NA-64-1298

SERIAL NO. 16

DEVELOPMENT AND TESTING OF A PROTOTYPE RESPIRATION ANALYZER

FINAL REPORT

PHASE I

NASA CONTRACT NAS 4-367

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TABLE OF CONTENTS

INTRODUCTION

Although great progress has been made in recent years in the area of in-flight monitoring of certain biomedical parameters, e. g., respiratory rate, heart rate, ECG and even blood pressure, suitable instrumentation for determining the mass or volume and composition of respiratory gas has not yet been perfected. Accurate and reliable laboratory instruments exist for this type of analysis, but they are large and heavy, exhibit slow response characteristics and are not compatible with the requirements for in-flight utilization.

North American Aviation, Inc., LAD, has long been active in the development and testing of physiological monitoring devices as exemplified by the X-15 Biomedical Instrumentation Package (WADD TR 60-83) developed for the Air Force and the Prototype Biomedical Package for Parachute Research (NA-62-1449) developed for the Navy Parachute Center, El Centro, California.

In the case of the subject contract, North American Aviation, Inc. was encouraged by Dr. James Roman, Chief, Bioastronautics, NASA FRC to initiate a joint effort with Beckman Instruments, Inc., for the purpose of developing to prototype status certain respiratory sensors and to test these sensors under various environmental conditions with human subjects. As subcontractor to NAA, Beckman constructed a prototype respiration analyzer which provides simultaneous breath-by-breath analysis of the following parameters:

1. pO_2
2. pCO_2
3. Expired air temperature
4. Total atmospheric pressure

Although not an integral part of the respiration analyzer, inspiratory flow and expiratory flow are measured by separate mass flowmeters provided by NASA as GFP.

The prototype analyzer was tested at sea level and at 25,000 feet in an altitude chamber with human subjects at rest, and during moderate and heavy exercise on a powered treadmill. The purpose of this testing was to evaluate the response characteristics and accuracy of the prototype analyzer and determine the feasibility of the prototype device for eventual in-flight utilization. The altitude of 25,000 feet was chosen to simulate the cockpit pressurization level of a fighter aircraft and the work levels were chosen to produce respiratory activity exhibited by test pilots flying experimental aircraft.

METHODS

GENERAL DESCRIPTION OF THE PROTOTYPE ANALYZER

The respiration analyzer consists of an infrared absorption unit for monitoring carbon dioxide, a polarographic sensor for monitoring oxygen, an absolute pressure transducer, and a fast responding thermistor for temperature monitoring (Figure 1). Two mass flowmeters for measuring inspiratory and expiratory mass flow are also included (Figure 2).

The purpose of the proposed instrumentation is to provide continuous monitoring on a breath-by-breath basis of the composition, mass flow rate and temperature of expired air. Although the instrumentation tested during this program can be eventually packaged into flightborne gear, this phase of of development utilized existing designs of laboratory prototype equipment to prove the feasibility of the concepts. The selected techniques of instrumentation are amenable to miniaturization and rugged packaging as normally required for airborne use.

Of the five parameters to be measured, four of them are sensed in a single compact sample volume of minimum dimensions to minimize sample integration and to assure rapid, accurate response. The fifth measurement (mass flow) is made external to the sample chamber, with flowmeters located in the inhalation and exhalation lines.

A compact signal conditioning unit (Figure 3), featuring pull-out printed circuit cards for the pO_2, pCO_2, temperature and pressure sensors, is supplied by Beckman Instruments. The two mass flowmeters by Technology Inc. (furnished as GFP) each have their own signal conditioning units.

SPECIFIC DESCRIPTION OF COMPONENTS

CO_2 SENSOR

An infrared absorption unit is employed to measure CO_2 concentration. The sensor consists essentially of a torsion vibrator which alternately places two IR filters in the light path between a source and a detector. One filter passes radiation in a CO_2 absorption pass band, while the other passes energy not absorbed by CO_2. The ratio of the two alternating signals is detected as a function of pCO_2. This unit has a time constant of approximately 0.2 seconds. Its design operating range is 0 to 30 mm CO_2 and is independent of the total operating pressure over ordinary ranges. A calibration curve is shown in Figure 4. A resistor within the analyzer package provides enough heat to prevent the sample cell windows from fogging.

The unit can be re-calibrated by introduction of known concentrations of sample gases into the chamber.

OXYGEN SENSOR

A polarographic sensor is employed for the measurement of O_2. This is an experimental "fast response" version of the standard Beckman hypoxia sensor. This version consists of a gold cathode of approximately .012 inch diameter and a silver anode, both contained within an assembly 0.45 inch in diameter. A KCl gel is used between the electrodes, and the entire assembly is covered with an unusually thin permeable membrane. Oxygen diffuses through the membrane and is reduced at the cathode by a polarizing voltage of 0.8 volts. The resultant output current is directly proportional to the partial pressure of oxygen and independent of total operating pressure. The output current is directly proportional to the area of the cathode and approximately 4.5 ua is produced at 100% O_2 at sea level (760 mm). The sensors put out zero current in the absence of oxygen and are linear to 1000 mm Hg with an accuracy of better than 1% once calibrated. The output current is passed through a load network which includes a thermistor to compensate for the temperature dependence of the sensor.

The O_2 channel can be easily calibrated by exposing the sensor to 100% N_2 (zero) and 100% O_2 at a known pressure. A high impedance readout device (3 meg minimum) must be used to monitor the output of this channel as the output impedance is approximately 30K.

The time constant of the O_2 channel is approximately 0.2 seconds. Power for the O_2 circuit is derived from a 1.35 volt mercury cell (Burgess Hg-12R). Operating life of this cell is approximately 3000 hours.

PRESSURE SENSOR

The pressure transducer is a flush diaphragm, solid state semi-conductor strain-gage type. It is designed to operate over the pressure range of 0 to 20 psia.

The output of this transducer is normally linear. However, the calibration curves supplied by Beckman and the manufacturer showed an unusual non-linearity which is apparently the result of a manufacturing defect. Since the calibration curves (Figure 6) supposedly showed good repeatability, it was decided to use the transducer rather than delay testing of the system.

TEMPERATURE SENSOR

A fast responding thermistor bead is utilized in a Wheatstone bridge circuit for measuring the expired air temperature. This thermistor has a time constant in still air of 0.1 second. Figure 7 shows the output versus temperature function of this channel. This circuit is calibrated over the range of 30°C to 45°C. Power for this circuit is derived from two 1.35 volt mercury cells in series (Burgess Hg-12R). Operating life of these cells is approximately 18,000 hours.

MASS FLOWMETER

The operation of the Technology Inc. mass flowmeter is based on the fact that the amount of heat required to maintain a known temperature difference across the boundary layer indicates the heat transfer rate; this rate is a measure of the mass flow rate of the fluids.

The linear mass flowmeter uses basically the same sensing element as in the X-15 instrumentation package, that is, a thermistor operated in the self-heating region. Thermistors are resistive elements possessing a high negative temperature coefficient and a voltage-versus-current characteristic. Hence, when sufficient current is drawn, considerable heat is developed within the thermistor, causing the resistance to decrease at a faster rate than the current increases and, thereby, yielding a negative slope. The curve shifts upward with increased flow rates. This shift occurs because the increased airflow effectively increases the heat sinking capacity of the environment and carries away heat which would otherwise heat the thermistor and decreases the resistance.

Therefore, the use of a thermistor and suitable allied electronics can produce a voltage output which is analogous to the rate of flow of the gas. This arrangement, in effect, is a flowmeter, but it lacks some of the characteristics essential to a linear flowmeter; for the output is non-linear and is dependent on the temperature of the gas. These deficiencies are eliminated by using an analog variable attenuator. As the voltage input increases, the attenuation is decreased at certain specific points. The degree of attenuation for the straight-line segments preceding and following each of these points is controlled by using a second thermistor which is not self-heated to any extent. Therefore, this second thermistor reacts only to the temperature of the gas and, thereby, provides compensation for changes in gas temperature. The function generator characteristic is adjusted so that its output is the inverse of the thermistor sensing element output for a linearly increasing voltage input. Hence, as the non-linear output of the sensing element is fed into the function generator, the opposing non-linearity of the function generator output has a cancelling effect which causes a single linear output. Because of the attenuation of the function generator and the relatively low input voltage to it, the output of the function generator is too small for most practical applications and, consequently, necessitates the use of an amplifier.

A calibration curve for both flowmeters used during the test program is shown in Figure 8.

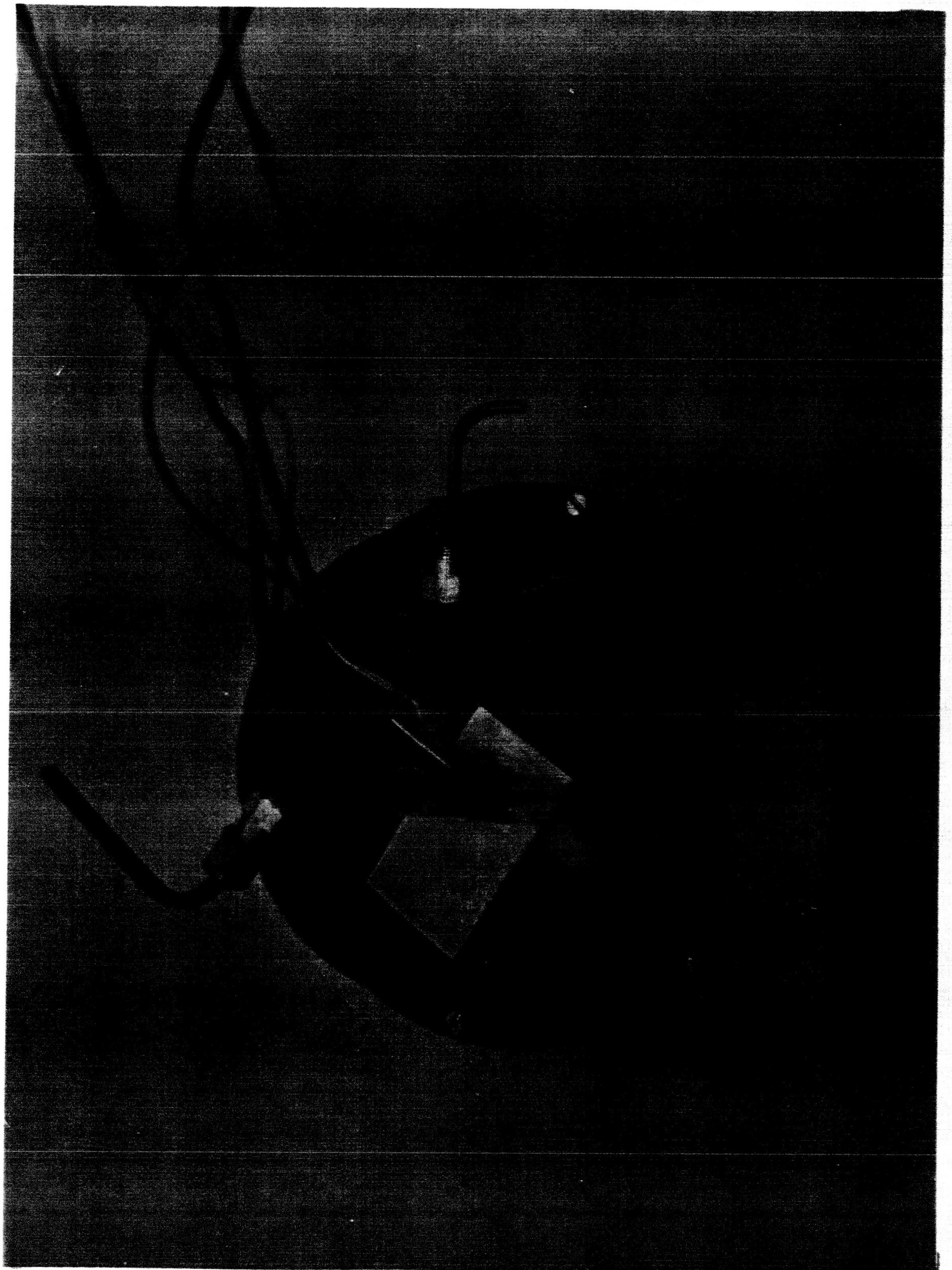

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FIGURE 1

RESPIRATION ANALYZER

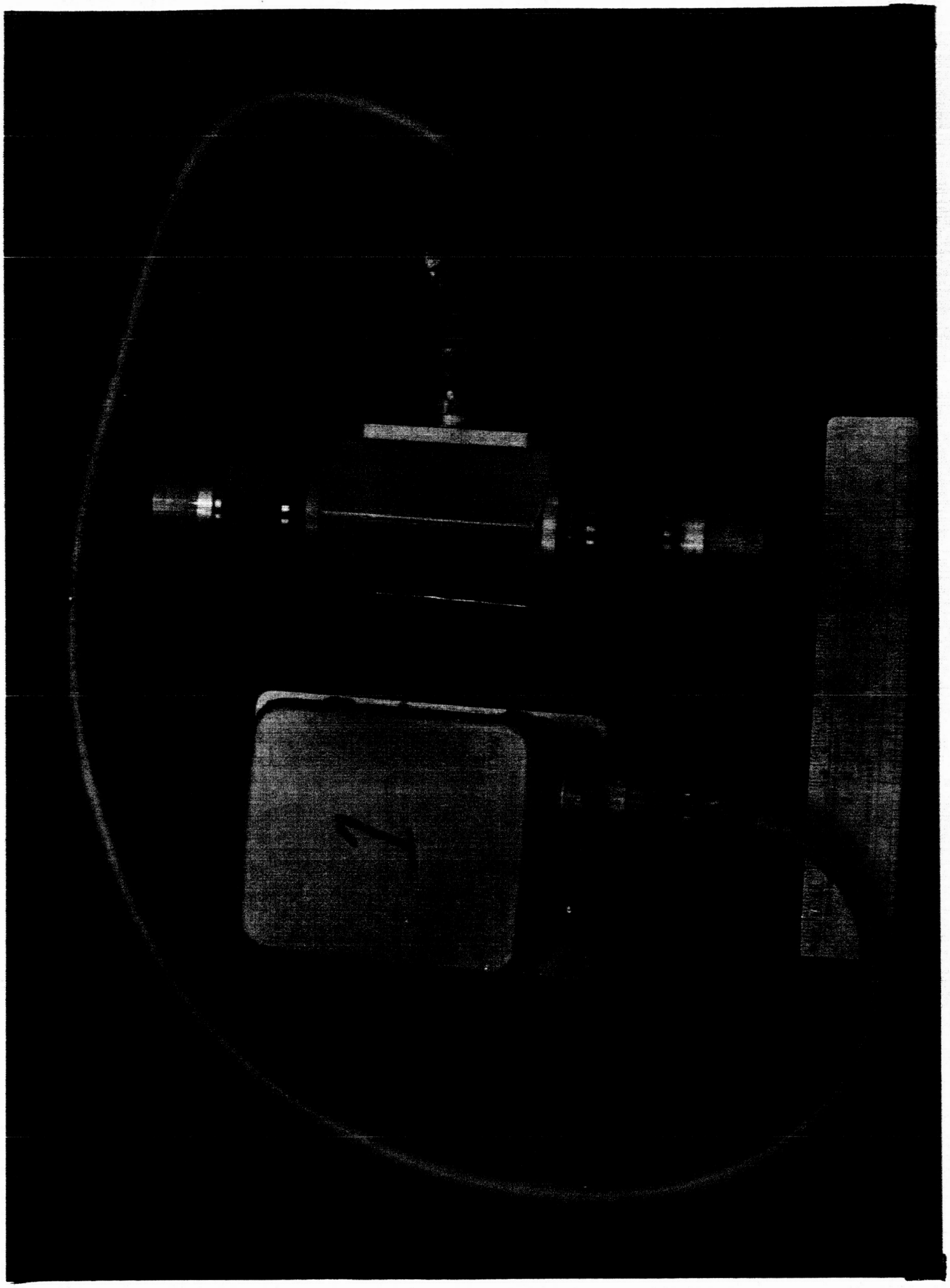

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FIGURE 2

MASS FLOW METER AND SIGNAL CONDITIONER

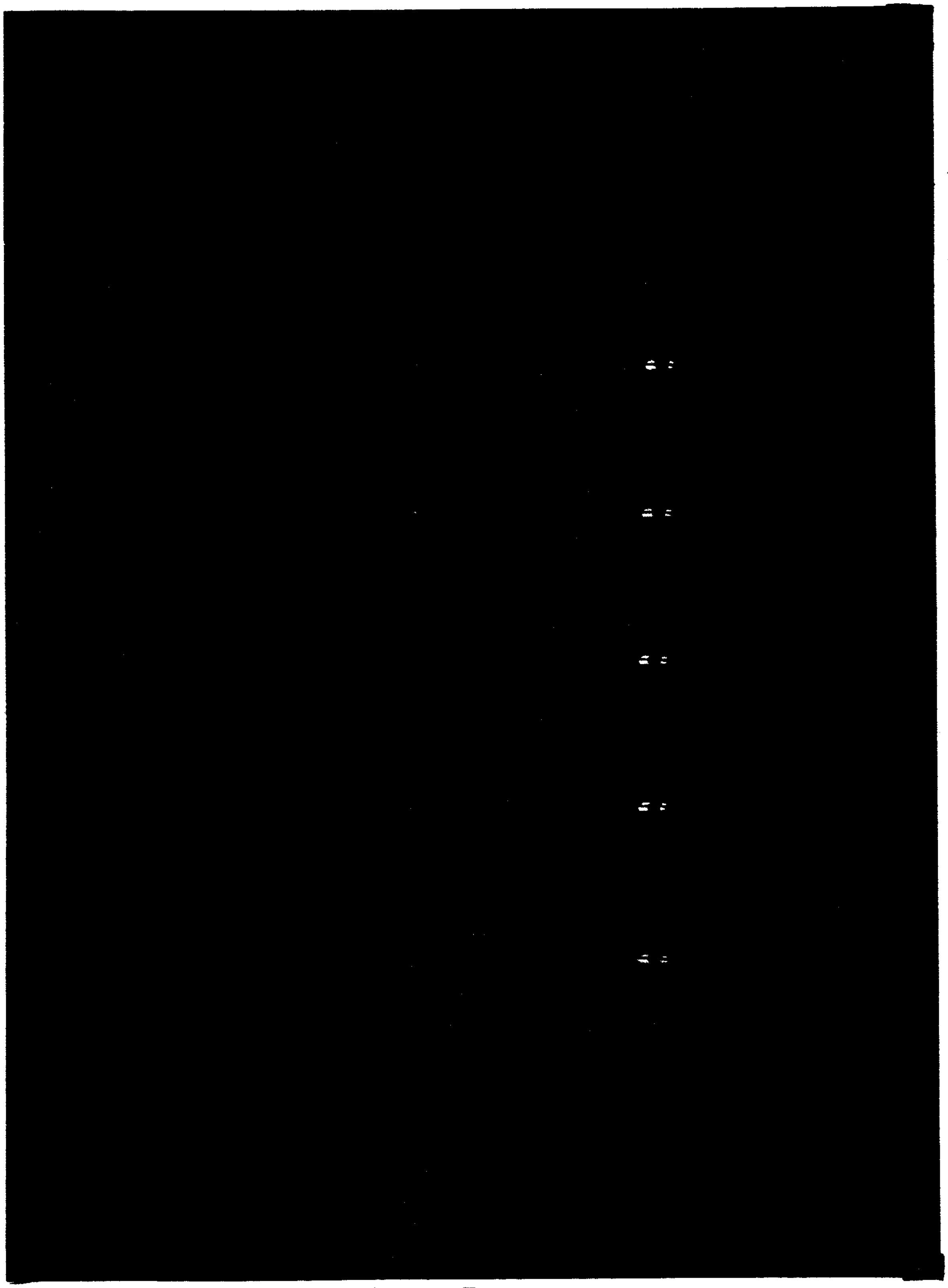

FIGURE 3

RESPIRATION ANALYZER SIGNAL CONDITIONER

FORM 1002-X (FORMERLY ED167)

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CHECKED BY:	Figure 4	REPORT NO. NA-64-1298
DATE: 12-14-64		MODEL NO.

