AD669904

TR 1124

15 DECEMBER 1967

Evaluation of Initial PROTECT Pilot Study

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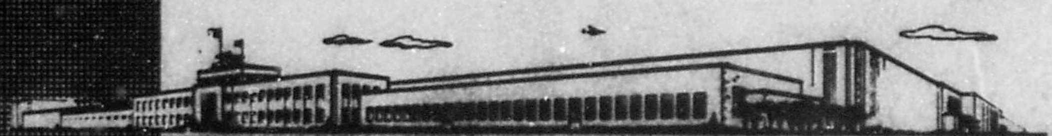

NAVAL AVIONICS FACILITY

INDIANAPOLIS, INDIANA 46218

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PREFACE

This report provides an evaluation of a successful pilot study of PROTECT (Probabilistic Recall Optimizing the Employment of Calibration Time). All pertinent information obtained during the operation of this pilot study is contained in this report.

It is strongly recommended that NAFI Technical Report 824 "PROTECT--A Method of Optimizing Available Calibration Time in a Test Equipment Recall System" (May 1966) be read first in order to become familiar with the background and purpose of PROTECT. The above technical report includes the derivation of the estimates for the failure rates and calibration times, and the method in which these parameters are utilized in selecting test equipments for calibration.

Prepared by Bruce R. Glenn
Mathematical Statistician

Reviewed by Robert Stike
Chief of Statistical Branch

Approved by Donald L. Cheak
Manager of Quality Assurance

C. E. Krusner
Manager of Standards & Calibration

Released by [signature] T. Updike
Director of Technical Evaluation

ABSTRACT

This report contains the results of a successful ten-month pilot study of PROTECT (Probabilistic Recall Optimizing the Employment of Calibration Time), a method used by a Standards and Calibration Laboratory for recalling test equipments for calibration.

Included is information on the classes of test equipments used and problems involved in the study. The results are presented in tables and graphs and conclusions are drawn from those results. NAFI TR-824 contains the development of the PROTECT calibration system.

ACKNOWLEDGMENTS

The author would like to express his appreciation to Mrs. Cynthia D. LaGue, a mathematical statistician in the Statistical Branch of the Quality Assurance Division who was the coordinator of this study and whose efforts contributed greatly to its success.

Appreciation is also extended to personnel in the Standards and Calibration Laboratory and the Statistical Branch who assisted in this study.

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I. CONCLUSIONS

A. During the course of the 10-month pilot study, the PROTECT calibration recall method significantly reduced the number of out-of-tolerance test equipments in the pilot system at any given time. This result was accomplished using approximately the same amount of calibration effort as would be normally expended by the fixed cycle method of recall.

B. A graph showing the relationship between the percent of test equipments expected to be out-of-tolerance in the system and the amount of calibration time to be expended, utilizing the PROTECT method, appears to be an effective management tool in planning workloads. This graph provides management with a means of predicting the reduction in the percentage of out-of-tolerance test equipments in the PROTECT system for a given increase in the manpower allocated for the calibration effort.

II. RECOMMENDATION

Since this initial pilot study has shown PROTECT to be an effective test equipment recall method, it is recommended that a longer more extensive study be made. This additional study should run for 12 to 18 months and include at least ten test equipments in each class with a total number of approximately 400 test equipments in the system. Computer programs and associated data processing procedures should be developed to automate the PROTECT workload and should be general enough to be able to expand to the entire system of NAFI test equipments.

III. INTRODUCTION

A. Definitions and Development of PROTECT.

PROTECT (Probabilistic Recall Optimizing the Employment of Calibration time) is a test equipment recall system which optimizes the use of available calibration manpower. NAFI TR-824 (Reference 1.) gives a complete account of this recall system and provides a worked example. The essential features of PROTECT will be discussed below to provide a background for the reader.

A test equipment (or instrument) is said to be out-of-tolerance or to have failed if, during the calibration procedure, any parameter exceeds the specifications established for the test.

PROTECT utilizes the probability of failure of the test equipments and the time required to calibrate the test equipments. This recall system selects those test equipments for calibration which are likely to be out-of-tolerance and whose calibration time "cost" is low. Test equipments are selected sequentially until the total amount of available calibration time is used up. Certain restraints on the time interval between calibrations are used to force the calibration of high time "cost" equipments which otherwise might not be recalled.

