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METHODOLOGY INVESTIGATION

FINAL REPORT

MEASUREMENT OF SMOKE DURING WEAPON FIRING

BY

LT. KENNETH C. GONGAWARE

FEBRUARY 1975

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ABERDEEN PROVING GROUND, MARYLAND

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A study was performed at US Army Aberdeen Proving Ground to determine the feasibility of measuring smoke density utilizing an optical sensing device. The anticipated advantage was to establish a quantitative method of measuring smoke produced by small arms weapon firing to replace the present qualitative method of still photography. In the study, a smoke obscuration box was used to contain the smoke while the smoke density was sensed using an optical device which measured the attenuation of an infrared, light-emitting diode

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20. source. It was determined that the amount of smoke produced was affected by the relative humidity, but for a given relative humidity, the data were consistent for the amount of smoke produced by a predetermined burst length. Calibration of the optical device with respect to per cent of light transmitted was possible with neutral density filters. An optimum time interval of 120 seconds after firing was determined to allow dissipation of swirling which occurred inside the box. It was concluded that the concept of measuring smoke in an enclosed area utilizing an optical device is feasible. It was recommended that further action be taken to implement further development of the basic concept developed during this investigation.

FOREWORD

This investigation was conducted by the Small Arms and Special Ordnance Branch, Materiel Testing Directorate (MTD), US Army Aberdeen Proving Ground (APG). Portions of this report have been extracted in part or entirety from MTD Laboratory Report No. 3-74 (Instrumentation Development Section), 4 October 1974, by Lt. Harry V. Cunningham.

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US ARMY ABERDEEN PROVING GROUND
ABERDEEN PROVING GROUND, MARYLAND 21005

TECOM PROJECT NO. 9-CO-001-000-057

METHODOLOGY INVESTIGATION
FINAL REPORT ON
MEASUREMENT OF SMOKE DURING
WEAPON FIRING

26 JULY 1971 THROUGH 3 OCTOBER 1974

SECTION 1. BODY

1. BACKGROUND

The presently established method of measuring gun smoke is described in paragraph 6.2.18 of TOP/MTP 3-2-045. Measurement of smoke resulting from automatic weapon firing has been qualitative, and inaccurate for comparing weapons and ammunition of various types. Proper quantitative evaluation of this important parameter of weapon performance which affects target visibility and weapon concealment has not heretofore been possible. Still photography has been used to determine the obscuration of a target and to indicate the degree that smoke would affect the disclosure of the weapon position. Accurate comparisons of test data could not be made because the data were dependent on local meteorological conditions.

An idea for capturing and containing the smoke in a box-like chamber, and measuring the enclosed smoke with an optical sensing device, was conceived as a possible approach for a more quantitative method for measuring smoke density. This investigation was conducted to determine the feasibility of that method. Additional work proposed in the methodology investigation proposal (Appendix A) was not undertaken due to constraints of funds and time.

The authority for testing is Reference 1.

2. OBJECTIVE

The objective of this investigation was to study various means of obtaining a quantitative and reproducible measure of the smoke produced by small-arms firings.

3. DETAILS OF INVESTIGATION

Findings in various agency reports were studied to determine which factors have the greatest apparent effect on the production and disposal of weapon smoke. Also, methods for measuring weapon-smoke density were reviewed.

Optical instrumentation capable of measuring smoke in a closed container by utilizing the attenuation of the output of an infrared source as a measure of smoke density was designed and fabricated at APG. Although the readings obtained were not from the visible spectrum, it was considered advisable to evaluate the reproducibility of readings obtained with the relatively low-cost, and readily available infrared device before attempting procurement of a more suitable spectral photometer.

3.1 DESCRIPTION OF MATERIEL

3.1.1 Smoke Obscuration Box

Figure 3.1-1 is a detailed drawing of the smoke obscuration box as designed and fabricated and used for obtaining data on smoke density. The main features of the box are as follows:

a. Box dimensions, 2 feet x 2 feet x 3 feet.

b. Material, 1/2 inch plywood.

c. Includes:

   1) Three rubber shock absorption windows.

   2) An external exhaust fan with sliding door cover.

   3) Two optical measurement windows with sliding shutter covers.

   4) A foam rubber muzzle entry window, and a foam rubber bullet exit window.

The above description is for the second box used. The first box, while of similar size and configuration, was of less rugged construction and had plexiglass-covered measurement windows, but no shock-absorption panels.

3.1.2 Optical Sensing Device

Figure 3.1-2 is a sketch of the optical sensing device used. The circuitry schematic developed for the operation of the optical sensing device is shown in Figure 3.1-3.

The system operates as follows:

a. The switch contact causes an infrared beam to be produced by the gallium arsenide light emitting diode (LED), which emits primarily a wavelength of 0.9 micron. This beam is modulated at 3000 Hz.

b. The photodiode detects the modulated infrared beam and produces a voltage dependent on the intensity of the beam it is receiving.

c. The signal produced by the photodiode is filtered and amplified and then displayed on a voltmeter.