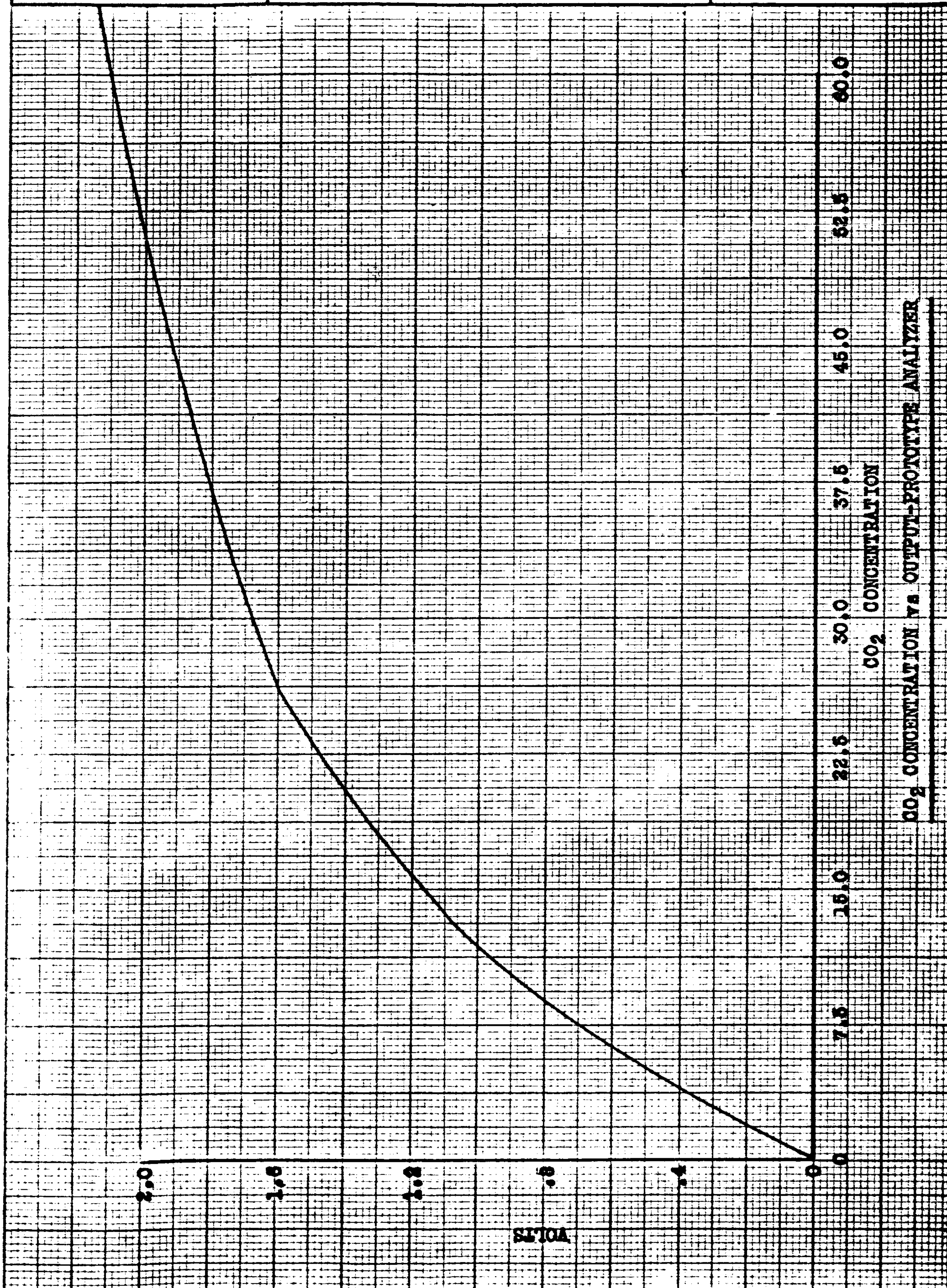
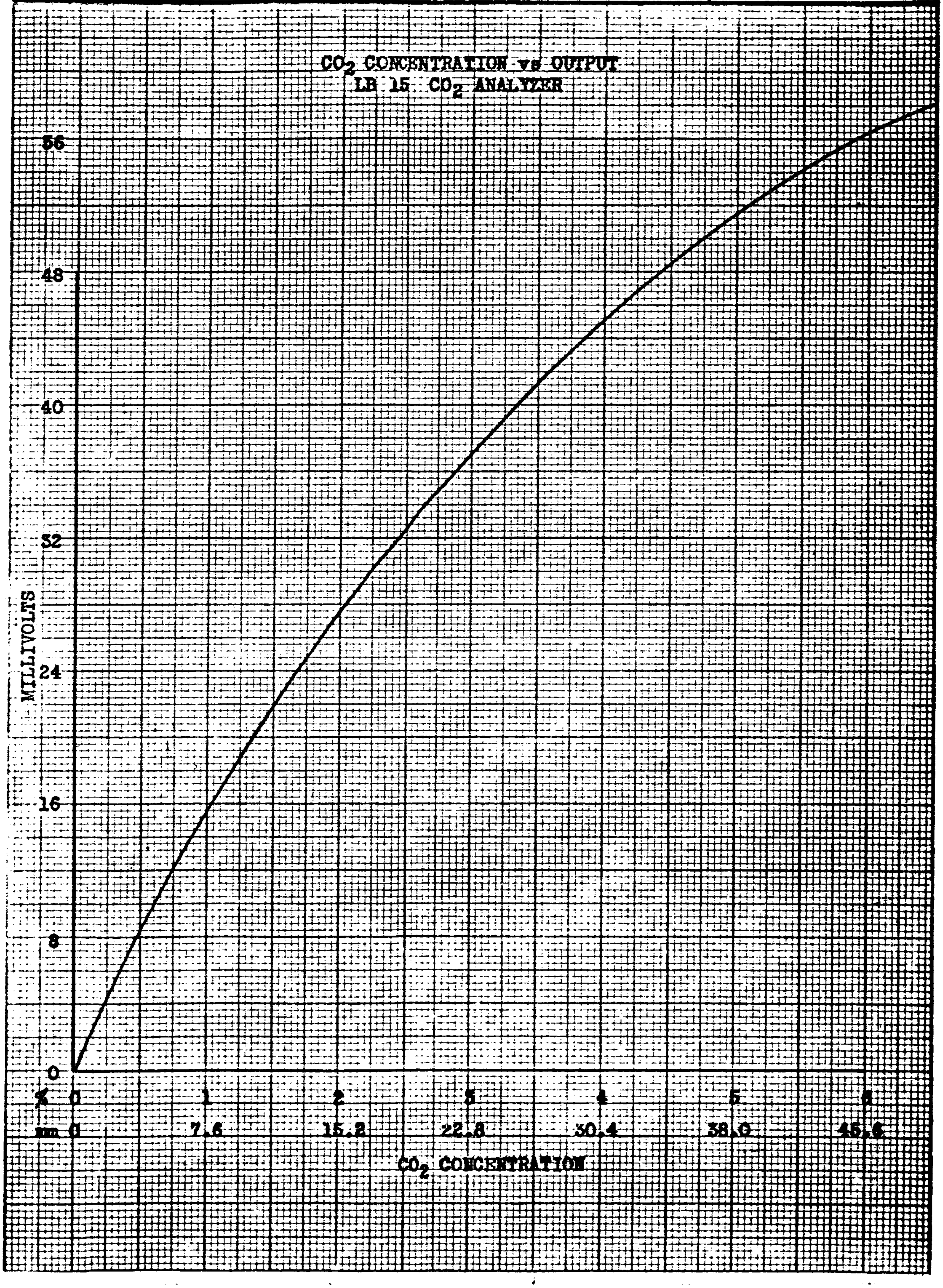


Figure 5


CO_2 CONCENTRATION vs OUTPUT
LB 15 CO_2 ANALYZER
MILLIVOLTS
0
8
16
24
32
40
48
56
% 0 1 2 3 4 5 6
mm 0 7.6 15.2 22.8 30.4 38.0 45.6
CO_2 CONCENTRATION

FORM 1002-X (FORMERLY ED147)

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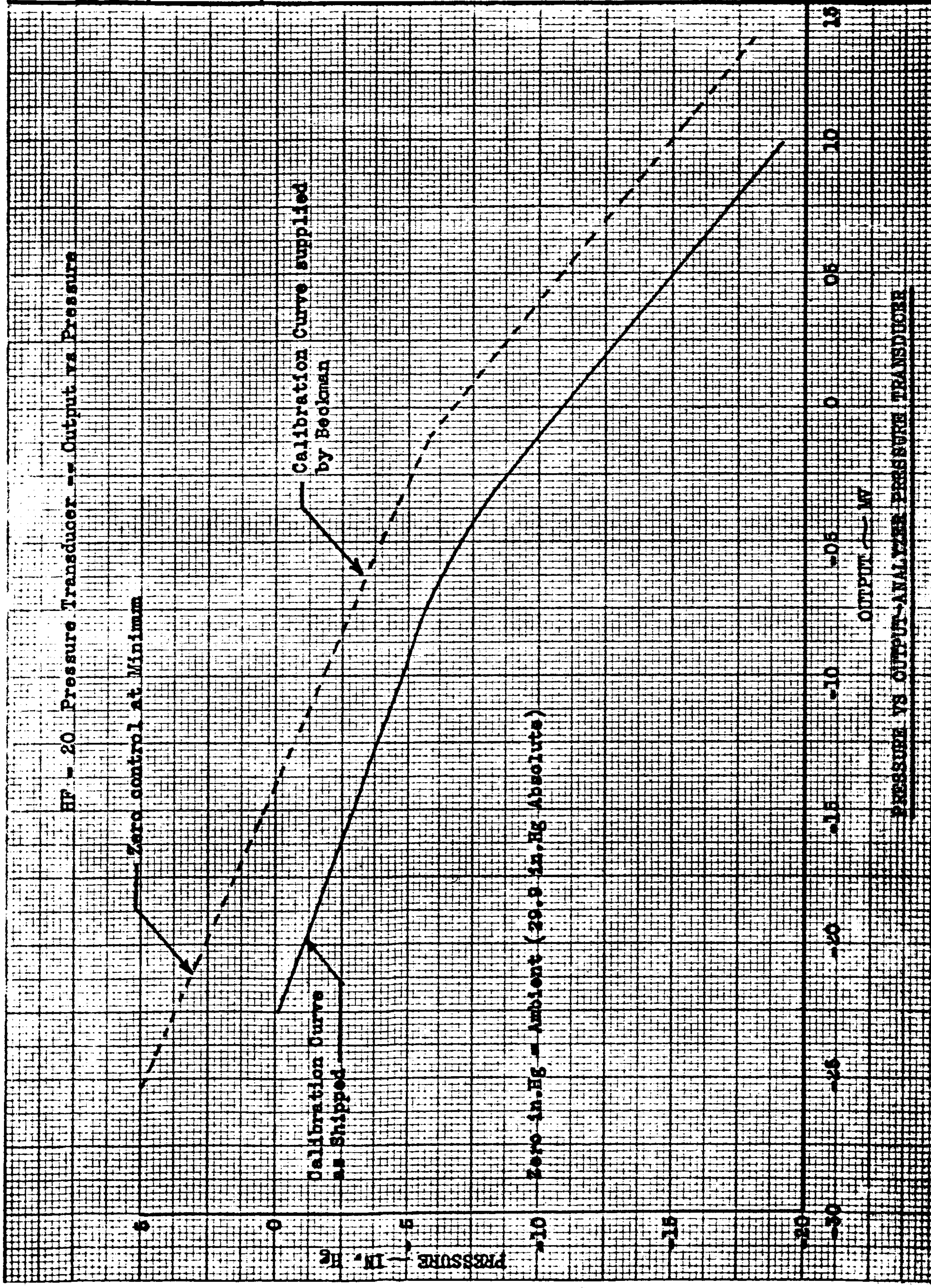
CHECKED BY:	Figure 6	REPORT NO NA-64-1298
DATE: 12-14-64		MODEL NO.



FORM 1002-X (FORMERLY SD147)

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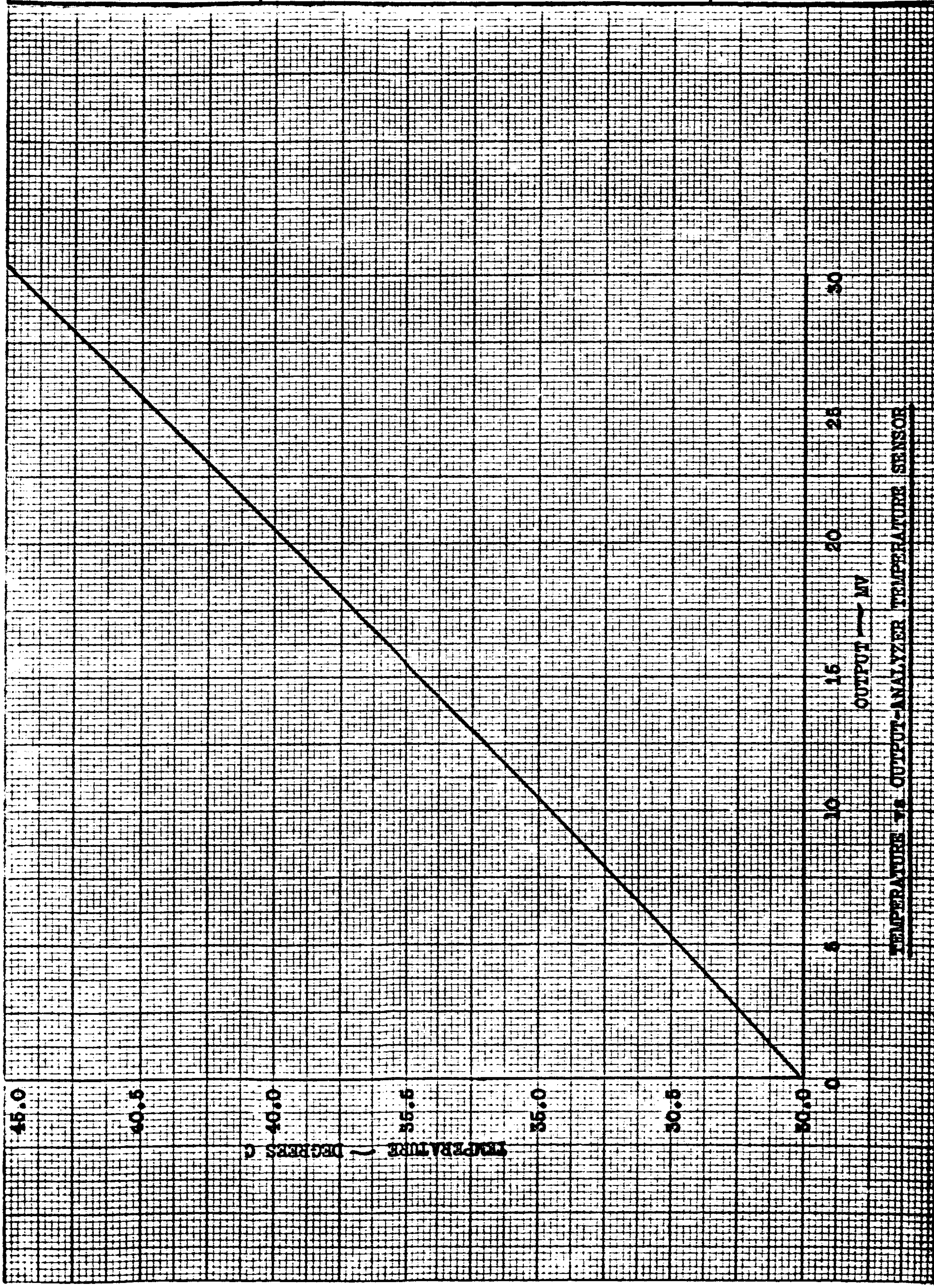
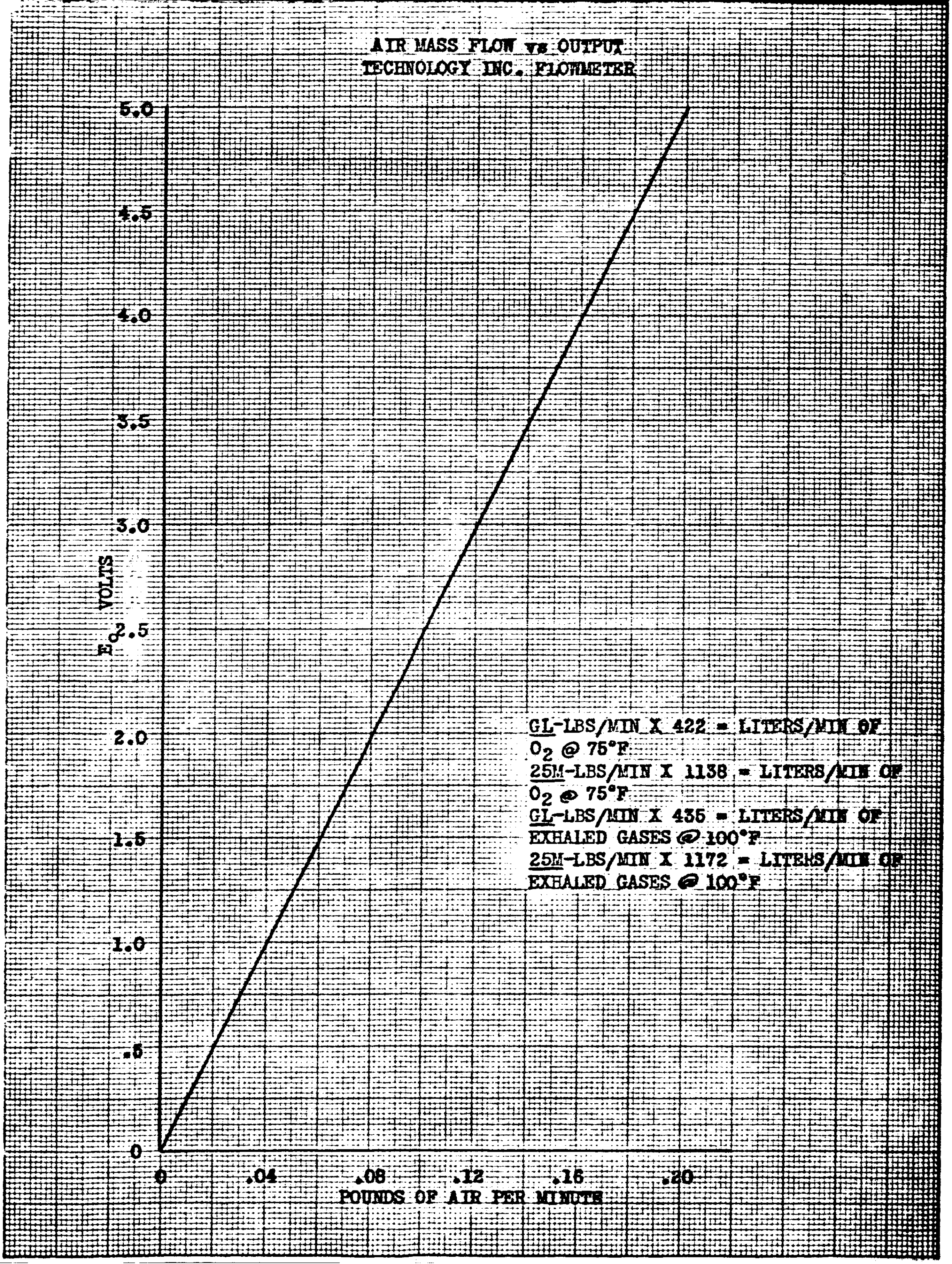
CHECKED BY:	Figure 7	REPORT NO NA-64-1298
DATE: 12-14-64		MODEL NO.



FORM 1021-B

PREPARED BY:	NORTH AMERICAN AVIATION, INC.	PAGE NO. 15 OF
CHECKED BY:	Figure 8	REPORT NO. NA-64-1298
DATE: 12-14-64		MODEL NO.



TEST APPARATUS DESCRIPTION

The general layout of test apparatus is shown in schematic form in figure 9 and in photographs of the apparatus installed in the altitude chamber in figures 10, 11, and 12. Breathing oxygen was supplied from the chamber oxygen storage manifold by a standard MD-1 crew regulator for both sea level and altitude runs. Demand oxygen passed through a dry gas meter (American Standard, calibrated in liters), thence through the #1 or inspiration mass flowmeter and on to the subject via a 3/4 inch flexible tube. The temperature of the inhaled oxygen showed minor variation as measured by a Yellow Springs Telethermometer and generally remained between 72° and 77°F. The subject breathed through a rubber spirometer mouthpiece and a nose clamp was utilized to prevent any leakage of respiratory gas from the nose. Initially, a modified Sierra oxygen mask as supplied by Beckman with the analyzer was used, but excessive leakage occurred around the mask periphery during respiratory activity associated with heavy exercise. The mouthpiece minimizes leakage, although examination of test results indicates that in a few instances, leakage may have occurred around the mouthpiece. The mouthpiece was attached to a plastic manifold block which contained one inhalation valve and two exhalation valves. Mouthpiece dead space was thereby minimized and represented approximately 100 cc. The optical requirements of the analyzer CO_2 sensor required a small bore passage through the analyzer (7/16 inch inside diameter). To prevent prohibitively high exhalation resistance, a duplicate 7/16 inch exhalation line bypassing the analyzer was provided. Both lines joined just upstream of the #2 or expiration mass flowmeter. Another thermister was located at the downstream end of this flowmeter. Just past the #2 flowmeter was located a three-way diverter valve so that exhaled gas could be directed either to the spirometer or to an electric hygrometer. Because of space limitations, the hygrometer was not utilized during the altitude runs, although all other apparatus, except for the LB-15 and the recorders, were located in the chamber.

Sample gas for the LB-15 CO_2 analyzer was drawn off just upstream of the prototype analyzer and returned to the exhaled air upstream of the #2 flowmeter. The LB-15 requires a sampling rate of approximately 300 cc/min.

To prevent condensation of moisture in the exhalation lines, Thermotape heaters were obtained and wrapped around these lines to an area downstream of the #2 flowmeter. The heaters were supposedly thermostated to maintain the flexible tubing at 100° to 110°F, but as seen from the results, much wider fluctuation was recorded. Moisture condensation did not, however, occur.

Although the respiration analyzer was located as close to the subject's face as possible, approximately 18 inches of flexible tubing (Tygon) was necessary to provide the freedom of movement required while walking on the treadmill. The analyzer was firmly installed on a shelf attached to the hose support bracket of the treadmill and therefore remained in the same relative position during all test runs. The two mass flowmeters were located ajacent to the analyzer while the spirometer, signal conditioners, gas meter, and telethermometer were located on a stand in front of the treadmill. Care was taken not to change the relative positions of any apparatus during the course of the experimental program.

Power for the respiration analyzer and the two mass flowmeters was supplied by a controlled power supply providing 28 volts d.c. The LB-15 analyzer, F-3 oxygen analyzer, and all recorders were operated with normal 110 volt a.c. power. Sanborn hot stylus recorders were utilized for all parameters.