The selection of test equipments is made on the basis of the ratio of "expected time needed"/"expected number of test equipments found out-of-tolerance". This ratio is the average amount of time necessary to find one out-of-tolerance test equipment. Test equipments whose ratio is low are recalled first as they will provide the most out-of-tolerance test equipments at the lowest time "cost" for the calibration personnel.

The following basic definitions are needed for PROTECT:

T - The number of months since a test equipment has been calibrated. $T = 1, 2, 3, \ldots$

N_i - The number of test equipments in the i^{th} class, $i = 1, 2, \ldots, k$. There are $k = 24$ classes in this pilot study of PROTECT.

$N_i(T)$ - The number of test equipments in the i^{th} class that were calibrated T months ago. $N_i = \sum_T N_i(T)$.

$F_i(T)$ - The probability that a test equipment in the i^{th} class was out-of-tolerance (failed) prior to time T. $0 \leq F_i(T) \leq 1.0$. Estimates of $F_i(T)$ for integer values of T must be available.

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I_i - The expected value (average) of the time to calibrate a test equipment of the i^{th} class if the equipment were in-tolerance at submission.

O_i - The expected value (average) of the time to calibrate a test equipment of the i^{th} class if the equipment were out-of-tolerance at submission. In general, $O_i \geq I_i$ because some repair or adjustment of the test equipment is usually required in addition to the calibration.

T_c - A maximum calibration cycle at which point the test equipment is calibrated regardless of the time "cost". This critical time can be set in such a manner so that the probability of failure $F_i(T_c)$ is less than some pre-determined value.

Class - A group of test equipments with a common F(T), I, and O.

The expected time required to calibrate a group of $N_i(T)$ test equipments is given by the following formula:

$$\text{Expected Time Needed} = N_i(T)\cdot F_i(T)\cdot O_i + N_i(T)\cdot[1 - F_i(T)]\cdot I_i$$
$$= N_i(T)\cdot\left\{F_i(T)\cdot O_i + [1 - F_i(T)]\cdot I_i\right\}$$

The expected number found out-of-tolerance is $N_i(T)\cdot F_i(T)$.

Hence, the ratio used to select test equipments is:

$$= \frac{\text{Expected Time Needed}}{\text{Expected Number Out-of-Tolerance}}$$

$$R_i(T) = \frac{N_i(T)\cdot\left\{F_i(T)\cdot O_i + [1 - F_i(T)]\cdot I_i\right\}}{N_i(T)\cdot F_i(T)}$$

$$= O_i + \frac{[1 - F_i(T)]\cdot I_i}{F_i(T)}$$

For each class of test equipments estimates of $F_i(T)$, I_i, and O_i are needed. The estimates of the calibration times I_i and O_i are straightforward. However, the estimation of $F_i(T)$, the failure probability distribution, is not so straightforward due to the nature of the calibration records. NAFI TR-824 provides several alternate methods for the estimation of $F_i(T)$.

B. Selection Procedure

The selection procedure is as follows:

(1) Recall all test equipments which have exceeded their respective T_c. Calculate the expected required time needed for these calibrations by:

$$\sum_{i=1}^{k} N_i\,(T_c)\left\{F_i(T_c)\cdot O_i + [1 - F_i(T_c)]\cdot I_i\right\}$$

Recall the remaining test equipments by the use of $R_i(T)$.

(2) Calculate $R_i(T)$ for those $N_i(T) \neq 0$.

(3) Rank the $R_i(T)$ from low to high.

(4) Recall test equipments with low $R_i(T)$ sequentially and calculate the cumulative expected time needed. Continue this until all of the available calibration time has been expended. A listing of these test equipments recalled in this manner is called the "solution table".

This procedure utilizes the available calibration manpower in the most efficient manner in servicing out-of-tolerance equipments. In addition, the solution table could also include a cumulative expected number of out-of-tolerance test equipments. This information can be graphed against the cumulative expected time needed to provide a visual indication of the relationship of manpower needed to service out-of-tolerance equipments.

IV. DISCUSSION

A. Classes of Test Equipments Used in Pilot Study.

The pilot study of the PROTECT program began with twenty-five classes of test equipments. Each equipment within a chosen class had the same manufacturer and model number and it was assumed that each had the same average calibration time, failure rate and maximum (cycle) time. A description of each class of equipments is given in Table 1.

