AD-A014 091

DETERMINATION OF RELIEF VENT AREAS REQUIRED TO CONTROL GASOLINE EXPLOSIONS IN CERTAIN BOAT ENGINE COMPARTMENTS

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Wyle Laboratories

Prepared for:

Coast Guard

July 1975

Report No. CG-D-132-75

DETERMINATION OF RELIEF VENT AREAS REQUIRED TO CONTROL GASOLINE EXPLOSIONS IN CERTAIN BOAT ENGINE COMPARTMENTS

FINAL REPORT

JULY 1975

Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

Prepared for

DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
Office of Research and Development
Washington, D.C. 20590

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CG-D-132-75		

4. Title and Subtitle	5. Report Date
DETERMINATION OF RELIEF VENT AREAS REQUIRED TO CONTROL GASOLINE EXPLOSIONS IN CERTAIN BOAT ENGINE COMPARTMENTS	July 1975
	6. Performing Organization Code 58901-05
7. Author(s) R. Losey	8. Performing Organization Report No. MSR 75-26
9. Performing Organization Name and Address Wyle Laboratories 7800 Governors Drive, West Huntsville, Alabama 35807	10. Work Unit No. (TRAIS) Project 755330.3
	11. Contract or Grant No. DOT-CG-40, 672-A
12. Sponsoring Agency Name and Address Commandant USCG HDQ (G-DST) 400 Seventh Street, SW Washington, D.C. 20590	13. Type of Report and Period Covered Final Report
	14. Sponsoring Agency Code G-DST-2

15. Supplementary Notes

Appendix A of Appendix C of this document was prepared from results of extensive tests conducted by the United States Coast Guard Research and Development Center, Groton, Connecticut.

16. Abstract

The work reported herein was performed to acquire necessary data to prepare a Design Guideline for pressure relief-flame deflectors installation in recreational boats of the inboard-stern drive type. Previous work had determined the feasibility of such pressure relief "valves." A model was constructed and carefully controlled explosion created with the simulated engine compartment over a range of explosion levels and with different compartment volumes and different area pressure relief values. The overpressures within the model were recorded for the various conditions using a unique acoustic vapor level detection system.

17. Key Words	18. Distribution Statement
Boat Safety, Fires and Explosions, Explosion Relief Valves, Inboard/Outboard Explosions, Boat Fire Safety, Explosion Overpressures	Unlimited PRICES SUBJECT TO CHANGE

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	~~112~~ 119	5.25/2.25

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

The work reported herein was accomplished for the U.S. Coast Guard's Office of Research and Development, Marine Safety Technolgy Division, as part of its program in Recreational Boating Safety.

The contents of this report reflect the views of Wyle Laboratories, Huntsville, Alabama, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policy of the Coast Guard. This report does not constitute a standard, specification or regulation.

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DETERMINATION OF RELIEF VENT AREAS REQUIRED TO CONTROL GASOLINE EXPLOSIONS IN CERTAIN BOAT ENGINE COMPARTMENTS

by

R. Losey

July 1975

for

Work Performed Under Contract DOT-CG-40, 672-A

Task Order 1, Subtask 5

WYLE LABORATORIES

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1.0 INTRODUCTION/SUMMARY

The reduction of the severity of the hazards of fires and explosions of gasoline vapors on inboard boats is desirable in the interest of boating safety.

The number of inboard/outdrive boats manufactured annually has increased fourfold in the last ten years to a point where the majority[1] of recreational inboard boats built today use this type of machinery.

Previous experiments demonstrated the feasibility of relieving the pressures of some low to moderate explosions of gasoline vapors in engine compartments by the use of pressure relief valves.

The objective of this experimental series was to obtain sufficient data pertaining to pressure relief - flame deflectors that specific recommendations could be made for proper installation of these pressure relief - flame deflectors in the engine compartments of boats powered by inboard gasoline engines which use outdrives or water jet pumps for propulsion.

The recommendations arising from this experimental series are considered to be economically practical as well as feasible from design standpoint and, therefore, may be implemented by builders using currently available materials and current manufacturing techniques. Requirements for exotic materials or manufacturing techniques which might discourage the use of these pressure relief-flame deflectors are neither necessary nor desirable.

This controlled experimental series of gasoline vapor/air mixture explosions demonstrated that the pressures and heat developed during those explosions could be safely released and directed.

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1 "An Investigation of the Value and Feasibility of Pressure Relief-Flame Deflectors in Medium Explosions in Small Craft." Wyle Technical Brief 74-9.

Specific recommendations (guidelines) were developed as a direct result of this series from which inboard/outdrive builders may obtain sufficient direction to install pressure relief - flame deflectors in their boats if they so desire. This Design Guideline is Appendix C to this report.

2.0 BACKGROUND - CONCEPT

The controlled explosion experiments previously performed by Wyle[1] showed that pressure relief - flame deflectors can be effective in safely releasing the built-up pressures during explosions of low to medium magnitudes.

In order to closely control this experimental series and to assure the acquisition of meaningful data, several items were given special attention.

2.1 Special Considerations

- Compartment leakage which can cause variations in fuel vapor concentration levels was minimized.
- Fuel vapor levels were constantly monitored so that ignitions could be made at predetermined vapor concentration levels.
- Pre-ignition of the fuel vapors was carefully prevented.
- Re-condensation of fuel vapors in the compartment due to internal compartment temperatures of less than 100° F. was prevented.

2.1.1 Compartment Leakage

It is recognized that real engine compartments are not vapor tight since ventilation systems are required, yet repeatability is essential in any test series in order to insure that the data is meaningful.

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1 ibid.

Any openings in a real engine compartment would act as additional pressure relief vents during an explosion. Therefore, conducting the experimental series without openings other than the intended vents would be a "worst case" test of the pressure relief - flame deflectors and offer the possibility of a slight safety factor, if anything, for a real boat.

2.1.2 Monitoring Vapor Concentration Levels

Previous work employed the use of a hydrocarbon analyzer for determination of fuel vapor levels only after the explosions. Although this system could be calibrated, it could not be used to obtain the pre-ignition fuel vapor level. A new concept of measurement was employed that achieved the desired results of constant monitoring so that the explosions could be ignited at desired vapor concentration levels.

"Speed-of-sound" techniques were used to determine the fuel vapor concentration. Since the speed of sound is dependent on the average molecular weight of the transmission media, it can be directly related to the concentration of a contaminate molecule (fuel) in a standard transmission medium (air). The instrumentation was designed to consider only changes in the speed of sound due to fuel vapor so error due to changes in temperature and environment could be calibrated out. A review of this technique is available in Appendix A.

2.1.3 Pre-ignition

Pre-ignition of the fuel vapor was prevented by vaporizing the fuel outside the chamber and injecting the fuel vapor through a preheated duct. The injection duct was heated with a submersible heating element to eliminate possible condensation.

2.1.4 Maintenance of Chamber Temperature

If the chamber wall temperature is below the ambient air temperature, then condensation will form on the chamber walls. To prevent this condition, the wall temperature must be greater than that necessary to sustain vaporization. This condition was reached when the chamber air temperature was maintained above 130° F. Temperature control within the chamber was accomplished through the installation of two 500 watt heating elements. One was installed on either side of the simulated engine.

2.2 Monitoring

The following parameters were monitored during the test series:

- Pressure levels inside the compartments at the time of ignition
- Amount of liquid fuel used
- Local vapor concentration levels near the ignition source
- Average vapor concentration levels for the compartment at the time of ignition
- Ambient atmospheric conditions
- Temperature inside the compartment near the source of ignition immediately preceding the ignition.
- Valve actions

3.0 APPARATUS

3.1 The Compartment

The test chamber (See Figure 1) was constructed entirely of 1/2" thick fir plywood. Corners and joints were glued and screwed together except for the removable tops which were caulked and then screwed in place and in this way the locations and sizes of the relief valves could be readily changed.

The features of the compartment are similar to those of the Model No. 2 engine compartment previously used[1] and include 1/4" thick plexiglass windows to facilitate viewing and filming the flames produced in the explosions.

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[1] ibid.

The design of the chamber was similar to a typical stern drive boat including:

- Boat/engine aft-enclosure
- Two jump seats
- Engine box
- Bilge Space

Two partitions were installed in the after portion of the chamber to simulate a small engine compartment and with the simulated engine installed the net compartment volume was 11.03 cu. ft.

With the partitions removed, the net compartment volume increased to 29.52 cu. ft.

Following the assembly of the box, all the corners were sprayed with rigid polyurethane foam to form an extra seal over the joints. This further limited leakage and enhanced the control of the fuel vapor levels.

The bottom of the simulated bilge was hinged and sealed with foam tape and positive hasps installed to secure it during explosions. The purpose of this hinged bottom was to permit rapid purging of the compartment following the explosions.

The chamber was placed on a dolly and fully instrumented.

3.2 Side Flame Deflectors

Side flame deflectors were deemed desirable (See Figure 2) because previous explosion testing showed that the "flame directing" capabilities of doors alone were not completely satisfactory. The flames and heat of the explosions shot out the sides of the vents once they had opened and could reach the passenger seating area (See Figure 3).

Non-flexible side flame deflectors would be acceptable, but since overhead space is limited in most boats, it was decided that flexible ones would be tried as they would fold up when the vent doors were closed. The flexible side flame deflectors would also be light weight and might, if properly installed, also be used as the only vent door restraints to limit the degree of opening of the vent doors.

Vinyl convertible topping material (Figure 4) was used for this purpose and worked very satisfactorily. The slight amount of "stretch" inherent in the material acted as a shock cord thus preventing the vent doors from exceeding their limits during any of the 73 explosions. The only problem that did occur was that if a fire continued after the explosion, as did happen twice, the vinyl would burn. This was not considered a failing of the material since the explosion pressures had already been safely released. The side flame deflectors were installed so that the vent doors would open approximately 85° from the horizontal closed position (See Figure 5) with the vinyl secured to the underside of the vent chamber top and the underside of the vent doors by using aluminum extrusions over the full length of the fabric/wood interfaces and attaching with tapping screws (See Figure 6).

3.3 Pressure Relief Doors

The material used for the construction of the pressure relief doors was 5/16" thick fir plywood which weighs 0.9 pounds per square foot. The doors were hinged to the chamber by machine screws with nuts using continuous length fixed pin hinges. For the tests, flexible foam tape was used to prevent leakage around the perimeter of the doors.

The doors were installed with the hinged edge forward in order to direct the resultant heat and flames aft and away from the position where passengers would normally be in a boat.

The location of the vent openings is shown in Figure 7. The forward vent opening was so placed on the simulated engine box to determine if the flames and heat could be effectively directed away from the adjacent simulated jump seat positions where passengers might be seated. While the experiments showed the flames could be directed away, still the resultant accompanying high heat would be a hazard to passengers occupying jump seats and it is felt that to move all openings to the aftermost part of the deck would be less hazardous.

3.4 Instrumentation

The following equipment and instrumentation was employed in this series of experimental tests:

- 15KV spark source

- Two 500 watt heaters
- 500 Watt hot plate
- 750 Watt submergable heater element
- 1/8 HP for motor/4" fan blade
- Two 1" PZT-5 piezoelectric transducers
- 8" Honeywell visicorder
- Model 7623A Tektronix oscilloscope
- Two 3/4" PZT-5 piezoelectric transducers (See Appendix A)
- Beckman 9030 generator (See Appendix A)
- RF-805 Power amplifier
- Control logic generator (See Appendix A)
- Logic signal processor (See Appendix A)
- 20 Ga. copper constantan thermocouple
- Thermocouple gauge
- Photography equipment

4.0 PROCEDURE

Listed below are the steps involved in obtaining one explosion signature. Each data point used for analysis was obtained by averaging a minimum of three explosion signatures to obtain a value for the maximum over-pressure for each transducer location on the engine compartment.

1) The engine compartment was purged of residual fuel vapor and fresh air allowed to enter.

2) The circulation fan was started.

3) The test compartment was closed and the temperature was allowed to rise to a predetermined value.

4) The presence of charged fire extinguishers was ascertained.

5) The test area was cleared.

6) A measured amount of liquid fuel was introduced into the vaporization system.

7) The vapor concentration level was monitored.

8) Once the fuel vapor/air mixture was homogeneous, the spark source was armed.

9) The visicorder (and cameras when used) were started.

10) The "clear" area was rechecked.

11) The spark source was triggered.

12) Once the explosive action stopped, the visicorder (and cameras) were turned off.

13) The spark source was disarmed.

14) Flames, if any, were extinguished.

15) The test chamber was purged by opening the top and bottom.

16) The chamber was checked for structural damage.

17) The instrumentation was checked for damage.

5.0 EXPERIMENTAL SERIES OBJECTIVES

The objectives of this test series were:

- To determine nominal values for LEL and UEL.
- To determine the effects of changing A/V.
- To determine maximum explosion overpressure as a function of fuel vapor level.
- To determine a preferred configuration for pressure relief.

These objectives were pursued through the program plan outlined in the following section.

6.0 TEST PROGRAM - EXPERIMENTAL SEQUENCE NARRATIVE ACCOUNT

6.1 System Check

The first experiments were conducted for the purpose of checking the sub-systems' performances for functional reliability and accuracy.

The fuel vaporization equipment, consisting of the remote hot plate and pot, performed satisfactorily.

The fuel vapor transfer duct (pipe) did not heat up enough to maintain the fuel in the vapor state and some fuel was condensed in it causing less than the total amount of the fuel to be vaporized in the chamber and causing fires in the duct following the explosions.

The ignition source performed satisfactorily.

The noise generated by the chamber's circulation fan was sufficient to create difficulty in "reading" the fuel vapor monitoring system.

Two explosion signature records were made, but showed excessive variation.

6.2 System Modifications and Recheck

A heating element was added to the fuel vapor transfer duct to maintain the temperature above 130° F. This eliminated the condensation problem.

The circulation fan noise problem was overcome by monitoring the received acoustic signal for determination of the fuel vapor concentration level.

The explosion signature problem was eliminated by the development and use of a new signature recording system. Two PZT-5 piezoelectric transducers were used for converting the pressure signals to an electrical signal. The electrical signal was then recorded on a Honeywell visicorder running at eight inches per second.

6.3 Determination of LEL and UEL

Since the LEL and UEL vary somewhat from gasoline to gasoline, it was necessary to document type as well as quantity of fuel used to induce explosion.

Two experimental series were run to independently determine the LEL and UEL. Explosions at or near the UEL had accompanying fires which were a threat to the instrumentation and it was decided to limit the number of explosions in this range.

Ignitions at or near the LEL created a condition of unexpectedly strong negative pressures (partial vacuums) in the chamber following the explosions due to the short "open" time of the vent doors and the integrity (vapor tightness) of the chamber with the vent doors closed.

Retainers were added to the chamber cover which held the doors partially (about 1/2") open after the explosion allowing air to enter the chamber and preventing the chamber's collapse. It was recognized that this was a condition that would not be encountered in real world boats since they have ventilation systems plus other incidental leakage; whereas, the test chamber was virtually vapor tight.

6.4 Small Chamber Low Level Test Sequence (Table I, Analysis Nos. 1-13)

A experimental series of low level explosions was conducted in the small center engine compartment chamber (net compartment volume of 11.03 cu. ft.) for use as a base for further decisions relative to the effects of varying the ratio of net compartment volume to relief area (See Table I). With the vapor concentration level at 1.7 percent by volume, and with 13.6 sq. in. of relief area per cu. ft. of net compartment volume (150 sq. in. per 11.03 cu. ft.), the maximum overpressure recorded was .26 psi. With the same chamber volume, the same vapor concentration level, but with 27.2 sq. in. of relief area per cu. ft. of net compartment volume (300 sq. in. per 11.03 cu. ft.), the maximum overpressure recorded was .17 psi. In viewing the actions of the relief doors during the explosions, it was evident that the smaller relief area, while sufficient for these low level explosions, would not be sufficient for higher level explosions. It also appeared that a relief area somewhat smaller than 300 sq. in. might be sufficient to release the overpressure of higher level explosions.

6.5 Large Chamber - Low to Medium Level Test Sequence (Table I, Analysis Nos. 14-22)

The initial low level explosion in the larger chamber (net compartment volume 29.52 cu. ft.) had a resultant implosion which fractured the rear viewing window and almost collapsed the chamber. The chamber divider partitions which had been removed to increase the volume had been acting as reinforcements for the rear bulkhead. Reinforcement braces were added to strengthen the rear bulkhead, a new plexiglas viewing window was installed, and the experimental series continued.

The relief area was was reduced to 450 sq. in. or 15.2 sq. in./cu. ft. for a series of seven test explosions by securing one vent door with a latch and ducting tape. The secured vent door partially opened during the test indicating that the area in the door was required for release of the pressures. The balance of the series was conducted with 600 sq. in. of relief area or 20.3 sq. in./cu. ft.

The witnessed sounds which were produced by the explosions changed noticeably the intensity of the explosions increased. The very low level ignitions produced only a "whump", but that increased to a loud bang as the fuel vapor concentration level increased to 2.3 percent (164 percent LEL). The actions of the relief doors changed also, accelerating as the fuel vapor concentration level increased.

The last four explosions in this series were conducted at night in order to enhance the filming.

6.6 Full Range Test Sequence (Table I, Analysis Nos. 23-36)

Since night explosions with a fuel vapor concentration level of 2.3 percent (164 percent LEL) did not destroy the test set-up, it was decided to perform a series of tests at fuel vapor levels up to 4.5 percent by volume. Therefore, the following day the full range sequence was begun again with explosions at fuel vapor concentration levels of 2.3 percent, 2.6 percent, 3.0 percent, 3.5 percent, 4.0 percent and 4.5 percent. At 4.5 percent, the brisance of the explosion was audibly reduced suggesting that the maximum level explosions had been reached previously. Examination of the recorded overpressures (transducer outputs) confirmed our suspicions.

The chamber with this configuration of pressure relief vent doors experienced maximum overpressure without failure when the ratio of vent area in square inches to net compartment volume in cubic feet was 20.3. The maximum overpressure of .32 psi (46 psf) had occurred in the explosion where the fuel vapor concentration level was 3.5 percent (250 percent LEL).

6.7 Second Full Range Sequence (Table I, Analysis Nos. 37-42)

The final sequence was conducted to compare the over-pressures resulting after the three aft vent doors on the top of the chamber were replaced with one long rectangular one vent of the same total area (450 square inches).

The initial explosion with its resultant implosion again fractured the rear viewing window and caused some minor structural damage to the aft bulkhead. Additional bracing was installed to stiffen the bulkhead and the plexiglas window was again replaced.

The series was completed with explosions conducted at vapor concentration levels of 3.0 to 5.5 percent (214 percent LEL to 393 percent LEL). The recorded over-pressures were slightly less than those for the three aft door configurations, but this was attributed to the placement of the pressure transducer which had, of necessity, been moved aft and not to any increase in designed relief efficiency.

7.0 DATA ANALYSIS

Data analysis was performed on the reduced data to a tolerence of $\pm$0.1 volt equivalent transducer output. An example of original data is shown in Figure 8; the reduced data may be found in Appendix B. Appendix B also includes a calibration curve for the instrumentation system trace (displacement vs. signal voltage level) (Figure B-1) along with the calibration curve for the PZT-5 microphone transfer function as depicted in Figure B-2. Figure 9 is a graphic representation of maximum overpressure versus fuel vapor level measured in percent by volume and percent LEL respectively. These data are summarized in Table II.

Four configurations were considered, each characterized by the value of $\frac{A}{V}\left(\frac{in.^2}{ft^3}\right)$ (relief area ($in.^2$) / chamber volume (ft^3)). Two configurations for A/V = 20.3 $\frac{in.^2}{ft^3}$ are indicated. "20.3 $in.^2$ / ft^3 long" represents an arrangement substituting three standard relief doors with one long door having the same relief area. Each analysis point on Figure 5 represents the average value for that particular configuration at a specified fuel vapor level. The variation in error bars is attributed to the logarithmic nature of the transducers. The trace line represents the general trend of the standard A/V = 20.3 ($in.^2$ / ft^3) configuration.

Measured overpressures generally decreased, as expected, with increasing A/V for fuel vapor levels below 3.0 percent (214 percent LEL). Consequently, overpressures associated with higher fuel vapor level explosions were measured only for A/V - 20.3 square inches vent area per cubic foot chamber volume.

The data representing the "20.3 long" configuration falls below the "standard 20.3" curve in the region of fuel level less than 321 percent LEL (4.49 percent vol.) and is within the possible error for levels greater than 321 percent LEL. This is attributed to the position of the recording microphone. For the "20.3 long" configuration, the microphone had to be located in a different position than in the "20.3 standard" configuration. This new position was located aft of the relief door at a greater distance from the explosion center.

This greater propagation distance led to lower recorded pressures. The new location was closer to the escaping air which also tended to reduce the immediate pressure. When the fuel vapor level was increased the explosion amplitude decreased and the shock front became less defined thus the difference in locations of the microphones became less pronounced and the effect was no longer dominant.

The conclusions drawn from the data analysis were:

1. Twenty square inches of relief vent openings per cubic foot of compartment volume may be expected to safely release the pressures for the anticipated full range of explosions.
2. The configuration of the relief vent openings did not materially affect their releasing capabilities so long as the proper vent area was provided.
3. Sufficient data was obtained to permit builder guidelines to be developed (Appendix C).

TABLE I. EXPERIMENTAL SEQUENCE

Sequence No.	Date	Date Number	Analysis No.	Volume Ft³	Liquid Fuel Charge (cc)	Recorded Vapor Level % Volume	Δt µs	Relief Area (in²)	Explosion* Level (Volts)	Explosion* Level (psi)	Comments		Ambient Conditions
1	2/28	1a		11.03	23	1.4	1.75	300	NA/NA	NA/NA	No Exp	Sequence of explosions 1-15 are used to verify values of UEL and LEL. No analog pressure signatures were recorded. New method of signature recording will have to be found. Old method is not reliable.	Wind - 3-5 mph Temp - 70° F. RH - 30° %
2	2/28	2a		11.03	25	1.5	2.0	300	NA/NA	NA/NA	No Exp		
3	2/28	3a		11.03	28	1.6	-	300	NA/NA	NA/NA	No Exp		
4	2/28	4a		11.03	33	2.0	-	300	NA/NA	NA/NA	No Exp		
5	2/28	5a		11.03	38	2.4	-	300	NA/NA	NA/NA	Ignition		
6	2/28	6a		11.03	125	7.6	10.0	300	NA/NA	NA/NA	Fire		
7	2/28	1b		11.03	28	1.5	2.50	300	NA/NA	NA/NA	Exp		
8	2/28	2b		11.03	23	1.4	2.0	300	NA/NA	NA/NA	Exp - Low		
9	2/28	3b		11.03	33	1.4	2.0	300	NA/NA	NA/NA	Exp		
10	2/28	4b		11.03	20	1.3	1.75	300	NA/NA	NA/NA	No - Exp		
11	2/28	5b		11.03	25	1.5	2.25	300	NA/NA	NA/NA	Exp		
12	2/28	6b		11.03	25	1.5	2.0	300	NA/NA	NA/NA	Exp		
13	2/28	7b		11.03	23	1.4	1.75	300	NA/NA	NA/NA	Exp - Low		
14	2/28	8b		11.03	23	1.4	1.75	300	NA/NA	NA/NA	Exp - Low		
15	2/28	9b		11.03	125	7.6	10.0	300	NA/NA	NA/NA	Exp & Fire		
16	3/11	1		11.03	30	2.0	-	300	.15/.08	.12/.03	Exp	New recording system used beginning with number 16.	Wind - 0-3 mph Temp - 60° F. RH - 90-100 % Light rain High water vapor - Rain
17	3/11	2		11.03	30	2.0	-	300	.18/.08	.16/.03	Exp		
18	3/11	3		11.03	30	2.0	-	300	.18/.10	.16/.04	Exp		
19	3/12	1		11.03	30	2.0	-	300	NA/NA	NA/NA	Poor Exp		
20	3/12	2		11.03	30	2.0	2.0	300	.18/.08	.16/.03	Exp		
21	3/12	3		11.03	30	2.0	2.0	300	.17/.07	.15/.02	Exp	Due to adverse weather conditions, sequence nos. 16-21 were not included in analysis.	Wind - 0-3 mph Temp - 70° F. RH - 90-100 % Adverse
22	3/17	1	1	11.03	30	1.7	1.75	300	NA/NA	NA/NA	Poor Exp	Not analyzed.	Wind - 3-5 mph Temp - 60° F. RH - 60 % Clear
23	3/17	2	2	11.03	30	1.7	2.25	300	.17/.13	.15/.10	Exp		
24	3/17	3	3	11.03	30	1.7	2.25	300	.17/.15	.15/.13	Exp		
25	3/17	4	4	11.03	30	1.7	2.50	300	.19/.20	.17/.18	Exp		
26	3/17	5	5	11.03	30	1.7	2.50	150	.30/.18	.26/.16	Exp	Used single aft door only.	
27	3/17	6	6	11.03	30	1.7	2.25	150	.20/.15	.18/.13	Exp		
28	3/17	7	7	11.03	30	1.7	2.50	150	.20/.15	.18/.13	Exp		
29	3/17	8	8	11.03	45	2.7	3.75	300	.30/.28	.26/.25	Exp		
30	3/17	9	9	11.03	45	2.7	3.75	300	.30/.25	.26/.25	Exp		
31	3/17	10	10	11.03	37	2.2	3.25	300	.23/.25	.21/.22	Exp		
32	3/17	11	11	11.03	37	2.2	3.50	300	.27/.30	.24/.26	Exp		
33	3/17	12	12	11.03	30	4.7	2.50	300	.20/.17	.18/.15	Exp		
34	3/17	13	13	11.03	30	1.7	2.50	300	.15/.15	.12/.12	Exp		
35	3/21	1	14	29.52	80	1.8	2.25	600	.15/.13	.12/.10	Exp		
36	3/21	2	15	29.52	80	1.8	2.25	450	.30/.17	.26/.15	Exp		
37	3/21	3	16	29.52	80	1.8	2.50	450	.20/.12	.18/.08	Exp		
38	3/21	4	17	29.52	80	1.8	2.25	450	.20/.12	.18/.08	Exp		
39	3/21	5	18	29.52	80	1.8	2.25	450	.17/.12	.15/.08	Exp		

* Mic. No. 1 / Mic. No. 2

TABLE I. EXPERIMENTAL SEQUENCE (cont.)

Sequence No.	Date	Date Number	Analysis No.	Volume Ft³	Liquid Fuel Charge (cc)	Recorded Vapor Level % Volume	Δt ms	Relief Area (in²)	Explosion* Level (Volts)	Explosion* Level (psi)	Comments		Ambient Conditions
40	3/21	6		29.52	100	-	-		-	-	Poor Exp	Do not analyze.	
41	3/21	7		29.52	100	2.3	2.50	450	.08/.06	.03/.02	Exp	Door tape came loose.	
42	3/21	8		29.52	100	2.3	2.50	450	.32/.20	.27/.13	Exp		Wind - 0-2 mph
43	3/21	9		29.52	100	2.3	2.75	600	.42/.23	.33/.21	Exp		Temp - 70° F.
44	3/21	10		29.52	100	2.3	2.75	600	.42/.24	.33/.22	Exp		RH - 50% Clear
45	3/24	1		29.52	110	2.25	2.75	600	NA/NA	NA/NA	Poor Exp	Door leaks.	Wind - 15-20 mph
46	3/24	2		29.52	110	2.25	2.75	600	NA/NA	NA/NA	Poor Exp	Replace seals.	Temp - 70° F.
47	3/24	3		29.52	110	2.25	2.50	600	NA/NA	NA/NA	Poor Exp		RH - 40%
48	3/24	1	19	29.52	80	1.8	-	600	.08/.06	.03/.02	Poor Exp	Sequence nos.	Wind - 0-2 mph
49	3/24	2	20	29.52	100	2.0	-	600	.32/.20	.27/.18	Exp	48-53 were	Temp - 55° F.
50	3/24	3	21	29.52	110	2.3	-	600	.42/.23	.32/.21	Exp	filmed at night.	RH - 40%
51	3/24	4	22	29.52	110	2.3	-	600	.42/.24	.32/.22	Exp		Partly cloudy
52	3/24	5	23	29.52	120	2.7	-	600	.45/.32	.34/.27	Exp		
53	3/24	6	24	29.52	132	3.0	-	600	.40/.23	.32/.21	Exp		
54	3/26	1	25	29.52	100	2.3	3.25	600	.26/.15	.23/.13	Exp - Med		Wind - 3-5 mph
55	3/26	2	26	29.52	100	2.3	3.50	600	.24/.13	.22/.10	Exp - Med		Temp - 60° F.
56	3/26	3	27	29.52	100	2.3	3.75	600	.33/.17	.28/.15	Exp - High		RH - 30%
57	3/26	4	28	29.52	116	2.6	4.0	600	.33/.21	.28/.19	Exp - High		Clear
58	3/26	5	29	29.52	116	2.6	3.75	600	.27/.13	.24/.10	Exp - Med		
59	3/26	6	30	29.52	116	2.6	4.25	600	.37/.23	.30/.21	Exp - High		
60	3/26	7	31	29.52	132	3.0	4.50	600	.37/.20	.30/.18	Exp - High		
61	3/26	8	32	29.52	132	3.0	4.50	600	.40/.20	.32/.18	Exp - High		
62	3/26	9	33	29.52	132	3.0	4.50	600	.35/.27	.29/.24	Exp - High		
63	3/26	10	34	29.52	155	3.5	5.0	600	.50/.17	.36/.15	Exp - High		
64	3/26	11	35	29.52	177	4.0	5.0	600	.45/.22	.34/.20	Exp - High		
65	3/26	12		29.52	200	-	-	600	NA/NA	NA/NA	Poor Exp		
66	3/26	13	36	29.52	200	4.5	4.50	600	.32/.15	.27/.12	Exp - High		
67	3/26	14		29.52	100	-	-	600	NA/NA	NA/NA	Poor Exp		
68	3/28	1	37	29.52	132	3.0	-	600	.21/.17	.19/.15	Exp - High	Back 3 relief	Wind - 15-20 mph
69	3/27	2	38	29.52	200	4.0	-	600	.23/.17	.21/.15	Exp - High	doors were	Temp - 60° F.
70	3/27	3	39	29.52	132	3.0	-	600	.20/.17	.18/.15	Exp - High	replaced by	RH - 40%
71	3/27	4	40	29.52	132	3.0	-	600	.27/.17	.24/.15	Exp - High	one long door.	
72	3/27	5	41	29.52	195	4.5	-	600	.27/.21	.24/.19	Exp - High	Fourth door	
73	3/27	6	42	29.52	243	5.5	-	600	.30/.25	.26/.22	Exp - High	was unlatched.	

* Mic. No. 1 / Mic. No. 2

TABLE II. SUMMARY OF ANALYZED DATA GROUPED BY VENT OPENING CONFIGURATION

Number of Explosions Analyzed	Volume (ft^3)	Relief Area (in^2)	Area/Volume (in^2/ft^3)	Percent Fuel Vapor by Volume	Average Over-Pressure PSI
3	11.0	150	15	1.7	.206
4	29.0	450	15	1.8	.192
2	29.0	450	15	2.3	.270
2	29.5	600	20.3	1.8	.120
1	29.5	600	20.3	2.0	.270
7	29.5	600	20.3	2.3	.290
3	29.5	600	20.3	2.6	.270
1	29.5	600	20.3	2.7	.340
4	29.5	600	20.3	3.0	.330
1	29.5	600	20.3	3.5	.360
1	29.5	600	20.3	4.0	.34
1	29.5	600	20.3	4.5	.27
3	29.5	600 (lg.)	20.3	3.0	.200
1	29.5	600 (lg.)	20.3	4.0	.210
1	29.5	600 (lg.)	20.3	4.5	.240
1	29.5	600 (lg.)	20.3	5.5	.220
6	11.0	300	27	1.7	.145
2	11.0	300	27	2.2	.225
2	11.0	300	27	2.7	.260

