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ANALYSIS OF MANUAL THREAT EVALUATION AND WEAPONS ASSIGNMENT (TEWA) IN THE AN/TSQ-73 AIR DEFENSE SYSTEM

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The research reported in this paper was conducted in 1975 during the early development of the AN/TSQ-73 missile minder. The missile minder is
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representative of a class of emerging air defense systems which place unusual demands on the processing capabilities of the human operator. The purpose of the research was to evaluate human operator performance under realistic task loading, aircraft threats, and manning configurations. As a result of this study, procedures were developed which can effectively be applied to assess operator performance under a wide variety of emerging air defense systems. The procedure can also be utilized to aid in firing doctrine development, assist human factors specification, and improve interoperability decisions in linked air defense systems.

Technical Report 419

ANAYLSIS OF MANUAL THREAT EVALUATION AND WEAPONS ASSIGNMENT (TEWA) IN THE AN/TSQ-73 AIR DEFENSE SYSTEM

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FOREWORD

The Army Research Institute Field Unit at Fort Bliss is actively engaged in a research program designed to improve the evaluation of human performance in air defense systems. As tactical air threats have increased, so has the need to efficiently coordinate ground defense. With the advent of computer-aided command and control systems, the identification of human strengths and limitations has become critical to the success of the Army air defense mission.

The research reported in this paper was conducted in 1975 during the early development of the AN/TSQ-73 missile minder. The missile minder represents a class of emerging air defense systems which place unusual demands on the processing capabilities of the human operator. The purpose of the research was to evaluate human operator performance under realistic task loading, aircraft threats, and manning configurations. As a result of this study, procedures were developed which can effectively be applied to assess operator performance under a wide variety of emerging air defense systems. The procedure can also be utilized to help develop firing doctrine, assist human factors specification, and improve interoperability decisions in linked air defense systems. This research is in response to requirements of Army project 2Q762722A765 and special needs of the U.S. Army Air Defense School (USAADS), Fort Bliss, Tex.

Joseph Zeidner

JOSEPH ZEIDNER
Technical Director

Analysis of Manual Threat Evaluation and Weapons Assignment in the AN/TSQ-73 Air Defense System

BRIEF

Requirement:

To investigate human performance under varying air defense threats.

To determine human overload points requiring transition from manual to automatic operational modes.

Procedure:

Air defense crews were evaluated over a six-day period under changing conditions of crew configuration, number of available fire units, and attacking aircraft threat. Switch action times were recorded by the AN/TSQ-73 computer and matched against event times in predetermined threat scenarios. Analysis of operator actions utilized switch actuation latencies and operator errors (identified via incorrect switch sequences). Results were subjected to advanced multiple regression analysis modeling in order to generate predictive formulas for operator performance under load.

Findings:

Hostile aircraft engagement latency averaged 3.47 minutes for system contact, identification, and weapon assignment during the simulated combat exercise. The chances were at least 50 percent that the aircraft would complete its run if it was in a major assault wave. A manning configuration in which the officer implements decisions directly through the weapon assignment console significantly improves assignment times. Wave size of aircraft had the greatest effect on the weapon assignment operator although the aircraft identification operator times increased linearly as a function of the number of aircraft. Manual weapon assignment operators tended to overload at eight aircraft and reaction times increased rapidly. Greater numbers of fire units improved weapon assignment times but only if eight or more were available. Operator fatigue may be a significant factor in weapon assignment under heavy task demands.

Utilization:

The techniques developed in this report can be applied in any air defense system having built in microprocessors that can record operator switch actions, such as the developing PATRIOT system. The resulting improved estimates of operator actions and reaction times can be applied to firing doctrine evaluation, system software development, the man/machine interface, and interoperability studies involved in linking together command and control systems.

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I. INTRODUCTION

The Army is fielding a new air defense system for command and control of Hawk and Hercules Fire Units. Called the AN/TSQ-73 (Missile Minder), the system contains software which will automatically perform threat evaluations and weapon assignment (TEWA). The chief advantage of the automatic TEWA is its speed in assigning hostile aircraft to available fire units. Given sufficient time, it is likely that the tactical director, by virtue of being able to take into account complex information and recognize event patterns, would make more "intelligent" TEWA than the machine since the machine TEWA is software limited.

The tactical director performing manual TEWA is subject to increased information loading and stress as the number of aircraft in an attacking wave increases. The present research sought to investigate human TEWA as a function of wave size to assist in the determination of a manual saturation point. Such a point would suggest the level at which the system should transition from manual/semi-automatic control to automatic control as the intensity of a battle increases and the number of radar tasks become too numerous for manual weapons assignment. While some argue for exclusive manual/semi-automatic mode operation and others for an all automatic mode, it is more likely that the system will reside in the manual/semi-automatic mode until the operators and tactical directors are overloaded by the sheer volume of tracks requiring attention. At this point, the operators and tactical directors would transfer the system to the automatic mode but still maintain constant monitoring and override capabilities.

The purpose of this experiment was to collect baseline data from which overload points could be determined. It was judged that such points would be a function of the number of hostile aircraft in an attacking wave or scenario, the number of fire units under direct control of the Q-73, and the rate at which the attacking wave approaches. The first two variables were systematically changed in the experiment, while the third was fixed. Also, a key command and control question concerned whether the tactical director could coordinate activities better from behind the console operators or at the weapons assignment console where he could implement his fire unit assignment decisions directly through the console. Thus, the third primary variable in the experiment was the manning configuration. In one configuration the officer was behind the console operators, while in the second configuration the tactical director sat at the weapons assignment console. Also included for control purposes were three minor variables. They were the specific raid scenario, the test day, and the crew.