SCHEMATIC OF THE PROTOTYPE RESPIRATION ANALYZER SYSTEM

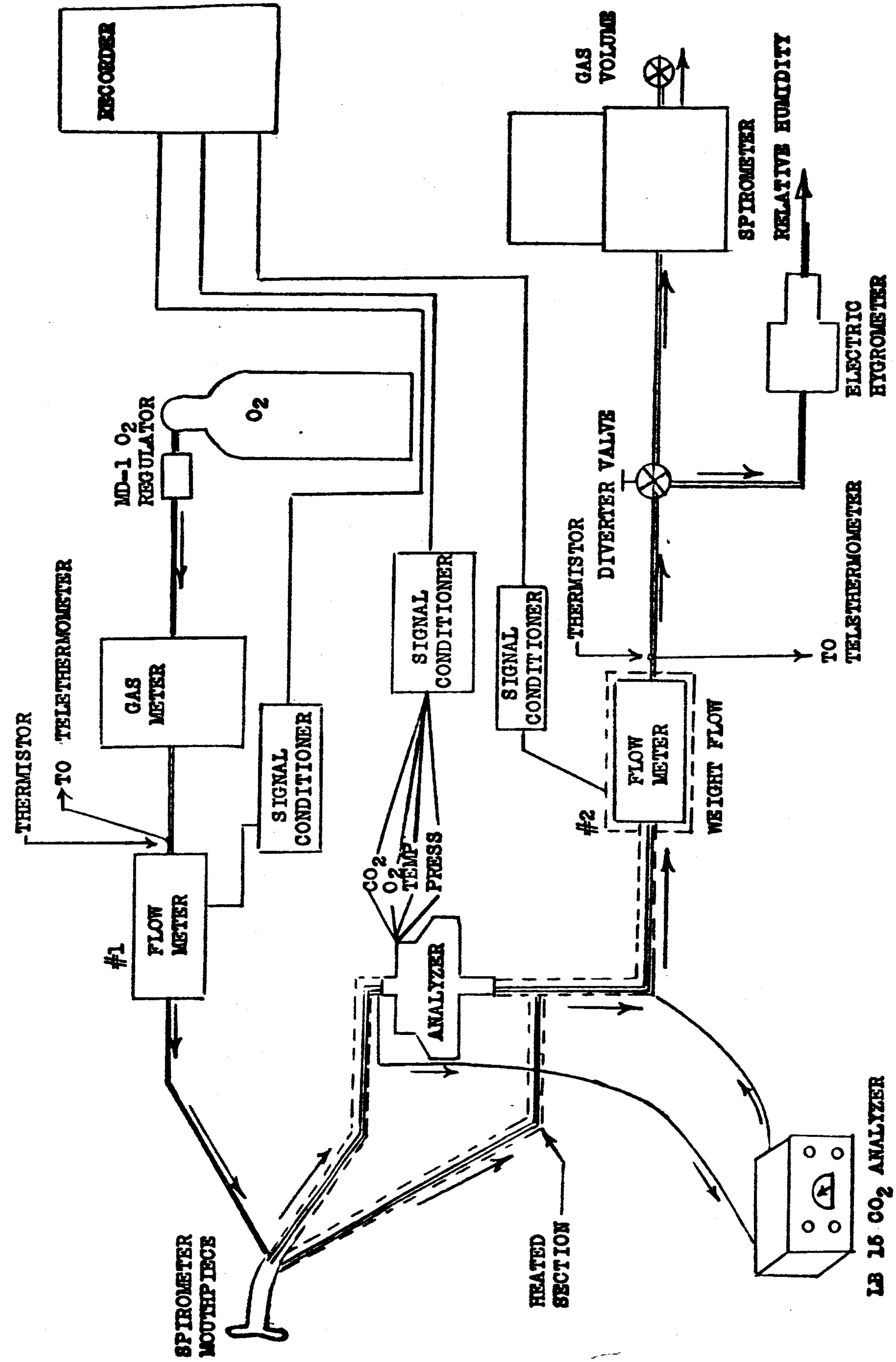


FIGURE 9

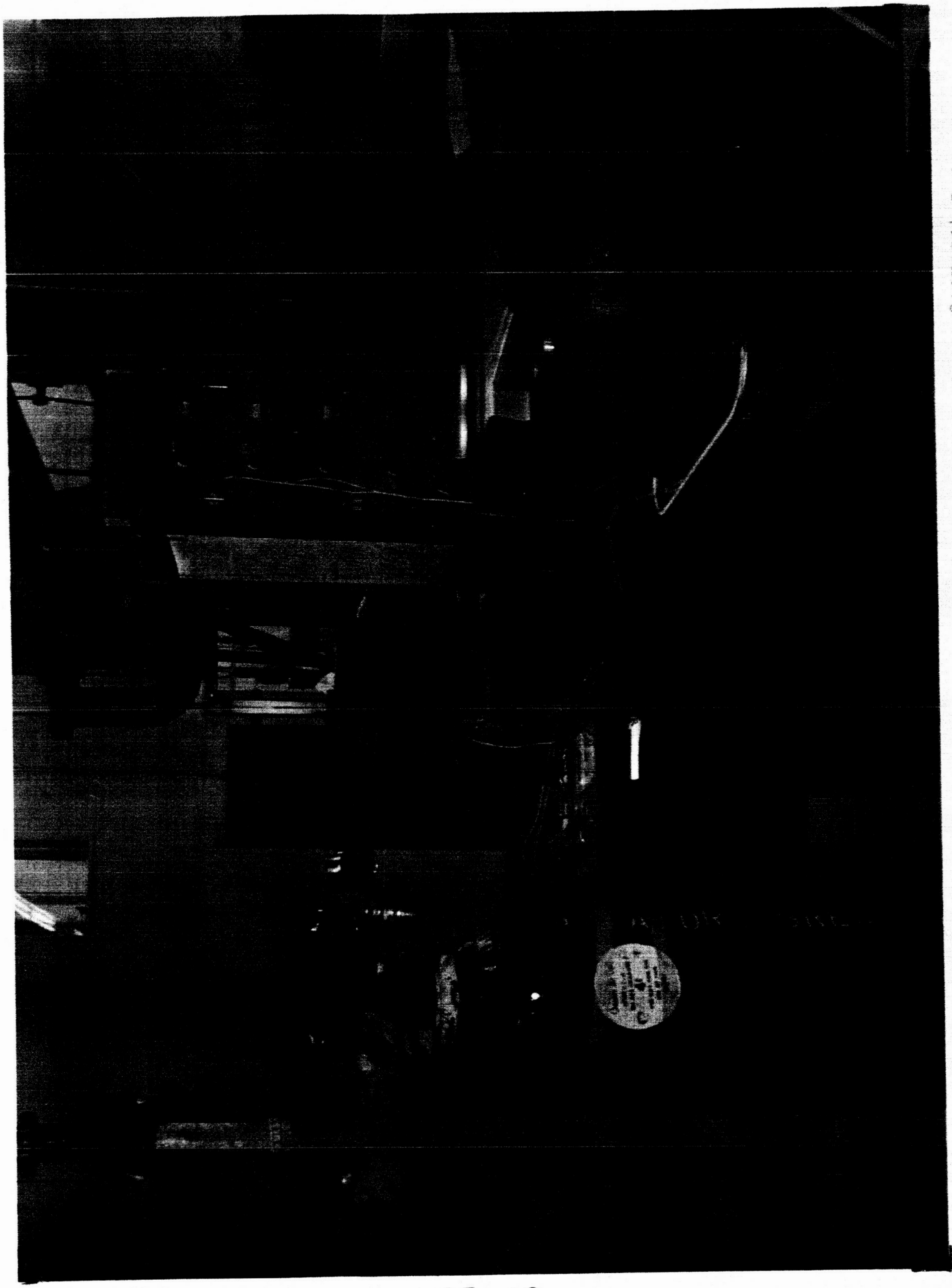


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FIGURE 10

EXTERNAL VIEW OF CHAMBER AND RECORDER

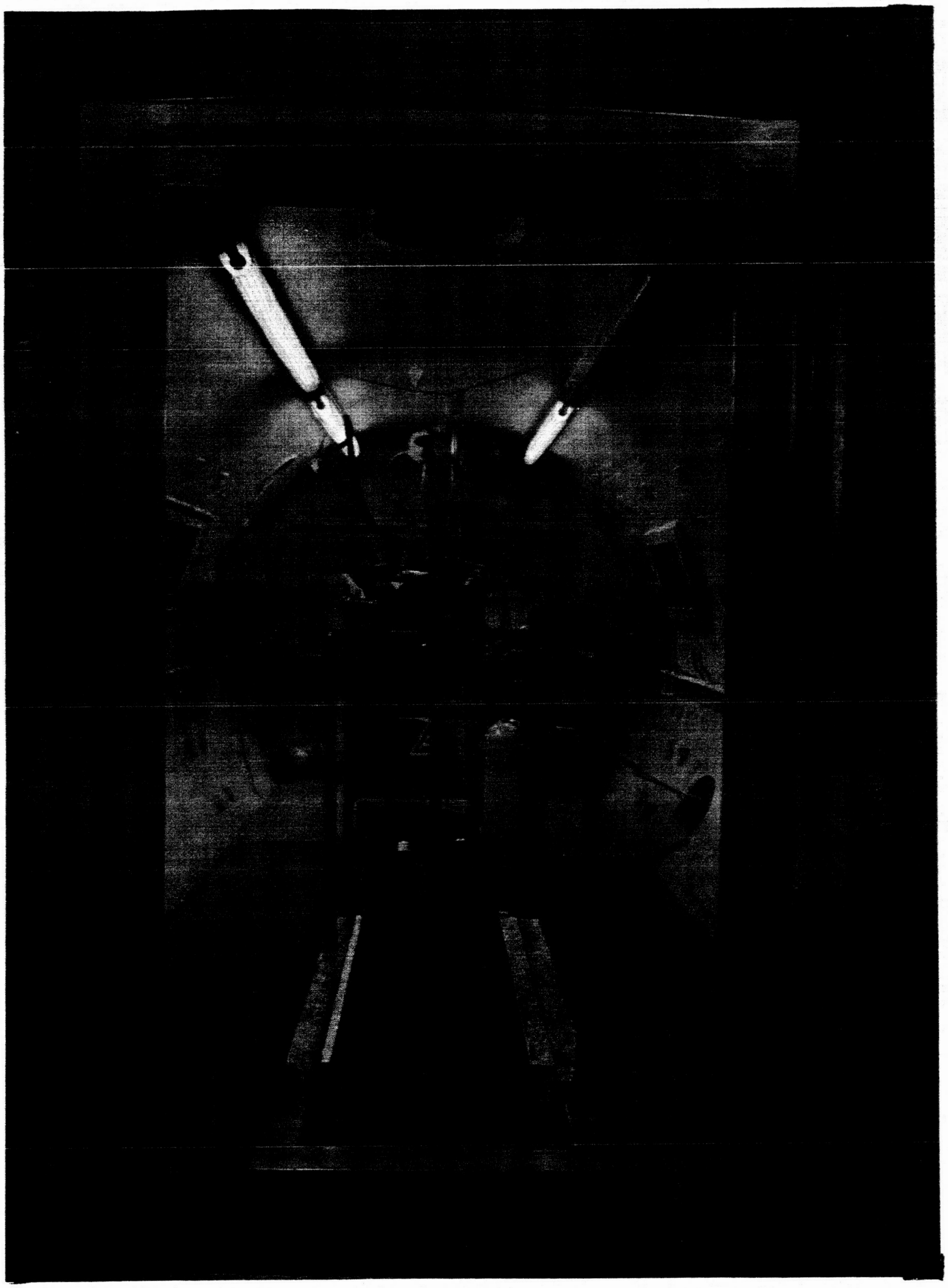

FIGURE 11

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VIEW OF TEST APPARATUS IN THE CHAMBER

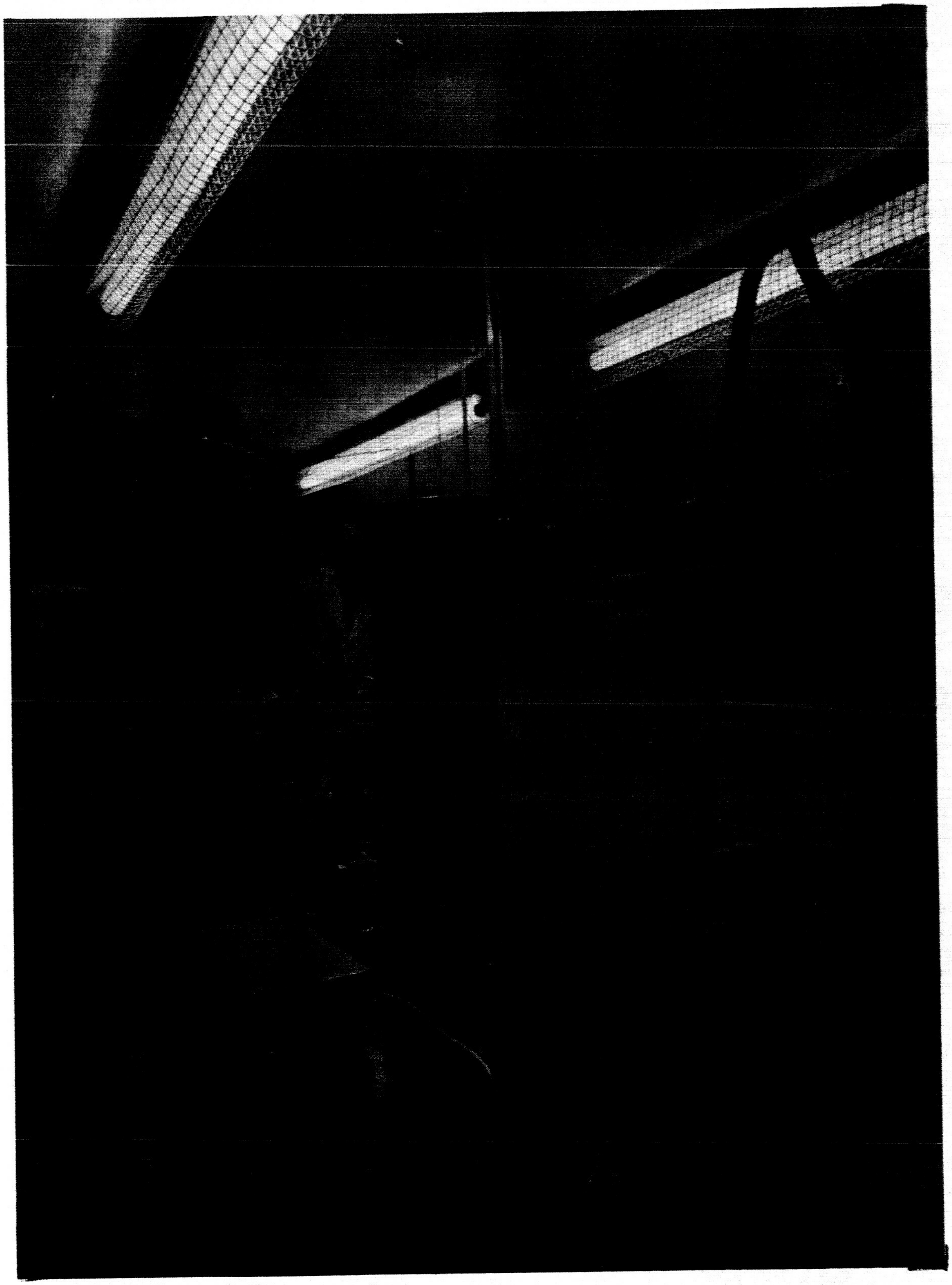


FIGURE 12

8667-964-1 E

INTERIOR VIEW OF INSTRUMENTATION IN THE CHAMBER

EXPERIMENTAL PROTOCOL

Examination of a sample data sheet (Figure 13) indicates the general organization of the experimental protocol. There were minor variations in procedure, however, as related to the three types of experiments listed below.

GROUND LEVEL RUNS

Upon arrival at the test area, the subject was shown the apparatus and was briefed on the experimental procedure. During this period, calibration gases were passed through the analyzer and recorder response verified. All recorders remained "ON" continuously during the tests to minimize drift and the analyzer was turned on two hours prior to a run. After analyzer calibration was accomplished, the subject inserted the mouthpiece, the nose clamp was positioned, and he breathed through the system for 20 minutes while seated at rest. Data were taken and all recorders run for a one minute period at the beginning of this phase and at five minute intervals thereafter. At the conclusion of the rest phase, the subject removed the mouthpiece and calibration gases were passed through the analyzer. This operation was about five minutes in duration. At the completion of calibration, the subject again inserted the mouthpiece, secured the noseclip, and the treadmill was run at a speed of 3.4 miles per hour, zero grade for a fifteen minute period. Data were taken and all recorders were again run for a one minute period at the beginning of this phase and at five minute intervals thereafter. At the conclusion of this exercise phase, the treadmill was stopped, the subject removed the mouthpiece, and calibration gases were again passed through the system. Phase three was identical to phase two, except that the treadmill was inclined at an angle of five degrees.

At the conclusion of the second exercise phase, the subject was dismissed and calibration gases were again passed through the system.

ALTITUDE RUNS

The altitude runs (25,000 feet) were conducted in an identical manner except that the subject pre-oxygenated for 60 minutes prior to chamber ascent, wore the oxygen mask to altitude (type MS-22001) and hand-held the oxygen mask to his face between test phases when not utilizing the mouthpiece. Calibration gases were passed through the system before, during, and after the experimental phases as in the ground level runs. A qualified inside observer accompanied each subject to altitude and made the necessary data notations specified on the data sheet. Ascent rate was 5000 feet per minute and descent rate was 4000 feet per minute.

"SYSTEM CHECK" RUNS

At the request of the NASA project monitor, two ground level runs were made with the experimental apparatus modified in a manner necessary to "close the loop" with the subject and the spirometer in the closed loop. This was accomplished by connecting the exhaust or inhalation side of the spirometer to the dry gas meter, thus closing the loop. For these runs, the subjects were pre-oxygenated for 20 minutes at rest to eliminate all pulmonary and some circulatory nitrogen. At the end of the 20 minute pre-breathing period, the subject was switched to the closed loop and all previous data determinations plus oxygen consumption as indicated by the spirometer were made. The subject was switched back to 100% O_2 from an MD-1 regulator while calibration gases were passed through the analyzer and the spirometer was flushed and filled with 100% O_2. The subject, still breathing from the MD-1 regulator was then exercised on the treadmill for 15 minutes at which time he was switched back to the closed system while continuing to walk at 3.4 miles per hour. As the subject exhausted the oxygen in the spirometer, the run was terminated, the subject was excused, and calibration gases were again passed through the system.

SCHEDULE OF TEST RUNS

The following list represents the schedule of test runs. Not included are check-out runs which preceeded these data runs.

TABLE 1

RUN NO.	SUBJECT	DATE	COMMENTS
		GROUND LEVEL	
1	S.C.	11-11-64	OK
2	G.M.	11-11-64	OK
3	B.M.	11-12-64	OK
4	N.L.	11-12-64	OK
5	J.K.	11-13-64	OK
6	G.M.	11-13-64	OK
7	M.G.	11-18-64	OK
8	J.P.	11-19-64	OK
		25,000 Feet	
9	B.M.	11-19-64	OK
10	G.M.	11-20-64	Prototype CO_2 sensor failed shortly after reaching 25,000 ft.
11	G.M.	11-23-64	CO_2 sensor failed just prior to ascent.
12	S.C.	11-23-64	CO_2 sensor failed just prior to ascent.
13	S.C.	11-24-64	CO_2 sensor failed shortly after reaching 25,000 feet.
14	J.P.	11-24-64	CO_2 sensor failed shortly after reaching 25,000 feet.
15	J.K.	11-24-64	Run completed at 25,000 feet, but ground level calibration showed CO_2 analyzer sensitivity shift.

TABLE 1 (Cont'd.)

RUN NO.	SUBJECT	DATE	COMMENTS
16	S.C.	12-1-64	OK
17	J.P.	12-2-64	OK
18	M.G.	12-2-64	OK
19	N.L.	12-3-64	OK
		SYSTEM CHECK	
20	G.M.	12-3-64	CO_2 analyzer ceased operating during run.
21	G.M.	12-9-64	O_2 analyzer ceased operation. Change of sensor not effective. Failure probably occurred in amplifier.
22	S.C.	12-9-64	O_2 analyzer ceased operation. Change of sensor not effective. Failure probably occurred in amplifier.

DATA ACQUISITION

Inspiratory mass flow, expiratory mass flow, LB-15 CO_2, analyzer CO_2, analyzer expired air O_2 concentration, expired air temperature, and total pressure were simultaneously recorded on Sanborn recorders for one minute periods at five minute intervals (see data sheet). Gas meter readings, thermister temperature, and spirometer temperature readings were manually recorded during the same period that the recorders were running. Exhaled air was also collected in the spirometer at this time. In this manner, a running check on the analyzer temperature and CO_2 output was possible. Because of the very slow response of the Beckman F-3 oxygen analyzer which was specified as the standard instrument against which the miniaturized O_2 sensor was evaluated, no simultaneous breath-by-breath analysis was possible. Instead, expired air collected in a Douglas bag and various calibration gases were simultaneously analyzed by the F-3 and prototype oxygen analyzers.

PREPARED BY:	NORTH AMERICAN AVIATION, INC.	PAGE NO. 26 OF
CHECKED BY:	Figure 13 Data Sheet	REPORT NO. NA-64-1298
DATE 12-14-64		MODEL NO.

SUBJECT:

DATE:

ALTITUDE:

Sample	TIME (MIN)	WORK LEVEL	AIR TEMP 1. INSP.	AIR TEMP 2. EXP.	SPIRO TEMP READING	SPIRO SET	GAS METER READING	REL. HUMIDITY	COMMENTS	
1	START	REST								
		↓								
2	+5									
3	+10									
4	+15									
5	+20	↓								
6	+25	3.4 mph 0%								
		Grade								
7	+30	↓								
8	+35									
9	+40	↓								
10	+45	3.4 mph								
		5% Grade								
11	+50	↓								
12	+55									
13	+60	↓								

RESULTS

Because of the large quantity of data collected and the limited scope of the contract, reduction of all data was impossible. In order to provide the most meaningful sampling procedure, a decision had to be made as to which data samples provided the most pertinent information. Samples 5, 8, 9, 12, and 13 were chosen for the following reasons. Sample 5 was taken at the end of the 20 minute rest phase and was chosen on the assumption that the subject was equilibrated at this point and that the data sample would be very representative of the rest condition. Samples 8 and 9 were taken five minutes before the end and at the end of the 15 minute moderate exercise phase. They were chosen as representative of the respiratory response to moderate exercise. Samples 12 and 13 were taken five minutes before the end and at the end of the 15 minute heavy exercise phase and were chosen as being representative of respiratory response to heavy exercise. Figures 14 through 23 and 24 through 33 show typical data traces for a subject during both ground level and altitude runs. Figures 34 through 40 show typical performance of the prototype O_2 analyzer and the F-3 paramagnetic O_2 analyzer during simultaneous exposure to expired air and calibration gases.

METHODS OF DATA REDUCTION

The following methods were utilized to interpret the data obtained from the various sensors.

CO_2 ANALYZERS

Because both CO_2 analyzers exhibited some breath-to-breath variation in output, an attempt was made to determine average output voltage. The voltage was converted to partial pressure of CO_2 in accordance with the calibration curves shown in figures 4 and 5.

PROTOTYPE O_2 ANALYZER

The O_2 analyzer provides a linear output and is readily calibrated with 0% O_2 and 100% O_2. Analyzer output was adjusted at the recorder so that 40 mm of paper equaled 760 mm Hg oxygen. Each mm of paper, therefore, was equivalent to 19 mm pO_2 at ground level. For altitude runs, pO_2 data were based on calibrations conducted at 25,000 feet because the sensor exhibited some drift at altitude.

MASS FLOWMETERS

The output of the mass flowmeters was adjusted at the recorder so that one mm of paper equaled 144 millivolts. Because of the nature of the flowmeter output, it was necessary to integrate the area under the curves over a period of one minute to get an average voltage for this period. This voltage was then converted to pounds of gas per minute. Based on the perfect gas laws, conversion factors were derived to convert mass flow to liters per minute in accordance with figure 8.

DRY GAS METER

The volume of gas indicated by the dry gas meter was recorded without application of conversion factors.

SPIROMETER

The spirometer volumes were corrected for temperature and pressure in accordance with conversion tables provided by the supplier, Collins Instruments, Inc.

PRESSURE SENSOR

Figure 6 shows calibration curves for the pressure transducer as supplied by both the manufacturer and Beckman Instruments. Actual performance of the transducer during altitude runs did not agree with either curve, but produced outputs as shown in figure 41.

TEST RESULTS

A summary of test results derived from the chosen data samples is presented in Table 2. All results with the exception of pressure transducer data are tabulated on this single sheet to facilitate comparative evaluation of the various sensors. Results of the system check runs are listed in Table 3.