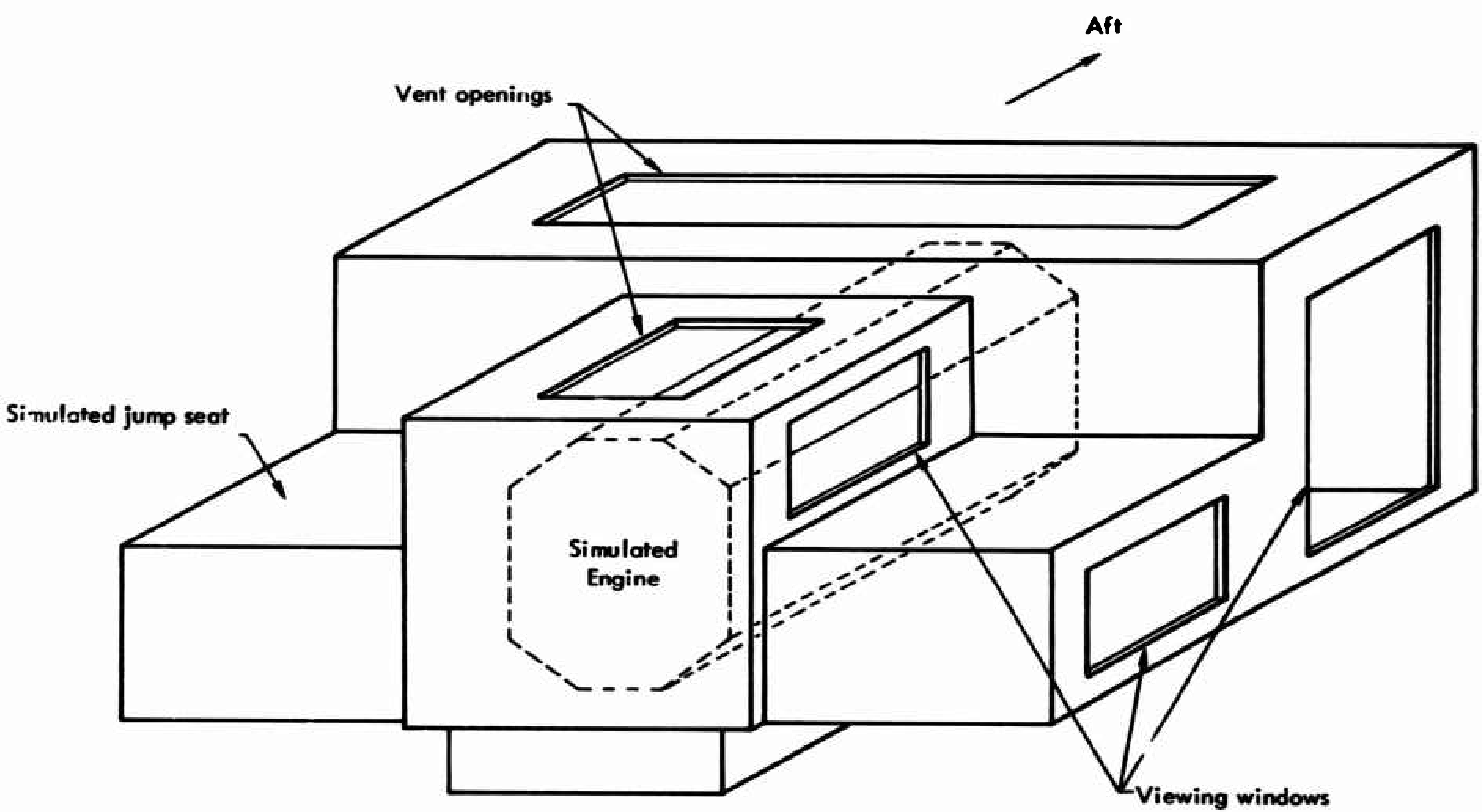

Figure 1. Simulated Engine Compartment

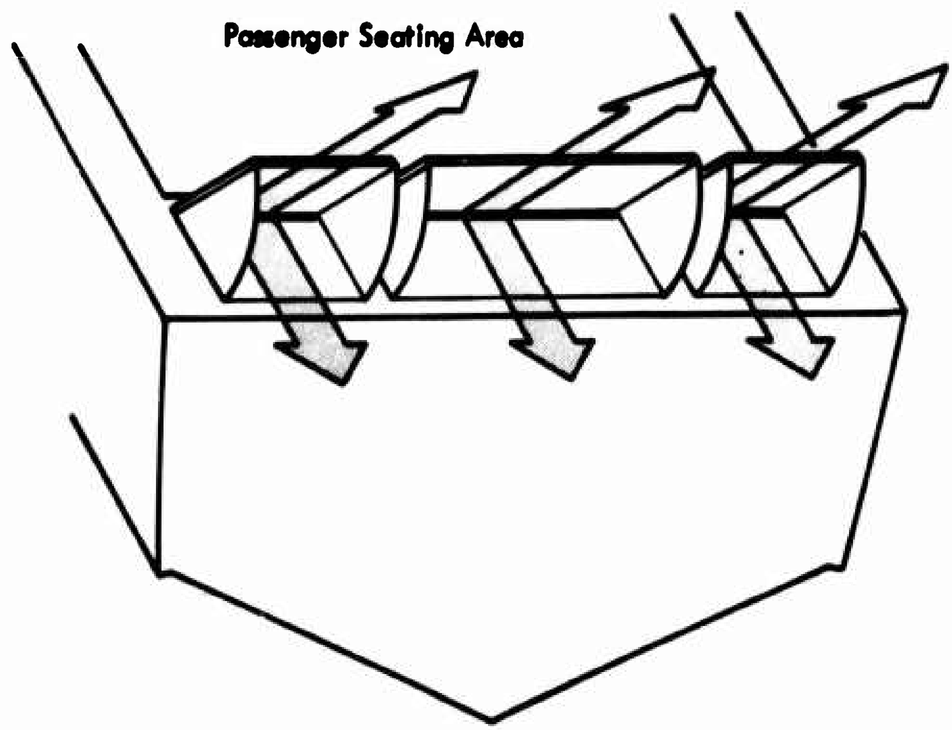

Figure 2. Flames Entirely Directed Away From Passenger Seating Area

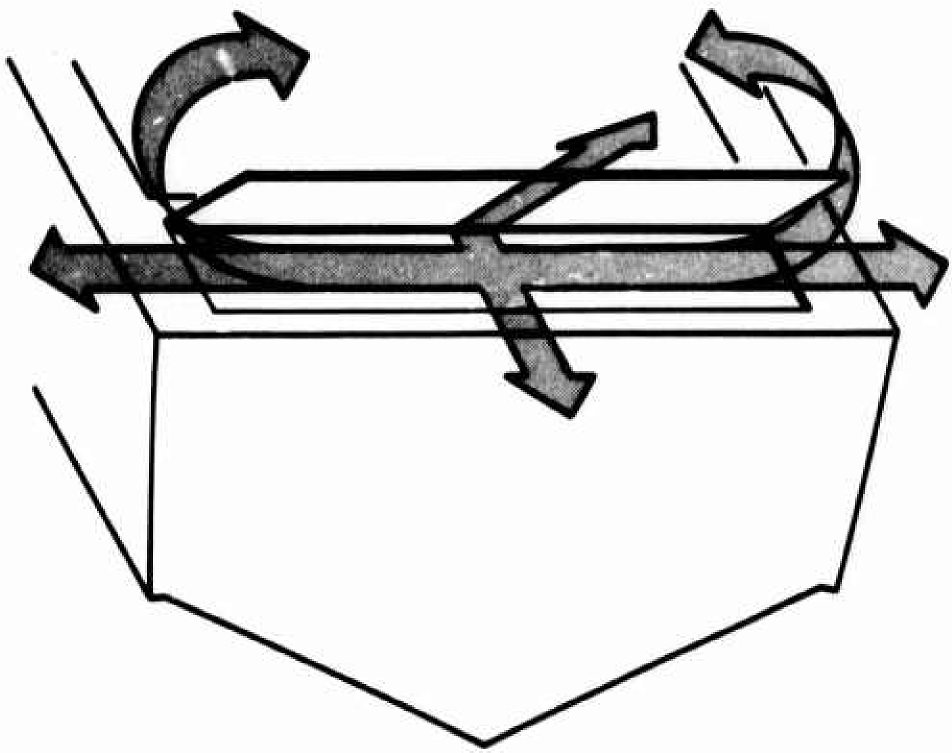

Figure 3. Flames Partially Diverted Away From Passenger Seating Area

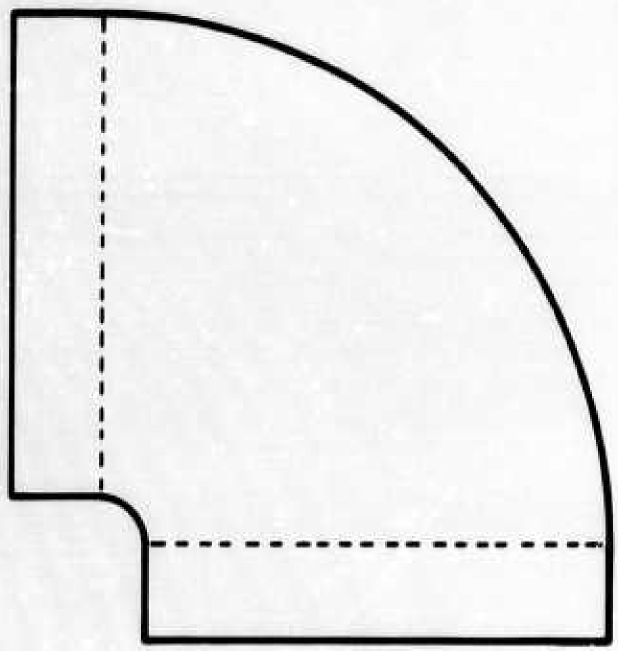

Figure 4. Typical Vent Door Side Flame Deflector/Restraint Pattern

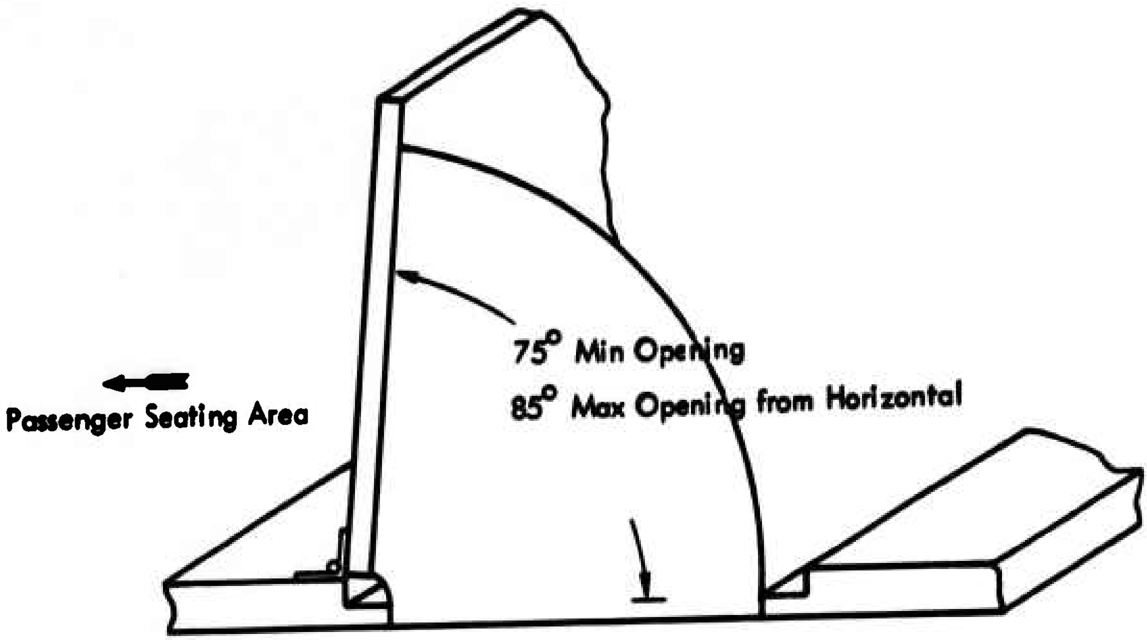

Figure 5. Vent Door Opening Limits

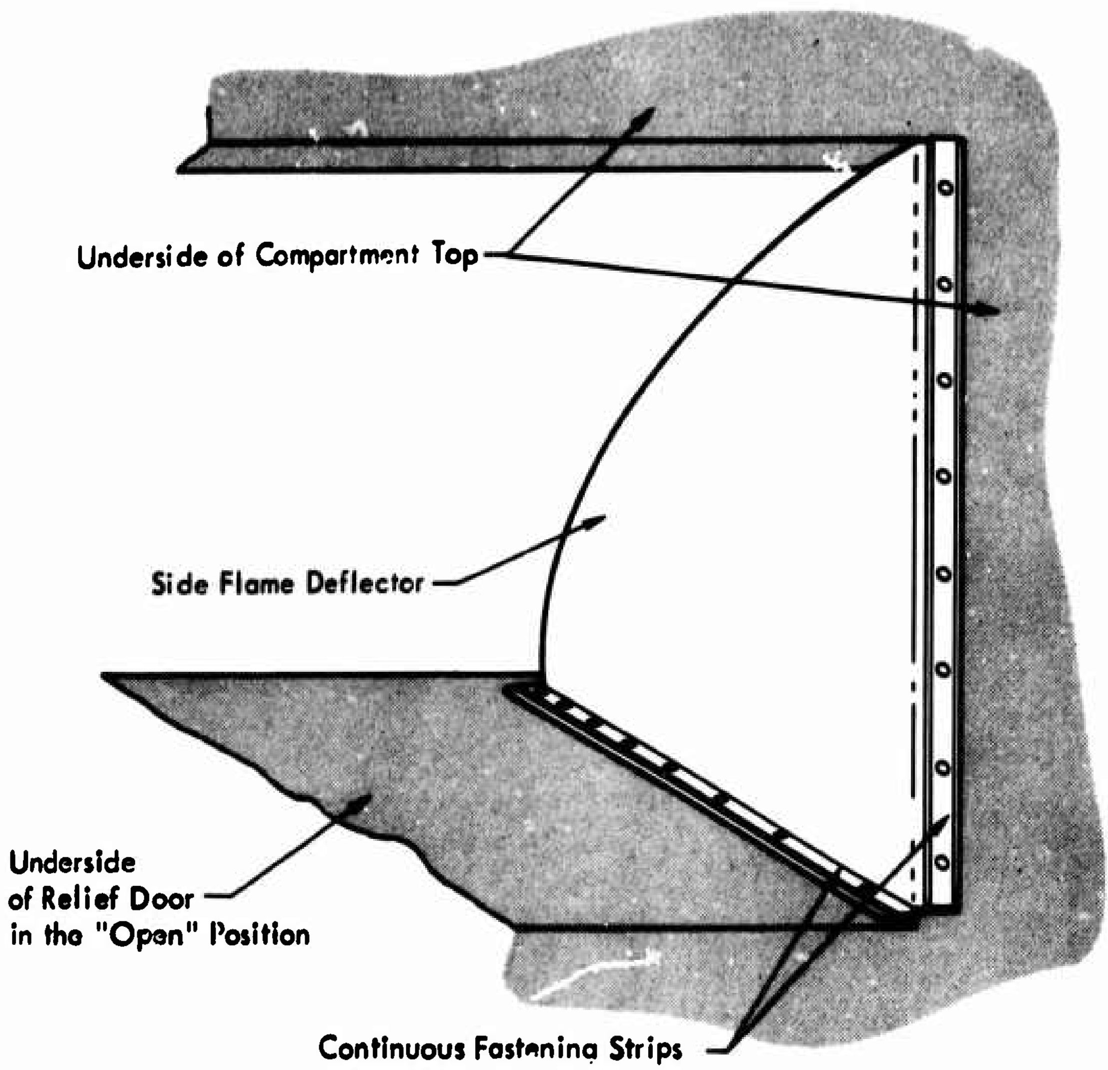

Figure 6. Continuous Fastening of Side Flame Deflector/Restraints (viewed from the inside of the compartment and looking up)

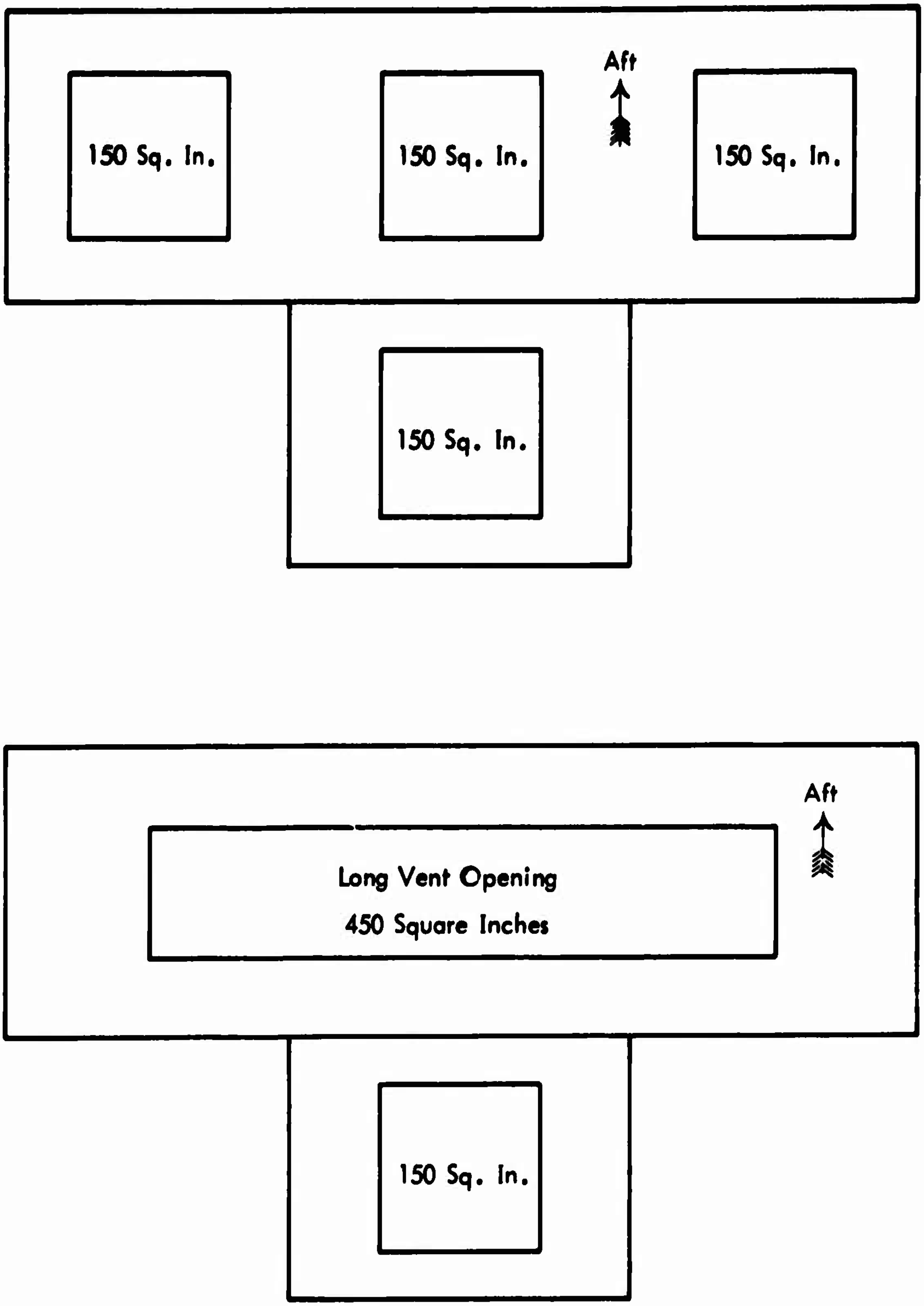

Figure 7. Plan Views of Chamber Vent Openings

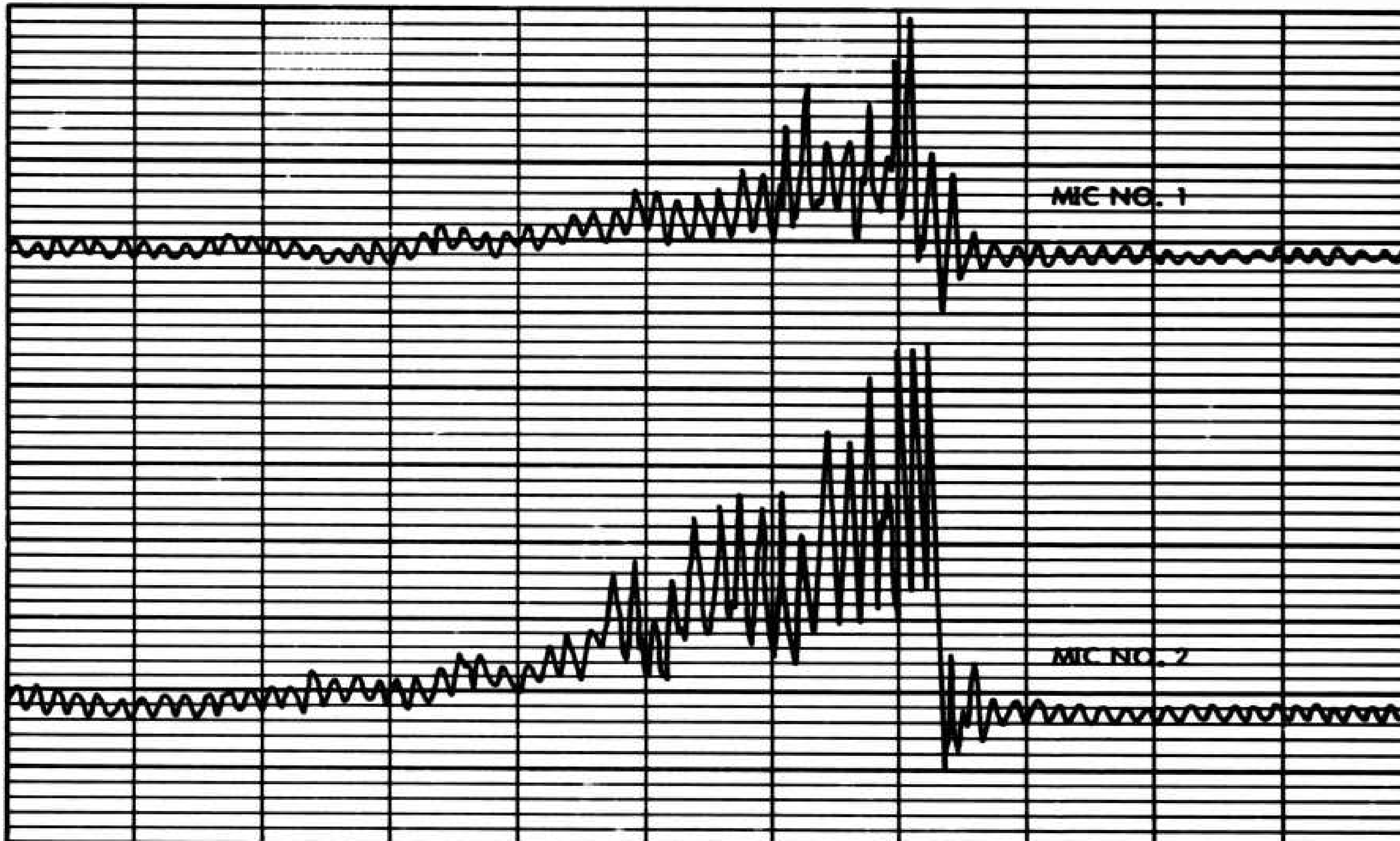

Figure 8. Typical Visicorder Recording

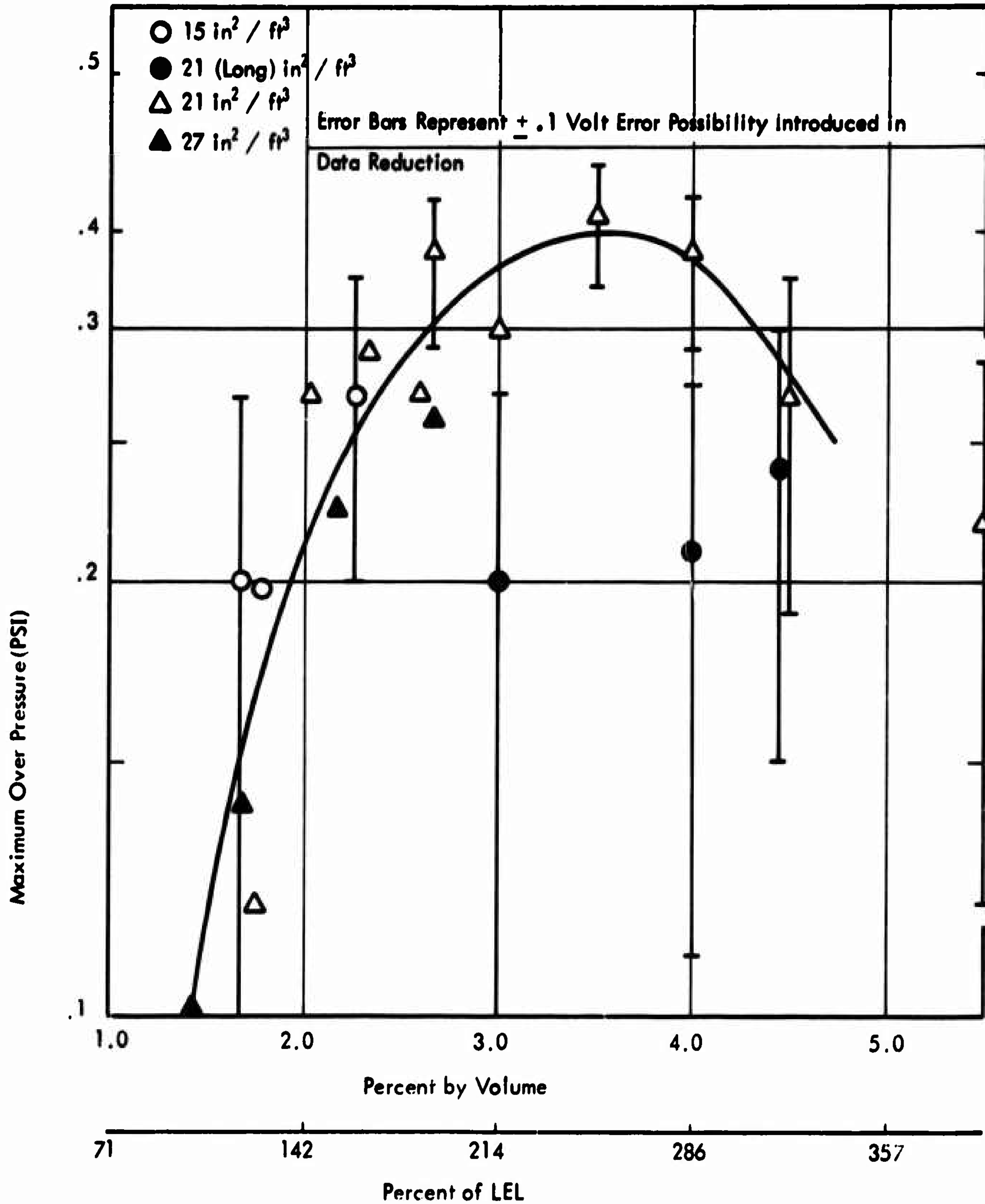

Figure 9. Analysis of Pressure Vs. Fuel Vapor Level

ACOUSTIC FUEL VAPOR MONITOR

1.0 MATHEMATICAL DEVELOPMENT

The speed of sound in a gas may be evaluated by the expression

$$v = (\gamma RT/m)^{1/2} \tag{1}$$

where v, γ, R, T, m are the velocity of sound propagation, ratio of specific heat, universal gas constant, absolute temperature, and gram molecular weight of the gas respectively.

For a two gas system the mass may be replaced by Equation (2)

$$m = X_A M_A + X_B M_B \tag{2}$$

where X_A, M_A, X_B, M_B represent the mole fraction and mass of gas A, and the mole fraction and mass of gas B.

Making the substitution and appropriate transformations, Equation (1) becomes Equation (3)

$$v = \left[\gamma RT/(X_A M_A + X_B M_B)\right]^{1/2} = \left[\gamma RT/((1-X_B) M_A + X_B M_B)\right]^{1/2} \tag{3}$$

if we consider gas A to be air at room temperature then equation (3) becomes

$$v = 330 \left[(1 - X_B) + X_B M_B/M_A\right]^{-1/2} \tag{4}$$

In Equation (4), γ was assumed to be 1.4 since the percent by volume for fuel vapor will be very small. γ for fuel vapor is 1.09 which introduces slight error and if accounted for, will enhance the variation of speed with temperature. Thus $(RT/M_A)^{1/2}$ = 330 m/sec at room temperature.

Pages 35 and 36 are Blank.

Substituting values for mass of air and mass of fuel into Equation (4), we obtain for room temperature $M_A = 29$; M_B $(C_8 H_{17}) = 113$

$$v = \left[330 \ (1-X_B) + X_B(3.9)\right]^{-1/2} = 330\left[1 + 2.9 X_B\right]^{-1/2} \tag{5}$$

using Equation (4) to find the change in v due to variations in X_B

$$dv/dX_B = M_A (330)\left[(M_B - M_A)/2\right]\left[(1 - X_B) M_A + X_B M_B\right]^{-3/2} \tag{6}$$

Once again using values for M_A, M_B we get

$$dv/dX_B = \left[7.45 \times 10^4/(29 + 84X_B)^{3/2}\right] \text{m/sec} \tag{7}$$

From the universal gas law PV = NRT we can determine the volume of a gas for a given mass.

$$V = NRT/P \tag{8}$$

where V is the volume, N is the number of moles, R is the universal gas constant, T is temperature and P is the atmospheric pressure. If the percent by volume of a gas is defined by

$$\text{Percent (vol)}_B = V_B/(V_A + V_B) \tag{9}$$

then substitution of (8) into (9) yields

$$\text{Percent (vol)}_B = \frac{N_B(RT/P)}{(N_A + N_B)(RT/P)} = N_B/(N_A + N_B) \tag{10}$$

which is just the definition of the mole fraction X_B, thus

$$\text{Percent (vol)}_B = X_B \tag{11}$$

Several values for Percent (vol) and velocity have been tabulated for a temperature of 150° F. at one atmosphere and are shown in Table I.

$\gamma = 1.4 \quad M_A = 29 \quad M_B = 100 \quad T = 150^\circ F \quad P = 1\ ATM$

TABLE I. VALUES FOR 150° F AND 1 ATM

Percent Volume	Percent LEL	Velocity (m/Sec)
0.0	0.0	368.4
1.0	71.4	363.9
2.0	142.8	359.7
3.0	214.3	355.5
4.0	285.7	351.5
5.0	357.1	347.7
6.0	428.6	344.0
7.0	500.0	340.3
8.0	571.4	336.9
9.0	642.8	333.5
10.0	714.3	330.2

$\gamma = 1.4 \quad M_A = 29 \quad M_B = 100 \quad T = 150^\circ F \quad P = 1$ ATM

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5.0	357.1	347.7
6.0	428.6	344.0
7.0	500.0	340.3
8.0	571.4	336.9
9.0	642.8	333.5
10.0	714.3	330.2

dv/dT has been determined from Equation (1) to be

$$dv/dT = \frac{1}{2}\left[\gamma RT/M\right]^{-1/2}\left[\gamma R/M\right] = v^2/2vT = v/2T \tag{12}$$

if $T = 293^\circ$ and $\Delta T = 1^\circ C$

$$\Delta v = 0.563 \text{ m/sec} \tag{13}$$

Thus the maximum error introduced at $X_B = 0$ due to a change in temperature of one degree centigrade is: Percent Error (0.563/330) 100 = 0.17.

The most practical means of determining v experimentally is to measure propagation time across a fixed distance. One can resolve the position of the leading edge of a pulse more accurately than 1/10 of a cycle or for a 1 MHz signal $\pm 1/10$ micro second with a conventional micrometer, we can measure distance to within ± 0.001 cm out of 2 cm. For a propagation distance of 2 cm, $t = 2.5 \times 10^{-4}$ sec or 250 micro seconds, thus we can measure velocity to one part in 2500 or 0.04 percent. Additional accuracy could be obtained by increasing the path length but would not be justified since we can monitor temperature to about $\pm 1^\circ C$. The error introduced by a temperature variation of $1^\circ C$ is 3.75 times greater than that of distance and thus dominates.

2.0 INSTRUMENTATION MODEL

The functional requirements of the instrument model are listed below.

- produce a timing control logic sequence to control a train of electrical pulses
- produce high frequency (1 megahertz) electrical signal that can be amplitude modulated (triggered) by the control logic
- electrically amplify the gated high frequency signal
- convert the amplified electrical signal to an acoustic signal for propagation measurements
- convert the propagated acoustic signal back to an electrical signal for processing
- logic process the received electrical signal to determine the propagation time.

3.0 FUNCTIONAL REQUIREMENTS

The approach to each requirement is addressed below. Refer to Figure 1 for functional diagram.

3.1 Timing Logic Sequence

Timing Logic Sequence is achieved through the use of a phase lock loop pulse generator. The LM 555 is a PLL timing device with variable duty cycle.

3.2 High Frequency Electrical Signal

The high frequency electrical signal is obtained from a Beckman 9030 Function Generator. The function generator was operated as a burst generator where the burst was triggered by the control logic and the duration of the burst was programmed into the generator as a fixed number of cycles.

3.3 Signal Amplification

Signal amplification was achieved through the use of a RF-805 power amplifier.

3.4 Electrical to Acoustic Conversion

Conversion to an acoustic signal was achieved through the use of a PZT-5 transducer, specially produced for our application by Valprey Fisher Corporation.

3.5 Acoustic to Electrical Conversion

Reconversion back to an electrical signal was again achieved by a PZT-5 transducer.

3.6 Logic Signal Processing

The control circuit turns the generator on for the number of cycles programmed and starts a time logic pulse. The time logic pulse stays on until the transmitted acoustic pulse is received. Once the pulse is received, it is rectified and level detected. A second logic pulse is generated as an offset signal to determine propagation time with zero percent fuel level. The difference between the time logic pulse and the offset logic pulse is the propagation time difference due to the presence of fuel vapor. This pulse denoted vapor pulse is used to turn on and off a megahertz clock. The clock time can then be checked on a graph of time vs. fuel level to determine the fuel vapor level.

4.0 SUMMARY

The range of fuel vapor level that we were most concerned with was from 1.0 to 8.0 percent by volume. The theoretical change in propagation time over this range is shown in Table I. Due to the small total change and desired accuracy, it was decided to monitor the electrical signal from the receiving transducer. This was done with a Tektronix 7623-A oscilloscope, using the start pulse for a trigger pulse. Since the high frequency signal was of one megahertz frequency, simply counting the cycles of the received acoustic pulse as they moved past a predetermined point on the screen determined the change in propagation time in microseconds.