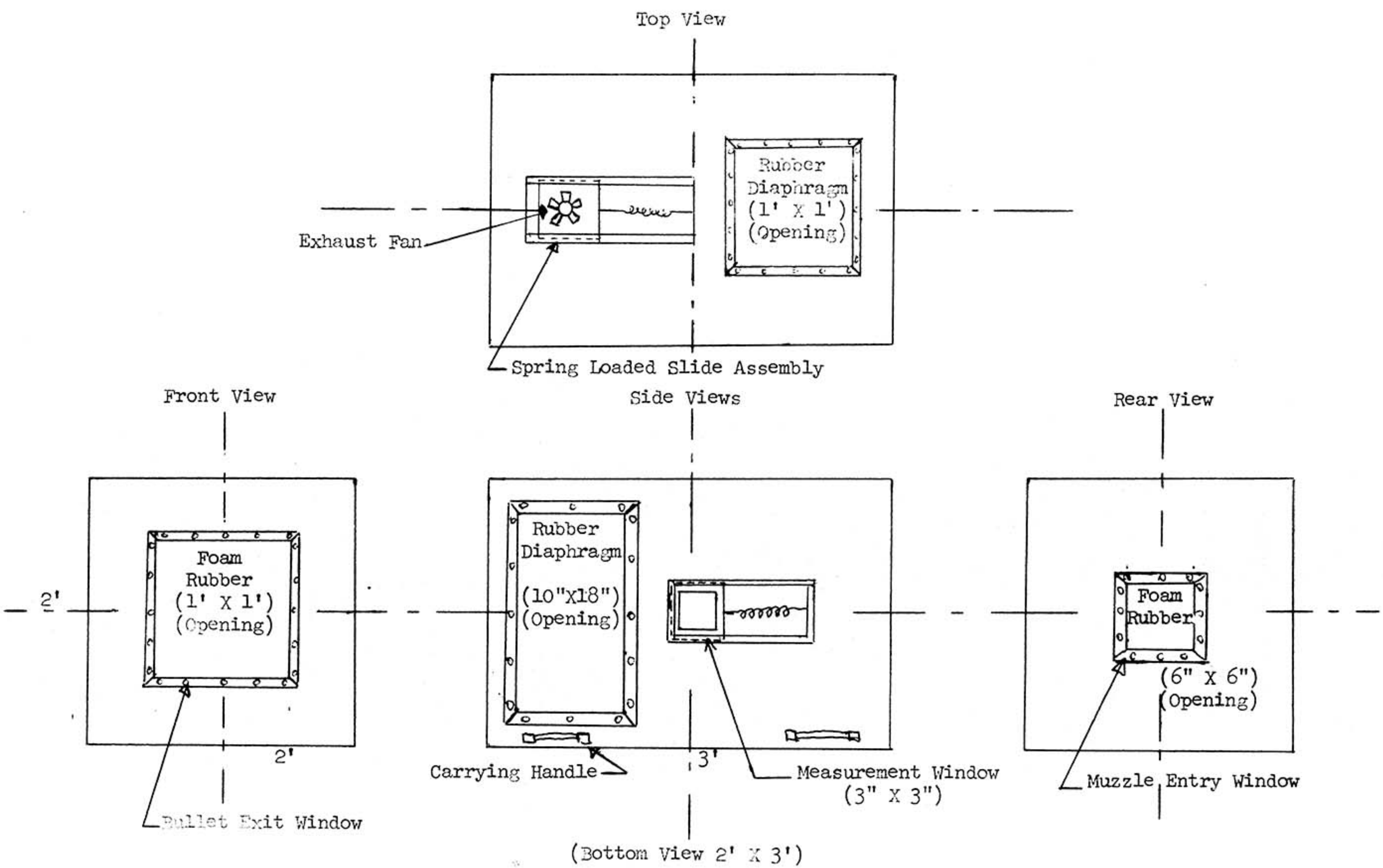

Figure 3.1-1. Smoke Obscuration Box

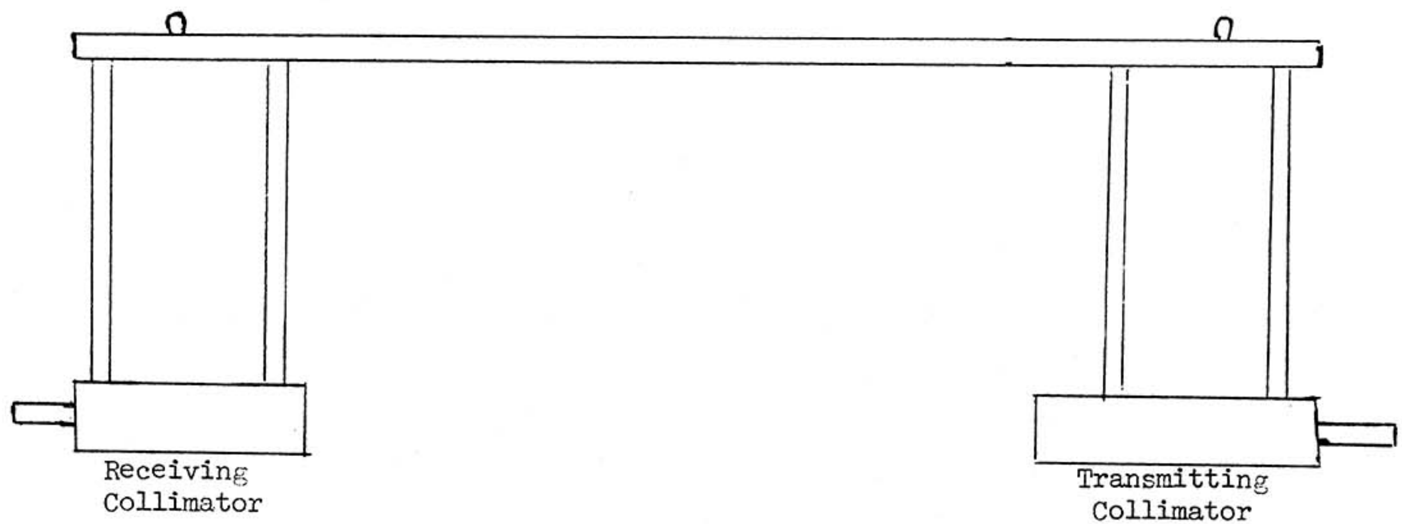

Figure 3.1-2. Optical Sensing Device

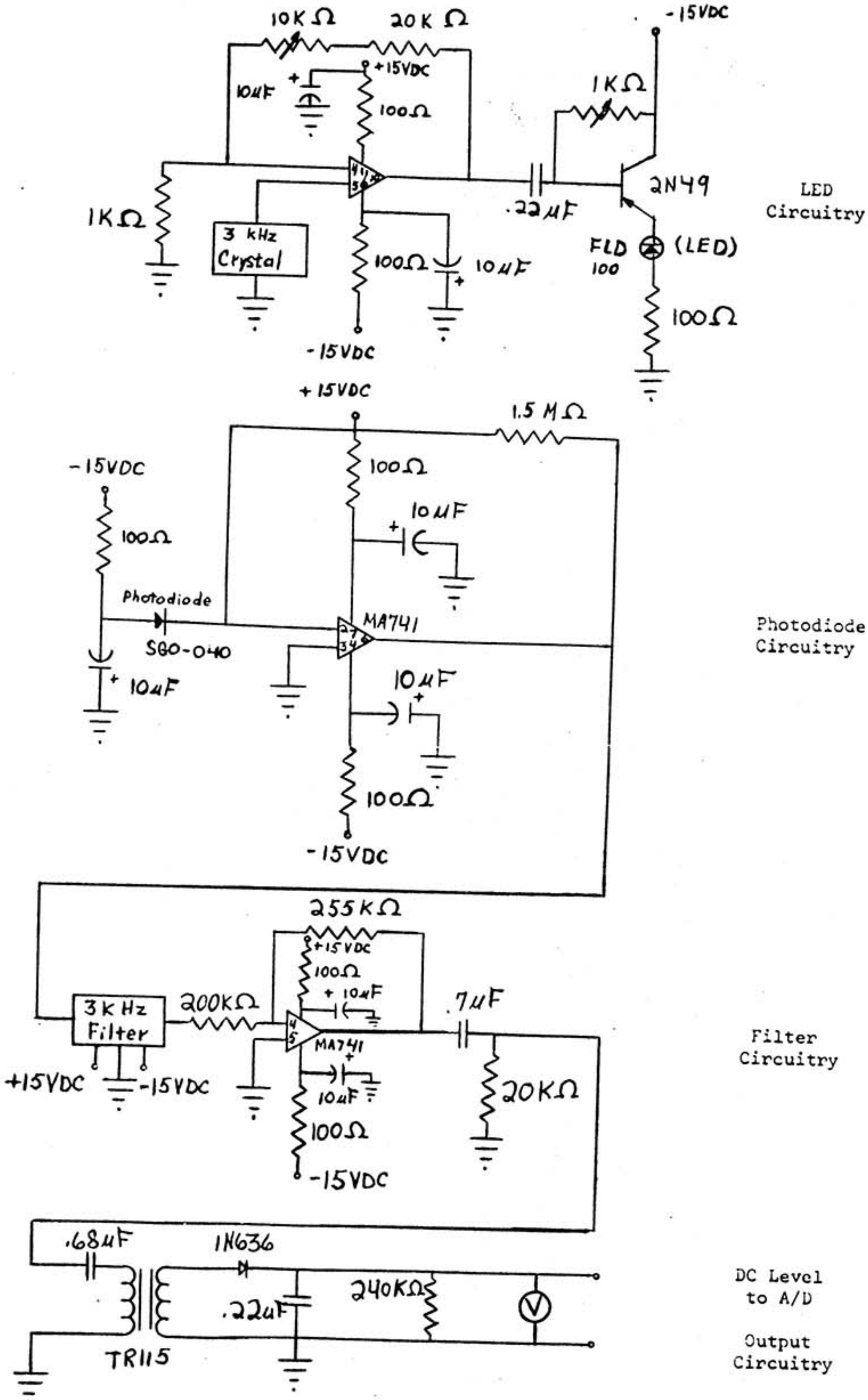

Figure 3.1-3. Circuitry Schematic

3.2 TESTING METHOD

Single shots and bursts, ranging from two to 20 rounds of 5.56-mm M193, ball ammunition, lot No. TWI-145, were fired from an M16A1 rifle, serial No. 791399 on 3 to 6 September 1974. The smoke produced by each burst was then sensed using the smoke obscuration box with the optical sensing device. Relative humidity was taken four times during each day of firing.

Prior to firing, the output voltage was adjusted to read 20 volts on the voltmeter by adjusting the amplifier. With all shutter doors on the box closed, the burst was fired. Voltage readings were taken at 30-second intervals after the burst. The smoke was then exhausted from the box using an externally mounted fan. The fan was operated until the voltage returned to 20 volts, and the procedure was repeated for the next firing.

Neutral density filters were obtained to calibrate the optical sensing device. Per cent transmission of individual filters with neutral density from 0.1 through 1.0 is shown in Table 3-1. Neutral density filters were placed in the path of the infrared light beam and the respective voltage readings were recorded as shown in Figure 3-1. It was therefore possible to correlate the smoke density in the box, for a given number of rounds fired, to a particular value of neutral density filter. The per cent of light obscurity can be determined from the value of the neutral density filter (Figure 3-2).

A total of 133 bursts was fired. Generally, five bursts were fired for each burst length evaluated (Appendix C).

Tests conducted prior to 3 September 1974 were conducted in a similar manner except the neutral density filters were not used and therefore the test results were not available in terms of per cent of light transmission.

Table 3-1. Calibration of Smoke Measuring Device

Neutral Density Value of Filters[a]	Per Cent of Light Transmission	Voltage Reading, volts
0.1	80	16.8
0.2	63.3	14.9
0.3	50	13.1
0.4	40	11.3
0.5	32	10.0
0.6	25	8.9
0.7	20	7.8
0.8	16	6.7
0.9	13	5.8
1.0	10	5.5
1.1	8	4.5
1.2	6.33	3.9
1.3	5	3.5
1.4	4	2.9
1.5	3.2	2.6
1.6	2.5	2.2
1.7	2	1.9
1.8	1.6	1.6
1.9	1.3	1.3
2.0	1	1.2
2.1	0.8	0.9
2.2	0.633	0.8
2.3	0.5	0.7
2.4	0.4	0.5
2.5	0.32	0.5
2.6	0.25	0.4
2.7	0.2	0.4
2.8	0.16	0.4
2.9	0.13	0.4
3.0	0.1	0.4

[a]Or of combinations of filters used for calibration.