Five equipments were selected from each of the twenty-five classes in PROTECT. The majority of the 125 equipments were selected from those currently being used by the Inspection and Equipment Evaluation Divisions at NAFI since these divisions are in the same department as the Standards and Calibration Division. This policy made the operation of this study easier to administer.

In a few cases, some individual equipments had to be replaced by another equipment within the same class. Such instances were due to equipments placed in long-term storage, change in application of the equipment, etc. These equipments were always replaced by another with the same manufacturer and model number, it being assumed that the values of the test parameters within each class were not affected by this substitution.

There were two instances when an entire class was deleted from the PROTECT program. Class 3 was deleted because the Naval Air Systems Command calibration procedure required an initial adjustment so that the "true" condition received could not be determined. Thus, no reliable failure rate data could be obtained for this class of equipments.

Class 25 was deleted because the equipments were placed on an inactive status. Since this was the only class of mechanical equipments on the PROTECT program, it was replaced with another group of mechanical equipments (Class 26).

TABLE 1. DESCRIPTION OF THE CLASSES OF TEST EQUIPMENT IN THE INITIAL PILOT STUDY OF PROTECT

CLASS	EQUIPMENT NOMENCLATURE	FAILURE RATE, λ	I_i	O_i	T_c
1	Vibrotest	.05975	1.0	2.0	6
2	Vacuum Tube Voltmeter	.10950	1.9	2.7	4
3*	Counter	.13200	1.7	3.9	12
4	Voltage Amplifier	.10400	2.5	5.3	5
5	Capacitance Decade	.00878	1.2	2.5	12
6	Function Generator	.13190	2.2	5.5	5
7	Audio Signal Generator	.06020	2.9	3.5	11
8	Vacuum Tube Voltmeter	.25170	1.6	2.7	3
9	Vacuum Tube Voltmeter	.03772	3.2	4.0	18
10	Oscillator	.10770	2.9	3.9	6
11	Wheatstone Bridge	.02397	2.4	3.2	24
12	Standard Resistor	.00500	0.7	0.7	12
13	Voltage Divider Decade	.00930	2.2	3.7	24
14	Wheatstone Bridge	.00878	3.0	4.0	24
15	Vibration Meter	.06778	2.1	3.7	10
16	Voltmeter AD	.00611	0.8	0.9	24
17	Resistance Decade	.02220	3.7	6.0	24
18	Voltohm Meter	.05000	1.3	2.0	12
19	Scope Plug In	.04658	1.2	2.7	12
20	Oscilloscope	.20130	2.8	5.8	5
21	Wattmeter AF	.02230	1.3	1.6	24
22	Ammeter AC	.00500	0.5	0.5	24
23	Milliammeter AC	.00600	0.5	0.5	24
24	Voltmeter AC	.00700	0.3	0.5	24
25*	High Vacuum Gauge	.00700	1.0	1.5	24
26	Force Gauge	.00700	1.6	2.0	24

* Deleted from Pilot Study

B. Estimates of Test Parameters.

Certain test parameters for each class of equipment had to be estimated before the PROTECT program could be implemented. They were:

--expected time to calibrate if the equipment were received in-tolerance, I_i, (in hours)

--expected time to calibrate if the equipment were received out-of-tolerance, O_i, (in hours)

--failure rate per month, λ

--maximum time between calibrations, T_c, (in months)

These estimates were based on data collected from July 1964 through November 1965. For more detailed information on how the above estimates were obtained, refer to TR-824, Section IV-B. The actual values of these estimates are shown in Table 1.

C. Preparation of the Monthly Workload and Graphical Prediction Curves.

Since the "fixed cycle" method of recall for calibration of equipments included in the PROTECT study required between 40 and 50 hours of calibration effort, it was initially decided to allocate 40 hours per month for the PROTECT recall method. This allowed a margin of 10 hours per month for any special calibration requests (unscheduled calibrations) for these test equipments.

The notification of recall of equipments was made to the custodians in much the same manner as used in the "fixed cycle" recall method. For each recalled equipment, a form, called a work ticket, was prepared which contained the equipment identification, custodian and other necessary information for the calibration.

The PROTECT work tickets were typed and mailed to the custodians along with the "fixed cycle" preprinted work tickets. Each work ticket pertaining to a PROTECT equipment was marked on one edge with green ink so that on completion the data could readily be obtained for feedback into the PROTECT record system.