RUN #	CO₂ MEASUREMENTS mm Hg pCO_2 — LB-15 ANALYZER					PROTOTYPE ANALYZER					ANALYZER OXYGEN mm Hg pO_2					INSPIRA… #1 FLO…	
	SAMPLE 5	SAMPLE 8	SAMPLE 9	SAMPLE 12	SAMPLE 13	5	8	9	12	13	5	8	9	12	13	5	8
#1 S.C.	35	36	36	38	38	37.5	38	38	40	40	693	684	684	684	684	7.2	20.6
#3 B.M.	31.4	38	38	42	42	32	40	40	45	45	665	665	665	646	646	9.5	23.5
#4 N.L.	31.4	38	38	40	40	33.7	39.5	39.5	45	45	665	665	665	665	665	9.7	21.1
#5 J.K.	32.4	45.6	45.6	45.6	45.6	33.7	48	48	48	48	693	665	665	665	646	6.95	20.9
#6 G.M.	30.4	36	36	38.5	38.5	31	37.5	37.5	40	40	684	665	665	665	640	14.7	25.0
#7 M.G.	28	38.5	38.5	39	39	29	39.5	40	40	40	665	665	665	665	675	9.7	23.8
#8 J.P.	28.5	39	39	40	40	28.5	40	40	42	42	676	680	680	674	674	9.5	27.8
#9 B.M.	20.5	27	27	28.5	28.5	21	27	27	28.5	28.5	215	215	215	215	215	9.1	22.2
#15 J.K.	20	32.4	32.4	38	38	22.5	33	33	38	38	X	X	X	X	X	5.7	22.2
#16 S.C.	21.5	23.8	23.8	24	24	20.5	23.5	23.5	24	24	218	218	218	207	207	7.4	17.6
#17 J.P.	? 10.7	? 15.2	? 15.2	? 18.5	? 18.5	19	22	22	23	23	210	190	210	210	210	12.5	22.2
#18 M.G.	20	21	21	23.8	23.8	21	22.5	22.5	24.5	24.5	210	210	210	200	200	8.5	19.9
#19 N.L.	18.5	21	21	21.7	21.7	20	21.5	21.5	22.5	22.5	200	210	210	200	200	6.4	22.7

TABLE 2

SUMMARY SHEET — TEST RESULTS

ATORY FLOW (LITERS / MIN)								EXPIRATORY FLOW (LITER / MIN)										
WMETER			GAS METER					#2 FLOWMETER					SPIROMETER					AT
9	12	13	5	8	9	12	13	5	8	9	12	13	5	8	9	12	13	5
21.0	24.4	23.2	7	17	18	18	23	8.7	19.3	20.9	24.0	23.0	7.2	16.2	16.3	22.2	24.2	73.5
22.7	26.8	27.6	7.3	18	19	23	23	9.6	22.6	20.8	26.1	27.6	9.7	21.0	25.4	28.4	25.4	75.5
28.7	28.1	33.5	8.4	22	23	26	26	8.3	23.3	29.6	28.9	34.1	8.3	23.3	27.9	27.3	31.7	76.7
24.1	25.9	27.6	6.5	15	18	20	22	7.0	19.4	24.1	26.1	28.0	7.8	20.3	24.1	25.4	25.4	73.5
29.1	38.6	37.3	10	25	24	30	29	14.8	27.6	29.6	39.8	38.3	15.9	29.2	31.7	43.4	40.6	75.5
21.1	26.9	24.0	8	19.8	20	21.5	24	9.6	24.4	21.8	27.4	24.6	9.1	21.0	21.1	26.0	24.8	72.4
28.9	32.9	33.5	8.9	22	24	27	28	9.2	28.5	28.5	33.7	33.5	9.2	23.5	26.5	29.2	31.7	73
22.6	28.5	28.5	7.7	12	18	22	25	8.8	21.7	22.3	28.1	28.1	8.1	19.8	20.4	26.4	28.3	71.2
25.5	25.0	25.0	8.1	16	17	19.6	18.6	5.9	21.1	24.6	24.6	24.6	X	X	X	X	X	75.7
21.0	22.7	27.3	6.8	18	18	24.4	26	7.6	18.2	21.1	21.7	27.0	7.2	17.6	23.7	23.7	26.4	74.3
25.6	27.8	30.7	8.0	19	20	24.6	27.4	12.5	22.9	25.6	27.5	30.5	13.2	26.4	26.4	33	33	71.5
22.2	24.4	27.9	6.3	17	16	21.2	20.6	8.8	19.9	22.9	24.6	26.4	7.7	19.8	21.7	22.7	24.4	73.0
2.2	24.4	26.7	6.7	20.2	20.4	26	25.4	6.5	22.9	21.1	24.0	27.6	6.7	22.8	23.1	26.6	28.7	72.6

30-A-2

NA 64-1298
12-14-64
PAGE 30A

TEMPERATURE MEASUREMENTS (°F)													
#1 FLOWMETER				AT ANALYZER					AT #2 FLOWMETER				
8	9	12	13	5	8	9	12	13	5	8	9	12	13
74.0	74.0	74.5	74.5	91.5/88	89.7/89	88.8/88.8	88.8/88.8	88.8/88.8	93	91	91	91.7	91.7
75.5	75.5	75.7	75.7	105/84.4	106/87.1	106/87	102.4/88	97/85	99.5	102	102	103	103
77.5	77.5	77.5	77.5	107/88	101/89	104/95	90/87	93/89	98	105	106	106	106
74	74	74.5	74.5	117/97	119/98	119/99	118/101	116/102	99	104.5	105	107.5	107.5
75.5	75.5	76	76	110/97	106/98	?	103/96	103/98	100	102	102	102	102
72.5	72.5	73	73	107/95	105/94	102/95	104/95	101/95	94	93.5	92	93	92
73.2	73.0	73.7	73.9	95/82	94/83	93/83	92/85	90/83	92	93	94	94	94
72.7	72	73.2	73.5	111/94	119/98	116/98	115/98	114/98	88.5	92.5	93	96.2	96.2
77	77	78.3	78.6	113/106	115/107	115/107	116/109	116/109	90	94.5	94.7	94.2	95
75.2	75.6	76.6	76.7	106/97	113/97	113/103	112/102	119/103	92.3	95.3	96	98.2	98.6
72.4	72.7	74.2	74.2	X	X	X	X	X	90.5	94	94.7	95.5	96.2
73.8	74.1	75.1	75.4	X	X	X	X	X	88	91.8	93	94.7	94.7
73.3	73.6	74.7	75.2	X	X	X	X	X	90.5	93.5	95.2	96.7	97.5

30A-3

RUN NO.	CO_2 (mm Hg)				O_2 Uptake (cc/min)		INSPIRATORY FLOW (L/M)				EXPIRATORY FLOW (L/M)				TEMPERATURE (°F)			
	LB-15		Prototype				#1 Flowmeter		Gas Meter		#2 Flowmeter		Spirometer		#1 Flowmeter		#2 Flowmeter	
	Rest	Work	Rest	Work	Rest	Work	Rest	Work	Rest	Work	Rest	Work	Rest	Work	Rest	Work	Rest	Work
20 GM	26.8	32.9	22.6	X	269.3	X	15.6	44.7	12.6	X	14.2	38.2	7.7	X	74.5		77.2	X
21 GM	23.7	34.5	24.0	34.0	189.0	954.7	15.4	35.4	12.3	29.8	12.6	26.1	10.2	28.0	75.6	75.5	80.5	78.6
22 SC	27.8	36.5	29.0	37.5	153.9	770.7	9.5	24.0	9.4	17.4	8.5	15.6	7.7	17.6	75.2	76.2	75.5	80.7