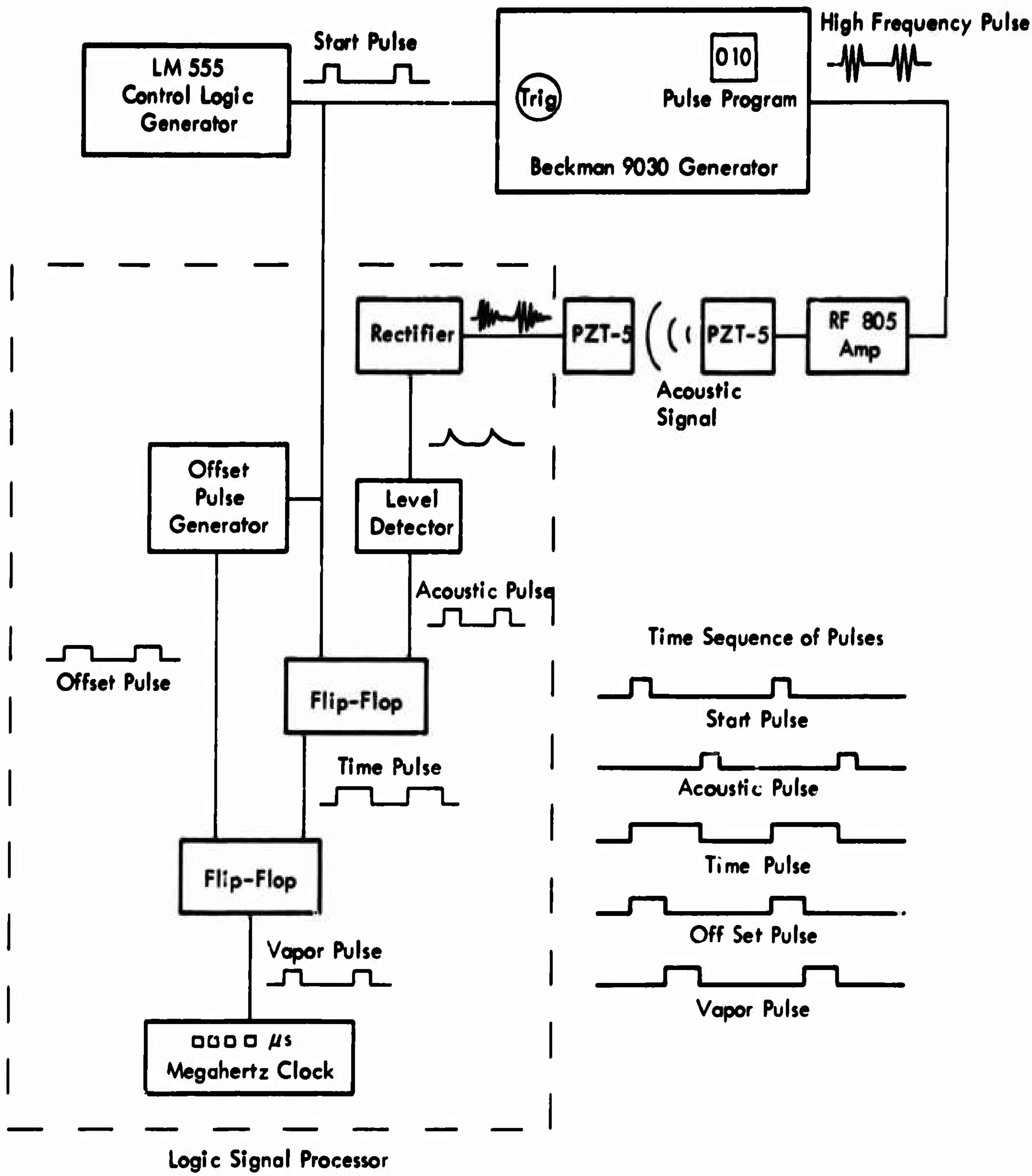


Figure 1. Fuel Vapor Level Detector Functional Diagram

APPENDIX B

REDUCED DATA WITH CORRESPONDING CALIBRATION CURVES

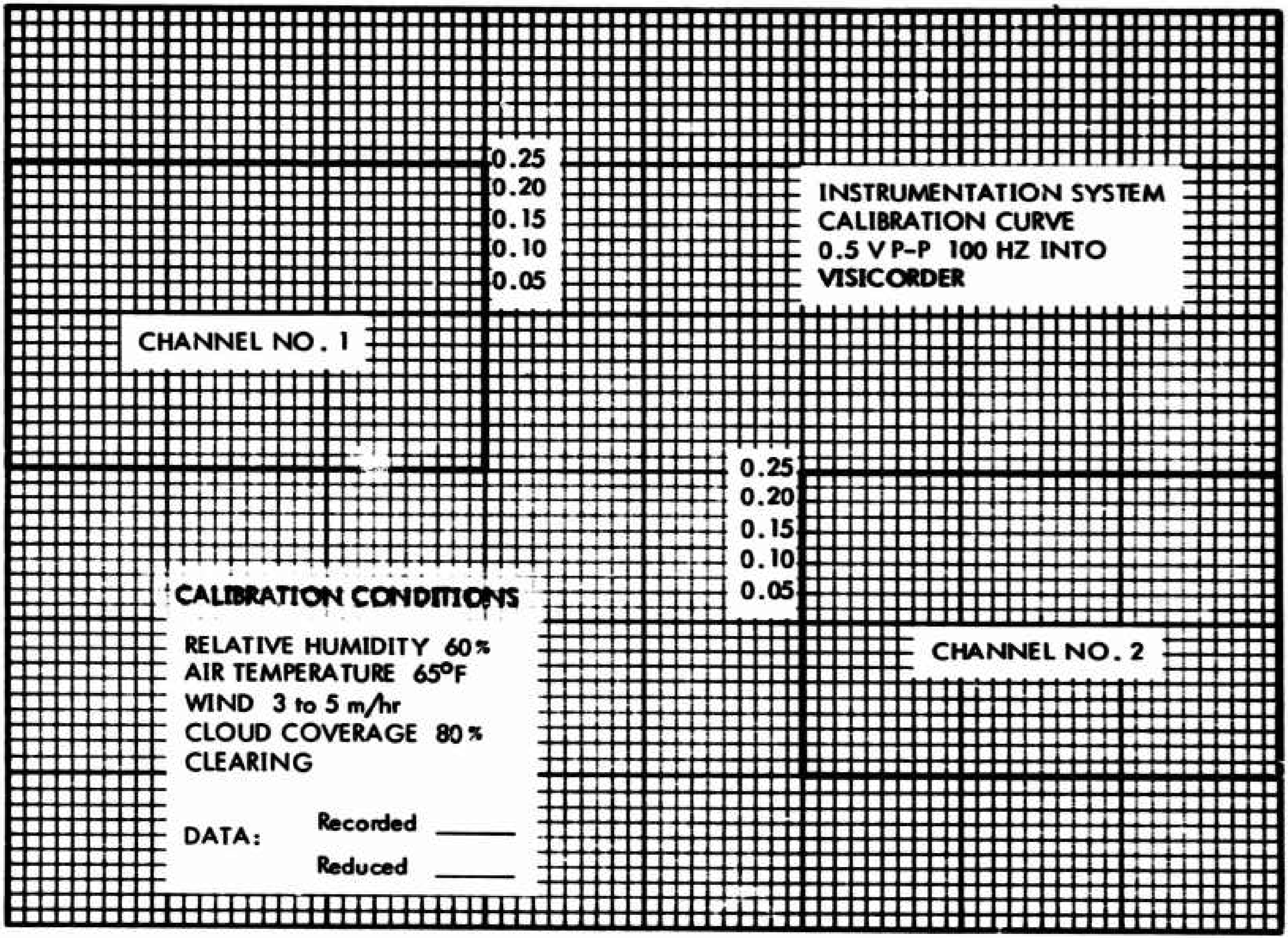


Figure B-1. Transducer Calibration

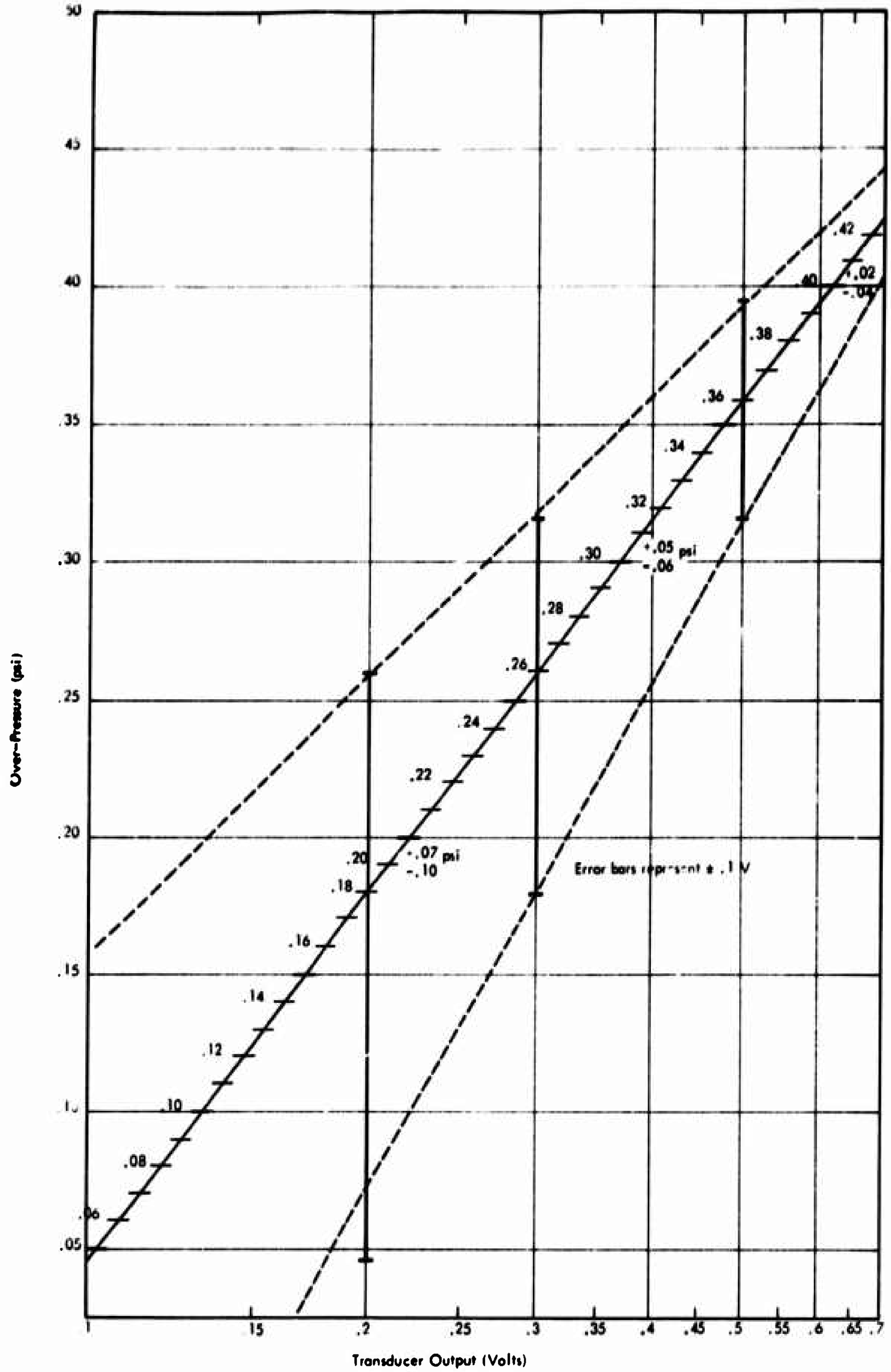
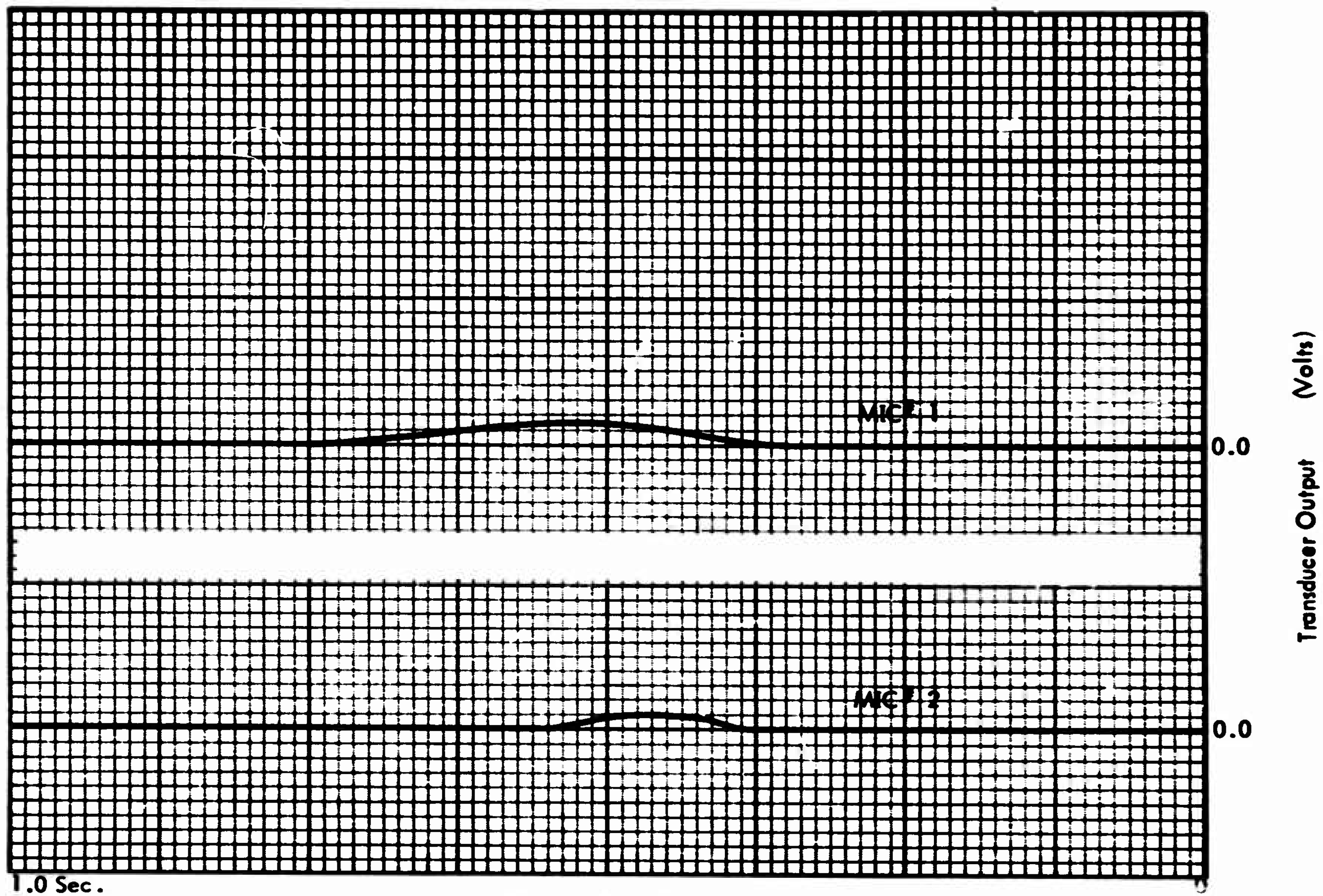
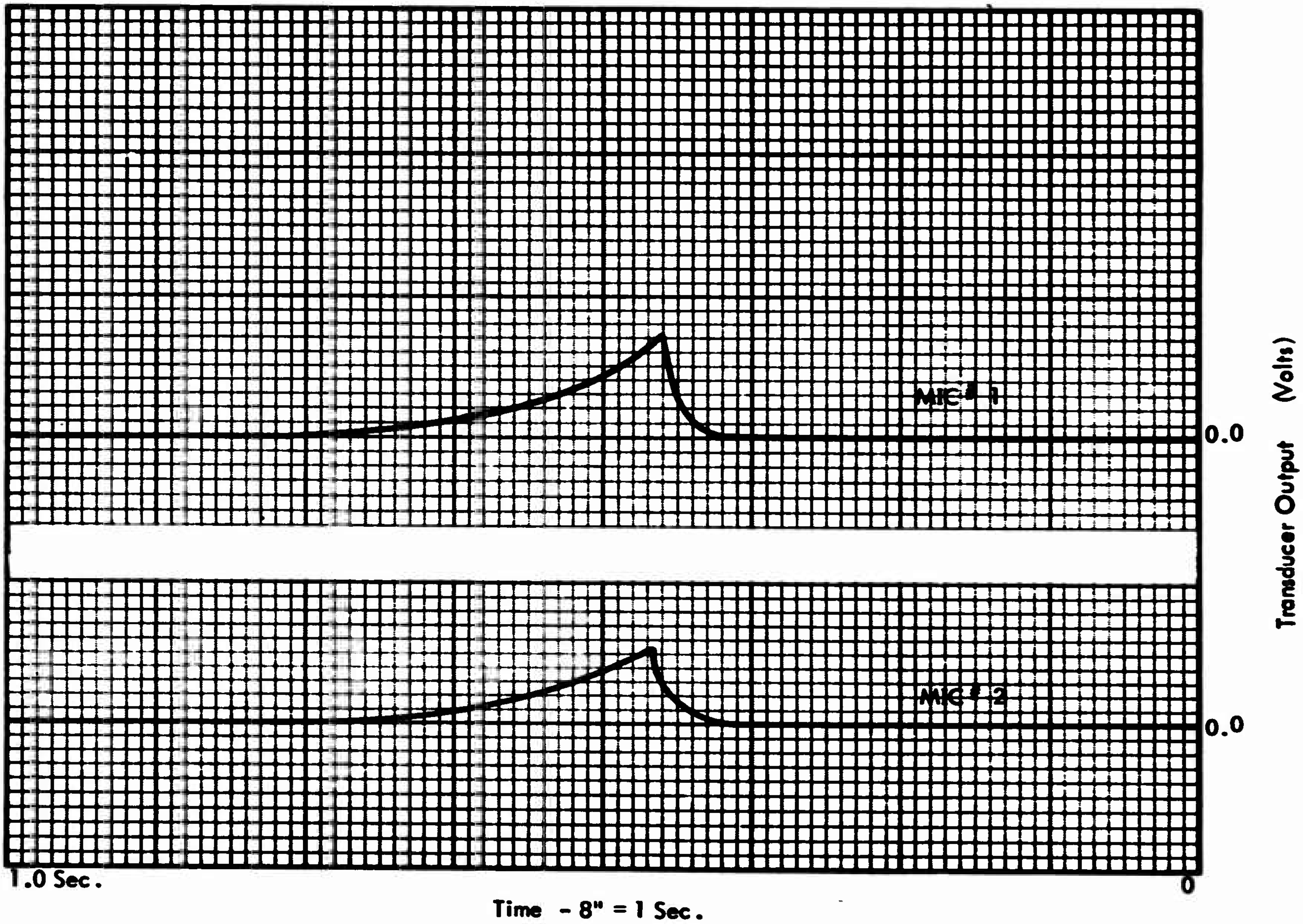


Figure B-2. Calibration Curve PZT-5 Transducers

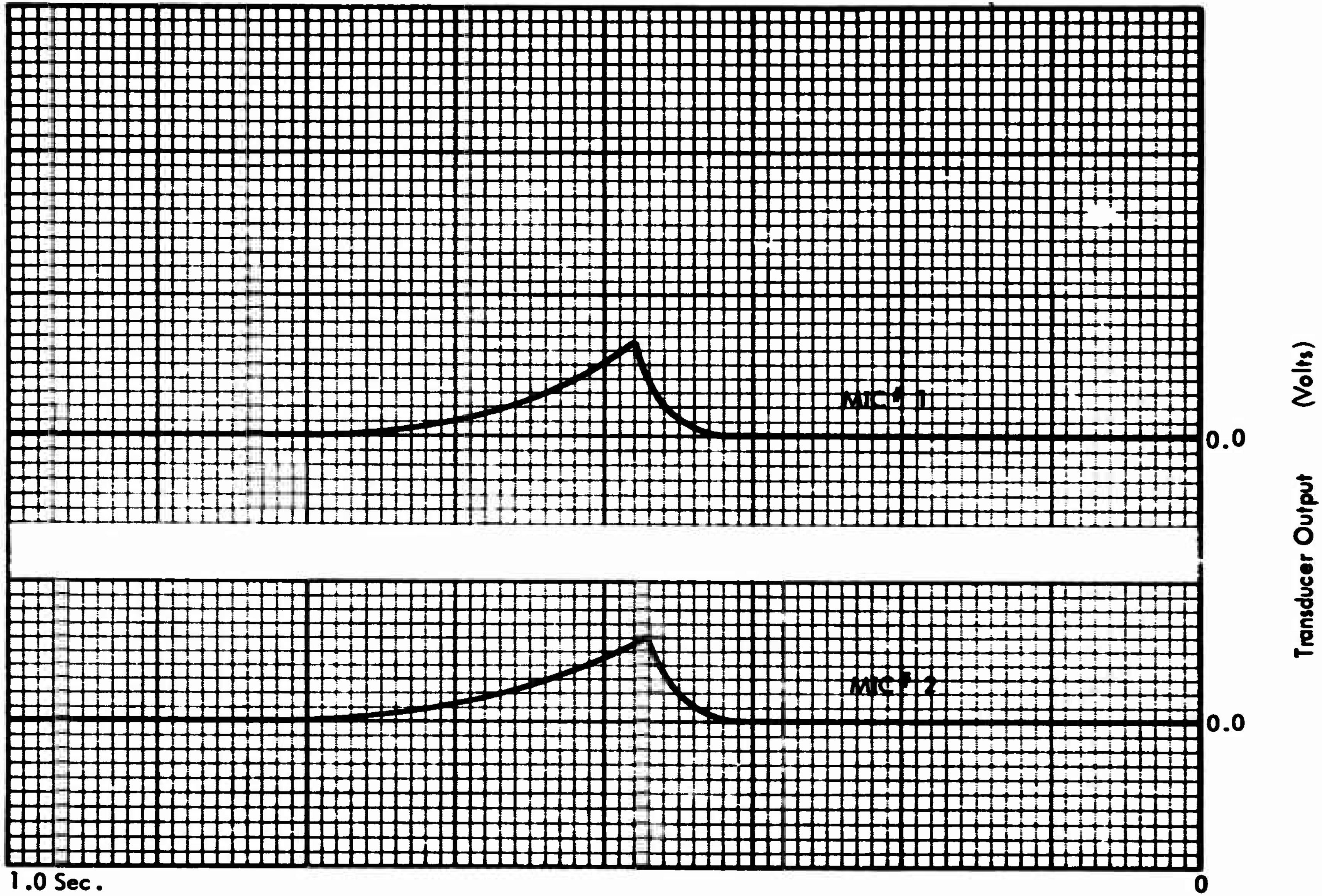


Time - 8" = 1 Sec.

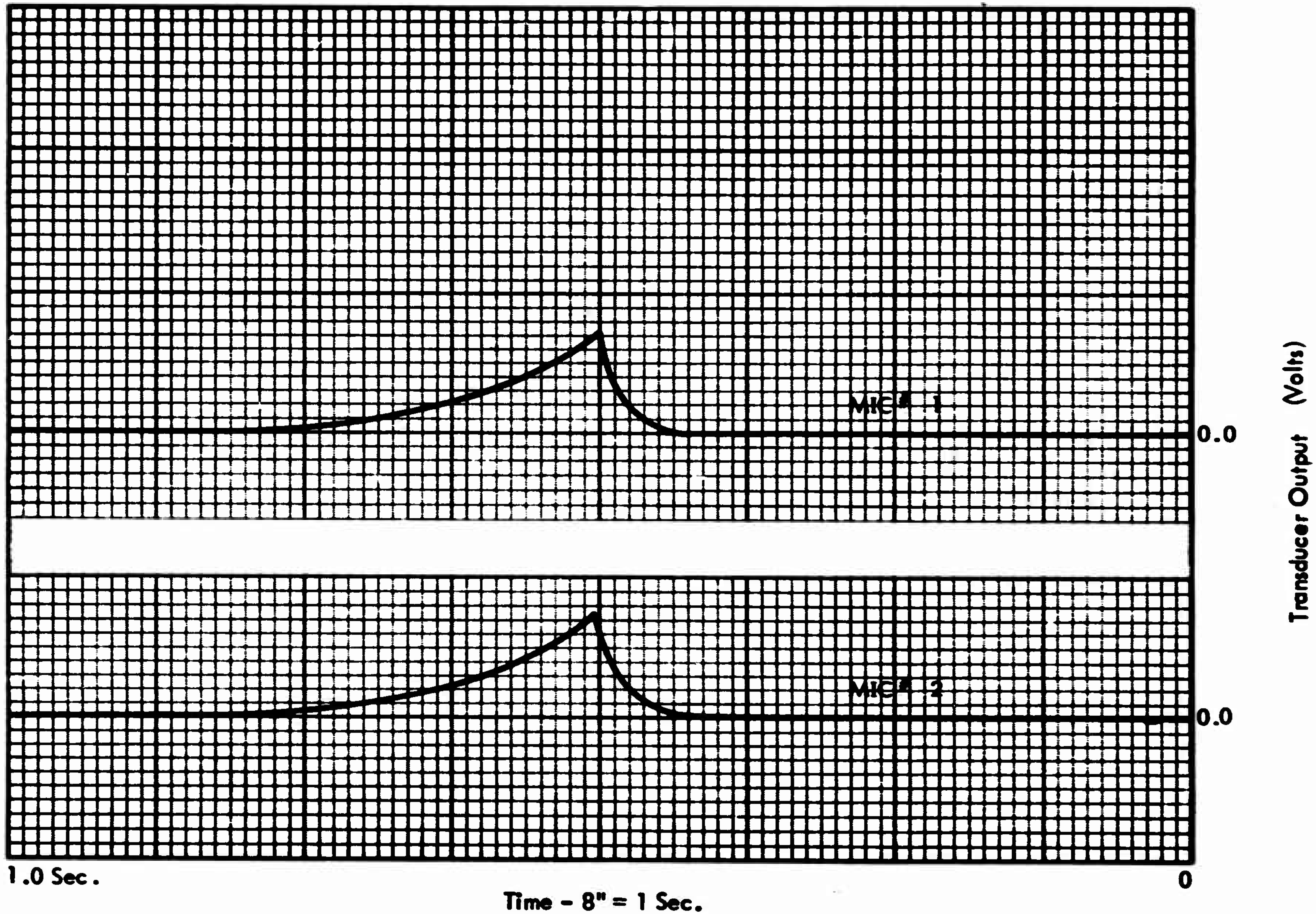
Analysis Number 1. 30 cc; 155°F; 10 Ft^3; 2 Doors



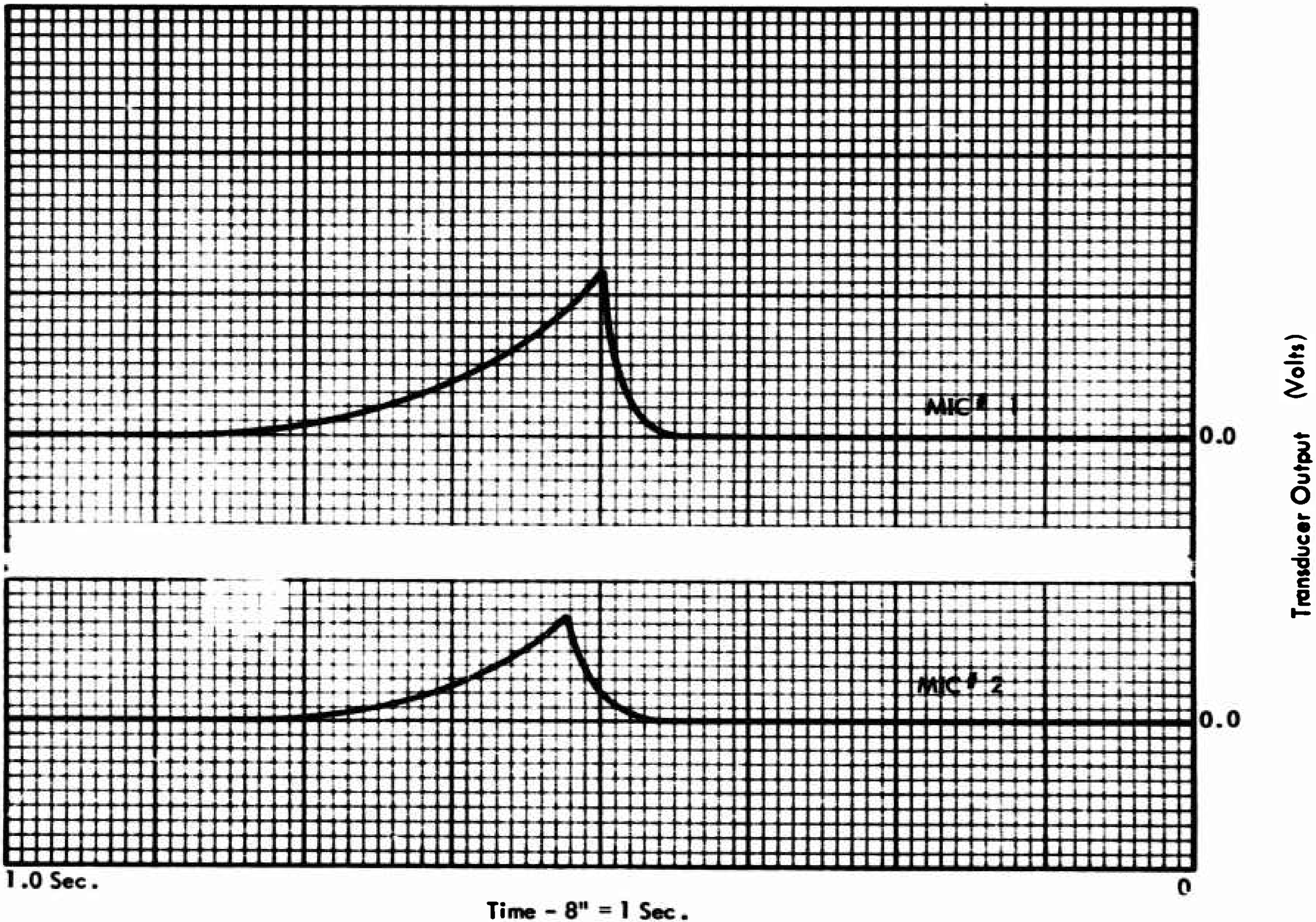
Analysis Number 2. 30 cc; 168F; 10 Ft^3; 2 Doors



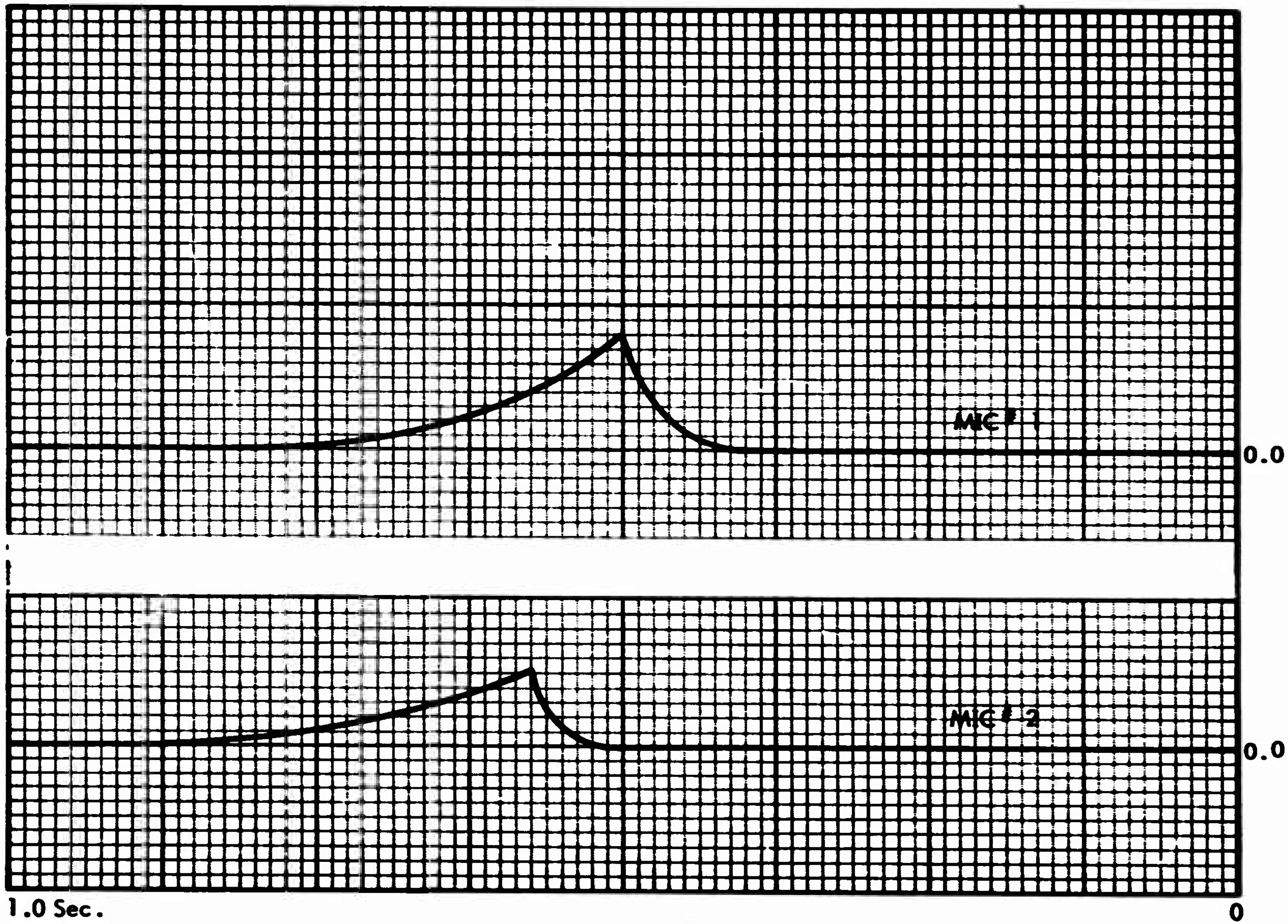
Time - 8" = 1 Sec.
Analysis Number 3. 30 cc; 160°F; 10 Ft^3; 2 Doors



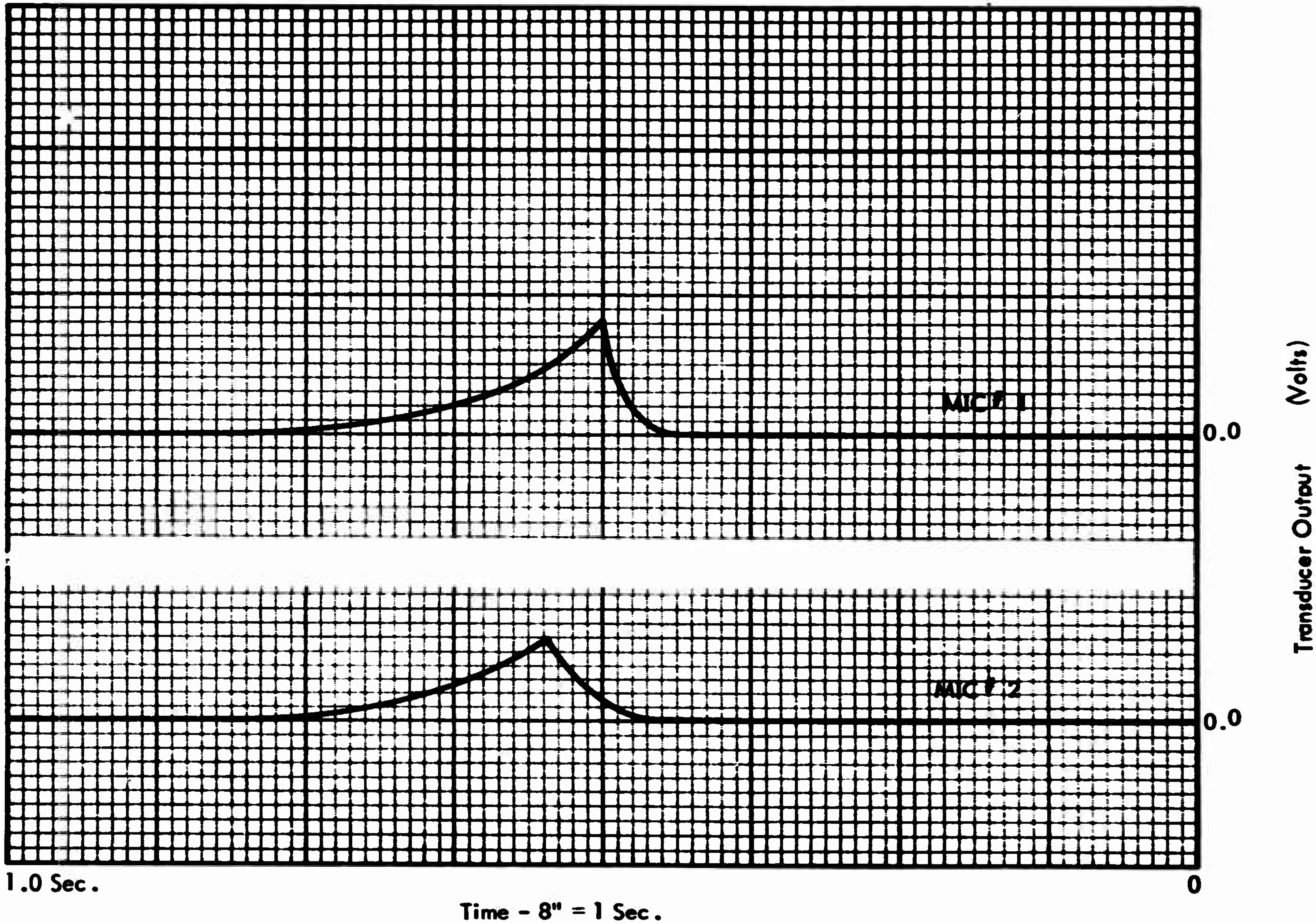
Analysis Number 4. 30 cc; 153°F; 10 Ft^3; 2 Doors



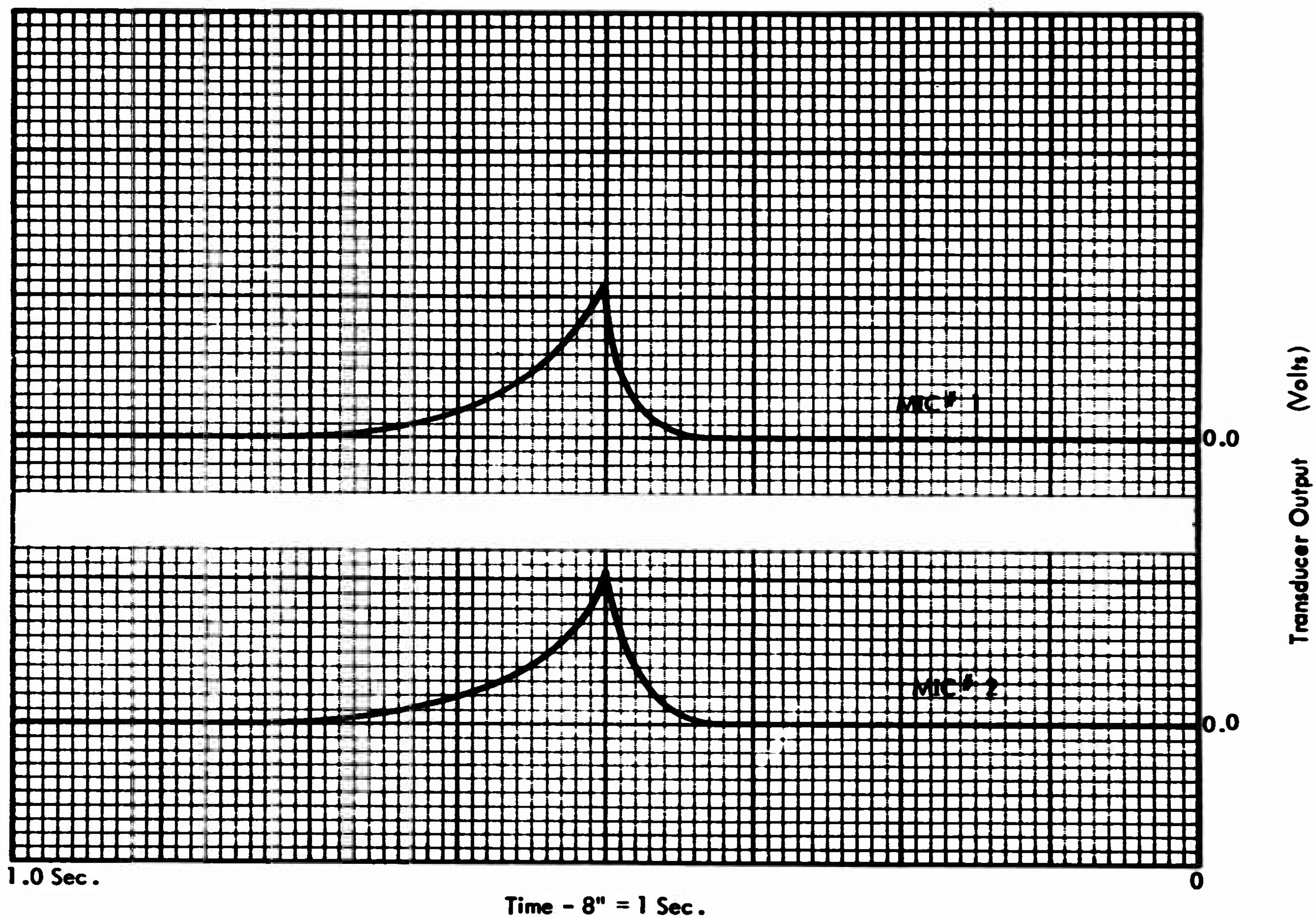
Analysis Number 5. 30 cc; 160°F; 10 Ft^3; 1 Door (Top)