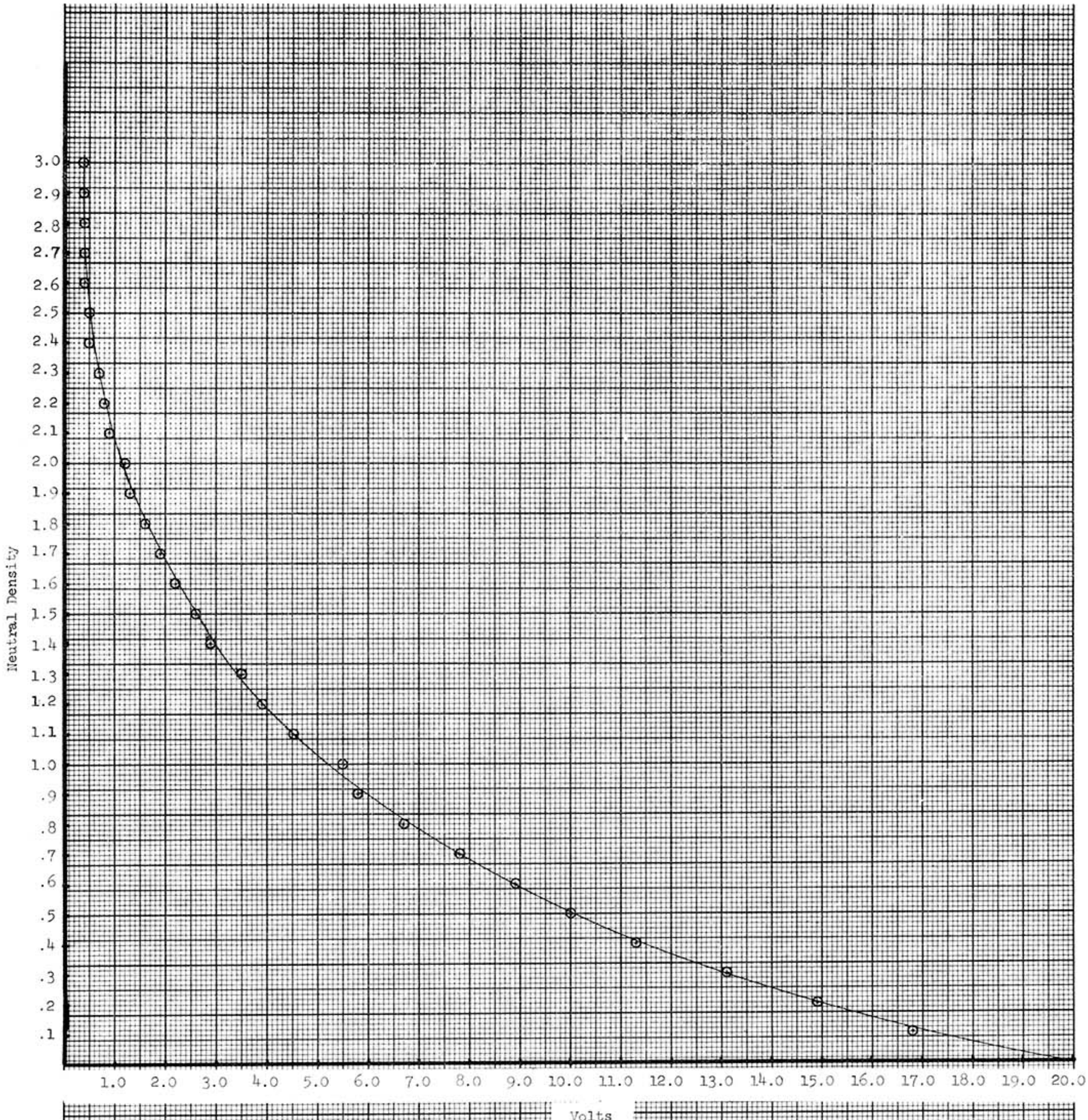

Figure 3.1: Neutral Density Transmission Voltages.

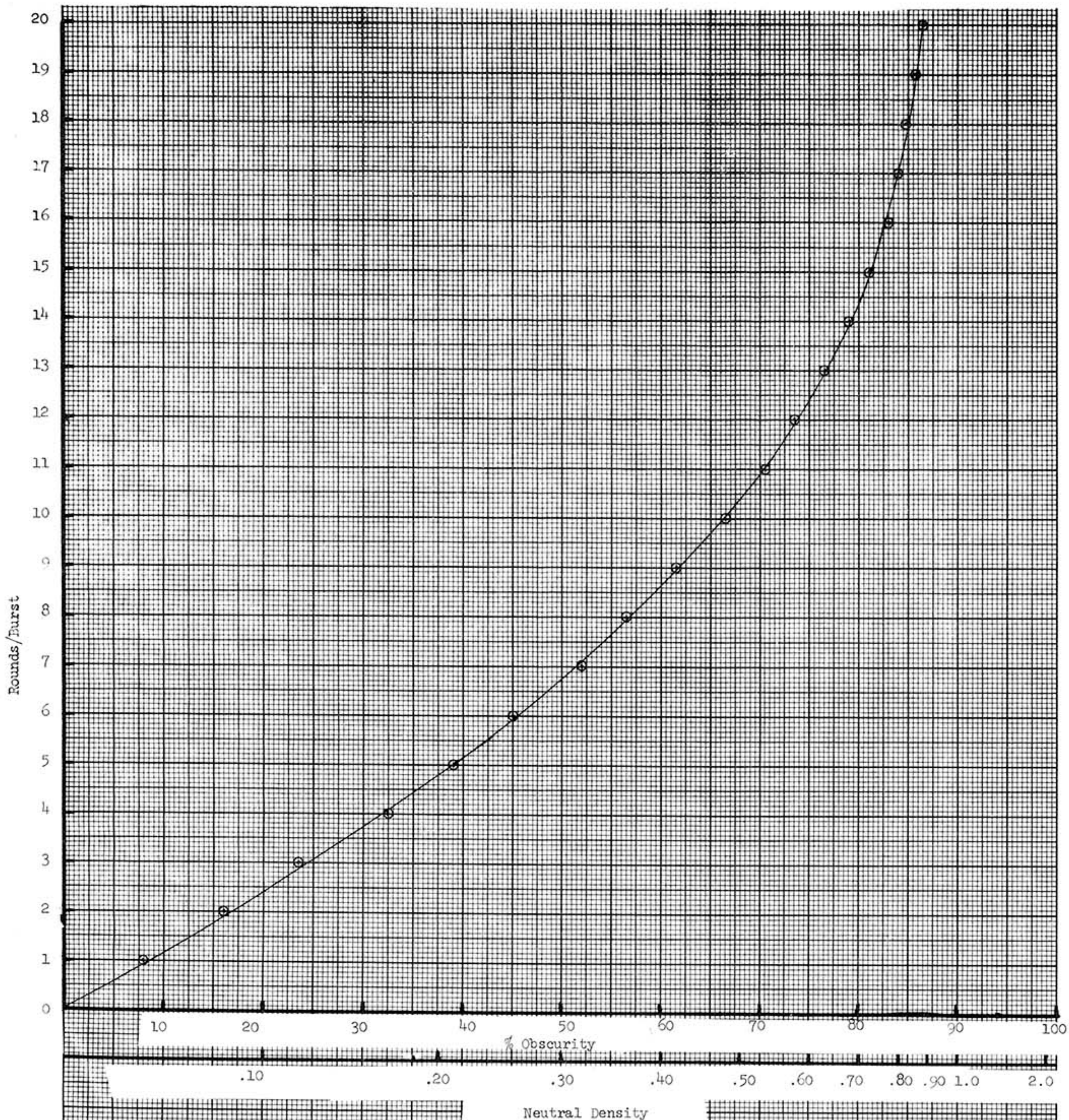

Figure 3.2: Number of Rounds vs Percentage of Obscurity.

4. ANALYSIS

Relative humidity was determined to be a factor in the test results. Readings obtained when the relative humidity was below 75% were fairly consistent, while readings taken at relative humidity levels above 75% differed noticeably from the others. Data indicated that more smoke was produced by the weapon at higher levels of relative humidity.

Test data were analyzed using the 5.56-mm ball ammunition firings. It was believed (based on earlier tests) that the smoke obscuration box could not withstand automatic fire of larger caliber weapons without being damaged. The specific test results obtained, which apply to only the one type of ammunition, nonetheless are considered to adequately demonstrate the feasibility of using this type of smoke-measuring system. If further development of this system is pursued (i.e., an improved optical device and a stronger, larger, better designed smoke obscuration box), tests with other types and sizes of ammunition should be conducted.

Concerning the use of an optimum time at which readings are taken, it was felt that while the voltage continued to change with increases in time, data obtained at these longer times were not useful. Some change was apparently due to continued motion of the smoke within the box. Also, both leaking and precipitation of the smoke particles could affect the validity of the smoke-density data with time. Thus a time had to be selected which would be long enough to provide a uniform smoke distribution without swirling, but short enough so that the data remained meaningful. The selected 2-minute time interval was demonstrated by the data to be a valid time for obtaining reproducible measurements.

An empirical formula was derived using the data obtained during this investigation. The derivation is in Appendix D. The formula agrees with the known fact that density of smoke is exponentially related to light transmission. The formula can be stated in terms of voltage readings as follows:

$$Y = Y_o A^x$$

where

Y = output voltage
Y_o = reference voltage
A = relative light transmission for a single round
X = total number of rounds fired.

For the M16 (with relative humidity less than 75%) this resulted in the following:

$$Y = 20(0.933)^x$$

In terms of percentage of transmission, the formula is as follows:

$$Z^b = A^x$$

For the M16: $Z = (0.933)^{\frac{x}{0.6}}$

where

- Z = relative light transmission. (If % transmission is desired multiply Z by 100.)
- b = constant (.6)
- A = relative light transmission for a single round
- X = total number of rounds fired.

The scope of the investigation performed was at variance with the description of investigation included in the methodology investigation proposal in a number of areas. As noted previously, the structural limitations of the smoke obscuration box effectively confined the investigation to the 5.56-mm weapon, except for a cursory look at 7.62-mm. In the preliminary firings, the 7.62-mm and 5.56-mm weapons appeared to produce sufficient smoke densities, so the one that was least damaging to the box was selected. Unquestionably, the box would not have withstood the larger caliber automatic weapons (e.g., 20-mm). Photographic methods were not explored because these techniques are well established and need be applied for comparison purposes only if the system is developed further. The infrared optical sensing device was used because it was readily available. Lastly, the methodology investigation proposal, when viewed in retrospect, seems overly extensive. Some of the ambitious areas, considering the constraints of funds, include controlling relative humidity in the box, sampling the smoke for toxicity and explosive mixtures, determining the effect of smoke absorption on the walls of the box, and noting on photographs taken outdoors, the effects of variables as inferred in the smoke-obscuration-box firings.

The feasibility of capturing and measuring smoke produced by weapon firing has been demonstrated. To develop a correlation of results obtainable from the method devised with real-world combat conditions would require a large amount of effort, and still the certainty of deriving such a correlation is questionable; however, this method does demonstrate a solution to the original problem in that it clearly provides an accurate and quantitative measurement for comparing weapons and ammunition of different types so that a relative level of smoke-density measurement can be obtained. A determination, based on cost-effectiveness and existing requirements should be made as to the direction in which developmental work should be accomplished.

5. SUMMARY OF RESULTS

5.1 PRELIMINARY TESTING

Results from preliminary testing of the smoke obscuration box with the optical sensing device, which took place at APG on 2 October 1972 and

14 to 16 March 1974, were neither consistent nor conclusive. However, these tests were useful in that serious flaws in the early prototype versions of the smoke box were revealed. Lack of shock absorption panels in the earlier box resulted in its quick destruction. Plexiglass windows, which passed the infrared light beam, were quickly covered with smoke residue. Interior mounted exhaust fans were rendered useless by the muzzle blast. Both 7.62-mm and 5.56-mm ball ammunition were fired. The smoke produced by the 5.56-mm ball ammunition was considered sufficiently representative to proceed with development of the optical sensing device with that caliber weapon alone.

