DOCTORAL DISSERTATION SERIES

PUBLICATION: 5110

AUTHOR: Rex Harry White, Jr., Ph. D., 1953
University of Michigan

TITLE: AN INVESTIGATION OF THE EFFECTS OF EXTREME LOW TEMPERATURES UPON COLD STARTING OF SPARK IGNITION ENGINES USING STANDARD GASOLINE

University Microfilms, Ann Arbor, Michigan, 1953

AN INVESTIGATION OF THE EFFECTS OF EXTREME LOW TEMPERATURES UPON COLD STARTING OF SPARK IGNITION ENGINES USING STANDARD GASOLINE

by

Rex Harry White, Jr.

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in the
University of Michigan
1952

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AN INVESTIGATION OF THE EFFECTS OF EXTREME LOW TEMPERATURES UPON COLD STARTING OF SPARK IGNITION ENGINES USING STANDARD GASOLINE

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This investigation was initiated with three primary objectives, namely:

1. To demonstrate that the problems of starting spark ignition engines at low temperatures may be explored to advantage by studying the effects of a single variable at a time.

2. To secure data pertaining to the effectiveness of the standard Ordnance primer nozzle as an aid to low temperature starting.

3. To secure basic data pertaining to the air-fuel ratios required for ignition at low temperatures.

A single cylinder of a modified four cylinder engine supplied with fuel by means of timed injection was used as the basic test apparatus.

1. Fuel quality

2. Primer nozzle

3. Volumetric efficiency

4. Ignition

For the various tests the following factors were varied, one at a time:

1. Primer nozzle location

2. Temperature

3. Priming Pressure

4. Quantity of fuel primed

In all tests, cranking was continued only until an indication of ignition was secured. No attempts were made to secure actual starts of the engine. Tests were conducted at temperatures from 0° to -60°F.

The following general results were obtained:

1. The primer nozzle investigated provided no advantage as an aid to securing ignitable mixtures at low temperatures over injection at low pressure of a solid stream of fuel.

2. Priming pressures in excess of 50 psi. did not increase the effectiveness of the primer nozzle.

3. For best results, as temperatures are lowered, the primer nozzle must be moved closer to the intake valve.

4. Evidences of combustion (as indicated by the presence of products of combustion and temperature rise) were found at low temperatures with air-fuel vapor ratios of 170:1 to 200:1.

The results of this investigation lead to the following general conclusions:

1. The effectiveness of high pressure primers as aids to cold starting is not as great as commonly believed. Other cheaper and simpler devices may be devised which will be just as effective.

2. Primer nozzle location, manifold design and valve timing are extremely critical at the lower temperatures.

3. Combustion of extremely lean air-fuel vapor mixtures will contribute to the difficulty of building up power producing mixtures in the cylinder by continuous cranking and may adversely affect starting ability.

PREFACE

The basic idea for this investigation grew out of my participation in the first tests conducted at the Climatic Test Facility at Eglin Air Force Base, Florida in 1947.

The disappointments, conflicting data and unexplained phenomena resulting from these tests lead to an investigation of the available information from tests in the field and in existing cold rooms. It was immediately apparent that most work had been conducted at temperatures above $-30^{o}F$. and had been directed toward the mechanics of securing actual starts of engines. Little or no data was available concerning the individual and cumulative effects of the various factors involved in the attainment of starts.

This investigation was planned with the view of evaluating the different factors involved in attaining a start by a process of changing only one variable at a time. To carry out the whole program will require many years and a number of engineers, however, this work represents a first step in the right direction. In addition, it has provided valuable experience for a number of young engineers and technicians, who at one time or another have come in contact with the project during the two and one-half years it has been in operation.

Low temperature investigations are a type of scientific endeavor that cannot be carried out by a single individual, they require the services of a number of skilled individuals, ranging from the refrigeration machinery

operators to chemists, hence detailed acknowledgements are not practical. Specific acknowledgement can be made to Brigadier-General David J. Crawford and Colonel W. A. Call who recognized the need for detailed low temperature investigations and permitted the use of the Detroit Arsenal facilities for this work; to Messrs. Tom Henderson and Domonic Messina who performed the necessary machine work; and to Miss Kay Stabile who was responsible for the typing of the manuscript.

Special acknowledgement must be made to Sgt. Ralph Marinelli without whose help this project would have never reached completion. Sgt. Marinelli voluntarily worked long hours, nights and weekends in order that we could utilize to the best advantage the available operating time in the cold room. I must admit, with embarrassment, that Sgt. Marinelli more often than not, was the person selected to spend his time inside the cold room while the project director basked in the warmth of the control room.

It is with deepest regret that I am forced to relinquish personal contact with the project due to the requirements of military service, however, the ground work has been laid, the equipment tested and a capable replacement remains behind to carry on.

Detroit Arsenal
Center Line, Michigan
26 June 1952

Rex H. White, Jr.
Major, Ord Corps

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INTRODUCTION

The starting of internal combustion engines of the automotive type has been the subject of rather intensive investigation at intervals during the last twenty-five years. Interest in this work reached a climax about 1930 and then declined, primarily because the starting problems of the average motorist seemed to have vanished by reason of the higher volatility gasoline placed on the market and the general adoption of the downdraft carburetor. After 1930, general interest shifted to problems of quick warm-up, fuel distribution during operation and various other problems. The net result of this work has been the modern automobile with its automatic choke, thermostatically controlled manifold heater and other refinements which enable even the most inexperienced driver to secure satisfactory starting under all but the most unusual cold weather conditions.

With the beginning of World War II attention was focused on the far north, Alaska in particular, and in the feverish activity to strengthen defenses in that area, the old problem of cold starting arose once more. The modern fuels which had served so well in the continental United States simply were not volatile enough to enable starting at temperatures down to -65°F. with ordinary equipment.

Many expedients were tried, some identical with those used by the drivers of the early Model T Fords. Engines were bundled up in blankets to keep them warm between periods of operation; engines were started and

run at set periods just for the purpose of keeping them warm; blow torches were directed down intake manifolds to facilitate starting; engine heaters of all types were employed. One taxi driver in Fairbanks was found to have solved his problem by welding his wife's electric iron to the crankcase of his vehicle.

The Air Force, concerned with world-wide operation, has encouraged continuing research in the problems of starting and operating internal combustion engines at low temperatures. With the gradual settlement and expansion of the Alaskan territory road net (Figure 1), the other branches of the Defense Department and civilian manufacturers have taken an increasing interest in low temperature problems. The result has been to gradually reduce the starting limit toward the desired goal of -65°F.

Cold starting troubles plagued not only Americans. In 1944, the Russians reported that their method of insuring starts of vehicles was "to use wood fires and tarpaulins", and that batteries, coolant and lubricating oil were often removed and kept warm over open fires during layovers. Their solution for quick starting of tactical aircraft was even simpler - "keep the engines running at all times"; anyone familiar with aircraft maintenance can visualize the result of this type of operation.

The present day solution to the problem of vehicle starting, particularly at temperatures below -35°F., is, in many cases, not so far removed from the Russian system of toasting the battery and oil over a roaring fire. Various types of gasoline burning heaters have been substituted for the wood fire and serve to heat the battery, coolant and oil

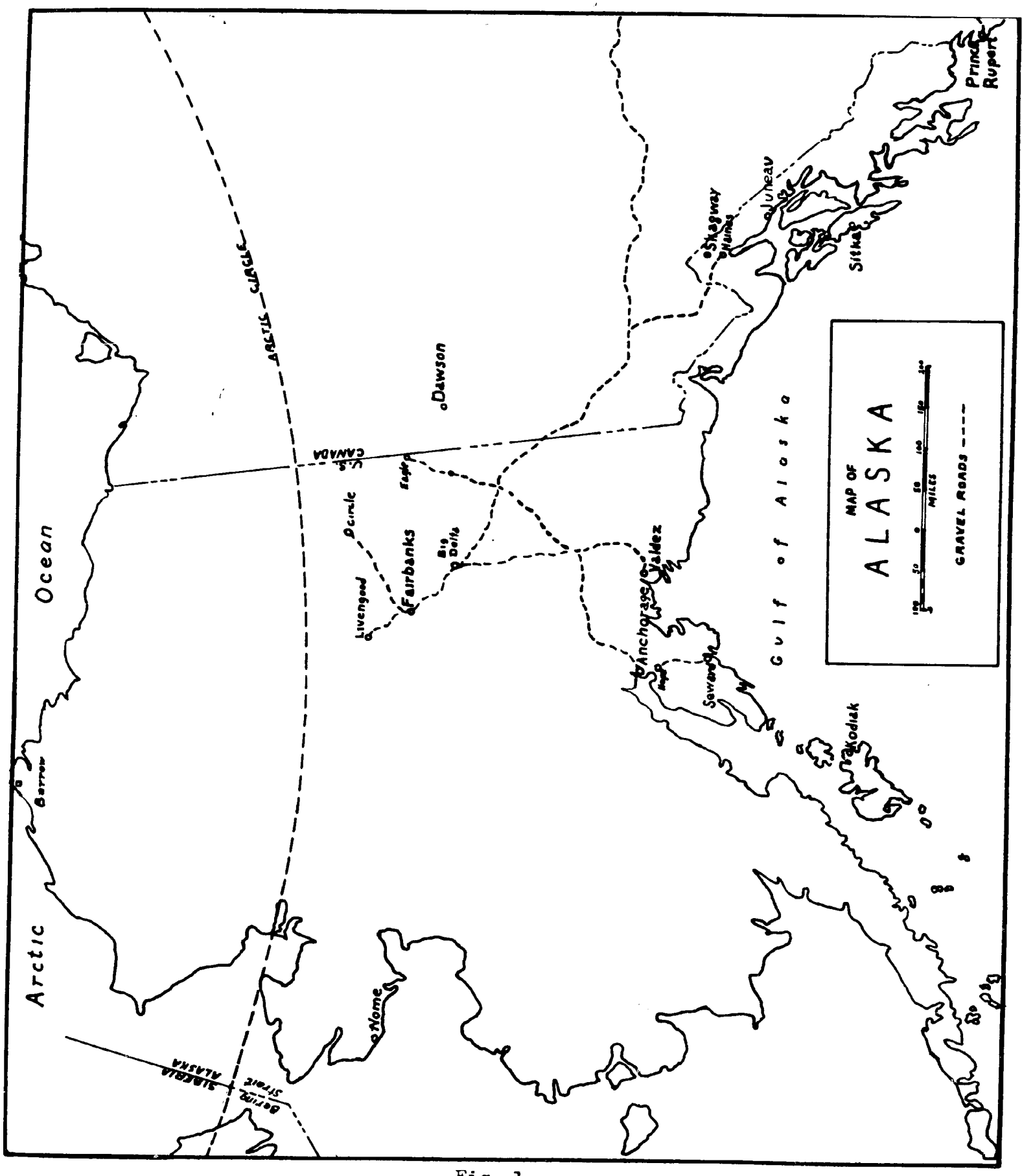

MAP OF
ALASKA
GRAVEL ROADS
MILES
Arctic Ocean
Gulf of Alaska
ARCTIC CIRCLE
CANADA
Dawson
Fairbanks
Livengood
Circle
Eagle
Big Delta
Valdez
Anchorage
Seward
Kodiak
Nome
Barrow
Juneau
Skagway
Sitka
Prince Rupert
BERING STRAIT
SIBERIA
ALASKA

Fig. 1

without removing them from the engine. The latest models of these heaters are fully automatic in their operation and will maintain the vehicle engine at any desired temperature regardless of outside conditions. Figure 2 illustrates the application of the modern military heater kit for cold starting.

The application of heat to vehicle engines is effective, however it solves the problem of cold starting by the rather round about way of bringing the climate to the vehicle instead of adapting the vehicle to the climate. In addition, heating systems are expensive, require modifications to be made on the vehicles, and burn appreciable quantities of fuel. Since it is not economically feasible to equip all vehicles for arctic operation, the military planners are forced to estimate their arctic needs. This sacrifices some of the flexibility desired by the armed forces.

From the military point of view, the ideal cold starting method would require no special fuel, demand a minimum of modification to the vehicle, require no special skill on the part of the operator, and would be relatively insensitive to temperature changes. The importance of being insensitive to temperature changes is illustrated by Figure 3 which shows the daily maximum and minimum temperatures recorded at Ladd Field (Fairbanks, Alaska) for the winter months of 1947-48. It is obvious that if vehicle fuel tanks were filled with special highly volatile fuel in anticipation of a low temperature, this fuel might be lost in several days through sudden and unexpected temperature

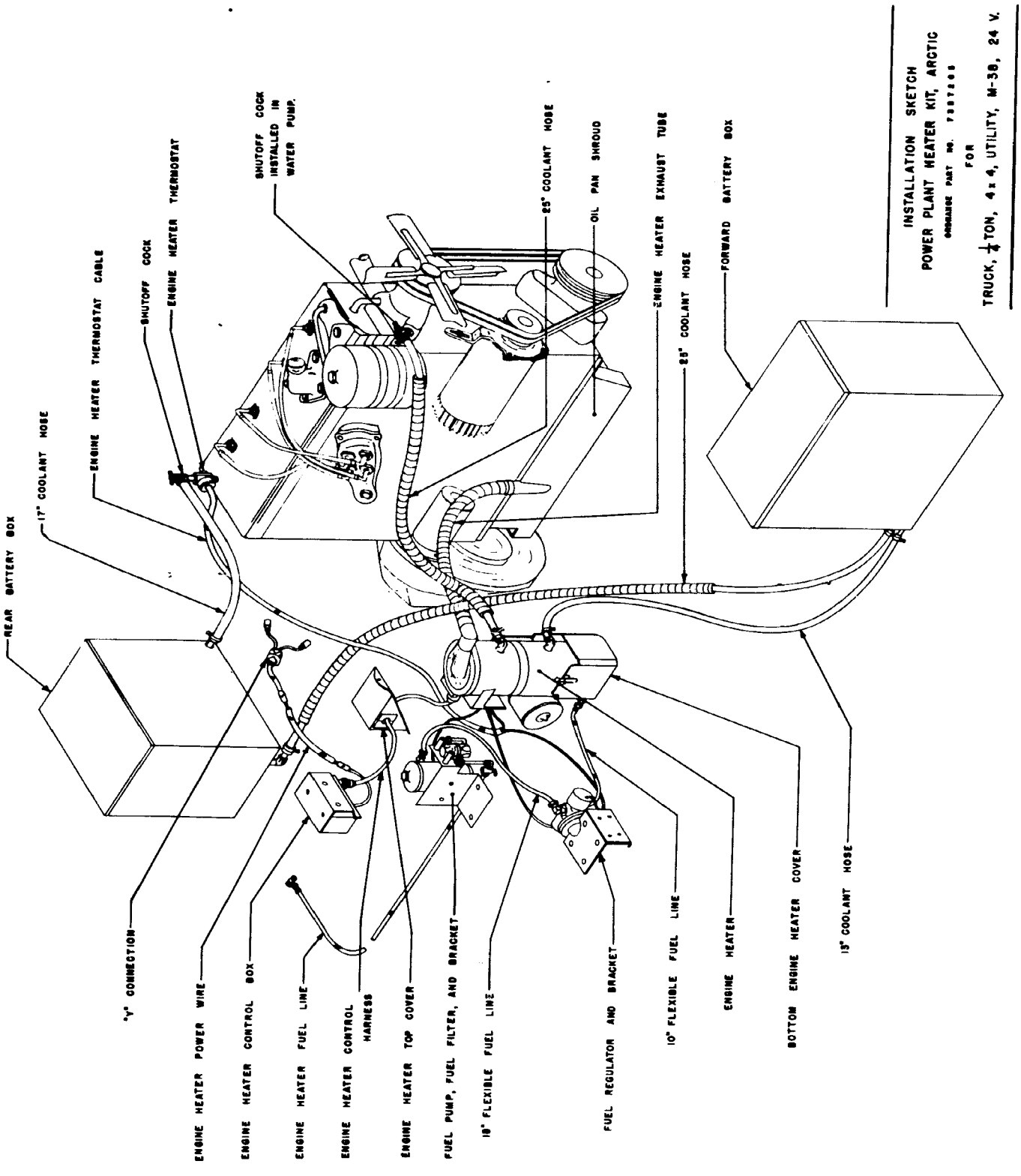

REAR BATTERY BOX
17" COOLANT HOSE
ENGINE HEATER THERMOSTAT CABLE
SHUTOFF COCK
ENGINE HEATER THERMOSTAT
SHUTOFF COCK INSTALLED IN WATER PUMP.
25" COOLANT HOSE
OIL PAN SHROUD
ENGINE HEATER EXHAUST TUBE
85" COOLANT HOSE
FORWARD BATTERY BOX
"Y" CONNECTION
ENGINE HEATER POWER WIRE
ENGINE HEATER CONTROL BOX
ENGINE HEATER FUEL LINE
ENGINE HEATER CONTROL HARNESS
ENGINE HEATER TOP COVER
FUEL PUMP, FUEL FILTER, AND BRACKET
18" FLEXIBLE FUEL LINE
FUEL REGULATOR AND BRACKET
10" FLEXIBLE FUEL LINE
ENGINE HEATER
BOTTOM ENGINE HEATER COVER
15" COOLANT HOSE
INSTALLATION SKETCH
POWER PLANT HEATER KIT, ARCTIC
ORDNANCE PART NO. 7887868
FOR
TRUCK, 1/4 TON, 4 x 4, UTILITY, M-38, 24 V.