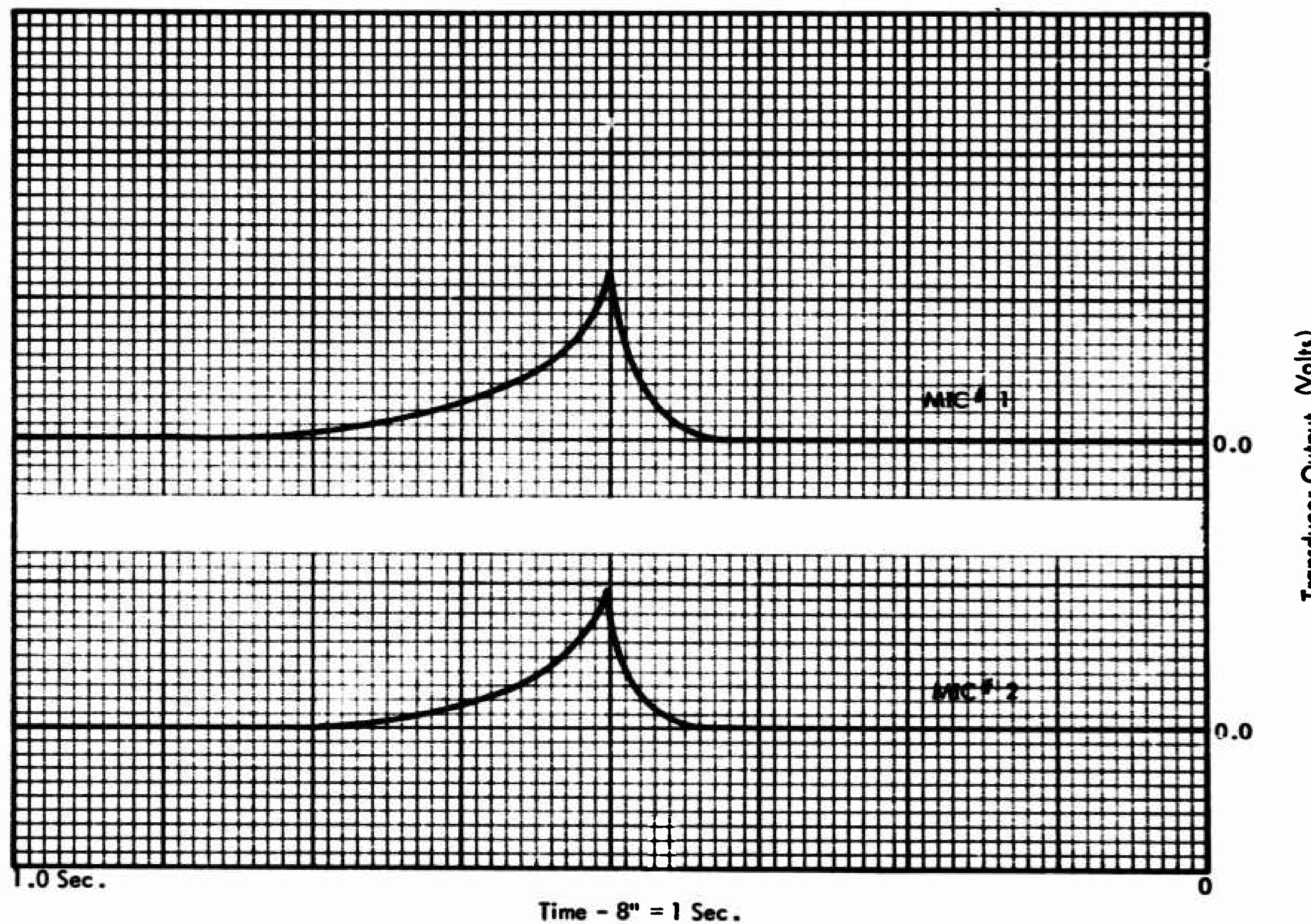
Analysis Number 6. 30 cc; 160°F; 10 Ft^3; 1 Door (Top)



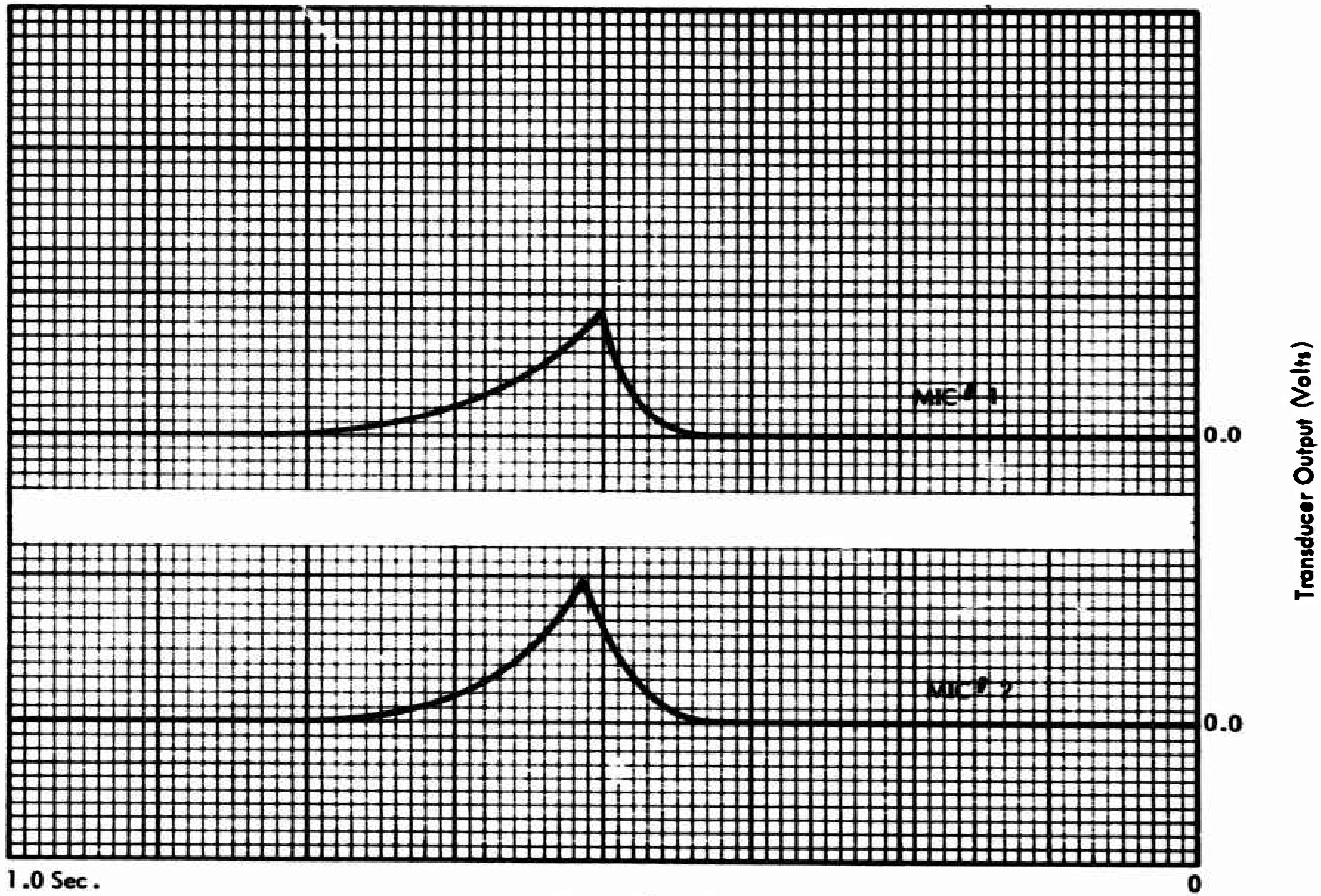
Analysis Number 7. 30 cc; 167°F; 10 Ft^3; 1 Door (Top)



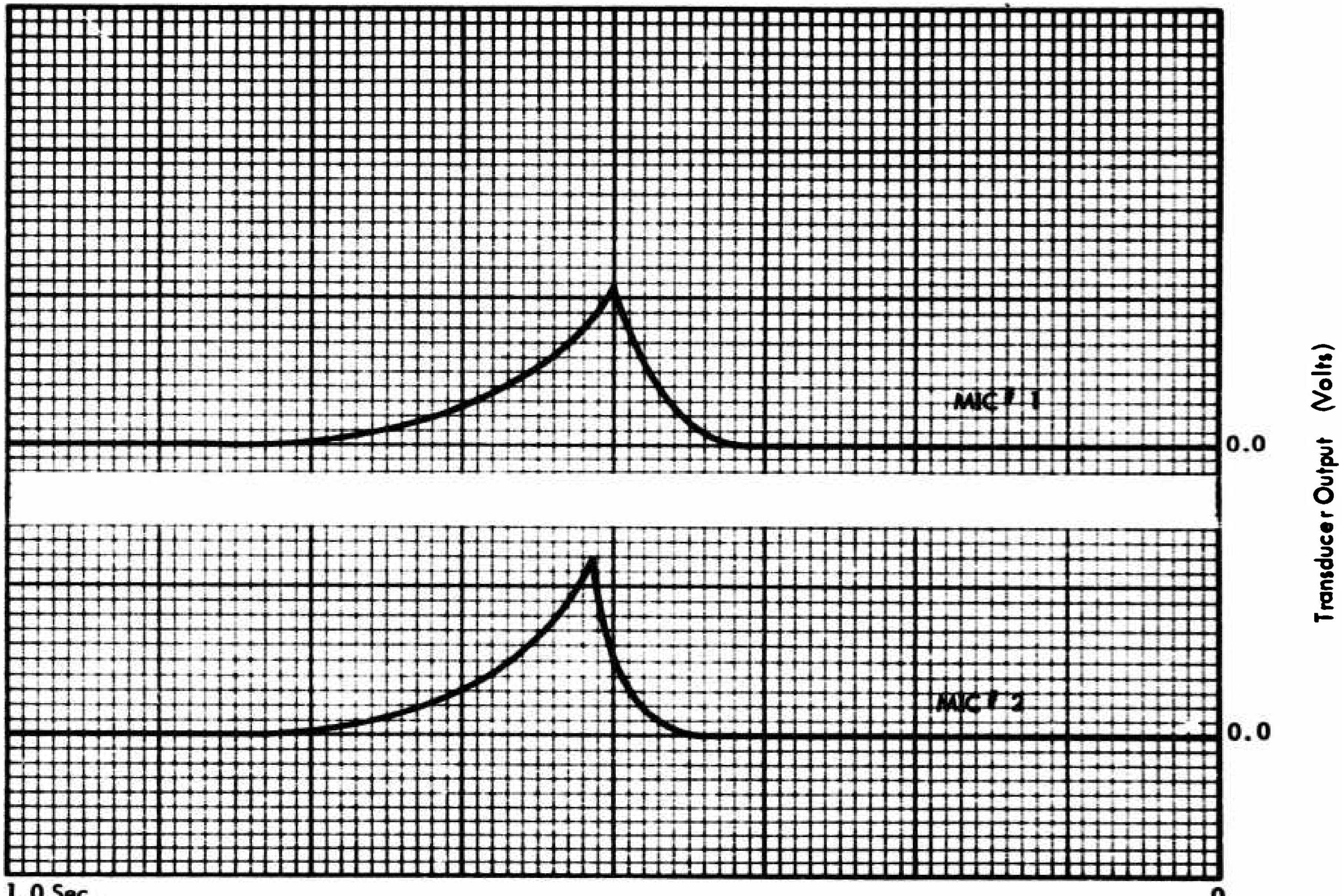
Analysis Number 8. 45cc; 160°F; 10 Ft^3; 2 Doors



Analysis Number 9. 45cc; 168°F; 10 Ft^3; 2 Doors

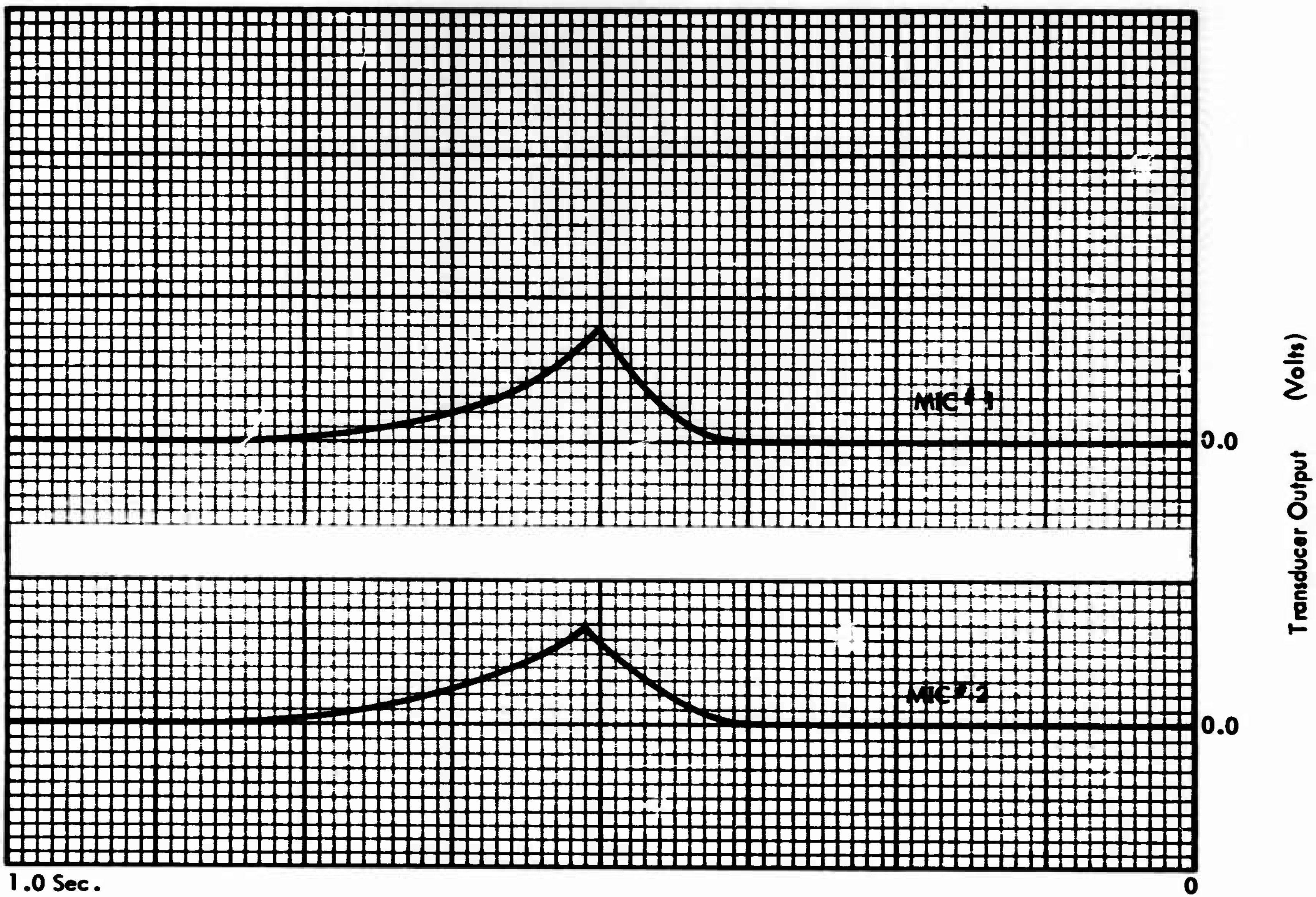


Analysis Number 10. 37cc; 172°F; 10 Ft^3; 2 Doors

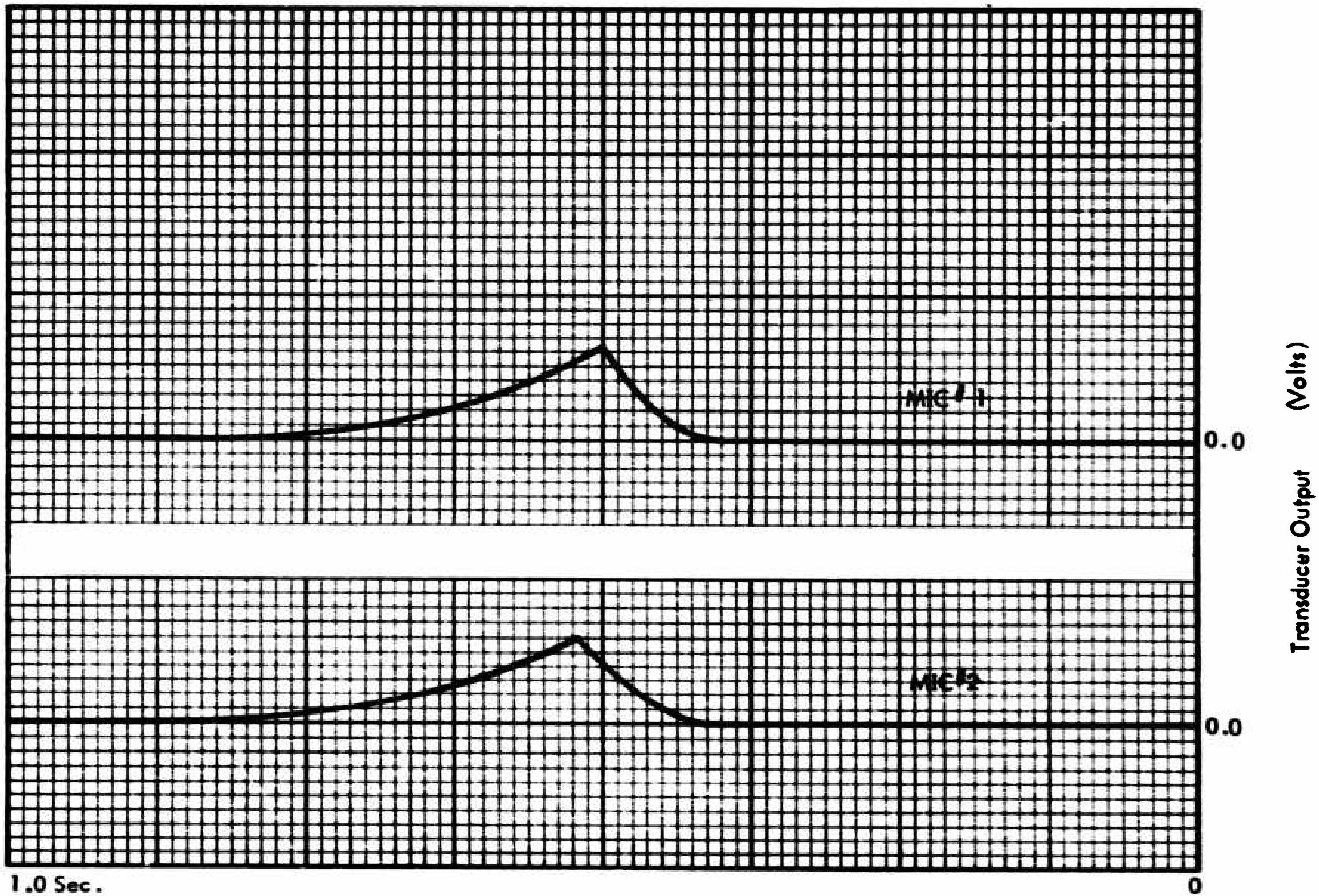


Time - 8" - 1 Sec.

Analysis Number 11. 37 cc; 172°F; 10 Ft³; 2 Doors

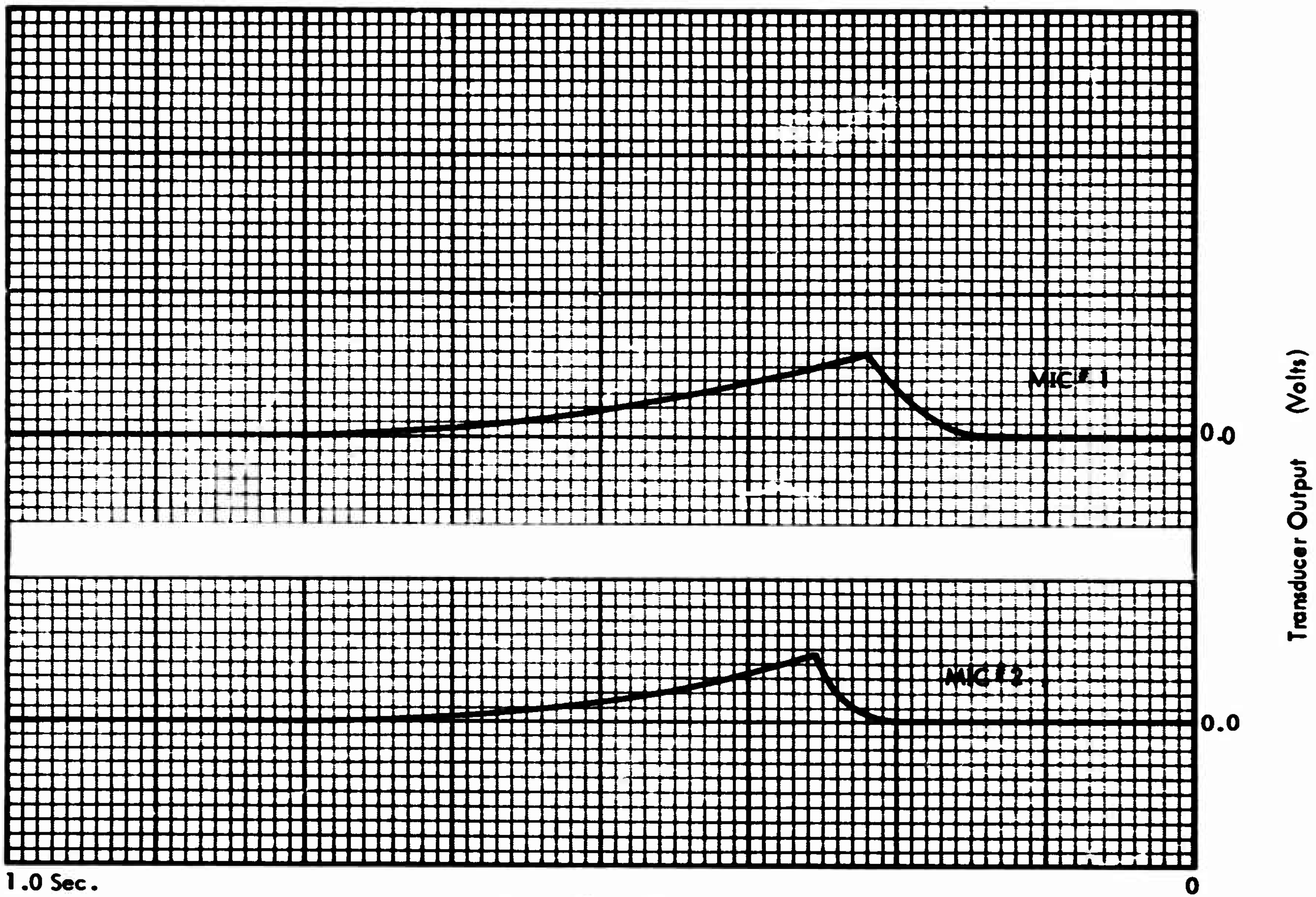


Analysis Number 12. 30 cc; 170°F; 10 Ft^3; 2 Doors



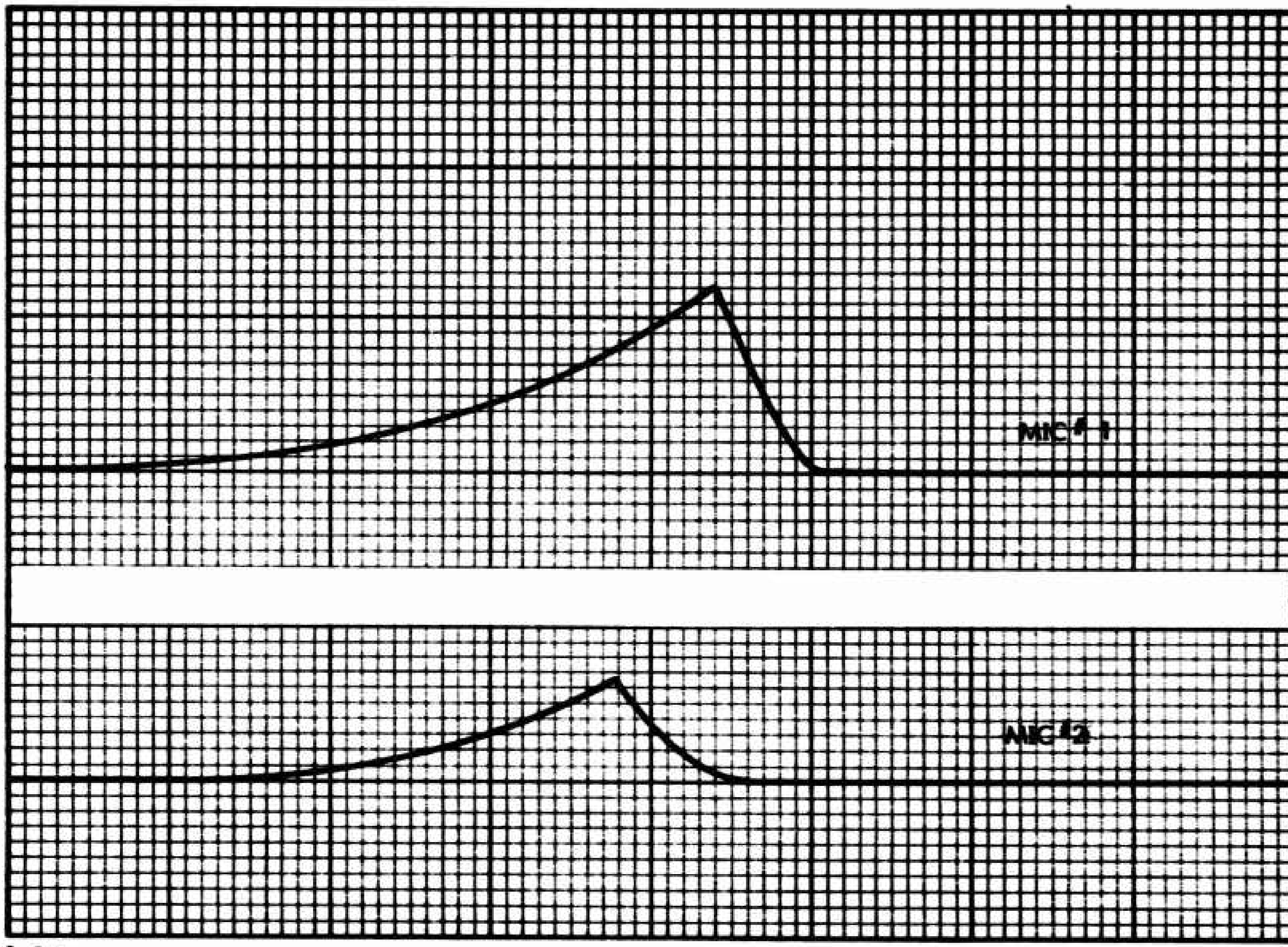
Time - 8" = 1 Sec.

Analysis Number 13. 30 cc; 175°F; 10 Ft^3; 2 Doors

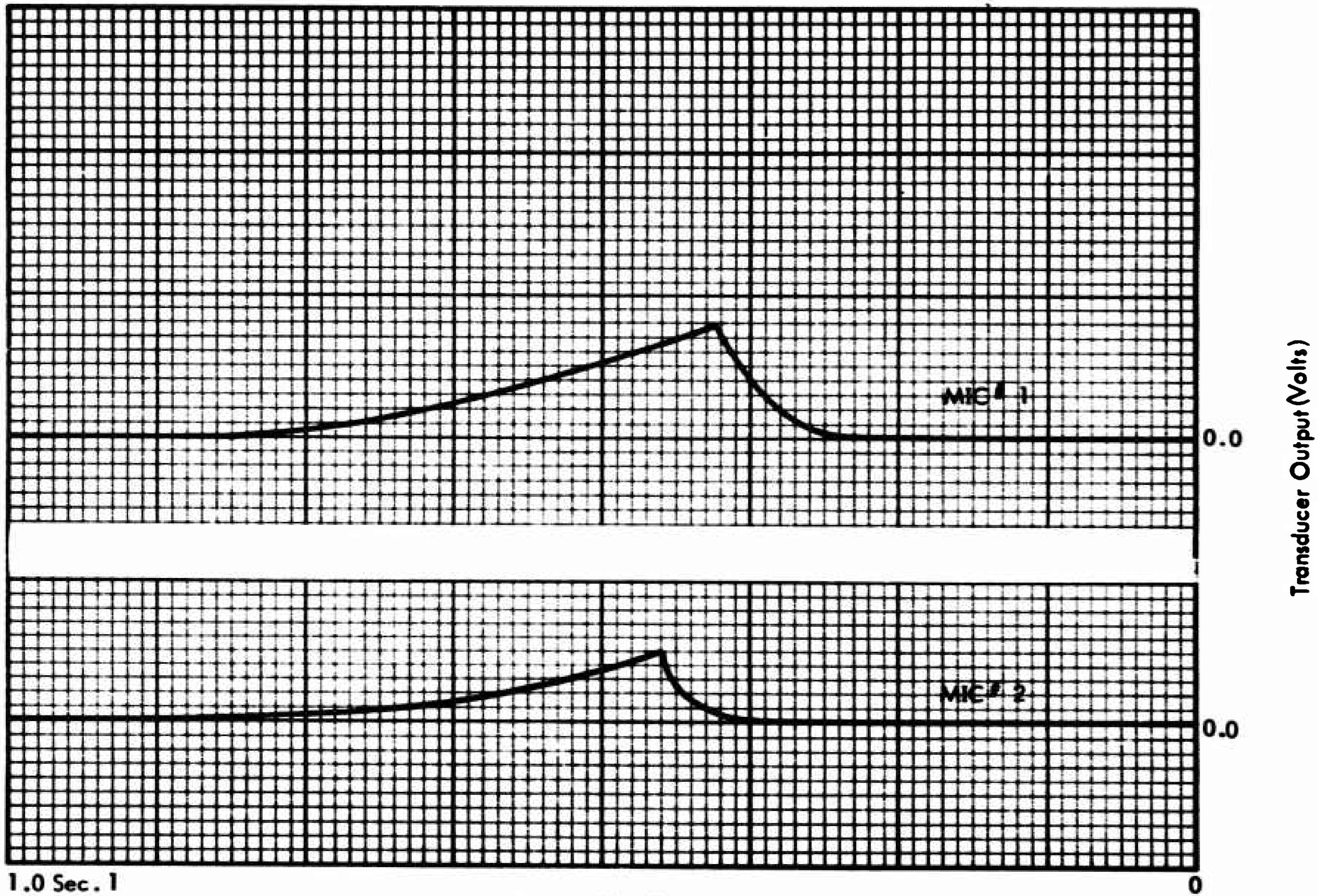


Time - 8" = 1 Sec.

Analysis Number 14. 80 cc; 125°F; 30 Ft^3; 4 Doors

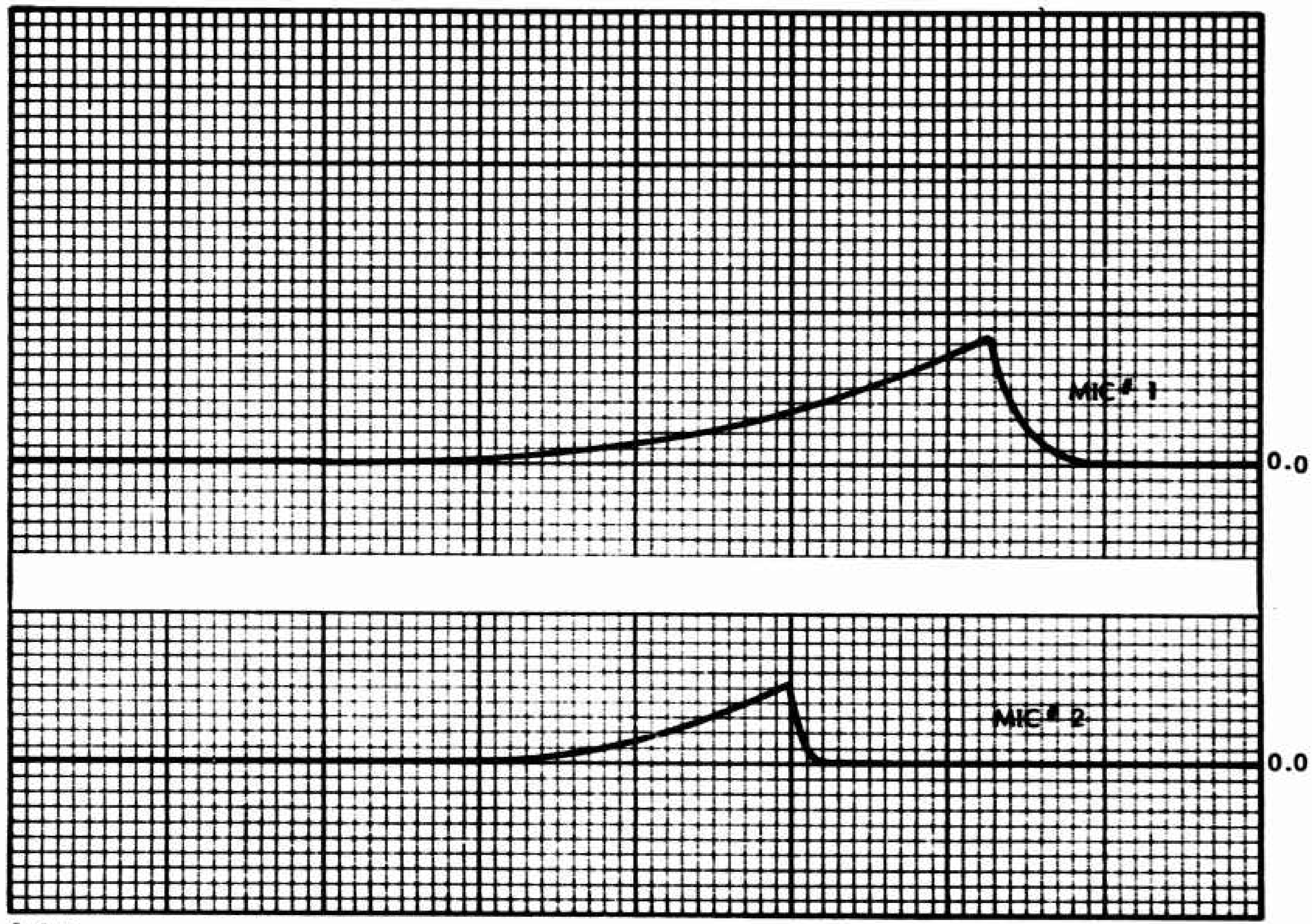


Analysis Number 15. 80 cc; 135°F; 30 Ft^3; 3 Doors



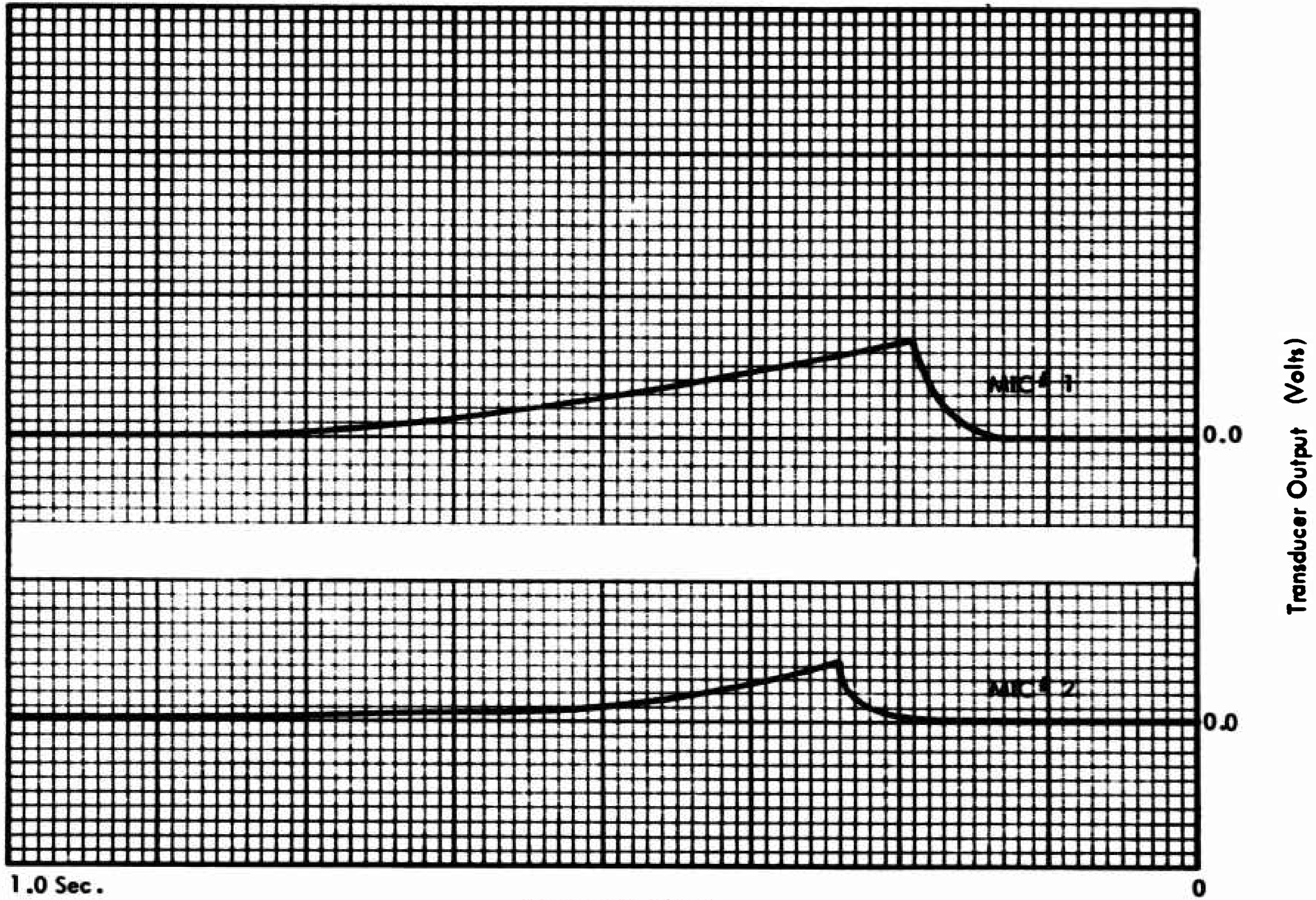
Time - 8" = 1 Sec.