Improvements in the construction of the box were made to overcome these deficiencies. The smoke box used during the final phase of the investigation on 3 to 6 September 1974, still had several shortcomings, but adequately proved the feasibility of the concept.

5.2 THE EFFECTS OF RELATIVE HUMIDITY

Relative humidity played a significant role in obtaining data. As long as the relative humidity was below 75%, results were fairly consistent. Readings obtained when the relative humidity was above 75% differed noticeably from those obtained when the relative humidity was below 75%, yet were consistent for a given relative humidity. Higher relative humidity resulted in lower voltage readings (Figure 5-1, page 14).

Due to constraints of time and funds, testing was not conducted under humidity-controlled conditions; therefore, accurate data for determining a numerical correlation between relative humidity and light absorption due to smoke could not be obtained. Future testing should include such controlled conditions, so that the effect of relative humidity on smoke production can be more clearly defined.

5.3 THE EMPLOYMENT OF THE SMOKE OBSCURATION BOX

Employment of the smoke obscuration box during the final series of tests conducted, demonstrated that such a technique for quantifying smoke density was possible. The box withstood the shock of firing the 5.56-mm M16A1 rifle successfully, with the exception that the rotor blade was blown off the body of the externally mounted fan. A replacement fan was also damaged, but remained operational throughout the remainder of the test.

5.4 DEPENDABILITY OF THE OPTICAL SENSING DEVICE

The output of the photodiode was not stable at all times. Twenty volts was used as the reference voltage before each firing. After firing, and clearing the box, the voltage would at times return to only 18 volts. At other times, the voltage would return to 22 volts instead of the reference voltage level. In each instance the appropriate adjustments were made to return the voltage to 20 volts.

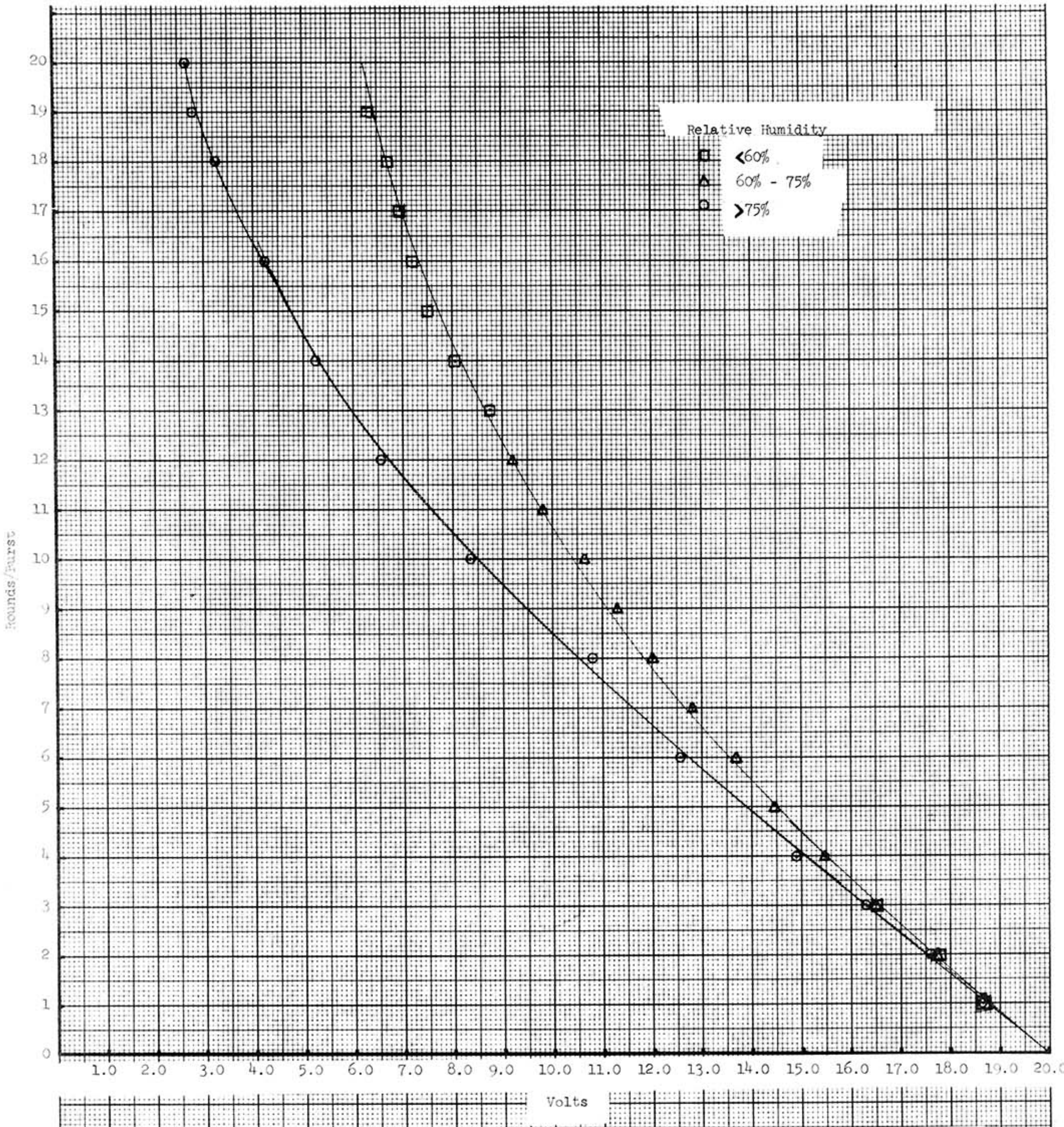

Figure 5.1: Smoke Obscurity as Affected by Relative Humidity.

It was difficult to maintain alignment of the source and detector throughout the testing, mainly because of the crudeness of the mounting hardware. This problem could be overcome in a future box design by giving appropriate consideration to the required alignment of the source, detector, and box.

5.5 THE OPTIMUM TIME INTERVAL

Data on smoke density were taken at 30-second intervals for up to 5 minutes. A time had to be selected which would not permit extensive leaking or precipitation of smoke but would provide a relatively uniform distribution within the box to get the best data. For a specific condition the voltage continued to decrease with increase in time for up to 5 minutes. This was especially noticeable with bursts of more than 12 rounds. This resulted from swirling of the smoke within the box, which was obvious when the side windows were open. The swirling activity tended to keep the smoke near the walls of the box, while the sensor was located in the center, where the smoke was less dense. An optimum time interval for measuring was found to be 120 seconds after firing, in that it provided sufficient time for the smoke to circulate and obtain uniform distribution within the box. Use of an optimum time to take readings removes the inherent error in averaging data values over protracted periods of time (Figures 5.2 and 5.3).

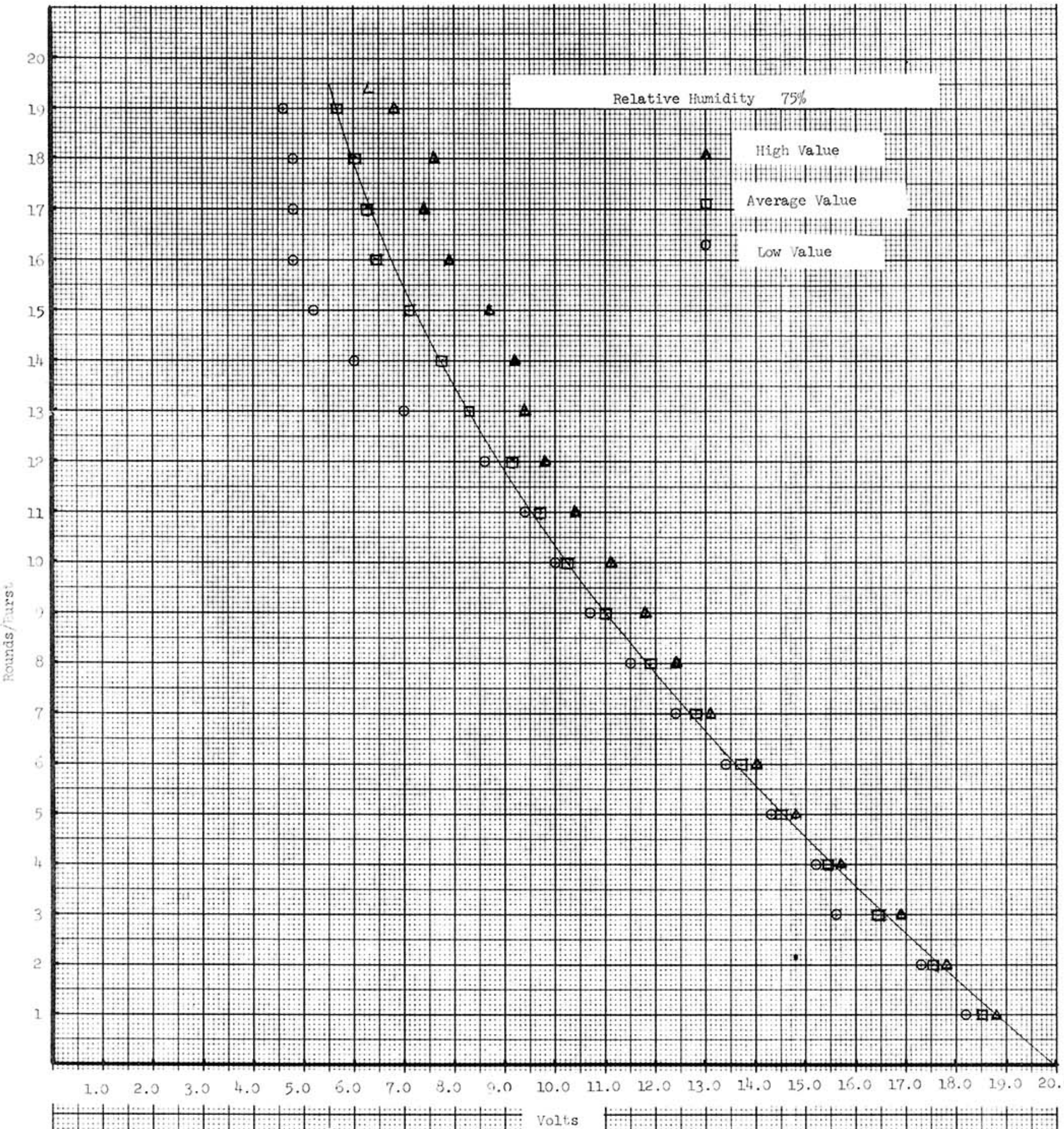

Figure 5.2: Smoke Obscurity Voltages Regardless of Time.

