for predicting loading in man-machine systems
4	1961	American Rocket Society	Arthur I. Siegel H. Ozkaptan	Models of the simulation of human behavior and their application
5	1961	American Psychological Association	Arthur I. Siegel J. Jay Wolf	A model for predicting team performance in man-machine systems
6	1963	Institute of Radio Engineers	Arthur I. Siegel	Human reliability evaluation
7	1967	Naval Material Command and National Academy of Engineering	Arthur I. Siegel	Prediction of individual and crew performance by computer simulation
8	1967	North Atlantic Treaty Organization	Arthur I. Siegel	Computing system effectiveness through digital simulation
9	1967	British Admiralty	Arthur I. Siegel	Prediction of individual and crew performance by computer simulation
10	1968	Symposium on Applied Models of Man-Machine Systems Performance Office of Naval Research and North American Rockwell Corp.	Arthur I. Siegel J. Jay Wolf	Stochastic simulation--savior, sanctuary, or silliness
11	1969	Human Factors Society	J. Jay Wolf Arthur I. Siegel	Progress of Monte Carlo simulation of man-machine systems
12	1970	Aerospace Medical Research Lab.	Arthur I. Siegel	Recent advances in man/machine system modeling--system vulnerability/survivability
13	1971	Symposium on Computer Simulation as Related to Manpower and Personnel Planning	J. Jay Wolf Arthur I. Siegel	A family of stochastic man/machine models

The validity of the model's predictions has been demonstrated in a wide range of applications. The validational studies completed at Applied Psychological Services included carrier landing, air-to-air missile firing, in-flight refueling, air intercept, sonar employment, and a series of other simulated man-machine interactive situations. Additional validity studies were completed by the Boeing Company (Outcalt et al., 1966) and Honeywell Incorporated (Lane et al., 1966). The ability of the model to predict independent outside criteria data was tested in all of these validational studies. With one exception, the results of all validational efforts reveal satisfactory correspondence (differences which are not statistically significant) between the model's prediction and the criterion data. Additionally, certain of the model's internal constructs were validated, and the ability of the model to predict part-task success was verified. The model has been adapted and successfully employed by a number of industrial and governmental organizations. Thus, the model has withstood reasonable tests of both validity and utility. Complete descriptions of these prior tests and applications are found in Siegel and Wolf (1969) and in the sources listed in Table 2.

Overview of the Model

The model provides the capability to simulate stochastically the acts and behaviors of a human as he performs the sequence of subtasks associated with the performance of a total task. On the basis of task analytic input data, the model sequentially mimics the "performance" of each subtask by each person simulated. The normal sequence of subtasks, whether linear or non-linear, may be modified if actions have to be skipped or repeated due to failure of a subtask by the operator or as a result of operator decisions. During the course of the computer's "performance" of the task, results are recorded indicating the area of operator overload, failure, idle time, peak stress, etc., for the given set of selected parameters. The model's output of principle concern in the present context is the time for task completion. The model records the amount of time involved in completing each subtask in the total task, the cumulative time for each subtask in the total task, and the total time for total task completion.

The major feature of the model of interest in the current context is calculation of task execution time. The following important items are also calculated or otherwise considered in the model:

- task precedence (variable sequencing of tasks)
- maximum stress encountered
- operator interaction (waiting for a partner)
- joint tasks (performed by both operators simultaneously)
- equipment delays
- operator decisions
- skipping of nonessential tasks
- operator cohesiveness
- idle time spent waiting for a prespecified event
- time allotted for the mission
- time precedence (idling until a given time occurs)

The simulation of intra and interindividual differences in performing any individual task is based, in part, on a random process. The total simulation process is a repetitive process, i.e., tasks are simulated sequentially to comprise a task trial and the task trials are repeated (iterated) many times to obtain averages of the data generated by randomization techniques.

The nature of the model is such that specific subtask input data, independent of parameter data, are required. Each discrete subtask is described for each technician by the data given in Table 4. A limit of 300 subtasks for each technician, prepared one per card in accordance with the format of Table 4, has been established.

Table 4

Subtask Input Data and Card Format

Contents	Symbol	Remarks	Symbolic FORTRAN Name	Card Columns	Format
operator number	j	1 or 2	J	1	I1
task element number	i	1, 2, ..., 300	I	3-5	I3
type of task element	-	J=Joint; E=Equipment; D=Decision; C=Cyclic	J, E, D, C	7	A1
essentiality indicator	E_{ij}	N=nonessential; Blank=essential	N; Blank	9	A1
task element precedence	d_{ij}	task element number of partner	IPREC(I, J)	10-12	I3
time precedence	I_{ij}	idle time	TMBEG(I, J)	13-20	F8.2
next task element success	$(i, j)_s$	next task element number, if successful	NXTS(I, J)	21-24	I4
next task element failure	$(i, j)_f$	next task element number, if failure	NXTF(I, J)	25-28	I4
average time	$\bar{t}_{ij}$	average task element execution time	AVGTM(I, J)	29-37	F9.2
time deviation	$\bar{\sigma}_{ij}$	average sigma* for $\bar{t}_{ij}$	AVGTMD(I, J)	38-45	F8.2
probability of success	p_{ij}	probability that next task element will be $(i, j)_s$	PRBSUC(I, J)	46-50	F5.2
time remaining, essential	T^E_{ij}	sum of time of remaining essential task elements	TMLE(I, J)	51-59	F9.2
time remaining, nonessential	T^N_{ij}	sum of time of remaining nonessential task elements	TMLN(I, J)	60-67	F8.2
special jump task element type	-	blank=none; 1=special type 1; 2=special type 2 (Team Decision)	ISJT(I, J)	69	I1
next task element for j, special	-	applies to j, special jump task element	NXTJ(I, J)	70-72	I3
next task element for j', special	-	applies to partner, special jump task element	NXTJP(I, J)	73-75	I3
job activity group	-	1 Electro-cognition; 2=Electro-repair 3 Instruction; 4 Electro-safety 5 Personnel Relationships 6 Electronic Circuit Analysis 7 Equipment Operation 8 Using Reference Material 9 Equipment Inspection	JAG(I, J)	76	I1

*Sigma refers to the standard deviation; task times are typically assumed to possess a truncated normal distribution. Thus, the mean and standard deviation completely define the probability density function used to generate times randomly during an actual simulation run.

The following paragraphs describe and explain some of the data specified in Table 4. A joint task (type J) is one performed simultaneously by both technicians. An equipment task (type E) is introduced to produce a delay in task performance due to a factor other than human performance. No stress functions are calculated for the type E tasks. A decision task (type D) is incorporated into the sequence to allow branching, skipping, or looping in the performance sequence. If the current subtask is a success, subtask $(i, j)_s$ is selected with a probability of $\overline{p}_{ij}$. If the current subtask fails, the next subtask selected is subtask $(i, j)_f$ with a probability $1-\overline{p}_{ij}$. A "cyclic" subtask (type C) provides for the case in which a subtask cannot be started until the next cycle time in a series of equitemporal intervals.

The subtask precedence input, d_{ij}, (mnemonic delay) represents a subtask number which must be successfully completed by the partner before a technician, j, can begin his own subtask i. The time precedence, (I_{ij}), is the time from mission start before which a technician is not permitted to begin a subtask. The values of essential and nonessential time remaining, T_{ij}^{E} and T_{ij}^{N} are calculated after other performance data are available, according to the procedure given in Siegel and Wolf (1969).

Two Special Jump Subtasks are provided. Special Jump Subtask 1 enables both technicians to jump to an individually specified subtask if one of the technicians ignores the Special Jump Subtask type 1. If a subtask, so identified, is ignored (due to stress levels), operator j will go to NXTJ(I, J) for his next subtask, and his partner (j') will go to NXTJP(I, J). If the subtask is not ignored, NXTS(I, J) and NXTF(I, J) apply as usual. Special Jump Subtask type 2 provides a team decision capability to the model. If a subtask, so identified, is a success (probability = $\overline{p}_{ij}$), then technician j will go to NXTS(I, J) for his next subtask. However, if the subtask is failed, technician j goes to NXTJ(I, J) and his partner goes to NXTJP(I, J). In these ways, one technician can make a decision which will determine the future sequence of subtasks for both technicians.

Four parameters are provided to the model on input cards in the format shown in Table 5. A pair of cards, one card for each operator, is supplied for each computer run desired. A run is composed of the simulation of N task performances (iterations). The stress threshold is considered the operator's "breaking point." The model's simulation is based on the psychological concept that time-pressure stress organizes behavior up to a threshold point and disorganizes it beyond that point. Stress is calculated as the ratio of the average time to complete the remaining essential subtasks to the total time remaining available to the operator. A value for stress greater than unity will increase both his speed and success probability. At the threshold, the effect of stress is reversed, simulating disorganization and confusion of the operator.

The F factor for each operator is an individuality indicator representing operator speed or proficiency. An average operator is given an F factor of unity; faster and more proficient operators have lower values.

The third parameter pair is the total time available to complete task performance--a time limit. Both operators must finish before their time limit is reached in order that an iteration can be considered successful.

The fourth parameter pair is the period of time applicable to cyclic (type C) subtasks. A cyclic subtask will be initiated only at a time which is a multiple of the period, P. If necessary, the simulated operator will wait until such a time occurs.

The task and parameter input data are preceded in the computer input deck by three cards which supply information on the general conditions of the runs. The card format and contents of these cards are shown in Table 6.

Figure 3 displays pictorially the sequence of cards in the input deck by card type. A maximum of 300 subtask input data cards are permitted per operator.

Table 5

Parameter Input Data and Card Format
Card Type 4

Contents	Symbol	Remarks	Symbolic FORTRAN Name	Card Columns	Format
operator number	j	1 or 2	J	1	I 1
stress threshold	M_j	$M_j > 1$	STRM(J)	2-11	F10.0
F factor	F_j	$F_j < 1$: faster $F_j > 1$: slower	SPEED(J)	12-21	F10.0
time available	T_j	time remaining	TMAVA(J)	22-31	F10.0
period	P_j	period for cyclic tasks (seconds)	PFD(J)	32-41	F10.0
job operator type	-	1. Electrician's mate 2. Electronics technician 3. Fire control technician 4. Interior communications electrician 5. Radarman 6. Radioman 7. Sonar technician 8. Torpedoman's mate	JOT(J)	43	I 1

Table 6

General Run Information and Card Format

Card Type 1

Contents	Symbol	Remarks	Symbolic FORTRAN Name	Card Columns	Format
run number	-	run identifier	NUMTRL	1- 5	I 5
number of runs	-	-	NUMRUN	6-10	I 5
number of iterations	N	per run	NUMIT	11-15	I 5
random number count	-	number of times random number generator subroutine is called before run starts	IND 1	16-20	I 5
type of output for first ICHG iterations (see below)	-	0 = run summary 1 = iteration summary 2 = detail output	IND 2	21-25	I 5
-	-	subtracted from IND 2 after ICHG iterations	IND 3	26-30	I 5
unit of time	-	value equals 1 0 = hours 1 = seconds 2 = minutes	IND 4 IND 5	31-35 36-40	I 5
-	-	number of iterations before changing type of output	ICHG	41-45	I 5

Card Type 2

Number of Task Cards

Contents	Symbolic FORTRAN Name	Card Columns	Format
total number of mission input data cards to follow; also sum of last task number for both operators.	NINPC	1- 5	I 5