Table 3 - SYSTEM CHECK DATA

G.L. BM 12 NOV RUN 3

NA-64-1298
12-14-64
Page 31

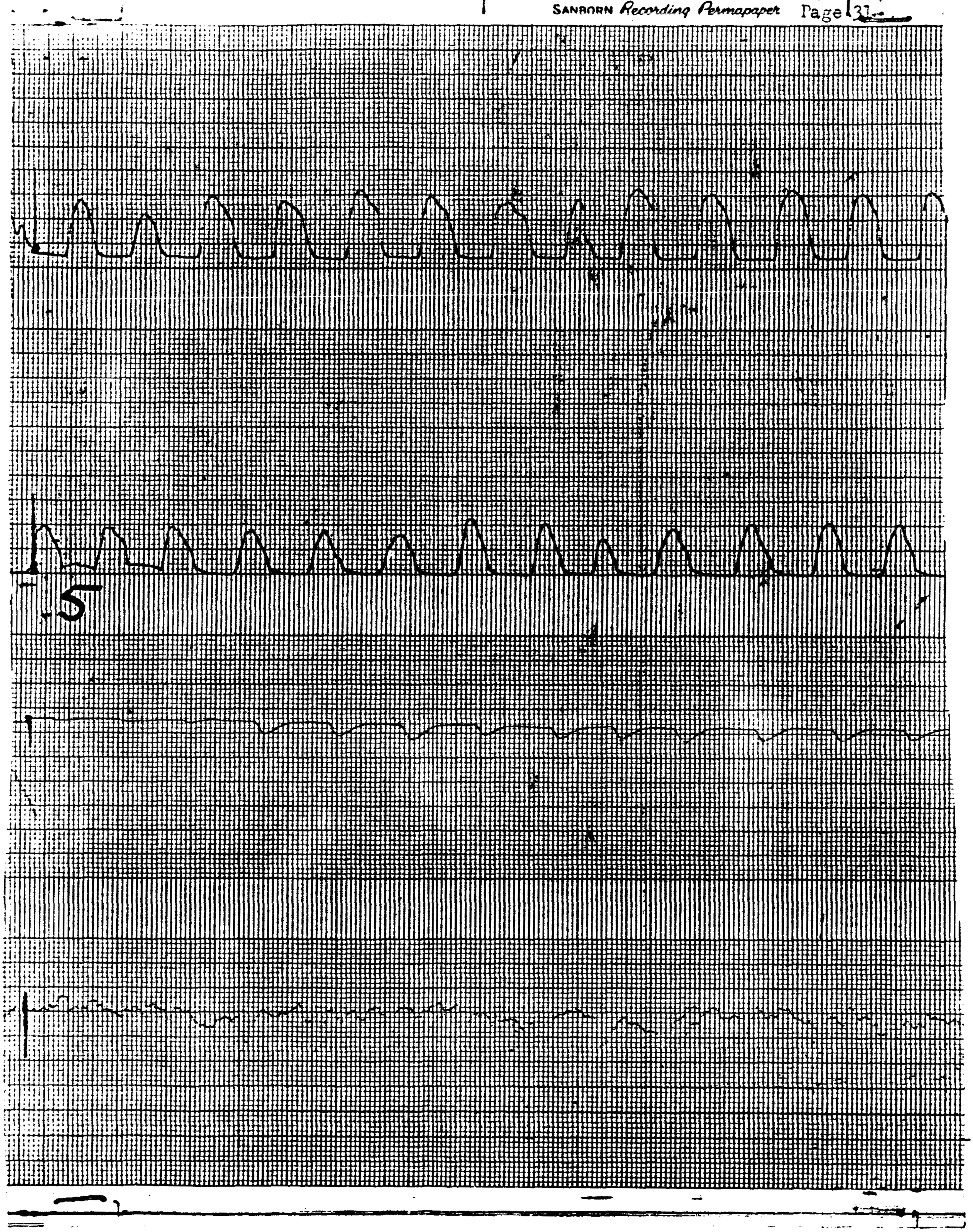


Figure 14

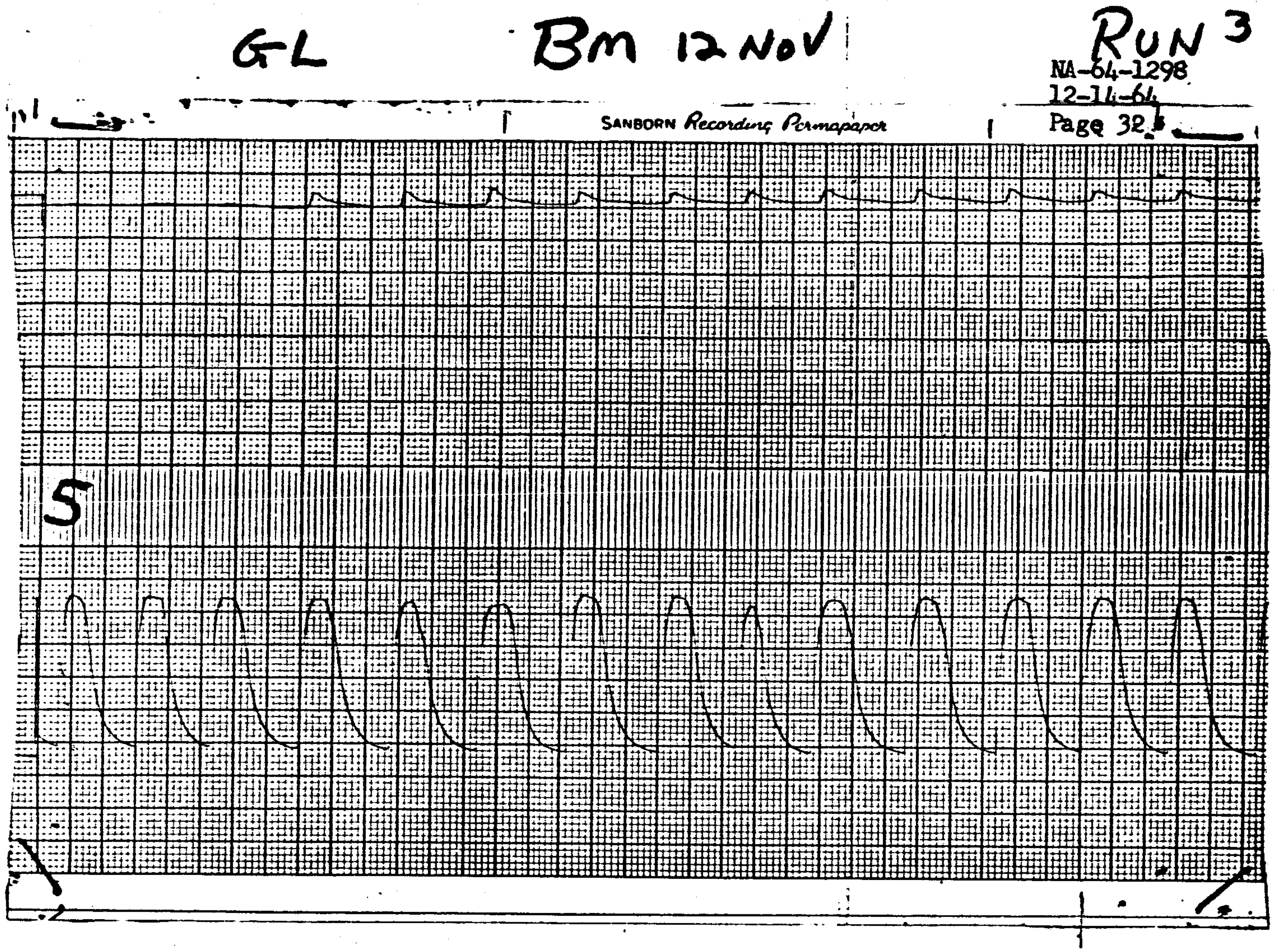

GL
BM 12 NOV
RUN 3
NA-64-1298
12-14-64
SANBORN Recording Permapaper
Page 32
5

Figure 15

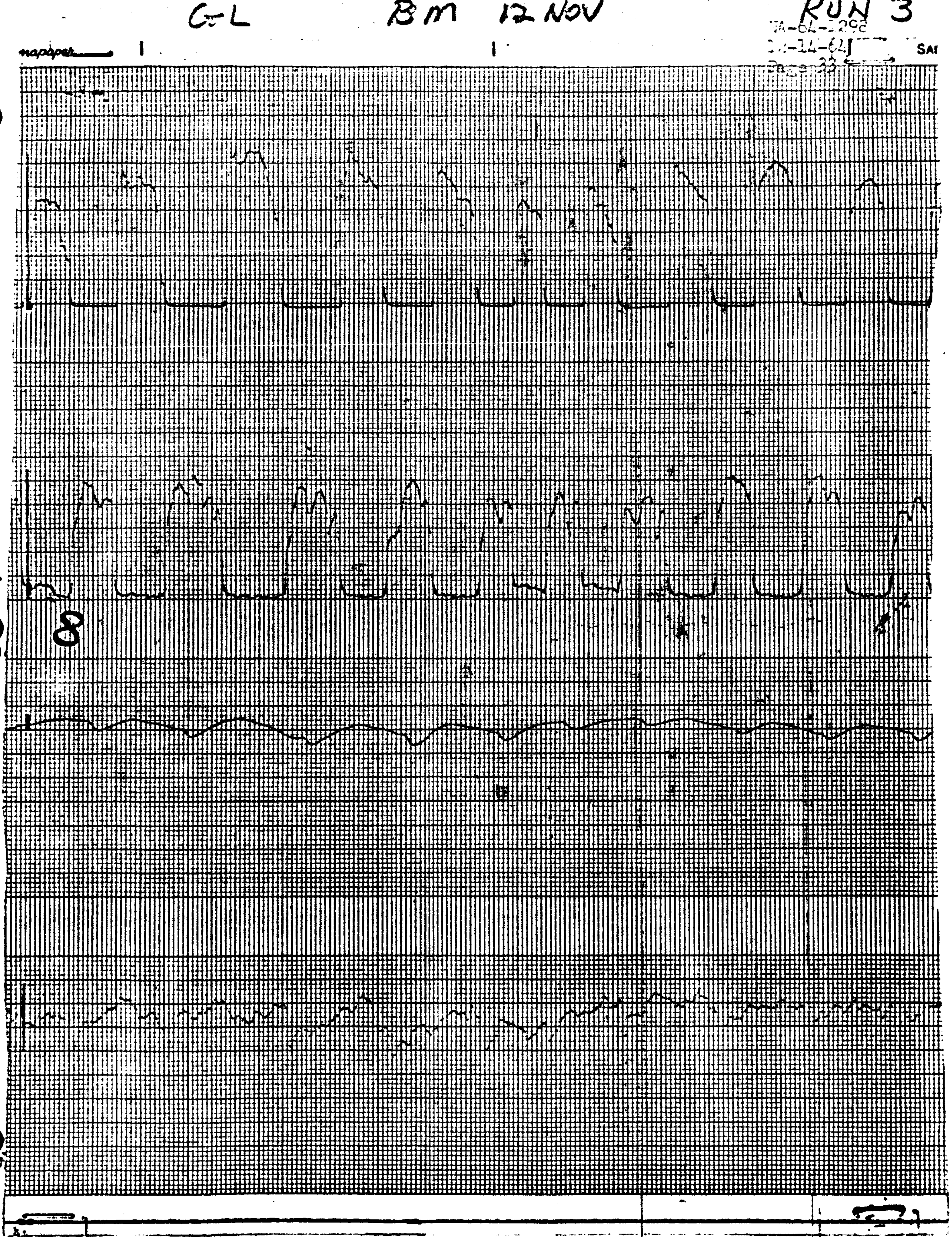


Figure 16

GL BM 12 NOV RUN 3

Figure 17

GL BM 12 NOV RUN 3

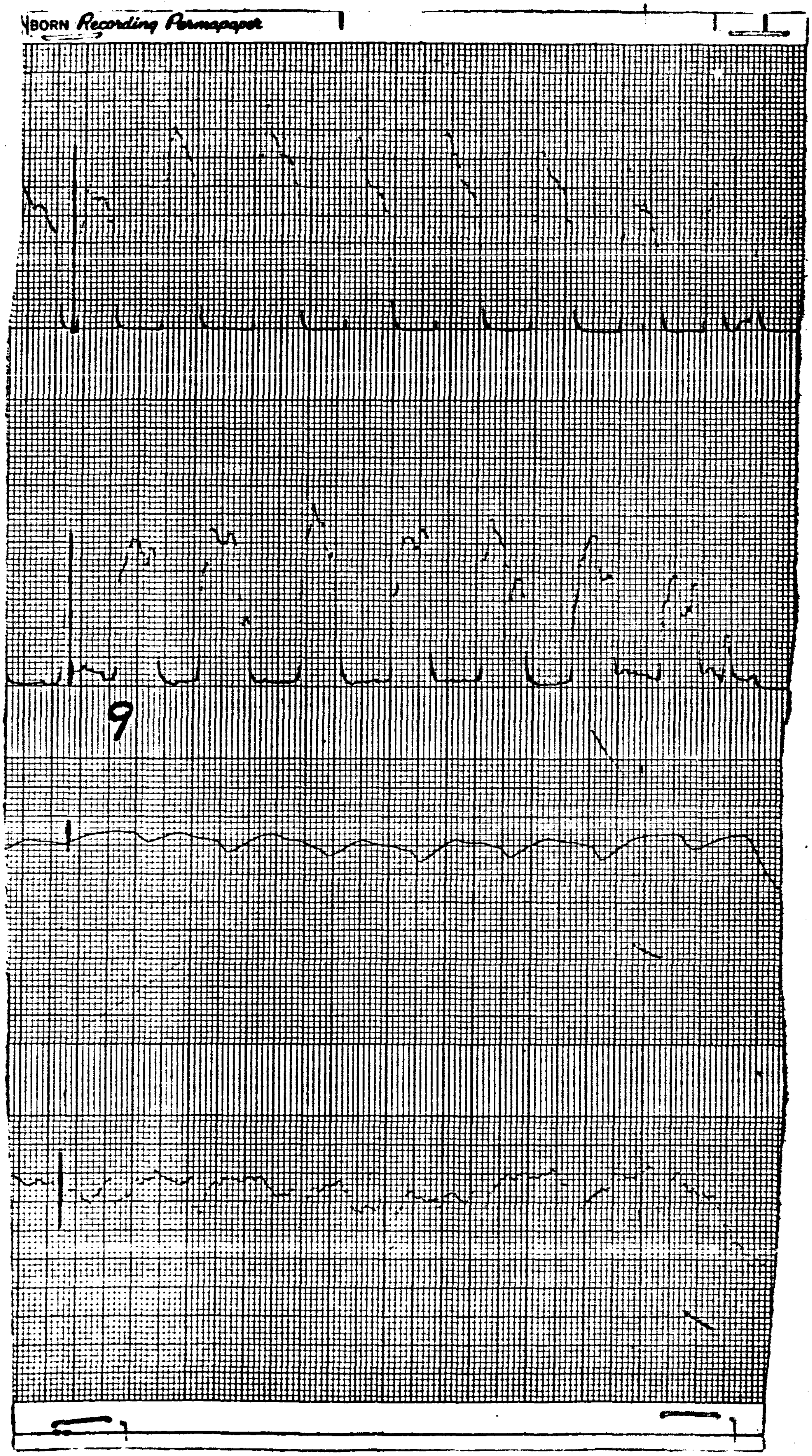


Figure 18

GL BM 12 NOV

RUN 3

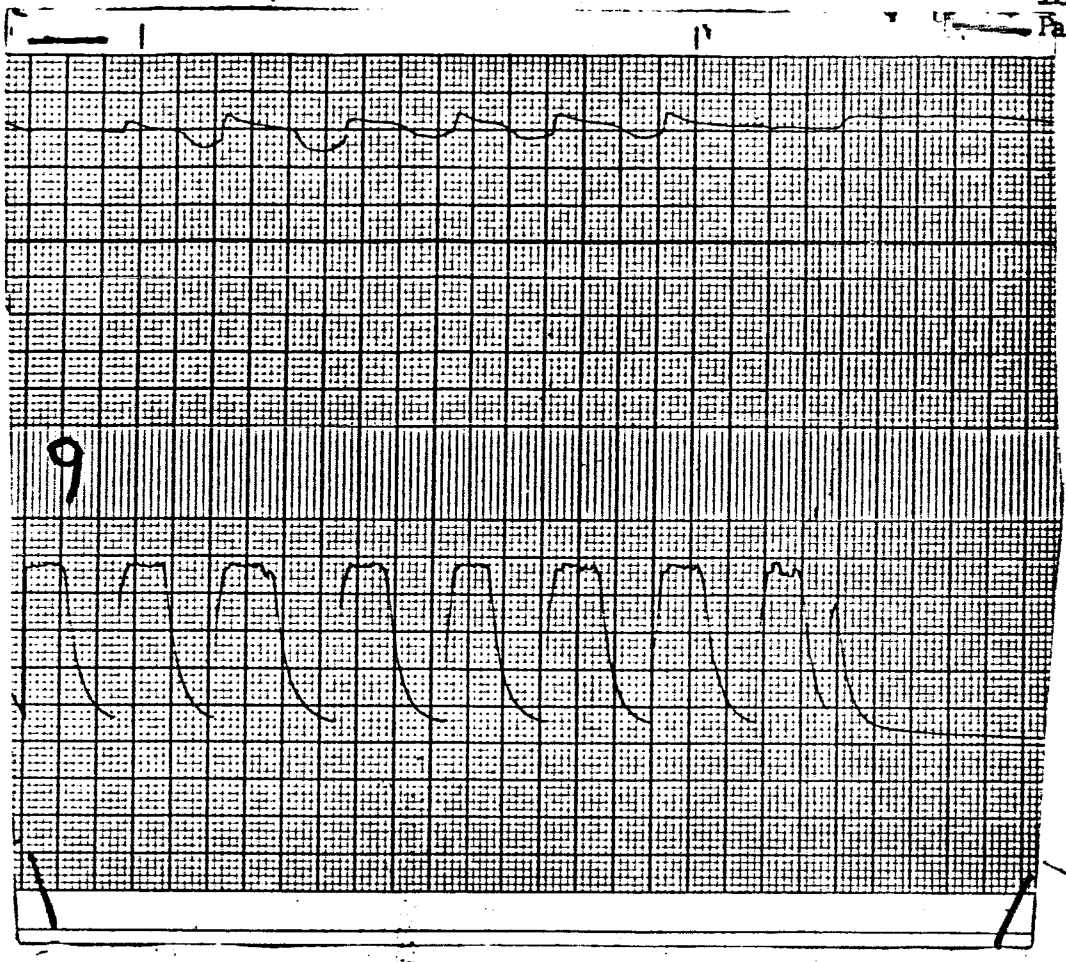


Figure 19

GL BM 12 NOV NA-64-1298 RUN 3

12-14-64

Page 37

SANBORN Recording

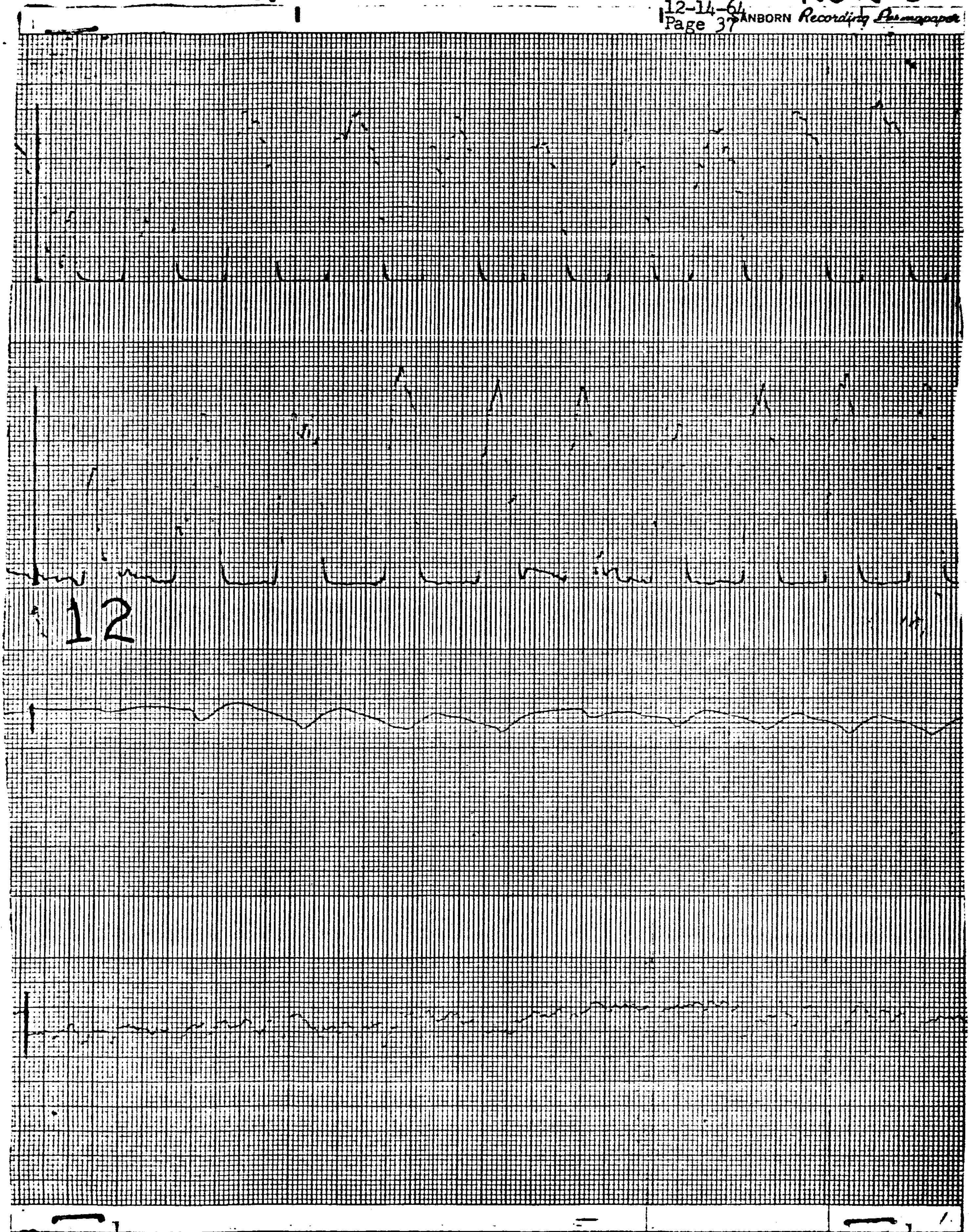


Figure 20

GL BM 12 NOV RUN 3

NA-64-1298
12-14-64
Page 38

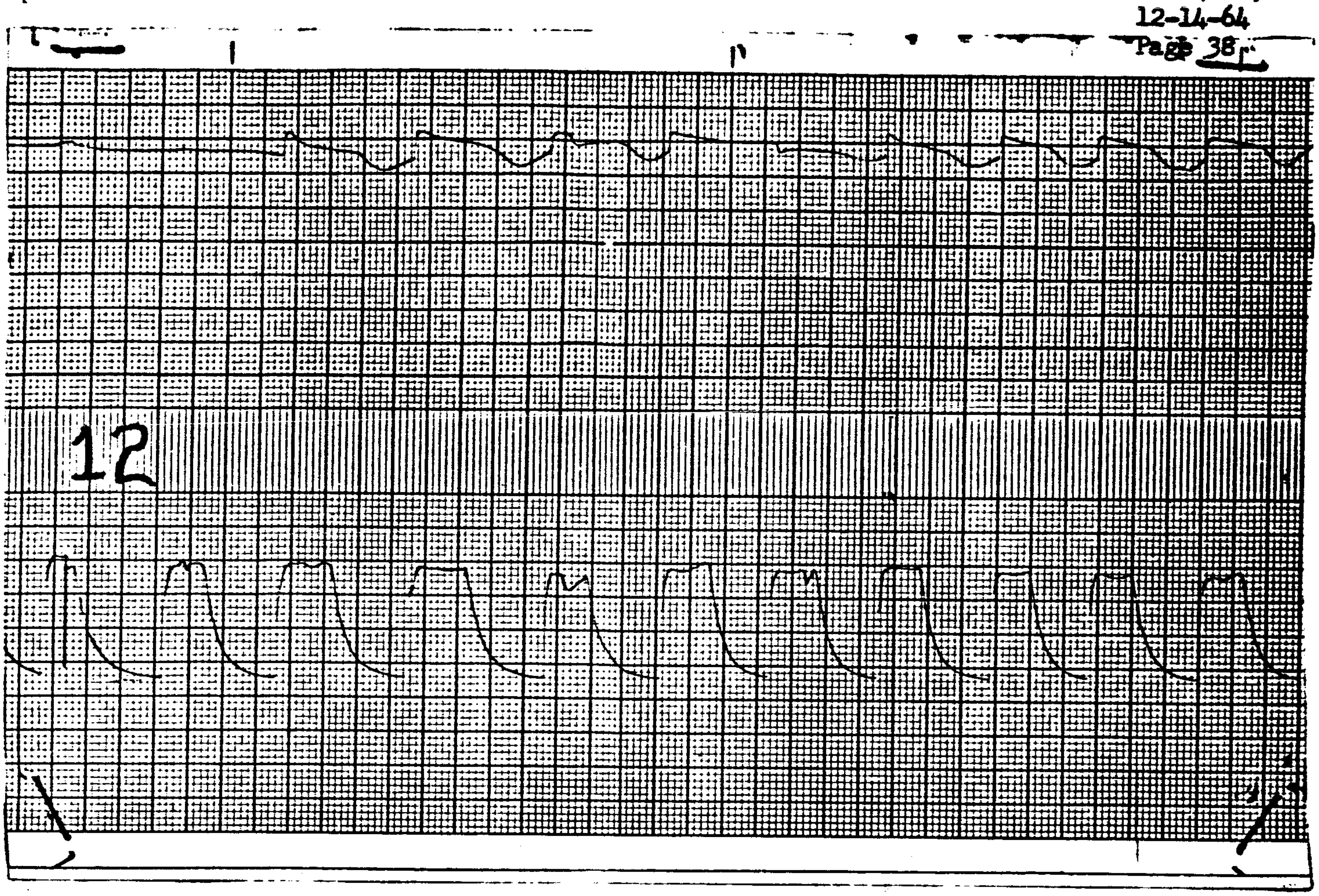


Figure 21

GL BM 12 NOV RUN 3

NA-64-1298