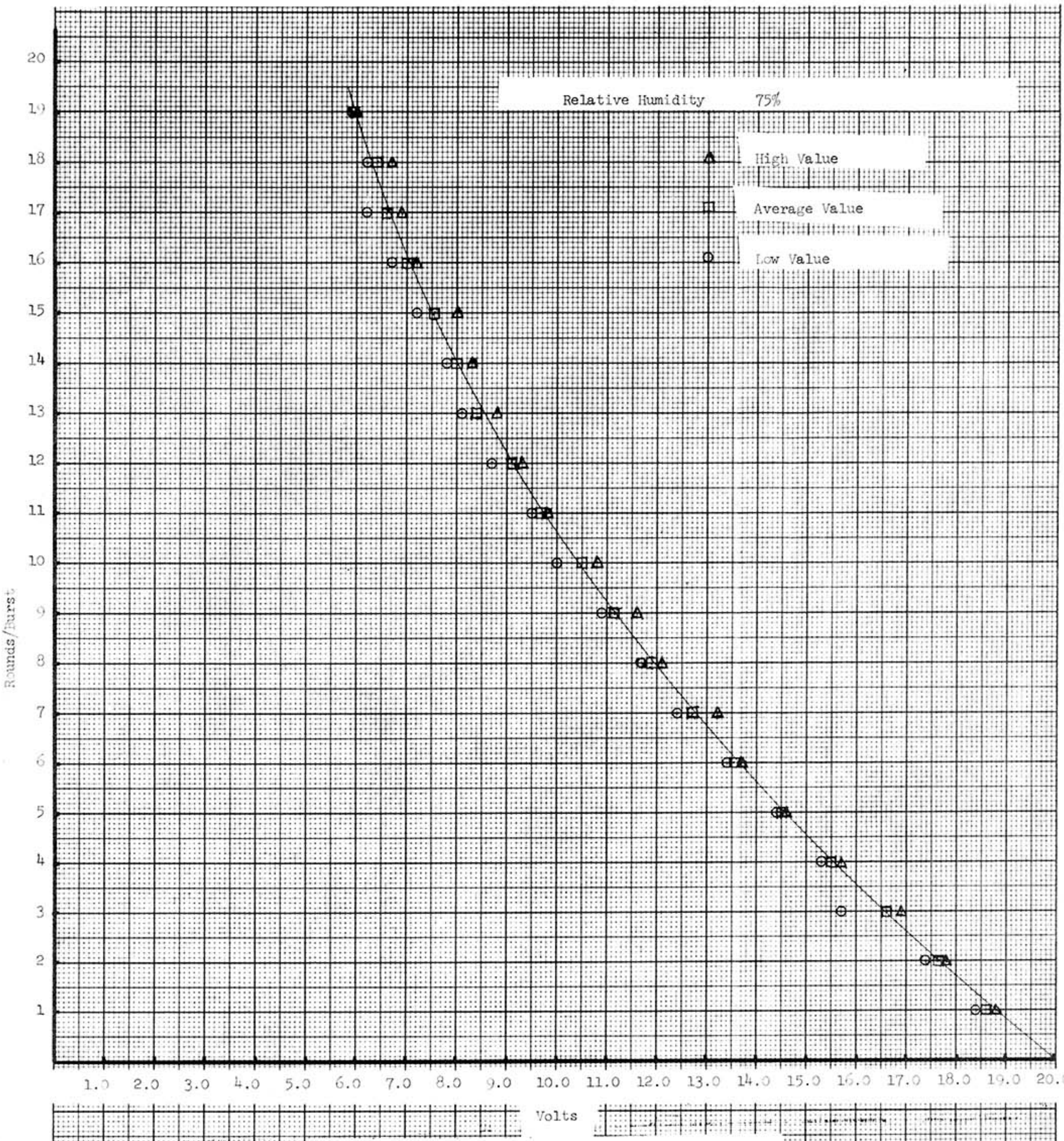

Figure 5.3: Smoke Obscurity at 120 Seconds.

6. CONCLUSIONS

It is concluded that:

a. It is feasible to use a smoke obscuration device to determine smoke density.

b. A determination should be made as to whether the smoke-measuring device should provide correlation with real-world conditions or just relative smoke measurements.

c. If the smoke obscuration device used in this test is to be developed further, the following improvements need to be made and tested:

1) An optical sensing device be used which represents the human eye response (visible spectrum).

2) Baffles be installed within the smoke obscuration box to control swirling activity.

3) A sturdier mount be designed and used for maintaining alignment of the detector and source.

4) A physical arrangement be devised for the smoke obscuration device which is compatible with testing the large caliber small arms automatic weapons.

7. RECOMMENDATIONS

It is recommended that further action be taken to construct an instrument to increase the capability of measuring gun smoke, using the basic concepts developed during this investigation with the improvements listed in paragraph 6. Further development of this item should be based upon a determination as to whether a correlation to real-world conditions or a relative smoke measurement is needed.

APPENDIX A - CORRESPONDENCE

METHODOLOGY INVESTIGATION PROPOSAL

1. TITLE: Measurement of Smoke During Weapon Firing

2. INSTALLATION: Materiel Testing Directorate
Aberdeen Proving Ground, Md. 21005

3. PRINCIPAL INVESTIGATOR: T. Ellison, Infantry and Aircraft Weapons Division, STEAP-MT-TI, Autovon 234-3350, Ext. 4910

4. STATEMENT OF THE PROBLEM: Present measurements of the smoke resulting from automatic weapon firing are qualitative and inaccurate for comparing weapons of different types. This important parameter of weapon performance which affects target visibility and weapon concealment cannot be properly evaluated. The requirement for evaluation exists with each new small arm, automatic weapon, or ammunition development.

5. DESCRIPTION OF INVESTIGATION:

a. This investigation will involve study of various means of obtaining a quantitative and reproducible measure of the smoke produced by small arms firing. Photographic and electro-optical (densi-tometer) measurements will be investigated under varying conditions of confinement, wind, ambient temperature, humidity, light, firing rate, burst length, and other factors in order to develop an empirical equation capable of accurately relating one weapon to another.

b. APG will:

(1) Study the findings of other agencies including USAWECOM and USAMUCOM to determine which factors have the greatest apparent effect on weapon smoke production and dispersal.

(2) Construct a chamber with flexible walls for measuring the density of a confined smoke cloud. The initial chamber will be of a size appropriate for testing of small (rifle caliber) automatic weapons. Stretched rubber sheets may be used for the sides. Projectiles will pass through a replaceable section designed to provide some degree of self-sealing. The muzzle of the weapon or the entire weapon may be confined within the chamber. Provision will be made to control the relative humidity within the chamber while temperature will be controlled by that of the surrounding room. A variety of weapons will be tested using the chamber. A predetermined burst will be fired remotely in the chamber from each weapon. The resulting gas mixture and particle suspensions will be sampled for toxic fumes and explosive mixtures. A densitometer consisting of a light source and detector plus a number of filters will be used to record light absorption and scattering throughout the visible spectrum. The effect of smoke adsorption on the walls of the chamber

will be studied and accounted for. Recorded densities will be plotted as functions of the following variables:

(a) Ambient temperature

(b) Chamber relative humidity

(c) Chamber volume

(d) Propellant per cartridge

(e) Number of cartridges fired

(f) Firing rate

(g) Time

(h) Wave length

(i) Illumination level

(j) Initial weapon temperature

From logarithmic plots an empirical density function will be defined including all significant variables. The density function will be a figure of merit by which one weapon may be compared to another. A graph will be provided in the report showing the relative positions of weapons tested to aid developers in the specification of technical characteristics for new weapon systems.

(3) Conduct tests using a variety of weapons out-of-doors and under similar conditions to obtain photographs for qualitative comparisons. Variables will be recorded and the effects of the variables as inferred by the closed chamber firings will be noted on the photographs. Particular attention will be given to target obscuration and the dispersion of the smoke as caused by wind and muzzle devices or other characteristics of the weapons.

(4) Analyze test results to determine the least objectionable smoke characteristics for each class of automatic weapons. The feasibility of a permanent smoke testing chamber with larger caliber capability will also be studied.

6. REASONS FOR CONDUCTING INVESTIGATION:

a. Present Capability.

APG conducts smoke tests by firing an automatic burst and photographing the smoke cloud. Photographs are taken at standardized camera settings from directly behind the weapon over the muzzle to determine obscuration of a checkerboard target placed at some distance downrange. Photographs from a distance are taken to indicate the degree that smoke would affect disclosure of the weapon position. A three-sided windbreak may be placed around the gun to partially confine the smoke.

b. Limitations of Present Capability.

The greatest limitations of the present capability is that the results are not reproducible and accurate comparisons cannot be made. Test data are dependent on weather conditions but the effect of these variables is unknown. Improvements in photographic film and the discontinuance and nonavailability of older film types may have an effect on comparability of photos taken at different times.

c. Anticipated Improvements to Result from Investigation.

The limitations above will be almost entirely removed for those weapons that can be tested in a closed chamber. The effect of environmental conditions on open air tests can be noted and compensation provided in the test analysis.

d. Pertinence to USATECOM Mission.