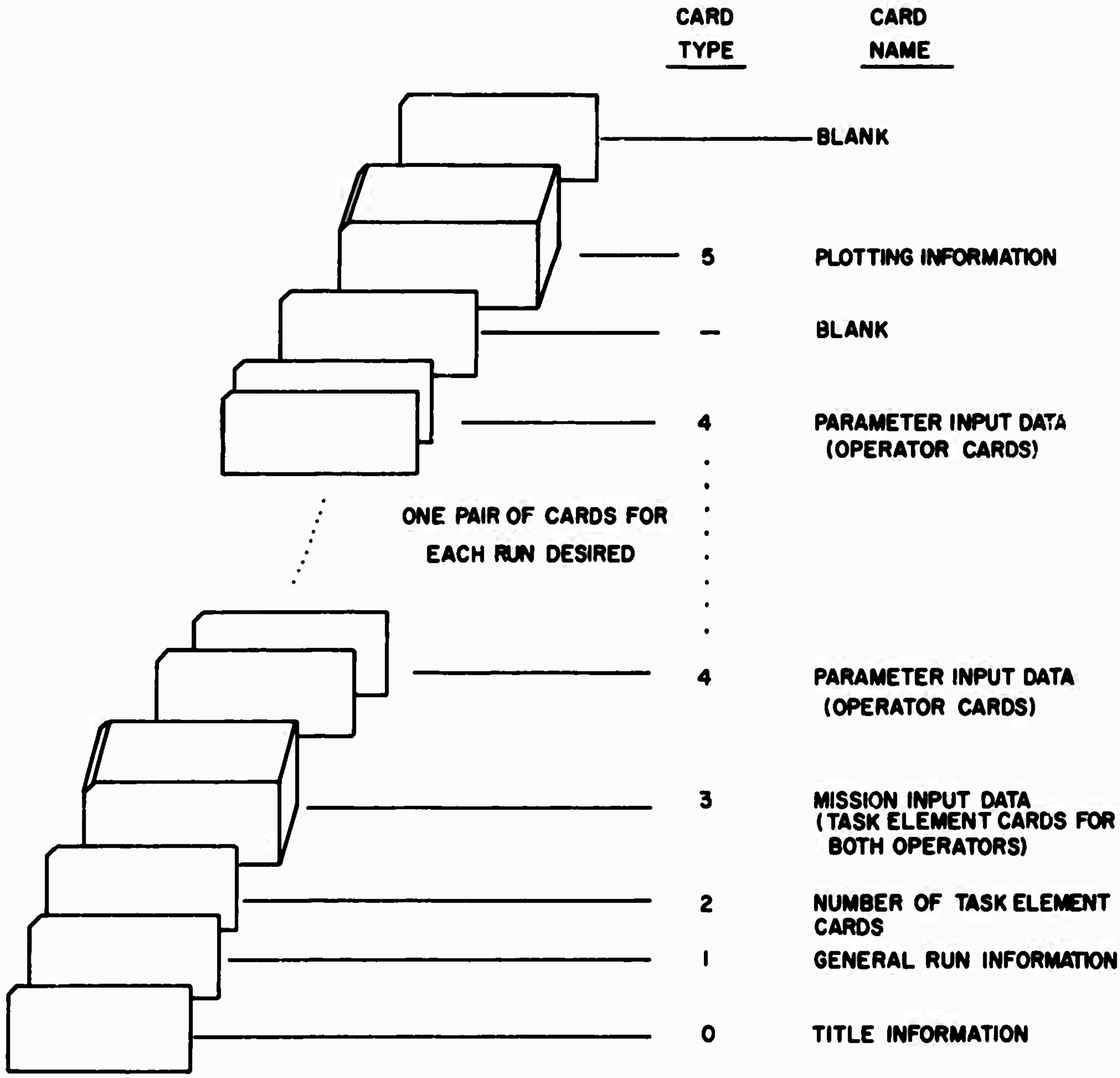

Figure 3. Card deck layout.

A variety of tabular data are available from the model. These data are typically recorded on magnetic tape during the runs for subsequent printout on a high-speed line printer. The following categories of results are available:

Title	Frequency	Remarks
detailed listing	every task	optional, 1 line per task
iteration summary	end of each iteration	optional, 7 lines per iteration
run summary	end of run	9 lines plus several frequency distributions (1 line per task)
plot	end of a series of runs	1 page per plot

In the optional detailed listing, the following data are recorded for each operator:

1. subtask number
2. type of subtask
3. essentiality (indicator)(N = nonessential, otherwise blank)
4. stress as well as augmented (total) stress (augmented stress is a stress value for one operator based on his stress value and that of his partner)
5. waiting time, time spent waiting for partner
6. subtask execution time
7. cumulative subtask execution time

8. result indicator

blank = success
F = failure
I = ignore

9. cohesiveness indicator - a factor indicating team cohesiveness based upon the stress and stress thresholds of each operator

The following information is optionally displayed in the iteration summary for each of the N iterations in a run:

1. iteration number

2. run number

3. trial number(indicator for a series of runs)

4. result indicator

overrun = task failure (time overrun)
underrun = task success

5. total time used - the larger of the total time used by either operator

6. the following data are provided for each operator:

a. operator number
b. stress threshold, M_j
c. speed factor, F_j
d. time available, T_j
e. time used for this iteration
f. difference (time available - time used)
g. total waiting time (does not include item 1 below)
h. value of highest (peak) stress
i. the task number on which the peak stress occurred
j. stress at end of iteration
k. cohesiveness at end of iteration

l. time spent in waiting for the period on cyclic tasks
m. goal orientation - difference at end of iteration (goal - performance)
n. goal orientation - maximum difference in goal orientation during iteration
o. goal orientation - minimum difference in goal orientation during iteration
p. performance at end of mission iteration
q. initial input goal orientation value (task 1)

The results of each run (set of iterations with constant parameter values) are displayed in tabular form. It contains the following:

1. run number

2. total number of iterations performed, N

3. number of successful iterations

4. per cent successful iterations

5. time available, T

6. the following data are listed for each operator:

   a. operator number
   b. stress threshold, M_j
   c. speed factor, F_j
   d. time available, T_j
   e. average time used over N iterations
   f. average difference (time available - time used)
   g. average waiting time
   h. average peak stress
   i. average final stress
   j. average cyclic waiting time

7. the following frequency distributions are displayed and values presented for each task. The items identified, below, with an asterisk are also totaled and averaged, per iteration, over all tasks:

a. subtask number
b. last subtask completed before finishing the iteration or running out of time--for both operators
*c. count of the number of subtasks failed--for each operator
*d. count of the number of subtasks ignored--for each operator
*e. time spent in performing subtasks which were failed
f. count of the number of subtasks for which the peak stress occurred--for both operators
g. time from beginning of mission that the subtask was completed on the average--for each operator
h. average stress prior to beginning each subtask--for each operator
i. average cohesiveness value--for each operator

In order to employ the model in the present context, a number of changes were implemented in the form of an independent subroutine. The changes serve to adjust the input data in such a manner that the subtask success probability for each subtask, in a total maintenance task, is concordant with the factor reliability values presented in Figure 2. This program modification was implemented by means of an independent preprocessor, and thus the structure of the simulation model (and, accordingly, its validity), per se, was left unmodified.

Specifically, the preprocessor takes the factor reliability values and allocates them across the sequence of subtasks involved in performing a maintenance task. The specific factor reliability values chosen depend on the Naval rating whose performance is to be simulated (i. e., if a technician in the radioman's rating is to be simulated, the factor reliability values for this rating are allocated). The performance of a specific repair is then simulated within the Siegel-Wolf model to yield an estimate of the time for malfunction correction. The details of the preprocessing subroutine are presented in Chapter II of the present report.

When the computer simulation and the computational technique are both applied to the same malfunction correction, the end result is a statement of time for malfunction correction (from the stochastic digital simulation) and of the probability of satisfactory performance (from the computational technique).

CHAPTER II

METHODS AND PROCEDURES

Chapter I of the present report reviewed the logic of a set of complementary methods for predicting human performance reliability in regard to electronic maintenance situations. Chapter I also described the results of efforts completed toward this goal prior to the present program. The purposes of the present program were to try these methods in a Navy context in order that an indication might be gained of the general applicability and reasonableness of the approaches described above. To this end, two current Navy systems were selected, the Radio Set AN/URC-35 and the Radar Set AN/APS-115. These two electronic equipments are described in Chapter II. In addition, the methods are described which were employed to select a malfunction correction sample which would provide a basis for evaluating the reasonableness and appropriateness of the proposed deterministic procedure for predicting the probability of successful malfunction correction and of the stochastic, digital computer procedure for predicting the time to perform the sequence of subtasks associated with malfunction correction. Then, the modifications to the Siegel-Wolf model which were implemented to achieve this time calculation are described. Finally, the methods for applying the deterministic calculation and the computer simulation to the selected sample are described.

EQUIPMENT DESCRIPTION AND SAMPLE SELECTION

Description of Radio Set AN/URC-35

As described in the technical manual, the Radio Set AN/URC-35 is a single sideband, high frequency set designed for use on shipboard, vehicular, and shore installation. The set also has capabilities for general purpose use, beach landing parties, and emergency operations. Transmission and reception on 280,000 channels, spaced 100 cps apart in the 2 to 30 MC range are provided. Circuits are employed for automatic digital tuning in 100 cps increments. The equipment includes vernier control for continuous tuning between 1 KC increments to permit compatibility with less stable transmitters. Transmission and reception can be performed in upper sideband (USB), lower sideband (LSB), continuous ware (CW), and compatible amplitude modulation (AM). A remote radio control set permits transmission and reception in USB, LSB, and AM from a remote station.

The receiver-transmitter accepts audio from a handset, microphone, or coded intelligence from a CW key and converts it to one of 280,000 operating frequencies. In all transmitting modes, except CW, voice signals modulate a 500 KC local carrier. The resulting double sideband signal is filtered according to the operating mode and converted to the desired RF operating frequency by a triple conversion process. In the CW mode, the 500 KC carrier is inverted directly into the IF amplifiers at a coded rate and then processed in the same manner as the voice signals. The frequency standard and synthesizer circuits of the receiver-transmitter generate the 500 KC local carrier and the injection frequencies required for the IF to RF and RF to IF conversions. In addition, the 500 KC signal is used as the carrier reinsertion signal during single sideband reception.

The Radio Set AN/URC-35 consists of the following units: Receiver-Transmitter RT-618/URC, RF Amplifier AM-3007/URT, Antenna Coupler CU-937/UR, Shock Mount MT-3761/URC-35, Whip antenna AT-1047/U, Handset H-169/U with cord and plug assembly CK-1846A/U; and the following optional items: Power Supply-Battery Charger PP-4679/URC-35, Remote Radio Control Set C-3697/URC, Microphone M-109/U with cord and plug assembly CX-1846A/U, CW Key, Headset, Rechargeable 28-volt Battery BB-421/U.

Selection of Failed Subassemblies and Components--AN/URC-35

To achieve a sample of failures which is representative of the failure distribution within the AN/URC-35, equipment reliability and maintainability data were employed. These data were developed by the manufacturer of the Radio Set AN/URC-35, General Dynamics, who performed maintenance task analyses for the Receiver-Transmitter unit (RT-618/URC) and the Radio Frequency Amplifier (AM-3007/URT). General Dynamics also developed equipment reliability data in terms of anticipated mean time between failure and failure rate (provided in percentage of 10,000 hours). Mean time between failure was given to the subassembly level, while failure rate was given at the component level.

The first phase of the sampling procedure involved subassembly selection on the basis of mean time between failure. Subassemblies were selected so that a representation across the range of mean time between failure was acquired. The range of mean time between failure given by General Dynamics for the 28 subassemblies in the AN/URC-35 was from 8,136 hours to 965,251 hours, with a mean of 157,950 hours and a standard deviation of 248,617 hours. Fifteen subassemblies were selected for inclusion in the present work from the 28 available. The subassemblies selected were distributed around the mean of 157,950 hours. The extremes at both the high end and low end of the mean time between failure distribution were not selected so that those subassemblies finally selected tended more toward the mean of the distribution.

A frequency distribution of the time between failure of subassemblies was constructed on the basis of the data presented by General Dynamics. This frequency distribution appears in Table 7. Table 7 indicates that 20 subassemblies fall in the first two class intervals, from 1,000 to 100,000 hours time between failure. The sample of subassemblies for inclusion in the present study was stratified to reflect this distribution. The predicted time between failure for the subassemblies selected for consideration in the present work is also presented in Table 7. Thus, 71 per cent of the subassemblies (11) in the sample were from the first two class intervals of Table 7 and 29 per cent (4 subassemblies) were from among the remaining time intervals.

Table 7

Actual and Sample Frequency Distributions of Time Between Failure for the Receiver-Transmitter and the Radio Frequency Amplifier Units

Time Between Failures (in thousands of hours)	Frequency	Sample
950-999	1	
900-949		
850-899		
800-849	1	1
750-799		
700-749		
650-699		
600-649		
550-599	1	1
500-549		
450-499		
400-449	1	1
350-399		
300-349		
250-299		
200-249	2	
150-199	1	
100-149	1	
50- 99	8	5
1- 49	12	6
	28	15

Twenty-five component failures were selected within the 15 selected subassemblies. These were selected primarily on the basis of component failure rate data. In order not to select components that required very frequent repair/replacement or very infrequent repair/replacement, the mean failure rate was computed for all the components in a selected subassembly. If a subassembly contained several component types, two different component types were selected from around the mean failure rate for all the components in the subassembly. If a subassembly contained only one or a few component types, a component failure was selected in such a manner as to yield a variety of different electronic component failures in the sample and to represent the continuum of predicted malfunction correction time.*

Table 8 identifies the components within subassembly so selected as well as the failure rate.

Description of Radar Set AN/APS-115

The Radar Set AN/APS-115 is an airborne radar designed for search and detection of surface targets. The equipment is a portion of the antisubmarine warfare system of the P-3C aircraft. The radar has a manually tunable transmitting frequency of from 8.5 to 9.6 GHz. Other characteristics of the radar set include its 60 MHz frequency bandwidth, 143 KW peak power, 0.5 and 2.5μ sec transmitter pulse width, 400 Hz line-locked with 2.5μ sec pulse width and 1600 Hz line-locked with 0.5μ sec pulse repetition frequency, 6 rpm with 2.5μ sec pulse width and 12 rpm with 0.5μ sec pulse width antenna scan speed, antenna scan modes of searchlight, 45° sector, and 360° scan, manual tilt coverage of + 10 to -20 degrees, and pitch and roll tilt stabilization. The complete radar set is composed of the following units: Antenna Position Programmer MX-7930, Receiver/Transmitter RT-889, Antenna AS-2146, Control Antenna C-7511, and Control Radar Set C-7512.