12-14-64

Page 39

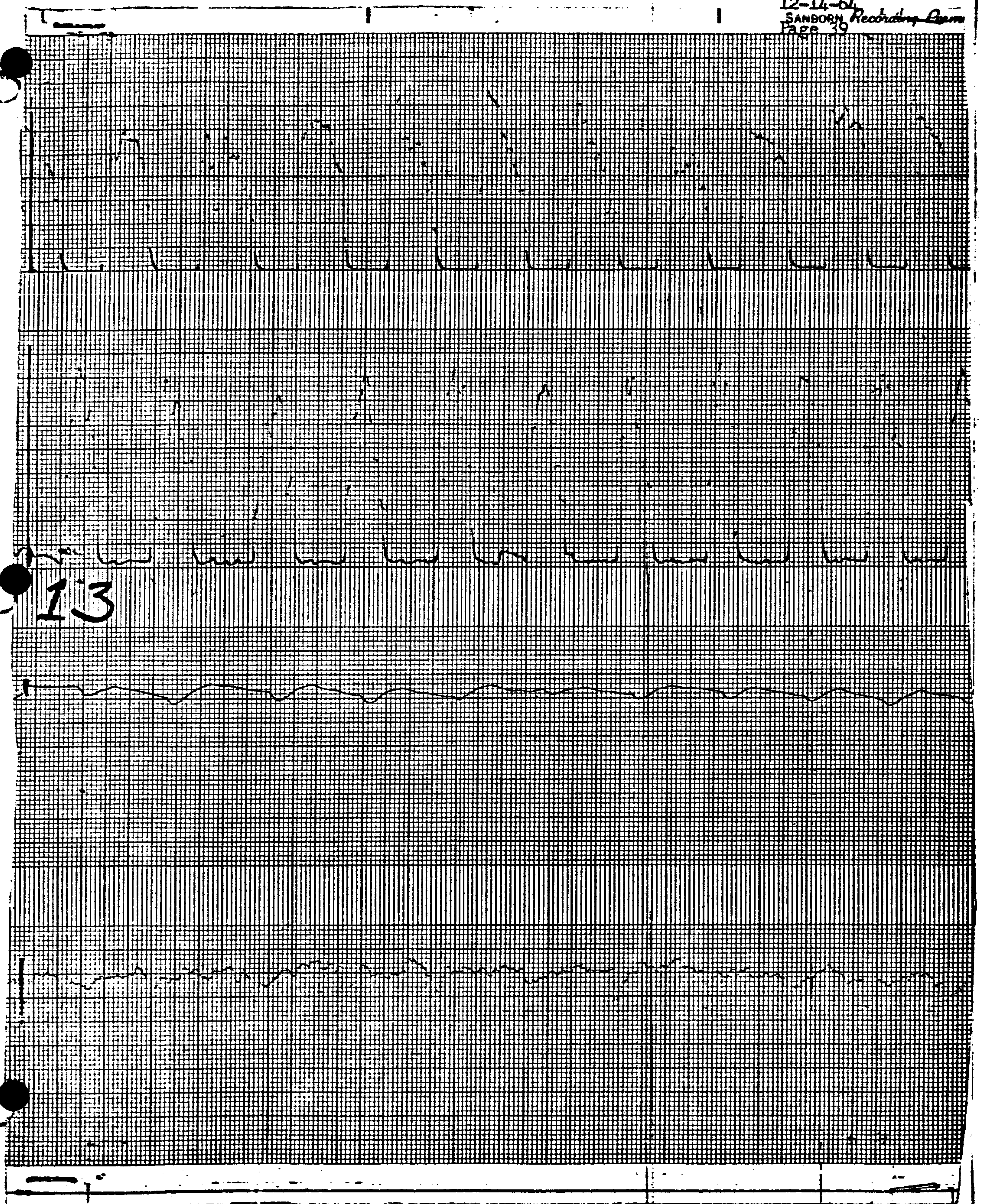


Figure 22

GL BM 12 NOV RUN 3

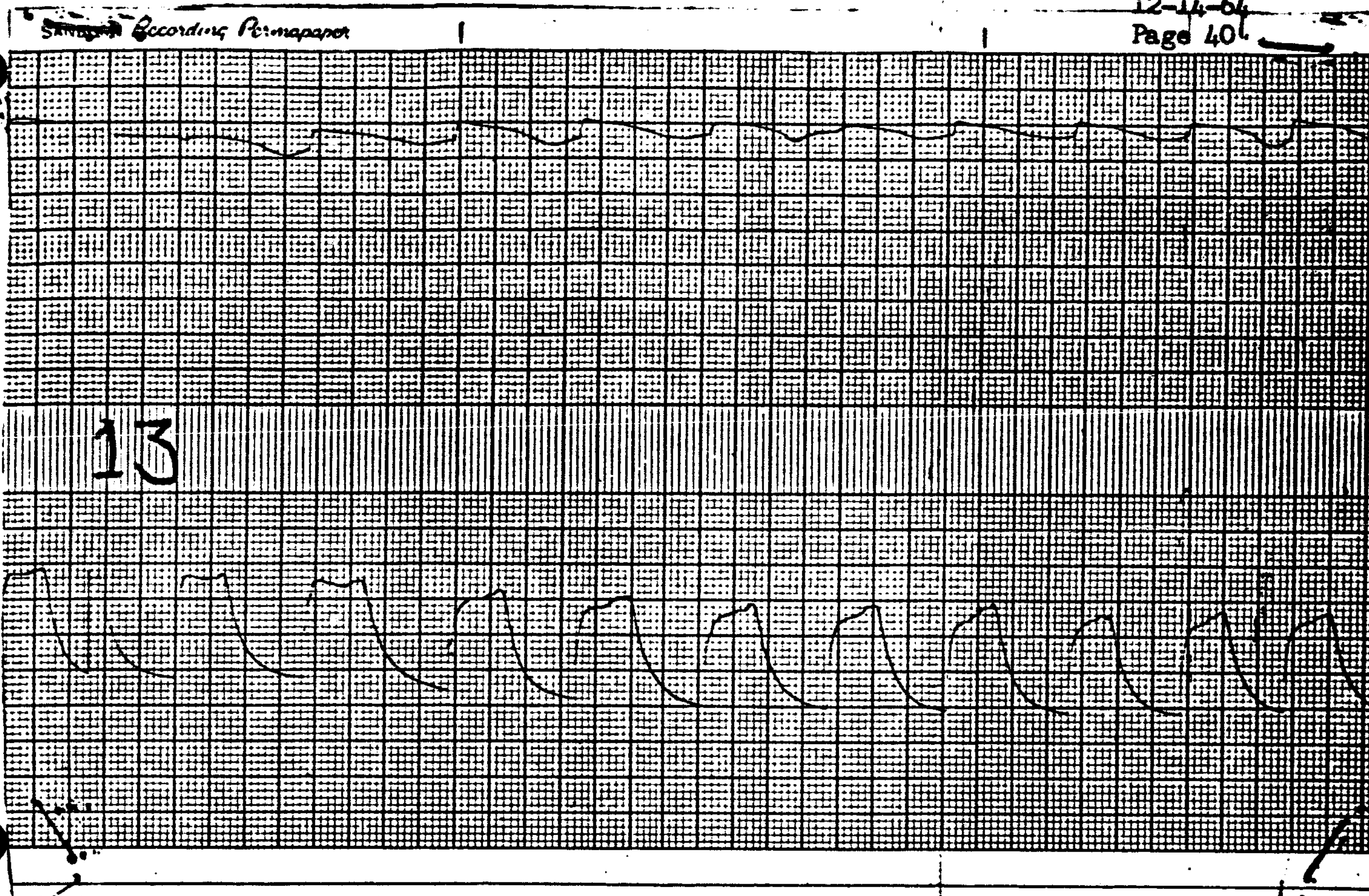


Figure 23

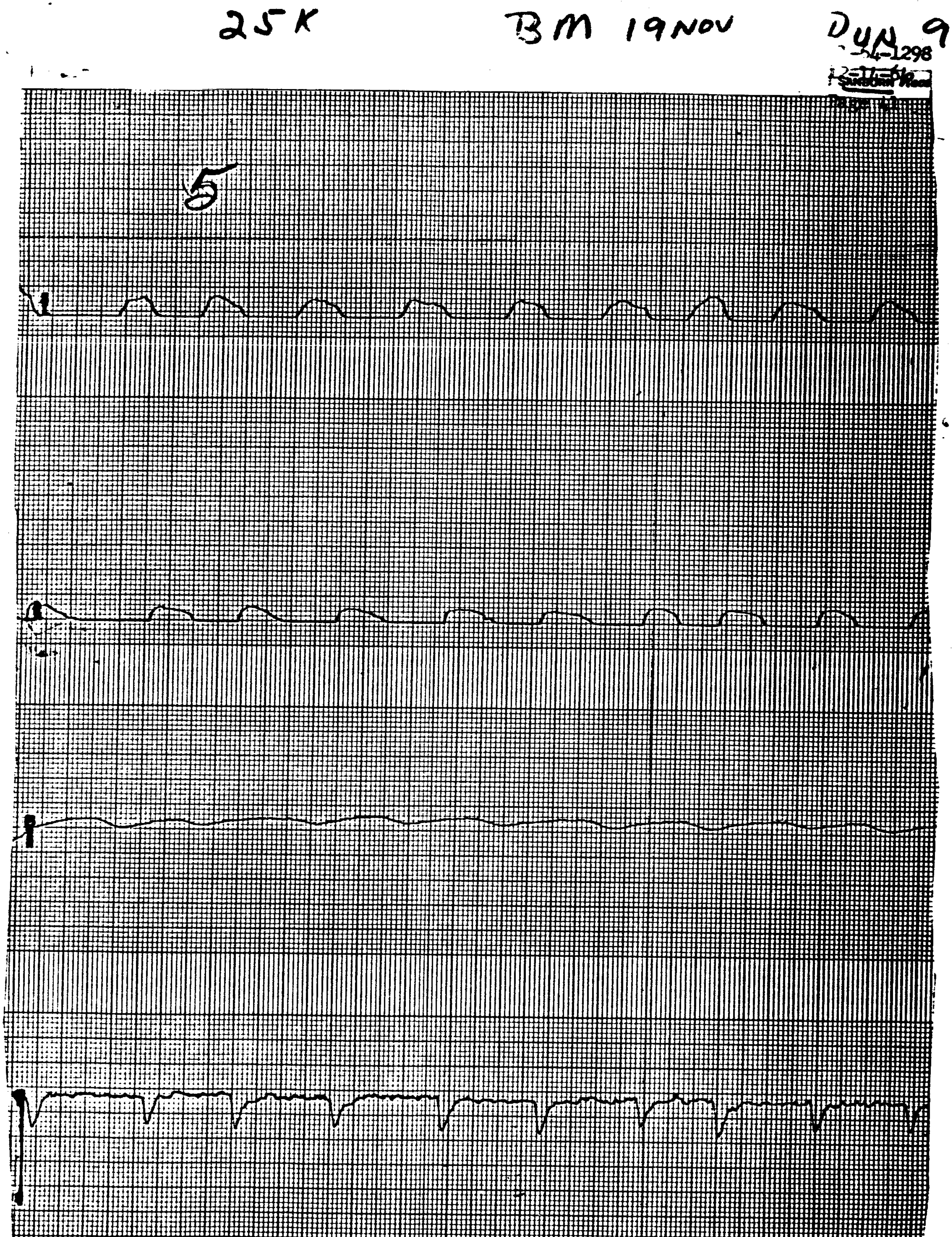


Figure 24

25K

BM 19 Nov RUN 9

NA-64-1298
12-14-64
Page 42

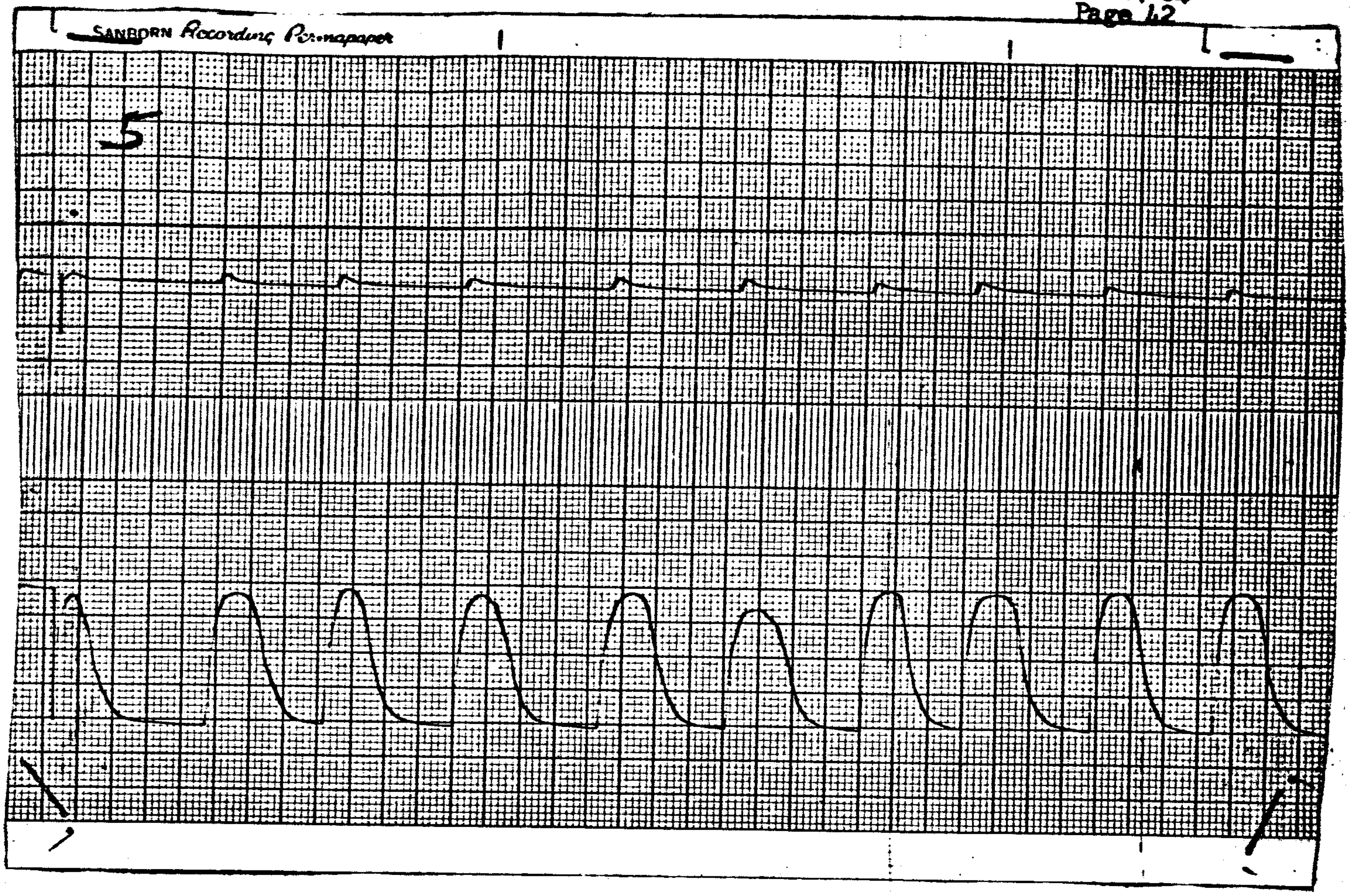


Figure 25

25K Bm 19NOV RUN 9

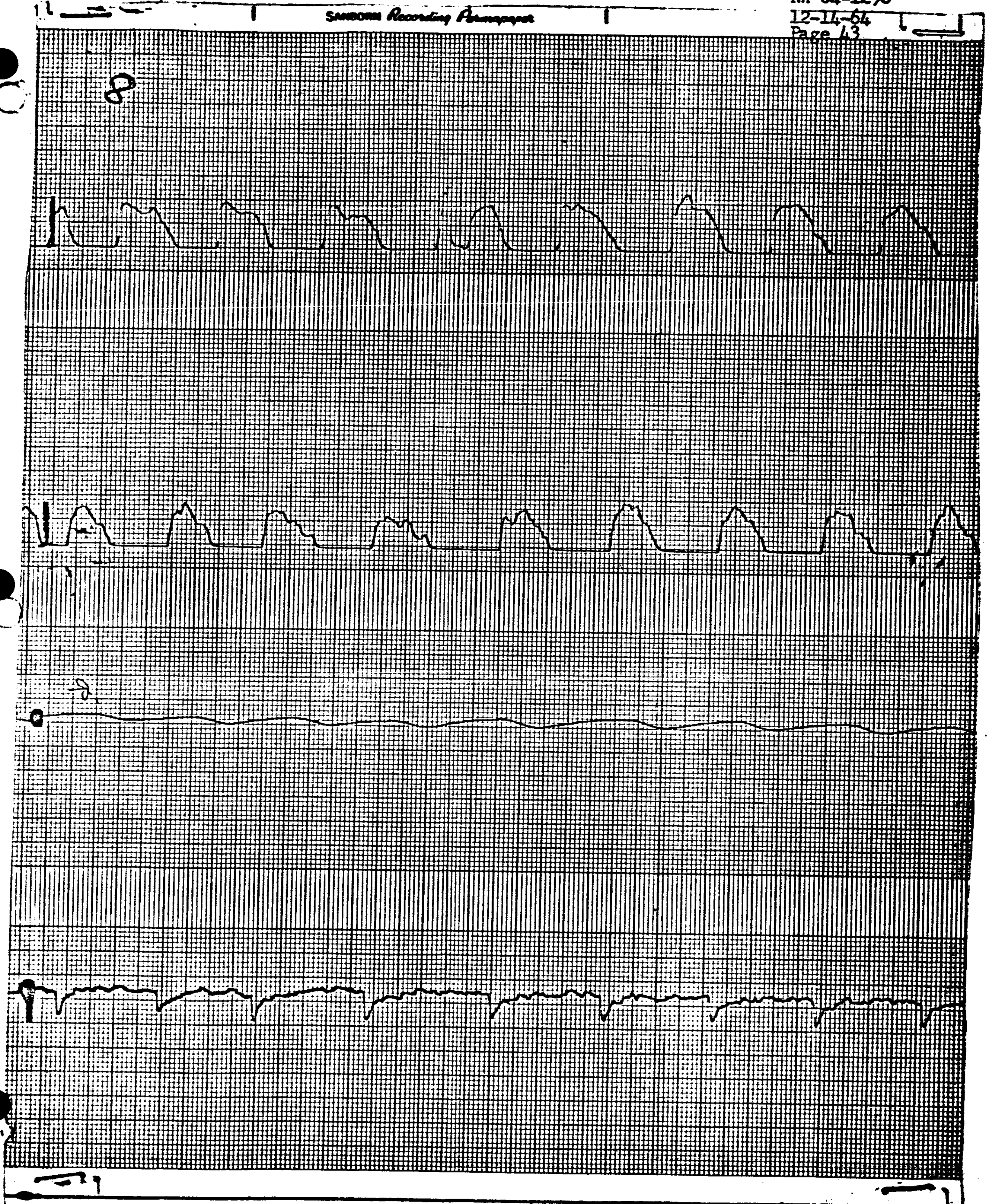


Figure 26

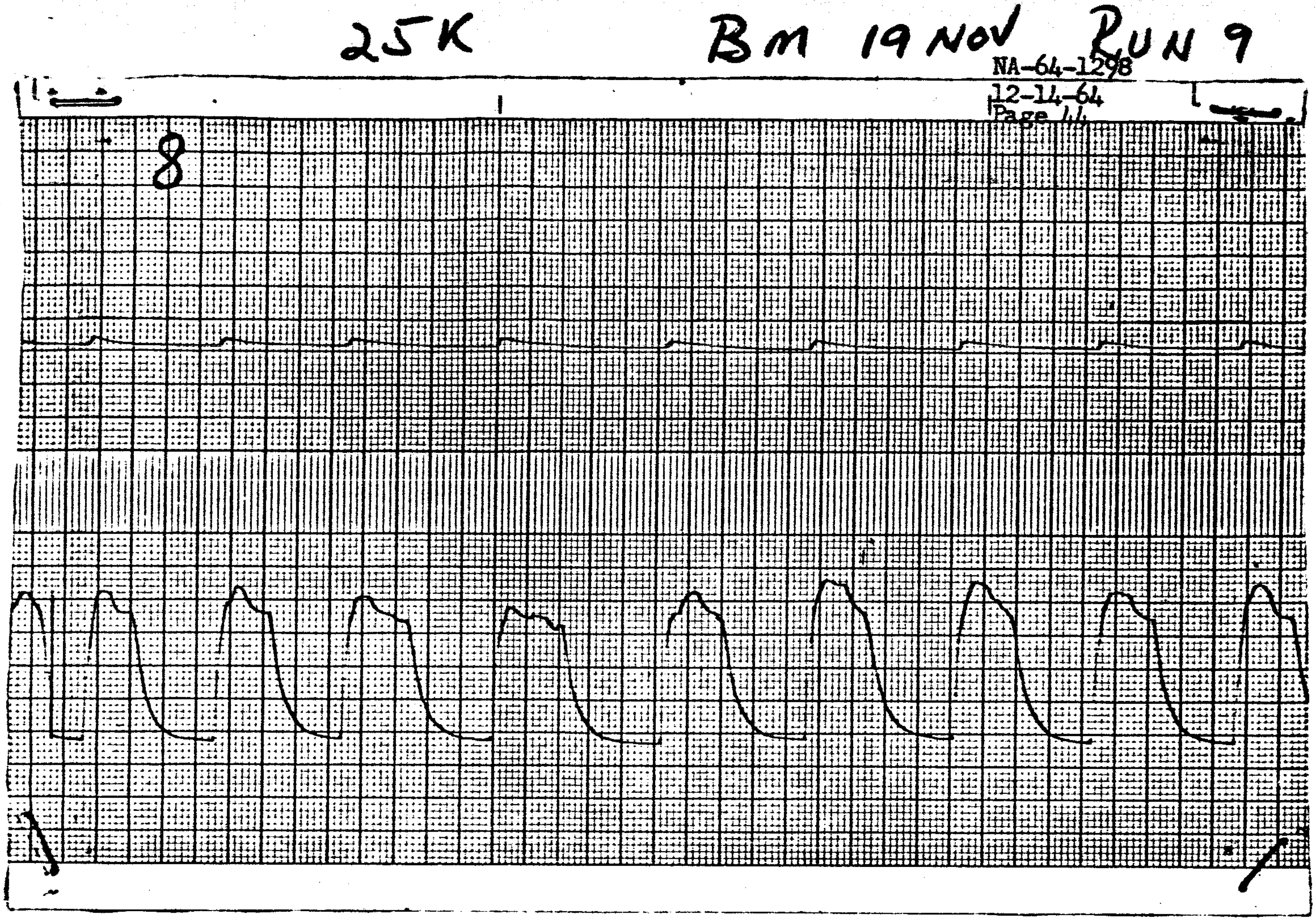


Figure 27

25K BM 19NOV RUN 9

NA-64-1298
12-14-64
Page 45

SANBORN Recording Permapaper

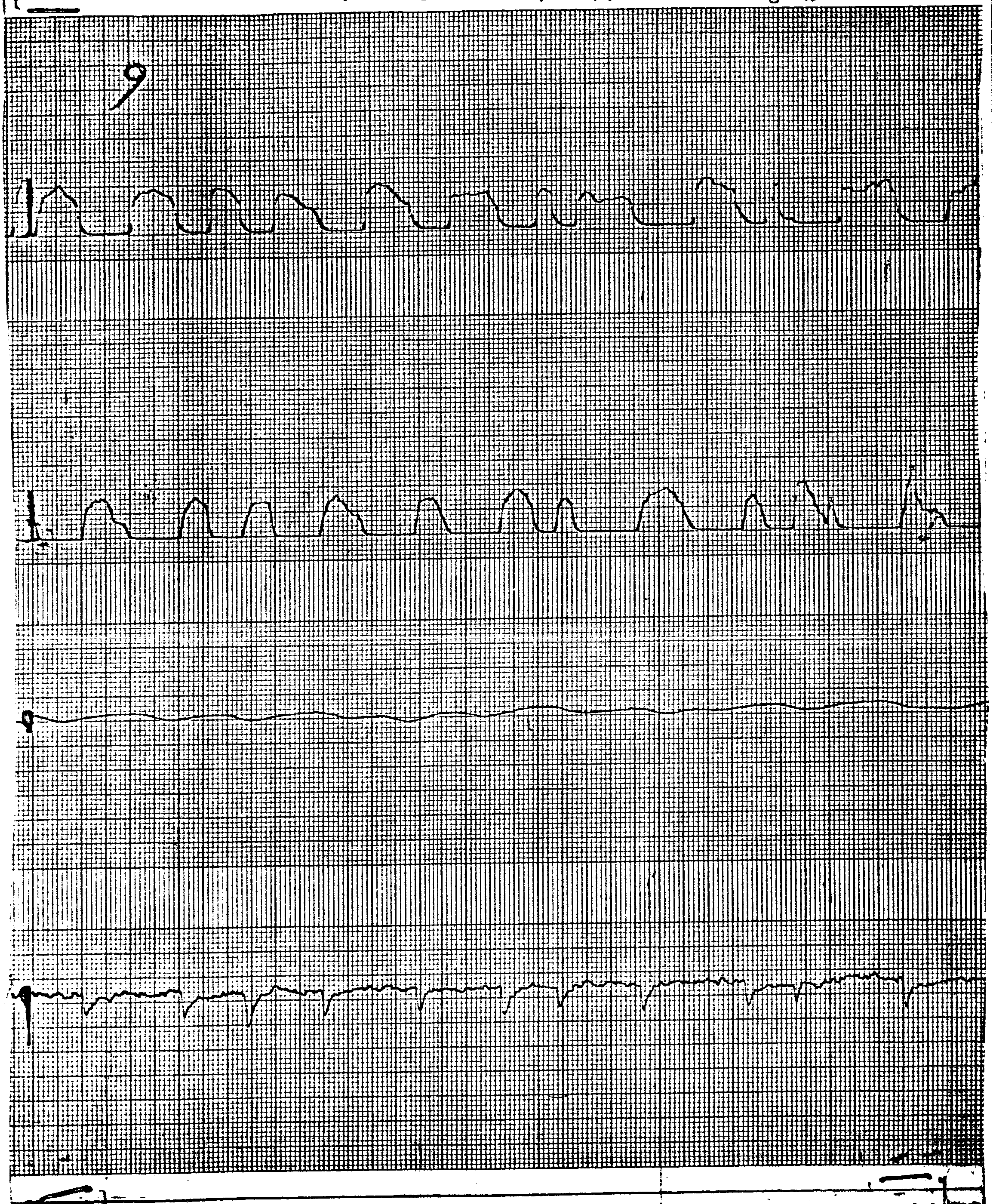


Figure 28

25K BM 19 NOV RUN 9

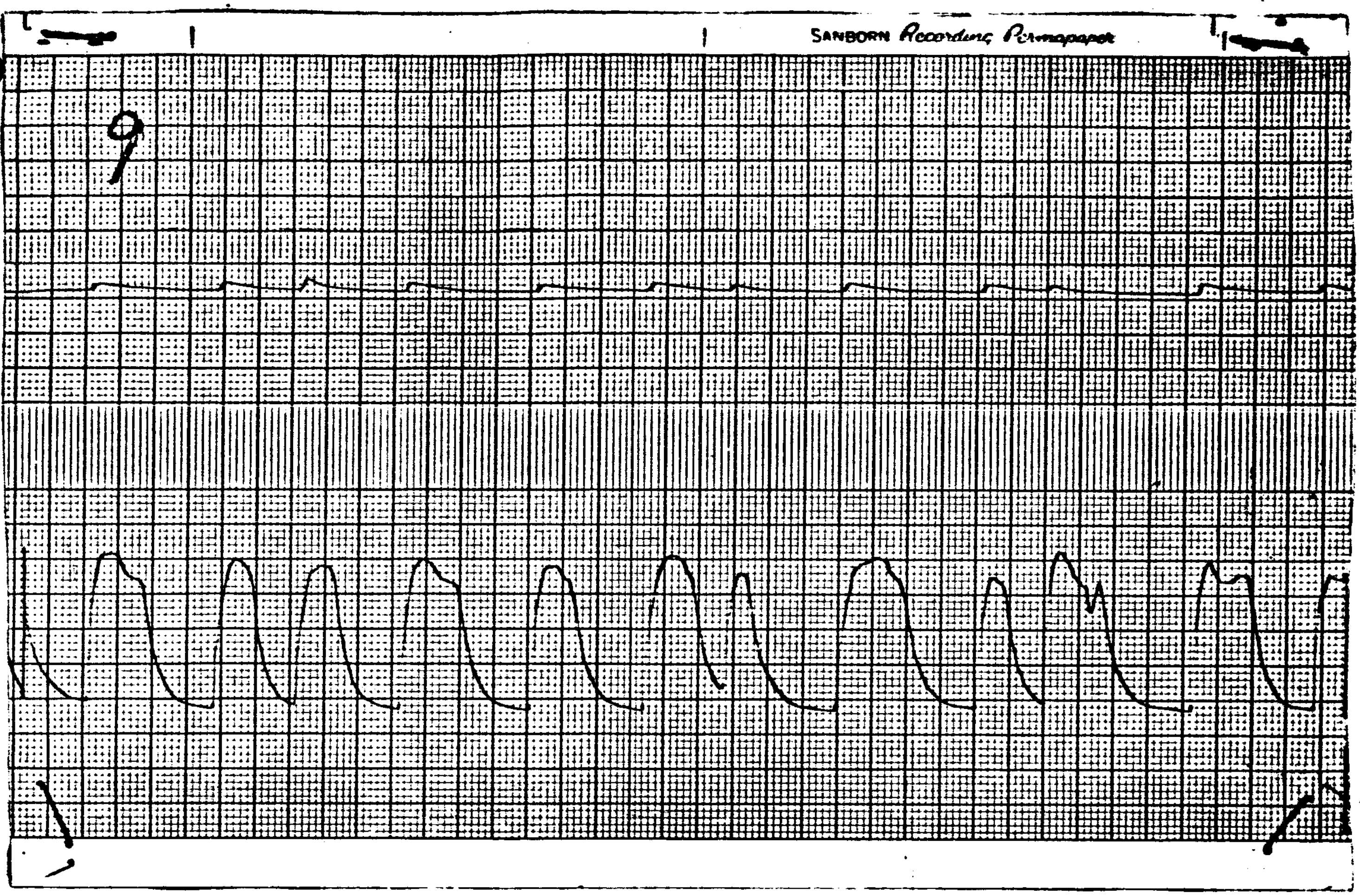


Figure 29

25K BM 19NOV RUN 9

NA-64-1298
12-14-64
Page 47

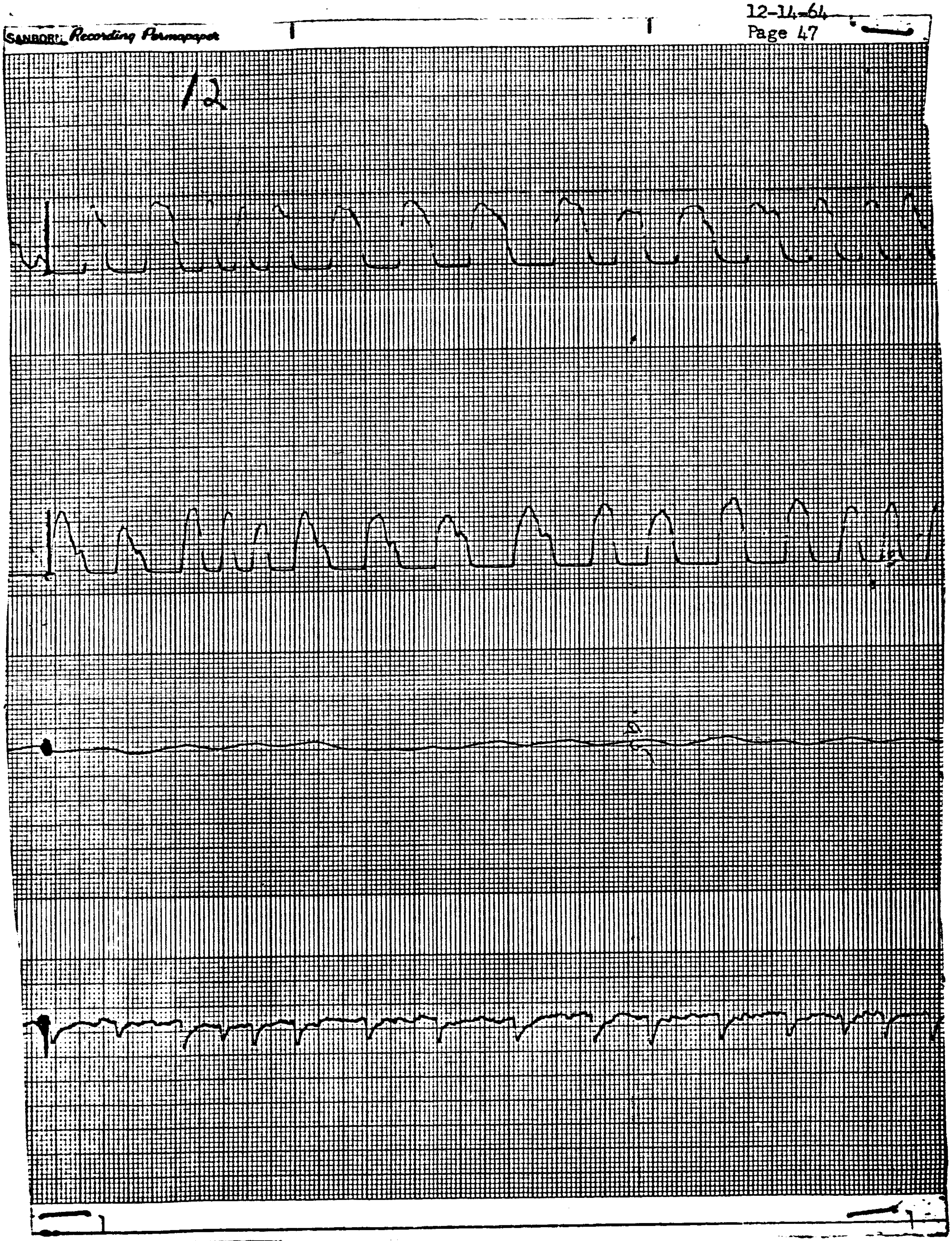


Figure 30

25K BM 19 NOV RUN 9