II. PROCEDURE

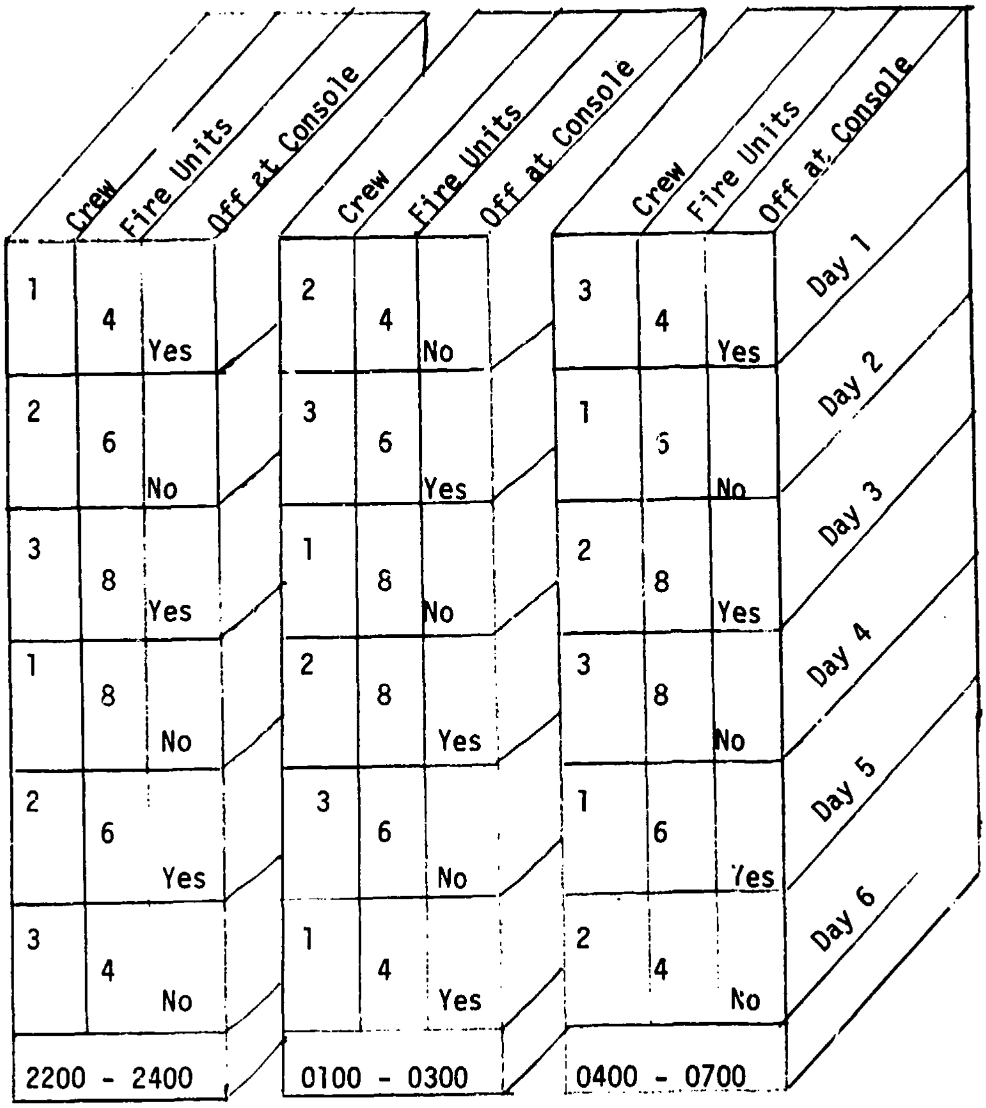
Personnel participating in the experiment (crews) consisted of three Air Defense officers and six enlisted men from the US Army Air Defense School (USAADS) recently detailed to Ft MacArthur, CA, in connection with the TACS/TADS effort in 1975. (Pilot data were collected from an "expert" team of one officer and two enlisted men who had been assigned to the TACS/TADS project for over a year.) While the crews did not receive a formal training program on the AN/TSQ-73, their arrival at the testing site approximately three weeks prior to the start of the experiment allowed sufficient time for them to become familiar with the functions and operations which would be required of them in the experiment. Although some practice effects were expected to be found over the six experimental sessions, all crews were judged to be qualified for operating in the Q-73 at the start of the experiment.

The testing environment consisted of the interior of a prototype Q-73 van. The principal items of equipment were two operator consoles, identical in configuration, which were placed side by side at the front of the van. The console on the left side was used for track identifications and the right console for weapon assignments. Other equipment included communication lines for cross talk between the simulated Group 73 and Battalion 73, and between the Battalion 73 and the fire units. An officer from USAADS served as Group 73 and issued directives to the Battalion 73 as required. Four experimenters rotated in the role of simulating "Squawk" from the fire units, e.g., acknowledgment of assignment, etc.

Data collection occurred during six consecutive evenings between 2200 and 0600 as shown at the bottom of Figure 1. Data was collected for the expert team on the morning of the seventh day between 0600 and 0800. Each team served for a two-hour period each evening. Each period consisted of two one-hour sessions. (Simulation equipment constraints precluded simulated raid tapes from being over one hour in length.)

USAADS prepared scenarios from which two raids were scripted and two raid tapes were developed for use in the Q-73's simulation mode of operation. To assure comparable group data, all video viewed by operators on their radar screens was generated from the tapes rather than from live radar signals. The simulation package also included the capability for periodic recordings of the status of all actions taken by the operators and the times of these actions. In addition, the system periodically recorded the status of all fire units under control of the Battalion Q-73.

During each one-hour session, a team would be exposed to three different assaults or waves of varying size. As soon as an aircraft track entered the system and three simulated radar sweeps verified its presence, the track became available to the ID operator seated at the left console. All tracks entered with an unknown identity. Simulated messages into the Q-73 resulted in change of status symbols replacing unknown symbols on the operator's screen. When the ID operator observed this special symbol, he "hooked" the track by placing his cursor over the symbol and pressing the appropriate function switches to reveal whether the track was friendly or hostile.