*Such data were provided as a part of the task analyses performed by the General Dynamics Corporation.

Table 8

Sample of Components for Technician Reliability Analysis of AN/URC-35

Subassembly*	Component	Failure Rate (per cent per 10,000 hours)
Receiver-Transmitter RT-618/URC		
1. Filter Box	1. Capacitor	.344
Filter Box	2. Filter	.350
2. Mode Selector	3. 500 KC Amplifier	2.683
3. Receiver IF Audio	4. Connector	.331
Receiver IF Audio	5. Amplitude Modulation Detector	3.745
4. Transmit Audio	6. Transformer	.213
Transmit Audio	7. Printed Circuit Board	.200
5. RF Amplifier	8. Megacycle Assembly	.699
RF Amplifier	9. RF Amplifier Assembly	1.023
6. Frequency Standard	10. Oven Housing	.310
7. Noise Blanker	11. Connector	.052
Noise Blanker	12. Blanker Board	9.943
8. 1 & 10 KC Synthesizer	13. 10 KC Switch	.400
1 & 10 KC Synthesizer	14. Output & Blanker	2.728
9. Spectrum Generator	15. 100 KC Spectrum	11.367
Spectrum Generator	16. Pulse Inverter	.856
10. RF Translator	17. Cordwood Module	7.177
11. Code Generator	18. Code Generator	2.365
12. 20 v. Regulator	19. 20 v. Regulator	18.938
13. Switch Assembly	20. Resistor Variable	.949
Switch Assembly	21. Switch Section	.600
Radio Frequency Amplifier		
14. Filter Box	22. Capacitor Feedthrough	.719
Filter Box	23. Capacitor	2.908
15. Interlock Switch Assembly	24. Interlock Switch	1.200
16. RF Board	25. RF Board	1.628

* A sixteenth subassembly was added to provide a greater range of components in the final sample.

Selection of Failures--AN/APS-115

The basic source for selecting the sample of AN/APS-115 failures for inclusion in the present study was Fleet collected time between removals data (the ratio of removals of faulted components to unit flying hours). Maintainability records for the AN/APS-115 covering the 13 months from January 1970 to February 1971 were made available by the group which compiled the data at NAS, Patuxent River. Only organizational level repairs were considered for inclusion in the sample. During this period, 29 component removals and replacements occurred at the organizational level. The range of time between removals was from 606 to 19,392 hours, with a mean of 9,375 hours and a standard deviation of 6,771 hours.

A frequency distribution of the time between removals appears in Table 9. The final sample, presented in the third column of Table 9, consisted of 24 failed components selected so as to reflect the distribution which appears in the second column of Table 9. Table 10 lists these 24 components. The sample of 24 components had a mean time between removals of 8,442 and a standard deviation of 6,271.

Table 9

Frequency Distribution of Time Between Component Removals for the AN/APS-115 and for Sample

TBR (in hundreds of hours)	Fleet Frequency	Sample Frequency
190-199	7	4
180-189		
170-179		
160-169		
150-159		
140-149		
130-139		
120-129	3	3
110-119		
100-109		
90- 99	6	5
80- 89		
70- 79	1	1
60- 69	1	1
50- 59		
40- 49	2	2
30- 39		
20- 29	4	4
10- 19	3	2
1- 9	2	2
	29	24

Table 10

Sample of Components for Technician Reliability Analysis of AN/APS-115

Nomenclature	Mean Time Between Removals
AZ Amp Assembly	12,928
PS Logic Assembly	6,464
P-M Logic Assembly	4,848
MSSW Logic Assembly	19,392
AS Synchronizer	19,392
BITE Logic Assembly	9,696
Tilt Function Generator Assembly	9,696
15 V Power Supply Assembly	19,392
AZ Scan Programmer Assembly	970
AFC Assembly	2,770
IF Amp Assembly	2,424
Solid State Oscillator	19,392
Transmitter Assembly	606
Thyratron Trigger-Regulator Assembly	2,041
Logic, Isolation Amplifier	12,928
BITE No. 2	9,696
20 V Power Supply	9,696
Pressurization Unit Assembly	2,586
Antenna Assembly	4,848
Gear Box 3/8 Azimuth	616
Gear Box, Elevation	1,847
Antenna Control Unit 4	9,696
Control Radar Unit	7,757
Tilt, Amplifier Assembly	12,928

AUGMENTATION OF COMPUTER SIMULATION MODEL

To augment the Siegel-Wolf simulation model so that its output would be based on the same input data substrate as the deterministic calculations of the probability of malfunction correction success, a number of changes were implemented in the computer routine.

All changes made to the basic simulation model, described in Chapter I, were made external to the basic mission simulation program. Programmatically, these changes were implemented through an independent subroutine called RAM (Reliability and Maintainability) and through changes to the INPUT routine. Thus, all changes to the simulation model constitute a new preprocessing of the basic probability (p_{ij}) input data to reflect improved personnel performance success/failure data. Following the preprocessing, the adjusted probability data are used by the original model, and the original program is essentially unmodified.

The decision to preprocess the input data, rather than modify the model per se, is basic to the approach to the design of the simulation here considered. The alternative was a recalculation of conditions at the time of simulation of each subtask. The preprocessing approach was selected for the following reasons:

1. It provided for adjustments to be made once for each N iteration simulations, rather than performmance of these calculations for each of N iterations. This reduces the computer time required for simulation.

2. It required only small changes to the original computer program for the simulation, those changes being restricted to the INPUT routine and formats. This reduced program development and checkout times.

3. It promised comparable accuracy and validity of results within the context of Monte Carlo simulation methods.

4. It left the original model essentially unaltered. Thus, its internal validity and operating characteristics remain known and unaffected.

Input Data Required

The input data required by the RAM preprocessor are essentially the same as those required by the basic Siegel-Wolf model except for the addition of two one-digit code fields in the input punched cards. The first of these new inputs, the Job Activity Group (JAG code) is punched into card column 76 of the card for every task element performed by any technician. The code assignments for the 9 active job activity (factor) groups are given in Table 11. That is, each task element is categorized during the task analysis as belonging to one and only one of the factors. The code assignments are also shown in Table 11.

The second one-digit code is contained in the operator cards as an addition to data previously punched in these cards. This digit represents the Job Operator Type (JOT) punched in card column 42 to identify the Navy rate of each of the technicians simulated. The code assignment is shown in Table 12. This code controls the selection of appropriate success probability factors, as described later, for the type of technician (Navy rate) selected for simulation.

Table 11

Job Activity (Factor) Group (JAG) Codes

Code	Description	
0	None of the following	
1	Electro-cognition	EC
2	Electro-repair	ER
3	Instruction	I
4	Electro-safety	ES
5	Personnel Relationships	PR
6	Electronic Circuit Analysis	ECA
7	Equipment Operation	EO
8	Using Reference Material	URM
9	Inspection	EI

Table 12

Job Operator Type (JOT) Codes

Code	Description	
0	None of the following	
1	Electrician's Mate	EM
2	Electronic Technician	ET
3	Fire Control Technician	FT
4	Interior Communications Technician	IC
5	Radar Technician	RD
6	Radioman	RM
7	Sonar Technician	ST
8	Torpedoman	TM

Flow Logic Description

A description of the logic and arithmetic operations performed by the preprocessor is given in this section. It is noted that the use of this preprocessor is designed to apply exclusively to maintenance and repair actions due to the unique tailoring of the processing to data available for Naval personnel performing these specific types of duties.

The function of this preprocessing is to adjust the data usually provided to the model as task element success probabilities ($\bar{p}_{ij}$ values) by type of technician (JOT) and by type of job activity (factor)(JAG).

The sequence of operation is given in the flow chart presented as Figure 4. It is assumed that all input data are prepared in card form as usually provided for the model plus the two additional codes discussed above. This general flow chart was implemented programmatically by the sequence of operations shown in the more detailed flow chart presented as Figure 5.

Each of the technicians to be simulated is preprocessed independently. If no JOT is given for either operator, then the entire preprocessor is bypassed and processing continues with the model directly. If a JOT from 1 to 8 is given for a technician, the processing is performed for each operator for which a non-zero JOT is given. The processing for each technician proceeds as follows for each of the JAG codes.

For a JAG of zero, no adjustment is made in subtask probability ($\bar{p}_{ij}$) values. When JAG is other than zero, first the number of subtasks in each JAG is determined and the product of the $\bar{p}_{ij}$ values (PG) in each JAG is calculated. In this and all preprocessor operations, decision subtasks are not utilized as the probability associated with them does not represent subtask success and is therefore not subject to modification in this process. This product represents the cumulative probability for all operator actions in each JAG. For example, if there are five subtasks to be performed by a technician in a repair task and all have JAG = 4 (electrosafety) then the product of these five $\bar{p}_{ij}$ values represents the likelihood of that operator successfully performing all electrosafety jobs required by the malfunction correction.

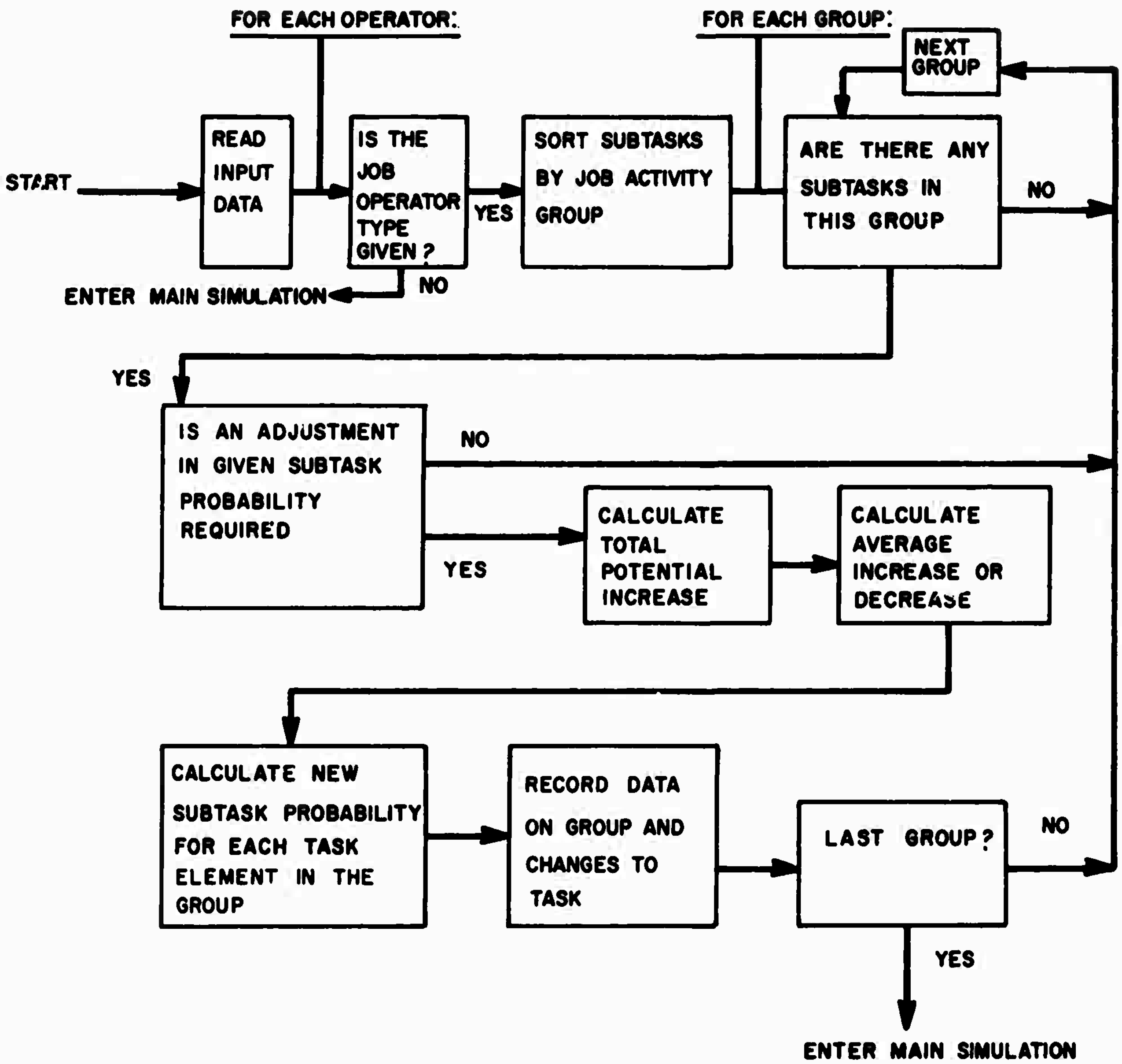

Figure 4. Summary flow chart of preprocessor.