Fig. 2

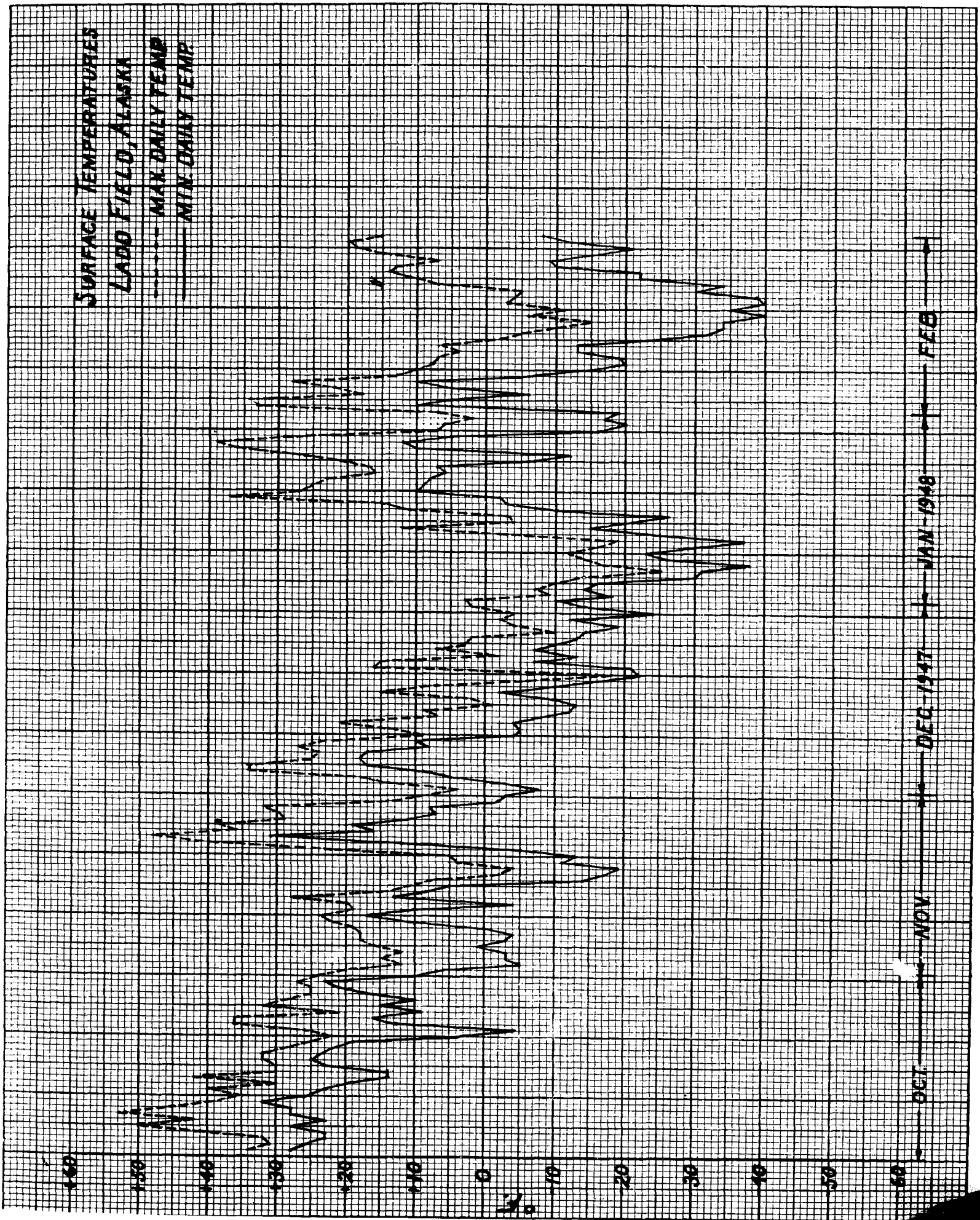

SURFACE TEMPERATURES
LADD FIELD, ALASKA
MAX. DAILY TEMP
MIN. DAILY TEMP
+60
+50
+40
+30
+20
+10
0
-10
-20
-30
-40
-50
-60
OCT.
NOV.
DEC. 1947
JAN. 1948
FEB

Fig. 3

changes. Also, any modifications made to the engine must permit starts at widely varying temperatures without adjustments.

Numerous cold starting tests with military vehicles have been conducted by the various branches of the Armed Forces, both in the field and in cold rooms. These tests have revealed that ease of starting varies from vehicle to vehicle and also that the ability to secure starts at low temperatures depends to a large extent upon the skill and experience of the operator. The lack of uniformity in the data has been attributed to various factors, but as far as can be ascertained, no extensive tests have been conducted to determine the various individual factors involved in the securing of cold starts. Table I illustrates the type of starting data available from current reports; the inconsistency of the data is readily apparent.

The problem of "cold starting" - the starting of internal combustion engines without the application of outside heat - has three major elements -

1. Free flowing lubricating oil.
2. Batteries capable of supplying sufficient energy for cranking and ignition.
3. Attainment of an ignitable fuel-air mixture.

The lubricating oil problem is being solved successfully by two methods which require no application of heat. For aircraft and other heavy engines, oil dilution is practiced. This involves the addition of sufficient gasoline to the oil prior to shut-down to insure a free flowing

DATA EXTRACTED FROM REPORT 34-12
(Winter 1948-1949)

Temp. °F.	RPM	Starting Time-Sec	Revs. to Start	Primer Strokes Prior to Cranking	Choke Position	Throttle Position
			TRUCK, 1/4 TON, 4x4, #822			
-18	75	1.6	1.85	6	1/2	1/4
-20	64	1.4	1.49	4	Full	1/2
-13	86	1.4	2.00	4	Full	1/4
-18	90	2.0	3.00	4	Full	1/4
			TRUCK, 3/4 TON, 4x4 #686			
- 7	200	0.6	2.00	5	3/4	1/3
-17	150	0.6	1.5	3	1/2	1/4
-30	53	4.0	3.5	9	Full	1/4
-33	133	1.8	4.0	8	Full	1/4
-28	100	21.2	35.3	6	1/2	1/2
-32	139	2.6	6.05	6	Full	1/4
-28	100	1.2	2.0	6	Full	1/2
-28	90	Inst.	Inst.	5	3/4	1/4
-30	193	3.0	9.66	6	Full	1/4
			TRUCK, 2 1/2 TON, #434			
-18	86	1.4	2.0	4	Full	1/3
-30	150	1.2	3.0	6	Full	1/4
-30	133	0.9	2.01	6	Full	1/4
-27	60	2.0	2.0	6	Full	1/4
			TRUCK, 4 TON, 6x6, #905			
-24	73	1.8	2.19	4	1/2	1/3
0	Inst.	Inst.	Inst.	6	1/2	1/3
-20	75	3.2	4.0	6	Full	1/4
-28	70	1.2	1.4	4	Full	1/4
-27	Inst.	Inst.	Inst.	6	Full	1/2
- 8	150	0.8	2.0	6	Full	1/4
			TRUCK, 12 TON, 6x6, #082			
-30	85	1.4	1.98	10	Full	1/4
			TRUCK, 12 TON, 8x8, #24			
-2	200	0.6	2.0	4	---	1/4
-20	?	1.0	?	5	---	1/4
- 6	133	1.8	4.0	10	---	1/4

NOTE 1 - All of above starts were made with type 0 Fuel (12-14 lbs. RVP)
NOTE 2 - Revs. to start calculated from Col. 2 & 3

TABLE 1

mixture at the time of the next start. When the engine is next operated the diluent quickly boils off leaving the oil apparently unharmed. Figure 4 illustrates the dilution required for three oils as determined by one investigator. Naturally the design of the lubrication system and the power available for cranking will cause the dilution requirements to vary for different makes and types of engines. For automobiles, medium trucks and other light engines, the Ordnance Corps of the U. S. Army has developed special light arctic oils that have been found satisfactory under all conditions of service.

The battery problem, at present, has not yielded to direct attack. At temperatures below -35°F. the lead-acid battery in common use just cannot furnish the necessary energy to crank a vehicle for an appreciable length of time. To alleviate this problem, insulated battery cases are being employed in conjunction with thermostatically controlled heating coils connected to the engine cooling system to maintain a satisfactory battery temperature. While not perfect, this system will permit retention of a satisfactory battery temperature for periods of shut down ranging from twenty-four to forty-eight hours.

The third factor, the attainment of an ignitable fuel-air mixture at low temperatures, is the one whose definite limits have not been established, nor the means of attaining such a mixture with any degree of reliability devised. One of the obvious solutions is to increase the volatility of the fuel. This can be done; however, insofar as the military is concerned, the supplying of special fuel presents many undesirable

From S.A.E Journal
May 1947
R.W. Goodale

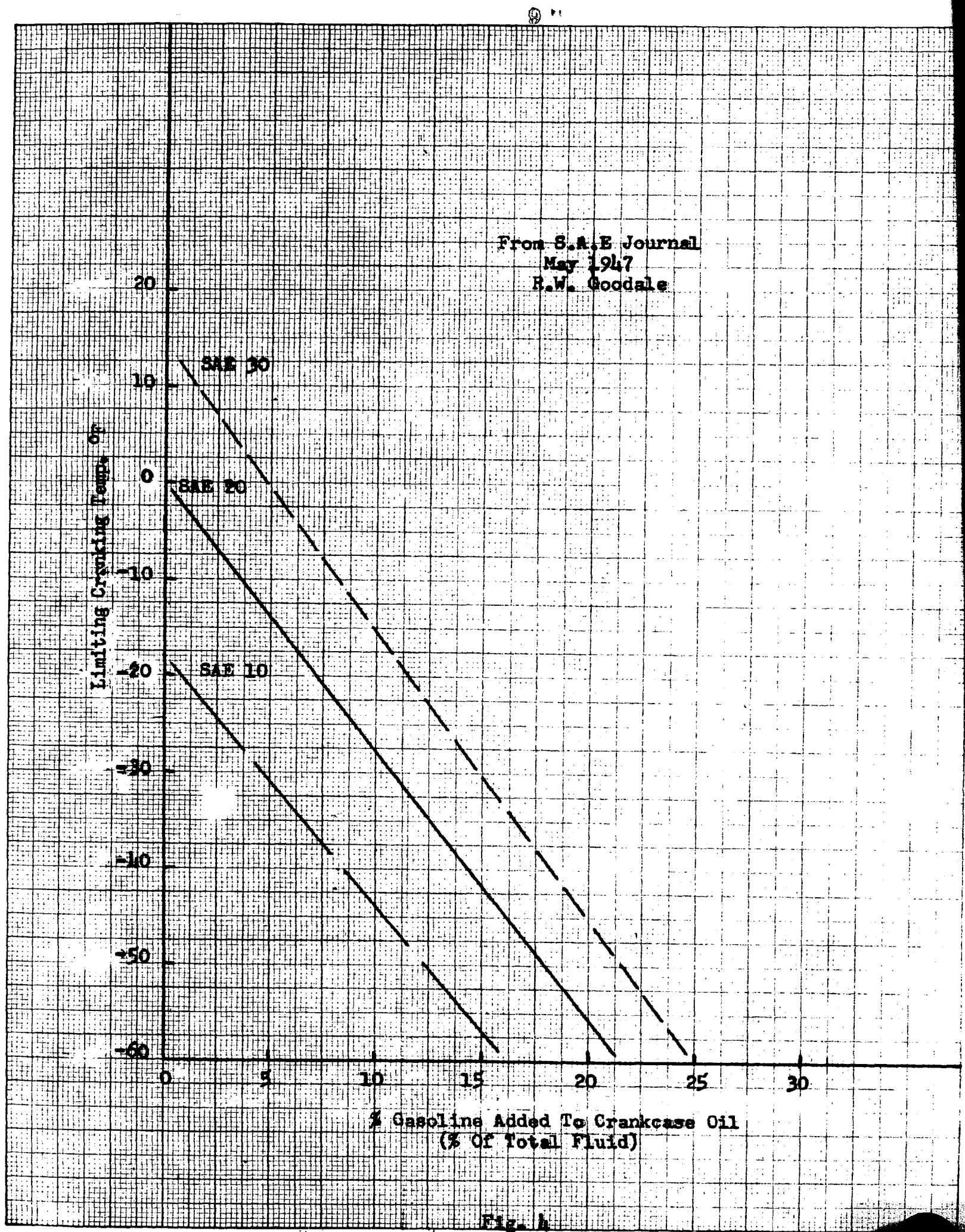


Fig. 4

problems among which are transportation in special containers, storage, distribution, and the fact that in wartime the production of special fuels ties up facilities that are needed for regular fuel. In addition, even in the far north, as previously stated, the temperatures vary over a wide range even during the winter. There are often long periods when such a high volatile fuel is not needed and when it would deteriorate rapidly in the tanks of vehicles fueled with it.

Progress to date, and it has been substantial, has resulted primarily from more efficient application of existing knowledge applied to the engine as a whole. Research and testing has largely been confined to attempting to secure actual starts on complete engines where the number of uncontrolled variables involved often produces misleading interpretations of results. This is a type of "shotgun" research that does not permit the accumulation of an orderly body of facts that will result in a steady evolution toward the desired goal.

The experimental work covered by this investigation is only the first step in a long and difficult program that will, if continued, eventually lead to an appreciation of the individual and cumulative effects of the various factors involved in "cold starting".

OBJECT OF THE INVESTIGATION

This investigation was initiated with three primary objects in view, namely:

First: To determine if standard Type C gasoline could be ignited consistently in an internal combustion engine at low temperatures and to secure basic data pertaining to the fuel-air ratios required for ignition;

Second: To evaluate the effectiveness of the standard Ordnance primer nozzle and its application as an aid to securing combustible mixtures at extreme low temperatures; and

Third: To demonstrate that the problems of low temperature starting may be explored to great advantage by studying the effects of a single variable at a time.

Throughout the tests conducted in connection with this work, the following items were constant:

1. Fuel quality.
2. Primer nozzle.
3. Volumetric Efficiency of Test Cylinder.
4. Ignition.

For the various trials, the following items were held constant for any one phase of the test, but their effects were evaluated by controlled changes on one variable at a time:

1. Primer nozzle position.

2. Temperature.

3. Quantity of fuel primed.

4. Priming pressure.

By changing the variables, one at a time, the answers to the following questions were sought:

1. What is the influence of pressure upon the effectiveness of the standard Ordnance primer nozzle?

2. What is the influence of location upon the effectiveness of the primer nozzle?

3. What is the effect of the quantity of fuel primed upon the attainment of an ignitable air-fuel mixture in the cylinder?