Analysis Number 16. 80 cc; 135°F; 30 Ft³; 3 Doors



Time - 8" = 1 Sec.

Analysis Number 17. 80 cc; 135°F; 30 Ft³; 3 Doors

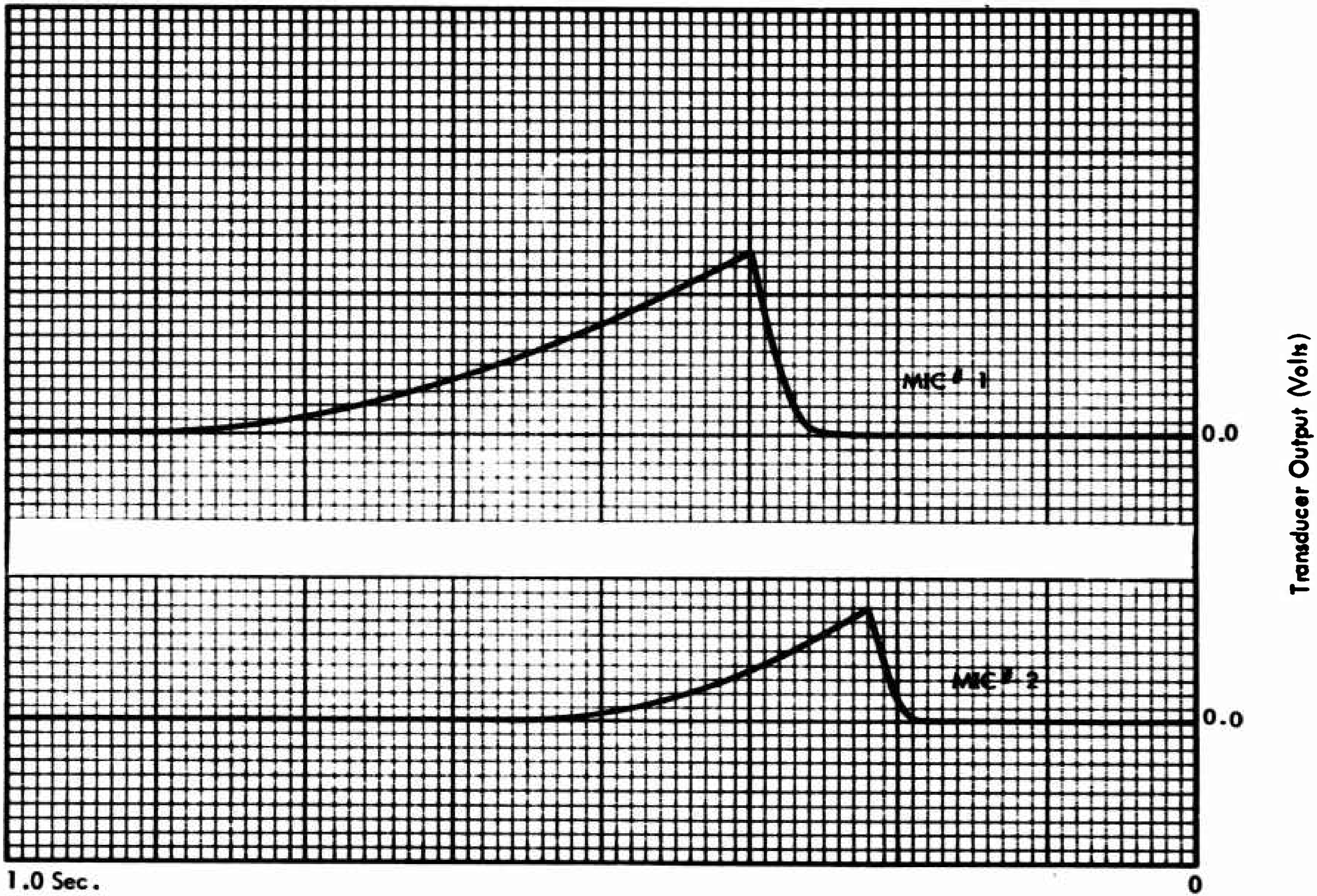


Time - 8" = 1 Sec.

Analysis Number 18. 80 cc; 135°F; 30 Ft^3; 3 Doors

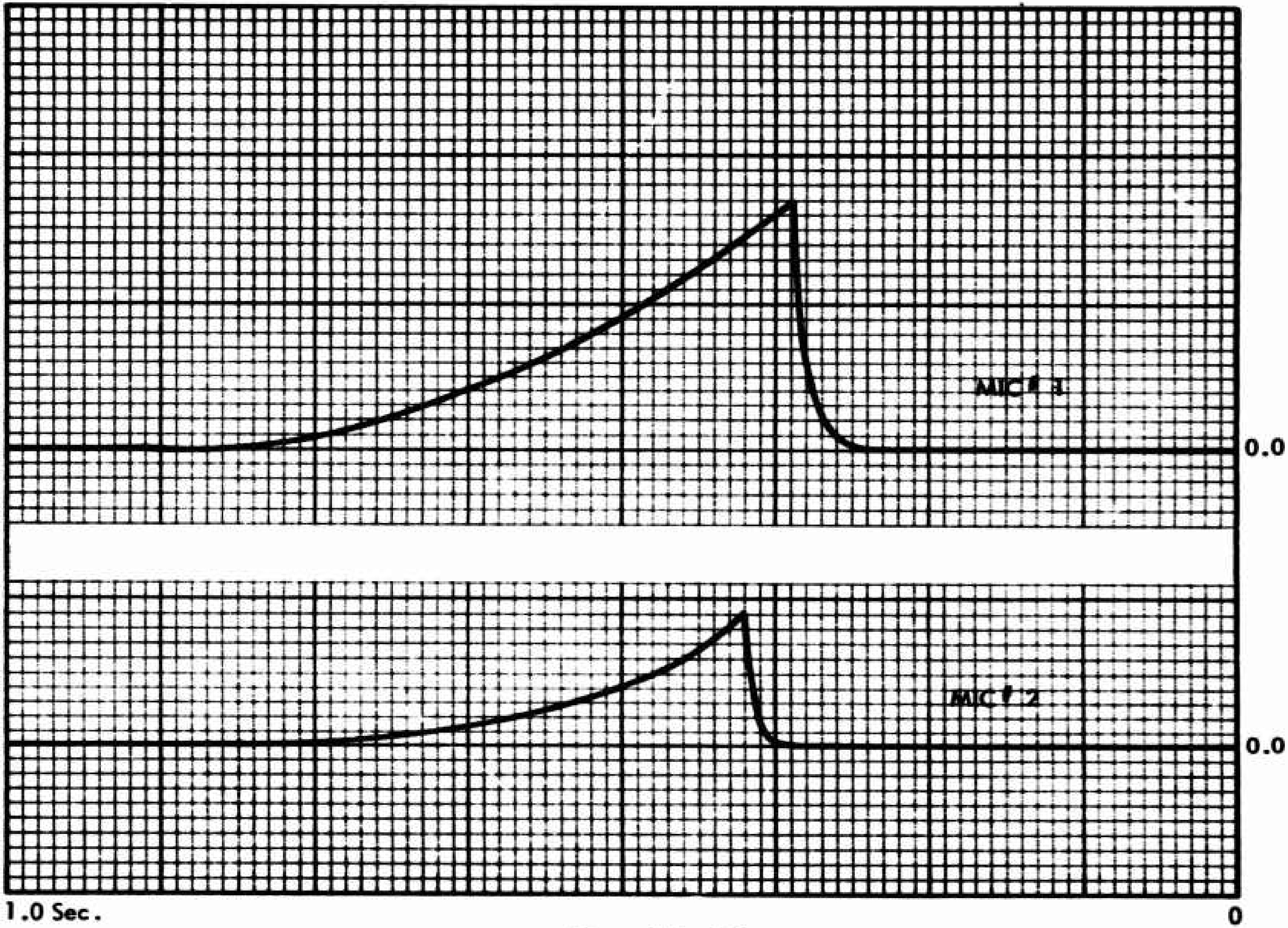
Time - 8" = 1 Sec.

Analysis Number 19. 80 cc; Film; 30 Ft^3; 4 Doors

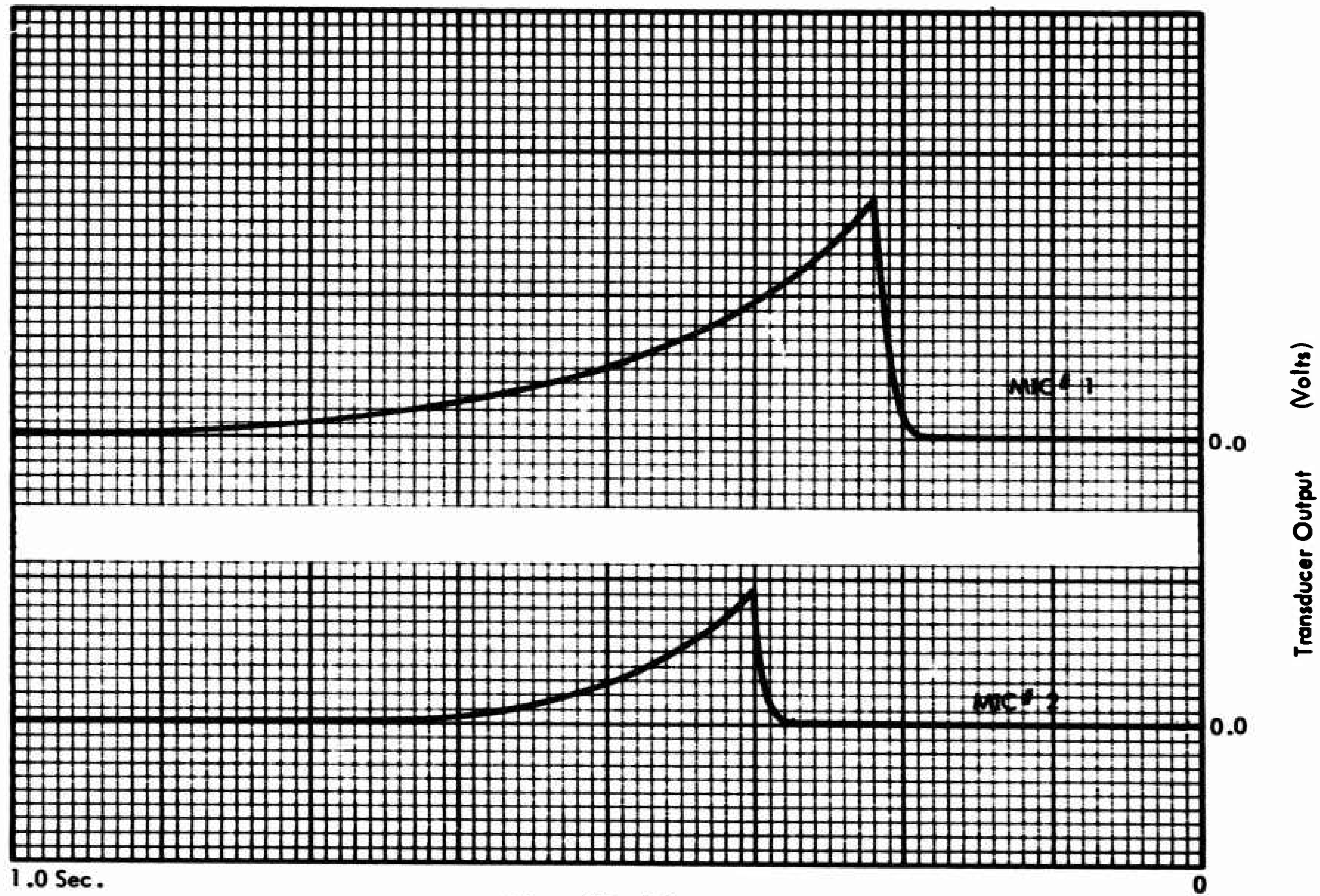


Time - 8" = 1 Sec.

Analysis Number 20. 100 cc; Film; 30 Ft^3; 4 Doors

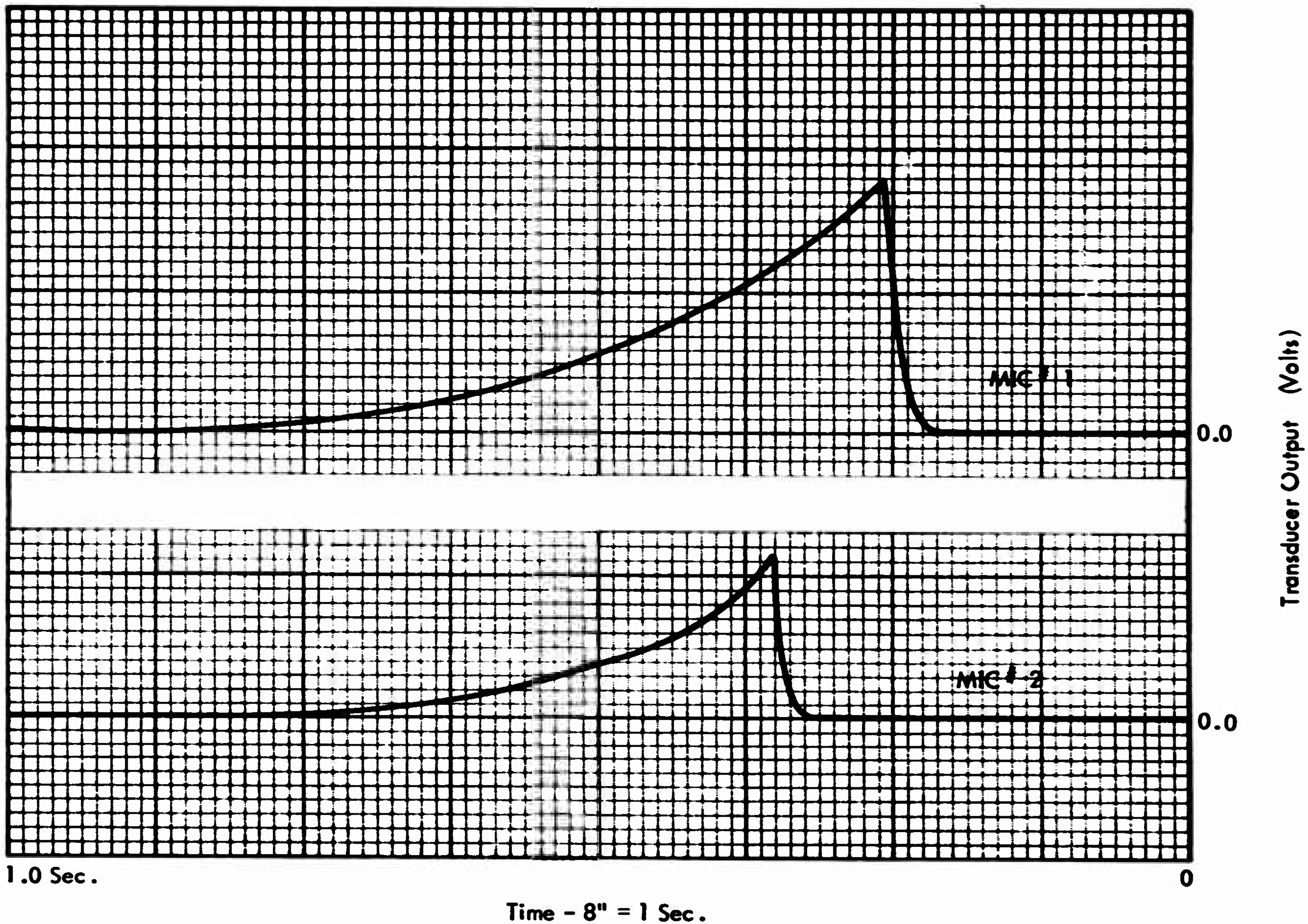


Analysis Number 21. 110 cc; Film; 30 Ft^3; 4 Doors



Time - 8" = 1 Sec.

Analysis Number 22. 110 cc; Film; 30 Ft^3; 4 Doors



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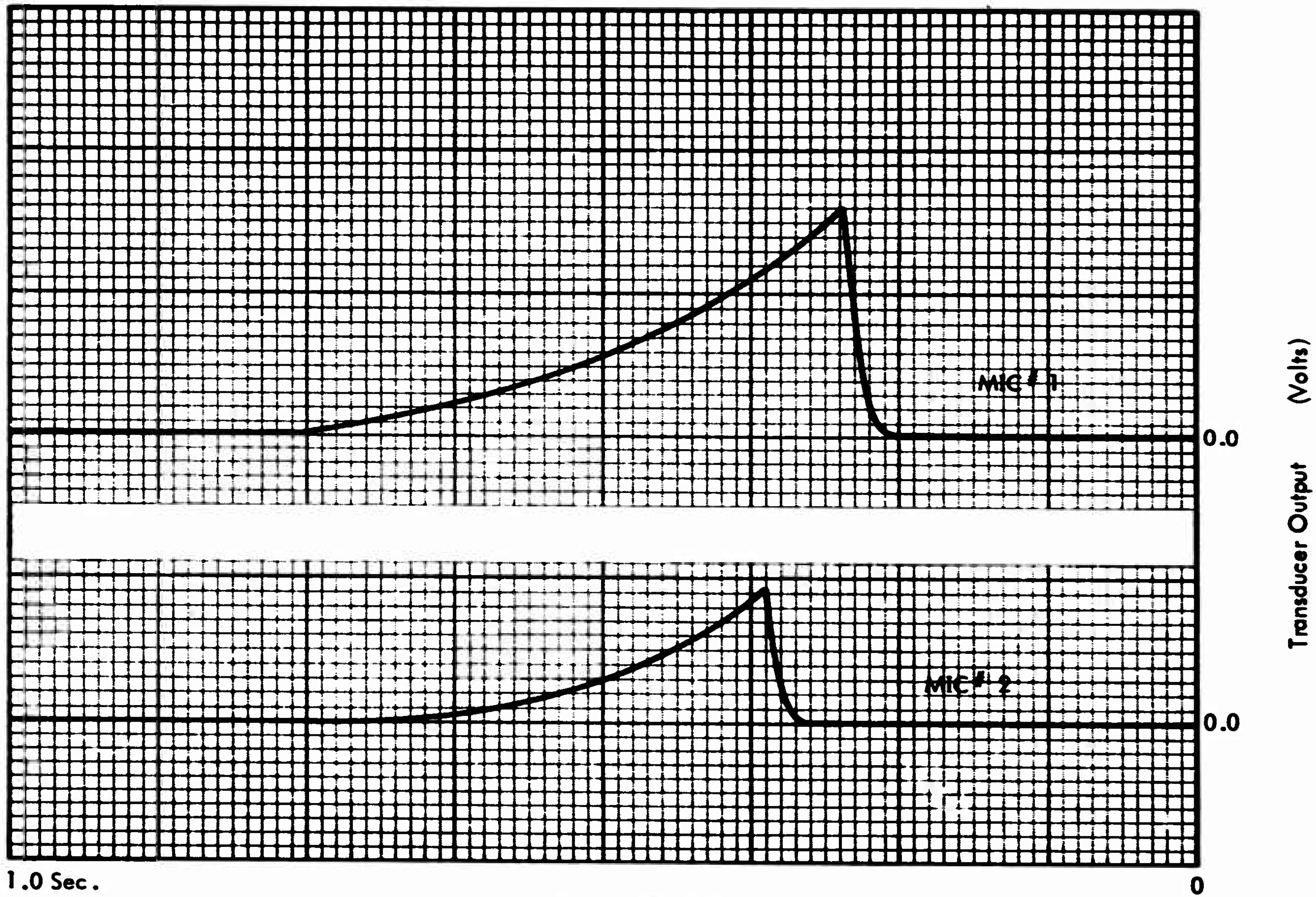

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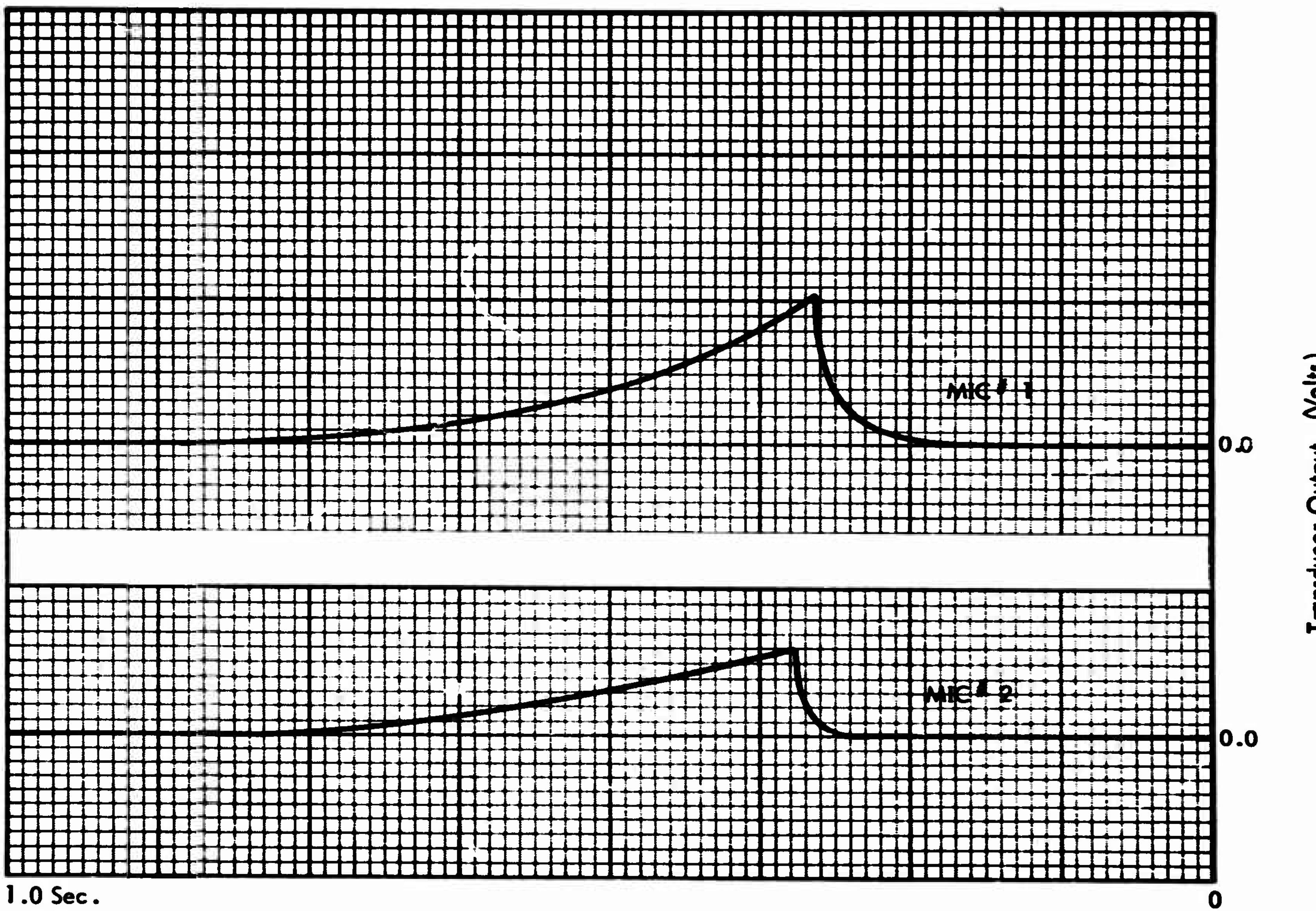

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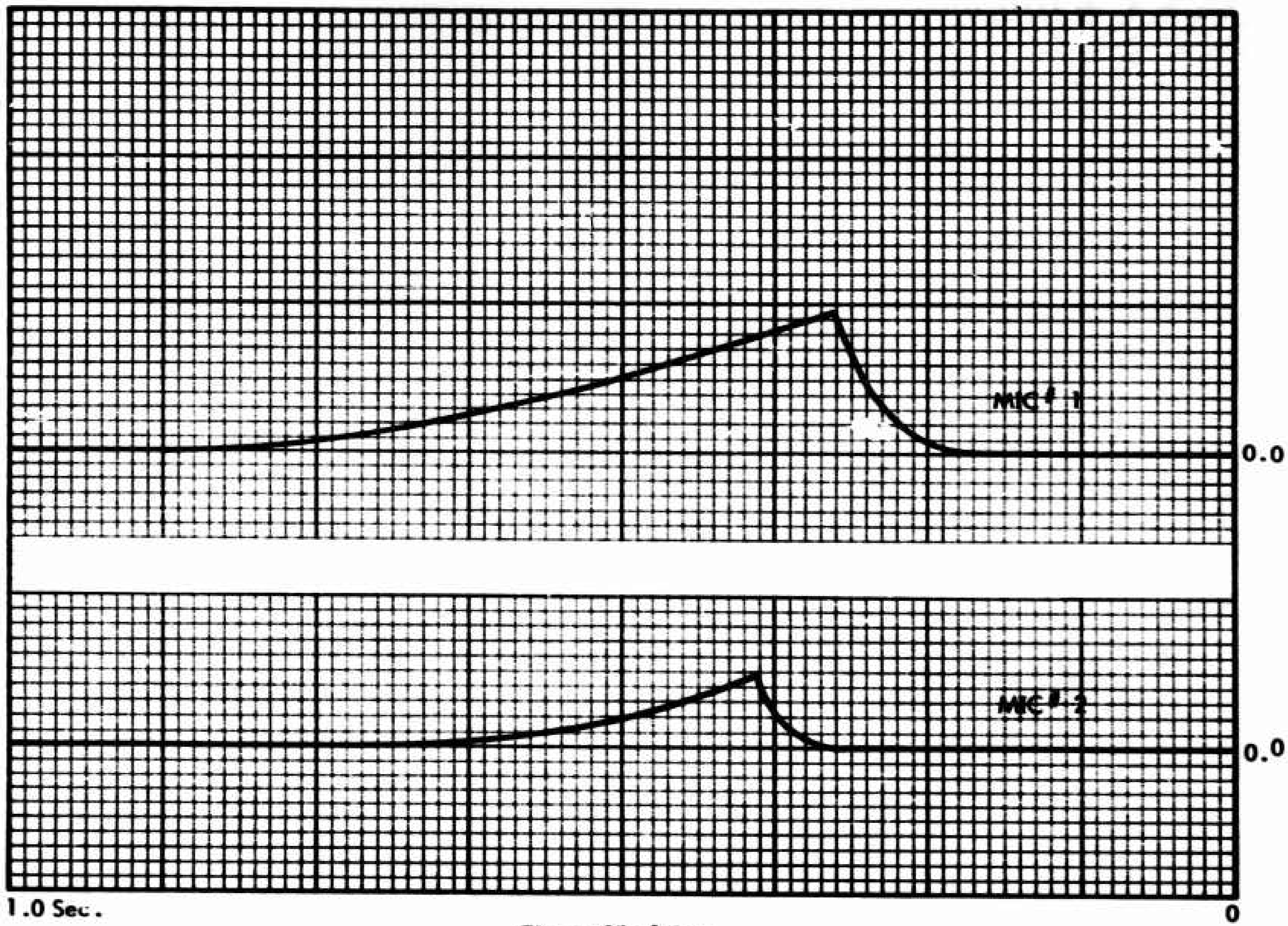

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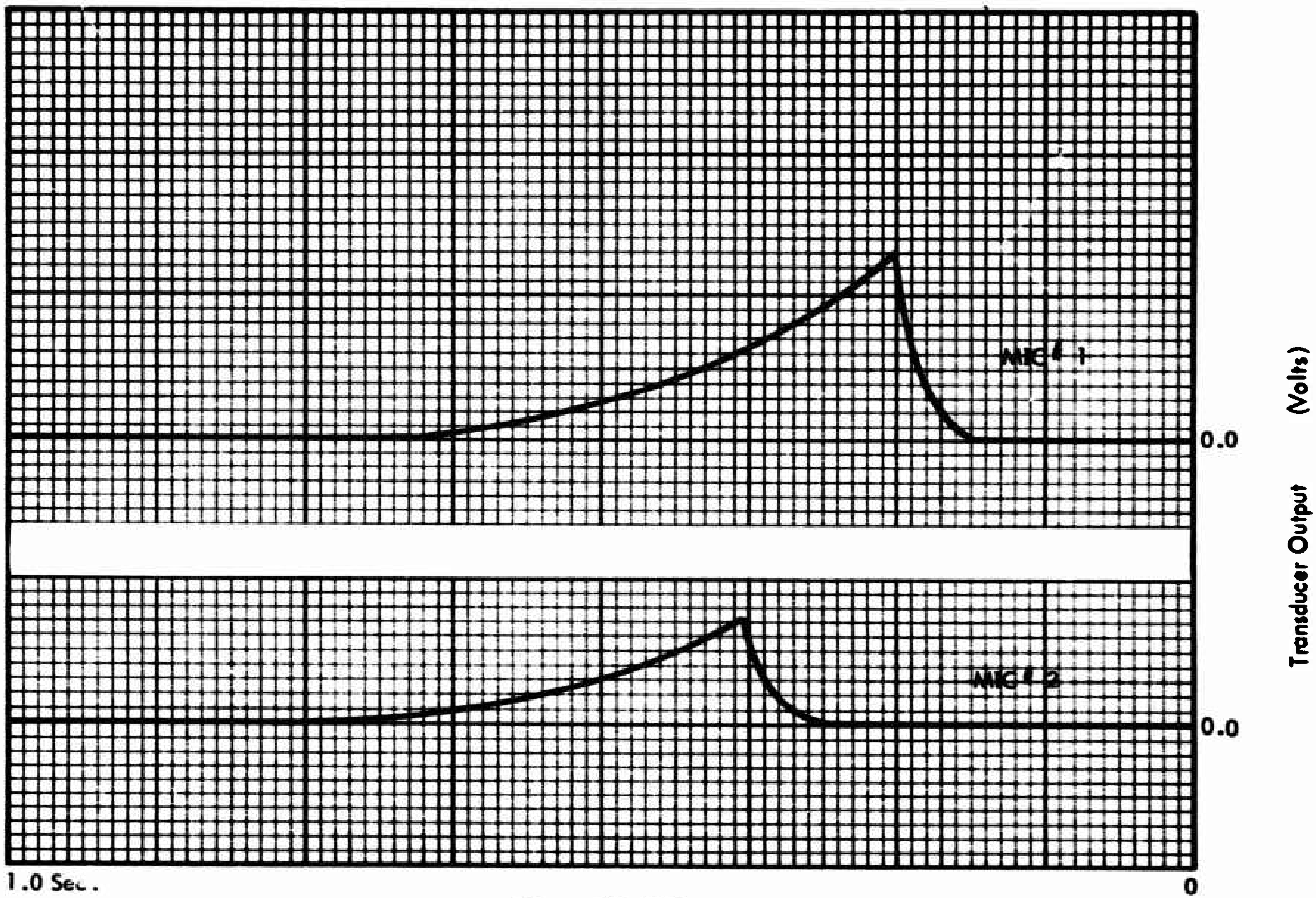
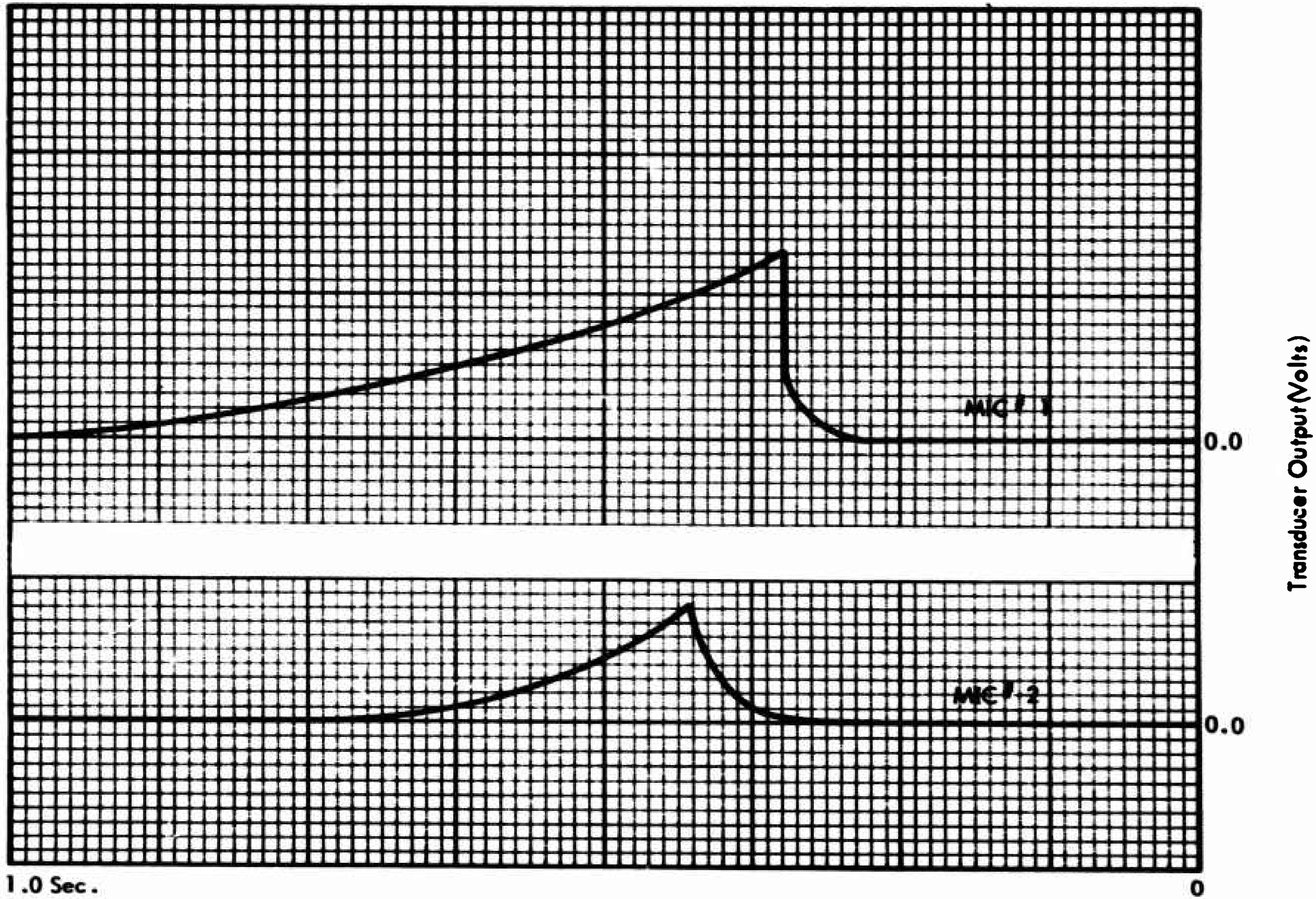
Analysis Number 26. 100 cc; 120°F; 30 Ft^3; 4 Doors



Time - 8" = 1 Sec.