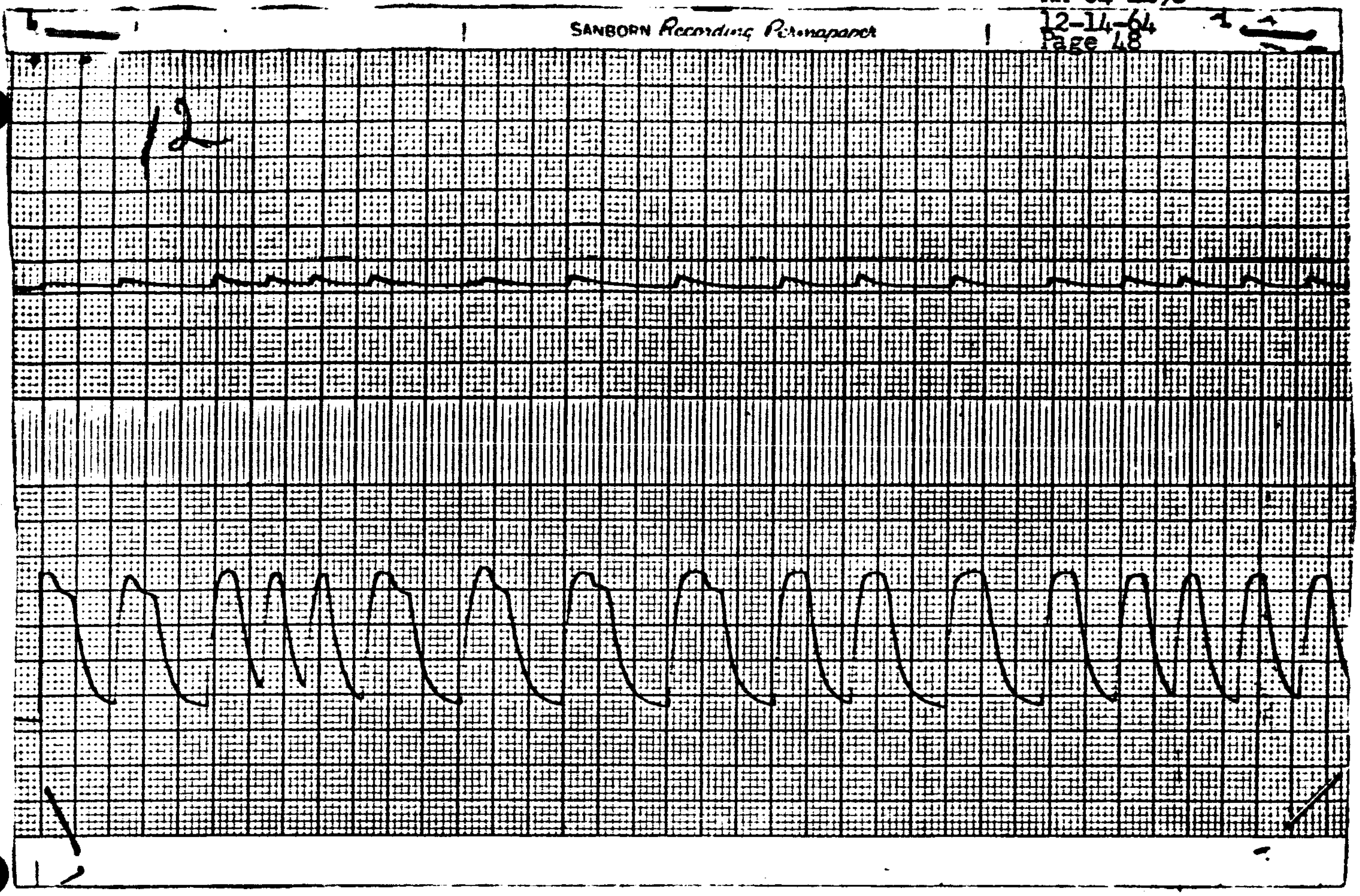


Figure 31

25K BM 19 Nov

RUN 9

NA-64-1298
12-14-64
Page 49

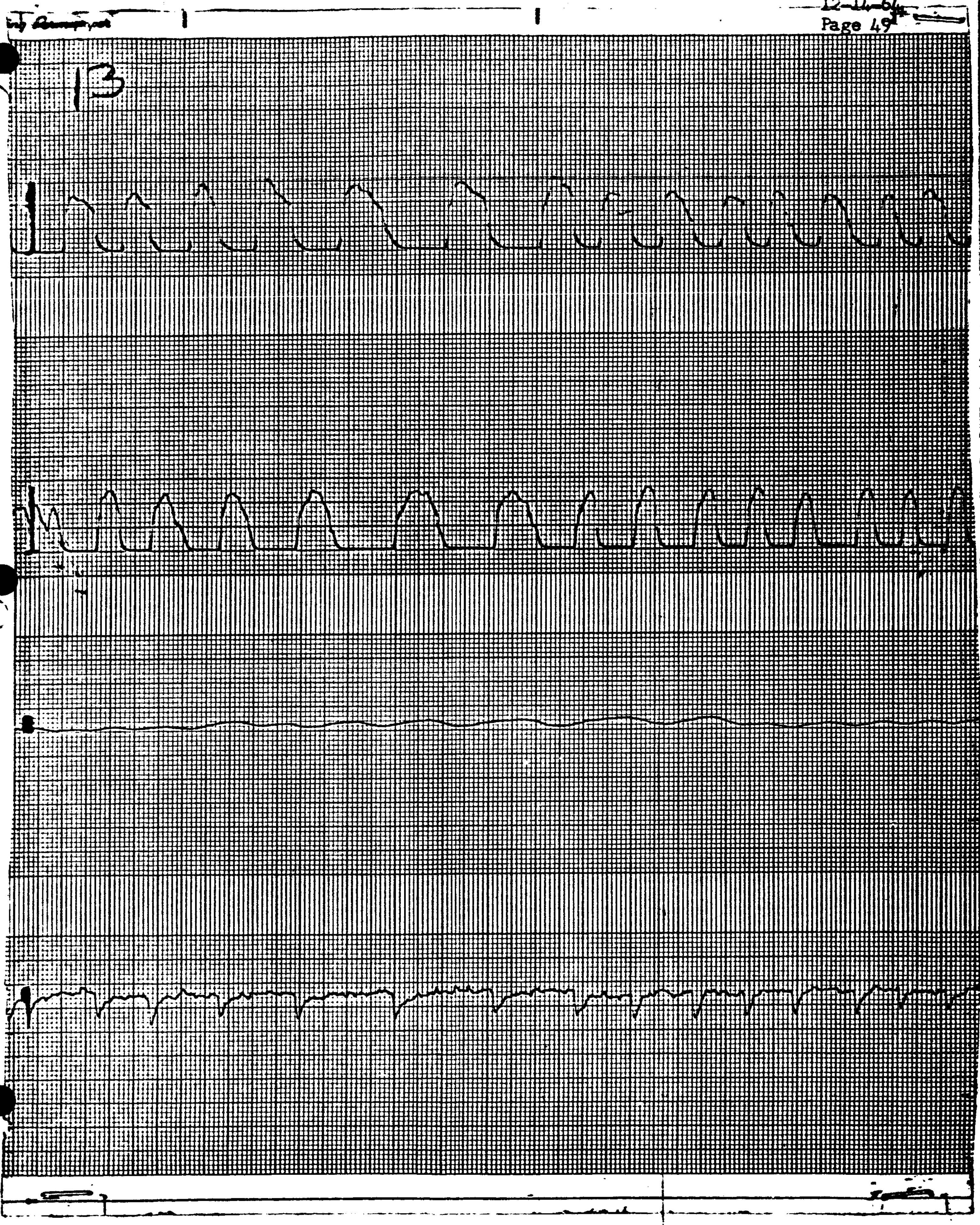


Figure 32

25K Bm 19 Nov RUN 9

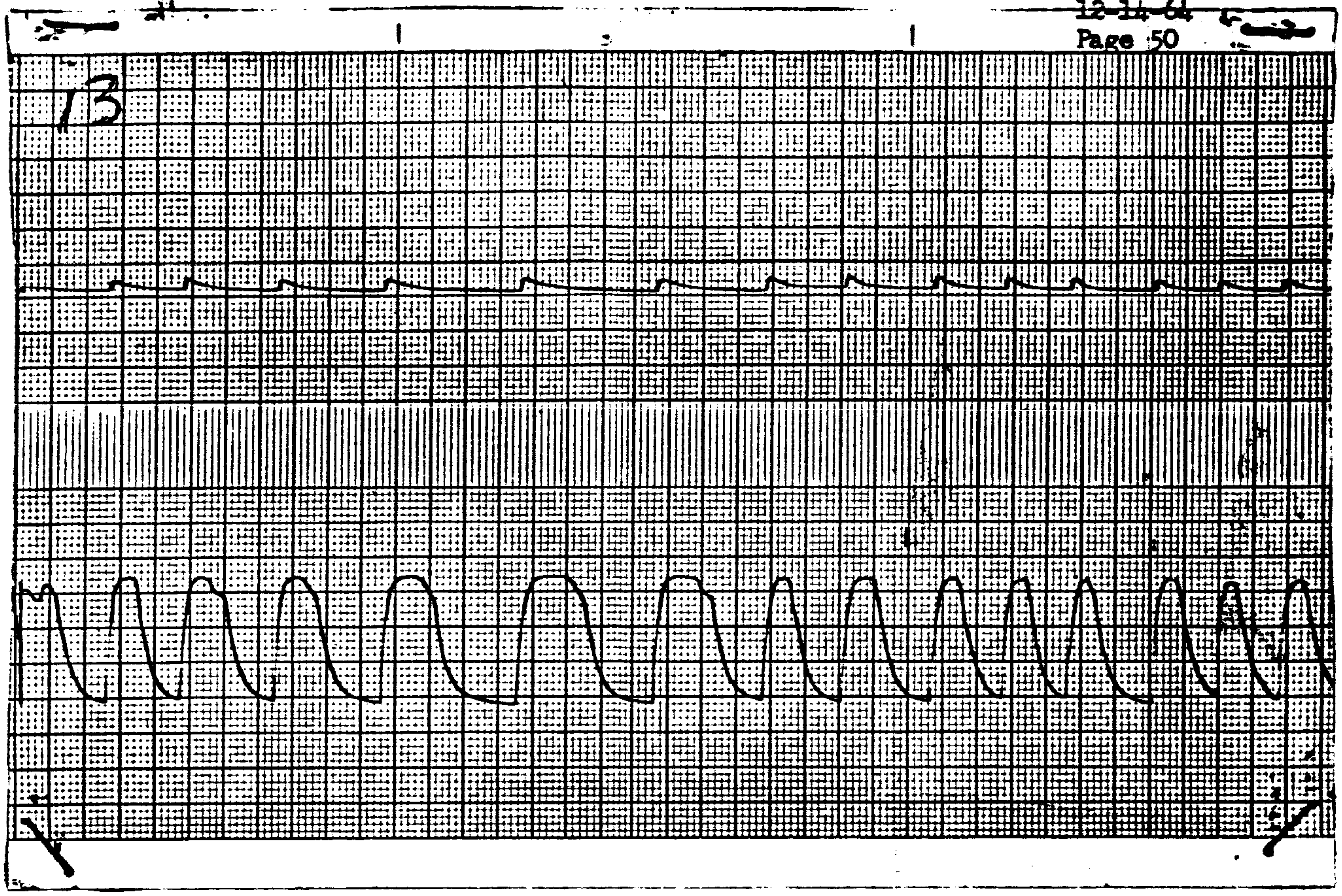


Figure 33

PROTOTYPE O_2 ANALYZER VS F-3 ANALYZER

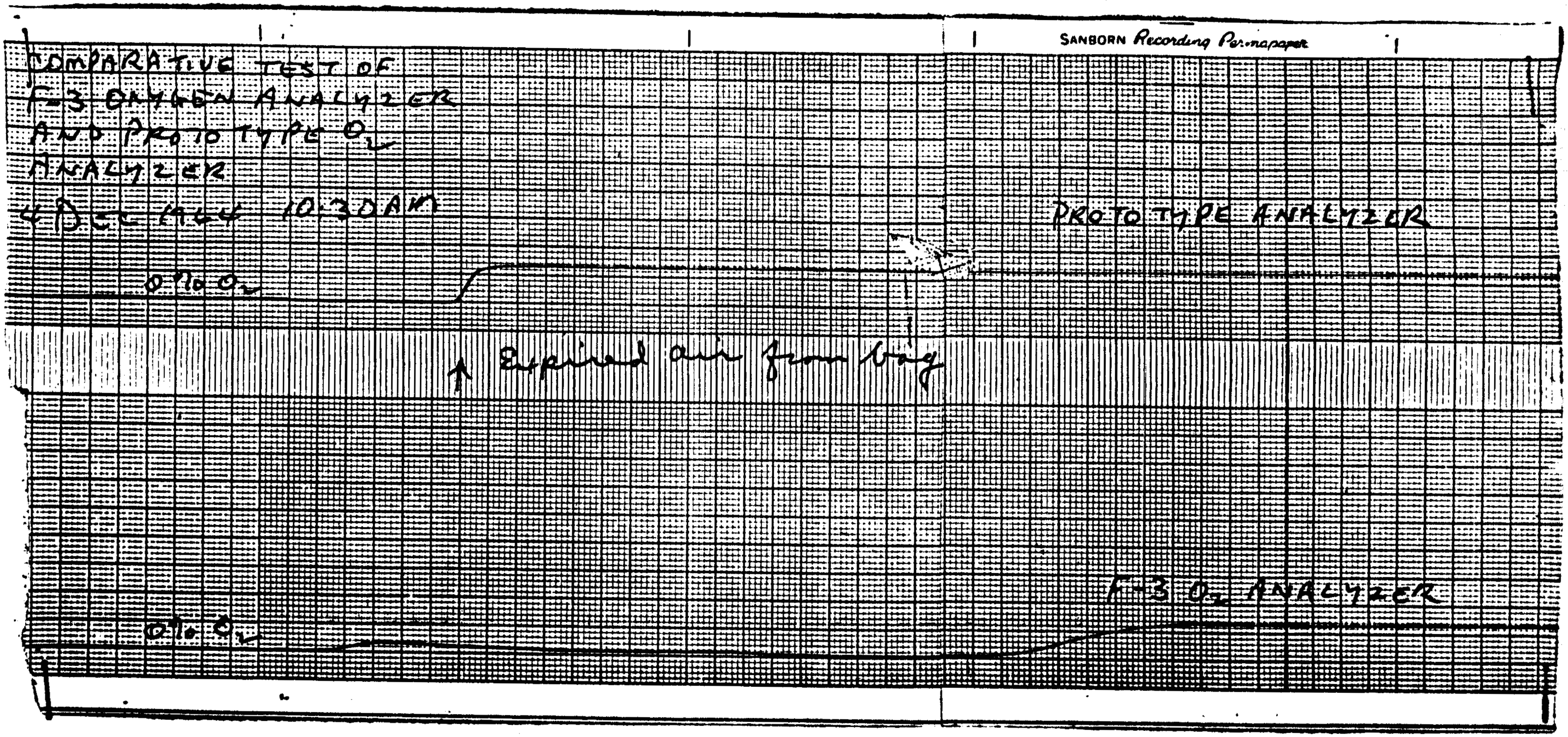


Figure 34

TEST #7

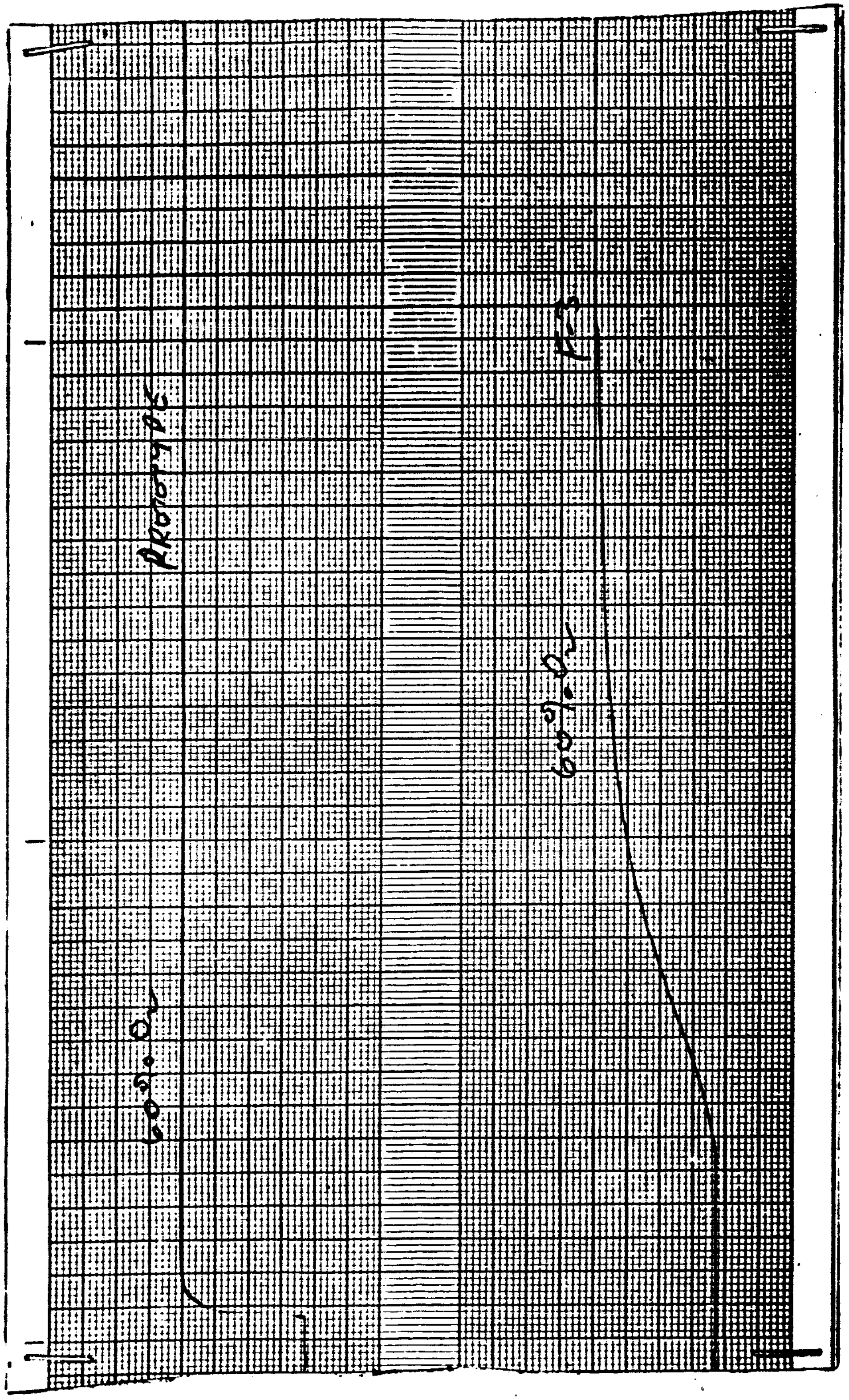


Figure 35

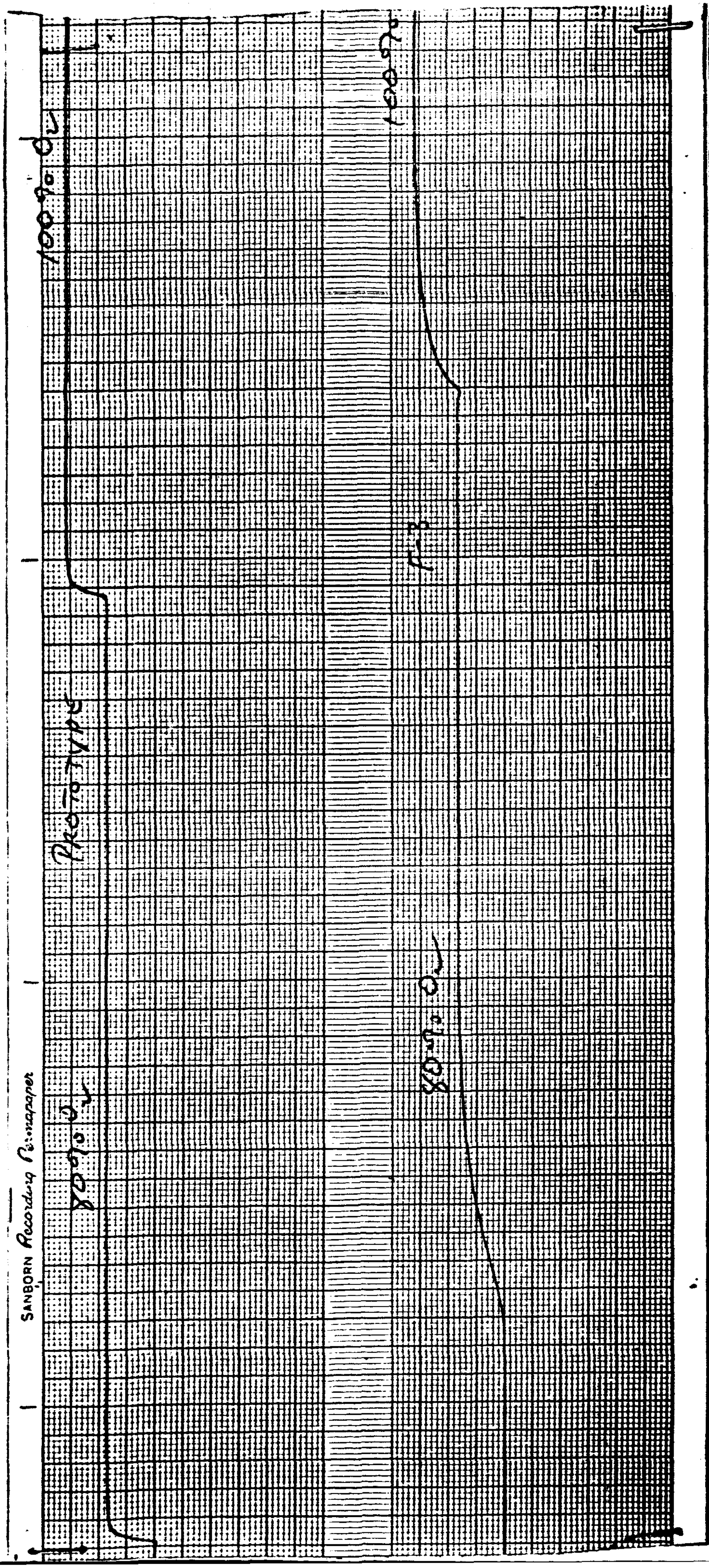

SANBORN Recording Permapaper
100% O2
Prototype
80% O2
F-3
100% O2
80% O2

Figure 36

TEST #2

PROTOTYPE O₂ ANALYZER VS F-3 ANALYZER

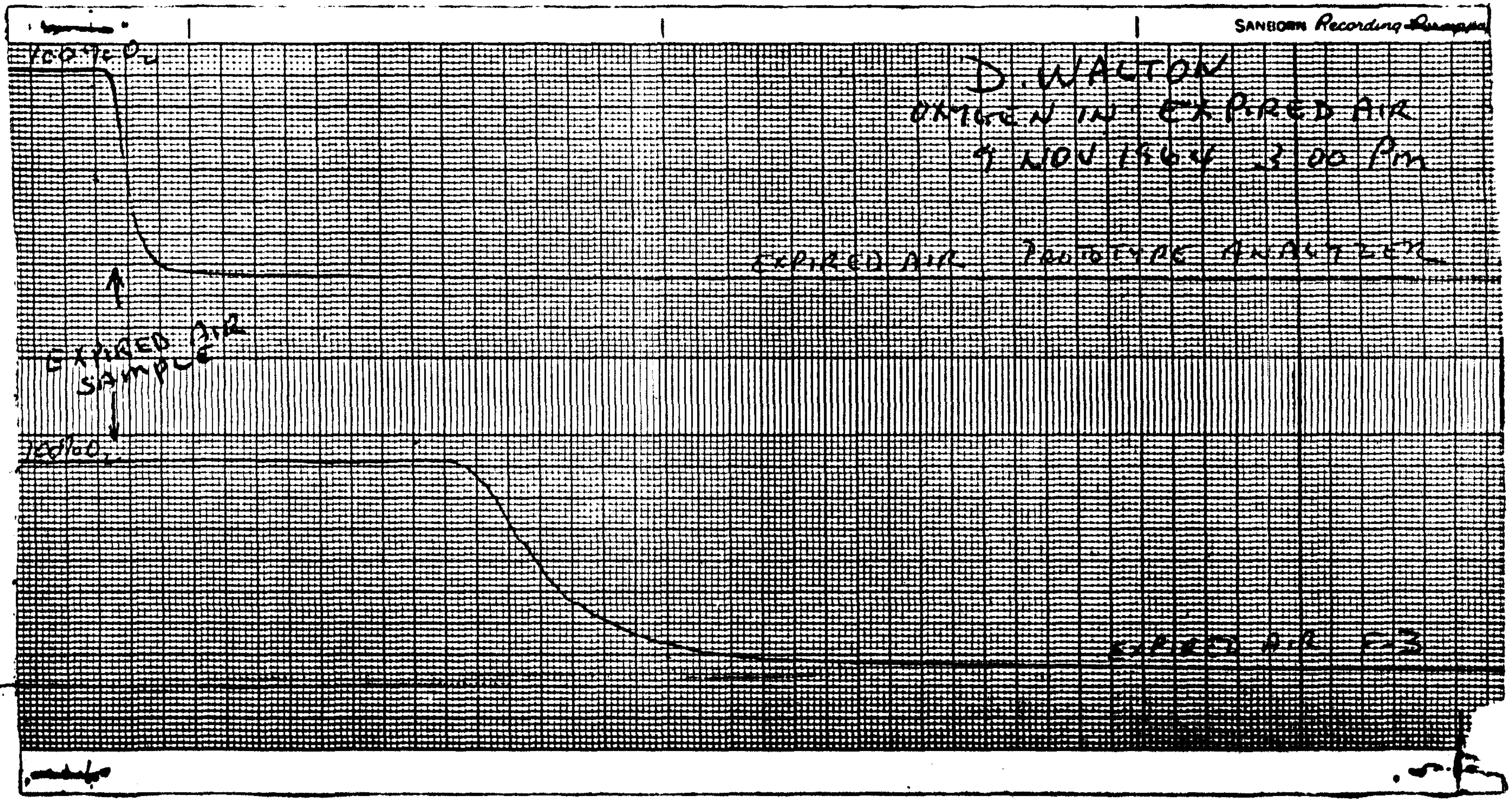


Figure 37

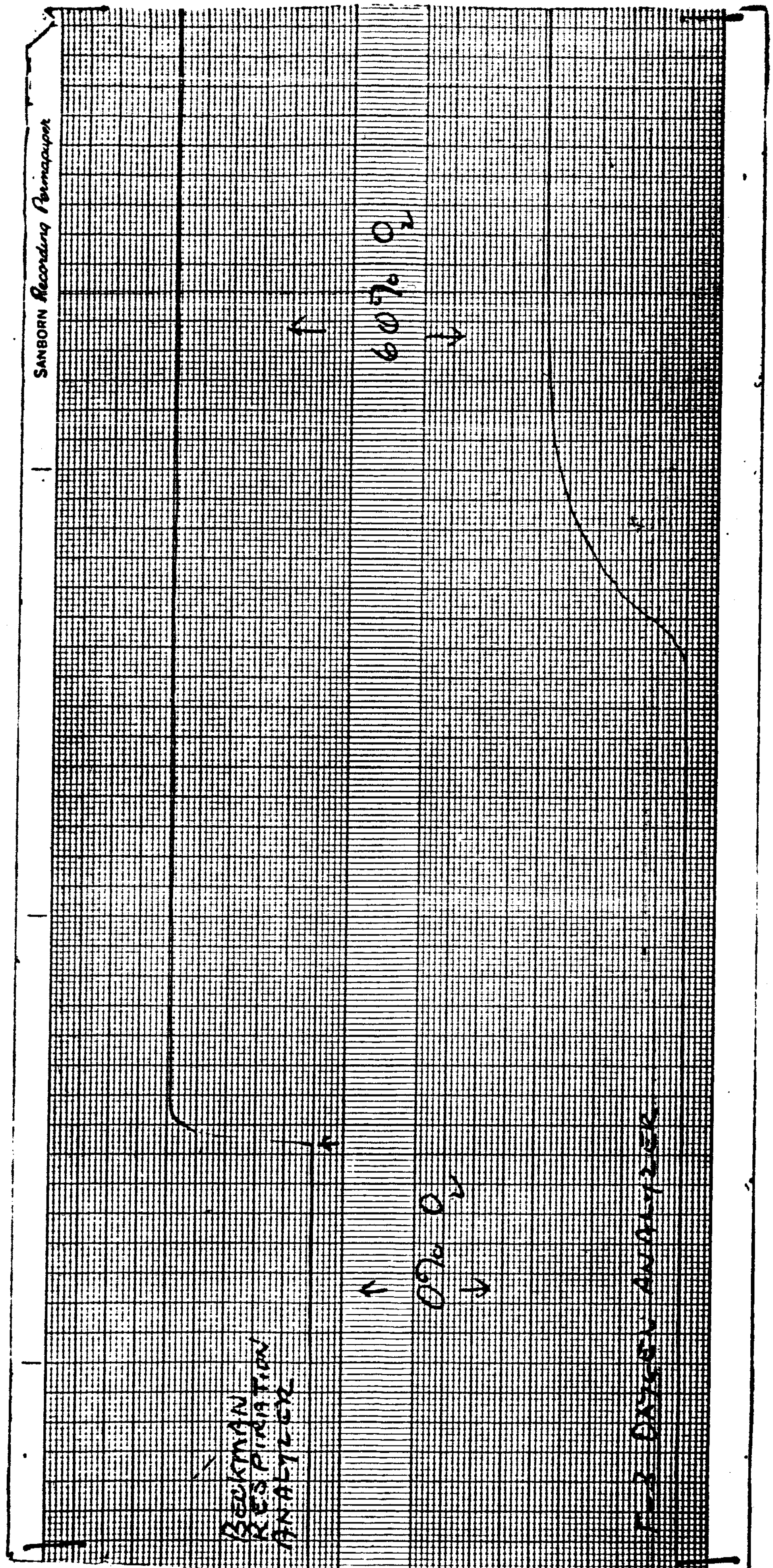

SANBORN Recording Permapaper
60% O2
0% O2
BECKMAN RESPIRATION ANALYZER
F-3 OXYGEN ANALYZER