4. What is the air-fuel ratio attained in the cylinder at time of ignition?

Throughout this investigation no attempts were made to actually start the engine, all efforts being directed to securing an ignitable mixture. This was done on the assumption that the first step in starting is to establish an ignitable mixture; having proven this possible, the second step is to investigate the means of supplying a steady, power-producing mixture to the cylinder.

TEST PROCEDURE

With the one cylinder test engine* installed in the cold cell and the instrumentation** connected, the cold cell was brought to the desired temperature level and stabilized for twenty-four hours prior to testing. The temperature of the test cell was held constant within + or - 2°F. at the selected level.

In making a test run, the following procedure was employed:

A. With fuel and ignition circuits de-energized, the cranking motor was placed in operation and the cranking speed adjusted by regulating the voltage. At the lower temperatures, two cranking motors connected in tandem were required to furnish the desired cranking speed during the intake stroke.

B. With the engine turning at the selected cranking speed, the priming and ignition circuits were energized and the engine allowed to crank until the first combustion occurred.

C. At the first combustion in the cylinder, the engine was automatically stopped, all circuits de-energized, and data recorded.

D. The engine was then rotated backward to a position 90° after top dead center, thereby compressing the exhaust

* Appendix I
** Appendix IV

gas. The Orsat connection was then opened and the engine rotated backward by hand, forcing a gas sample from the cylinder into the Orsat apparatus. This procedure insured that the exhaust gas trapped in the cylinder was not diluted by air seeping past the valves and piston rings.

E. The engine was then rotated until the intake valve was fully open. The exhaust valve was forced open and wedged. The reverse flow purging blower was started, forcing air backward through the exhaust valve and out through the intake manifold. For the first ten minutes of purging, the intake manifold was plugged and the purging air forced out through the manifold residue drain in order to trap any liquid fuel that might be forced out. With the manifold completely open, purging was continued for one hour.* In using this method of purging, an effective snow filter was required over the air intake of the fan to prevent ice crystals from being deposited in the cylinder.

The following data was recorded for each test run:

A. Atmospheric pressure in the test cell.

*It was found by experiment that 1/2 hour of reverse purging was sufficient to clear gasoline fumes from the engine and enable consistent results to be obtained. To be safe, the purging was continued for an additional half hour while the results of the preceding test were being analyzed.

B. Test cell temperature.

C. Distance of nozzle from face of cylinder block.

D. Priming pressure at nozzle.

E. Total quantity of fuel passing through nozzle.

F. Pressure-Time curve for each injection.

G. Residue of fuel in manifold at end of test.

H. Number of intake strokes required for first combustion.

At each nozzle position for each temperature level, one Orsat analysis was run on the products of combustion.

The data obtained is summarized for the various temperature levels in Tables II, III, IV, V and VI. Appendix VI presents the computations involved in the preparation of the data.

TABLE II

SUMMARY of DATA at 0° F.

INJECTION PRESSURE 200 psi

CRANKING SPEED 50 - 100 r p m

DATE	TIME	ATMOS. IN of Hg.	ATMOS. (psi)	DISTANCE NOZZLE TO BLOCK	OSCIL REF. No.	ORSAT No.	INTAKES TO START	GROSS INJ'N (cc)	RESIDUE (cc.)	RESIDUE (%)	NET INJECTION (cc)	CC PER IN TAKE	AIR PER INTAKE (LBS)	FUEL PER INTAKE (LBS)	AIR / FUEL (DELIVERY)	AIR / FUEL (COMB.)	%FUEL EVAP.
28-8-51	1200	29·34	14 40	2"	1	-	2	5.35	5.15	96.3	.20	.10	1.35×10^{-3}	$.168 \times 10^{-3}$	8.04	-	-
28-8-51	1545	29·31	14·39	2"	3	-	2	3.73	3.55	95.2	.18	.09	1.35×10^{-3}	$.151 \times 10^{-3}$	8.94	-	-
28-8-51	1620	29·31	14·39	2"	4	-	2	5.31	4.90	92 3	.41	.21	1.35×10^{-3}	$.353 \times 10^{-3}$	3.82	-	-
30-8-51	1120	29·36	14·40	2"	5	-	1	2.88	1.85	64.2	1.03	1.03	1.35×10^{-3}	1.90×10^{-3}	.71	-	-
30-8-51	1600	29·27	14·38	2"	12	8	1	2.25	1 50	66 6	.75	.75	1.35×10^{-3}	1.26×10^{-3}	1.07	24	4.5
28-8-51	1405	29·30	14·39	4"	2	-	2	5.32	5 20	97 7	.12	.06	1.35×10^{-3}	$.101 \times 10^{-3}$	13.40	-	-
29-8-51	1545	29·36	14-40	4"	5	-	2	3 96	3 80	95 9	.16	.08	1.35×10^{-3}	$.134 \times 10^{-3}$	10.05	-	-
30-8-51	1045	29·37	14·41	4"	4	-	1	2.67	1.80	67.4	.87	.87	1.35×10^{-3}	1.46×10^{-3}	.925	-	-
30-8-51	1315	29·33	14·40	4"	8	9	1	2.59	2.05	79.2	.54	.54	1.35×10^{-3}	$.907 \times 10^{-3}$	1.49	24	6.20
31-8-51	0905	29·14	14·30	4"	1	-	2	5.34	5 00	93.6	.34	.17	1.34×10^{-3}	$.285 \times 10^{-3}$	4.70	-	-
29-8-51	0940	29·40	14·42	6"	1	-	2	5.32	5.10	95.7	.22	.11	1.352×10^{-3}	$.185 \times 10^{-3}$	7.30	-	-
30-8-51	0830	29·39	14·41	6"	1	-	1	2.64	1 80	68.2	.84	.84	1.35×10^{-3}	1.40×10^{-3}	.96	-	-
30-8-51	1000	29·40	14·42	6"	3	10	1	2.65	2,00	75.5	.65	.65	1.352×10^{-3}	1.09×10^{-3}	1.24	29	4.28
30-8-51	1400	29·31	14·39	6"	9		1	2.66	1.80	67.6	.86	.86	1.35×10^{-3}	1.45×10^{-3}	.935	-	-
31-8-51	0945	29·13	14·30	6"	2	-	2	5.34	5 00	93.6	.34	.17	1.34×10^{-3}	$.319 \times 10^{-3}$	4.20	-	-
29-8-51	1050	29·41	14·45	8"	2	-	2	5.38	5.10	94.7	.28	.14	1.355×10^{-3}	$.235 \times 10^{-3}$	6.76	-	-
29-8-51	1250	29·39	14·41	8"	3	-	2	5.26	4.80	81.2	.46	.23	1.35×10^{-3}	$.386 \times 10^{-3}$	3.50	-	-
30-8-51	1200	29·35	14·40	8"	6	11	2	5.28	4.70	89.0	.58	.29	1.35×10^{-3}	$.487 \times 10^{-3}$	2.77	35	7.9
30-8-51	1440	29·30	14·39	8"	10	-	1	2.49	1.70	68.4	.79	.79	1.35×10^{-3}	1.33×10^{-3}	1.02	-	-
31-8-51	1035	29·13	14·30	8"	3	-	2	5.29	5.10	96.7	.19	.10	1.34×10^{-3}	$.168 \times 10^{-3}$	7.97	-	-
29-8-51	1430	29·37	14·41	10"	4	-	2	4.34	4.10	94·6	.24	.12	1.35×10^{-3}	$.202 \times 10^{-3}$	6.70	-	-
30-8-51	0915	29·37	14·41	10"	2	12	2	5.33	4.70	88.3	.63	.32	1.35×10^{-3}	$.538 \times 10^{-3}$	2.51	39	6.45
30-8-51	1240	29·34	14·40	10"	7	-	1	1.65	1.00	60.5	65	.65	1.35×10^{-3}	1.09×10^{-3}	1.24	-	-
30-8-51	1525	29·28	14·38	10"	11	-	2	4.87	4.50	92.5	.37	.19	1.35×10^{-3}	$.319 \times 10^{-3}$	4 23	-	-
31-8-51	1200	29·10	14·29	10"	4	-	2	5.29	5.10	96.6	.19	.10	1.34×10^{-3}	$.168 \times 10^{-3}$	7.97	-	-

SUMMARY of DATA at -20°F.

INJECTION PRESSURE 200psi

CRANKING SPEED 50-100 rpm

TABLE III

DATE	TIME	ATMOS. IN of Hg.	ATMOS. (psi)	DISTANCE NOZZLE TO BLOCK	OSCIL. REF. No.	ORSAT No.	INTAKES TO START	GROSS INJ'N (cc)	RESIDUE (cc)	RESIDUE (%)	NET INJECTION (cc)	CC PER INTAKE	AIR PER INTAKE (LBS)	FUEL PER INTAKE (LBS)	AIR / FUEL (DELIVERY)	AIR / FUEL (COMB.)	% FUEL EVAP.
17-7-51	1300	29·45	14·44	2"	1	-	2	6.34	5.40	85.5	.94	.47	1.416×10^{-3}	$.798 \times 10^{-3}$	1.775	-	-
18-7-51	0900	29·37	14·40	2"	2	-	2	6.36	5.60	86.4	.88	.43	1.412×10^{-3}	$.730 \times 10^{-3}$	1.935	-	-
18-7-51	1100	29·36	14·40	2"	3	-	2	6.37	5.20	81.7	1.17	.59	1.412×10^{-3}	1.00×10^{-3}	1.412	-	-
18-7-51	1580	29·29	14·37	2"	4	1	2	6.49	5.25	81.0	1.24	.62	1.410×10^{-3}	1.053×10^{-3}	1.340	43.	3.1
18-7-51	1330	29·28	14·37	2"	5	-	2	6.46	5.25	81.2	1.21	.61	1.410×10^{-3}	1.036×10^{-3}	1.360	-	-
19-7-51	0830	29·24	14·35	4"	1	-	2	5.08	4.25	83.7	.83	.42	1.408×10^{-3}	$.714 \times 10^{-3}$	1.970	-	-
19-7-51	0930	29·24	14·36	4"	2	-	2	4.97	3.90	78.5	1.07	.54	1.408×10^{-3}	$.917 \times 10^{-3}$	1.535	-	-
19-7-51	1030	29·24	14·36	4"	3	-	2	5.00	4.30	86.0	.70	.35	1.408×10^{-3}	$.594 \times 10^{-3}$	2.370	-	-
19-7-51	1130	29·24	14·35	4"	4	2	2	5.04	3.95	78.4	1.09	.55	1.408×10^{-3}	$.934 \times 10^{-3}$	1.510	46.	3.26
19-7-51	1230	29·23	14·35	4"	5	-	2	4.96	3.50	70.5	1.46	.73	1.408×10^{-3}	1.240×10^{-3}	1.135	-	-
19-7-51	1330	29·22	14·34	6"	1	-	2	5.09	4.40	86.5	.69	.35	1.408×10^{-3}	$.594 \times 10^{-3}$	2.370	-	-
19-7-51	1430	29·20	14·32	6"	2	-	2	5.17	4.15	80.2	1.02	.51	1.408×10^{-3}	$.865 \times 10^{-3}$	1.620	-	-
19-7-51	0800	29·37	14·40	6"	3	-	2	5.10	3.55	69.5	1.55	.78	1.412×10^{-3}	1.325×10^{-3}	1.067	-	-
20-7-51	0930	29·38	14·40	6"	4	3	2	5.15	3.80	74.0	1.33	.67	1.412×10^{-3}	1.138×10^{-3}	1.242	48.3	2.74
20-7-51	1030	29·38	14·40	6"	5	-	2	5.22	3.65	70.0	1.57	.79	1.412×10^{-3}	1.340×10^{-3}	1.053	-	-
20-7-51	1130	29·38	14·40	8"	1	-	2	5.19	4.30	83.0	.89	.45	1.412×10^{-3}	$.764 \times 10^{-3}$	1.850	-	-
20-7-51	1230	29·38	14·40	8"	2	-	2	5.23	3.95	75.5	1.28	.64	1.412×10^{-3}	1.087×10^{-3}	1.300	-	-
20-7-51	1400	29·36	14·40	8"	3	-	2	4.93	3.75	76.0	1.18	.59	1.412×10^{-3}	1.000×10^{-3}	1.412	-	-
23-7-51	1100	29·50	14·47	8"	4	4	2	4.95	3.70	75.0	1.25	.63	1.419×10^{-3}	1.070×10^{-3}	1.325	48.6	2.9
25-7-51	0800	29·45	14·44	8"	5	-	2	5.04	3.60	71.7	1.44	.72	1.417×10^{-3}	1.223×10^{-3}	1.160	-	-
25-7-51	1000	29·44	14·44	10"	1	-	2	5.38	4.25	79.0	1.13	.57	1.417×10^{-3}	$.968 \times 10^{-3}$	1.465	-	-
25-7-51	1130	29·44	14·44	10"	2	5	2	5.23	4.15	79.4	1.08	.54	1.417×10^{-3}	$.917 \times 10^{-3}$	1.545	51.8	2.98
25-7-51	1300	29·42	14·43	10"	3	-	2	5.14	4.90	95.5	.24	.12	1.417×10^{-3}	$.204 \times 10^{-3}$	6.940	-	-
26-7-51	0900	29·42	14·43	10"	4	-	2	4.58	3.20	70.0	1.38	.69	1.417×10^{-3}	1.170×10^{-3}	1.210	-	-
26-7-51	1030	29·42	14·43	10"	5	-	2	5.27	4.15	78.8	1.12	.56	1.417×10^{-3}	$.951 \times 10^{-3}$	1.490	-	-
26-7-51	1400	29·38	14·40	10"	6	-	2	5.35	3.95	74.0	1.40	.70	1.412×10^{-3}	1.190×10^{-3}	1.188	-	-

TABLE IV

SUMMARY OF DATA at -40 F.