	2200 - 2400			0100 - 0300			0400 - 0700		
	Crew	Fire Units	Off at Console	Crew	Fire Units	Off at Console	Crew	Fire Units	Off at Console
Day 1	1	4	Yes	2	4	No	3	4	Yes
Day 2	2	6	No	3	6	Yes	1	6	No
Day 3	3	8	Yes	1	8	No	2	8	Yes
Day 4	1	8	No	2	8	Yes	3	8	No
Day 5	2	6	Yes	3	6	No	1	6	Yes
Day 6	3	4	No	1	4	Yes	2	4	No

Figure 1. Experimental Design

When a track symbol changed to hostile, it became the duty of the weapons assignment officer to select a fire unit to engage the track. The Q-73 system has limited software to provide automatic assignment of fire units, but it was the purpose of the present experiment to assess human performance capabilities in the manual weapon assignment mode.

For each two-hour session, there were either four, six, or eight fire units under control of the Q-73 (see Figure 1). The manning configuration consisted of having the tactical director behind the console operators or seated at the weapons assignment console. Thus, each combination of fire unit number and manning configuration resulted in six different conditions constituting the six experimental sessions.

III. RESULTS AND DISCUSSIONS

The analyzed data consisted of 383 sets of reaction times corresponding to complete actions taken by AN/TSQ-73 operators on hostile aircraft during days 1 through 6. Thirty-three additional sets of times were obtained from the expert group and were used in non-parametric analysis of operator training and familiarization. Each set was composed of three values for a given hostile aircraft: (1) the total time to identify an aircraft and assign a firing unit; (2) the proportion of the time required by the ID operator; and (3) the proportion of the time required by the weapons assignment operator. As an estimate of terminal system effectiveness, percentages of successfully engaged aircraft were tabulated for days 5 and 6. A breakdown of these percentages into detailed categories of actions, e.g., number of friendly aircraft incorrectly engaged, was precluded due to extraneous factors such as uncontrolled instructions to the operators, system problems, and errors on the radar track tapes. It was still possible, however, to estimate overall performance against hostile aircraft. These percentages are reported in Table 1.

This Table shows the percentage effectiveness of the operators. It is based on ratio of the average number of completed identification/weapon-assignment sequences to the average number of completed identifications in a wave. Effectiveness remains at about 70% for low- and medium-size waves. It drops to about 49% for high-wave sizes. In this experiment a high-wave size was 25 or more aircraft. It is possible that these estimates may be conservatively low. Effectively completed sequences

TABLE 1

ACCURACY DATA (DAYS 5 & 6)

WAVE SIZE	AVERAGE # OF ATTACKING AIRCRAFT	AVERAGE # OF COMPLETED SEQUENCES	PERCENTAGE EFFECTIVENESS
LOW	7.8	5.5	70%
MEDIUM	14.9	10.3	69%
HIGH	22.8	11.2	49%
TOTAL	15.2	9.0	60%

may have been restricted by uncontrolled instructions issued during the experiment to reduce extraneous noise on the operators' screens, such as bogus track identifiers created by rapidly turning aircraft.

A detailed investigation of operator reaction times added insight into the variables influencing overall effectiveness. By examining operators' switch actions on the AN/TSQ-73 console, it was possible to accurately determine ID and weapon assignment times. These times were analyzed in relation to the experimental variables of manning configuration, number of fire units, number of aircraft in an attacking wave, training group, day of test, and raid-tape scenarios. To maximally explore the relationships present in the data, times were subjected to multiple linear regression analysis using an IBM 360-65 computer. The data were tested against 90 different models corresponding to plausible psychological outcomes. Multiple F-tests were then used to choose the most parsimonious models with the greatest degree of explained variance.[1]

The following conclusions were supported by reaction time data. The average total time to identify and successfully engage a hostile aircraft was 208 seconds. (Start time was estimated at about 24 seconds after the system first contacted the radar track.) The average time to correctly

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[1] It should be noted that the degrees of freedom used in these F statistics represent model comparisons and are not always directly related to the number of experimental variables as is the case in the usual ANOVA Table. The reader is referred to the appendix for reference detailing this procedure.

identify a friendly aircraft was 57 seconds. The ID and weapons assignment (WA) operators did not always respond in the same manner to the experimental variables. Manning configuration had a significant effect on WA reaction times ($F_{(1,318)}$=9.49 P<.01). When the officer implemented decisions through the console his mean reaction time was 91.6 seconds versus 131.4 seconds when he served as tactical director. This was an average improvement of 39.8 seconds, or about 30%.

Number of fire units also effected WA time ($F_{2,380)}$=4.14 P<.05). Reaction times were approximately equal for four or six fire units ($\overline{X}_4$=116 seconds versus X_6=114 seconds). Eight fire units reduced the average WA times to $\overline{X}_8$=69 seconds. Caution should be used in interpreting this result however. The percentage of explained variation due to fire units was low (M^2=.0213 where M^2 is squared multiple correlation coefficient of the fire unit variable) which means that although the effect was statistically significant, number of fire units contributed little to overall prediction of reaction time. Increased numbers of fire units may improve overall effectiveness as well, but due to a lack of usable performance data, this question could not be answered.

The most powerful predictive variable was wave size. The most efficient predictive model was a linear function of ID ($F_{(1,381)}$=7.22 P<.001) and a cubic function of WA ($F_{2,380)}$=8.06 P<.001). Least squares fitting of alternate models show ID is best fit by the linear function:

$$RT_{ID}=60.3 + 2.05W$$

where W is the numberof aircraft in the attacking wave. Actual mean values for ID times are plotted in Figure 2 as a function of wave size. For WA the linear trend seen in ID times was not evident. Figure 3 shows mean reaction times already rising rapidly at eight aircraft, suggesting that the WA operator was already overloaded. Latencies reach a peak of 176 seconds per aircraft at 16 aircraft and recede to a steady state level of 100 seconds thereafter. Though dropping from the highest value, terminal WA times are still well over a minute longer per aircraft than at a wave size of eight. This decrease coincides with a loss in overall effectiveness and may be due to the forced adoption of faster but less optimal WA strategies for assigning hostile targets to the most appropriate fire units. Comparisons between possible wave models showed the WA data was best fit by a cubic equation:

$$RT_{WA}=13.23w-.012w^3-29.37$$

The cubic fit was a significantly better predictor than either a linear or a second order equation ($F_{(1,380)}=4.29 P<.05$).