Analysis Number 27. 100 cc; 120°F; 30 Ft^3; 4 Doors



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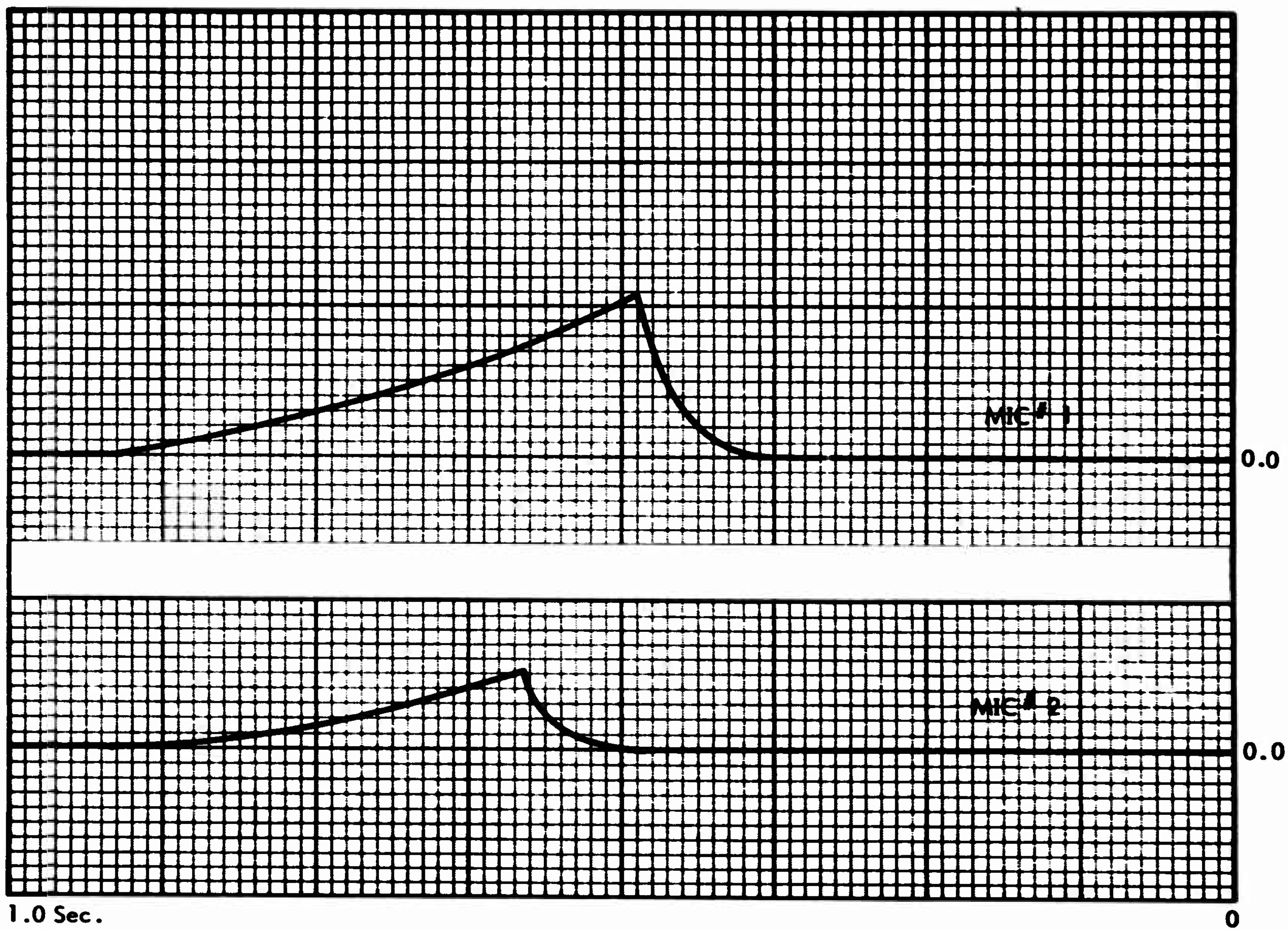
Analysis Number 28. 116 cc; 125°F; 30 Ft^3; 4 Doors



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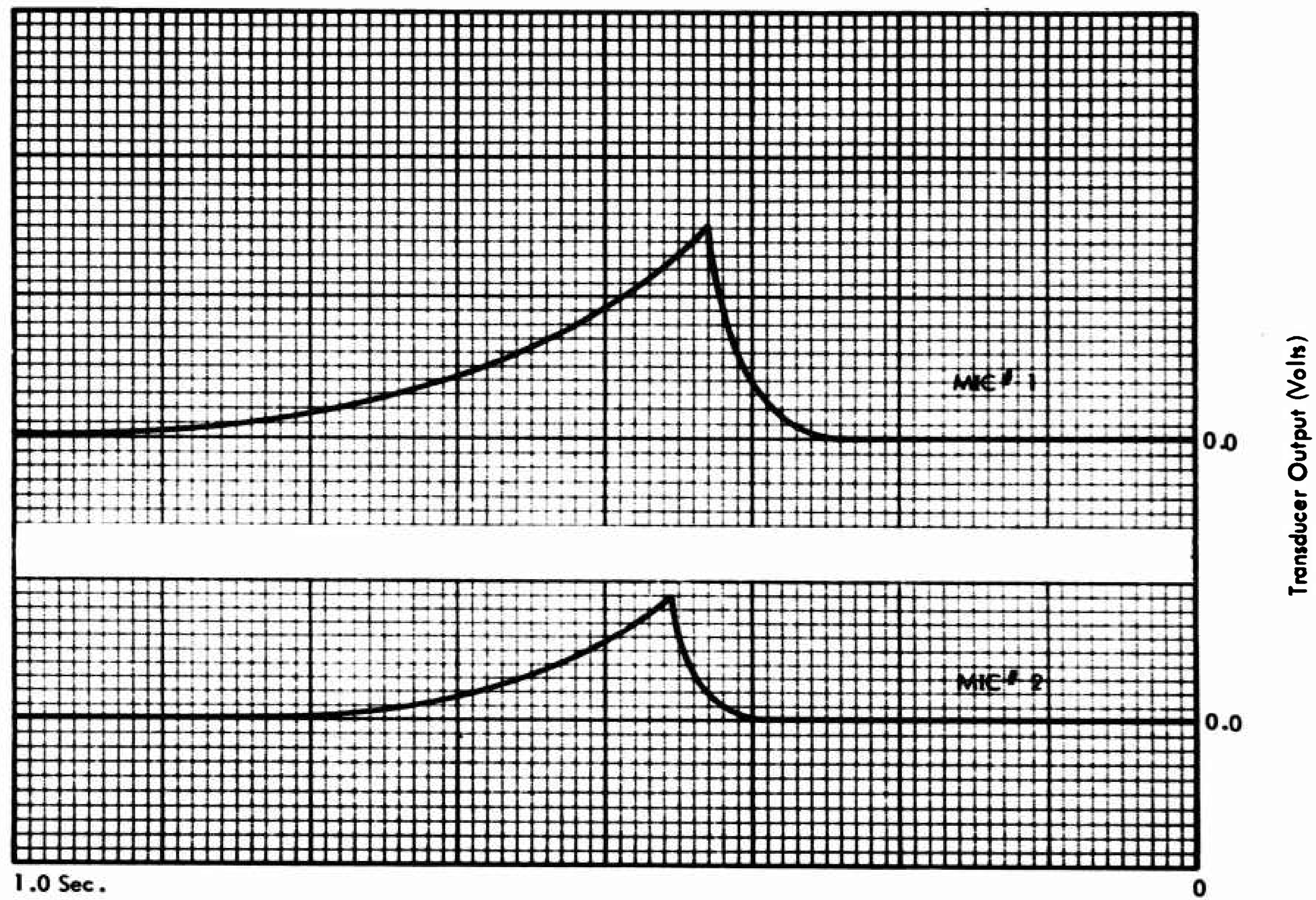
Analysis Number 29. 116 cc; 120°F; 30 Ft^3; 4 Doors



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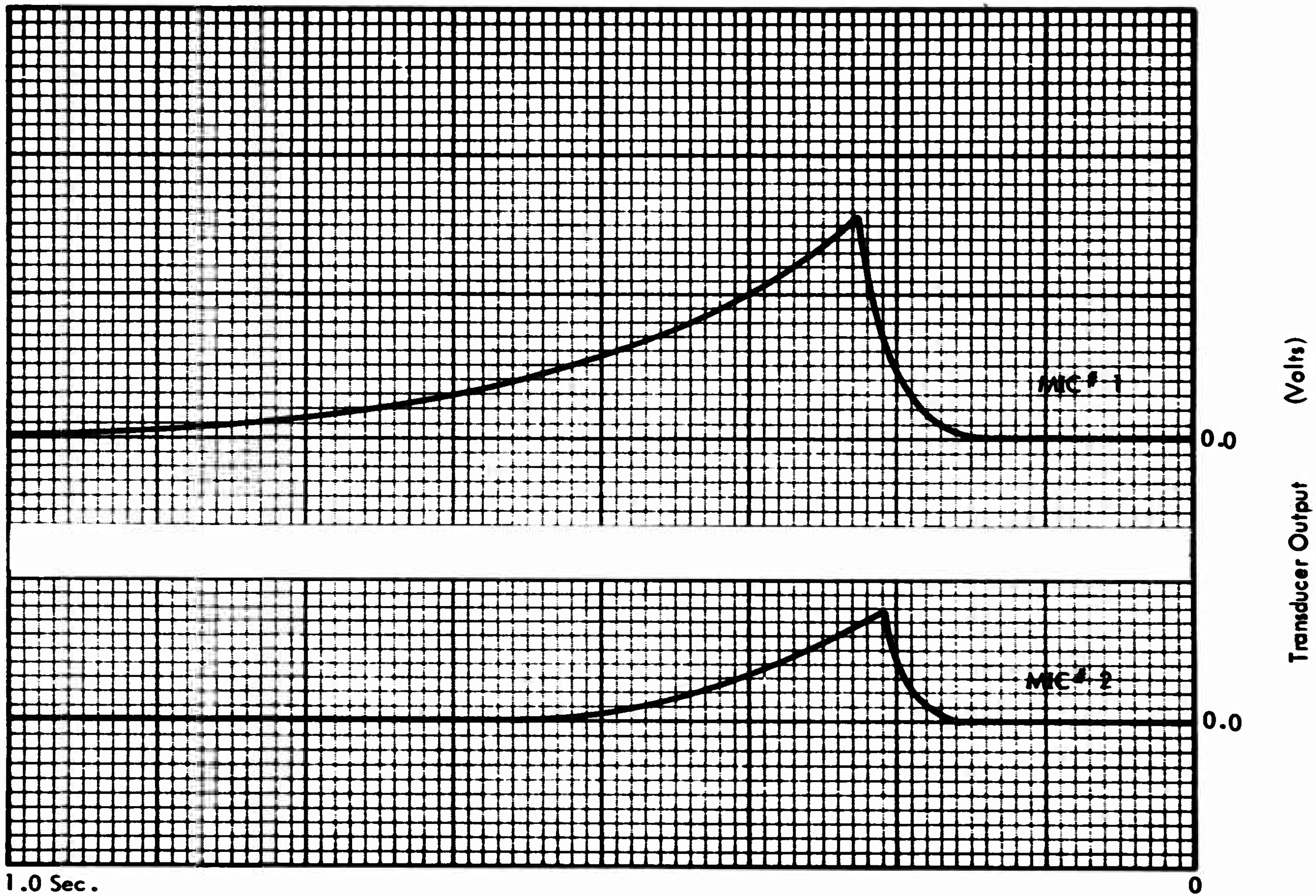

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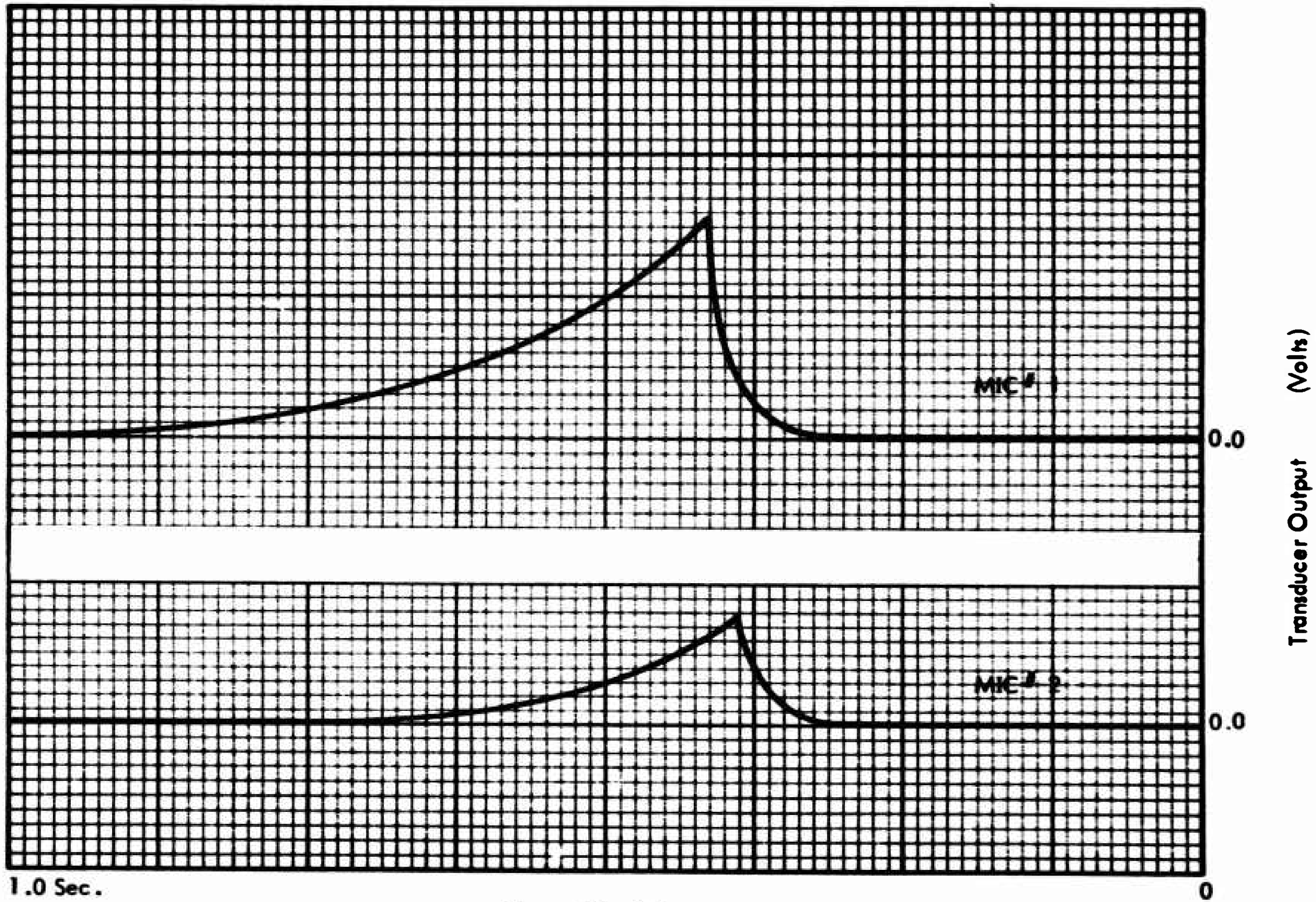

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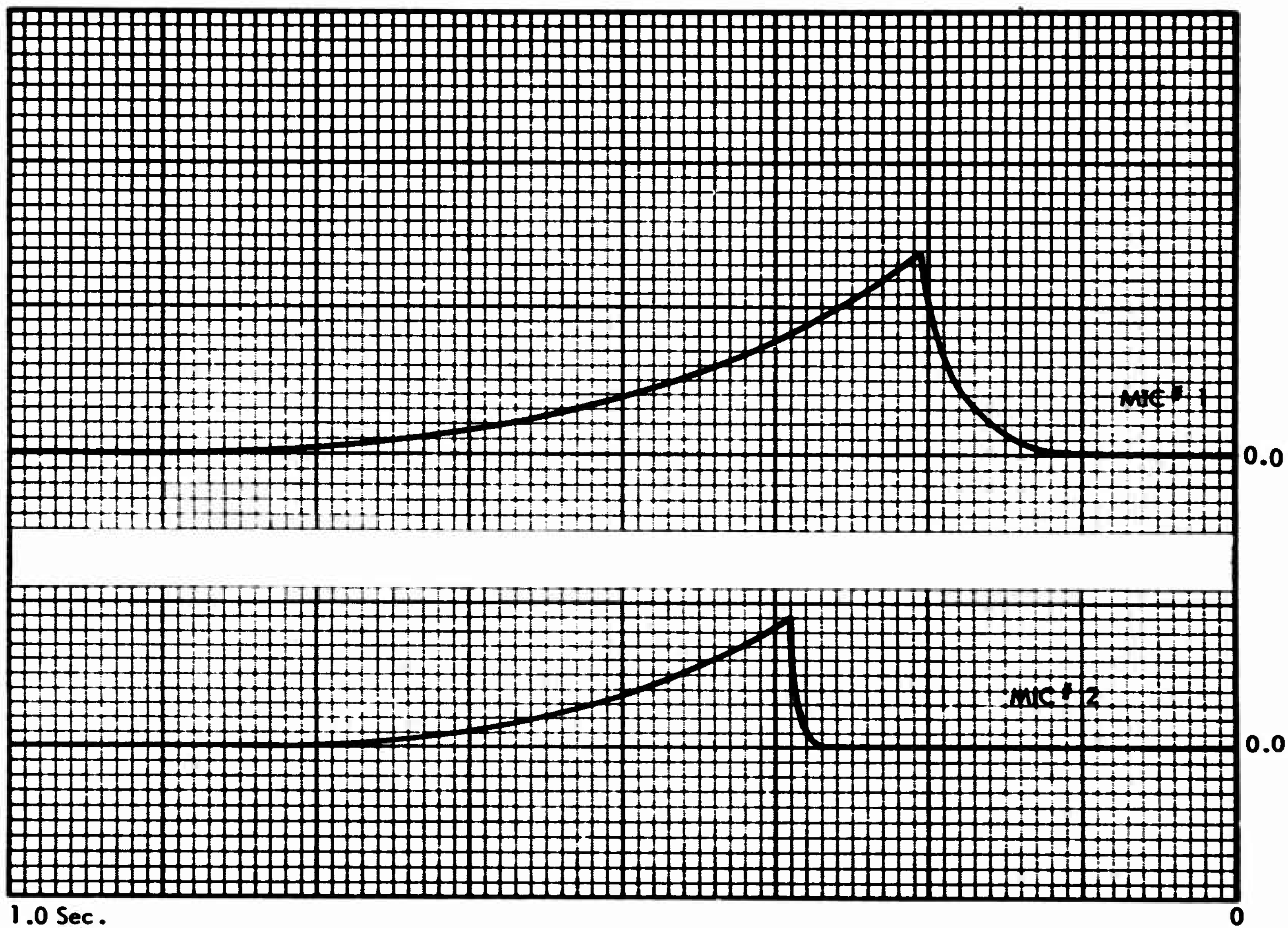
Analysis Number 32. 132 cc; 120°F; 30 Ft^3; 4 Doors



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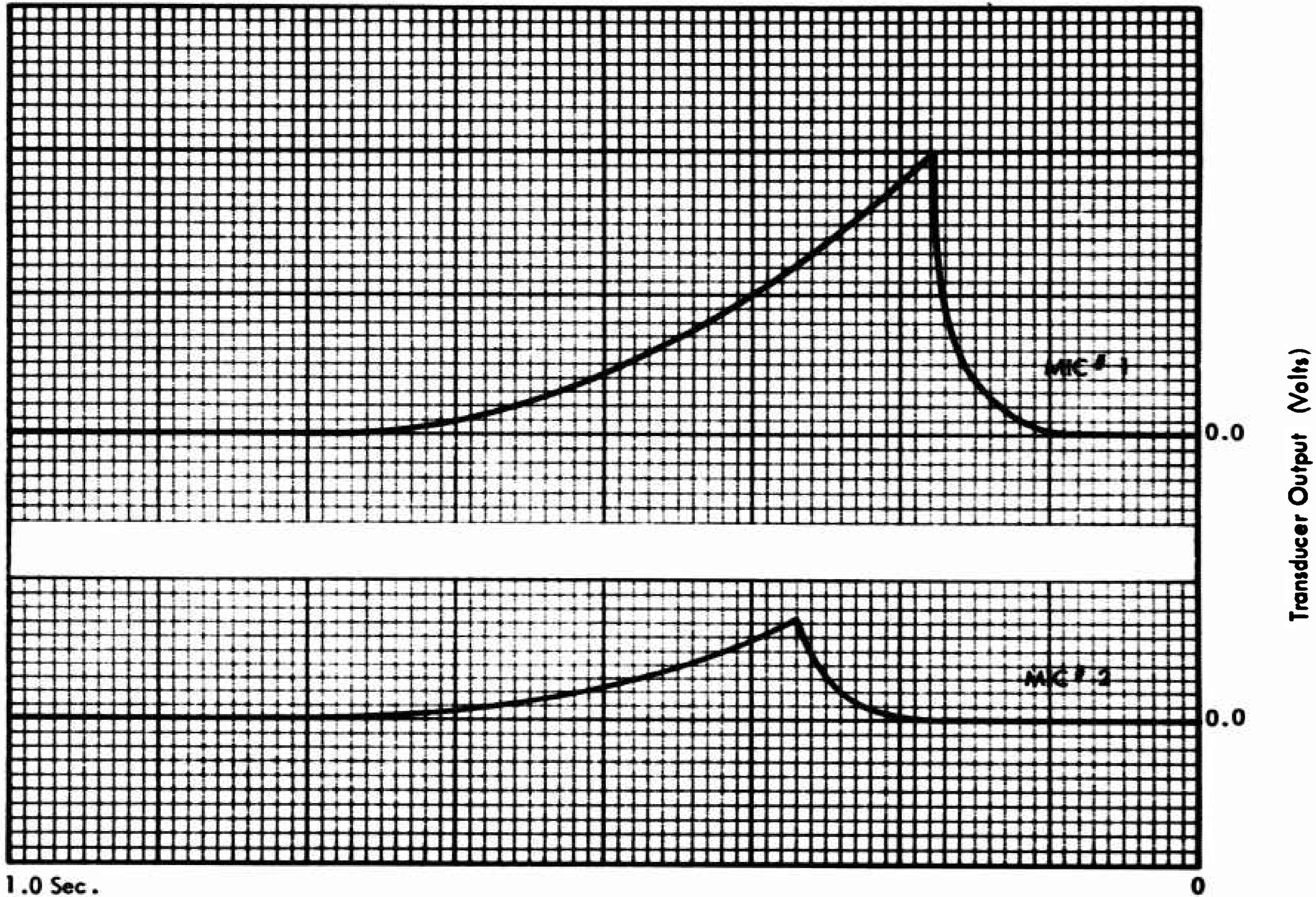

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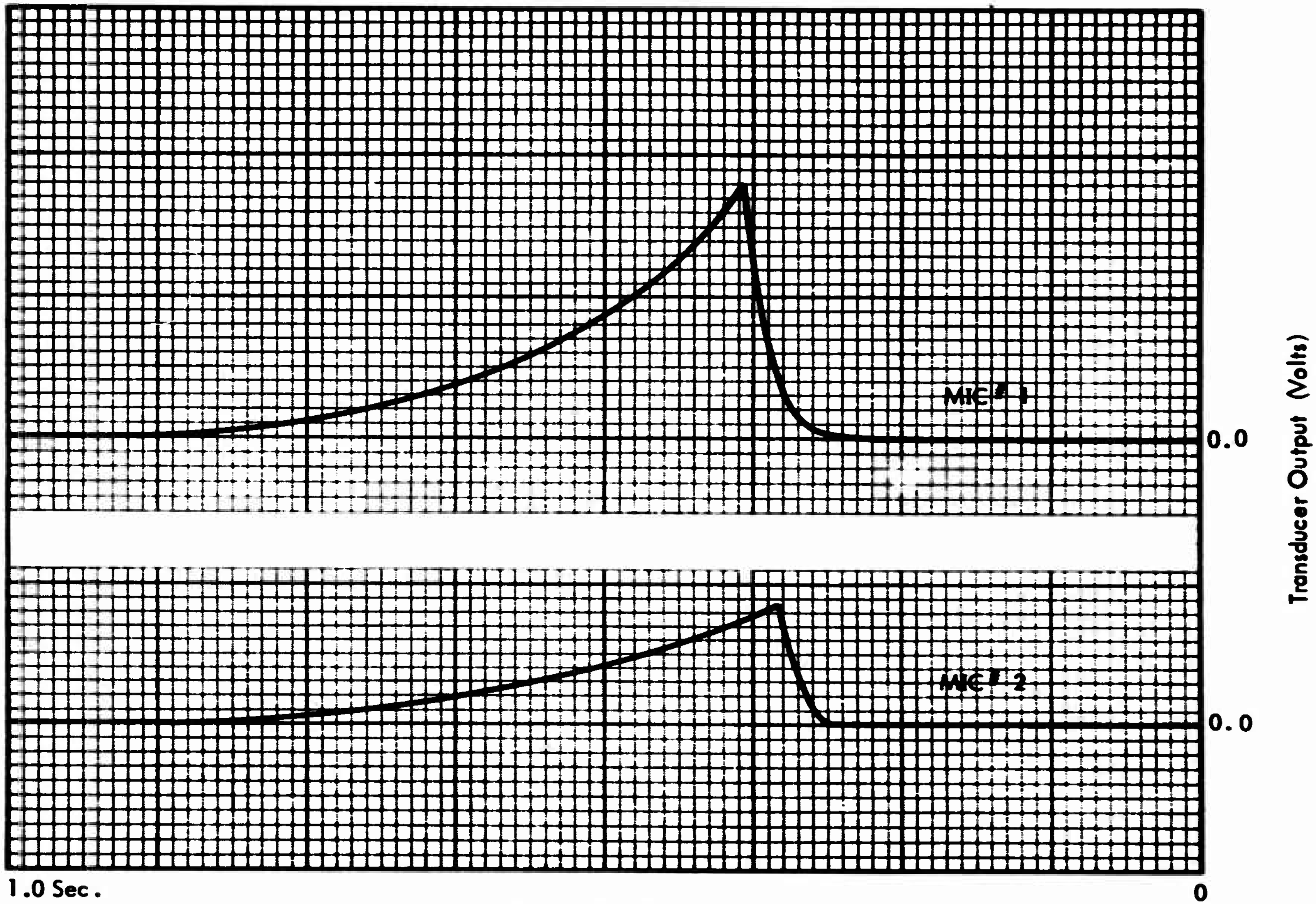

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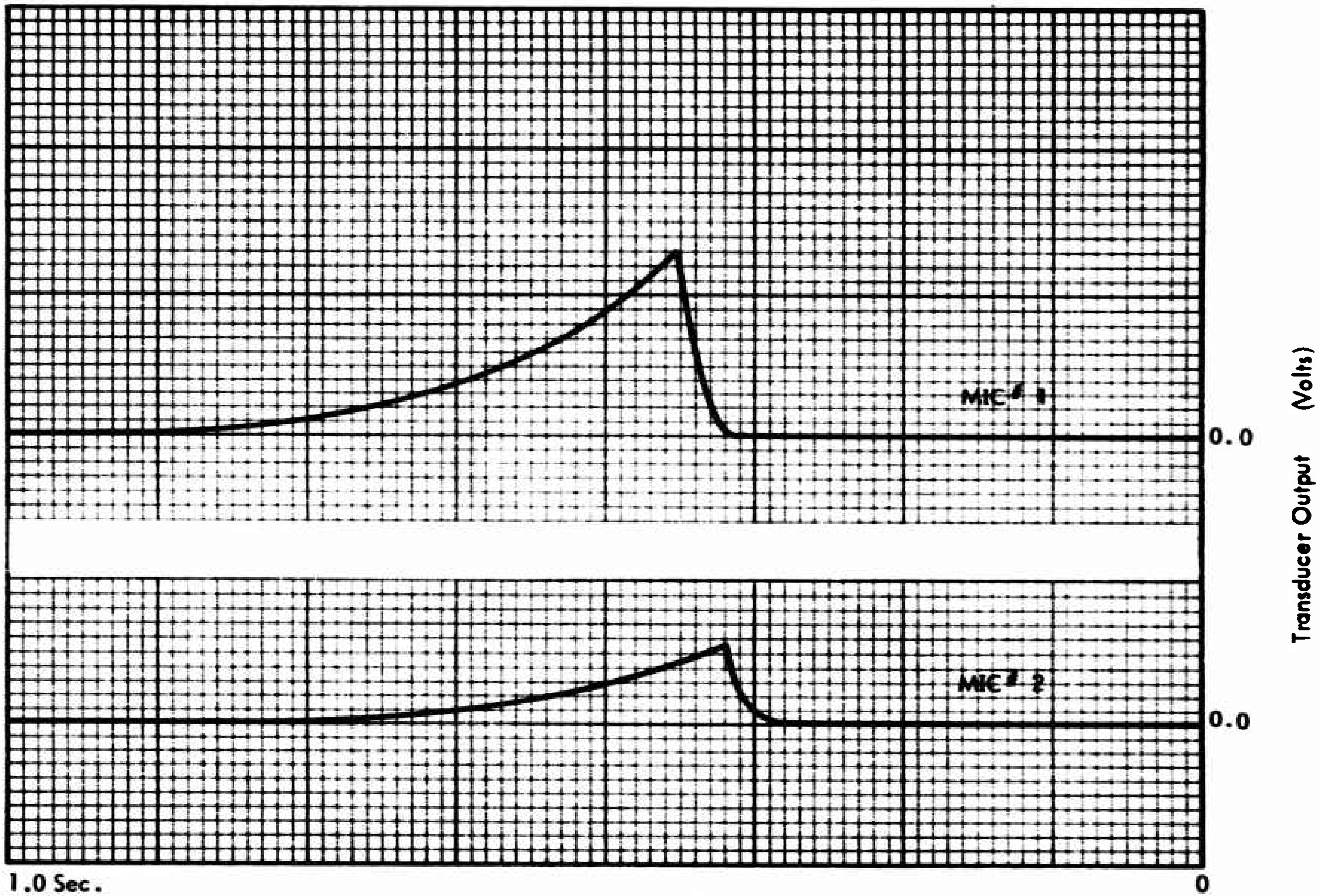
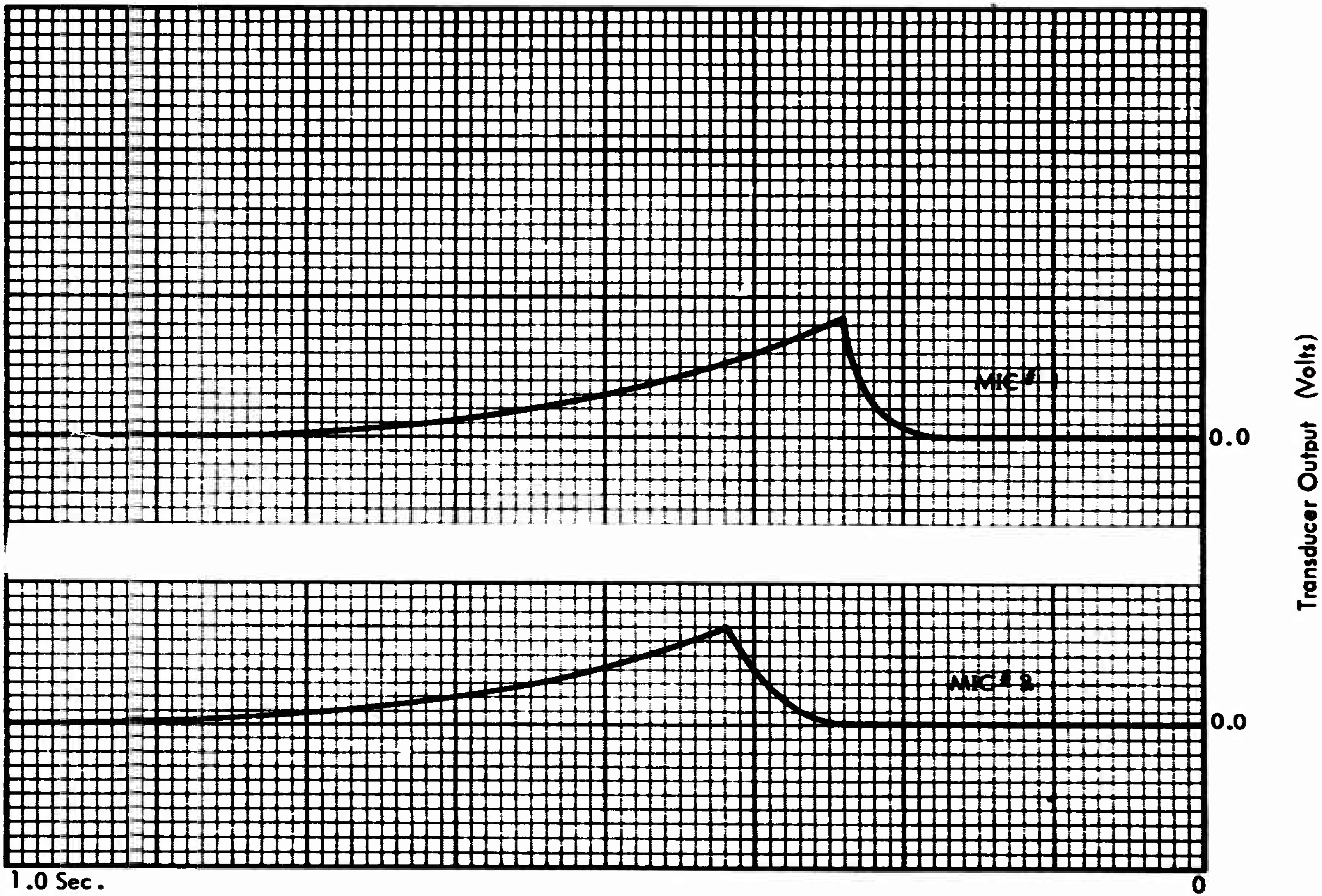
Analysis Number 35. 177 cc; 120°F; 30 Ft^3; 4 Doors