INJECTION PRESSURE 200 psi

CRANKING SPEED 50 - 100 rpm

DATE	TIME	ATMOS. IN of Hg.	ATMOS. (psi)	DISTANCE NOZZLE TO BLOCK	OSCIL. REF. No.	ORSAT No.	INTAKES TO START	GROSS INJ'N (cc)	RESIDUE (cc)	RESIDUE (%)	NET INJECTION (cc)	CC PER INTAKE	AIR PER INTAKE (LBS)	FUEL PER INTAKE (LBS)	AIR/FUEL (DELIVERY)	AIR/FUEL (COMB.)	% FUEL EVAP.
6-8-51	1130	29.40	14.44	2"	2	-	3	9.61	6.15	64.0	3.46	1.15	1.480×10^{-3}	1.970×10^{-3}	.750	-	-
6-8-51	1300	29.38	14.41	2"	1	-	5	16.28	11.10	67.6	5.18	1.04	1.479×10^{-3}	1.781×10^{-3}	.827	-	-
7-8-51	1100	29.12	14.30	2"	2	-	4	13.01	9.15	70.3	3.86	.97	1.467×10^{-3}	1.660×10^{-3}	.884	-	-
8-8-51	0900	29.12	14.30	2"	1	-	3	9.82	6.50	66.1	3.32	1.11	1.467×10^{-3}	1.910×10^{-3}	.767	-	-
8-8-51	1030	29.12	14.30	2"	5	7	6	15.83	11.20	70.7	4.63	.77	1.467×10^{-3}	1.320×10^{-3}	1.11	82.	1.35
14-8-51	1400	29.41	14.45	4"	2	-	5	12.99	8.80	68.0	4.19	.84	1.481×10^{-3}	1.439×10^{-3}	1.030	-	-
14-8-51	1530	29.41	14.45	4"	3	-	4	10.21	6.75	66.0	3.46	.87	1.481×10^{-3}	1.490×10^{-3}	.994	-	-
7-8-51	0900	29.12	14.30	4"	2	-	4	11.39	8.20	72.0	3.19	.80	1.467×10^{-3}	1.370×10^{-3}	1.069	-	-
6-8-51	1000	29.41	14.45	4"	1	6	5	15.92	11.85	74.5	4.07	.81	1.481×10^{-3}	1.386×10^{-3}	1.070	98.	1.09
9-8-51	1230	29.23	14.37	4"	1	-	8	20.69	14.50	70.0	6.19	.78	1.472×10^{-3}	1.337×10^{-3}	1.102	-	-

6" 5 ATTEMPTS at 20 INJECTIONS - NO COMBUSTION

8" 5 ATTEMPTS at 20 INJECTIONS - NO COMBUSTION

10" 5 ATTEMPTS at 20 INJECTIONS - NO COMBUSTION

TABLES V & VI

SUMMARY of DATA at -50°F.
INJECTION PRESSURE 200 psi
CRANKING SPEED 50-100 rpm

DATE	TIME	ATMOS. IN of Hg.	ATMOS. (psi)	DISTANCE NOZZLE TO BLOCK	OSCIL. REF. No.	ORSAT No.	INTAKES TO START	GROSS INJ'N (cc)	RESIDUE (cc)	RESIDUE (%)	NET INJECTION (cc)	CC PER INTAKE	AIR PER INTAKE (LBS)	FUEL PER INTAKE (LBS)	AIR/FUEL (DELIVERY)	AIR/FUEL (COMB.)	% FUEL EVAP.
17-8-51	0900	29.37	14.40	2"		13	17									143.2	
17-8-51	1100	29.28	14.37	2"		14	16									133.4	
17-8-51	1250	29.24	14.35	2"			12										
17-8-51	1400	29.24	14.35	2"			15										
17-8-51	1600	29.24	14.35	2"			16										
18-8-51				4"	5 ATTEMPTS at 20 INJECTIONS - NO COMBUSTION												
20-8-51				6"	5 ATTEMPTS at 20 INJECTIONS - NO COMBUSTION												
21-8-51				8"	5 ATTEMPTS at 20 INJECTIONS - NO COMBUSTION												
22-8-51				10"	5 ATTEMPTS at 20 INJECTIONS - NO COMBUSTION												

SUMMARY of DATA at -60 F°
INJECTION PRESSURE 200 psi
CRANKING SPEED 50-100 rpm

24-8-51	0800	29.31	14.39	0"			20										
24-8-51	0930	29.31	14.39	0"		15	25									202.6	
24-8-51	1100	29.36	14.40	0"			17										
24-8-51	1300	29.27	14.38	0"			23										
25-8-51	1550	29.27	14.38	0"		16	27									170.6	
25-8-51				2"	5 ATTEMPTS at 30 INJECTIONS - NO COMBUSTION												
27-8-51				4"	5 ATTEMPTS at 30 INJECTIONS - NO COMBUSTION												
28-8-51				6"	5 ATTEMPTS at 30 INJECTIONS - NO COMBUSTION												
29-8-51				8"	5 ATTEMPTS at 30 INJECTIONS - NO COMBUSTION												
30-8-51				10"	5 ATTEMPTS at 30 INJECTIONS - NO COMBUSTION												

NOTE: THE LARGE QUANTITIES OF FUEL REQUIRED FOR COMBUSTION AT THESE TEMPERATURES CAUSED OVERFLOWS OUT OF THE INTAKE MANIFOLD, MAKING IT TOO DIFFICULT TO MEASURE RESIDUES.

DISCUSSION

For convenience, the discussion of the results will be considered under the main topics which lead to the conclusions drawn from this experimental work.

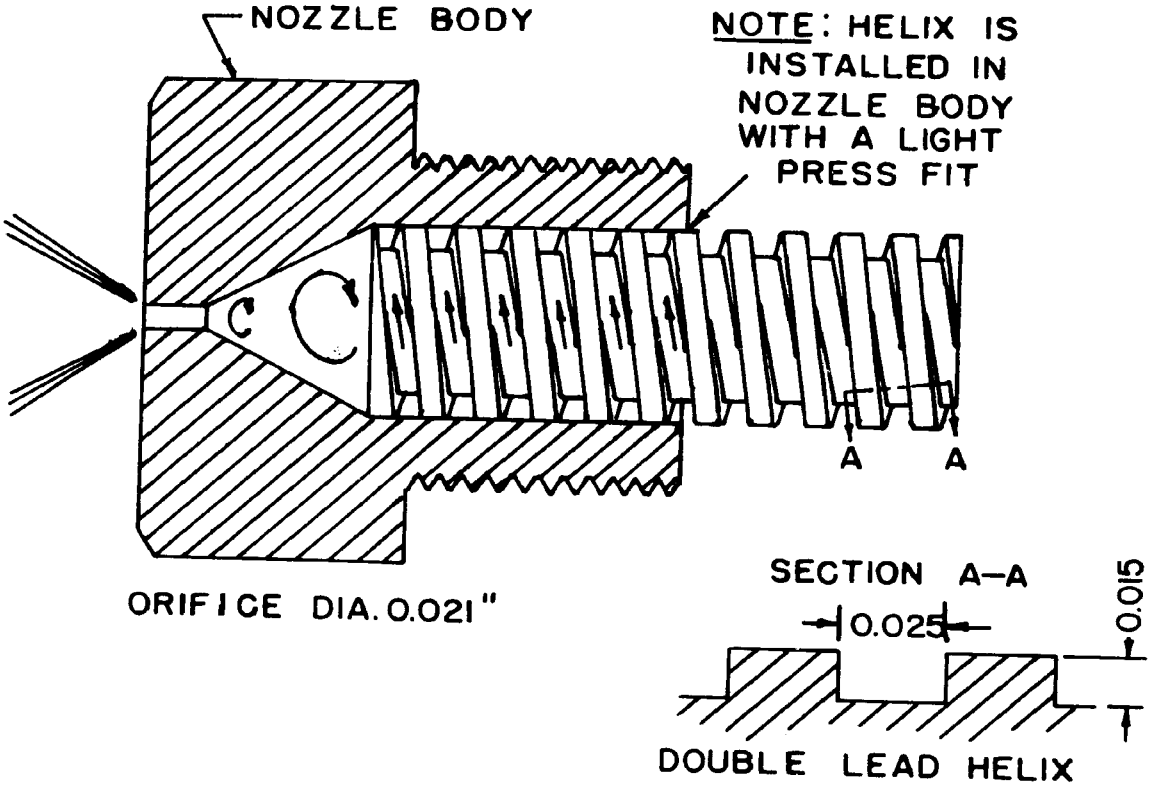
1. The Influence of Pressure Upon the Effectiveness of the Standard Ordnance Primer Nozzle.

For many years the belief has been rather widespread that the use of a spray nozzle in conjunction with a primer pump increased the effectiveness of the priming action. Since the Ordnance Corps uses only one type of primer nozzle (Ordnance Drawing No. A29675), shown schematically in Figure 5, the investigation was limited to this standard nozzle and the conclusions drawn apply to it alone.

A search of the military records revealed no test data upon which the selection of this nozzle was based. Inquiry to the Dole Valve Co., present manufacturers of the item, revealed that they had conducted no tests whatever and were only building the nozzles to government drawings.*

Due to the lack of test data, five production nozzles were selected at random and the flow characteristics determined. The results of these

*Mr. C. H. Jorgenson, Chief Research Engineer, Rochester Products Div., General Motors Corp. stated that he designed this nozzle in 1913 to go with a primer pump he had invented. He could recall no performance tests on the nozzle. In World War II, when cold starting became a problem, this part was in the Ordnance catalogue and was pressed into service once more. Mr. William Day, now of the Perfection Stove Co., who was in charge of winterization of vehicles during World War II for the Office, Chief of Ordnance, Detroit, has verified that the nozzle and primer pump were used because they were already in the Ordnance system.



TEST NOZZLE
(SCHEMATIC)

In this nozzle the column of liquid is given a regular rotary motion and is accelerated to a high velocity in the helix. The liquid then passes into the swirl chamber where the velocity is further increased by the decreasing diameter of the cone inside of which the fluid is rotating. Upon reaching the orifice the fluid is peeled off as a thin film which breaks up into droplets after leaving the orifice.

This nozzle is not theoretically correct in all dimensions, but it represents a reasonable compromise between low cost through mass production and acceptable performance.

Fig. 5

tests are shown in Figure 6. In addition, high speed photographs were made of the spray pattern at various pressures from 25 to 200 pounds per square inch. See Figures 7 through 14. It will be noted theat this nozzle produces a relatively wide spray cone, approximately 60°.

For use in the experimental work at low temperatures, a standard nozzle was selected and carefully calibrated for flow at various pressures at 0°, -35°, and-66°F. It was found that the flow characteristics of the nozzle were unaffected by temperature. The calibration of the test nozzle is presented in Figure 15.

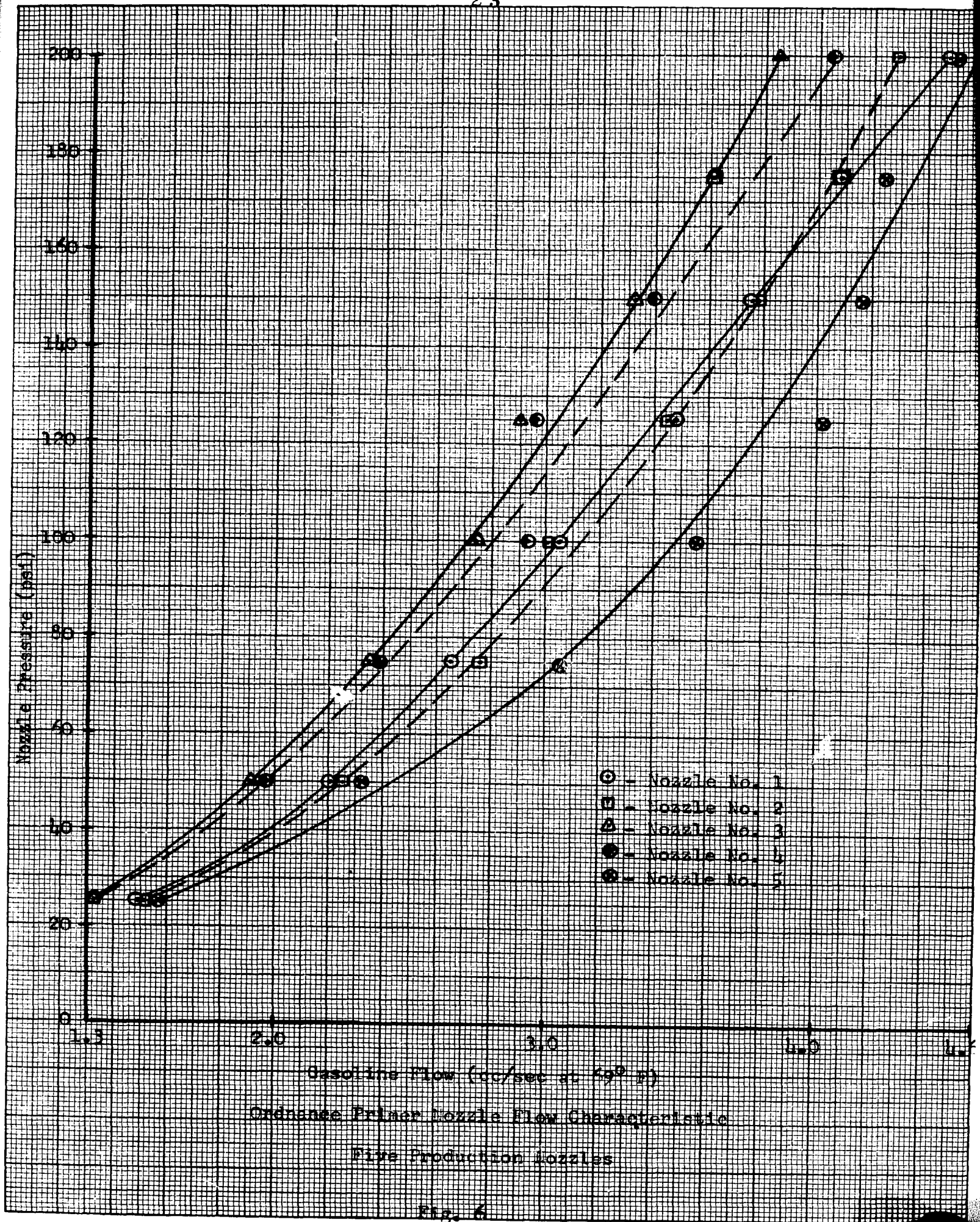
Selecting the 0 nozzle position*, since this position was the only one found effective at the lower temperatures, the number of intake strokes to secure an ignitable mixture was determined. Table VII presents the data.

Spray injection with 500 psi. shock pressure is shown as an item of interest only. On the early test set-up, the quick opening of the electric valve combined with the lack of an accumulator was found to be creating momentary shock pressures at the nozzle in the neighborhood of 500 psi. On the chance that this extremely high pressure might aid vaporization, a complete run was made to obtain data for comparison.

Solid injection (the flowing of a solid stream of gasoline into the manifold) was accomplished by replacing the primer nozzle with a plain plug having an orifice of a size sufficient to achieve the same flow rate as the standard primer nozzle.

Figure 16 graphically compares the effect of priming pressure

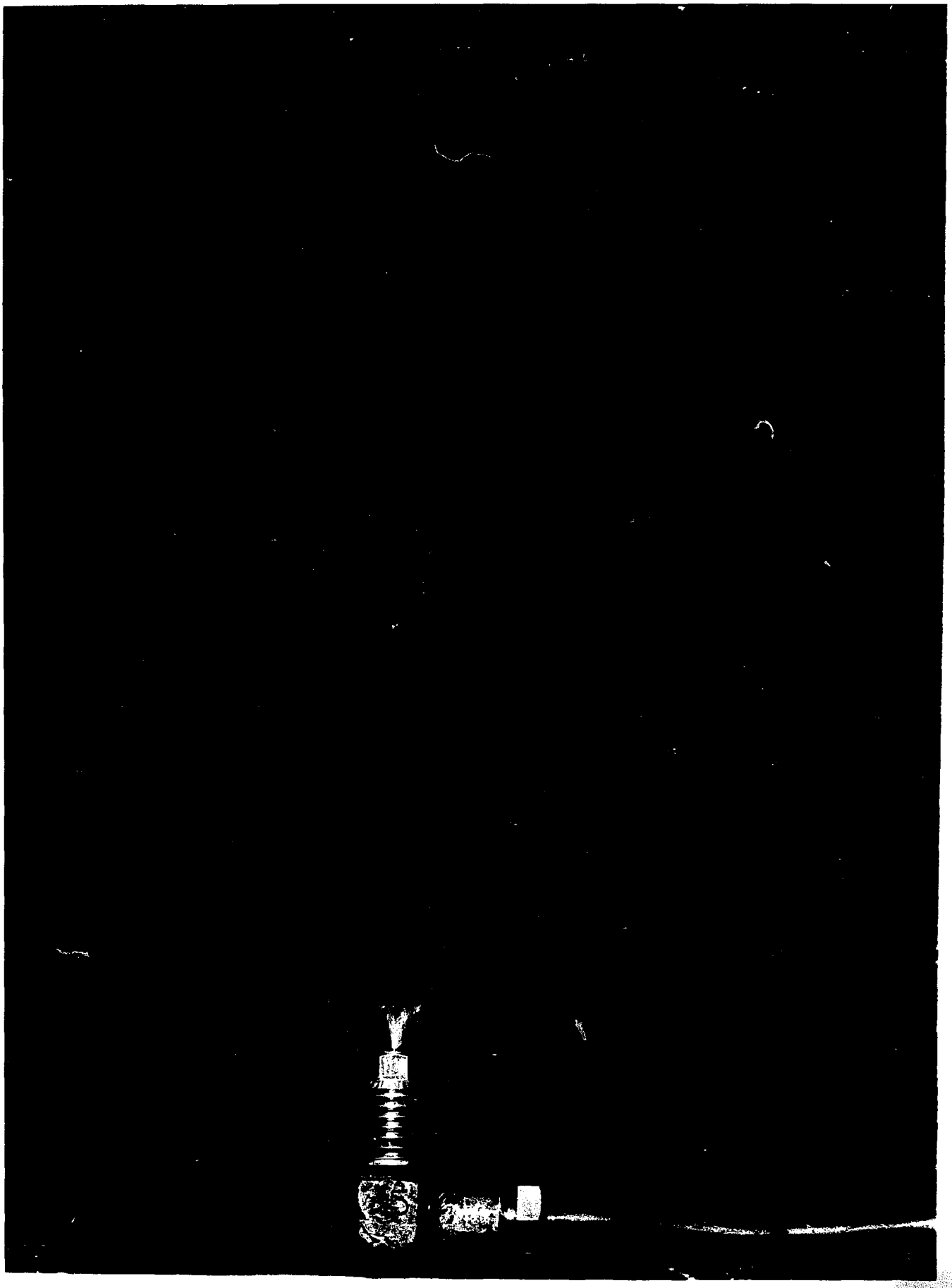
*See Figure 30, Appendix I for nozzle positions.