An overall best equation for estimating total reaction time is the sum of the optimal ID and WA equations:

$$RT_{TOT}=30.93+15.28w-.012w^3.$$

The mean RTs for the total data are shown in Figure 4 along with the predictive curve generated by the above formula.

Analysis of the variables of days and raid tapes generated new research questions. Times from two raid tapes showed no difference for ID ($F_{(1,381)}=2.18$ $P>.20$) but a significant difference for WA ($F_{(1,381)}=9.05$ $P<.005$). This could imply that the WA task is more sensitive to the attack configuration than the ID task, since the raid tapes generated different numbers of artificial tracks on the radar screens depending on the aircraft maneuvers utilized in the raid.

Reaction time data show a significant effect over days on ID and WA times ($F_{ID}(5,377)=2.59$ $P<.25$, $F_{WA}(5,377)=5.64$ $P<.001$). Times over days were best fit by simple linear functions which are plotted in Figures 5 and 6.

$$RT_{ID}=149.66-13.14d$$

$$RT_{WA}=32.97+19.87d$$

where d is the day's number $d \in \{1, 2, 3, 4, 5, 6\}$. The most interesting fact about these data is that ID and WA functions had opposite slopes. The negative slope of the ID function means RT decreased over days for the ID operator. The positive slope for WA showed just the opposite effect. The interpretation of this finding is difficult. One possible explanation could be that the WA task is more fatiguing to the operator and increased latency due to fatigue obscured normal improvement resulting from practice effects. If this is the case, it implies that WA operator fatigue during combat could markedly increase response times. To more fully investigate repetition effects, an additional analysis was conducted using the 33 time sets from the expert group. Since the expert group participated only during one special session of the experiment but were still highly trained, it was felt that their performance could reflect ID and WA training effects without experiment fatigue. Expert times were paired with mean times from the experimental groups on days 5 and 6 on the basis of aircraft simulation numbers coded into the raid tapes.

Due to the low number of expert scores and the possible violation of normality assumptions, a non-parametric Wilcoxen matched pairs signed-ranks test was chosen. The results showed no significant difference for ID times ($Z=1.03$ $p<.15$), but faster weapons assignment times for the expert group ($Z=3.39$, $p<.01$). Mean WA time for experts was 62.6 versus 82.0 seconds for days 5 and 6. This difference could still represent only greater familiarity with the Q-73 operating system. Such a possibility receives support from the experts greater use of system switch options as well as superior ability to handle extraneous verbal "squawk" evidenced on tape recordings made of the sessions. However, it could also be a result of fatigue differences. Additional research could provide the answer by testing the issue directly.

IV. CONCLUSIONS

Tentative conclusions may be drawn for some of the original research questions. First, TEWA in the semi-automatic mode is not instantaneous. Average time for system contact, identification, and weapons assignment in the AN/TSQ-73 system was 3.47 minutes. Second, manning configuration in which the officer implements decisions directly through the WA console significantly improves assignment times. Third, wave size has its greatest effect on the WA operator, although ID times do increase linearly as the number of aircraft increase. Fourth, WA is overloading at eight aircraft and reaction times increase rapidly. Increased numbers of fire units do improve WA times but only if eight or more are available. Finally, operator fatigue could be a consideration in WA under heavy task demands.

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Ward, Joe H. and Jennings, Earl, Introduction to Linear Models, 1973, Prentice-Hall, Inc.