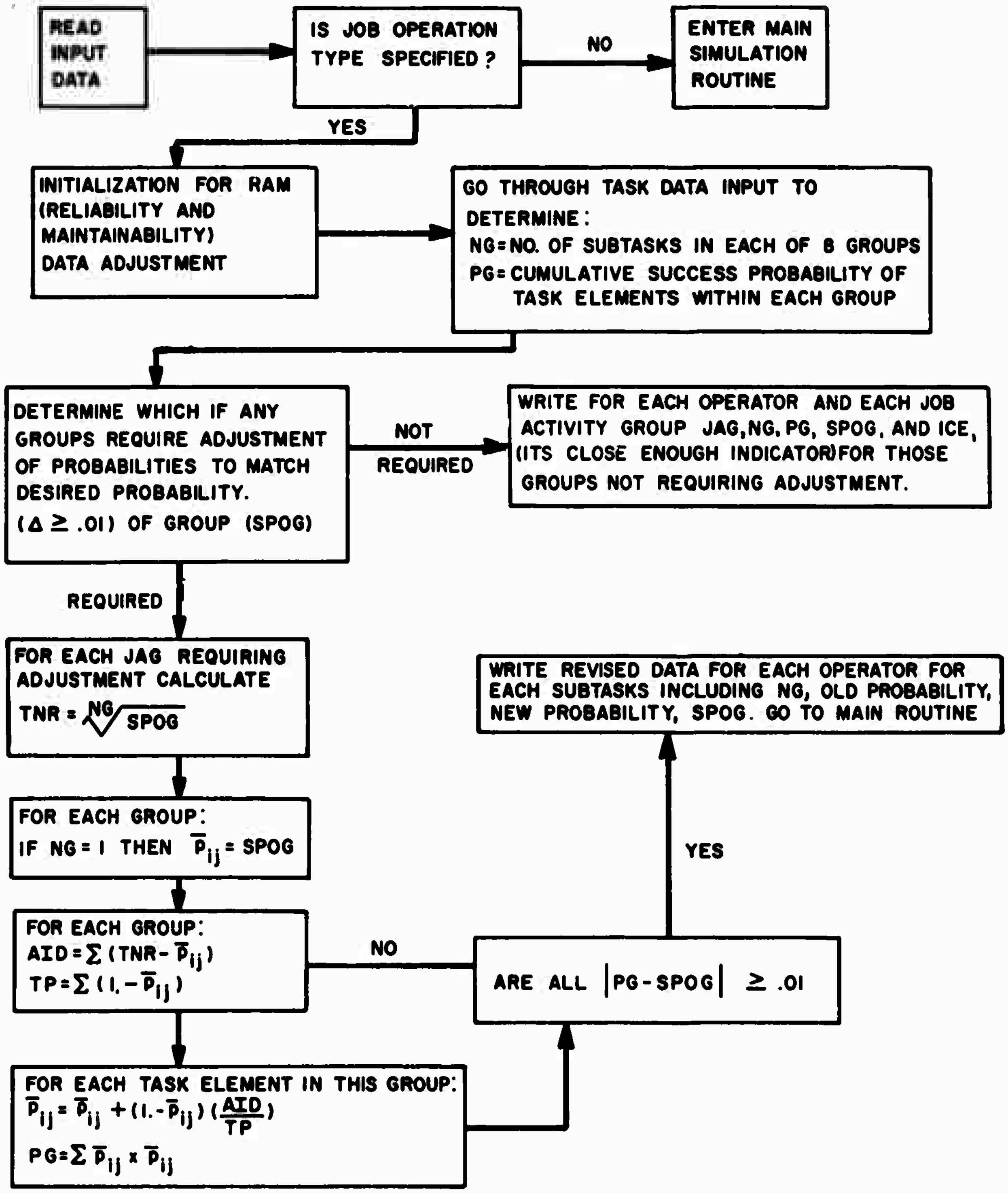

Figure 5. Basic programming elements for preprocessor.

It is this product which ideally should equal the personnel factor reliability values described in Chapter I and shown in Figure 2. These are called success probability of the group (SPOG). It is the basic purpose of this preprocessor to adjust, if necessary, each input $\bar{p}_{ij}$ value (by JAG) so that this agreement occurs within a reasonable tolerance. The tolerance was selected to be 0.01. Thus, if the product $|PG - SPOG(JAG, JOT)| \le 0.01$, then no further processing is required and the next JAG is considered. In the case that only one subtask appears in a given JAG, the $\bar{p}_{ij}$ of the subtask is set equal to the SPOG value for the JAG and JOT under consideration.

In the event that further processing is required, the NGth root of SPOG is calculated where NG is the number of task elements having a given JAG. This root represents an initial value for $\bar{p}_{ij}$ which satisfies the desired condition. That is, if all task elements possess an equal $\bar{p}_{ij}$, then their product would equal the appropriate SPOG value. Consequently, this root, called TNR, is an initial value used in the determination of individual new $\bar{p}_{ij}$ values.

A value is then calculated for the average increase or decrease in $\bar{p}_{ij}$ for individual task elements. This value is

$$AID = \sum_{i=1}^{NG} (TNR - \bar{p}_{ij}).$$

The total potential increase for all task elements of the group is then calculated:

$$TP = \sum_{i=1}^{NG} (1 - \bar{p}_{ij}).$$

New success probabilities for each task element in the group are then calculated according to the formula:

$$\text{new } \bar{p}_{ij} = \text{old } \bar{p}_{ij} + (1 - \bar{p}_{ij})\frac{AID}{TP}.$$

This represents a change to the original $\bar{p}_{ij}$ value which is a function of the potential increase of the individual subtask $(1 - \bar{p}_{ij})$ and the ratio of average to total possible change.

To verify that this process has given $\bar{p}_{ij}$ values which meet the SPOG criterion, the product PG is again calculated and the test $|PG - SPOG| < 0.01$ is again applied. If passed, processing proceeds to the next JAG; otherwise another iteration is made of the $\bar{p}_{ij}$ adjustment algorithm.

In tracing through the task analysis in order to determine the number of subtasks of each type, the computer follows the most probable success failure probabilites, $(i, j)_s$ and $(i, j)_f$. Those task elements which are not included along that path are therefore not modified in $\bar{p}_{ij}$.

A computational example is presented as Figure 6.

INPUT

JAG: ES, group 4
JOT: IC, operator type 4
SPOG: 0.65

Task elements with JAG = 4	$\bar{p}_{ij}$	new $\bar{p}_{ij}$ (see below)
1	0.85	0.947
4	0.98	0.993
5	0.75	0.912
6	0.90	0.965
7	0.75	0.912
8	0.99	0.996
9	0.90	0.965
18	0.75	0.912
NG = 8		

$$PG = \prod_{1}^{NG} \bar{p}_{ij} = 0.85 \times 0.98 \ldots \times 0.75 = 0.320; \qquad |0.65 - 0.32| < 0.01?$$

$$TNR = \sqrt[8]{0.65} = 0.95$$

$$TP = \sum_{i=1}^{NG} (1 - \bar{p}_{ij}) = 0.15 + 0.02 + \ldots + 0.25 = 1.13$$

$$AID = \sum_{i=1}^{NG} (TNR - \bar{p}_{ij}) = 0.10 - 0.03 + \ldots + 0.2 = 0.73$$

new probabilities:

$$\bar{p}_{11} = 0.85 + (0.15)\left(\frac{.73}{1.13}\right) = 0.947$$

$$\bar{p}_{41} = 0.98 + (0.02)\left(\frac{.73}{1.13}\right) = 0.993$$

$$\vdots$$

$$\bar{p}_{18,1} = 0.75 + (0.25)\left(\frac{.73}{1.13}\right) = 0.912$$

Figure 6. Example of preprocessing calculation

Recorded Preprocessor Output

Prior to adjustment of task element success probabilities, a short table of data is recorded for printing by the preprocessor. It includes for each job activity (JA) the number of task elements in the group (NG), the product of group $\bar{p}_{ij}$ values (PG), and the target success probability of the group (SP). Groups for which no adjustment in $\bar{p}_{ij}$ values need be made are identified by OK = 1; others by OK = 0. A sample of this output is given in Figure 7.

Following the preprocessing, a table is recorded for printing (Figure 8) for each operator. It contains for each task element the task element number, the JAG (GROUP), the number of task elements in the group (N-GRP), and both the old and new task element probabilities (OLDPROB and NEWPROB).

Frequency Distribution Augmentation

Because of the importance in this research of frequency distribution plots of the amount of time used by the simulated operator, the Siegel-Wolf simulation model was further augmented with a subroutine to record and plot such frequency distributions.

ORIGINAL DATA BEFORE ADJUSTMENT FOR OPERATOR 1

JA	NG	PG	SP	OK
1	1	.890	.89	0
2	8	.567	.98	0
~~3~~	~~0~~	~~0.000~~	~~.98~~	~~1~~
4	1	.980	.97	0
5	0	0.000	.72	1
~~6~~	~~6~~	~~.941~~	~~.89~~	~~0~~
7	15	.444	.92	0
8	4	.245	.90	0
~~9~~	~~0~~	~~0.000~~	~~.78~~	~~1~~

Figure 7. Example of initial preprocessor output.

REVISED DATA FOR OPERATOR 1

TASK-EL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1	-0			.880	.880
2	6	1	.55	.980	.970
3	7	15	.92	.580	.949
4	7	15	.92	.990	.944
5	1	1	.55	.890	.890
6	7	15	.92	.990	.944
7	8	8	.88	.990	.981
8	7	15	.92	.990	.944
9	8	4	.73	.500	.949
10	8	8	.88	.990	.981
11	7	15	.92	.990	.944
12	-0			.990	.990
13	8	4	.73	.500	.949
14	8	8	.88	.990	.981
15	7	15	.92	.990	.944
16	-0			.990	.990
17	8	8	.82	.990	.981
18	7	15	.92	.990	.944
19	8	4	.73	.990	.944
20	-0			.990	.990
21	7	15	.92	.990	.944
22	-0			.980	.980
23	-0			.990	.990
24	-0			.550	.550
25	-0			.750	.750
26	-0			.950	.950
27	2	8	.78	.890	.948
28	2	8	.78	.990	.998
29	2	8	.78	.980	.949
30	2	8	.78	.980	.944
31	2	8	.78	.970	.944
32	2	8	.78	.970	.949
33	2	8	.78	.890	.998
34	2	8	.78	.890	.998
35	8	8	.82	.990	.981
36	7	15	.92	.990	.944
37	8	8	.82	.990	.981
38	7	15	.92	.990	.944
39	-0			.950	.950
40	-0			.950	.950
41	-0			.980	.980
42	7	15	.92	.990	.944
43	7	15	.92	.990	.944
44	7	15	.92	.970	.946
45	7	15	.92	.990	.944
46	-0			.840	.890
47	-0			.980	.960
48	7	15	.92	.890	.947
49	-0			.980	.930
50	-0			.880	.880
51	-0			.980	.980
52	-0			.990	.990
53	-0			.810	.810
54	-0			.990	.990
55	-0			.990	.990
56	-0			.980	.930
57	-0			.890	.890
58	-0			.700	.700
59	-0			.800	.800
60	-0			.950	.950
61	-0			.950	.950
62	8	4	.73	.990	.944

Figure 8.

Sample final preprocessor output.

TECHNIQUE APPLICATION

Having selected two current Navy electronic systems and a representative sample of malfunction corrections within these systems and having developed and tested the preprocessing subroutine to the Siegel-Wolf model, the deterministic technique (for predicting the probability of successful malfunction correction) and the computer simulation (for predicting time to complete successfully the correction) were applied.

Task Analyses

In order to obtain the basic data required for application of these techniques, complete task analyses were completed for all malfunction corrections included in the samples. These task analyses were first developed with the assistance of Fleet personnel at the Naval Ships Engineering Center, Norfolk Division (AN/URC-35) and at NAMTD, NAS Patuxent River (AN/APS-115), who possess the responsibility for maintaining these equipments.

Having developed and set the task analyses in proper preliminary form, the task analyses were resubmitted to the Fleet personnel for review. Revisions and modifications suggested by these persons were incorporated into the analyses. In all, 49 such analyses were completed. A sample of one such task analysis is presented in Table 13.