The quantity of smoke produced during firing of an infantry weapon is one of the most important factors upon which to base a decision on suitability. It is essential that means to accurately measure this characteristic be available in order to provide a proper evaluation of an automatic weapon system. Test and evaluation of Army weapons and ammunition is a part of the USATECOM mission.

7. IMPACT IF NOT FUNDED OR DELAYED:

a. If the investigation is not conducted: APG will continue to use qualitative measures that are not reproducible and that cannot be related to technical requirements except in a very cursory way. Inability to perform an adequate and scientific smoke test will reflect adversely on the competence of APG to perform small arms testing. Technical requirements in the form of QMRs, SDRs, and TCs are generally vague with respect to smoke, apparently due to the lack of a means to measure it. Specific requirements are classified but statements such as "Smoke shall be minimized" are included in technical characteristics . It is obvious that QMR and TC authors have nearly as great a requirement for a quantitative measure of smoke as does the Proving Ground. The results of this study may provide the weapon developers with adequate terms to express the requirement for minimization of smoke. No manhours or dollars have been spent to date specifically to improve smoke testing methodology, although testing using inadequate methodology continues.

b. If the investigation is deferred until FY73: The information of Par. 7a is applicable. Additionally, the development of ammunition for the 20mm VULCAN and Hispano-Suiza and for the BUSHMASTER guns during FY72 and FY73 will be affected.

8. TEST PROJECTS TO BENEFIT FROM THE INVESTIGATION:

Title	TRMS No.	FY
ET Stoner 63A1 LMG (XM207)	8-WE-400-63A2-001	71
ET Stoner 63A1 Rifle & Carbine	8-WE-400-63A2-002	71
EDT 5.56MM FN Rifle	8-WE-300-203-006	71
EDT Lightweight SMG	(not assigned)	71
Vulcan Air Defense System	3-MU-005-000-001	71
ET, IPT, 20MM H-S CONUS Ammo	1-MU-001-206-001	71
ET Bushmaster	1-WE-100-BUS-002	73

NOTE: Certain of the above tests may be over before an improvement in methodology is effected; however, it is expected that similar tests will materialize in the meantime. Smoke measurement is a continuing requirement that will exist as long as guns and ammunition are being tested.

9. RESOURCES:

a. Financial

	Dollars in Thousands			
	FY72		FY73	
	in-house	out-of-house	in-house	out-of-house
Personnel Compensation Permanent Full-Time				
Part-time	14.0			
Travel	.5			
Contractual Support				
Consultants and Other Svcs				

	Dollars in Thousands			
	FY72		FY73	
	in-house	out-of-house	in-house	out-of-house
Materials & Supplies	1.0			
Equipment				
G&A Costs	3.5			
Subtotals	19.0	0.0	0.0	0.0
FY Totals	19.0		0.0	

b. Explanation of Cost Categories

(1) - (6) Not required.

(7) G&A Costs. This includes cost of supporting activities provided by APG (i.e., post); it does not include operating overhead incurred by MTD.

c. Obligation Plan

FQ	1	2	3	4	Total
Obligation Rate FY72 (Thousands)	2.0	2.0	8.0	7.0	19.0

d. In-house personnel

	Number	Manhours, FY73 Required	Manhours, FY73 Available	Total Manhours Required
Mech Engr GS-0830	1	400	400	400
Mech Engr Tech GS-0802	1	400	400	400
Editing & Typing		40	40	40
		840	840	840

10. INVESTIGATION SCHEDULE:

	FY72 J A S O N D J F M A M J	FY73 J A S O N D J F M A M J
In-house	- - - - - - - - - - - -	R
Contract		

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APPENDIX B - REFERENCES

1. Letter, TECOM, AMSTE-PA-M, Measurement of Smoke During Weapon Firing - TRMS No. 9-CO-001-000-057, 26 July 1971.

2. Cunningham, Lt Harry V., Smoke Obscuration Device, US Army Aberdeen Proving Ground. Instrument Development Section. Report No. 3-74.

3. TOP/MTP 3-2-045, Machine Guns and Automatic Weapons.

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APPENDIX C - DATA

BURST #	# ROUNDS	HIGH VALUE[a]	LOW VALUE[a]	AVERAGE VALUE[a]	RELATIVE HUMIDITY	120 SEC VALUE[a]	AVERAGE 120 SEC VALUE[a]
				3 September 1974			
1	1	18.5	18.3	18.4	72%	18.3	
2	1	18.5	18.2	18.375	"	18.4	
3	1	18.8	18.5	18.7	"	18.8	
4	1	18.6	18.5	18.55	"	18.6	
5	1	18.7	18.5	18.6	"	18.6	
							18.58
6	2	17.4	17.3	17.35	66%	17.4	
7	2	17.6	17.5	17.55	"	17.5	
8	2	17.8	17.6	17.65	"	17.7	
9	2	17.8	17.4	17.65	"	17.8	
10	2	17.8	17.4	17.6	"	17.8	
							17.64
11	3	16.8	16.4	16.575	64%	16.8	
12	3	16.9	16.3	16.6	"	16.9	
13	3	16.8	16.5	16.65	"	16.8	
14	3	15.9	15.6	15.7	"	15.7	
15	3	16.9	16.6	16.75	"	16.9	
							16.62
				4 September 1974			
16	1	21.0	18.6	19.625	69%	21.0	
17	1	18.8	18.5	18.7	"	18.8	
18	1	18.8	18.5	18.725	"	18.8	
							19.53
19	2	17.8	17.4	17.6	69%	17.8	
20	2	17.7	17.3	17.525	"	17.7	
21	2	17.9	17.6	17.7	"	17.9	
							17.8
22	3	16.9	16.6	16.75	69%	16.9	
23	3	16.7	16.5	16.625	"	16.7	
24	3	16.5	16.3	16.425	"	16.5	
							16.7

[a]Measurements are in volts.

BURST #	# ROUNDS	HIGH VALUE[a]	LOW VALUE[a]	AVERAGE VALUE[a]	RELATIVE HUMIDITY	120 SEC VALUE[a]	AVERAGE 120 SEC VALUE[a]
25	4	15.6	15.4	15.5	75%	15.6	
26	4	15.7	15.5	15.575	"	15.7	
27	4	15.5	15.3	15.375	"	15.4	
28	4	15.4	15.2	15.3	"	15.3	
29	4	15.7	15.4	15.575	"	15.5	
							15.5
30	5	14.6	14.5	14.525	75%	14.6	
31	5	14.4	14.4	14.4	"	14.4	
32	5	14.7	14.5	14.55	"	14.5	
33	5	14.5	14.3	14.4	"	14.4	
34	5	14.6	14.4	14.5	"	14.6	
							14.5
35	6	13.8	13.6	13.65	75%	13.6	
36	6	13.9	13.6	13.7	"	13.6	
37	6	13.7	13.4	13.55	"	13.4	
38	6	13.7	13.6	13.65	"	13.7	
39	6	14.0	13.6	13.825	"	13.6	
							13.58
40	7	12.8	12.5	12.625	68%	12.7	
41	7	13.0	12.5	12.775	"	12.7	
42	7	13.2	13.0	13.075	"	13.2	
43	7	13.0	12.4	12.75	"	12.4	
44	7	13.0	12.6	12.775	"	12.7	
							12.74
45	8	12.2	11.8	12.025	68%	11.8	
46	8	12.0	11.7	11.9	"	11.7	
47	8	12.4	11.5	12.016	"	12.0	
48	8	12.0	11.5	11.816	"	11.9	
49	8	12.4	12.0	12.166	"	12.1	
							11.9
50	9	11.7	11.2	11.533	64%	11.6	
51	9	11.8	11.0	11.4	"	11.3	
52	9	11.5	10.8	11.133	"	10.9	
53	9	11.4	10.6	11.066	"	11.2	
54	9	11.5	10.7	11.166	"	11.2	
							11.24
55	10	11.0	10.4	10.666	64%	10.7	
56	10	10.7	10.0	10.266	"	10.0	
57	10	11.1	10.1	10.583	"	10.7	
58	10	11.0	10.6	10.8	"	10.8	
[illegible]	10	10.8	10.3	10.533	"	10.5	
							10.54

Measurements are in volts.

BURST #	# ROUNDS	HIGH VALUE[a]	LOW VALUE[a]	AVERAGE VALUE[a]	RELATIVE HUMIDITY	120 SEC VALUE[a]	AVERAGE 120 SEC VALUE[a]
60	11	10.4	9.4	9.833	60%	9.6	
61	11	10.3	9.6	9.816	"	9.7	
62	11	10.2	9.4	9.733	"	9.5	
63	11	10.2	9.5	9.8	"	9.8	
64	11	10.3	9.6	9.983	"	9.6	
							9.64
65	12	9.7	8.7	9.05	60%	8.7	
66	12	9.4	8.6	9.083	"	9.2	
67	12	9.8	9.2	9.4	"	9.2	
68	12	9.4	9.1	9.283	"	9.1	
69	12	9.5	9.0	9.333	"	9.3	
							9.1
			5 September 1974				
70	1	18.5	18.4	18.425	52%	18.5	
71	1	19.3	18.6	18.95	"	19.3	
72	1	18.8	18.5	18.7	"	18.7	
							18.83
73	2	17.8	17.7	17.775	52%	17.8	
74	2	18.1	17.7	17.9	"	18.1	
75	2	17.7	17.5	17.6	"	17.5	
							17.8
76	3	16.6	16.4	16.475	52%	16.4	
77	3	16.7	16.5	16.575	"	16.5	
78	3	16.7	16.5	16.6	"	16.6	
							16.5
79	13	9.4	7.5	8.566	52%	8.2	
80	13	9.2	7.2	8.15	"	8.1	
81	13	9.3	7.5	8.316	"	8.3	
82	13	9.4	7.0	8.15	"	8.3	
83	13	9.2	7.4	8.5125	"	8.8	
							8.34
84	14	9.2	6.5	7.7625	52%	7.9	
85	14	8.9	6.0	7.525	"	7.8	
86	14	9.0	6.4	7.8125	"	7.9	
87	14	9.0	6.9	7.9875	"	8.2	
88	14	9.0	6.7	7.925	"	8.3	
							8.02
89	15	8.1	5.9	6.93	50%	7.2	
90	15	8.4	5.2	6.81	"	7.7	
91	15	8.7	5.7	7.05	"	7.6	
92	15	8.1	5.8	7.06	"	7.6	
93	15	8.5	6.5	7.43	"	8.0	
							7.62

[a]Measurements are in volts.