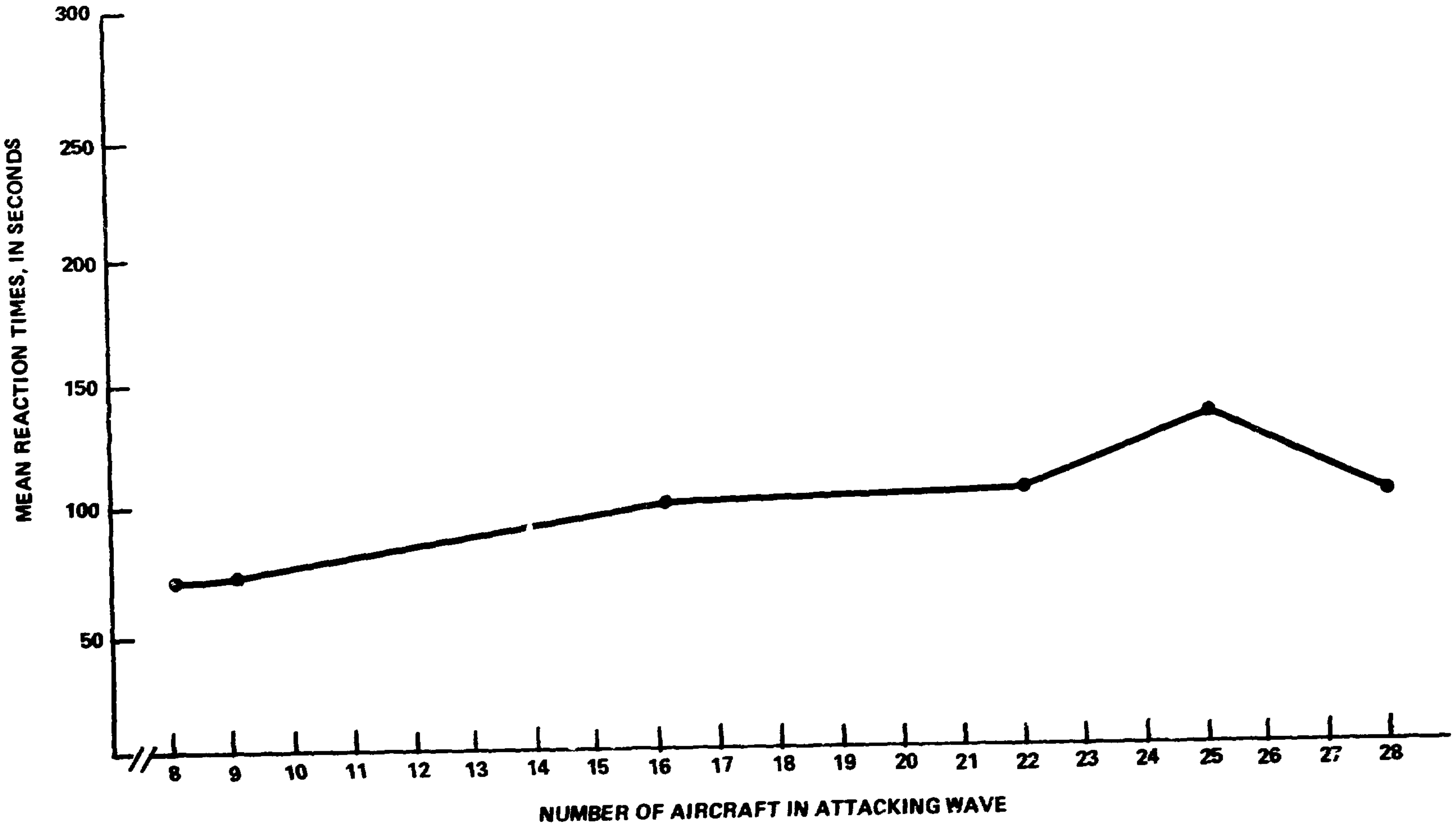

Figure 2. Mean reaction times for ID as a function of six wave sizes.

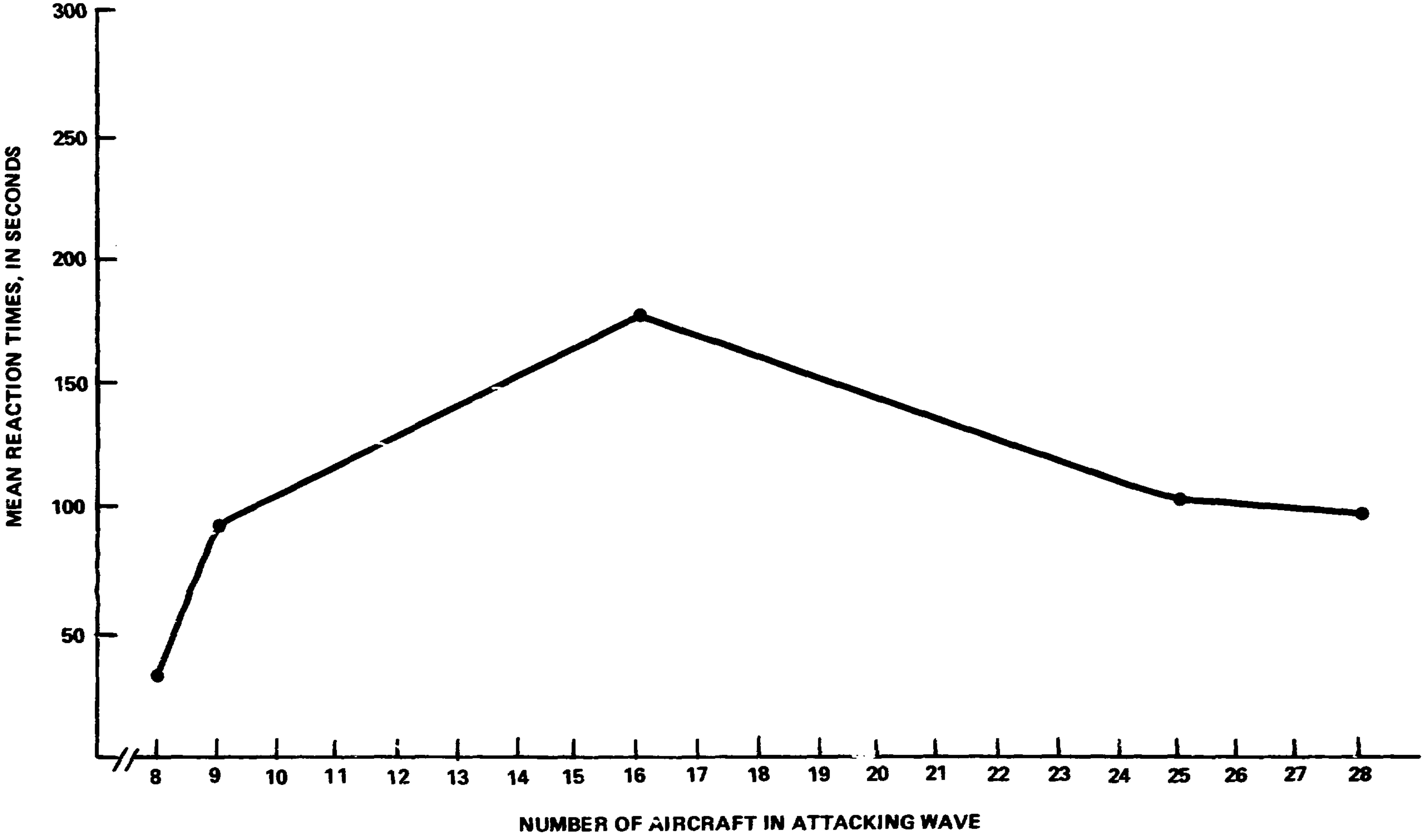

Figure 3. Mean reaction times for WA as a function of six wave sizes.