Table 13

Sample Task Analysis

Task: Repair Filter--AN/URC-35

1. Opens drawer (AM3007)
2. Defeats interlock switch
3. Keys handset to check power
4. Checks power meter
5. Adjusts APC on module and checks meter
6. Turns off power at set
7. Tests pin 2 with ohmmeter
8. Reads ohmmeter
9. Manual lookup
10. Tests pin with ohmmeter
11. Reads ohmmeter
12. Removes cable 1A2J21 on 618
13. Manual lookup
14. Tests pin with ohmmeter
15. Reads ohmmeter
16. Removes filter box
17. Tests on open coil with ohmmeter
18. Reads ohmmeter
19. Fills out requisition form for pts C39 and L10
20. Walks to bulkhead and back
21. Turns off power at bulkhead
22. Pulls out chassis from 618 cabinet
23. Tilts cabinet upward
24. Unlocks chassis
25. Removes chassis
26. Removes plugs and screws from filter box cover
27. Unsolders wires from capacitor
28. Unsolders wires from choke
29. Removes old capacitor
30. Removes old choke
31. Replaces new capacitor
32. Replaces new choke
33. Solders wires on new capacitor
34. Solders wires on new choke
35. Checks choke with ohmmeter
36. Reads ohmmeter
37. Checks capacitor with ohmmeter
38. Reads ohmmeter
39. Walks to bulkhead and back
40. Turns on power at bulkhead
41. Turns on power at set
42. Turns Tune-Operate SW to tune
43. Reads meter
44. Removes screws from AM-3007
45. Pulls AM-3007 out to lock position
46. Adjusts APC Adjust on module
47. Replaces plugs and screws on filter box cover
48. Locks chassis
49. Pushes in chassis
50. Untilts chassis
51. Replaces chassis
52. Replaces filter box
53. Replaces cable 1A2J21
54. Closes drawer(AM-3007)
55. Replaces screws in AM-3007
56. Fills out failure report

Probability of Successful Malfunction Correction Determination

To apply the mathematical technique for predicting malfunction correction success probability, an analyst, who was thoroughly familiar with the malfunction correction procedure and with the definitions of the job factors, reviewed each task analytic statement to determine which job factor(s) are applicable to each of the 49 malfunction corrections. An example of the result (for the task analysis shown in Table 13) is presented below:

Series Case: $P_r[s] = R_{EC}R_{ER}R_{EO}R_{URM} =$

Parallel: $P_r[s] - [1 - (1-R_{EC})^2][1 - (1-R_{ER})^2][1-(1-R_{EO})^2]$
$[1 - (1-R_{URM})^2]$

These data were then compounded in accordance with the methods described in Chapter I of this report to yield separate series and parallel malfunction correction success probability predictions for each of the 49 malfunctions in the samples. In all cases, the malfunction correction was assumed to be performed by persons in the electronics technician rate, the Navy rate which possesses the responsibility for maintaining the AN/URC-35 and the AN/APS-115 equipments.

Time for Malfunction Correction Determination

For 10 of the AN/URC-35 malfunction corrections and for five of the AN/APS-115 malfunction corrections the input data, required by the Siegel-Wolf model and the preprocessor developed in the course of the present work, were prepared. Computer simulation of the performance of these 15 malfunction corrections was performed to yield estimates of malfunction correction time.

To select the malfunction corrections to be involved in the computer simulations, a set was selected for the AN/URC-35 so as to reflect the MTTR range and mean. The AN/APS-115 sample for computer simulation was selected on the basis of the MTBR range and mean for this equipment. The malfunction corrections computer simulated were:

AN/URC-35

1. Filter
2. Connector on Receiver IF Audio
3. Transformer
4. RF Amplifier Assembly
5. Megacycle Assembly
6. Connector on Noise Blanker
7. Switch 10 KC
8. Code Generator
9. Interlock Switch
10. RF Board

AN/APS-115

1. Azimuth Servo Amplifier Assembly
2. AS Synchronizer
3. Automatic Frequency Control Assembly
4. Thyraton Trigger-Regulator Assembly
5. 20 V Power Supply

The Siegel-Wolf model allows for simulation of persons who work at various speeds (also interpreted as persons at different proficiency levels). In the case of a single technician being assigned to the malfunction correction, the speed parameter (F_j) was varied over three levels. This variation allowed the determination of time predictions in the unitechnician case for average speed (proficiency) technicians ($F_j = 1.0$), for "fast" technicians ($F_j = 0.9$), and for "slow" technicians ($F_j = 1.1$). In all cases, the stress threshold parameter in the model was set at 2.3. This value was previously found to represent an average value for Naval technicians.

For those computer simulations involving two technicians assigned to the same malfunction correction (parallel case), the $F_{j1,2}$ values assigned to the teams were: $F_{j1,2}$ = 0.9, 0.9; $F_{j1,2}$ = 1.0, 1.0; and $F_{j1,2}$ = 1.1, 1.1. This parametric variation allowed for predictions of time for successful malfunction correction for teams composed respectively of two "fast," two "average," or two "slow" technicians.

Since the Siegel-Wolf simulation model is stochastic in nature, a number of simulations (iterations) must be performed. Each iteration will yield a different output (malfunction correction time). In the present case, 100 simulations were performed for each malfunction correction and for each operator type (F_j value) or team composition involved. The resultant data are held to represent the predicted malfunction correction time distribution for each malfunction and for each operator type or team composition.

Interuser Reliability

Since the deterministic technique depends on analyst assignment of relevant job factors, a subinvestigation was performed into the extent of interuser agreement to be anticipated from such factor assignments. To this end, three analysts independently made job factor assignments to each of the 49 malfunction corrections here involved. These assignments were made on the basis of the task analyses, described above. Phi coefficients were then calculated to represent the extent of agreement between analysts and the overall agreement among the three analysts. This latter determination was based on a procedure suggested by Guilford (1965, p. 334).

CHAPTER III

RESULTS

The computational technique, described in Chapter I of the current report, was applied to all 25 malfunction corrections sampled for the URC-35 radio set. The probability of success prediction for a given malfunction correction involves the multiplicative relationship among all job factors involved in that malfunction correction. For example, if the following job factors were involved for a given malfunction correction: electro-cognition, electro-repair, equipment operation, and using reference material, the formula for the probability of task success in the series (single technician) case is:

$$P_r[s] = R_{EC}R_{ER}R_{EO}R_{URM}$$

since each must be performed satisfactorily for successful task performance. For the parallel case (two technicians assigned to the malfunction correction) the formula is:

$$P_r[s] = [1 - (1-R_{EC})^2][1 - (1-R_{ER})^2][1 - (1-R_{EO})^2][1 - (1-R_{URM})^2]$$

The predicted probability that a maintenance technician (in the electronics technician rating) will satisfactorily complete each malfunction correction on his own, and the parallel personnel reliabilities are presented in Table 14. For the single technician, the range of predicted probability for successful malfunction correction on the first attempt is from .66 to .90. The parallel technician situation indicates a considerable increase in success probability. Here, the range is from .95 to .98.

Table 14

Technician Reliability Predictions for Sample of Malfunction Corrections for the Radio Set AN/URC-35

Malfunction Correction Number	One Technician	Two Technicians
1	.73	.96
2	.71	.95
3	.74	.97
4	.74	.97
5	.74	.97
6	.72	.96
7	.72	.96
8	.74	.96
9	.74	.97
10	.74	.97
11	.74	.97
12	.74	.97
13	.74	.97
14	.74	.97
15	.74	.97
16	.74	.97
17	.74	.97
18	.74	.97
19	.74	.97
20	.73	.96
21	.90	.98
22	.77	.96
23	.79	.97
24	.72	.96
25	.66	.96

The probability that a maintenance technician in the electronics technician rating will satisfactorily complete any random one of the 25 AN/URC-35 malfunction corrections sampled may be expressed by a measure of central tendency. In this instance, the median and mean result in the same probability value, .74. The probability that two maintenance technicians in the electronics rating working together will satisfactorily complete any random one of the 25 malfunction corrections on the first attempt is .97.

Reliability Estimations for the AN/APS-115

The probabilities of successful malfunction correction (technician reliabilities) were calculated in the same manner for the AN/APS-115 as for the AN/URC-35. The technician reliabilities for the 24 malfunctions sampled in the APS-115 are presented in Table 15.

The APS-115 is a largely modularized electronic system, as is the URC-35. In a modularized system, and at the organizational level of repair, the correction of a traced malfunction is often the simple replacement of the entire module. This has the effect of inducing a fair degree of similarity in the job factors involved in various malfunction corrections. The result in terms of the present calculations is a grouping of the probability values into approximately six classes.

For the single technician situation, the probability of successful malfunction correction on the first attempt ranged from .50 to .63. This range shifts upward for two technicians working together. For the parallel situation the range is .90 to .92. The probability that any random one of the 24 malfunctions can be corrected satisfactorily on the first attempt is .56 for the electronics technician working alone. For a pair of electronics technicians working together the probability of satisfactory completion is .91.

Table 15

Technician Reliability Predictions for Sample of Malfunction Corrections for the Radar Set AN/APS-115

Malfunction Correction Number	One Technician	Two Technicians
1	.56	.91
2	.63	.92
3	.56	.91
4	.56	.91
5	.56	.91
6	.56	.91
7	.56	.91
8	.56	.91
9	.56	.91
10	.63	.92
11	.50	.90
12	.51	.91
13	.56	.91
14	.56	.91
15	.50	.90
16	.56	.91
17	.56	.91
18	.63	.92
19	.50	.90
20	.56	.91
21	.56	.91
22	.50	.90
23	.56	.91
24	.56	.91

TIME FOR MALFUNCTION CORRECTION

As stated in Chapter I, the logic of the present method for determining human reliability rests on two separate analytic methods: (1) a deterministic calculation of the probability of successful malfunction correction, and (2) a computer simulation in order to determine the predicted time for successfully completing the malfunction correction. The results from the application of the deterministic method were presented above. The present section of this report presents the malfunction correction time predictions, as derived from application of the modifications to the Siegel-Wolf stochastic simulation model. The modifications of the model, to make the model compatible with the deterministic calculations, were described in Chapter II.

Series Case--AN/URC-35

The predicted time [for the series case (single repair technician)] to repair the 10 AN/URC-35 malfunctions included in the malfunction correction subsample subjected to computer simulation is presented in Figures 9 to 11. For each malfunction represented in Figures 9 to 11, the cumulative percentage of repairs (ordinate) within a given time period (abscissa) is given. In each presentation, separate plots are given for the "fast" and for the "slow" simulated technician. For purposes of presentational clarity, the plot for the "average" technician is not given. Such a plot may easily be interpolated between the plots for the "fast" and the "slow" technician.*

Thus, for malfunction correction 2 (replace filter) and a "fast" technician, 50 per cent of the corrections of this malfunction are predicted to be performed successfully in 2280 seconds (38 minutes). For a "slow" technician, 50 per cent of the corrections of this malfunction are predicted to be completed in 2340 seconds (39 minutes). The range of predicted time for the "fast" technician is from 1925 seconds (32.1 minutes) to 2425 seconds (40.4 minutes). The range of predicted time for successful malfunction correction in the case of the "slow" technician is from 2145 seconds (35.8 minutes) to 2425 seconds (40.4 minutes). The predicted probability of successful malfunction repair within these ranges of time, as stated earlier, is .74.

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* "Fast" technician: $F_j = 0.9$
"Slow" technician: $F_j = 1.1$