BURST #	# ROUNDS	HIGH VALUE [a]	LOW VALUE [a]	AVERAGE VALUE [a]	RELATIVE HUMIDITY	120 SEC VALUE [a]	AVERAGE 120 SEC VALUE [a]
94	16	7.6	4.9	6.36	52%	7.2	
95	16	7.9	4.8	6.12	"	6.8	
96	16	7.7	5.6	6.55	"	7.2	
97	16	7.3	6.0	6.65	"	6.7	
98	16	7.5	5.9	6.73	"	7.1	
							7.0
99	17	7.1	4.8	6.1	51%	6.5	
100	17	7.4	5.2	6.22	"	6.7	
101	17	7.3	5.3	6.41	"	6.9	
102	17	7.2	5.4	6.38	"	6.7	
103	17	6.7	5.1	6.02	"	6.2	
							6.6
104	18	7.2	5.2	6.21	52%	6.4	
105	18	6.7	5.0	5.93	"	6.2	
106	18	6.7	5.0	5.98	"	6.7	
107	18	6.9	4.8	6.01	"	6.5	
108	18	7.6	5.0	5.99	"	6.2	
							6.4
109	19	6.8	4.6	5.71	52%	6.0	
110	19	6.7	4.6	5.49	"	5.9	
111	19	6.7	4.7	5.69	"	6.0	
							5.966
			6 September 1974				
112	19	6.6	2.7	4.14	81%	4.4	
113	19	7.4	2.4	4.06	"	4.4	
							4.4
114	20	7.0	2.2	3.87	81%	4.3	
115	20	6.8	2.1	3.94	"	4.3	
116	20	6.6	2.4	3.9	"	4.3	
117	20	6.6	2.4	3.87	"	3.8	
118	20	6.4	2.4	3.94	"	4.6	
							4.26
119	2	17.6	17.4	17.49	81%	17.4	17.4
120	3	16.5	16.2	16.32	81%	16.3	16.3
121	4	15.0	14.7	14.89	81%	14.9	14.9
122	6	13.6	12.3	12.92	81%	12.9	12.9
123	8	12.4	10.3	11.3	81%	11.6	11.6

[a] Measurements are in volts.

BURST #	# ROUNDS	HIGH VALUE[a]	LOW VALUE[a]	AVERAGE VALUE[a]	RELATIVE HUMIDITY	120 SEC VALUE[a]	AVERAGE 120 SEC VALUE[a]
124	10	10.6	8.0	9.28	81%	9.8	
125	10	10.4	8.1	9.13	"	9.8	
							9.8
126	12	9.0	5.5	6.85	81%	7.2	
127	12	9.6	6.2	7.64	"	8.2	
128	12	9.6	6.2	7.66	"	7.9	
							7.766
129	14	8.9	4.9	6.51	81%	7.2	7.2
130	16	7.4	4.0	5.37	81%	5.8	
131	16	8.0	3.2	4.76	"	5.3	
							5.55
132	18	7.3	2.9	4.56	81%	4.9	4.9
133	19	6.7	2.6	3.87	81%	3.8	3.8

[a]Measurements are in volts.

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APPENDIX D - FORMULA DERIVATION

Examination of data obtained from the Smoke Obscuration Device led to the hypothesis that light transmission decreased as a function of the "percent of light transmitted after a single round was fired" raised to the "number of rounds fired" power. Stating it in terms of an equation:

$$y = y_o A^x$$

where y = output voltage
y_o = reference voltage
A = percent of light transmitted after a single round was fired.
x = number of rounds fired.

Having derived this formula it was naturally imperative to test the validity of this hypothesis. It was decided that a value had to be ascertained for A. Using the data available, volts vs rounds per burst (at the 120-second interval) was plotted on semi-logarithmic paper. The calculations were as follows:

$$y = y_o A^x$$

$$\ln y = \ln y_o + x \ln A \qquad (1)$$

$$\ln y = x \ln A + \ln y_o$$ - which is the equation for a straight line

$$\therefore \text{slope} = m = \ln A$$

from Figure 1:

$$m = \frac{\Delta y}{\Delta x} = \ln A$$

$$\ln A = \frac{\ln 6 - \ln 19.5}{18 - 1}$$

$$" = \frac{1.79 - 2.97}{17}$$

$$" = -\frac{1.18}{17}$$

$$\ln A = -.069$$
$$-\ln A = .069$$
$$\ln \frac{1}{A} = .069$$
$$\frac{1}{A} = 1.072$$
$$A = .933$$
$$\therefore\ y = y_o\,(.933)^x$$

Utilizing y_o as 20 volts, it is possible to duplicate the graph produced on the semi-logarithmic paper. Thus using this formula, it is possible to predict the percent of light transmitted after the firing of any number of rounds. The unknown A will vary with relative humidity. The value calculated above was derived from the data accumulated when the relative humidity was below 75%. Using Figure 2, the value of A was calculated to be .9 for relative humidity above 75%.

There now existed a formula for predicting the voltage reading on a voltmeter after a given number of rounds were fired. However, it was felt that it would be more meaningful to predict the percent of transmission using this formula, rather than to predict voltage readings. It became necessary therefore, to equate known values of transmissibility to the derived formula of y_oA^x. Using Table 3 - II, volts vs per cent of light transmission was plotted on logarithmic paper as shown in Figure 3. Calculations were as followed:

$$\frac{V}{V_o} = z^b$$

where
- V = output voltage
- V_o = reference voltage
- z = % of transmission
- b = slope of the graph (Figure 3)

$$\therefore\ \ln \frac{V}{V_o} = b \ln z$$

going back to equation (1):

$$\ln y = \ln y_o + x \ln A$$

which can be expressed as:

$$\ln \frac{y}{y_o} = x \ln A$$

and since

$$y = V$$
$$y_o = V_o$$
$$\therefore \frac{V}{V_o} = \frac{y}{y_o}$$
$$\text{and } \ln \frac{V}{V_o} = \ln \frac{y}{y_o}$$

$$\therefore b \ln z = x \ln A$$

$$\text{or } z^b = A^x \text{ or } z = A^{x/b} \qquad (2)$$

where z = per cent of transmission
b = slope of voltage vs % of transmission graph
A = per cent of light transmitted after a single round was fired.
x = number of rounds fired

b is a constant whose value is:

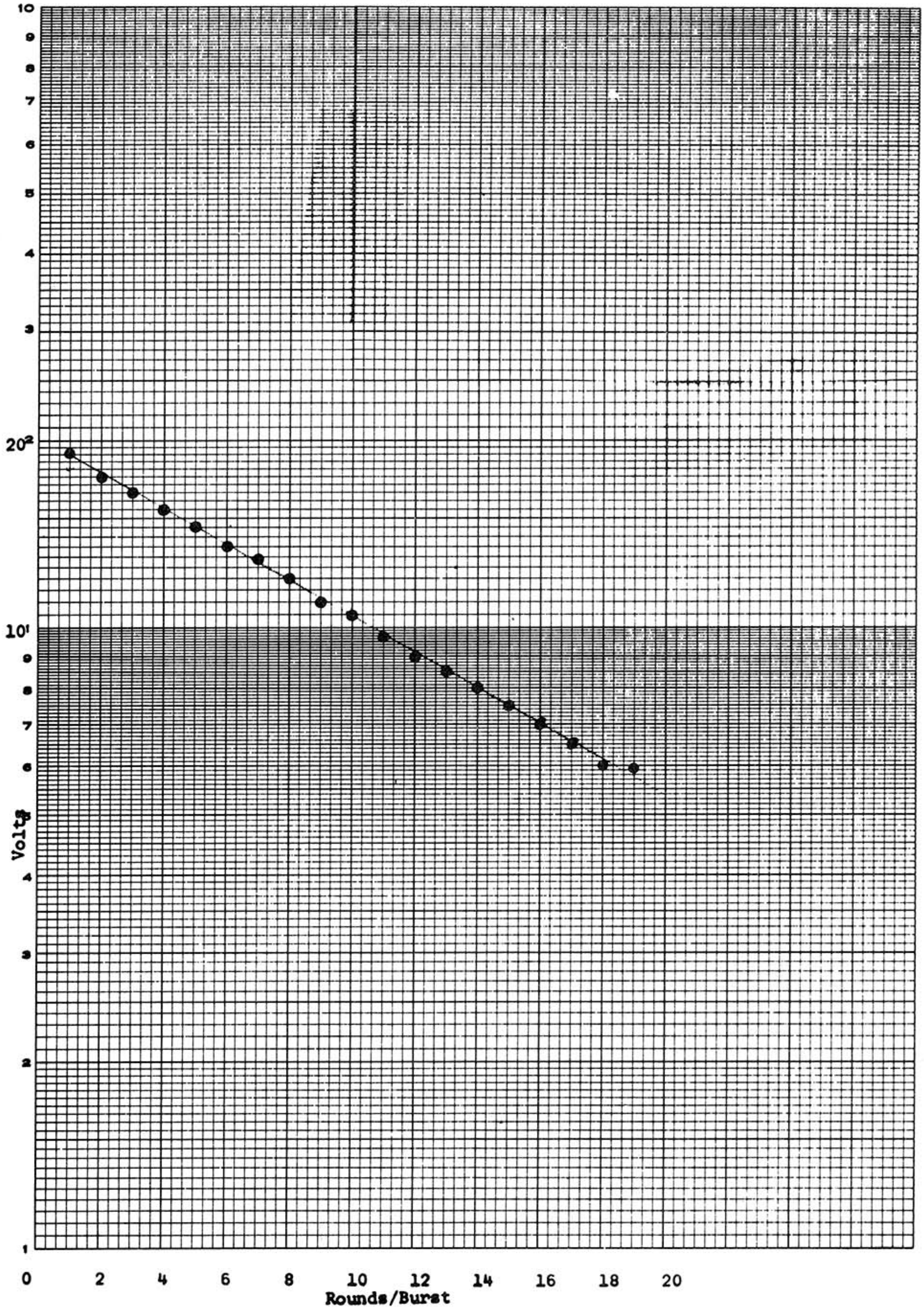
$$m = \frac{\Delta y}{\Delta x} = b$$
$$b = \frac{\ln 16.8 - \ln 1.6}{\ln 80 - \ln 1.6}$$
$$b = \frac{2.82 - .47}{4.38 - .47}$$
$$b = \frac{2.35}{3.91}$$
$$b = .6$$