To facilitate the calculation of the workload each month, a group of punched cards were updated monthly. Each card contained the class number, i, T, $N_i(T)$, T_c, λ, I_i, O_i, and the ratio $R_i(T)$. In preparing the workload, those cards that had $N_i(T) = 0$ were deleted from the deck. The remaining cards were sorted on $R_i(T)$ and processed on a computer.

TABLE 2. THE PROTECT SOLUTION TABLE FOR MAY WORKLOAD

RATIO	CLASS	T	F(T)	EXPECTED TIME/EQUIP.	N_i(T)	CUMULATIVE TIME	CUMULATIVE NO. FAILED
3.14	5	12	.6513	2.047	3	6.141	1.954
3.24	5	11	.6193	2.005	1	8.146	2.513
3.35	5	10	.5844	1.960	1	10.106	3.158
4.12	8	3	.5300	2.183	4	18.838	5.278
4.87	1	5	.2583	1.258	1	20.096	5.536
5.15	8	2	.3955	2.035	1	22.131	5.931
5.70	1	4	.2127	1.213	2	24.557	6.357
5.72	18	6	.2592	1.481	2	27.519	6.875
6.16	2	4	.3547	2.184	1	29.703	7.230
6.58	18	5	.2212	1.455	1	31.158	7.451
6.80	21	10	.1999	1.360	1	32.518	7.651
7.09	1	3	.1641	1.164	2	34.846	7.979
7.28	19	5	.2078	1.512	3	39.382	8.602
7.36	11	19	.3658	2.693	1	42.075	8.968
. . .				. . .			. . .
71.33	3	1	.0246	1.754	1	254.439	24.552
116.40	14	3	.0260	3.026	1	257.465	24.578
140.35	12	1	.0050	0.700	1	258.165	24.583
173.35	14	2	.0174	3.017	1	261.182	24.601
					125		

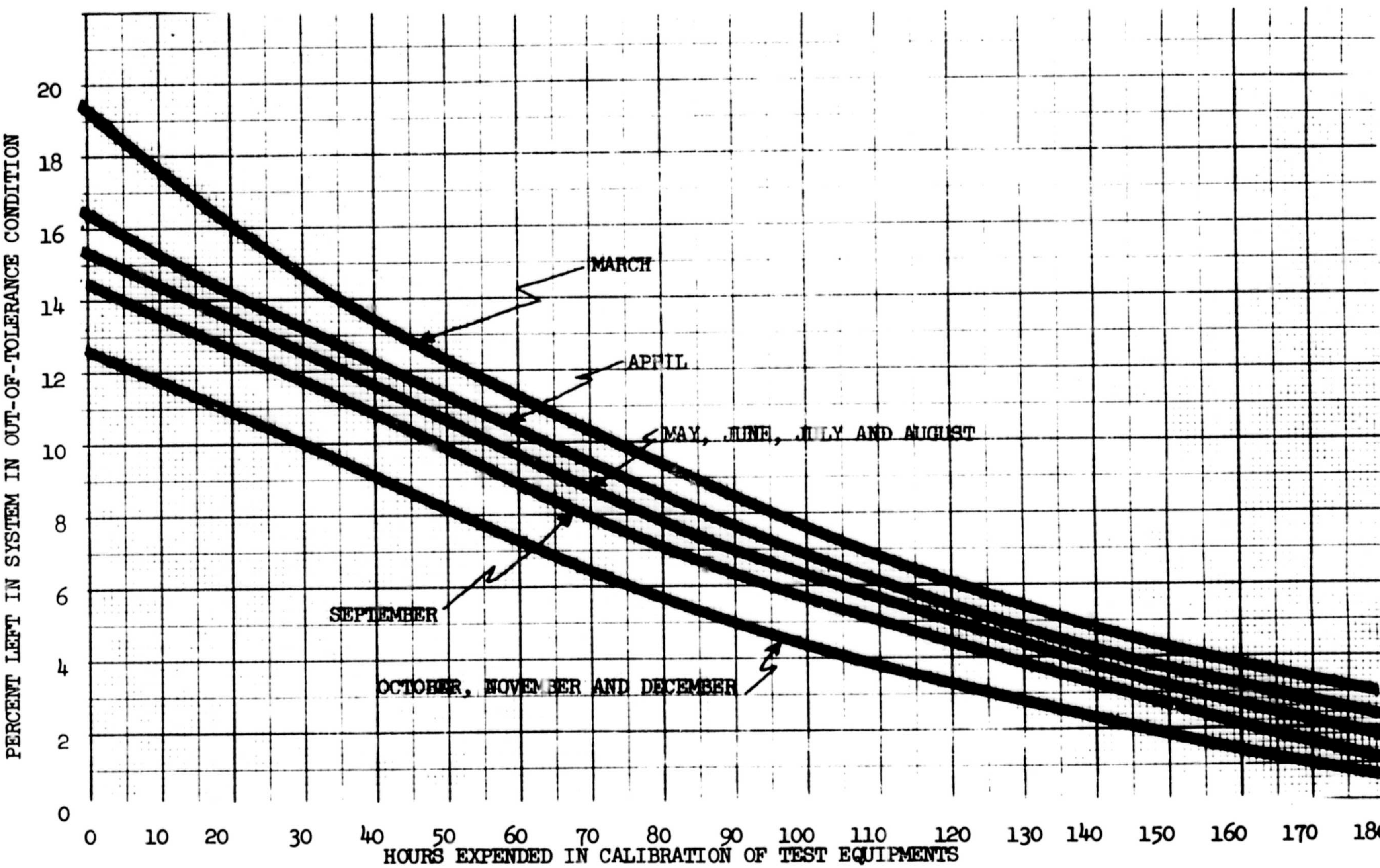
The computer printed out the solution table from which the workload would be prepared. Table 2 shows the beginning and end of the solution table for the March 1966 workload.