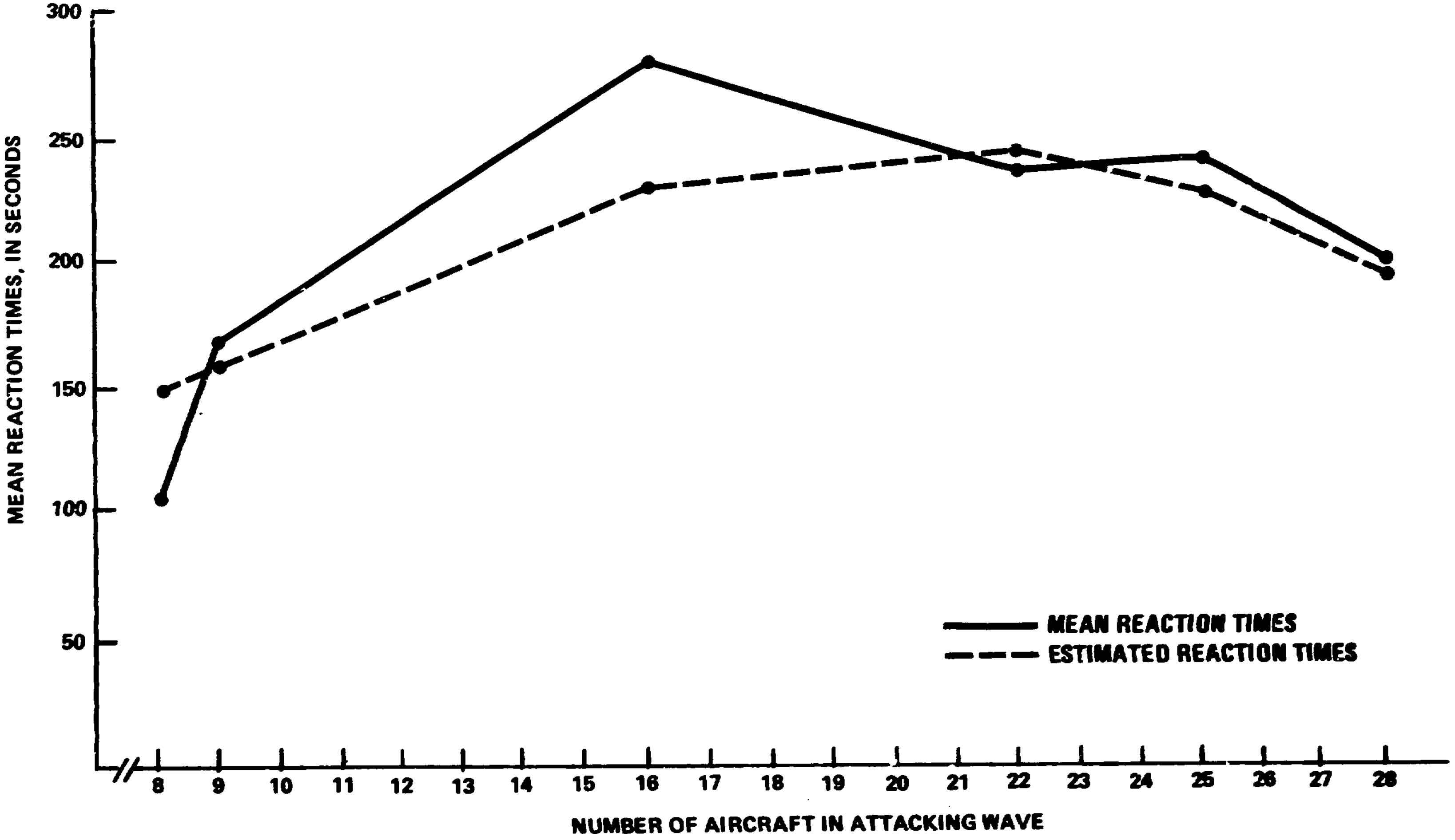

Figure 4. Mean reaction times and estimated reaction times for total reaction to a hostile aircraft as a function of wave size.