It was considered essential to verify the above mathematical calculations. Using the Hewlett-Packard HP-65, verifications were performed. The HP-65 confirmed our calculation for slope in the three cases in which it was calculated. Using the statistics programs available with the HP-65 it was considered advisable to check the "fit" of the graph, i.e. to check if the best representative straight line to define the data points available had been used. The coefficient of determination described the "fit", with 1.00 being the best line to represent the data points and 0.00 being the worst. For Figures 1 and 3, the coefficients of determination were 1.00. For Figure 2 the coefficient of determination was 0.99. It is believed that these verifications further support the calculations performed and the equations derived. The final formula is:

$$z^b = A^x$$

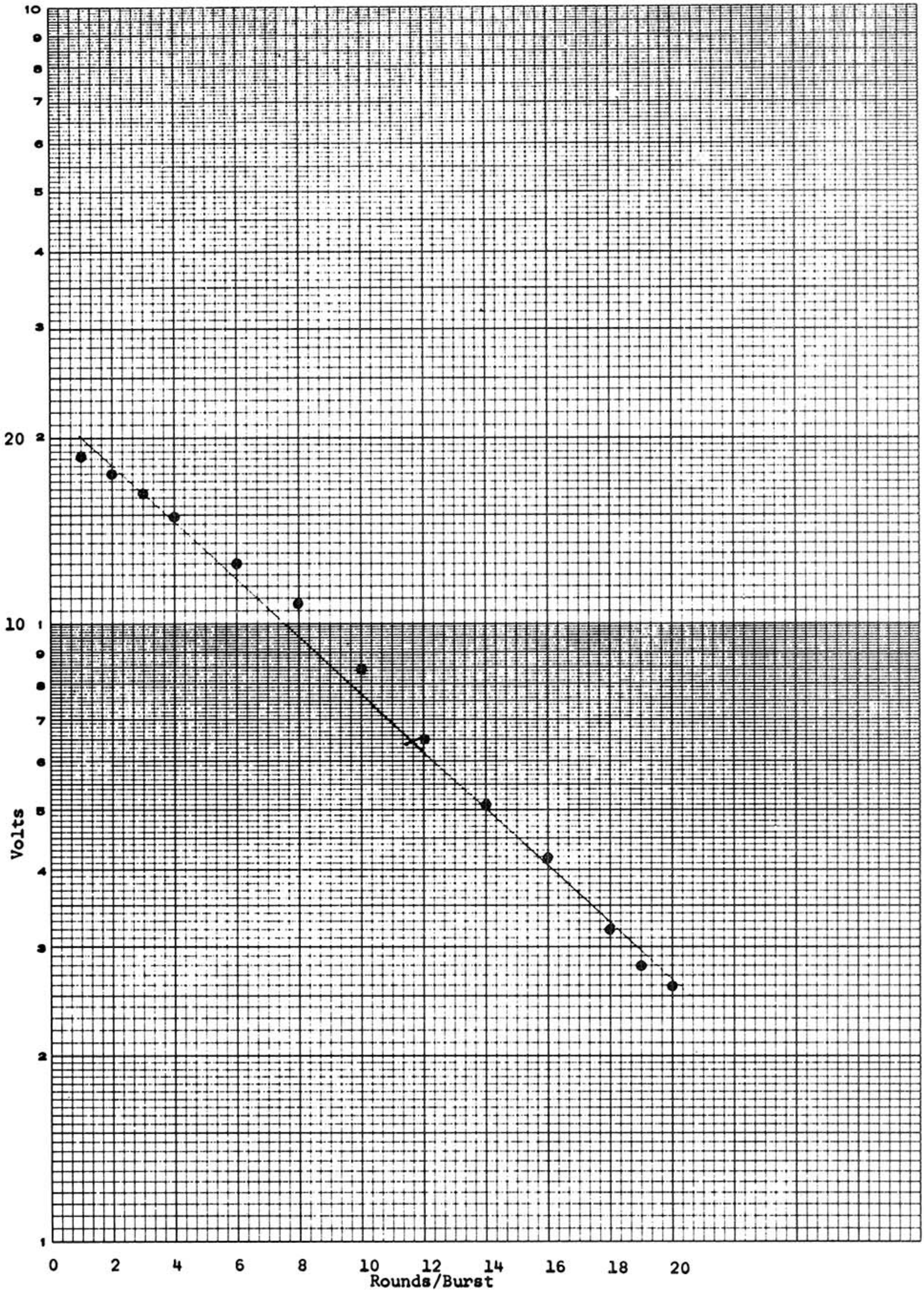
where
- z = percent of light transmission
- b = .6
- A = percent of light transmission after a single round was fired.
- x = number of rounds fired.

Figure 1



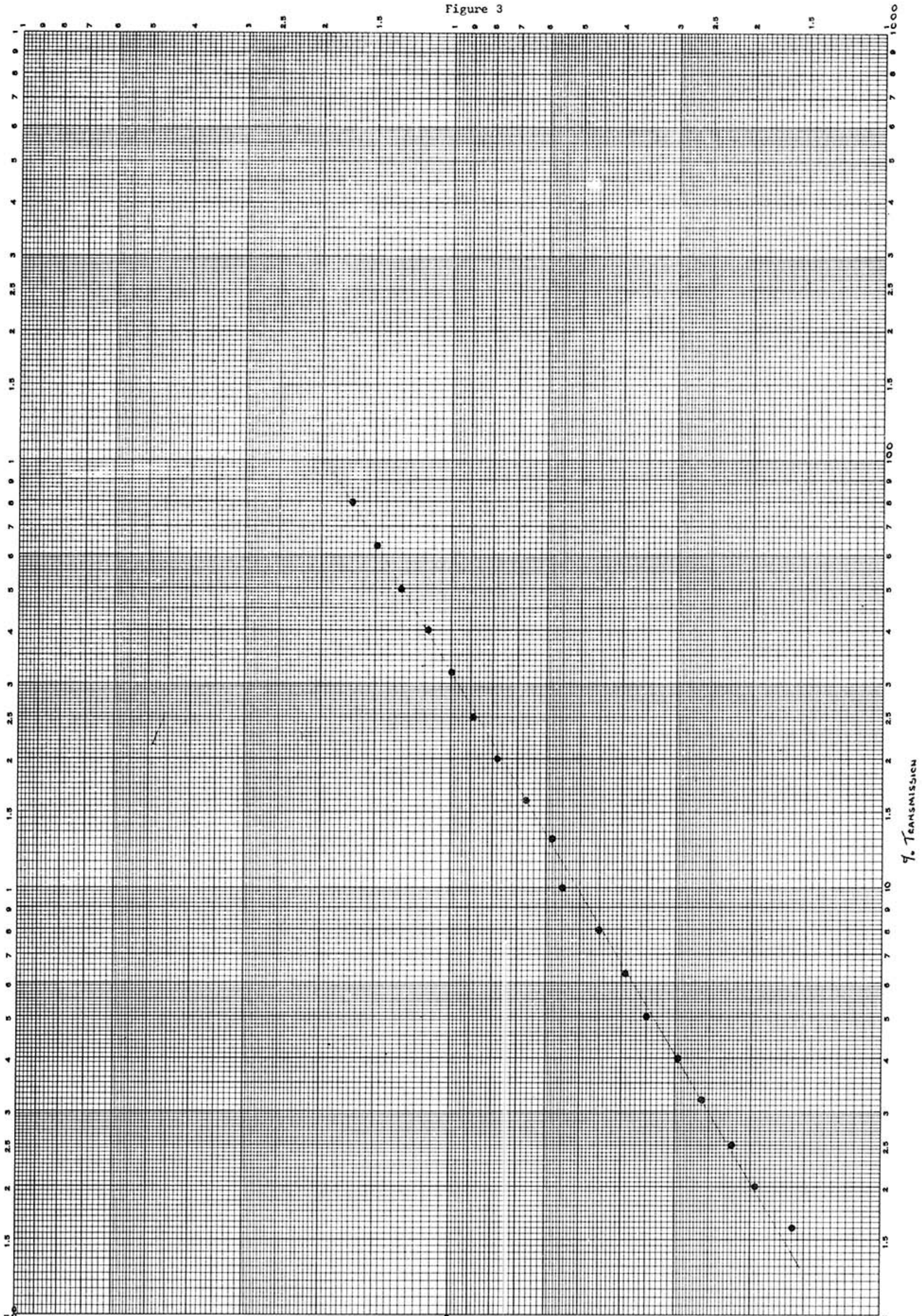
10
9
8
7
6
5
4
3
20^2
10^1
9
8
7
6
5
4
3
2
1
Volts
0
2
4
6
8
10
12
14
16
18
20
Rounds/Burst

Figure 2



10
9
8
7
6
5
4
3
20 2
10 1
9
8
7
6
5
4
3
2
1
Volts
0
2
4
6
8
10
12
14
16
18
20
Rounds/Burst

Figure 3



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