Analysis Number 36. 200 cc; 125°F; 30 Ft^3; 4 Doors



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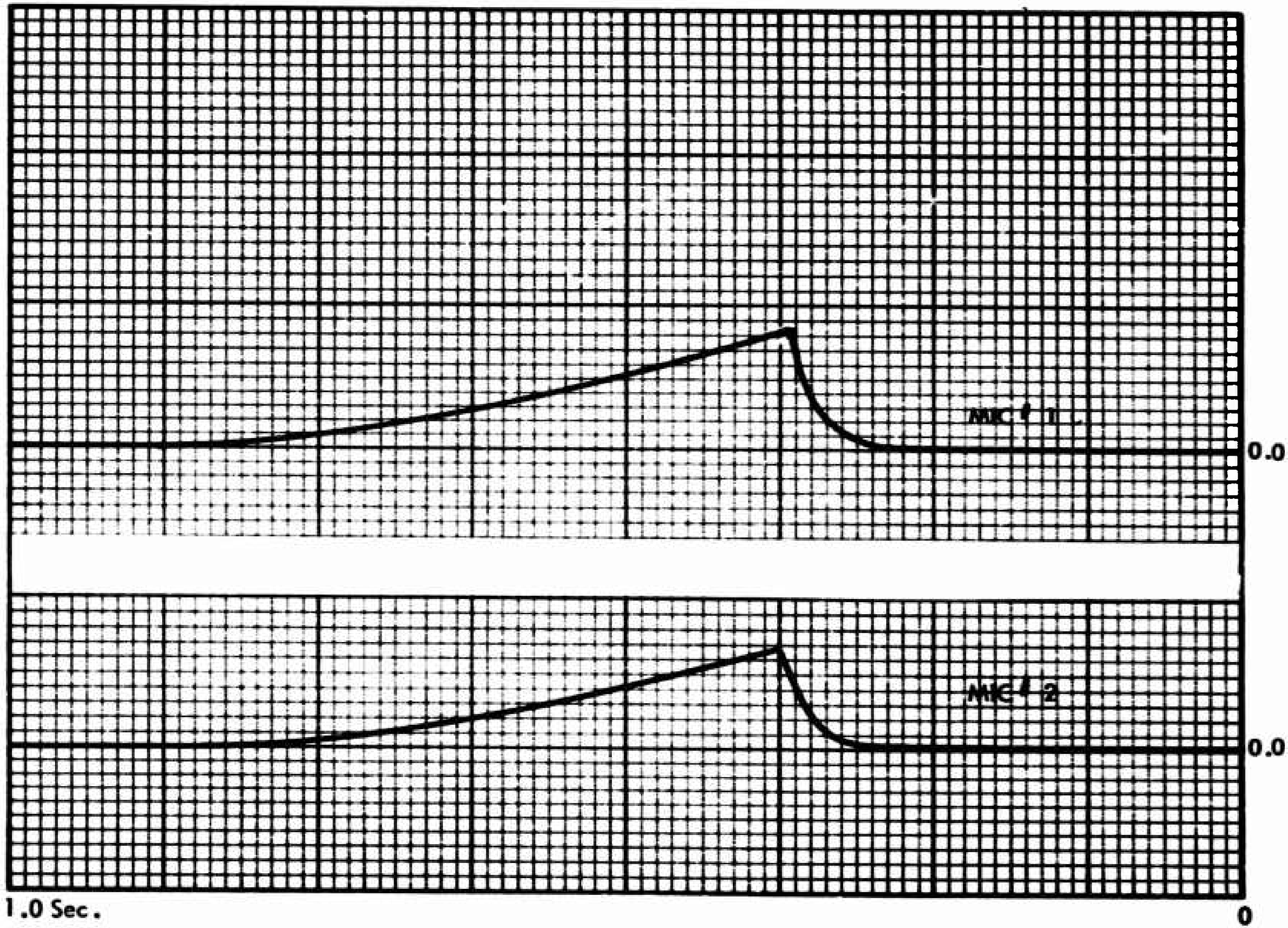
Analysis Number 37. 100 cc; 120°F; 30 Ft^3; Long Lid



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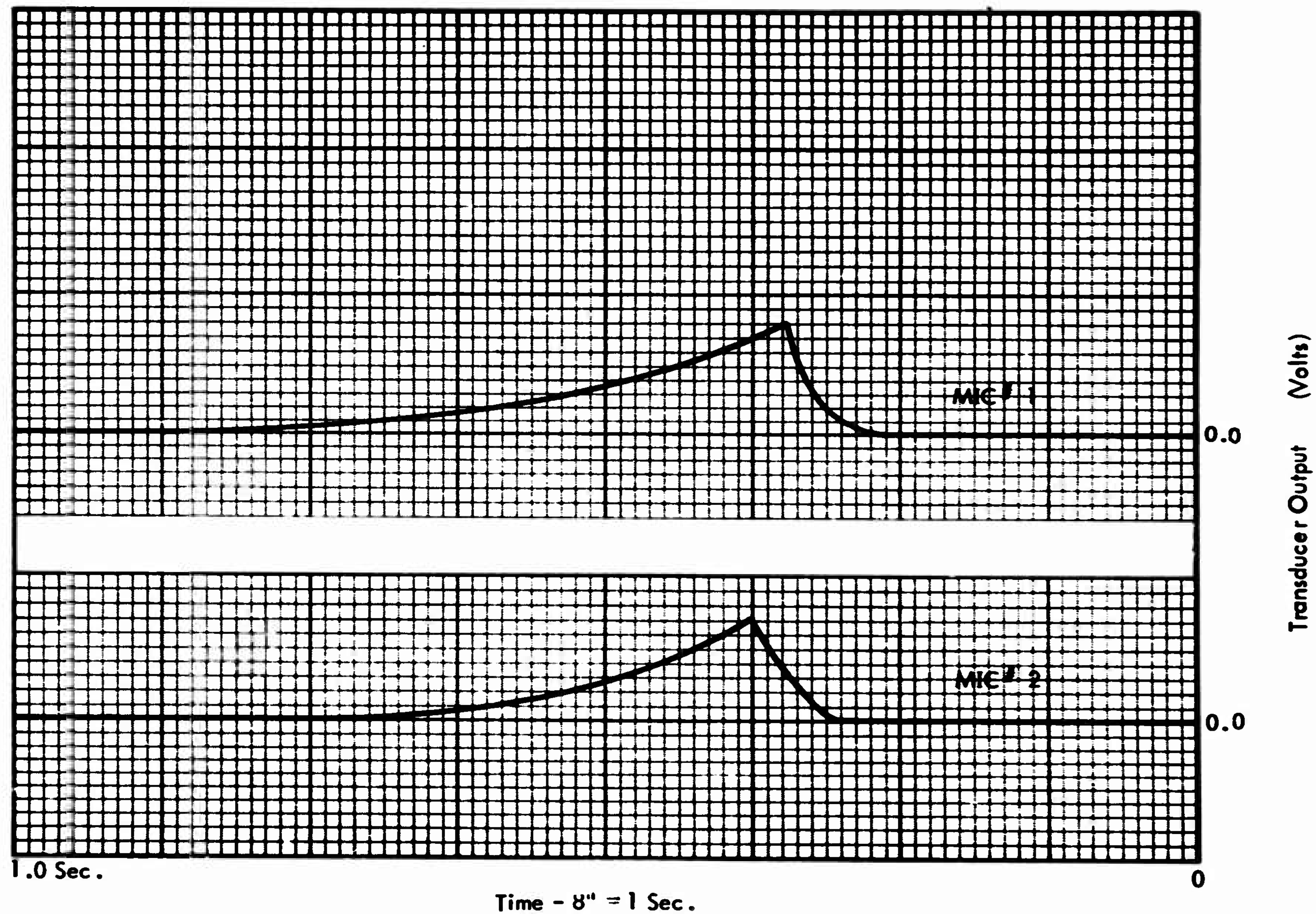
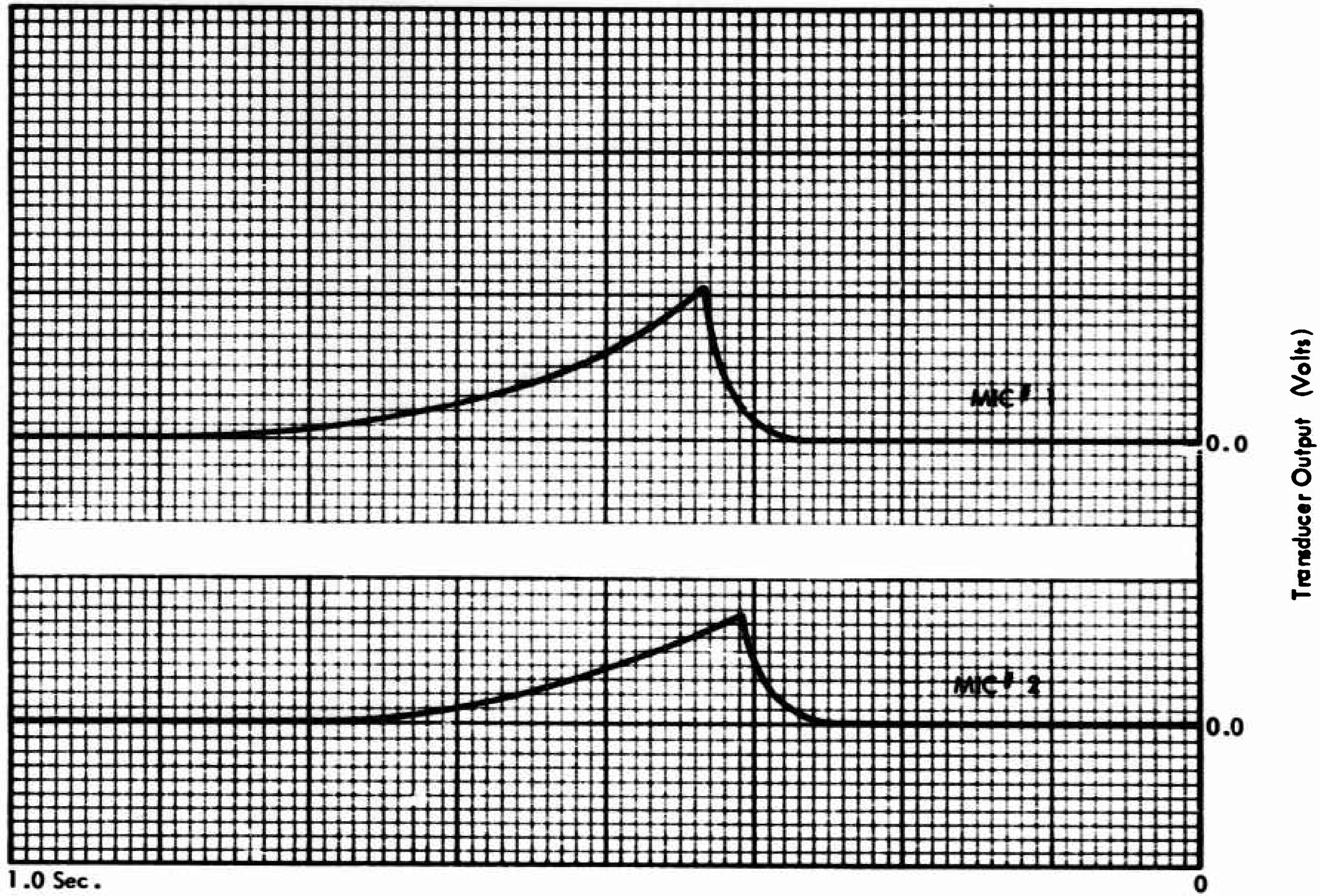
Analysis Number 36. 132 cc; 130°F; 30 Ft^3; Long Door



Analysis Number 39. 200 cc; 130°F; 30 Ft^3; Long Door



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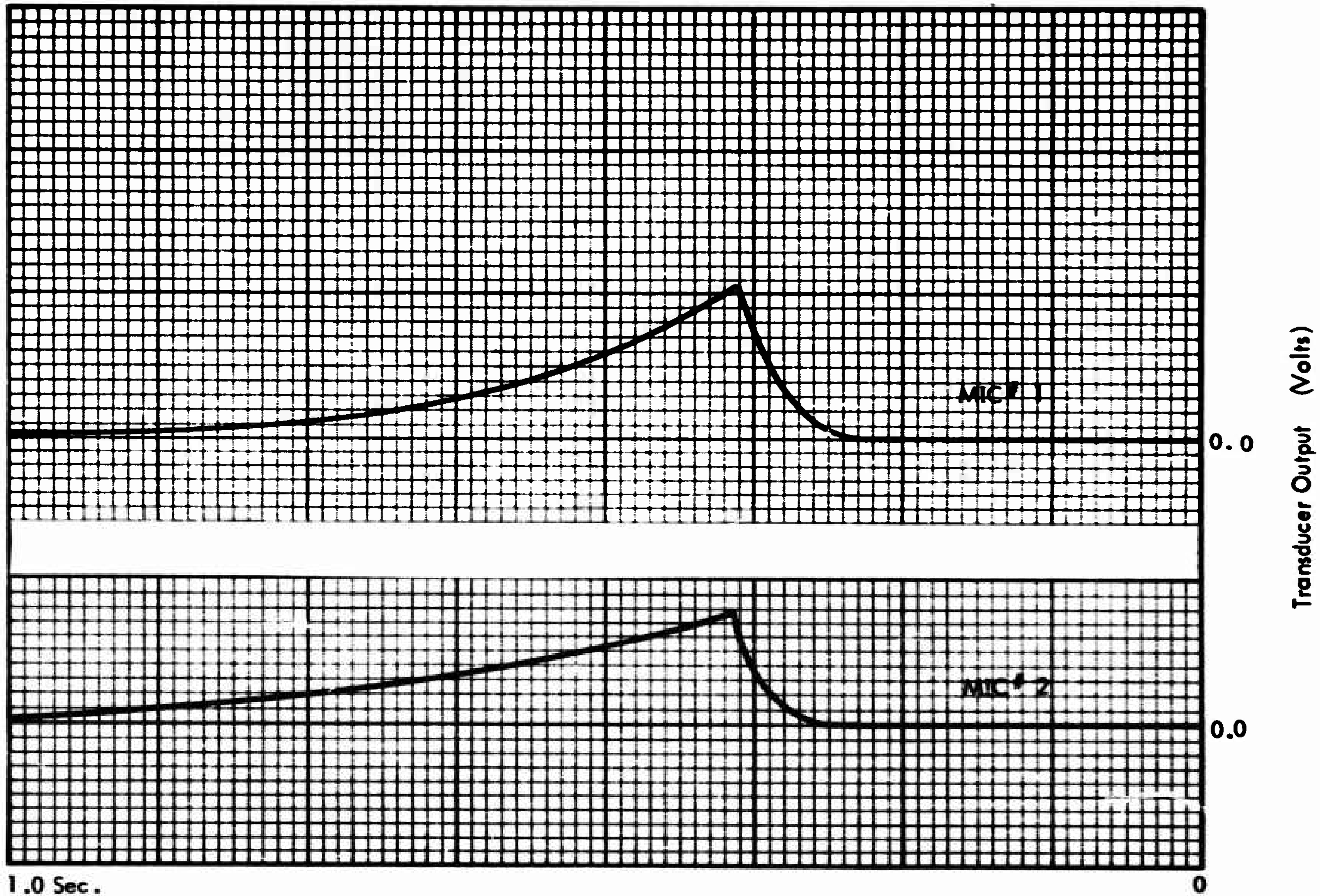
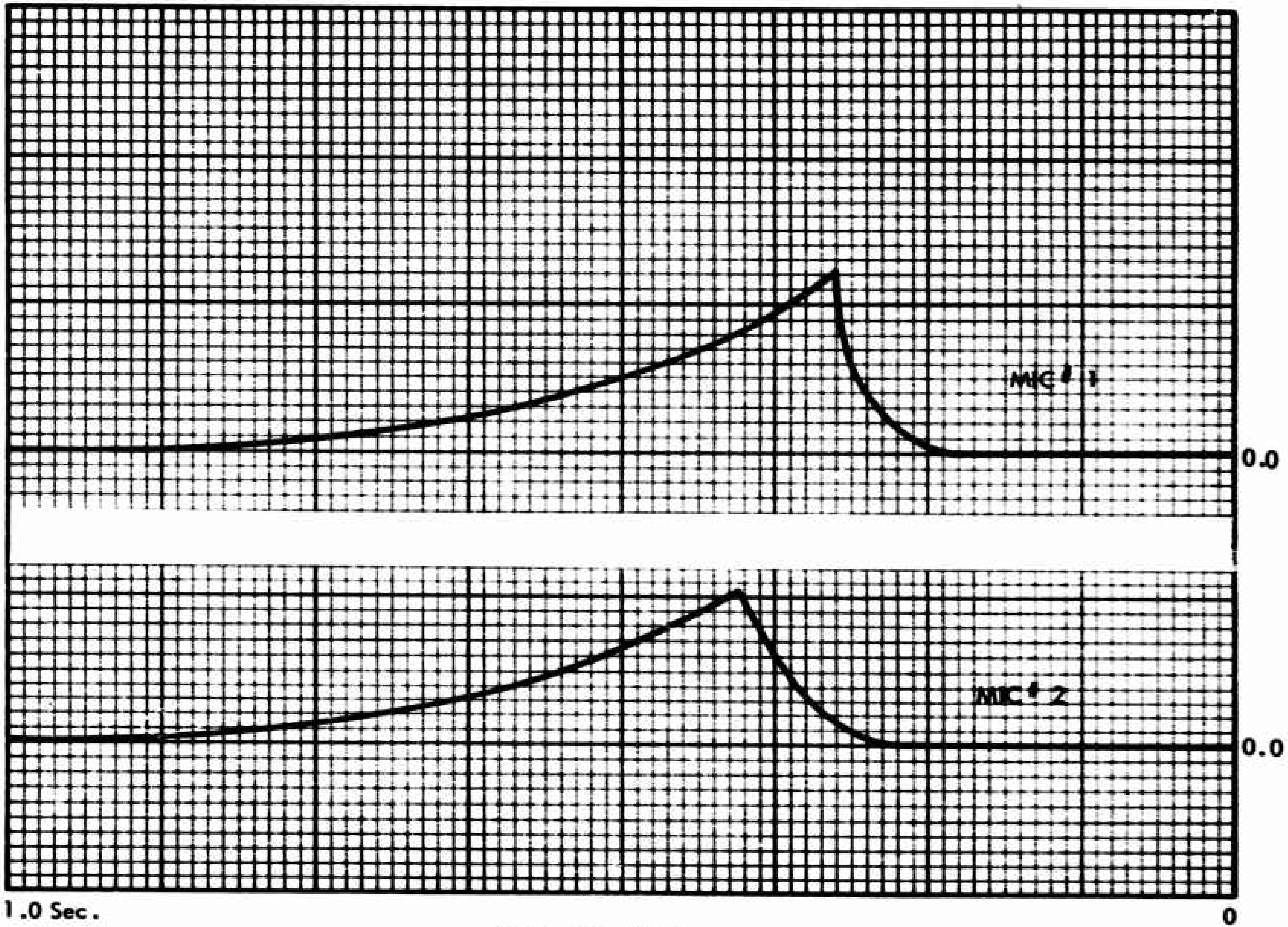
Analysis Number 40. 132 cc; 130°F; 30 Ft^3; Long Door



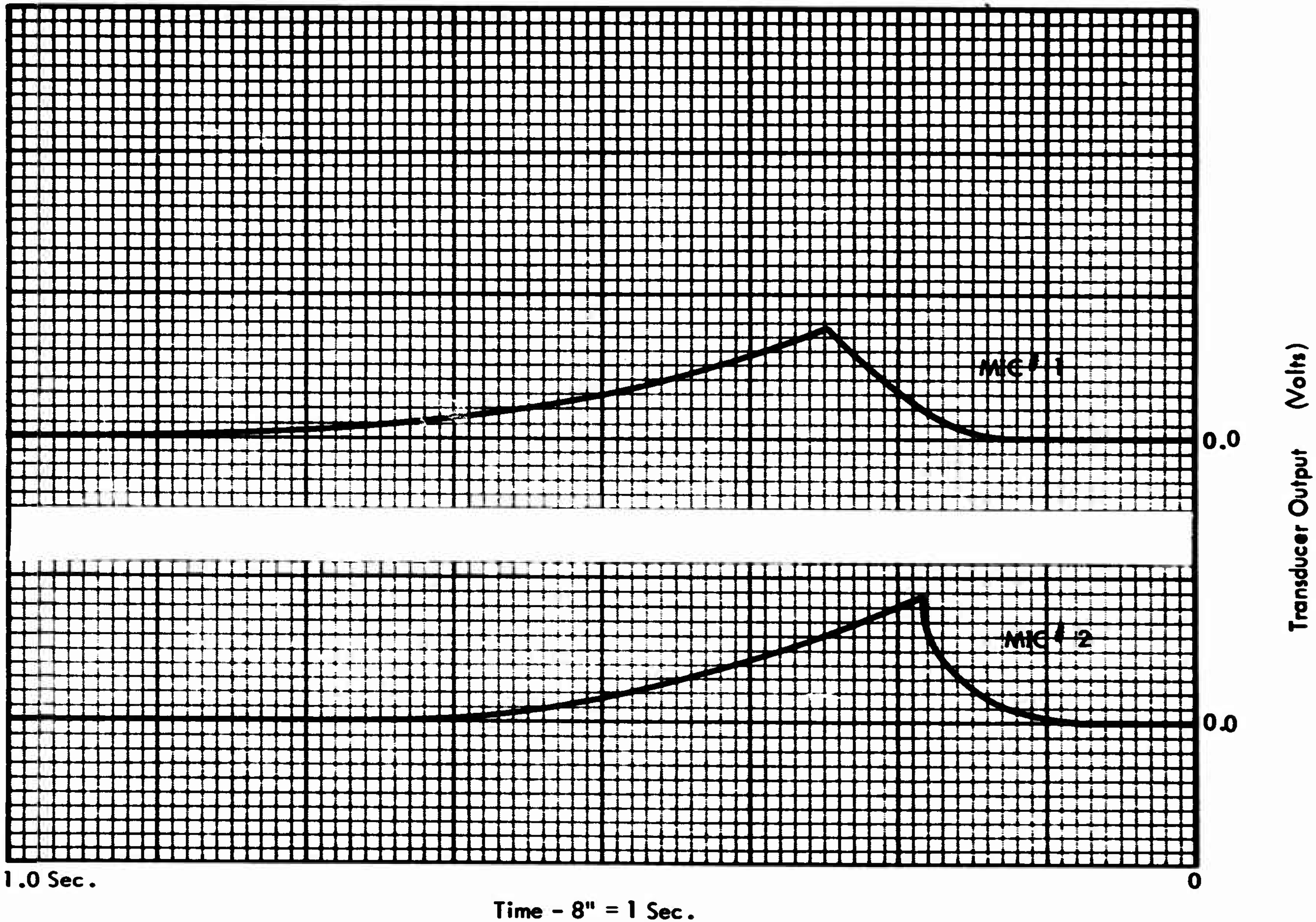
Time - 8" = 1 Sec.

Analysis Number 41. 132 cc; 130°F; 30 Ft^3; Long Door



Time - 8" = 1 Sec.

Number 42. 195 cc; 130°F; 30 Ft^3; Long Door



Analysis Number 43. 243 cc; 130°F; 30 Ft^3; Long Door

DESIGN GUIDELINES FOR
PRESSURE RELIEF-FLAME DEFLECTORS FOR INBOARD/OUTDRIVE RECREATIONAL BOATS

1.0 INTRODUCTION/SUMMARY

The number of reported fires and explosions of fuel on board recreational boats for the past several years is eight percent of the total number of accidents reported according to Coast Guard statistics as published in CG-357.

While this appears to be a relatively small percentage, the actual number of reported fires and explosions is still substantial averaging well over 300 per year, and even more important is the fact that greater than one out of every four reported fires and explosions results in a personal injury (usually severe burns) and one out of every 22 such accidents results in a fatality. The lion's share of these accidents occur on boats powered by inboard gasoline engines. The number of inboard/outdrive boats sold annually has increased four fold over the last 10 years to an average of greater than 70,000 per year for the past three years. This represents a majority of the inboard boats being built today.

This report has been prepared in order to offer the boat manufacturer a method of lessening the hazardous effects of accidental explosions of gasoline vapors onboard small and medium size boats powered by inboard engines which use outdrives or water jet pumps for propulsion.

The methods and recommendations described herein do not directly apply to boats with inboard engines installed in engine compartments which are located other than directly at the boat's stern, nor do they directly apply to boats with engines installed below flush decks with hatches in them.

Special considerations not discussed in this report must be taken if pressure relief-flame deflector doors are to be successfully installed in inboard boats other than those described herein.

The recommendations offered in this report are not meant to be a substitute for properly designed, constructed, or installed fuel or electrical systems which together can prevent most fires and explosions, but are intended as a method of building an additional safety feature into certain recreational boats.

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2.0 BACKGROUND-CONCEPT

Despite the use of good practices in designing, constructing, and installing fuel systems and electrical systems on inboard/outdrive boats, and despite the presence of properly installed natural and powered ventilation systems, unexpected explosions do occur, usually because of combinations of some of the following:

- Fuel accumulations due to
  - Carburetor overflow
  - Fuel line and hose failures
  - Loose fittings and clamps
  - Fuel tank leaks
  - Improper filling practices
  - Failure to ventilate properly
- Ignition sources from
  - Loose connections and wires
  - Open motors, generators, etc.
  - Improper repair or maintenance
  - Overheated wiring
  - Static electricity
  - Conductor insulation failures
  - Use of improper replacement parts.

When gasoline vapors and air are mixed in the proper proporations, ignition of that mixture is possible. The lower explosive limit (LEL) is approximately 1.4 percent gasoline vapor to air by volume. The upper explosive limit (UEL) is approximately 7.6 percent gasoline vapor to air by volume. The exact explosive limits vary with gasoline grade and brand mixture.

When less than 1.4 percent gasoline vapor is present, the mixture is too lean to ignite and when more than 7.6 percent gasoline vapor is present, the mixture is too rich to ignite. Any gasoline vapor to air mixture between the LEL and the UEL will ignite. The most violent explosions occur when the gasoline vapor concentrations are in the mid-ranges of the explosive limits (3 to 5 percent). The violence is measured by the pressures developed during the explosion.

As expected, gasoline vapor to air mixtures in the mid to upper ranges of the explosive limits produce more flames and heat than those in the lower ranges of the explosive limits since more fuel is present. The heat and flames which accompany the pressures developed in an explosion can be as hazardous to passengers as the pressures and resultant flying debris.

The safety concept of utilizing pressure relief vents is not new. For many years the NFPA (National Fire Protection Association) has recognized the value of pressure relief vents in buildings and has recommended their use where the possibility of an accidental explosion exists.[1]

Carefully controlled and monitored experiments in simulated engine compartments and on actual boats[2] have demonstrated that properly designed, constructed, and installed pressure relief vents can likewise safely release the pressures of gasoline vapor/air mixtures explosions. In addition, the use of proper flame deflectors can direct the flames away from passenger seating areas in the boat. The design guidelines in this report are based upon carefully controlled model test, using gasoline, as well as tests mentioned above.[3] Data from over 100 explosions has been analyzed in the development of these pressure/relief value design considerations.

Also included in this report as Appendix A are recommendations for the location of an extinguishing port for fire fighting without opening the engine cover, based upon work performed at the Coast Guard R and D Center, Groton, Conneticut.

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1 Fire Protection Handbook - NFPA Thirteenth Edition, Section 17, Chapter V.

2 Wyle Technical Brief 74-9, "An Investigation of the Value and Feasibility of Pressure Relief - Flame Deflectors in Medium Explosions in Small Craft."

3 Wyle Marine Safety Report 75-26, "Determination of Relief Vent Areas Required to Control Gasoline Explosions in Certain Boat Engine Compartments" - May, 1975.

3.0 DESIGN AND CONSTRUCTION REQUIREMENTS

The prime design and construction considerations for the proper installation of effective pressure relief-flame deflector vents are:

- Vent location and vent door arrangements
- Vent area requirements
- Vent door construction and hinging
- Compartment integrity, and
- Compartment structural requirements.

When properly designed, the successful safe release of the pressures and flames of an explosion depend on two essential prerequisites:

(1) The vent doors must be free to open, and

(2) Everything else must be held tightly in place.

The materials required for construction of the pressure relief-flame deflectors are those normally used by recreational boat builders and no special materials are specified.

The manufacturing techniques required for construction and installation of the pressure relief-flame deflectors are within the capabilities of recreational boat builders.

A builder should carefully consider all the pecularialties of his boat before attempting to install pressure relief-flame deflectors.

Less than adequate or improperly arranged, constructed, or installed pressure relief-flame deflectors could actually increase the hazard to the boat passengers if those passengers were lulled into a false sense of security and did not take proper precautions to prevent an accidental explosion.

Also, the locations of items such as equipment, flotation material and engine servicing accesses should be fully considered prior to installation of the pressure relief-flame deflectors.

3.1 Vent Locations and Vent Door Arrangements

Vent openings should be located as remotely as practicable from passenger seating areas (usually this means as far aft as possible - See Figures 1, 2, 3, 4 and 5).

Vent openings should be located at or near the top of the compartment and facing away from passenger seating areas wherever possible. Vent doors shall be arranged to open away from all passenger seating areas.

3.2 Vent Area Requirements

Total vent areas should be provided such that no less than 20 square inches of vent area per foot of net compartment volume[4] exists. The vent area is the total unobstructed opening size, and should not be confused with the covering door sizes (see Figure 6). One large vent opening, or several smaller vent openings, may be used. Square openings or rectangular openings may be used. On boats where greater than 20 square inches of vent area is feasible, it is recommended that the greater vent area be provided since the greater vent area will reduce the internal compartment pressures resulting should an explosion occur.

3.3 Vent Door Construction and Hinging

3.3.1 Explosion Pressures Versus Resistance of Vent Doors

The rise in pressure during an explosion within an enclosure with restricted vents[5] is affected greatly by the delay in time necessary to open the vent doors. The weight of the door itself is a major restriction to its opening up freely and instantly as are the friction of the hinges or any unintended adhesion (sticking) between the door and the opening's edges.

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[4] Net compartment volume means the gross compartment volume less the volume of any permanently installed engines, batteries, fuel tanks, or other permanently installed equipment.

[5] Vents with any coverings are restricted. Unrestricted vents would be those with no coverings at all.

Failure of a vent door to open instantly could cause increased internal compartment pressures sufficient to cause failure of some other compartment structure(s). For this reason, it is extremely important that the vent doors are:

- lightweight, and
- absolutely free to open in case of an explosion.

Failure to provide these two essential ingredients will negate the intended safety feature of pressure relief vents.

3.3.2 Vent Door Materials of Construction

Vent doors should weigh no more than 1-1/2 pounds per square foot including trim edgings, paints, and coverings (see Table I).

If any door extends (overlaps) more than one inch beyond the opening in any direction, the weight of the door should be reduced accordingly.

If vent doors weigh more than 1-1/2 pounds per square foot as described above, extra special considerations must be taken for the structural integrity of the entire compartment in order that the compartment can safely withstand the increased pressures to which it could be subjected because of the added inertia of the heavier vent doors.

Heavier doors will require stronger hinges to prevent them from breaking during an explosion thus allowing the vent door to become a flying missile.

Heavier doors will also require stronger restraints to halt the vent door in a proper open position during an explosion since the momentum of the opening door increases when the weight increases.

Vent door materials should also be strong enough to withstand normal use.

Vent doors may be made water tight where necessary by the use of foam tapes or molded shapes (See Figure 6). Care must be taken that inadvertent adhesion (sticking) does not take place which could restrict the door's opening capabilities.

TABLE I. VENT DOOR MATERIAL NOMINAL WEIGHTS

Material	Thickness	Approximate Weight Per Square Foot
Fiberglass Reinforced Plastics	0.125 inch	1.0 pounds
Fir Plywood	0.375 inch	1.1 pounds
Aluminum	0.090 inch	1.3 pounds

3.3.3 Vent Door Hinging

Full length metallic piano type hinges with stainless steel pins (to prevent corrosion binding) are recommended. Piano type hinges will prevent the passage of flames between the opened vent door and the structure to which the hinge is fastened.

If piano type hinges are not used, care must be taken to minimize the gap between the opened door and the structure and if that gap will allow the passage of flame, then a flame deflector must be installed (see Figure 7).

Loose pin, pull-apart type, light duty hinges are not acceptable.

Hinges must be aligned when installed to prevent binding.

Hinges must be securely fastened to the vent door and the boat. If rivets are used to fasten hinges to fiberglass or plywood, they must penetrate through the material and back-up washers must be used.

3.3.4 Vent Door Side Flame-Deflector/Restraints

The vent door itself acts as a flame deflector. However, flames will escape from the openings at the sides of the vent doors (see Figure 8) unless side flame deflectors are installed.

The flame deflectors can also become the restraints which limit the degree to which the vent doors open. With the flame-deflector/restraints installed, the flame of an explosion can be directed away from the passenger seating areas (see Figure 9). Where space below the vent openings allow, rigid flame-deflector/restraints may be installed. Where the space below the vent openings is limited, flexible materials may be used.

The flexible materials recommended for flexible flame-deflector restraints are either knit back vinyl upholstery material (marine grade and preferably with synthetic backing rather than cotton) or bonded vinyl convertible topping material, since these materials resist the effects of a marine atmosphere.

These materials will stretch slightly and this "shock cord" like feature will help prevent them from ripping when the vent door opens should an explosion occur.

Two pie-shaped pieces cut from the vinyl material are required for each vent door (see Figure 10). The exact sizes of the pieces will be determined by the vent door size and the degree of angle desired for the vent door in its fully open position.

If the closed vent doors are horizontal, the side flame-deflector/restraints should be installed such that the vent door will open no less than 75° and no more than 85° in order to effectively direct the flame and return the vent door to the closed position after an explosion.

Vent doors which, when closed, are other than horizontal should be restrained such that they will open no less than 75° from the closed position to effectively release the pressures of an explosion and no more than 85° <u>from horizontal</u> to effectively direct the flame away from the passenger seating areas (see Figure 11) and return the vent door to the closed position after an explosion.

The vinyl deflector/restraints must be securely fastened to both the vent door and the vent opening structure. Staples are <u>not</u> recommended for this purpose.

Cleats or pieces of trim moldings are recommended to be screwed or bolted in place to secure the vinyl deflector/restraints (see Figure 12).

3.3.5 Vent Door Latches

It is recommended that no latches be provided to fasten the vent doors in the closed position. If latches are considered absolutely necessary, then special considerations must be taken as follows:

- The latches must be capable of being placed in an unlatched position such that they cannot be inadvertently latched by vibrations, shocks, or other movements to which the boat might be expected to encounter in service.
- A warning label must be permanently displayed on the exposed surface of each vent door instructing the operator to disengage the latches immediately upon boarding the boat and prior to starting the engine and to maintain the unlatched position continuously until all persons have deboarded the boat. The same warning should be prominently displayed at the helm station.
- Provisions shall not be made for locking the latches.
- Latches which require tools to open are not acceptable.

3.4 Compartment Integrity

The compartment integrity which is required to effectively and safely release the pressures and direct the flames of a gasoline vapor/air mixture explosion does not demand that the compartment be vapor tight. An engine compartment is required to have a ventilation system anyway.

However, if, for example, effective pressure relief-flame deflectors are to be installed in an engine compartment, then there shall be no direct free communication between that engine compartment and any adjacent compartments[6] unless those compartments are also provided with pressure relief-flame deflectors because:

- gasoline vapors diffuse, and
- the flame fronts travel during explosions.

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[6] Adjacent compartments include such as double bottom spaces, spaces behind trim panels, spaces under seats, spaces under decking, cabins, and entire cockpits.

Again, the builder should be wary of lulling the boat user into a false sense of security.

All bulkheads and other separations between engine compartments and adjacent compartments (without pressure relief-flame deflectors) must be permanently installed.

There must be no openings through which flames can travel in bulkheads or other separations which face any passenger seating areas.

Small cracks and other small openings may be protected by covering with such as secured upholstery vinyls, caulking, trim moldings, or cleats.

Engine covers, hatches, doors, and seating which are separators between engine compartments and adjacent compartments must be secured by permanent fastenings or adequate positive type mechanisms such as hasps, catches, latches, locks, clamps, or hooks which are installed in such a way that when closed, they will not open due to the vibrations, shocks, or other movements to which the boat is expected to be subjected in service.

Securing methods such as friction catches, magnetic catches, shock cords, spring clips, or snaps are not considered adequate for this purpose.

Curtains, regardless of the fastening methods, are not considered permanent bulkheads. Sliding doors without positive catches are not considered permanent bulkheads.