Ordnance Primer Nozzle Flow Characteristic

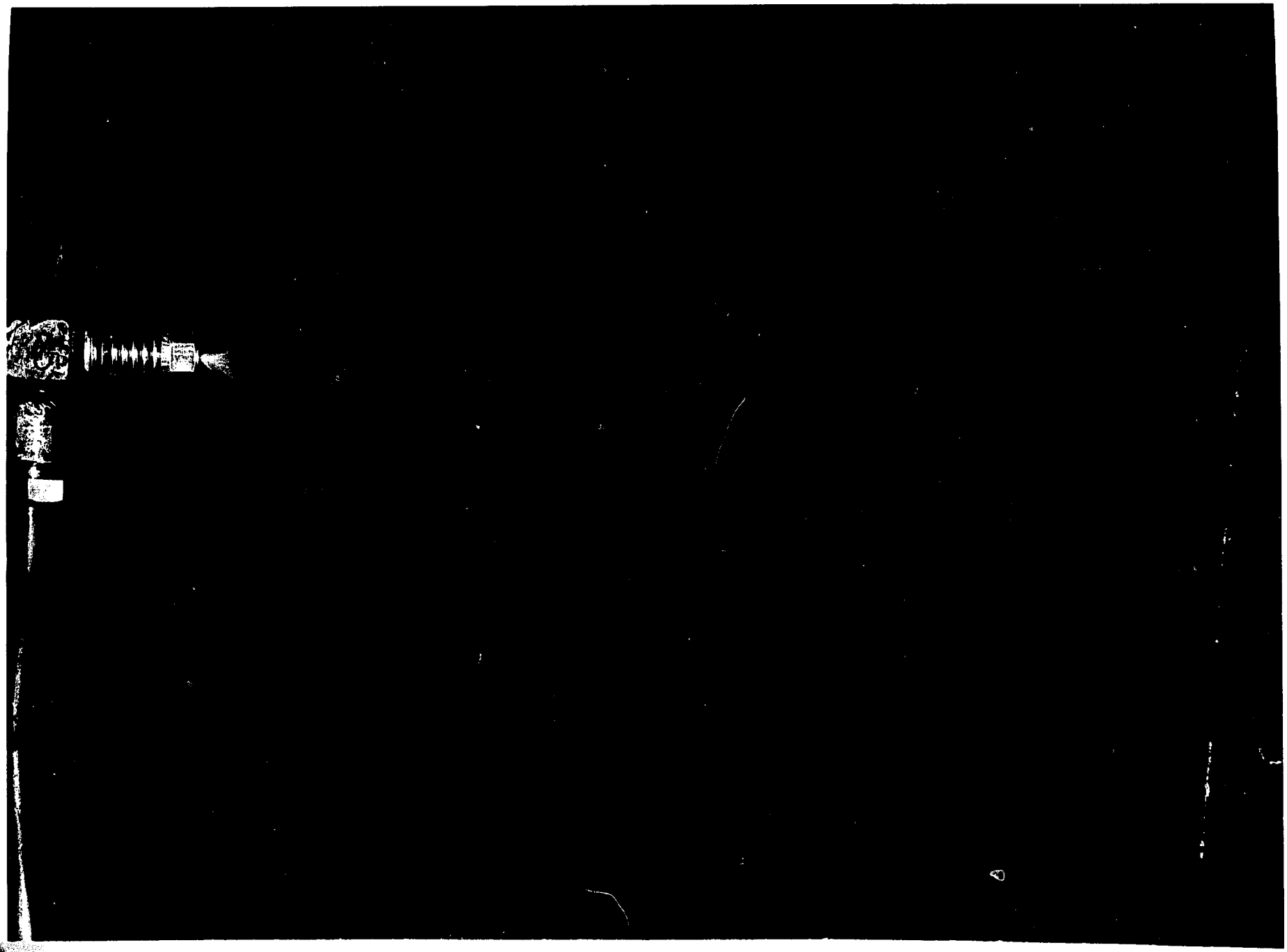
Five Production Nozzles

Fig. 6



DETROIT ARSENAL
NEG. NO. 24151 DATE 6 Jan 1951 DEVELOPMENT & ENGINEERING
Primer Nozzle Pattern Test at Varied Pressures. Nozzle
(Ord. Dwg. A296725) Gasoline Spray at 25 P.S.I.

Fig. 7

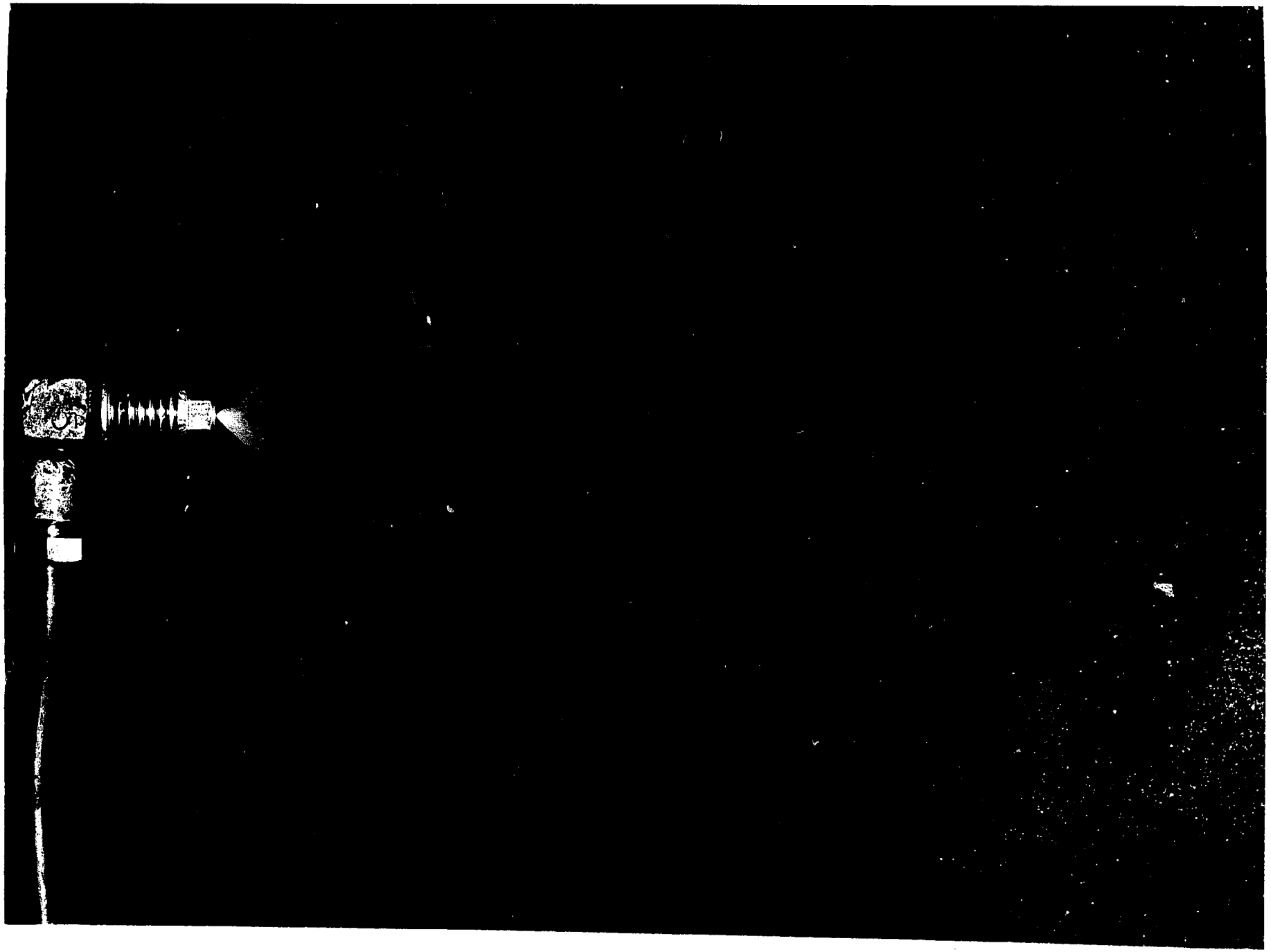


—DETROIT ARSENAL—

NEG. NO. 24152 DATE 6 Jan 1951 DEVELOPMENT & ENGINEERING

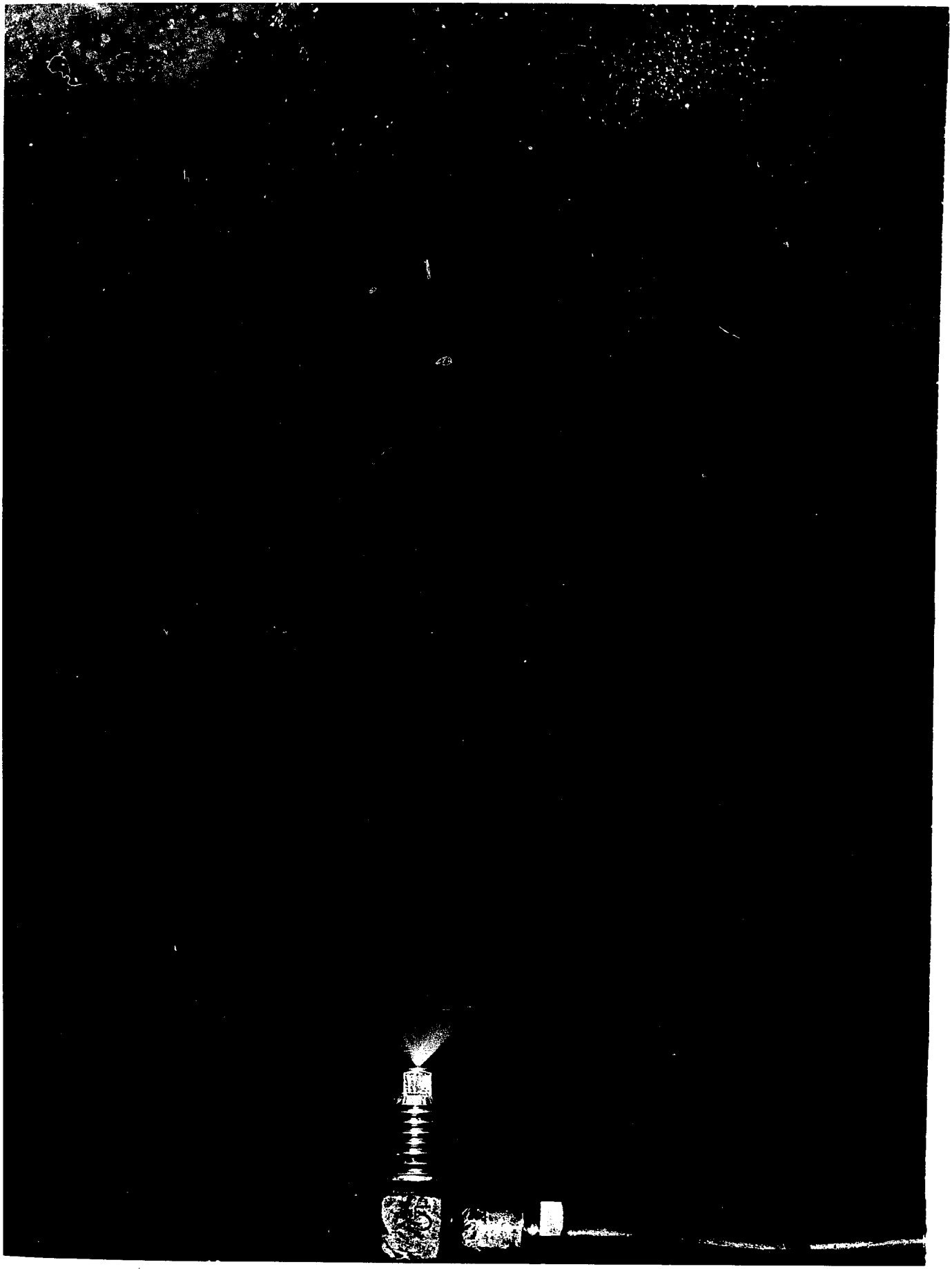
Primer Nozzle Pattern Test at Varied Pressures. Nozzle (Ord. Dwg. A296725) Gasoline Spray at 50 P.S.I.

FIG. 8



—DETROIT ARSENAL—
NEG. NO. 24153 DATE 6 Jan 1951 DEVELOPMENT & ENGINEERING
Primer Nozzle Pattern Test at Varied Pressures. Nozzle
(Ord. Dwg. A296725) Gasoline Spray at 75 P.S.I

Fig. 9



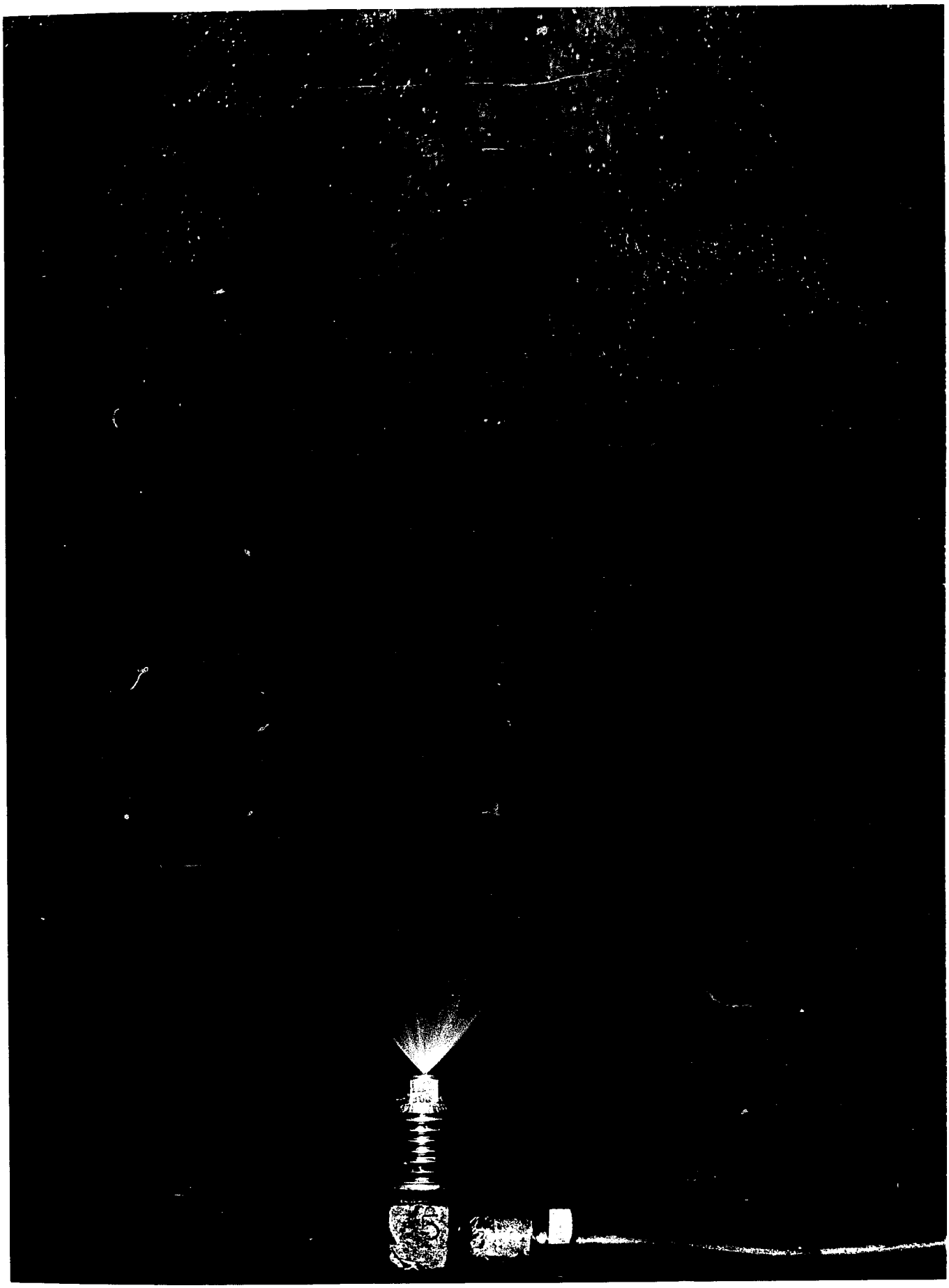
DETROIT ARSENAL
NEG. NO. 2454 DATE 6 Jan 1951 DEVELOPMENT ENGINEERING
Primer Nozzle Pattern Test at Varied Pressures. Nozzle
(Ord. Dwg. A296725) Gasoline Spray at 100 P.S.I.