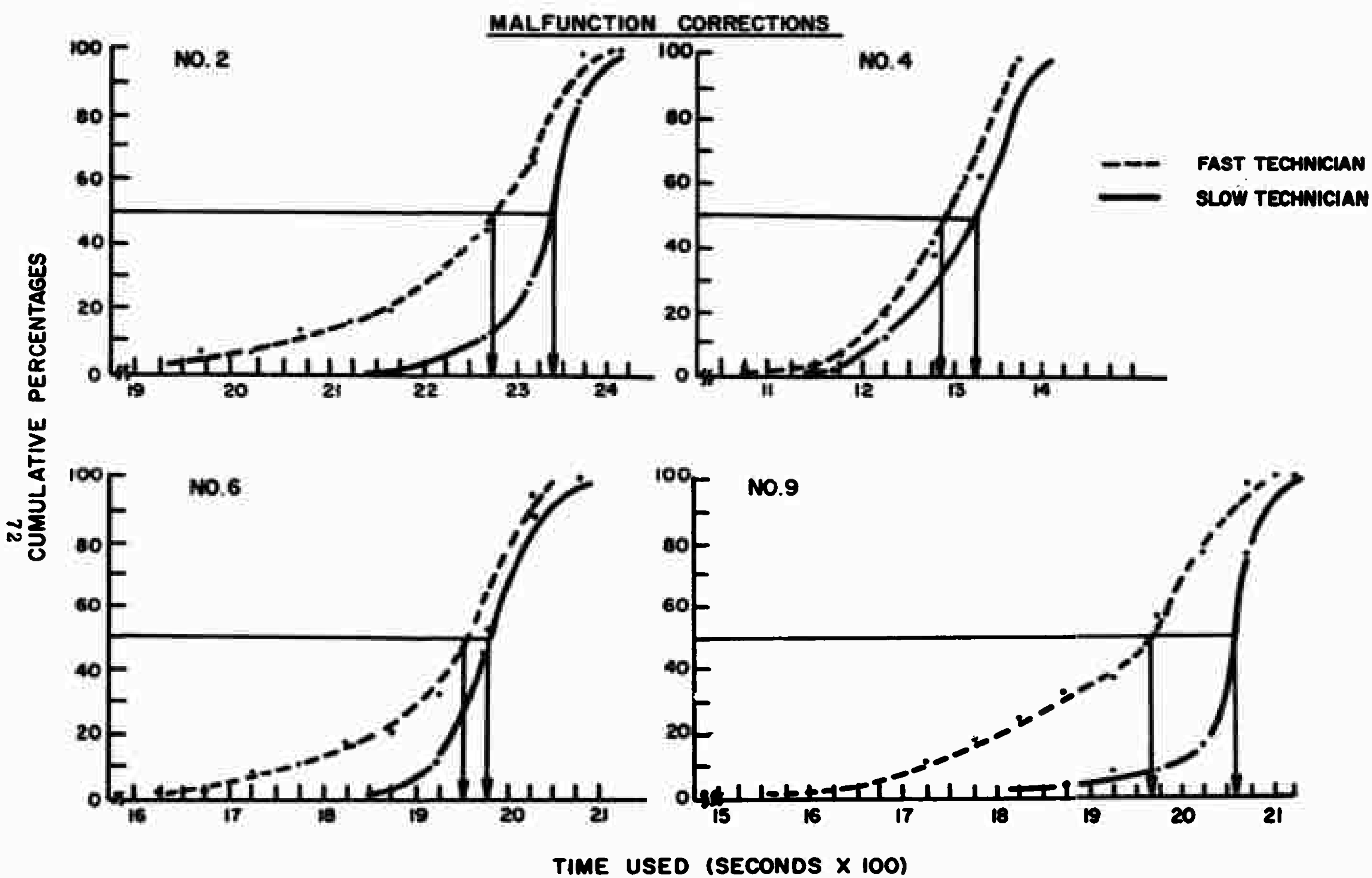

Figure 9. Predicted malfunction correction time (single technician) for malfunctions 2, 4, 6 and 9 (AN/URC-35).

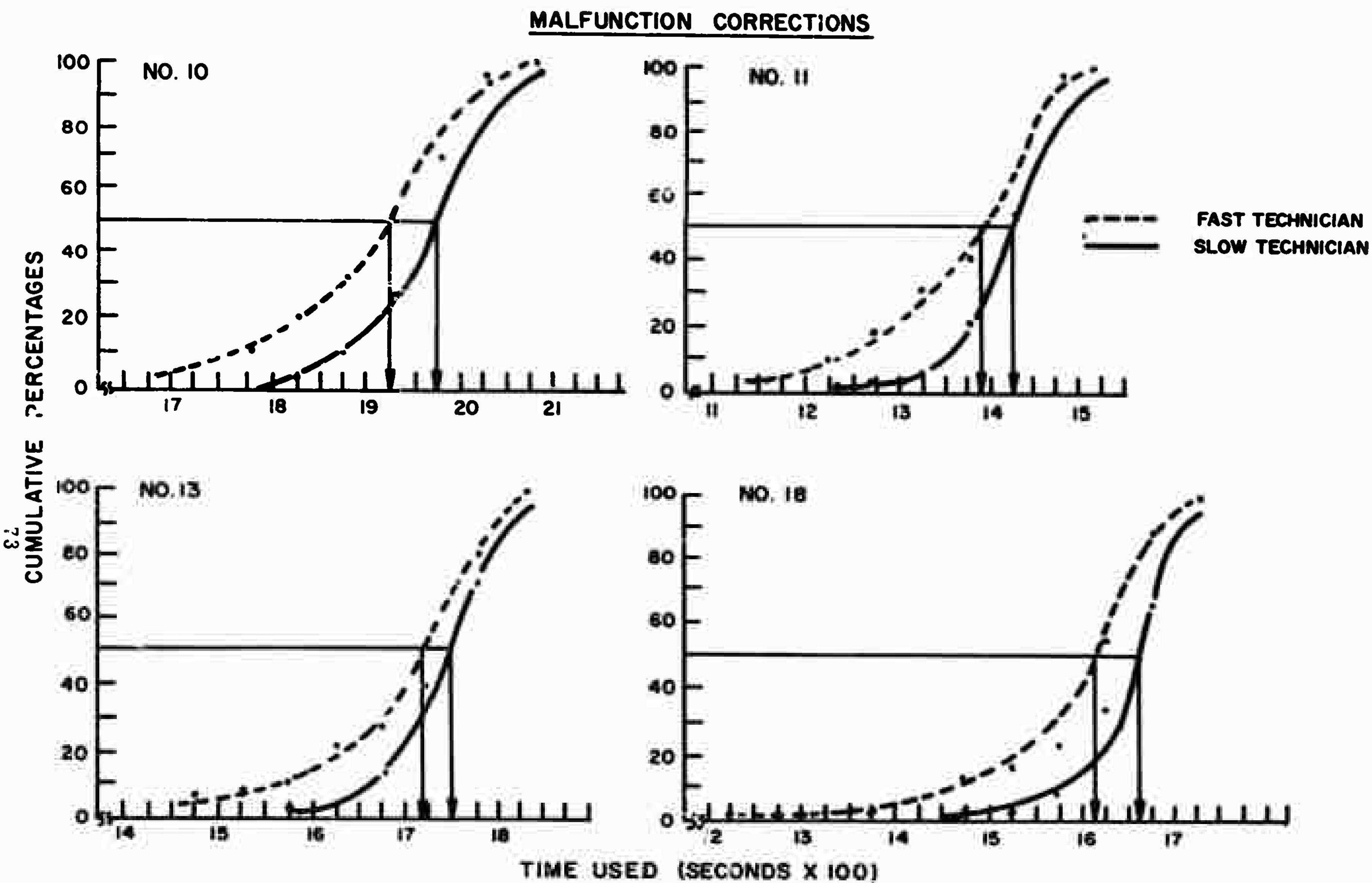

Figure 10. Predicted malfunction correction time (single technician) for malfunctions 10, 11, 13 and 18 (AN/URC-35).

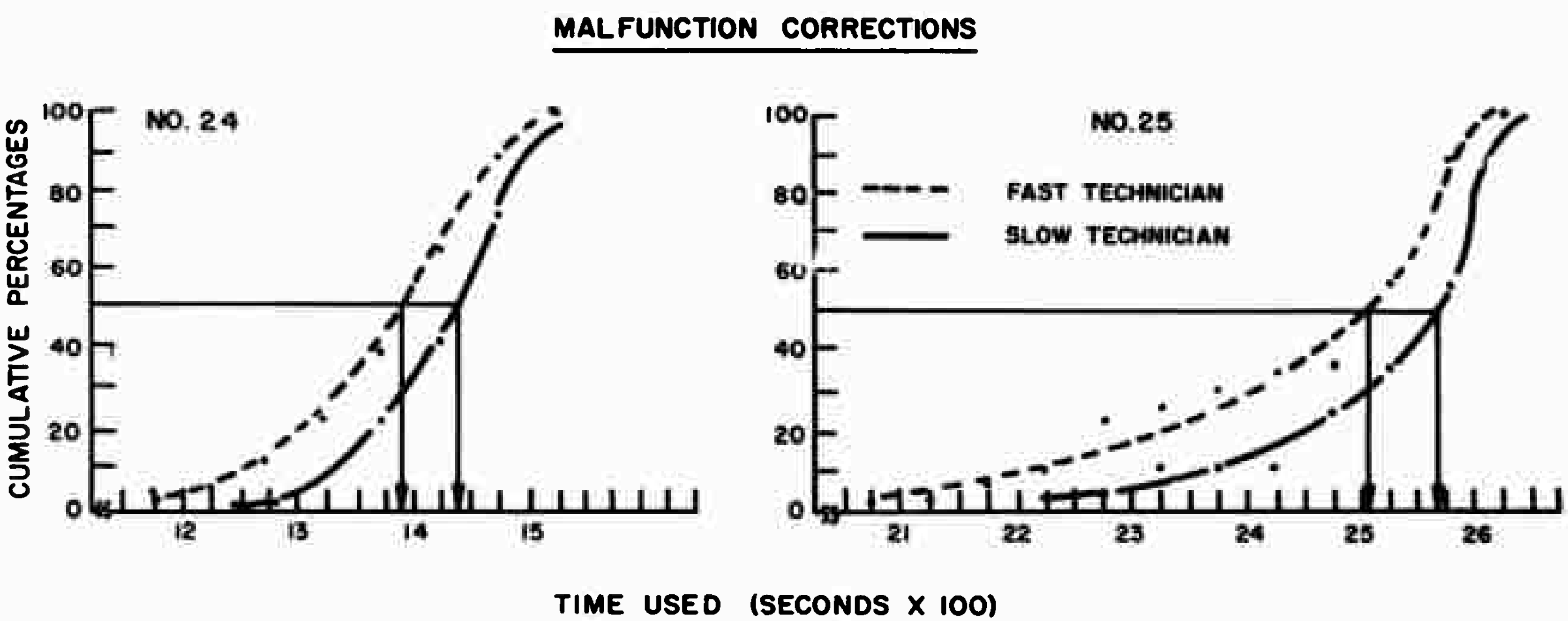

Figure 11. Predicted malfunction correction time (single technician) for malfunctions 24 and 25 (AN/URC-35).

The remaining plots in Figures 9 to 11 may be similarly interpreted.

If one considers all 10 malfunctions in the sample, the minimum predicted time for malfunction correction in the AN/URC-35 appears to be 1075 seconds (17.9 minutes)(malfunction 4, replace receiver IF audio module) and the maximum time appears to be 2625 seconds (43.8 minutes) (malfunction 25, replace RF board). The range of median values over the 10 simulated malfunction corrections is summarized below:

"fast" technician	-	1285 to 2500 seconds
"average" technician	-	1303 to 2535 seconds (interpolated)
"slow" technician	-	1325 to 2570 seconds
overall	-	1969 seconds

Accordingly, for the single technician case and on the basis of these results, the methods predict that: (1) the median time to repair the AN/URC-35 radio set is between 21.4 and 42.8 minutes, (2) the overall median is 32.8 minutes, and (3) the mean probability of accomplishing a repair within this time interval is .74.

We note that the results suggest greater time variation within operator speed (proficiency, F_j) values than between speed values. Since most of the trouble shooting on this equipment unit is performed with the use of simple test equipment and since most of the repair actions consist of module replacement, such a result might have been anticipated. With such an equipment design, malfunction correction is reduced to a least common denominator, and differences in maintenance technician proficiency may receive little opportunity to manifest themselves. Possibly, only with more sophisticated and demanding equipment repair actions would such differences become manifest. Moreover, we note that even for the $F_j = 1.1$ operator, basic electronic training and training on the equipment involved is assumed. This interpretation has been placed on the predictions generated by the Siegel-Wolf model in prior employments and continues to hold in the present case.

Parallel Case--AN/URC-35

A similar set of analyses was conducted from the situation in which two maintenance technicians are assigned to complete each malfunction correction. This is the case of parallel manning. The resultant data are presented in Table 16. The data included in Table 16 parallel those found in Figures 9 to 11. Specifically, in Table 16, the cumulative percentage of simulations completed within a given time interval is presented by malfunction for the simulated team composed of two "fast" maintenance technicians and for the simulated team composed of two "slow" maintenance technicians. Again, malfunction 4 (replace receiver IF audio module) is indicated to be at the extreme low end of the malfunction correction time distribution. However, when two technicians are assigned to the task, malfunction corrections 11 (replace noise blanker module) and 24 (replace interlock switch) also assume some low ordering. Malfunction correction 25 (replace RF board) is, as in the series case, the malfunction with the greatest predicted correction time. The range of median values over the 10 simulated malfunction corrections involving parallel manning is summarized below:

"fast" team	-	1315 to 2510 seconds
"average" team	-	1335 to 2555 seconds (interpolated)
"slow" team	-	1355 to 2590 seconds
overall	-	1945 seconds

Comparison of the above summary with the prior summary suggests that the parallel manning, although increasing the mean probability of success over the unioperator manning from .74 to .97, had little effect on the time for successful malfunction correction. Such a result is believed to be reasonable since the malfunction corrections simulated are of such a nature that little time savings can be introduced by a second man. Accordingly, the present data suggest that a second man serves to introduce greater accuracy and to decrease the number of unsuccessful malfunction corrections, but does little in terms of positively affecting the repair time.