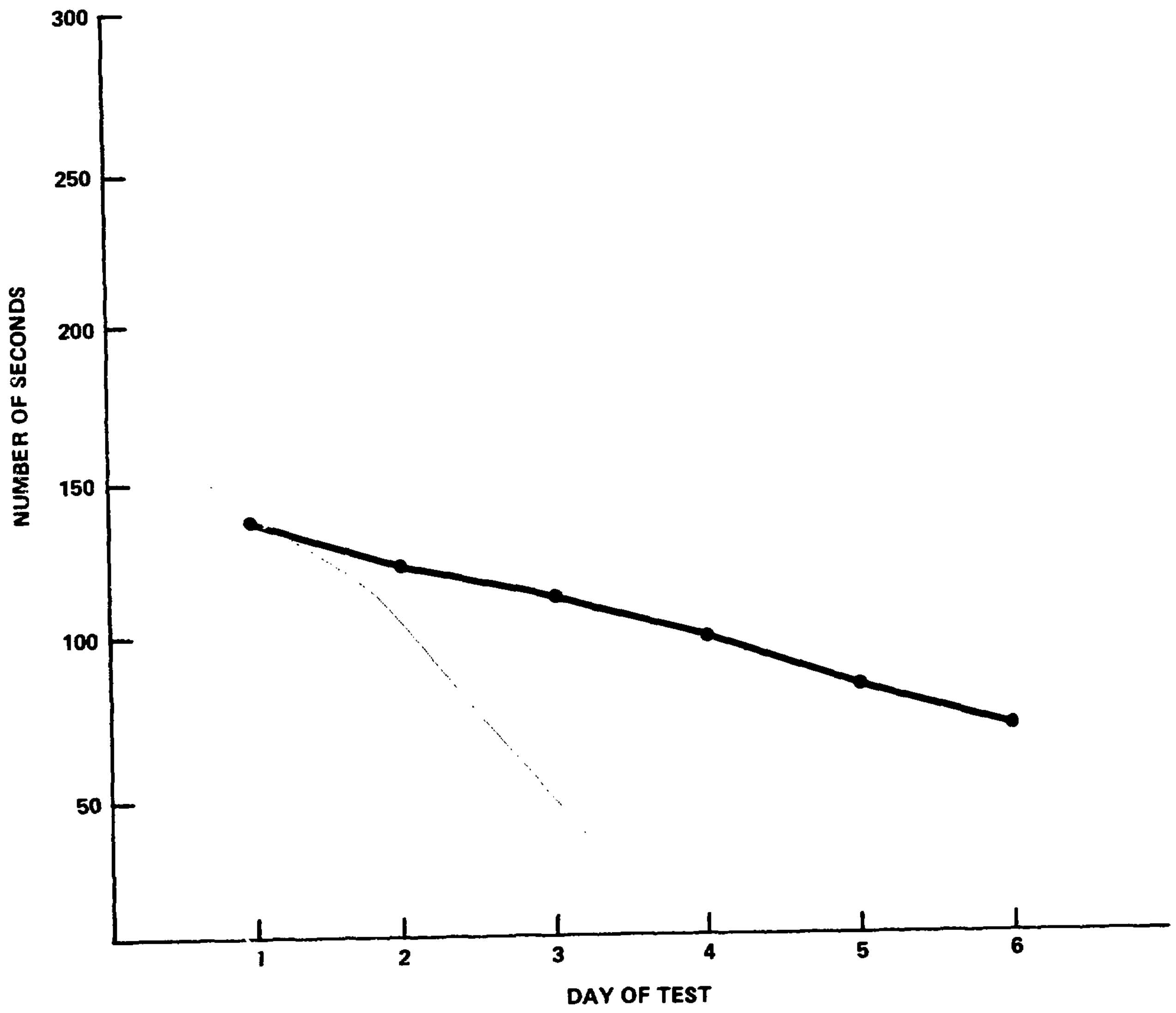

Figure 5. Best fit estimated ID reaction times as a function of day of test.

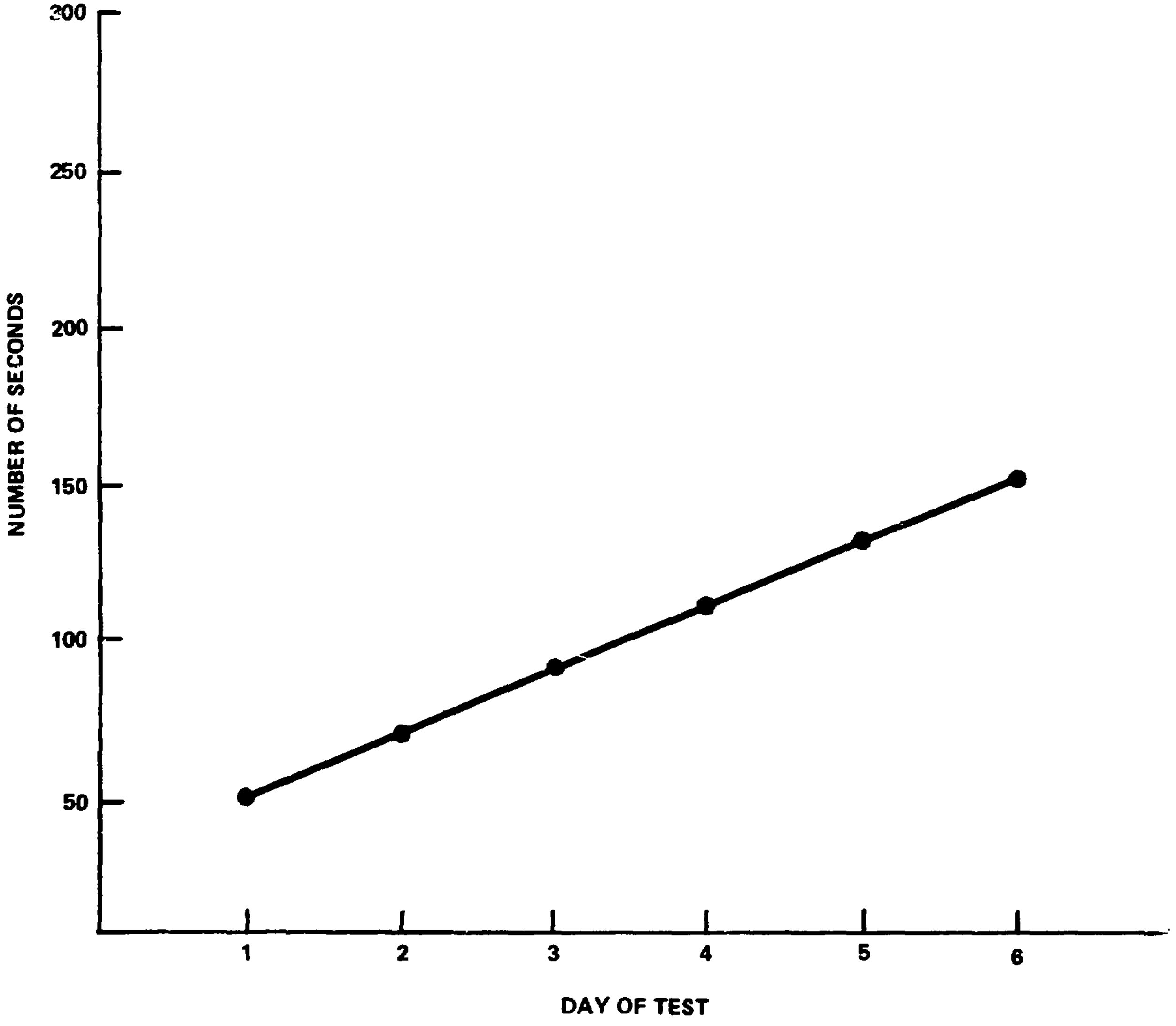

Figure 6. Best fit estimate of WA reaction times as a function of day of test.