Fig. 10



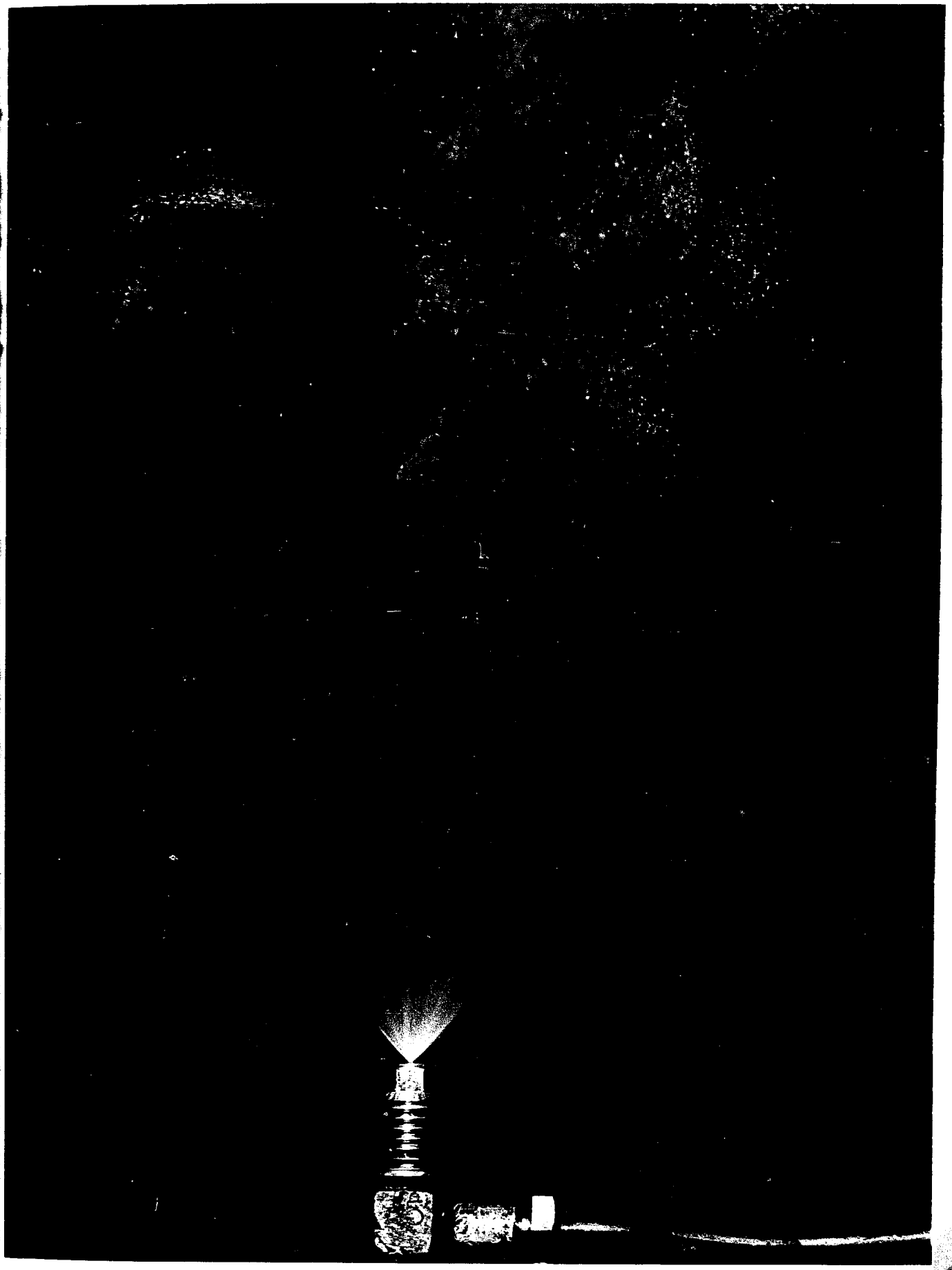
DETROIT ARSENAL
NEG. NO. 24155 DATE 6 Jan 1951 DEVELOPMENT & ENGINEERING
Primer Nozzle Pattern Test at Varied Pressures. Nozzle
(Ord. Dwg. A296725) Gasoline Spray at 125 P.S.I.

Fig. 11



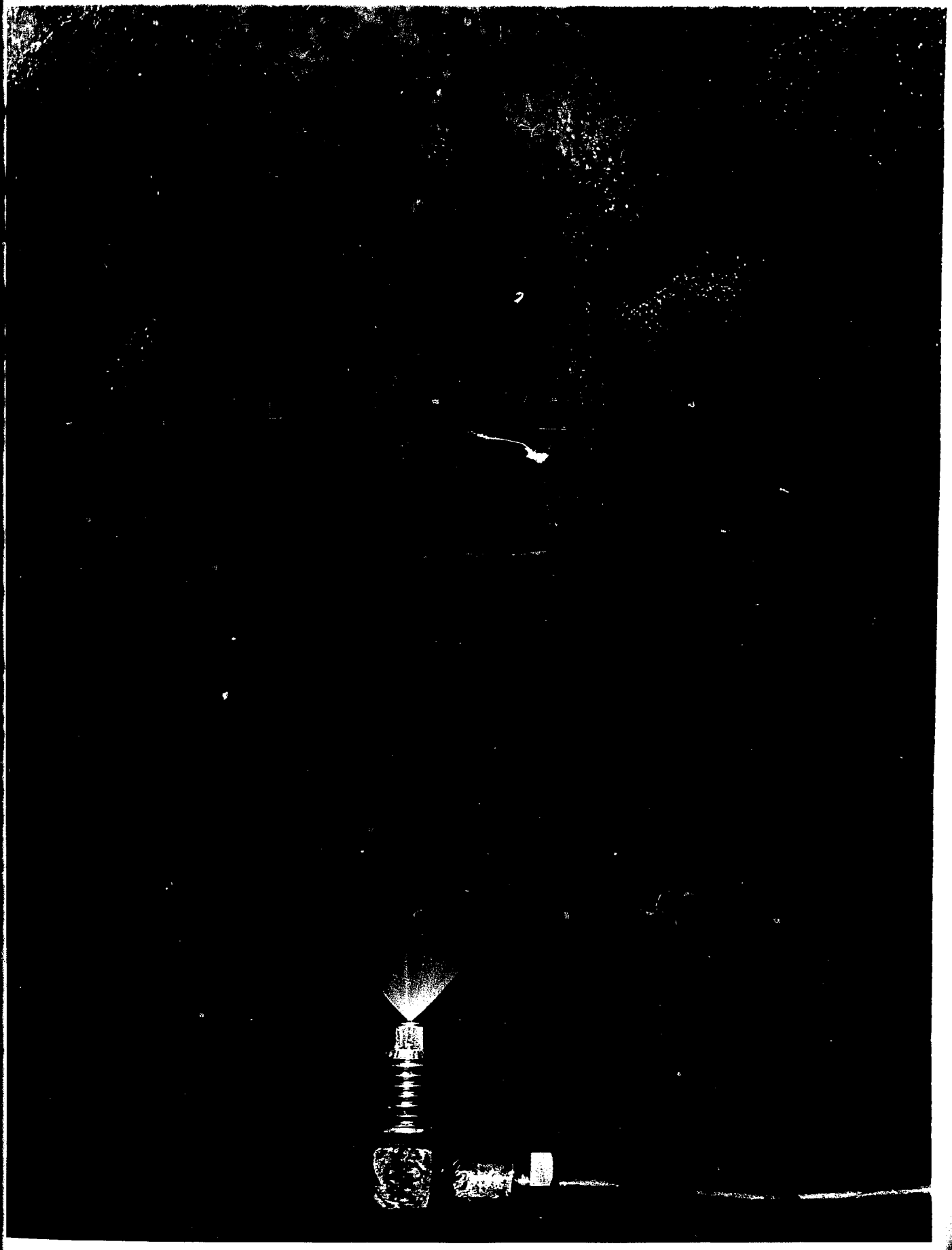
DETROIT ARSENAL
NEG. NO. 24156 DATE 6 Jan 1951 DEVELOPMENT & ENGINEERING
Primer Nozzle Pattern Test at Varied Pressures. Nozzle
(Ord. Dwg. A296725) Gasoline Spray at 150 P.S.I.

Fig. 12



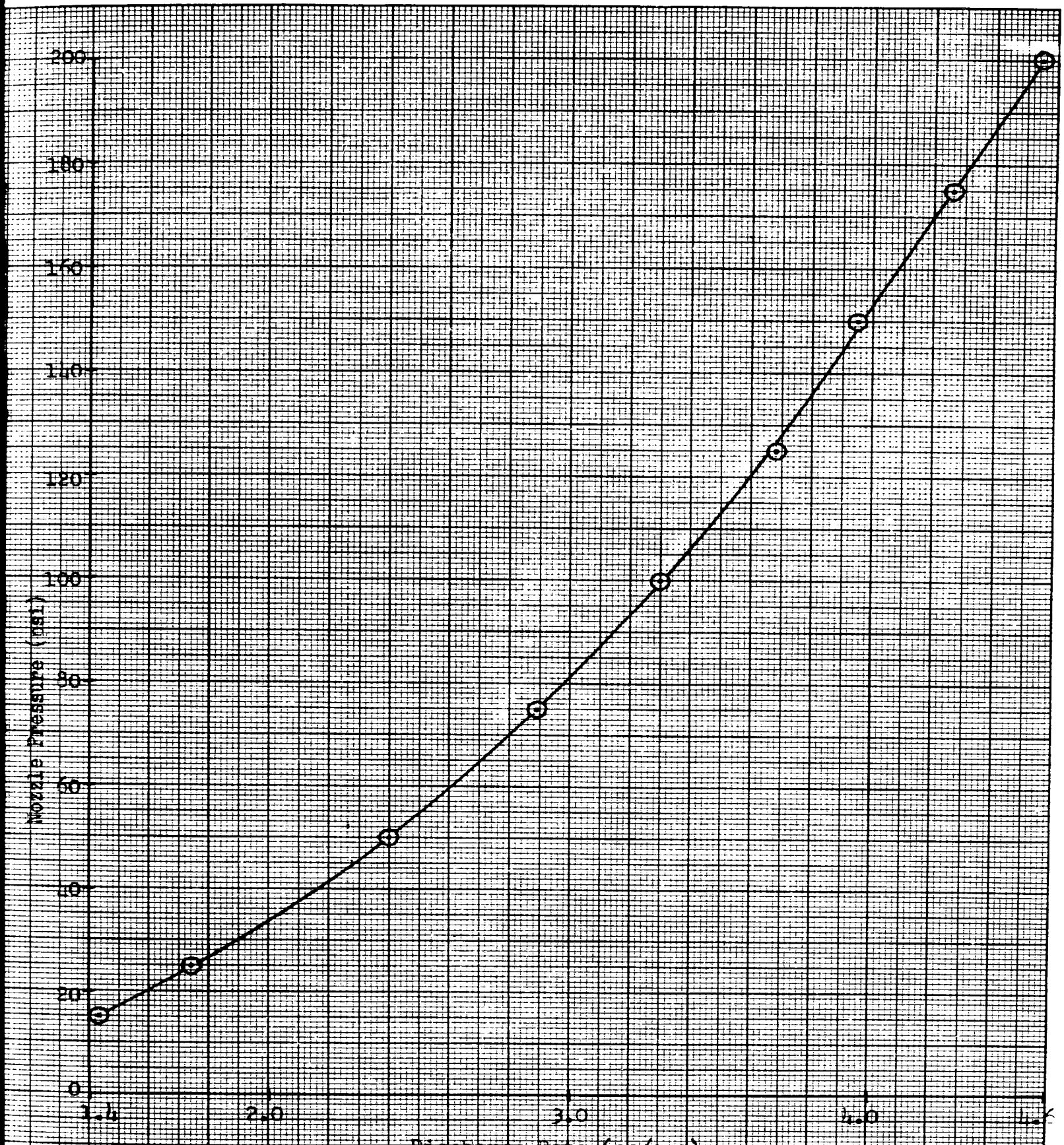
DETROIT ARSENAL
NEG. NO. 24157 DATE 6 Jan 1951 DEVELOPMENT & ENGINEERING
Primer Nozzle Pattern Test at Varied Pressures. Nozzle
(Ord. Dwg. A296725) Gasoline Spray at 175 P.S.I.

Fig. 13



DETROIT ARSENAL
NEG. NO. 24158 DATE 6 Jan 1951 DEVELOPMENT & ENGINEERING
Primer Nozzle Pattern Test at Varied Pressures. Nozzle
(Ord. Dwg. A296725) Gasoline Spray at 200 P.S.I.

Fig. 14



Flow Calibration For Test Primer Nozzle

(Calibration Holds For 0° to -65° F)

Fig. 15

EFFECT of PRIMING PRESSURE on COMBUSTION

NOZZLE POSITION 0" FROM BLOCK

INJECTION TIME ADJ. to DELIVER 2.5 cc of GASOLINE PER INTAKE

CRANKING SPEED 50 - 100 rpm

TEMP. °F	INTAKES TO FIRST COMBUSTION			
	SPRAY INJECTION			SOLID INJECTION
	200 psi	200 psi Line Pres. With 500 psi Shock Pressure	50 psi	50 psi
0	2	2	2	1
	1	2	2	2
	1	1	2	2
	1	No Trial	No Trial	2
	2	No Trial	No Trial	No Trial
-20	1	2	2	2
	2	2	2	2
	2	2	2	2
	2	No Trial	No Trial	2
	2	No Trial	No Trial	No Trial
-40	3	2	3	5
	5	5	4	6
	4	2	2	5
	3	1	2	8
	6	No Trial	No Trial	4
-50	17	15	16	13
	16	15	16	15
	12	17	16	17
	15	No Trial	No Trial	13
	16	No Trial	No Trial	13
-60	20	22	25	25
	25	25	24	23
	17	25	28	19
	23	27	26	26
	27	No Trial	No Trial	18

TABLE VII

Effect of Priming Pressure on Combustion
Priming Pressure
50 psi fuel spray
200 psi line pressure with
500 psi shock pressure
400 psi spray
Average intake strokes to first combustion
0
5
10
15
20
25

Fig. 16

upon intake strokes necessary to secure combustion and indicates that for all practical purposes this primer nozzle contributes nothing to the attainment of an ignitable mixture that cannot be attained as readily by injecting a solid stream of fuel into the manifold. In addition, the use of priming pressures above 50 psi. with this nozzle are unjustified, even though actual photographs seem to indicate a much greater atomization of the fuel at higher pressures.