Table 16

Cumulative Percentage of Corrections within Stated Times for the AN/URC-35 (Parallel Technicians)

Interval (seconds)	Malfunction Correction 2		4		6		9		10		11		13		18		24		25	
	F*	S**	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S
1050-1100			3								4						3			
1100-1150			3								4						3			
1150-1200			13	5							6						5			
1200-1250			20	10							14	2					13			
1250-1300			39	32							28	4					22			
1300-1350			74	43							38	17	2				36	6		
1350-1400			100	100							54	41	4				52	34		
1400-1450											74	67	4		5		70	59		
1450-1500											100	98	9		14		90	87		
1500-1550					2				2		100	100	15		21	5	100	100		
1550-1600					2				4				18		26	5				
1600-1650					2		4		4				28	7	45	20				
1650-1700					4		4		8				35	22	78	41				
1700-1750					4		9		15				52	46	100	100				
1750-1800					7		16		20				83	61						
1800-1850					13		24		28	3			100	100						
1850-1900					24	13	35	3	32	13										
1900-1950	2				38	21	38	6	46	27										
1950-2000	3				58	45	53	18	70	50									3	
2000-2050	3				[illegible]	92	73	38	98	93									3	
2050-2100	6				100	100	95	88	100	100									10	
2100-2150	13						100	100											13	
2150-2200	17																		15	
2200-2250	30																		16	
2250-2300	43	14																	23	
2300-2350	70	46																	28	
2350-2400	95	91																	33	3
2400-2450	100	100																	39	6
2450-2500																			46	19
2500-2550																			66	25
2550-2600																			85	56
2600-2650																			100	100

*F = "Fast" team
**S = "Slow" team

As for the single maintenance technician case, there is again greater within team variation than between team variation. The interpretation given in the unitechnician case, which ascribed this finding to the nature of the AN/URC-35 malfunction correction requirements, is also offered here.

To summarize from the parallel manning point of view, the techniques here applied yielded a predicted median malfunction correction time for the AN/URC-35 which ranged between 21.9 minutes and 43.2 minutes. The best overall estimate of malfunction correction time in this case is 32.4 minutes. The mean probability of malfunction correction was estimated to be .97.

Series Case--AN/APS-115

The data relevant to the time for malfunction correction in the AN/APS-115 are presented in the same manner as were the time predictions for the AN/URC-35. Cumulative percentages of successful repairs within the given time intervals are presented, for the five AN/APS-115 malfunction corrections subjected to this analysis, in Figures 12 and 13. At least for the malfunction corrections sampled, the total range of malfunction correction time in this system seems to be greater than for the AN/URC-35. A total range of times from around 700 seconds (11.7 minutes)(malfunction correction 105) to 4350 seconds (72.5 minutes)(malfunction correction 117) was indicated. Malfunction correction 105 involves replacing the AS synchronizer module, while malfunction correction 117 is concerned with the 20 V power supply module.

Moreover, greater differences are noted between the "fast" and the "slow" maintenance technician in the present case than for the AN/URC-35. The reason for this finding seems to rest in the increased complexity of the AN/APS-115 as compared with the AN/URC-35.

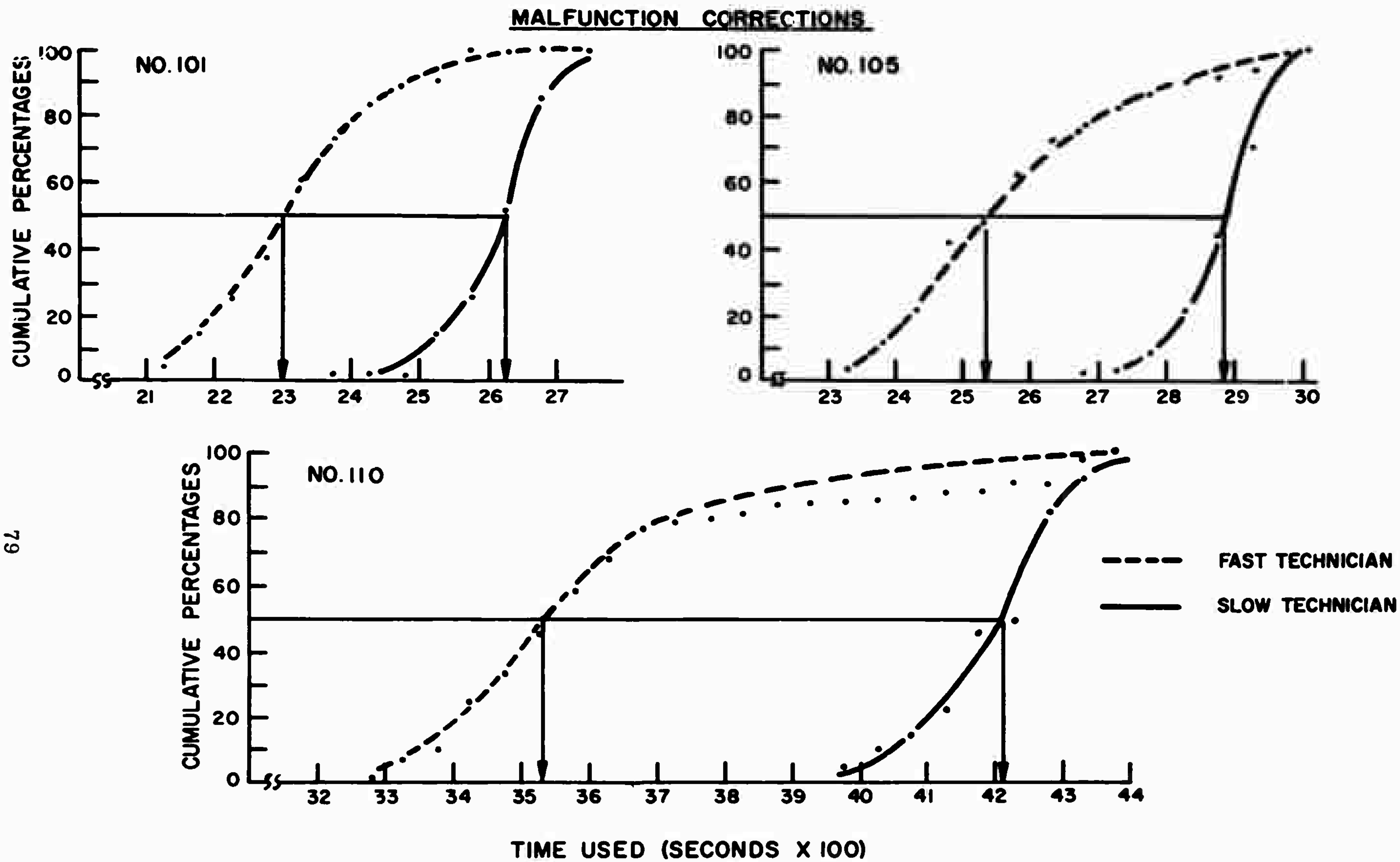

Figure 12. Predicted malfunction correction time (single technician) for malfunctions 101, 105 and 110 (AN/APS-115).

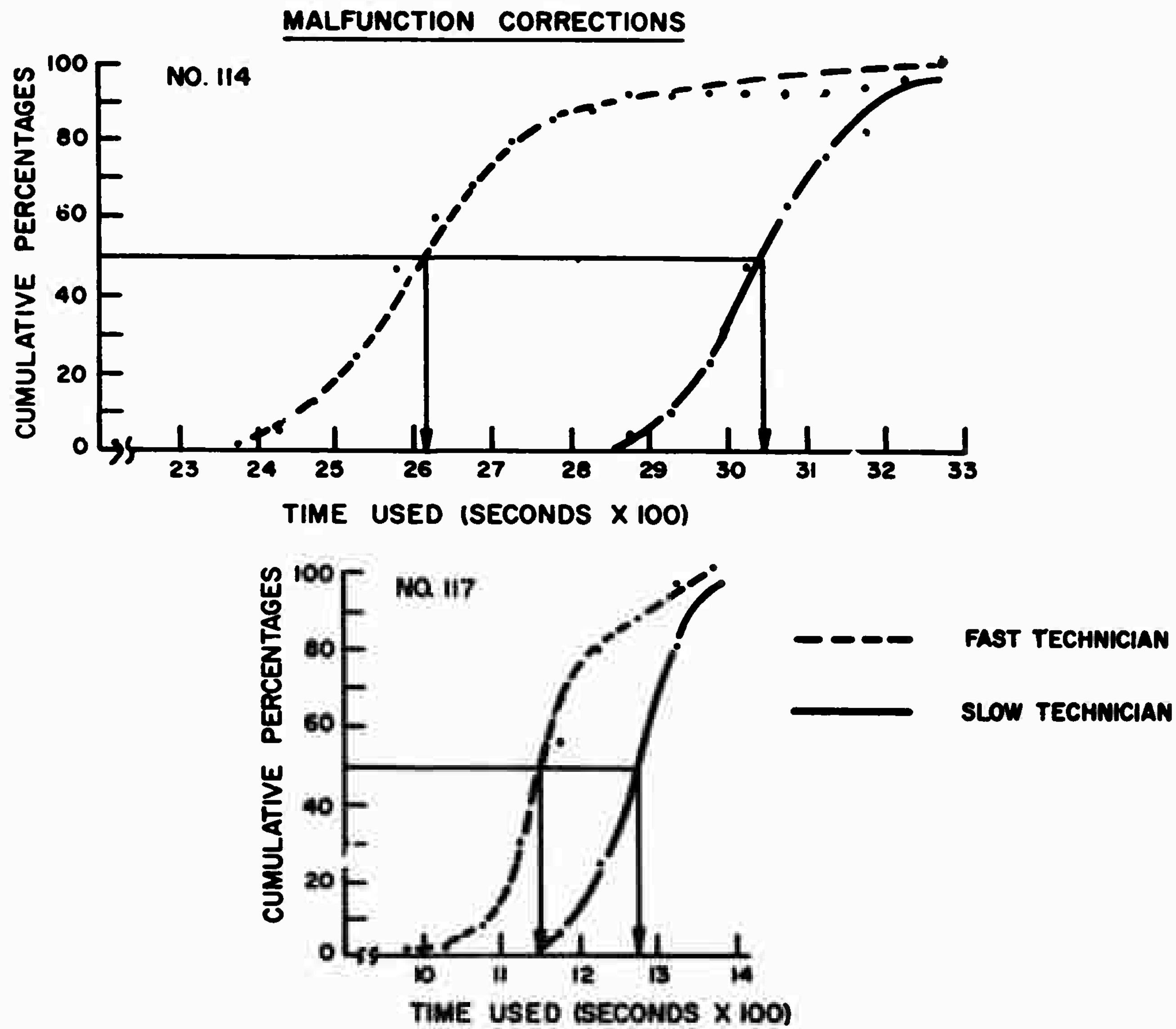

Figure 13. Predicted malfunction correction time (single technician) for malfunctions 114 and 117 (AN/APS-115).

The range of median malfunction correction time predictions for the "fast," "average," and "slow" maintenance technician is:

"fast" technician	-	1150 to 3530 seconds
"average" technician	-	1213 to 3870 seconds (interpolated)
"slow" technician	-	1275 to 4210 seconds
overall	-	2541 seconds

Here, for the single technician case, the data suggest the median time to repair the AN/APS-115 radar set to be between 19.2 minutes and 70.2 minutes with an overall median of 42.4 minutes. The predicted probability of a successful malfunction correction within this time interval was previously given as .56.

Parallel Case--AN/APS-115

As for the AN/URC-35 radio set, the data relative to the parallel manning situation are presented in tabular form (Table 17). Table 17 indicates a rather large total range (from 975 seconds to 4375 seconds). A rather extensive range spread was also indicated for the unitechnician case. There is also considerable difference indicated, in each case sampled, between the predicted median malfunction correction time for the "fast" (more proficient team) and the "slow" (less proficient) team. As for the unitechnician malfunction correction simulation, malfunction correction 10i(azimuth servo amplifier assembly) was predicted to take the least time and malfunction correction 110 (automatic frequency control assembly) was predicted to require the most time. For all five malfunctions in the sample, the range of predicted median values is:

"fast" team	-	1170 to 3565 seconds
"average" team	-	1233 to 3895 seconds (interpolated)
"slow" team	-	1295 to 4225 seconds
overall		2561 seconds

Again, we note no exceptional time savings to accrue from parallel manning. For the AN/APS-115 and for the parallel manning case, the overall prediction of malfunction correction time is 42.7 minutes. The mean probability of successful malfunction completion is .91.