Remember —
Compartment integrity must be maintained in order to prevent flames from reaching the boat's passengers, and to prevent the hazards of flying boat parts and debris.

3.5 Compartment Structural Requirements

The compartment structure including all perimeter separators such as bulkheads, floors, doors, hatches, engine covers, overheads, hull shells, and seating must be capable of withstanding pressures of at least 150 psf without loss of the integrity of the compartment.

This means that:

- The thickness of the materials of construction shall be such that the materials themselves will not fail when 150 psf is momentarily applied uniformly over the entire interior surfaces, and
- All the material must be secured such that the compartment shall not collapse or split apart when 150 psf is momentarily applied uniformly over the entire interior surfaces, and
- Hardware items used as positive type closures to secure moveable compartment components such as engine covers, doors, hatches, and seating must be capable of withstanding the forces exerted on them when 150 psf is momentarily applied uniformly over the entire interior surfaces of the item which they are expected to secure.

Material thicknesses required to withstand 150 psf will vary greatly depending on the reinforcement methods and the distances between reinforcements. Flat panels which are unsupported for no more than twenty inches in any direction, when adequately secured, will be considered to have sufficient thicknesses according to Table II.

TABLE II. MATERIAL THICKNESSES

Material	Minimum Thickness	Maximum Unreinforced Span
Steel	0.0478 in.	20 in.
Aluminum	0.090 in.	20 in.
Fir Plywood	0.375 in.	20 in.
Fiberglass Reinforced Plastic	0.188 in.	20 in.

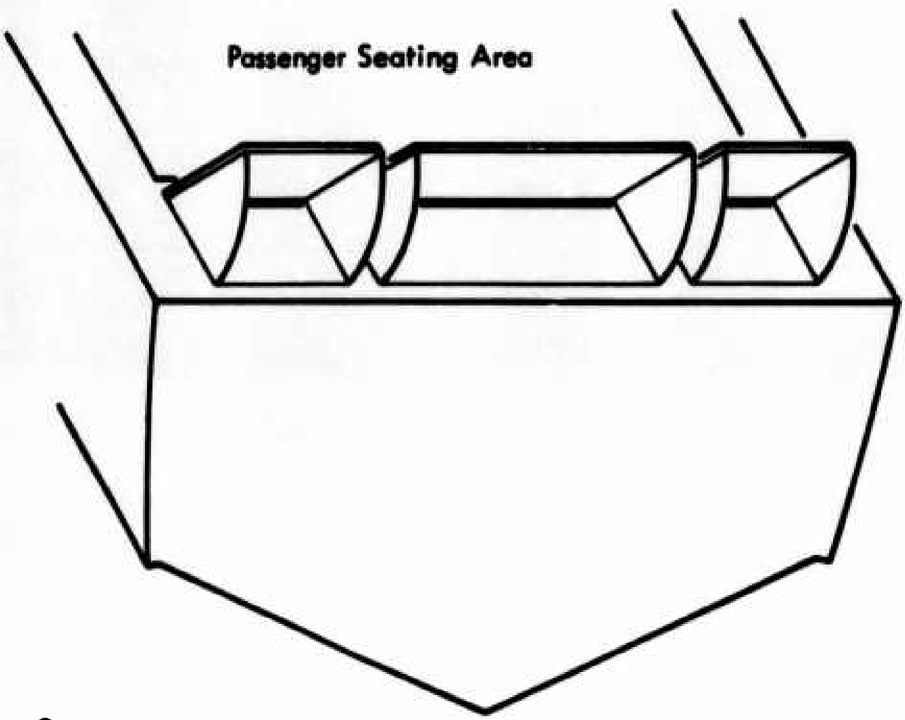
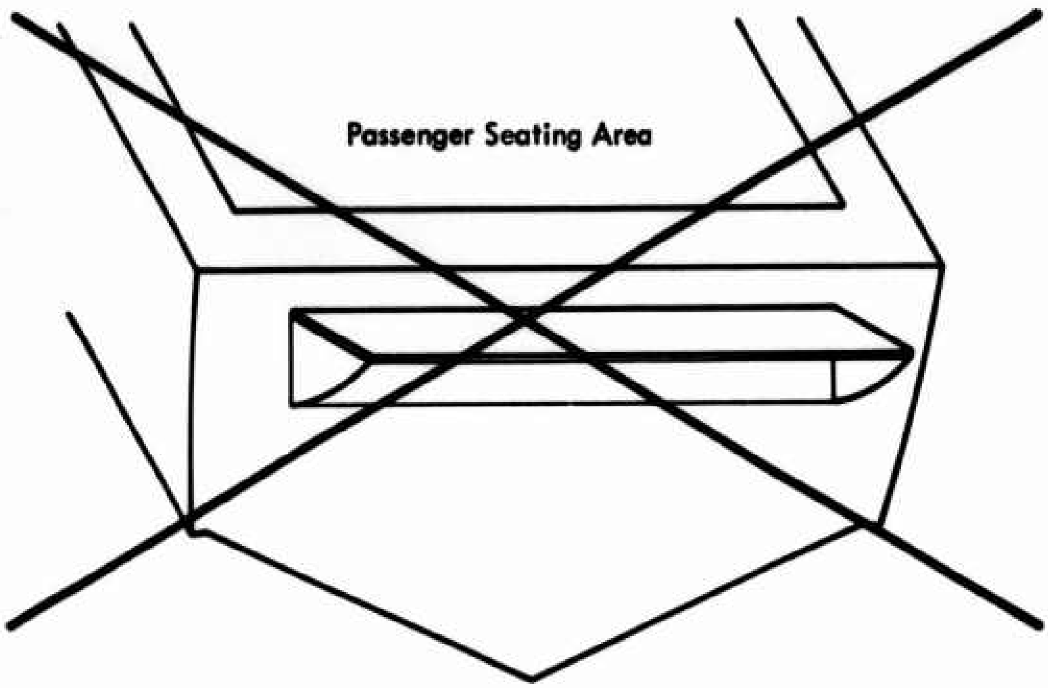


Figure 1. Multiple Vent Doors in the Aft Deck



(Not recommended because the boat would be susceptible to flooding from following seas. Could be used if sufficient freeboard exists.)

Figure 2. Single Vent Door in the Transom

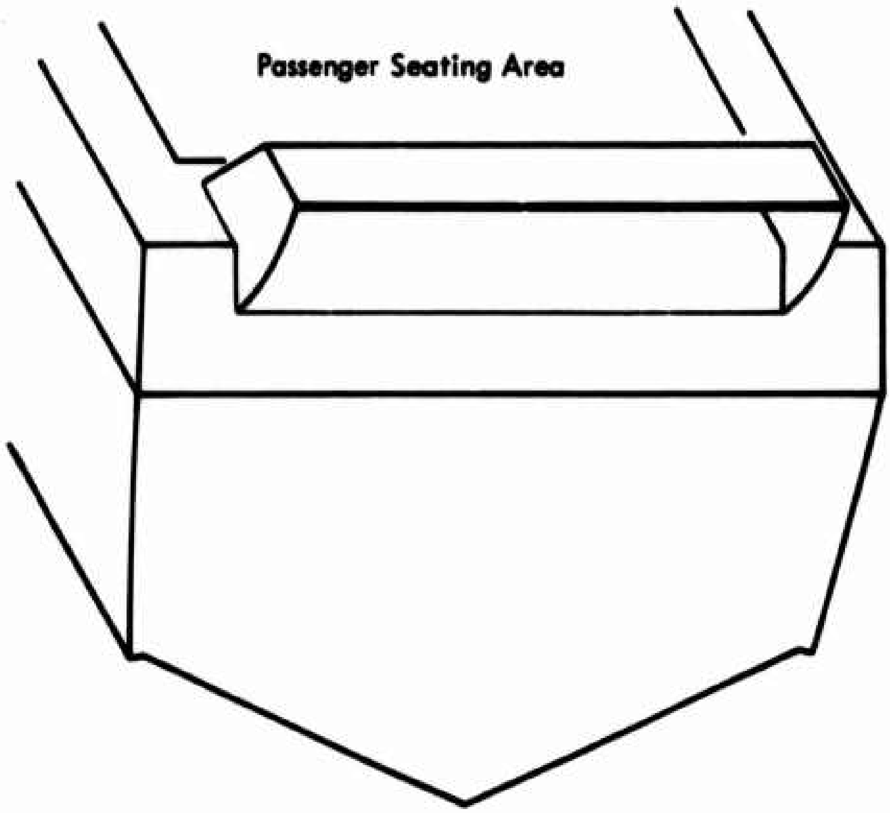


Figure 3. Single Vent Door in the Aft Deck

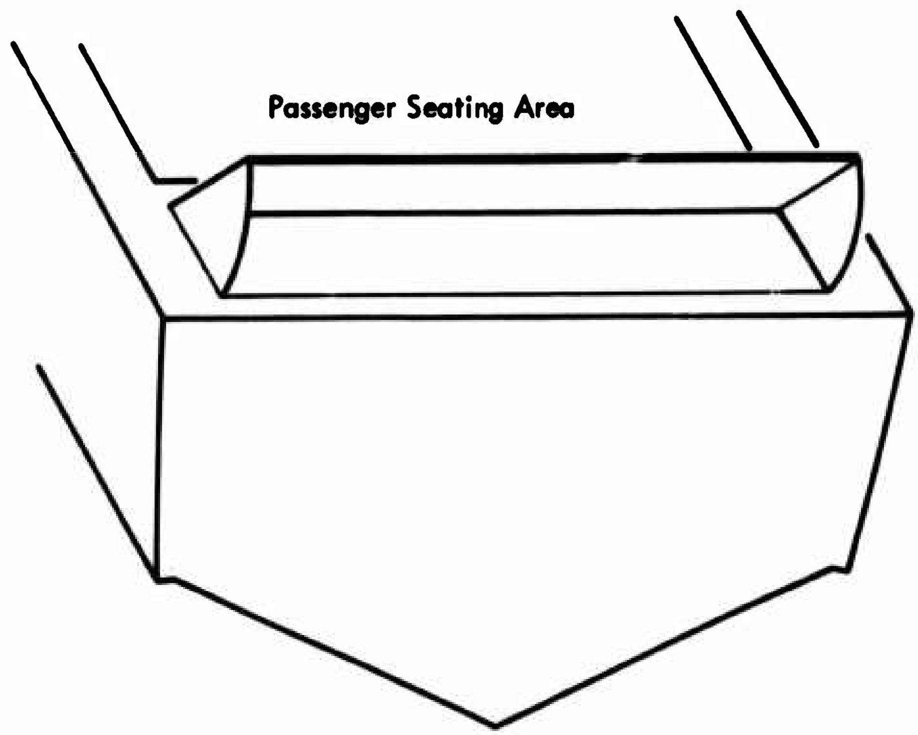


Figure 4. Single Vent Door in the Aft Deck

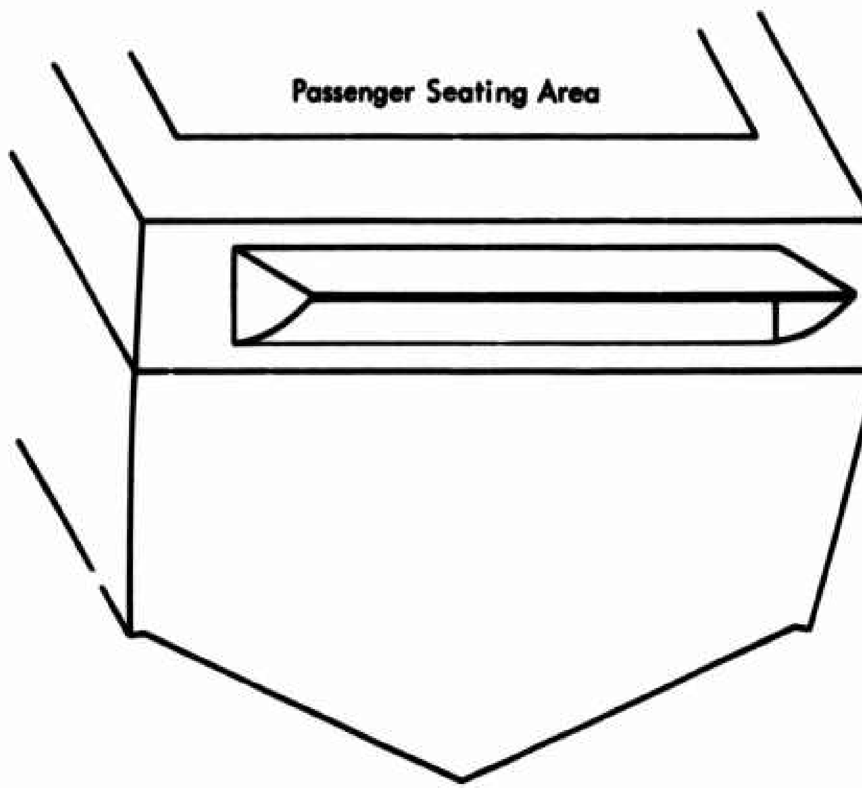


Figure 5. Single Vent Door in the Deck

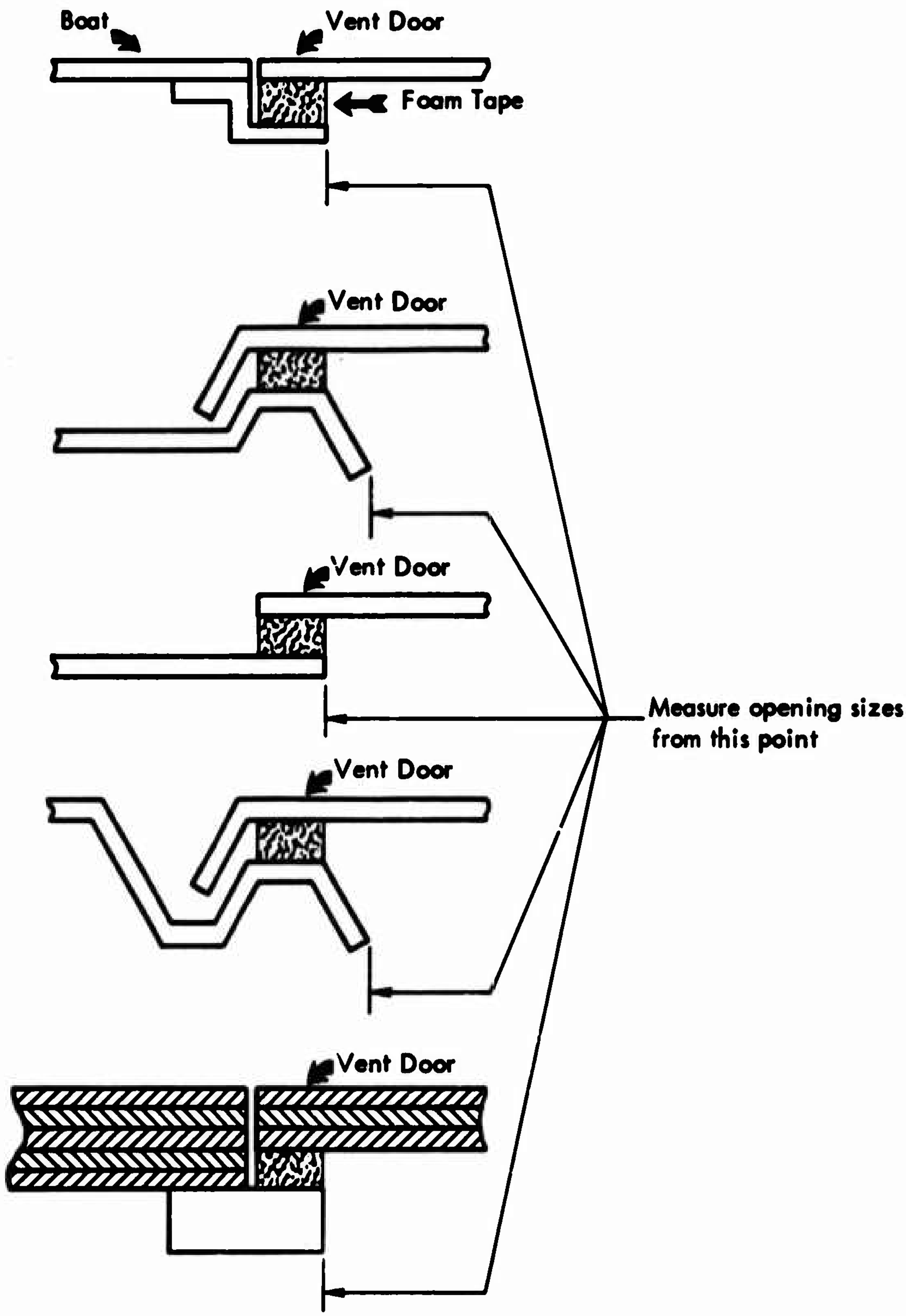


Figure 6. Typical Vent Door/Boat Interfaces

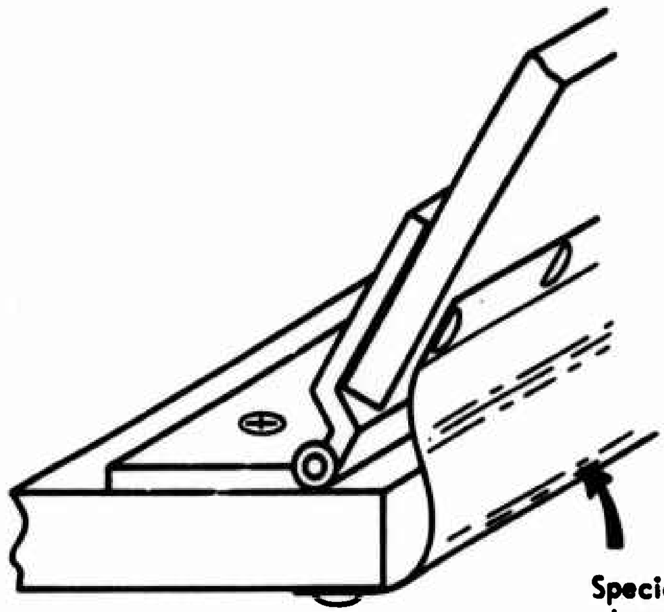


Figure 7. Special Flame Deflector

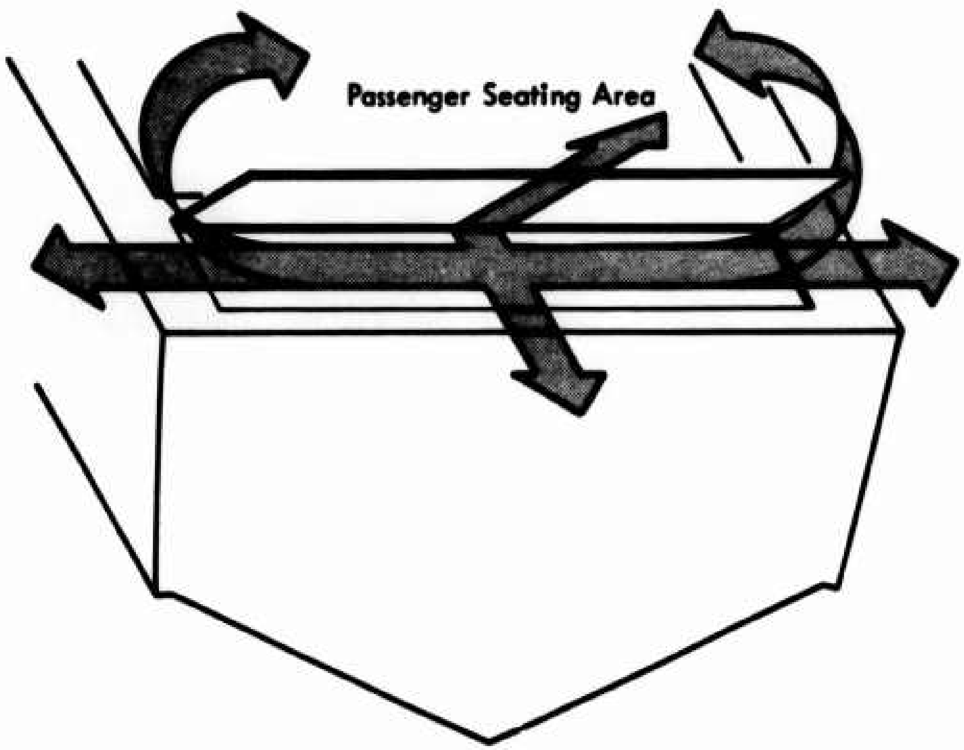


Figure 8. Flames Partially Directed Away From Passenger Seating Area

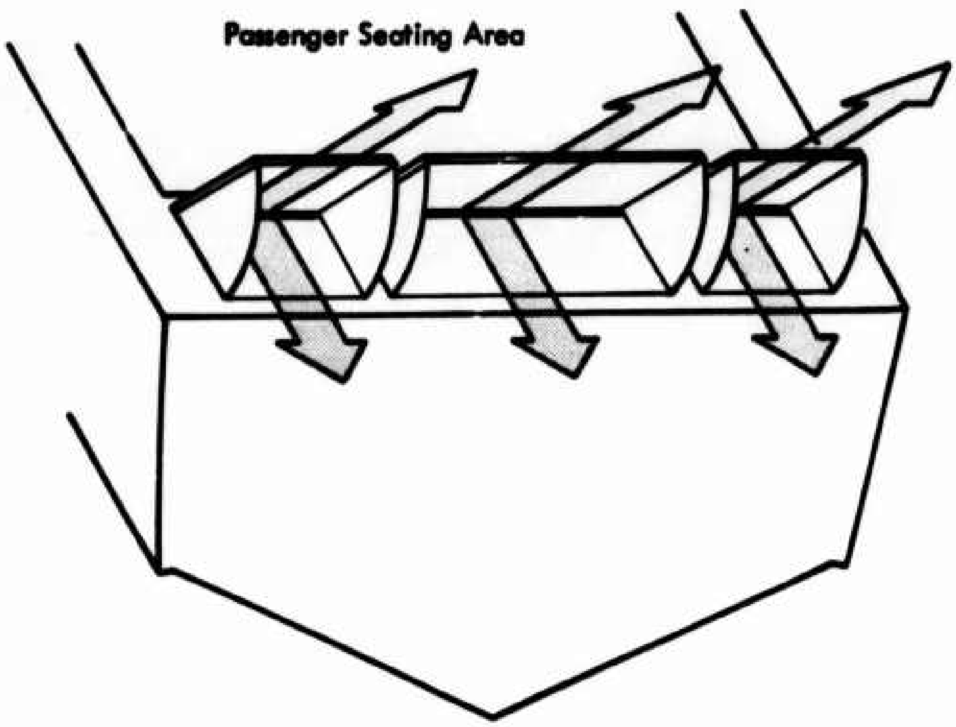


Figure 9. Flames Entirely Directed Away From Passenger Seating Area

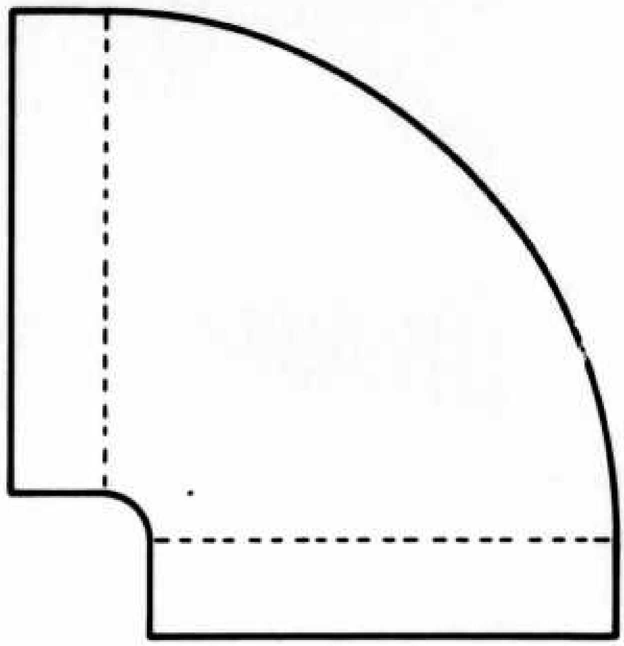


Figure 10. Typical Vent Door Side Flame Deflector/Restraint Pattern

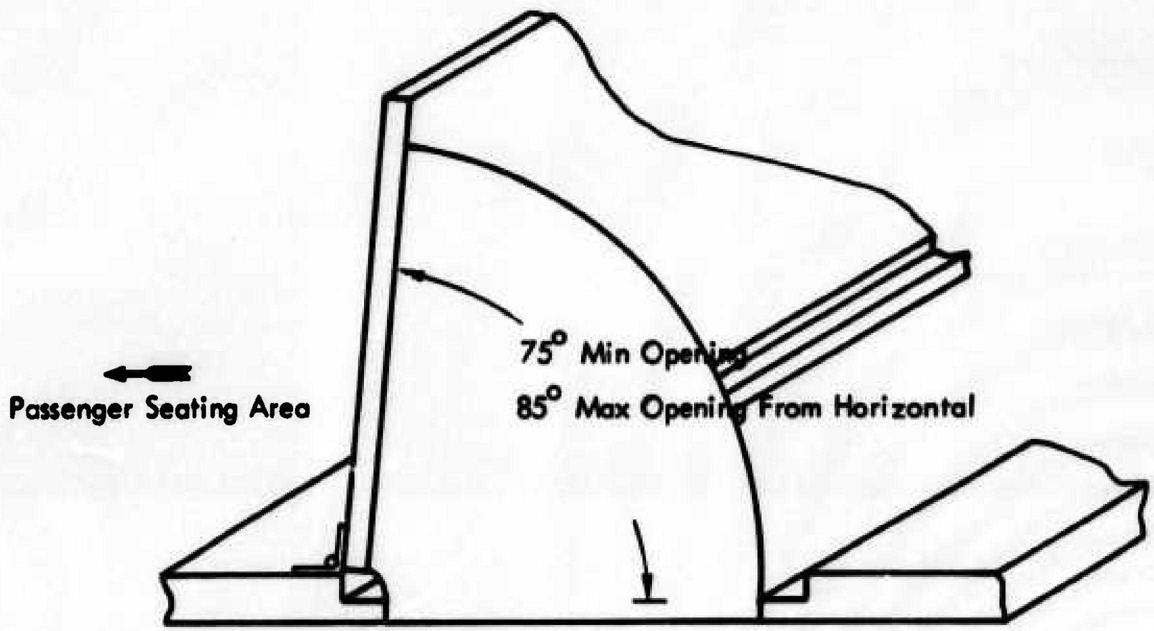


Figure 11. Vent Door Opening Limits

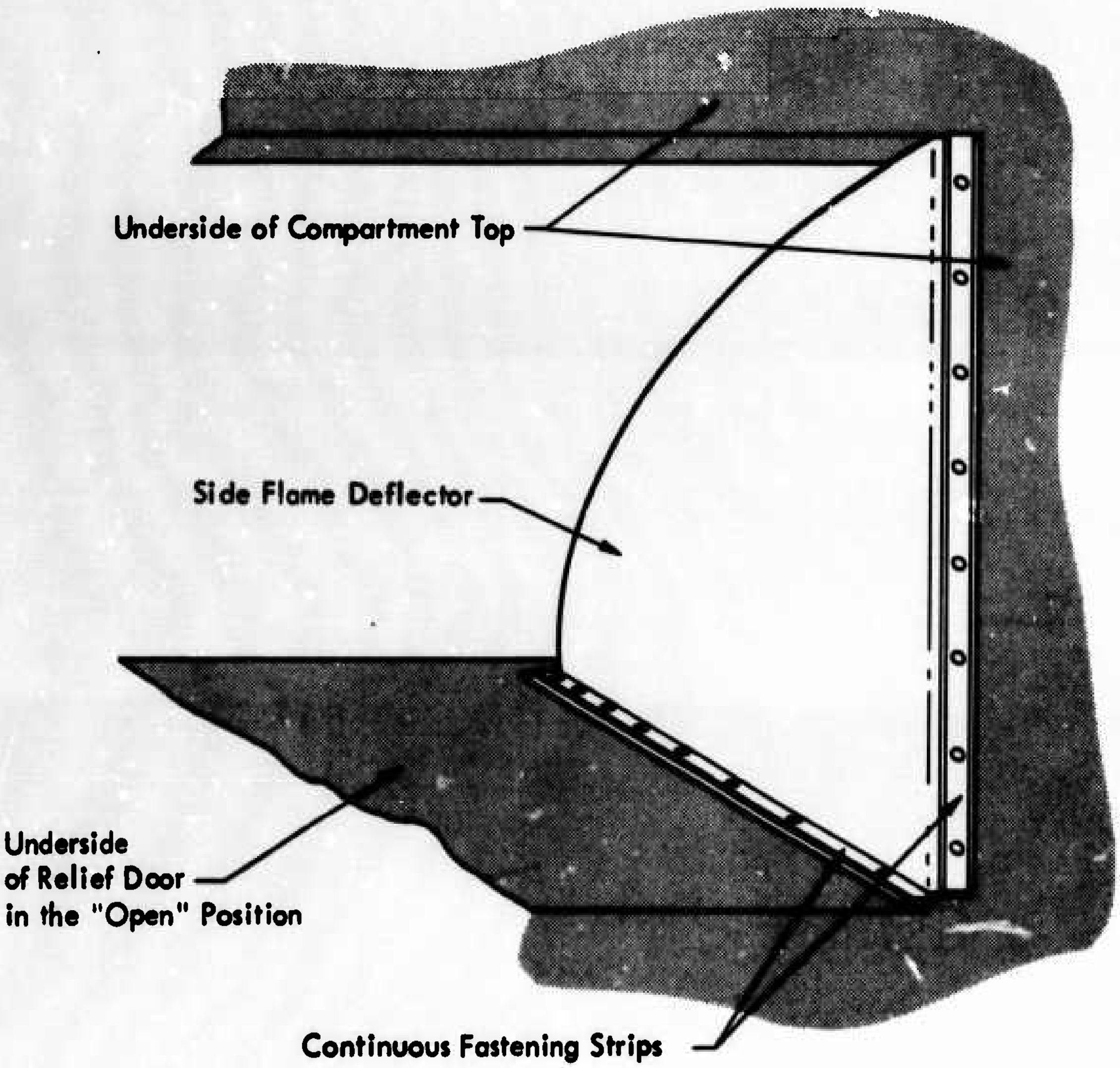


Figure 12. Continuous Fastening of Side Flame Deflector/Restraints (viewed from the inside of the compartment and looking up)

RECOMMENDATIONS FOR THE LOCATION OF EXTINGUISHER PORT IN INBOARD/OUTDRIVE RECREATIONAL BOAT ENGINE COMPARTMENTS

1.0 BACKGROUND

The present design of typical I/O engine enclosures require that the enclosure be removed/opened in order to use fire extinguishing equipment in the event of a fire in the engine/bilge area. Research performed by the Coast Guard R and D Center indicates considerable improvement in the fire fighting efficiency if a port is provided through which the equipment nozzle can be discharged without opening the compartment enclosure.

The ports perform at least two additional important safety functions:

1. They enable extinguishing efforts to be carried out without unnecessarily exposing the fire fighter to the direct heat and flames of the fire, and
2. Their use reduces the amount of oxygen available to support continued combustion.

2.0 RECOMMENDATIONS

The test results reported[1] established the desirability and improved effectiveness of fighting an I/O engine compartment fire without having to open the cover. The data did not indicate any one port location as being particularly more effective than another. However, from a purely practical standpoint, considering the typical machinery arrangement within the engine enclosure, a port located in the center of the forward side of the engine box at a convenient height above the cockpit deck is recommended as the best location.

While a port on the carburetor side of the box would allow direct access to a carburetor fire, the bilge area on the opposite side would be obstructed. Similarly a port located on the top would not give unobstructed, direct access to the bilge area. Locating the port on the forward end of the box affords reasonable access to the bilge and to the engine in general. In addition, the forward end location affords maximum accessibility to the operator.

[1] USCG, "A Technique for Extinguishing Engine Compartment Fires in Recreational Boats," to be published.

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Four inches is the recommended port diameter in order to accommodate the horn of carbon dioxide extinguishers. The port cover should be attached in a manner which will permit easy access for the extinguisher nozzle yet not become a potential missile in the event of an explosion. A flush mounted hand grip should be provided for easy removal. Other arrangements such as the swing cover would be acceptable. Figure 1 illustrates the recommended location and arrangement for the port.

The port and attachment should be designed to remain intact with an explosive pressure of two psi or higher.

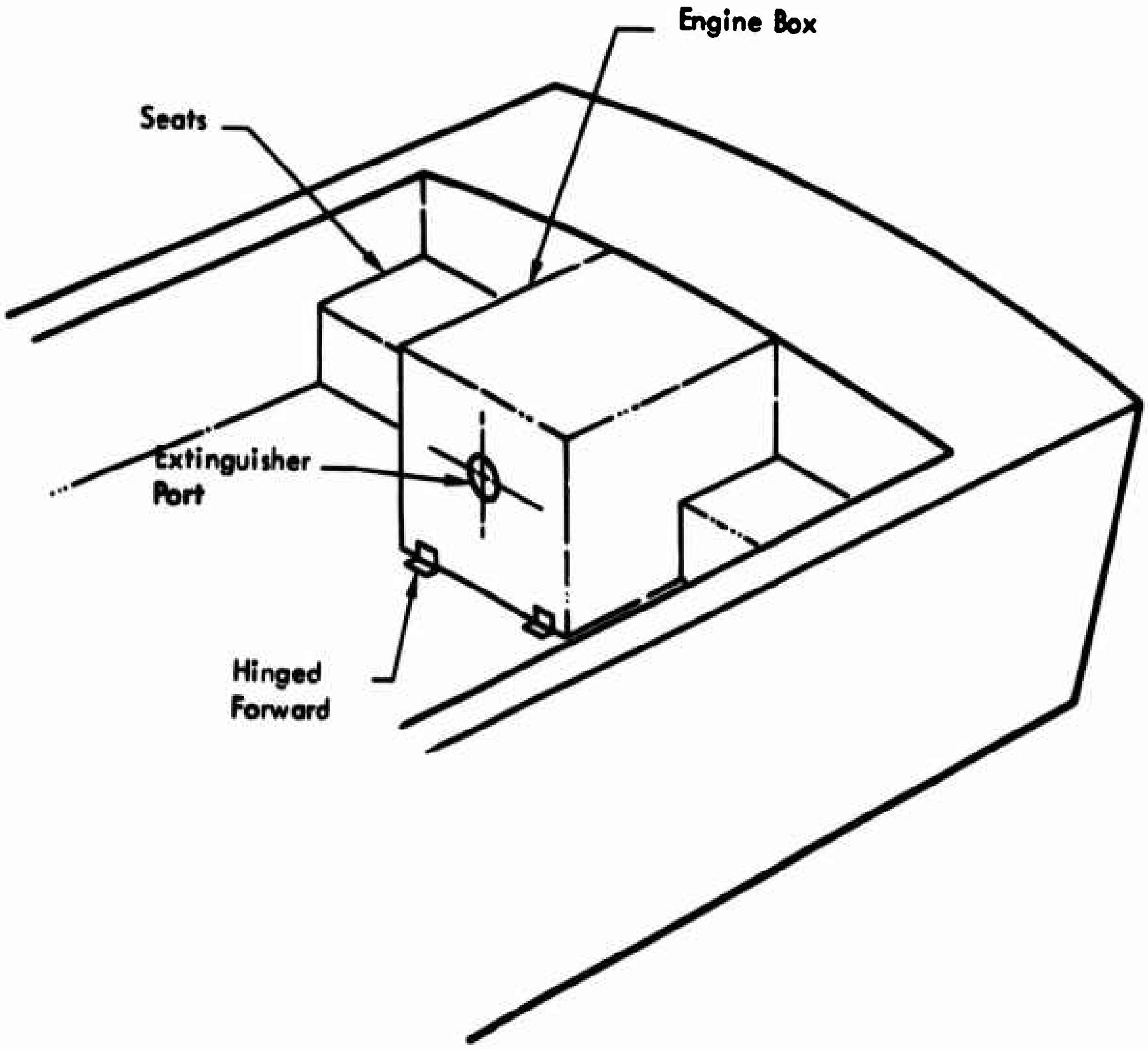

Figure A-1. Extinguisher Port Typical Arrangement