APPENDIX

The techniques used in this report to determine predictive formulas involved a multiple linear regression program modified by Jorgensen to permit rapid generation of model vectors. A discussion of the statistical logic, model construction, and general programming methods is available in "An Introduction to Linear Models" (Ward & Jennings, 1973).

Briefly the technique involves solving for parameters in a theoretical equation previously defined by the experimenter to reflect specific psychological assumptions. This is done through a least squares fit of the equation parameters to raw or transformed data. The program then generates the standard beta weights and regression constant for that solution. The predictive power of the equation is specified by M^2, the squared multiple correlation coefficient. M^2 is mathematically equivalent to the percent of explained variation. Through the use of alternate equations, F ratios can be set up to compare various assumptions in terms of their explained variation. Analysis of variance and factorial analysis of covariance are two of the many possible model formulations which could be utilized within the regression framework.

Usually the most efficient strategy for finding optimal models consists of postulating a general all-encompassing equation which takes into account a linearly independent set of predictor variables based on conditions used in the experiment. The M^2 for this model serves as a maximum against which the predictive power of other simpler models is judged. The simplest possible predictive model is the mean of the distributions. An F ratio formed between the general model and the mean model tests the usual null hypothesis for equality of means. By using the same technique with more complex models, F tests can be set up comparing various models to the general model and to each other. This is analogous to analysis of covariance. The pattern of significant F ratios as well as the M^2 efficiency of the models quickly points out the most efficient and parsimonious equations for a given set of assumptions and predictive power.

For example, in this experiment the three general models were all predictive equations taking into account raid tapes, low, medium, or high wave sizes, days, manning configuration, groups and fire units. A different general equation was generated for total, ID, and weapons assignment times. In this analysis four types of models were considered: orthogonal component models for each variable of interest (these are equivalent to a one-way analysis of variances for each variable), linear models (equivalent to simple linear regression fits), second and third order polynomial models (which investigated parabolic curves) and mixed models, such as a linear model going second order at a specific point. The following are examples of a general 12-element orthogonal model for total times, a model based on six wave sizes, a linear model, and a polynomial model:

$$\text{Time}_{(\text{total})} = a_0X_1 = a_1S_2 + a_2X_3 \ldots a_{11}X_{12}$$

$$\text{Time}_{(\text{total})} = a_0Y_1 + a_1Y_2 + a_2Y_3Y_4 + a_4Y_5 + a_5Y_6$$

$$\text{Time}_{(\text{total})}\ U + aW$$

$$\text{Time}_{(\text{total})} = U + aW + a_1W^2 + a_2W^3$$

where $X_1 \ldots X_{12}$ are column vectors of 0's and 1's partitioning total data times into orthogonal sets as a function of such variables as days, waves or raid tapes.

$Y_1 \ldots Y_6$ are column vectors of 0's or 1's partitioning total times into sets for wave size one through 6, respectively.

U is a unit vector of 1's. W is a column vector containing the numbers one through 6 corresponding to the size of the wave.

W^2 is the direct product of W with itself.

a is a beta weight for the regression.

Though many models were considered and fit, only the most parsimonious and experimentaly meaningful are reported in this paper. The equations derived represent best fits for the available data. Their generalizability assumes the generalizability of the experimental situation to the combat usage of the AN/TSQ-73.

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1 OFC OF NAVAL RESEARCH ATTN: CODE 455 (DR. MARTIN A. TOLCOTT)
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1 US ARMY AVN ENGINEERING FLIGHT ACTIVITY ATTN: SAVTE-TD
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1 HQ WRAIR DIV OF NEUROPSYCHIATRY
1 USACACDA ATTN: ATZLCA-CI-C
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1 HQDA ATTN: DASG-HG (LTG RICHARD E. HARTZELL)
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1 USACDEC TECHNICAL LIBRARY
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1 HUMAN RESOURCES RSCH ORG (HUMRRO) LIBRARY
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1 USA TRADOC SYSTEMS ANALYSIS ACTIVITY ATTN: ATAA-SL (TECH LIBRARY)
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1 USA COMPUTER SYSTEMS COMMAND ATTN: COMMAND TECHNICAL LIBRARY
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1	USAMERDC TECHNICAL LIBRARY
1	DEPARTMENT OF THE NAVY TRAINING ANALYSIS AND EVALUATION GP
1	NATIONAL CENTER FOR HEALTH STATISTICS ATTN: M. DUPUY (PSYCHOLOGICAL ADVISOR)
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1	US NAVY CNET SUPPORT RESEARCH LIBRARY
1	OLD DOMINION UNIVERSITY PERFORMANCE ASSESSMENT LABORATORY
1	USA COMMAND AND GENERAL STAFF COLLEGE ATTN: LIBRARY
1	USA TRANSPORTATION SCHOOL USA TRANSP TECH INFO AND RSCH CEN
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1	NAVAL MEDICAL R AND D COMMAND (44)
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1	INSTITUTE FOR DEFENSE ANALYSES
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1	MARINE CORPS INSTITUTE
1	NAVAL SAFETY CENTER ATTN: ROBERT A. ALKOV PH.D
1	USAAVNC AND FT. RUCKER ATTN: ATZQ-ES
1	US ARMY AVN TNG LIBRARY ATTN: CHIEF LIBRARIAN
1	USAAVNC ATTN: ATZQ-D
1	US MILITARY ACADEMY OFC OF MILITARY LEADERSHIP
1	US MILITARY ACADEMY DIRECTOR OF INSTITUTIONAL RSCH
1	USA AIR DEFENSE SCHOOL ATTN: ATSA-CD-MS
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1 USA INSTITUTE OF ADMINISTRATION ATTN: RESIDENT TRAINING MANAGEMENT
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1 ORGANIZATIONAL EFFECTIVENESS TNG CEN + SCH ATTN: LIBRARIAN
1 US ARMY INTELLIGENCE CENTER + SCHOOL ATTN: ATSI-TD
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