Table 17

Cumulative Percentage of Corrections within Stated Times for AN/APS-115 (Parallel Technicians)

Interval (seconds)	Malfunction Correction 101 F*	101 S**	105 F	105 S	114 F	114 S	117 F	117 S
950-1000							1	
1000-1050							1	
1050-1100							11	
1100-1150							38	2
1150-1200							68	6
1200-1250							78	20
1250-1300							90	54
1300-1350							93	74
1350-1400							100	100
2050-2100	1							
2100-2150	4							
2150-2200	7							
2200-2250	14							
2250-2300	35		2					
2300-2350	49		7					
2350-2400	61		13		1			
2400-2450	85	1	32		3			
2450-2500	89	7	49		9			
2500-2550	92	13	63		29			
2550-2600	92	31	75		48			
2600-2650	93	54	88		65			
2650-2700	94	76	95		72			
2700-2750	100	100	96	3	76			
2750-2800			96	8	78			
2800-2850			98	22	86	1		
2850-2900			98	47	88	8		
2900-2950			99	74	88	19		
2950-3000			100	100	88	35		
3000-3050			100	100	90	48		
3050-3100					92	64		
3100-3150					92	82		
3150-3200					94	92		
3200-3250					96	100		
3250-3300					100	100		

Interval (seconds)	110 F	110 S
3350-3400	5	
3400-3450	17	
3450-3500	34	
3500-3550	47	
3550-3600	58	
3600-3650	67	
3650-3700	74	
3700-3750	79	
3750-3800	84	
3800-3850	86	
3850-3900	86	
3900-3950	87	
3950-4000	88	1
4000-4050	88	3
4050-4100	89	11
4100-4150	89	26
4150-4200	89	44
4200-4250	89	56
4250-4300	90	78
4300-4350	97	94
4350-4400	100	100

*F = "Fast" team

**S = "Slow" team

Interuser Reliability

To determine the extent of agreement among different users of the techniques for predicting technician reliability, three separate analysts performed job factor assignments to each of the 49 malfunctions in the samples. Between analyst agreement was estimated on the basis of phi coefficients and the total agreement across the three raters was estimated on the basis of an average phi coefficient (Guilford, 1963, p. 334).

Table 18 presents the resulting phi coefficients. The overall phi coefficient for the AN/URC-35 was .90 and for the AN/APS-115 it was .92. The agreement between the individual analysts also seems acceptable. The somewhat higher agreement for the AN/APS-115 may be attributable to the fact that approximately seven months intervened between the analysis of the AN/URC-35 and that of the AN/APS-115. During this interval, the three analysts were engaged in completing various aspects of the program, and this exposure may have contributed to a greater understanding of the job factors.

Table 18

Reliability Coefficients Among Analysts Using the Job Factors

URC-35

Analysts	ϕ
A, B	.94
A, C	.91
B, C	.85
Overall	.90

APS-115

Analysts	ϕ
A, B	.89
A, C	.97
B, C	.89
Overall	.92

CHAPTER IV

DISCUSSION AND CONCLUSIONS

The major purpose of the present study was to appraise in a Navy situation two techniques (a mathematical technique for predicting probability of successful malfunction correction on the first attempt and a computer simulation technique for predicting malfunction correction time) previously developed by Applied Psychological Services for assessing and/or predicting technician reliability in restoring malfunctioned equipment. For this purpose, two Naval electronic systems were used: Radio Set AN/URC-35 and Radar Set AN/APS-115. A sample of 49 different malfunctions, across the two equipments, was selected. The malfunction corrections were analyzed in terms of the specific maintenance job factors involved in the correction of the sampled malfunctions, and the mathematical technique was applied to yield malfunction correction success probability predictions for the case in which a single technician performs the malfunction correction and for the case in which two technicians perform the repair actions as a team. The computer simulation technique was applied to a subsample of 15 malfunctions for the specific purpose of obtaining the mean time (for both the series and the parallel cases) to complete satisfactorily each malfunction correction.

The data and methods presented in the body of this report exemplify the techniques for determining technician reliability. The predictive validity of the techniques has yet to be tested. Test of predictive validity represents the next logical step in the sequence of developing an evaluative technique and will be performed during the next period. To this end, those malfunctions to which both the malfunction correction probability predictive technique and the computer simulation technique were applied will be inserted into actual Fleet equipments. A sample of electronics technicians will be asked to correct these malfunctions and performance measurements made. These performance measurements will be correlated with the predictive data (probability of malfunction correction on the first attempt and time for malfunction correction) here reported. Both the single technician and the parallel technician malfunction correction cases will be investigated.

However, the validity of the present set of techniques can be supported on other grounds. In regard to the computer simulation, Chapter I of the present report presents a number of instances in which the validity of the Siegel-Wolf model was investigated. These validational studies represented situations which were analogous to those here considered. In regard to the deterministic technique, it can be argued that the technique possesses construct validity in that the job factors are drawn from a factor analysis of the electronic maintenance job. Moreover, the actual probabilities employed in the calculations are derived from a rather large Fleet sample and, as such, are believed to represent an acceptable data bank. The reliability of these basic data was demonstrated by Siegel and Federman (1970). In that study, retest measures were obtained on the evaluations of 100 technicians. When the means of the eight ratings were used and correlated with the means of the ratings in a second time period, the resulting coefficient of correlation was .97. When the product moment coefficient of correlation for the individual technicians was calculated, the resulting correlation was .72.

The probability combinatorial methods employed to yield an overall probability estimate are reasonable and are used in other predictive situations. The assumptions of the probability combinatorial technique in the present context are not different from those made when such probability combination is performed in other contexts.

The discriminating power of the methods here described is supported by the indications that they were sensitive to both system and parametric variation. The techniques were able to differentiate from both the probability of successful malfunction correction and the time for malfunction correction points of view both across the AN/URC-35 and the AN/APS-115 systems and for individual malfunction corrections within these systems. Moreover, time differences were shown by the computer simulation technique for "fast" (above average) and for "slow" below average technicians. The lowered probability and increased time estimates for the AN/APS-115 as compared with the AN/URC-35 might have been predicted since the AN/APS-115 is the more complicated and sophisticated gear of the two.

Contentions supporting the utility of the techniques here involved are supported, first, by the interanalyst reliabilities obtained in the present study. When three analysts separately performed the basic analyses (the professional and training backgrounds of the analysts were varied over psychology and mathematics), phi coefficients of .90 and .92 were obtained for the two electronic systems considered. Second, the methods were found to be applicable to the two different electronic systems involved and to yield results which appear to be reasonable, at least from the intuitive point of view. Moreover, the reliability specialist, on the basis of a set of data such as those here presented, is able to know which specific aspects of a system contribute to low malfunction correction probability or to unacceptable malfunction correction time predictions. In regard to the utility of the techniques, we also note that they can be employed comparatively early in the system design cycle, i.e., at a time when design modification, if indicated, can be implemented.

We further note that the application of the techniques do not depend on excessive mathematical, electronic, or human factors sophistication. They were here employed by persons with only reasonable backgrounds in these areas. This suggests that others, with similar reasonable backgrounds, should be able to employ the techniques.

The overall probability of malfunction correction on the first attempt metric produced by the present technique is highly similar in characteristics with the equipment reliability metric determined during the system design stage by the reliability engineer. Accordingly, it seems entirely reasonable to combine the current technician reliability index with the equipment reliability index to yield a total maintenance system (man and equipment) reliability index.

Finally, and of some importance, the computer simulation logic has been tailored, through the preprocessing subroutine, to be entirely compatible with the probabilistic, combinatorial technique. The two methods constitute a complementary set. While the data yielded by each method are different, the data produced by each method are entirely interpretable against the backdrop of the data yielded by the other method. Hence, the two techniques may be held to represent a coordinated set which, when applied, yields an integrated statement regarding maintenance technician reliability in the context of a specific equipment system.

Conclusions

The following conclusions seem indicated:

1. The utility, applicability, discriminating power, and reasonableness of the mathematical, probabalistic, job factor combinatorial method for predicting probability of successful malfunction correction on the first attempt appear to have been demonstrated.

2. Similarly, the computer simulation method for predicting malfunction correction time appears to represent a reasonable method for achieving this end result.

3. The two techniques may be used individually or in concert in accordance with the data and information requirements of an individual system developmental program.

4. The predictive validity of the techniques remain to be demonstrated in a malfunction repair context.

REFERENCES

Abelson, R. P. A technique and a model for multidimensional attitude scaling. Public Opinion Quarterly, 1954, 18, 405-418.

Abelson, R. P. Multidimensional scaling of facial expressions. Journal of Experimental Psychology, 1962, 63, 546-554.

Anderson, D. H., & Bakkers, A. P. Maintainability task analysis for RF amplifier AM-3007/URT. Naval Electronics Command, Washington, D. C., MA-0769-3544, October 15, 1968. (a)

Anderson, D. H., & Bakkers, A. P. Maintainability task analysis for Receiver-Transmitter RT618/URC. Naval Electronics System Command, Washington, D. C., M-0769-39, October 15, 1968. (b)

Guilford, J. P. Fundamental statistics in psychology and education. New York: McGraw-Hill, 1965.

Gullicksen, H. Linear and multidimensional scaling. Psychometrika, 1961, 26, 9-25.

Jackson, D. N., Messick, S. J., & Solley, C. M. A multidimensional scaling approach to the perception of personality. Journal of Psychology, 1957, 44, 311-318.

Lane, D. S., Schaefer, R. W., Schwarta, H. F., & Braley, G. F. Man system criteria for extra-terrestrial roving vehicles. 12504-ITR3, Honeywell Inc., 1966.

Martin, F. F. Computer modeling and simulation. New York: Wiley, 1968.

Mayberry, J. Principles for assessment of simulation model validity. In Proceedings, Symposium on Computer Simulation as Related to Manpower and Personnel Planning. Naval Personnel Research and Development Laboratory, Washington, D. C.. 1971.

Messick, S. J. The perception of attitude relationships. A multidimensional approach to the structuring of social attitudes. Unpublished doctoral dissertation. Princeton University, 1954.

Messick, S. J. The perception of social attitudes. Journal of Abnormal and Social Psychology, 1956, 52, 57-66. (a)

Messick, S. J. An empirical evaluation of multidimensional successive intervals. Psychometrika, 1956, 21, 367-375. (b)

Outcalt, N. R., & Laughlin, J. One versus two man crew study, general purpose attack aircraft, Vol. IV, crew performance computer model. D6-16276-3, Boeing, 1966.

Reeb, M. How people see jobs. A multidimensional scaling analysis. Occupational Psychology, 1959, 33, 1-17.

Richardson, M. W. Multidimensional psychophysics. Psychological Bulletin, 1938, 35, 659-660.

Saunders, D. R. Trans-varimax: Some properties of the ratiomax and equamax criteria for blind orthogonal rotation. American Psychologist, 1962, 17, 395-396 (abstract).

Siegel, A. I., & Federman, P. J. Development of performance evaluative measures: Investigation into and application of a Fleet posttraining performance evaluation system. Wayne, Pa.: Applied Psychological Services, 1970.

Siegel, A. I., & Miehle, W. Extension of a prior personnel subsystem reliability determination technique. Wayne, Pa.: Applied Psychological Services, 1967.

Siegel, A. I., & Pfeiffer, M. G. Post-training criterion development and application. Personnel psychophysics: Operational correlates of electronic circuit complexity. Wayne, Pa.: Applied Psychological Services, 1966. (a)

Siegel, A. I., & Pfeiffer, M. G. Post-training performance criterion development and application. Personnel psychophysics: Estimating personnel subsystem reliability through magnitude estimation methods. Wayne, Pa.: Applied Psychological Services, 1966. (b)

Siegel, A. I., & Schultz, D. G. Post-training performance criterion development and application: A comparative multidimensional scaling analysis of the tasks performed by Naval aviation electronics technicians at two job levels. Wayne, Pa.: Applied Psychological Services, 1963.

Siegel, A. I., & Wolf, J. J. Man-machine simulation models: Performance and psychosocial interaction. New York: Wiley, 1969.

Siegel, A. I., Leahy, W. R., Wolf, J. J., & Chubb, G. A digital computer program for estimating the effects of a nuclear environment on human performance and simulating the impact human factors can have on mission success. Dayton: Aerospace Medical Research Laboratory (in press).

Silver, C. A., Landis, D., & Jones, J. M. Development of criteria for evaluation of large-screen displays. Rome, N. Y., RADC-TR-65-198, 1965. AD#621231.

Smith, R., & Siegel, A. I. A multidimensional scaling analysis of the job of civil defense director. Journal of Applied Psychology, 1967, 51, 476-480.

Whitlock, G. H. Application of the psychophysical law to performance evaluation. Journal of Applied Psychology, 1963, 47, 15-23.

APPENDIX A

Project RAM Computer Data Element List

FORTRAN Name	Meaning/Function
SPOG(JA, JT)	SUCCESS PROBABILITY OF GROUP
JAG(IJ)	JOB ACTIVITY GROUP
NG	NO OF TASK ELEMENTS IN GROUP
PG(JA, J)	PRODUCT OF PROBABILITIES IN GROUP
TP(JA, T)	TOTAL POTENTIAL INCREASE
ICE(JA, J)	ITS CLOSE ENOUGH INDICATOR
TNR(JA, J)	(NG)THE ROOT OF PG
AID(JA, J)	AVERAGE INCREASE/DECREASE
JT	OPERATOR TYPE
JOT	JOB ACTIVITY TYPE
JA	JOB ACTIVITY
OLPROB(IJ)	STORAGE FOR ORIGINAL VALUES OF TASK ELEMENT SUCCESS PROBABILITIES
J	OPERATOR NUMBER
I	TASK ELEMENT NO

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