The workload for March would consist of all equipments on this list down through the $N_{19}(5)$ equipments, since the calibration of any more equipments than this would exceed the 40 hours of available calibration time.

In the entire system of test equipments, there is an expected number of 24.6 equipments (19.7%) out-of-tolerance. With a calibration effort of 40 hours, 8.6 of these are expected to be found, thus lowering the percentage of out-of-tolerance equipments in use to 12.8%.

The last two columns in Table 2 can be used to prepare a prediction curve of the percentage of out-of-tolerance equipments in the system plotted against the calibration time. The percentage would be calculated (as illustrated above for 40 hours) for various calibration times and then plotted. Figure 1 shows this curve for March. Also in Figure 1 are similar graphs for the remaining ten months of this pilot study.

Figure 1. GRAPHICAL PREDICTION CURVES FOR MARCH THROUGH DECEMBER FOR SCHEDULING WORKLOADS



D. Effectiveness of the PROTECT Method.

For each of the first six months of this study, forty hours were allotted for the workload. However, during the first three months, the total calibration time spent varied from 53 to 73 hours due to unscheduled calibrations of some equipments (discussed further in the next section). This extra calibration time helped to reduce the prediction curves (see Figure 1) so much that the prediction curve reached a stabilization point in May, although a few additional months were needed to verify this fact.

For the seventh month (September) of operation, it was decided to increase the allotted time to 60 hours with expectations of seeing the prediction curve decrease another 2 - 3%. The prediction curve did decrease by this amount in October and stabilized at that level for the remaining months of the study even though only 40 hours were used for the last three months.

The overall lowering of these prediction curves as time progressed illustrates the effectiveness of the PROTECT recall method. Under the "fixed cycle" recall method, the percentage of equipments out-of-tolerance each month prior to workloading would be approximately at the 20% level as shown at the beginning of the March curve. If the usual 40 - 50 hours were expended in calibration, one would not expect this percentage to vary except for random causes. The only way to lower this value under the 20% level would be to expend more calibration effort across all of the equipments in the system. This would require more calibration personnel. The use of PROTECT, however, utilizes the available manpower in the best possible manner each month. The prediction curves also stabilize under PROTECT, but at a lower level than the "fixed cycle" recall method.

In addition, this study also illustrated that one can predict how much the prediction curve can be expected to lower by expending more hours in calibration. An examination of the curves in Figure 1 provides management a method of determining the "gain", - reduction in percentage, versus the "cost", - personnel required. In the "fixed cycle" recall method, no advance prediction can be made of such gains for a given increase in personnel expended in calibration of test equipments.

The remainder of this report discusses some of the special problems encountered and provides more detailed results of this study.