These results are far from what was expected; the spray nozzle definitely breaks the fuel up into many minute particles, increasing its surface area and thus should increase its rate of evaporation. The fact that the use of the nozzle failed to attain the expected results may be attributed to several factors; first, the spray angle of the nozzle was so wide that in the small diameter manifold the fuel impinged upon the manifold walls before it had time to evaporate in appreciable quantities; secondly, with a position so close to the valve seat, the particles of fuel from the nozzle did not wet the available area of the manifold as effectively as did the solid stream of fuel which traveled into the valve stem pocket and splashed completely over the valve pocket and back into the manifold, thus spreading the fuel in a thin film over a rather large area; and finally, due to the short flight of the droplets from the spray nozzle, combined with the slowness of evaporation at the lower temperatures, most of the evaporation of the fuel may take place from the manifold surfaces, thus eliminating the advantage thought to accrue from the use of the nozzle.

This experiment indicates, that insofar as the present standard Ordnance nozzle is concerned, the nozzle could be replaced by a simple tube running from the primer pump to the manifold, thus eliminating the present difficulties due to nozzle clogging and probably reducing cost. It also indicates that the time, effort and money being spent to develop more satisfactory high pressure priming pumps may result in little real benefit in securing easier starts at low temperatures.

2. The Influence of Location Upon the Effectiveness of the Standard Primer Nozzle.

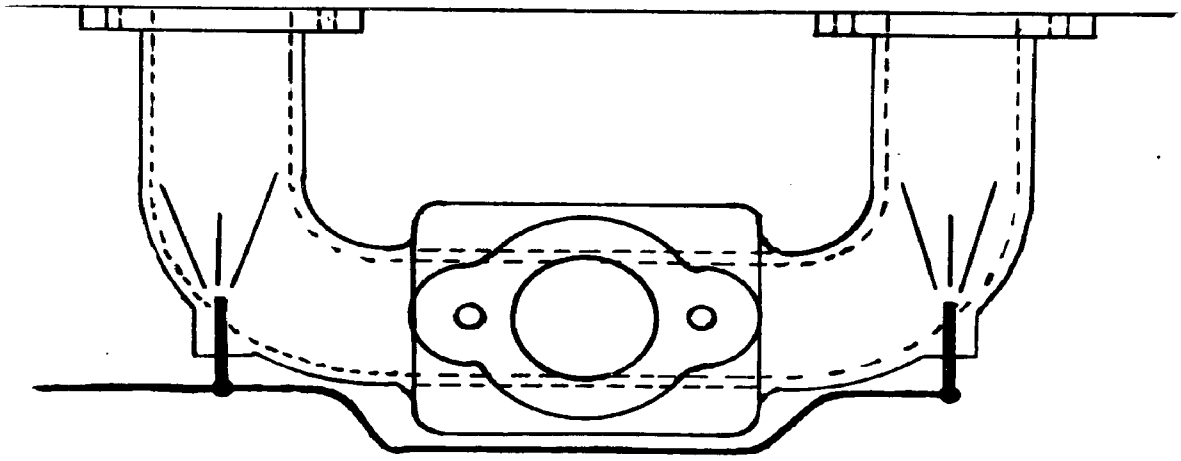
At the present time, primer nozzles are located on the intake manifold at the points which are most convenient for the installation. On truck engines the most common point of application is at the branches of the manifold leading to each pair of cylinders. Figure 17 illustrates the common points of application.

The relation between nozzle location and starting ability at the various temperature levels was thoroughly investigated with six different nozzle positions being used.*

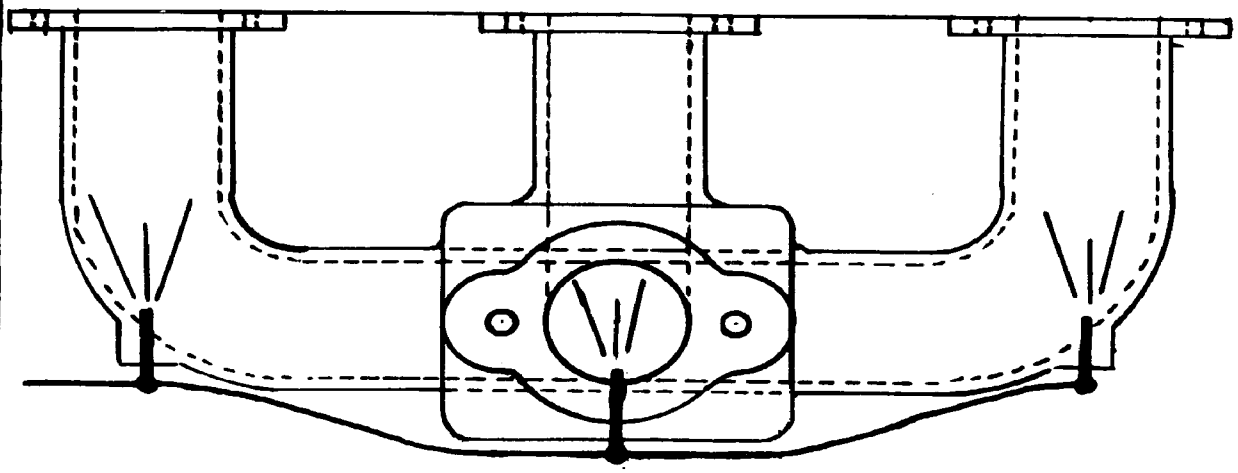
From the Summary of Data, Figure 18 was plotted showing the maximum distance the nozzle could be removed from the cylinder block and still permit combustion to be attained within 20 intake strokes.

To further analyze the effect of nozzle location, the basic data was considered in another way. At each nozzle position and each

* See Appendix I, Figure 30 for nozzle positions.



FOUR CYLINDER ENGINE



SIX CYLINDER ENGINE

COMMON INSTALLATION POINTS FOR PRIMER NOZZLES

Fig. 17

Effect of Temperature on the Farthest Nozzle Position
Resulting in Combustion Within 20 Intakes
Nozzle Position (Inches from Engine Block)
0
2
4
6
10
t_1
t_2
t_3
Temperature t_0

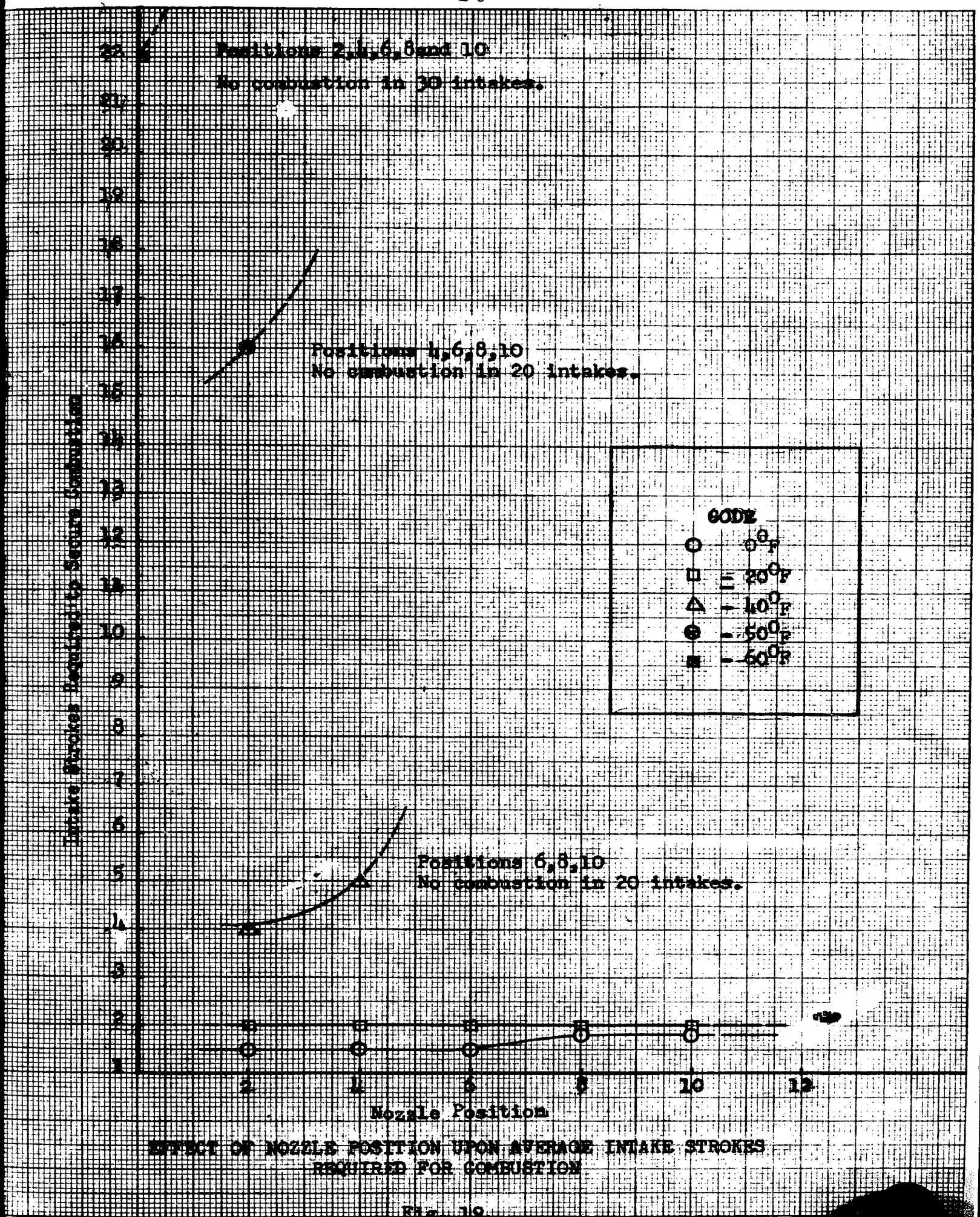
Fig. 18

temperature level, the average number of intake strokes required to secure combustion was determined. In computing the average, trials wherein the fuel injection varied widely from stroke to stroke were omitted. Figure 19 presents this information graphically. It shows quite clearly that with the present nozzle, the closer the nozzle is located to the intake valve, the more effective it will be over a wide range of temperatures. At 0° and -20°F. the nozzle position is of little importance, however at -40°F. it became critical and with an additional 10°F. reduction in temperature the nozzle position was not only critical, but many more intake strokes were required to secure combustion.

3. Net Injection Required For Combustion Using the Standard Ordnance Primer Nozzle.

At temperatures below -40°F. the test equipment was not capable of accurately handling the excess gasoline collected in the manifold and no data relative to net injection of fuel is recorded for the lower temperatures. At temperatures of -40°F. and above, however, it was possible to trap and measure the fuel not inducted into the engine.

From the Summary of Data, the following information may be extracted for the 2" and 4" nozzle positions at the 0°, -20° and -40°F. temperatures:



EFFECT OF NOZZLE POSITION UPON AVERAGE INTAKE STROKES REQUIRED FOR COMBUSTION

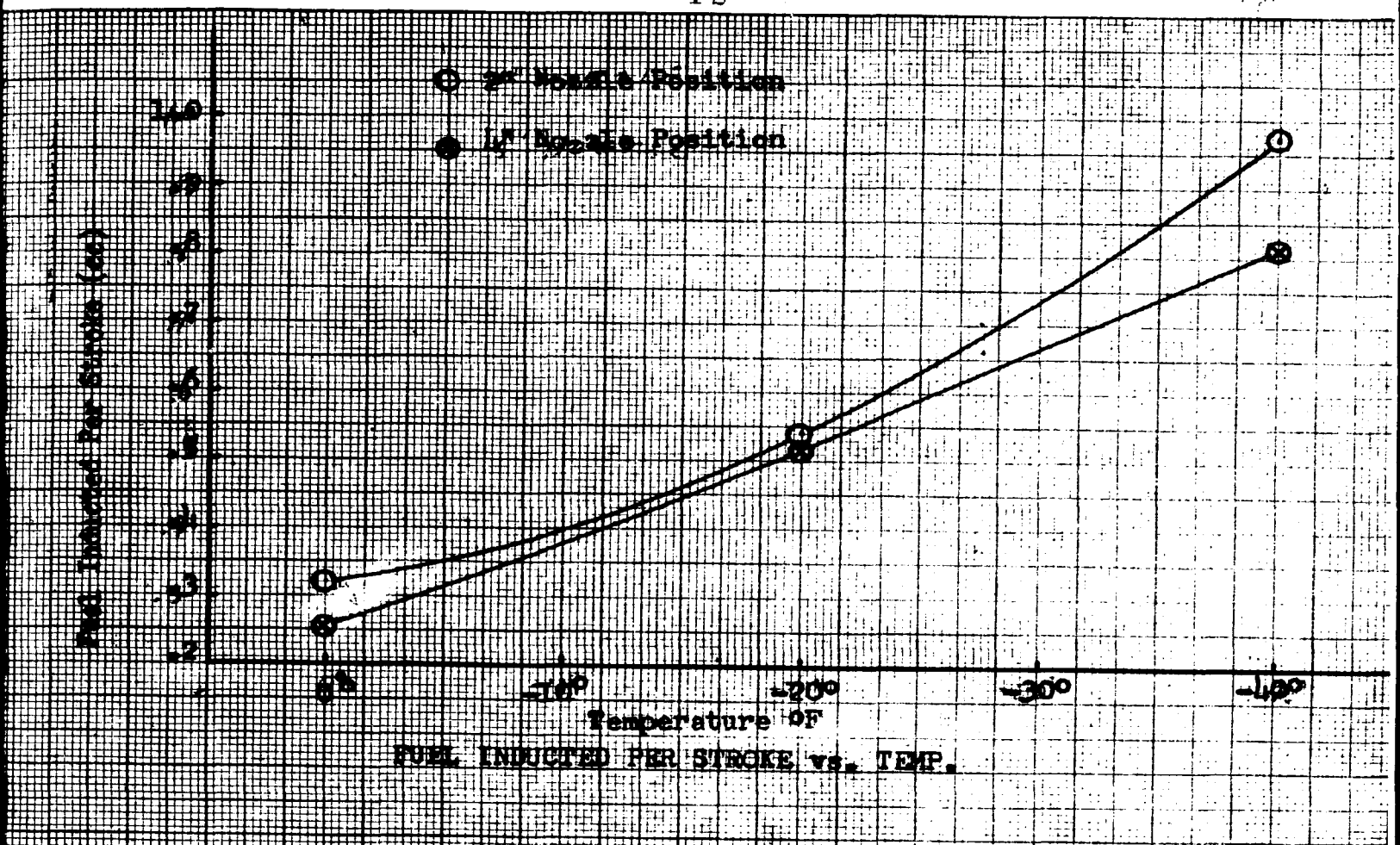
Fig. 19

Temp. °F.	Intake Strokes For Comb. (Ave.)	Fuel Inject. Per Stroke cc. (Avg.)	Fuel Induct. Per Stroke cc. (Avg.)	% Injected Fuel Apparently Inducted Per Stroke
		2" NOZZLE POSITION		
0	1.6	2.44	0.321	13.1
-20	2.0	3.202	0.542	16.9
-40	4.2	3.074	0.973	31.6
		4" NOZZLE POSITION		
0	1.6	2.485	0.254	10.2
-20	2.0	2.505	0.515	20.6
-40	5.2	2.738	0.811	29.6