Figure 38

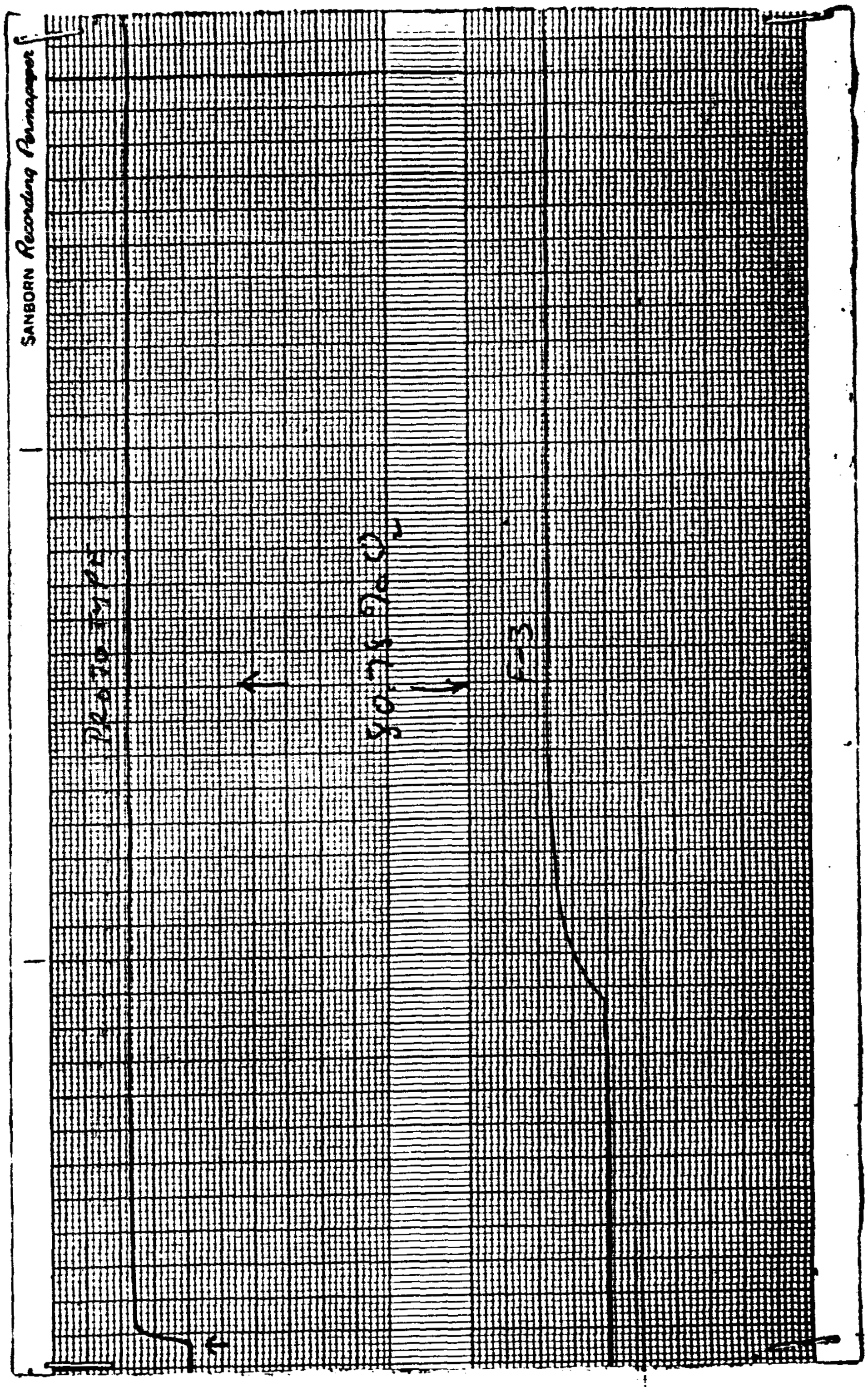


Figure 39

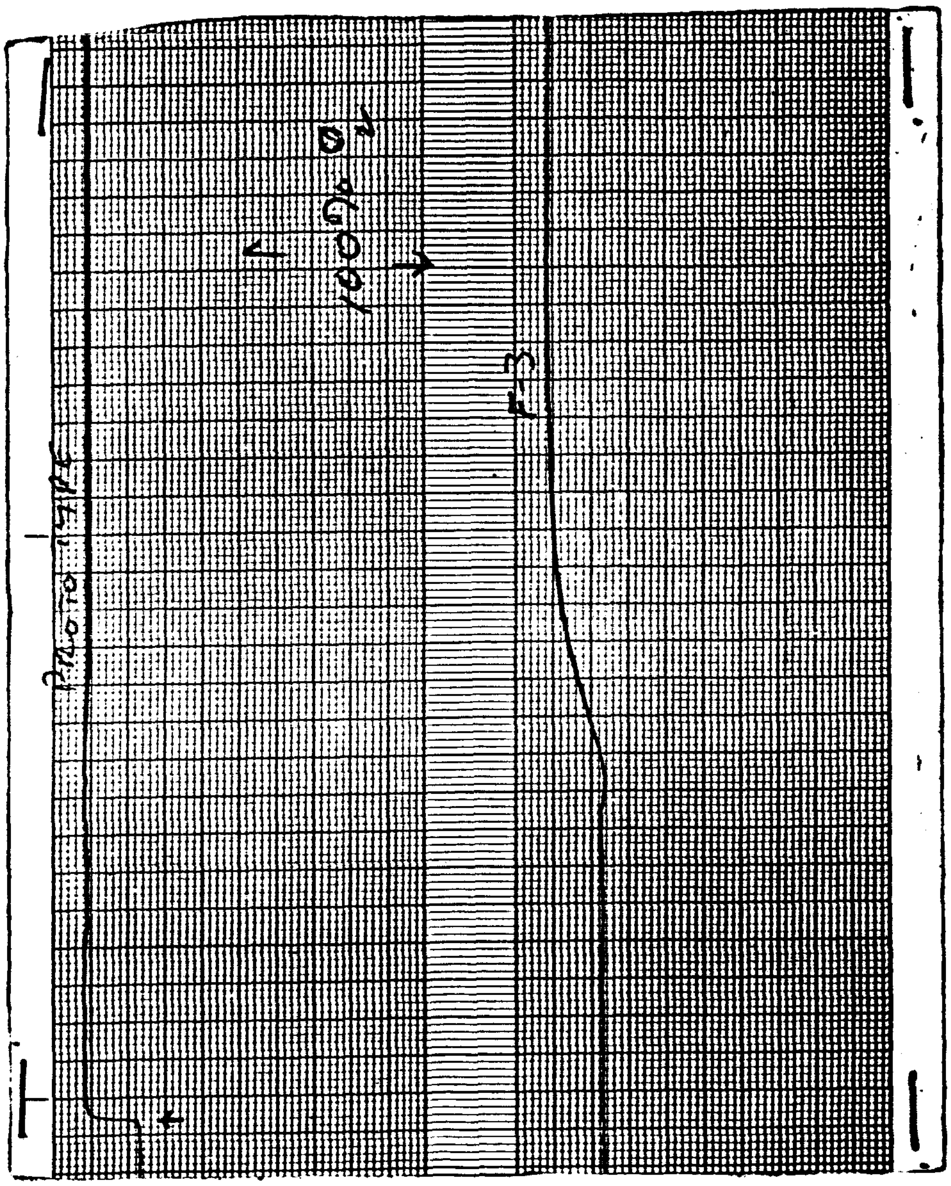
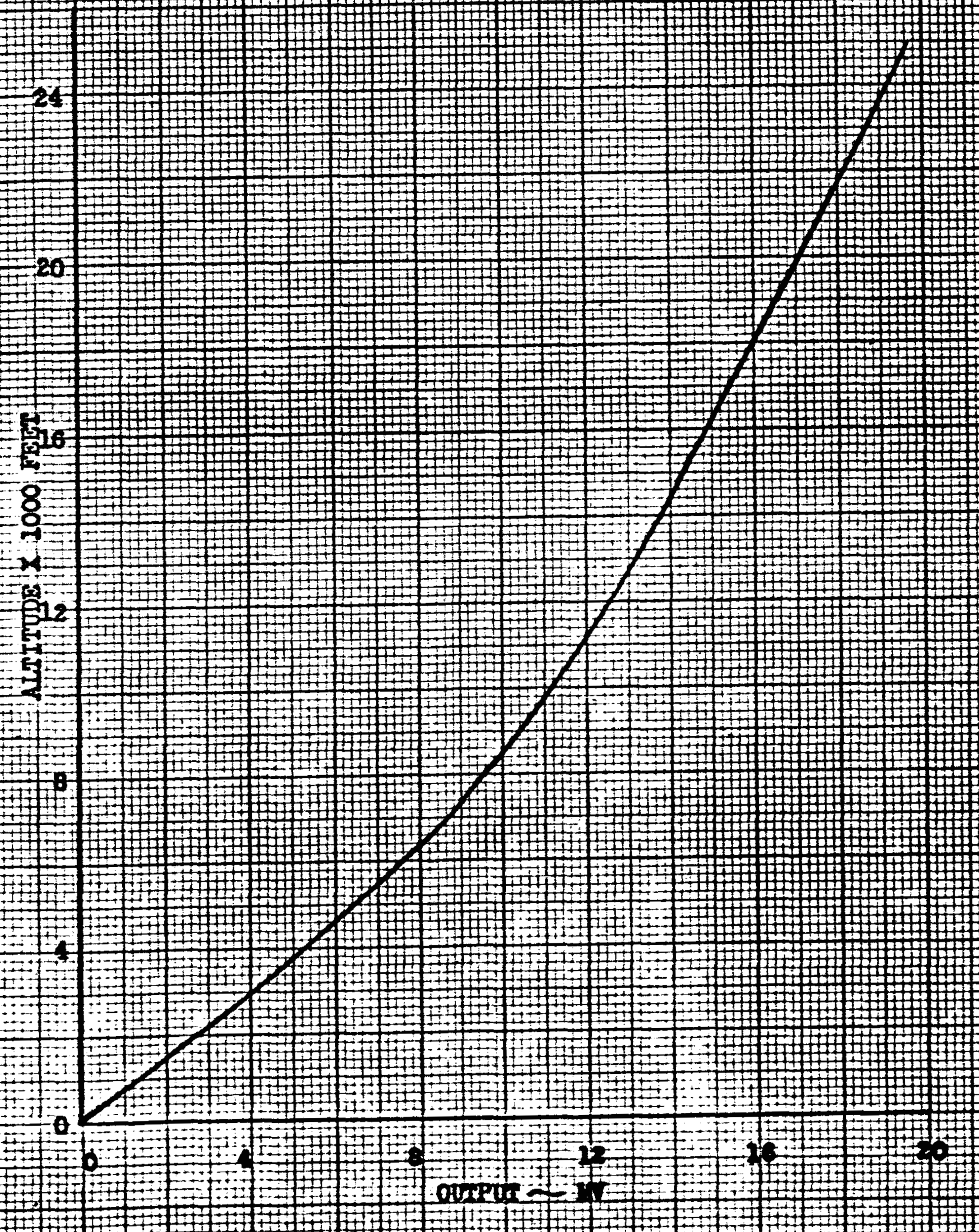


Figure 40

FORM 1002-X (FORMERLY 22147)

PREPARED BY:	**NORTH AMERICAN AVIATION, INC.**	PAGE NO. 58 OF
CHECKED BY:	HF - 20 PRESSURE TRANSDUCER	REPORT NO. NA-64-1298
DATE: 12-14-64	OUTPUT vs PRESSURE	MODEL NO.

Figure 41



DISCUSSION

In general, the various prototype sensors performed in a completely satisfactory manner. Occasional difficulties arose with some of the components and certain discrepancies are evident in the various methods of flow measurement, but the overall test program went well, particularly in light of the fact that "breadboard" components were being evaluated.

Because of the large number of data entries shown in Table 2 and the diverse nature of the parameters involved, the discussion of test results and other aspects of the test program will be categorized in relation to each parameter evaluated.

CARBON DIOXIDE ANALYSIS

The results of the prototype analyzer and the LB-15 show good general agreement. The prototype analyzer consistently indicated higher partial pressures than the LB-15, although the difference was within the desired 5%. The reason for this discrepancy in analyzer output is thought to be related to the dynamic response characteristics of the two instruments. The prototype analyzer "sees" the CO_2 in the direct path of the expired air. Response of the analyzer is very rapid and marked breath-to-breath changes in CO_2 concentration are evident. In the case of the LB-15, a sample of expired air was continously withdrawn from the exhalation line just above the prototype analyzer at a rate of 500 cc per minute and returned to the exhalation upstream of the #2 flowmeter. The long sampling line necessitated by the test arrangement was of very small bore but nevertheless contained about 100 cc of dead space. Appreciable integration of breath samples, therefore, took place as evidenced by only slight variation in output during breathing. In reducing the CO_2 traces, an attempt was made to determine average CO_2 levels and because of the greater excursions and more rapid response of the prototype analyzer, the apparent discrepancy in the outputs of the analyzers may actually be a result of the method of data reduction.

CO_2 analyzers employing the infrared absorption principle undergo a phenomenon termed "pressure broadening" at reduced atmospheric pressures, and therefore, produce a lowered output signal in response to a given pCO_2. To correct for this characteristic, all CO_2 voltage outputs recorded at altitude must be corrected. Sufficient data on the response of the LB-15 and prototype CO_2 analyzers at altitude were not available for application to the altitude CO_2 measurements. The necessary information will be obtained shortly and corrected figures will be submitted with the engineering analysis report now in preparation. The data shown in Table 2, therefore, represents uncorrected pCO_2 values.

As may be seen from an examination of the original traces, the prototype analyzer exhibited a fairly large degree of "noise" during the first five ground level runs, but this condition spontaneously improved during subsequent runs. Some degree of noise is characteristic of the present circuitry of the prototype analyzer.

Several minor difficulties developed in the CO analyzer during the altitude runs. During run #10, the analyzer ceased to function. On return to Beckman Instruments, it was discovered that a transistor in the amplifier power supply had failed. The transitor was replaced, but subsequent failure of signal output occurred during runs #11, 12, 13, and 14. Beckman representatives discovered that readjustment of the demodulation phasing was necessary, probably as a result of the transistor replacement. At the conclusion of run #15, which was routine in all other respects, a marked zero shift was noted during post-run calibration. The analyzer was returned to Beckman and it was determined that sample gas was contaminating the optical pathway resulting in absorption of infrared radiation outside the sample cell. This condition was eliminated by attaching a small gas line to the analyzer housing permitting a constant purge of the interior of the housing with 100% oxygen, thereby, preventing any accumulation of CO_2 in the optical pathway outside of the sample cell. During all subsequent runs (#16 through #22), the analyzer exhibited very stable and reliable response.

OXYGEN ANALYSIS

The prototype oxygen analyzer gave very consistent and reliable performance during most test runs. As demonstrated by comparative evaluations (illustrated in figures 34 through 40), the prototype analyzer exhibited very rapid response and produced outputs identical to the F-3 paramagnetic analyzer when both were simultaneously exposed to expired air samples and various calibration gases.

During ground level testing, the prototype sensor gave reliable service for periods of over two weeks without recharge. Altitude runs were apparently more demanding and the sensor had to be recharged after three or four runs because of sensitivity shifts. As an example, the sensor was apparently in need of recharge when run #15 was made, but in the attempt to complete a successful run after five successive failures due to CO_2 analyzer malfunction, the sensitivity shift was overlooked until the run was in progress. Since the O_2 results did not appear reasonable, no O_2 data are shown for that run.

The oxygen analyzer again gave spurious signals during the last two system checks. It was discovered that the sensor had not been recharged during the previous checkout at Beckman. The sensor had been subjected to several prior altitude runs. Lack of time prevented return of the sensor for recharge and re-run of the system checks. Oxygen data are, therefore, absent from these runs.

FLOW ANALYSIS

The correlation between the various methods of flow measurement is not considered satisfactory. As may be seen by examination of the flow data, the output of the two mass flowmeters agrees more closely than the gas meter versus #1 flowmeter, spirometer versus #2 flowmeter, or gas meter versus spirometer. It is felt that the intermittent nature of respriatory gas flow was responsible for the discrepancies in the data. Since both the mass flowmeters and the gas meter were calibrated under conditions of constant flow, it is impossible to authoritatively state at this point which of the instruments exhibited the greatest accuracy. The gas meter gave generally lower flow rates than either mass flowmeter while the spirometer indicated generally higher flows than the gas meter.

The two mass flowmeters agreed fairly well with each other. Discrepancies in output were less at altitude than at ground level and were generally within the desired range of 5% deviation. Integration of area under the curves was very difficult during ground level runs because of the rapid and extended recorder excursions during flows associated with exercise. Much of the indicated difference in output of the two flowmeters was probably a result of data reduction. This assumption is supported by the fact that the altitude flows were much easier to read and also show much closer agreement. It would appear that computerization of flowmeter output is a necessity for accurate and reliable data read-out.

The dry gas meter utilizes a bellows arrangement, thereby creating some degree of inertia which must be overcome during intermittent flow. This may be one reason for the lower gas meter readings. A second factor which tended to depress the readings is the fact that although the gas meter was read at five minute intervals just as the flowmeters and spirometer, the gas meter readings were cumulative. The five minute readings, therefore, represent an average minute flow based on a five minute average; whereas, the flowmeter and spirometer data represent a true one minute average. Increasing respiratory flows occurring during the exercise phases were, therefore, not accurately recorded on the gas meter.

Although the spirometer gave higher flow indications than the gas meter, the discrepancy in flowmeter versus spirometer data was not consistant and the error was random in nature. These errors are probably the result of spirometer trace interpretation, which is difficult to accomplish accurately for high respiratory flow rates.

The entire problem area of flow measurement and data interpretation as related to this test program will receive additional attention during the phase two engineering analysis now in progress. The mass flowmeters appeared to operate in a totally satisfactory manner during the test program. During the period of instrumentation checkout prior to the initiation of test runs, however, it was observed that the #2 flowmeter was not operating in a proper manner. Upon return to the manufacturer, it was discovered that the instrument was either damaged in shipment or was improperly assembled. Upon being repaired, it was returned to NAA, a calibration check was accomplished and no further difficulty was experienced with the item.

TEMPERATURE ANALYSIS

Gas temperature was measured just upstream of each flowmeter by a Yellow Springs thermister and telethermometer. As seen in Table 2, the inspiration gas temperature remained fairly constant at 75°F ± 2.5. The exhalation gas temperature showed wider variations because of the poor thermostatic control of the heater tape applied to the exhalation lines and the gas temperatures ranged from 88°F to 107.5 °F. By varying the spacing of the heater tape around the exhalation lines the temperature of the exhalation gas at #2 flowmeter was kept more constant (note runs #7 through #19).

The prototype temperature sensor in the analyzer gave rapid response and marked breath-to-breath fluctuation is seen in Table 2. Gas temperatures were appreciably higher in the analyzer since a resistor kept the internal temperature between 100 to 110°F to prevent condensation of moisture in the optical path of the CO_2 analyzer.

It is felt that the prototype temperature sensor gave very satisfactory performance. Unfortunately, it is a very delicate device and was damaged during calibration prior to run #17. Sufficient time for repair was not available, so analyzer temperature data are lacking for runs #17 through #19.

The heater tape was added to the experimental arrangement at the suggestion of the NASA Project Monitor, Mr. L. R. Carpenter. It successfully prevented moisture condensation in the exhalation lines and as demonstrated in the system check runs, prevented the gross discrepancies in flow output seen in these runs when heat was not utilized. Without heat, water condensed out all along the exhalation line and within the body of the #2 flowmeter.

PRESSURE ANALYSIS

As previously stated, the pressure transducer performance did not agree with either calibration curve shown in figure 6 . The output during altitude runs and check flights in the chamber is shown in figure 41. It is felt that the pressure transducer is the one component of the prototype analyzer which did not perform satisfactorily. The curve in figure 41 represents an average output of the transducer and random variations occurred to either side of the curve. These variations in certain instances were as great as 10%. On some occasions, the transducer would undergo a base line shift during the course of a run to 25,000 feet and return. As stated earlier under Methods, the sensor was utilized to prevent delay of the program, but the recommendation at this point is that it be replaced.

SYSTEM CHECK RUNS

The three system check runs (closed cycle) were less than completely satisfactory due to failure of the CO_2 analyzer during run #20 and the oxygen sensor during runs #21 and 22. These runs were made at the request of the NASA Project Monitor but because of missing data, the derivation of any acceptable conclusions is not feasible. All instrumentation indications appear to maintain the relationships observed in previous open cycle runs except for the two mass flowmeters. Here a large discrepancy is observed between #1 and #2 flowmeter with #2 indicating up to 41% less flow than #1. It is felt that the depressed output is due to moisture condensation in the body of the flowmeter. The significance of the data collected during the system check runs will be studied in greater detail in the engineering analysis now in progress.

CONCLUSION

The accuracy and response characteristics of the various prototype components are considered satisfactory with the exception of the pressure sensor. The response and accuracy of the oxygen analyzer must be considered outstanding. The prototype CO_2 analyzer and the LB-15 analyzer results show good agreement. The temperature sensor shows extremely rapid response and the two mass flowmeters show rapid response and good correlation with each other. (Theoretically, they should agree within 1 to 2%.) The performance of the present pressure sensor is considered inadequate for precise inflight monitoring of absolute pressure.

It must be pointed out that the task of evaluating sensors with such rapid response as that exhibited by those in the prototype analyzer is made difficult because standard laboratory instruments have a much slower response. In addition, the effects of rapidly changing rates of flow on both prototype and standard instruments may introduce errors in output since these instruments, i.e., flowmeters, gas meters, and temperature sensors are generally calibrated with constant gas flows. It was recommended by NAA that this particular problem be investigated in detail during the phase two engineering analysis now in progress, but this effort which seemed vital to the entire program was not funded. However, within the scope and context of the statement of work, it must be concluded that the prototype analyzer provided acceptable standards of response and accuracy.

It would appear that the parameters chosen for measurement give a satisfactory indication of total respiratory function. Respiratory rate, volume, CO_2, and oxygen composition of the expired air along with expired air temperature and absolute pressure provide adequate basic data from which other parameters may be calculated, e.g., oxygen consumption and respiratory quotient. A vital requirement, however, is to make provisions for transferal of analyzer output to tape which may be fed to an analog computer for rapid and accurate data reduction. Manual data reduction very likely introduces errors which are several orders of magnitude greater than the inherent mechanical error of the analyzer. To take advantage of the rapid response of the sensors, some method of rapid data read-out is mandatory in future development of the analyzer.

The performance of the analyzer at both ground level and 25,000 feet gave ample evidence that the prototype sensors are suitable for application to inflight respiratory monitoring. Additional refinement and miniaturization of the analyzer and its components are required but the concept is sound. It must be emphasized that the prototype analyzer as tested represents no more than a laboratory "breadboard". Total performance must, therefore, be evaluated within this context.