E. Special Calibration Labels.

Since PROTECT recalls equipments for calibration utilizing the probability of failure of the equipment it is impossible to know the exact recall month during which the equipment is due for re-calibration. However, the custodian of the equipment needs to know the maximum time between calibrations so that an equipment does not remain uncalibrated indefinitely. Special calibration labels were ordered and placed on all equipments involved in this pilot study of PROTECT. A sample label is shown below:

As can be seen, this label has a due date of the form "Due Prior To _____". The equipment can be used with reasonable assurance of being accurate up to that month. In this pilot study, the equipments were normally recalled before the stated month. All unscheduled calibrations were handled as before.

A short memorandum was written to all custodians affected by this study giving a brief background of PROTECT and asking for their co-operation during the pilot study. This memorandum explained the use of the special calibration label for PROTECT.

Unfortunately, this special label was not delivered prior to the start of the PROTECT study. Consequently, for the first three months of operation, the usual calibration labels remained on the PROTECT equipments and the custodians were bringing some of these equipments in for calibration based on the due dates shown on these old labels. Such calibrations were classified as "uneconomical" effort.

F. Tabular Summary and Discussion of Scheduled Calibrations.

Table 3 gives a month-by-month summary of the predicted and actual number of out-of-tolerance equipments and total time cost for the completed scheduled calibrations. The predicted figures were based on the actual number of equipments calibrated, since not all scheduled equipments were sent in for calibration. Since the pilot-study was operated on a manual basis, no effort was made to remind custodians of any overdue equipments. Overdue equipments are rescheduled by PROTECT automatically.

TABLE 3. MONTHLY SUMMARY OF PROJECT SCHEDULED CALIBRATIONS

MONTH	NUMBER SCHEDULED	NUMBER CALIBRATED	PREDICTED NO. OUT-OF-TOLERANCE*	ACTUAL NO. OUT-OF-TOLERANCE	PREDICTED TIME COST	ACTUAL TIME COST
1-March	23	21	8	6	36.5	28.2
2-April	18	12	4	4	27.0	23.0
3-May	16	14	5	5	36.6	44.5
4-June	18	16	5	1	34.4	28.5
5-July	14	13	4	7	32.1	29.5
6-August	24	23	5	3	38.7	33.8
7-September	31	27	5	4	46.6	42.1
8-October	31	28	6	4	59.1	51.1
9-November	28	22	5	4	51.5	35.1
10-December	29	24	5	2	55.1	40.8
TOTALS	232	200	52	40	417.6	356.6

* Based on Number Calibrated

(1) Estimates of Number of Out-of-Tolerance Equipments.

The estimates of the failure rates used were somewhat conservative. There were only two months in which the predicted estimate equaled the actual number of out-of-tolerance equipments. For most of the other months, the actual number of out-of-tolerance equipments was less than that predicted. These slightly over-estimated failure rates mean that the prediction curve always showed the system being a little worse than it actually was, with respect to the number of out-of-tolerance equipments.

An investigation of the estimates of the failure rates was made to see if any recently accumulated data could change these estimates. For this pilot study, the difference between the actual and predicted number of out-of-tolerance equipments was hardly significant to warrant a re-evaluation of failure rates.

If another pilot study should be conducted, it is recommended that the classes be chosen so that 10 or more equipments would be included within each class. Then, with this larger sample size, estimates of the failure rate should be in closer agreement with the actual number of out-of-tolerance equipments.

(2) Estimates of Time Cost.

The total calibration time spent was usually less than the expected calibration time. This is partially due to the fact, that the expected time to calibrate any equipment is directly dependent on the failure rate, as well as the estimates of the time to calibrate an equipment, depending on whether the equipment was in- or out-of-tolerance at submission. However, an "over-estimate" of total calibration time required is better because any "under-estimate" of calibration time required may result in necessary overtime to complete a month's scheduled workload. One of the main features of the PROTECT recall system is that the available time is an input to the workload and PROTECT optimizes the use of this allocation of available manpower. One of the major drawbacks to the present "fixed cycle" recall system is that this method may recall too many equipments for the available calibration time.

Table 3 does not show the amount of "uneconomical" time spent in calibrating equipments brought in for calibration due to the PROTECT label problems.

(3) Turnaround Time Problems.

Since the operation of this pilot study was done on a manual basis, no effort was made to notify custodians of overdue equipments as is done in the present ADP recall system. Consequently, some equipments scheduled for calibration by PROTECT were not calibrated at their scheduled time. These equipments were calibrated a month or so later than the scheduled month. This delayed the monthly progress reporting of the PROTECT System. As can be seen in the column totals of Table 3, only 200 of a total of 232 equipments were actually calibrated. Several of these overdue equipments were calibrated in January 1967. Some of the other equipments did not come in as scheduled because the custodian had an urgent need for them.

Due to this delay in completing a month's workload, the next month's workload assumed that all equipments scheduled for the previous month would be calibrated. If not, the following month's workload would reschedule any scheduled equipment not calibrated two months ago. For example, the March PROTECT workload scheduled 23 instruments. Only 16 of these were calibrated during March. When the April workload was prepared, it was assumed that all 23 equipments had been calibrated in March. During April, an additional five equipments from the March workload were calibrated. This left two equipments from the March workload which were not calibrated. Thus, in May's workload, these two equipments would be included, since it is even more economical to do so within the amount of allotted calibration time.

G. Tabular Summary of Non-Scheduled Calibrations.

A non-scheduled calibration is any calibration performed on an equipment submitted on an unscheduled basis or on one received from a repair agency after the repair work has been completed. Both types of submissions are unpredictable. Calibration data obtained from such submissions for calibration are not included in the computation of the failure rate for a class of equipments, but allowance of time to calibrate these equipments must be made in the preparation of the workload. Ten hours for non-scheduled calibrations were allowed for each month's scheduled workload which turned out to be an over-estimate. Table 4 gives the monthly summary of these non-scheduled calibrations.

Table 4. MONTHLY SUMMARY OF PROTECT NON-SCHEDULED (UNSCHEDULED AND OFF-STATION) CALIBRATIONS.

Month	# Unsc	# Out-of-Tol	Time Cost	# Off-Station	# Out-of-Tol	Time Cost
1-March	3	1	1.5	1	0	3.0
2-April	1	1	4.5	-	-	-
3-May	5	3	14.0	-	-	-
4-June	2	1	9.0	-	-	-
5-July	-	-	-	-	-	-
6-August	3	1	7.5	-	-	-
7-September	-	-	-	1	1	1.0
8-October	2	0	4.0	-	-	-
9-November	1	0	1.5	-	-	-
10-December	-	-	-	1	0	2.0
TOTALS	17	7	42.0	3	1	6.0

H. Final Evaluation of the Pilot Study of PROTECT.

The general lowering of the prediction curves in Figure 1 is a good measure of the effectiveness of the PROTECT system for recall of electronic test equipments. As can be seen from Figure 1, the maximum percentage of out-of-tolerance test equipments in the system prior to workloading in this manner dropped from about 20% to less than 13%. This decrease was made with no unusual expenditure of manpower allotted to calibration except for the month of September, during which the calibration effort was increased by 50% over the previous and later months. Thus this study of PROTECT can be declared successful.

This study was limited to only five equipments in each class. As such, this pilot study did not provide sufficient data for re-evaluation of failure rates or calibration times. For this reason, it is recommended that another, more extensive study be made of PROTECT. This additional study should include ten or more equipments in each class and run for 12 - 15 months. With more equipments in each class and a longer time period of study more data on failure rates will be accumulated so that re-evaluation of all PROTECT parameters can be made.

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Avionics Facility Indianapolis, Indiana 46218	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP
3. REPORT TITLE Evaluation of Initial PROTECT Pilot Study	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Interim 1964 - 1967	
5. AUTHOR(S) (Last name, first name, initial) Glenn, Bruce R.	
6. REPORT DATE 15 December 1967	7a. TOTAL NO. OF PAGES 15 7b. NO. OF REFS 2
8a. CONTRACT OR GRANT NO. b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NAFI - 1124 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
10. AVAILABILITY/LIMITATION NOTICES Distribution of this report is unlimited	
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Air Systems Command

13. ABSTRACT

This report contains the results of an initial ten month pilot study of PROTECT (Probabilistic Recall Optimizing the Employment of Calibration Time). Included is information on the classes of test equipments used and problems involved in the study. The results are presented in tables and graphs and conclusions are drawn from these results.

DD FORM 1 JAN 64 1473 0101-807-6800

UNCLASSIFIED

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. Calibration system 2. Recall system 3. Optimization technique						

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