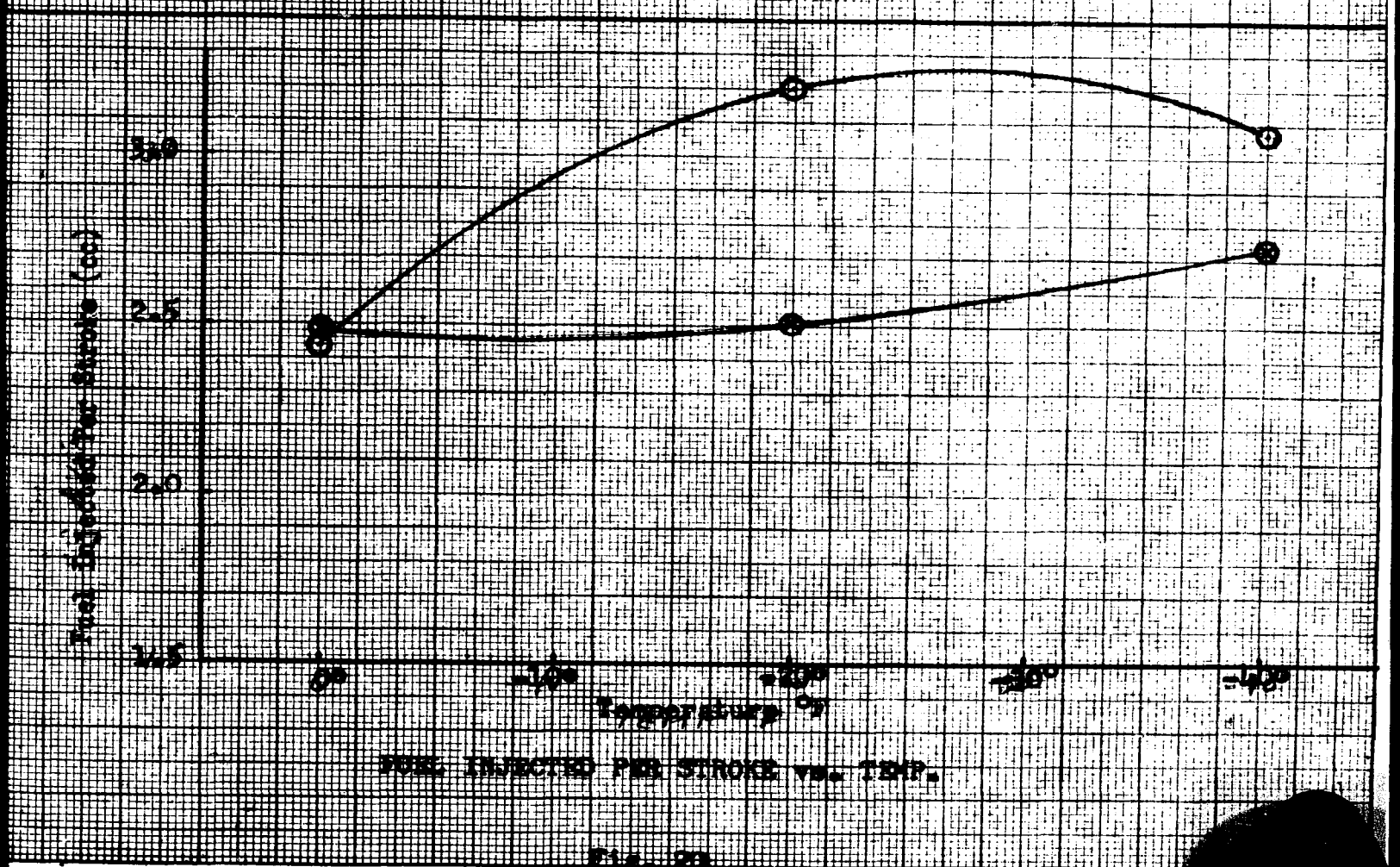
By plotting the average fuel injected per stroke and the fuel inducted into the cylinder per stroke against temperature (Figure 20) it appears that even though the quantity of fuel primed is held fairly constant, the amount of fuel inducted into the cylinder per stroke increases as the temperature is lowered and the number of strokes required to attain a combustible mixture increases.

In considering this data it must be borne in mind that the injection apparatus was adjusted for each test and, within reasonable limits, delivered the same quantity of fuel on each successive stroke. At the beginning of each test, the manifold and cylinder were dry and free of gasoline and the cranking rate was adjusted prior to activating the primer. The action taking place in the manifold of the single cylinder test engine may be assumed to be as follows:

As the intake valve begins to open, the primer nozzle begins to spray fuel into the manifold and continues to spray for a specified time interval (in no case longer than the time the intake valve is open). As the first air is drawn into the cylinder, the only fuel vapor available is that created at the nozzle tip and by the travel of the droplets of fuel



FUEL INDUCTED PER STROKE vs. TEMP.



FUEL INJECTED PER STROKE vs. TEMP.

Fig. 23

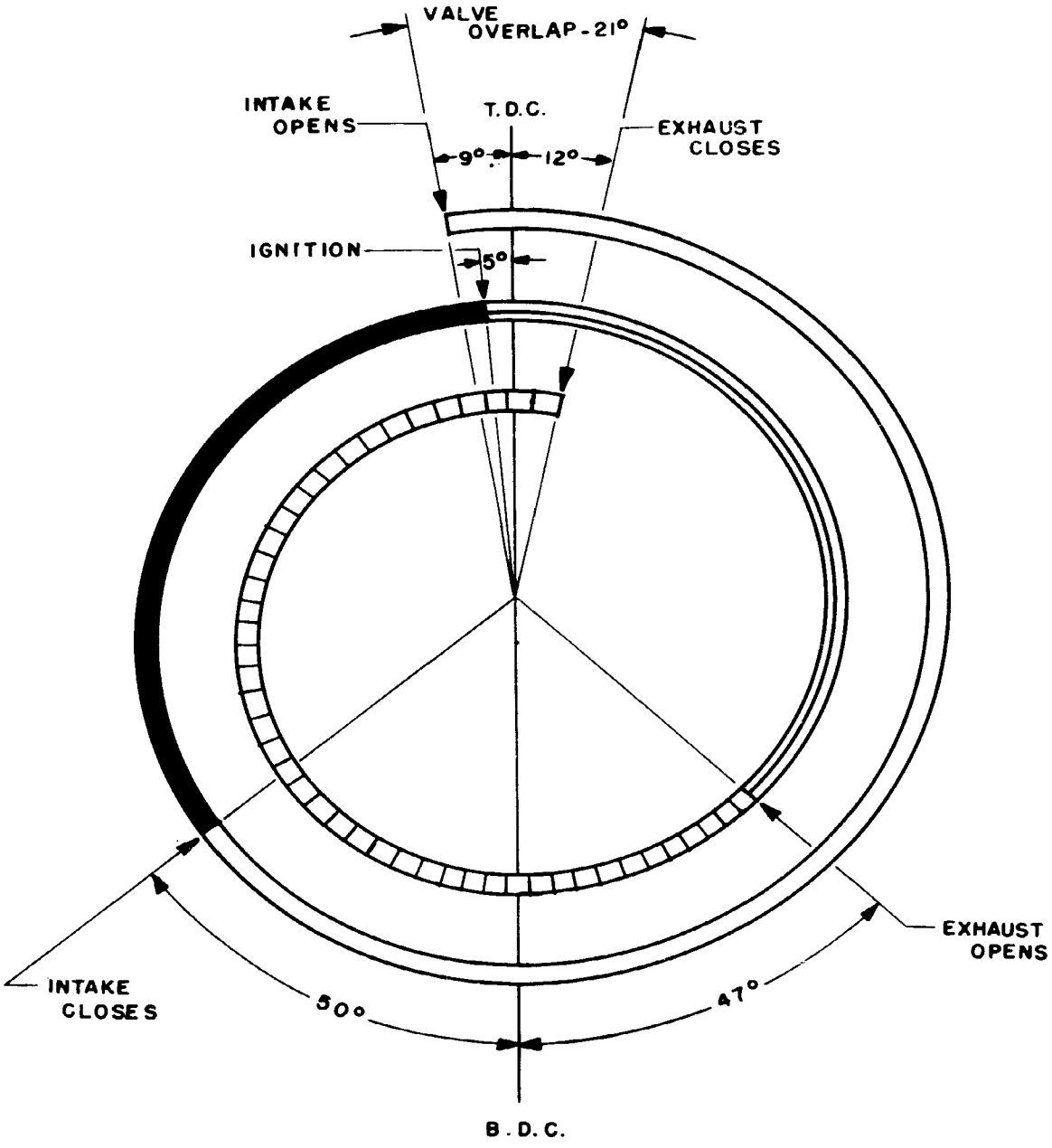
through the manifold. As the intake continues, the heavier droplets impinge upon the manifold walls and vaporization from the wet manifold surfaces is added to that occurring at the nozzle. After the primer nozzle cuts off, the manifold wall evaporation continues to furnish vapor to the incoming air at a diminishing rate until the end of the intake stroke. Thus, on the first stroke, the maximum rate of vapor formation probably occurs just prior to the shut-off of the primer nozzle. If combustion does not occur and the cranking process is continued, the residue fuel from the first injection continues to vaporize in the manifold until the second intake stroke begins. With the second intake stroke, the first air inducted contains the products of vaporization built up from the residue of the first stroke, plus the extra vapor formed by the spray nozzle and the additional vapor created by new fuel evaporating from the manifold walls; since the second injection adds more fuel to the manifold, it is reasonable to assume that a larger area is wetted than was the case on the first stroke and hence more evaporation takes place from the manifold walls. This, of course, would result in an evaporation of a higher percentage of the total fuel injected on the two strokes, than was the case with a single stroke. The process will continue with successive intake strokes until the manifold is saturated, an equilibrium condition established and liquid fuel flows from the manifold at a uniform rate from stroke to stroke.

Since the amount of fuel evaporated or actually inducted on each stroke could not be determined, Figure 20 was drawn on the assumption

that the total fuel unaccounted for after attaining a combustible mixture* divided by the number of strokes to attain the combustion would provide a basis of comparison. At the temperatures and nozzle positions considered in Figure 20, the equilibrium condition was never attained. At the lower temperatures and other nozzle positions, where combustion did not occur in twenty or more intake strokes it is probable that the equilibrium condition, as evidenced by a flooded manifold, occurred and combustible mixtures would not have been attained with any number of intake strokes.

It is conceivable that some liquid fuel droplets could be drawn into the cylinder where they may have evaporated and entered into the process of varporization, or the vapor may have been lost to the exhaust system. This possibility has been considered and its effects deemed negligible. The gasoline trap on the exhaust line, even after unsuccessful attempts to start with as many as thirty intakes strokes, was always found to be dry, and secondly, since all tests were conducted with a wide open manifold (no restrictions) air velocities were low (1.7 ft./sec.). This, combined with the right angle turn and upward rise of the intake valve pocket, would reduce the opportunity for entrained liquids to be drawn into the cylinder. By observation it was determined that a small amount of vapor was lost out of the intake manifold through blow back due to the intake valve timing. (See Figure 21) This loss, however, was so small that it could not be measured and was considered insignificant.

* This would be the fuel evaporated and drawn into cylinder.



TEST ENGINE VALVE TIMING DIAGRAM

Fig.21

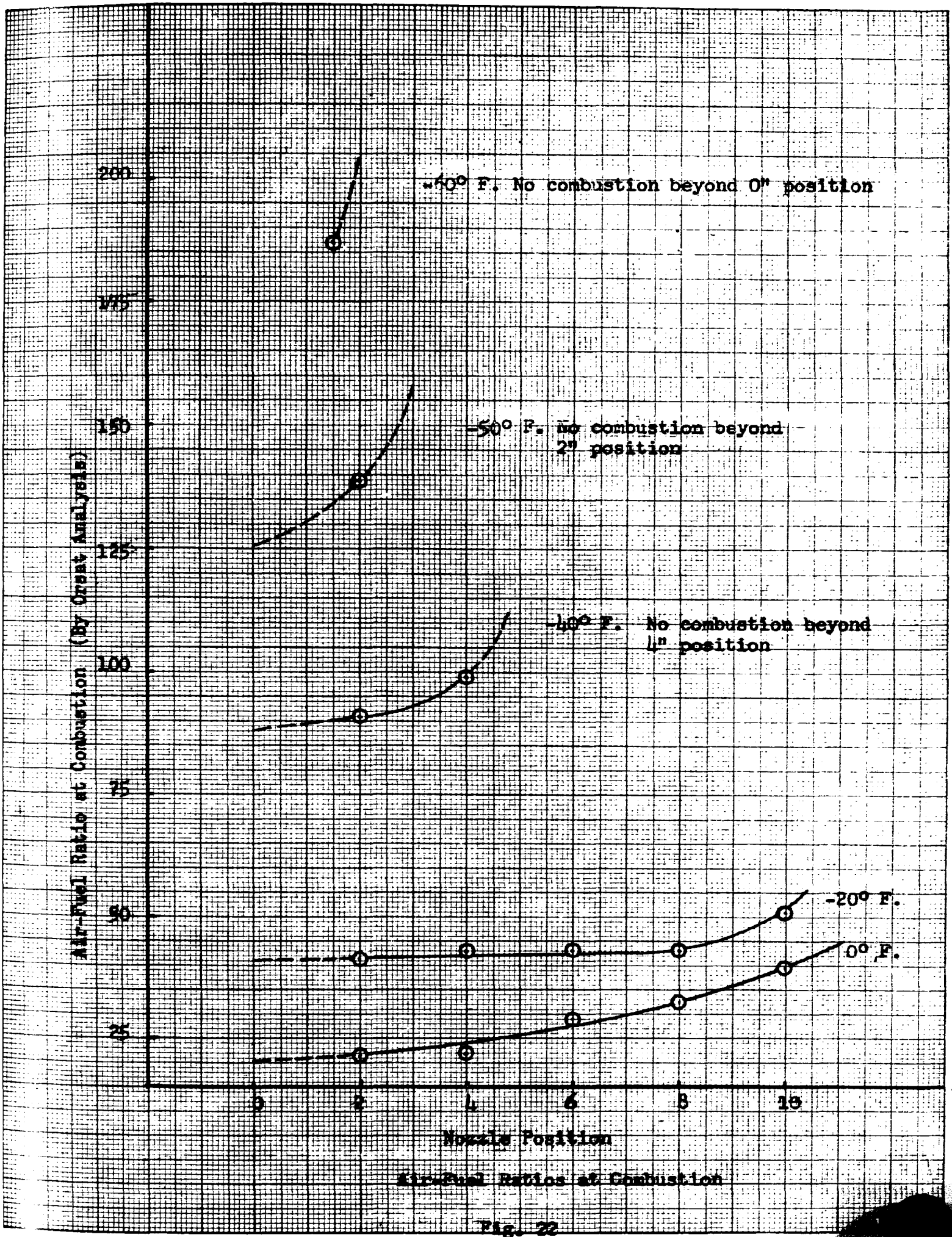
It is apparent that with a given quality of gasoline, a given manifold design and a particular manifold pressure pattern, a point will be reached at any temperature level where a maximum quantity of fuel can be evaporated. Increasing the amount of fuel being primed will result in no further benefits.

When this equilibrium condition is established and does not result in the cylinders receiving an ignitible charge, the design of the fuel induction system should be investigated. Two logical steps may be taken to increase the fuel being evaporated, i.e., to attempt to increase the wetted areas of the manifold by the use of honeycomb or plate type inserts; to lower the manifold pressure and hold the fuel under this lower pressure as long as possible. Either of these two steps or a combination of both should be the subject of intensive investigations.*

4. Air-Fuel Ratio at Time of Combustion.

By means of the method described in Appendix IV-6 samples of the products of combustion were obtained immediately after combustion occurred in the test cylinder. Due to the time consuming nature of this operation, only one sample was analyzed for each nozzle position. Figure 22 presents the data in graphic form.

*Preliminary tests have shown marked starting improvement (at the expense of peak horsepower) by reducing valve overlap on large engines. A similar improvement has been noted by increasing the spring tension on the choke relief valve of automotive type engines.



Air-Fuel Ratios at Combustion

Fig. 22

Figure 22 indicates once more that at 0° and -20°F. the attainment of an ignitable mixture is relatively independent of nozzle position. The important characteristic exhibited by the curves of Figure 22, however, is the indication that as temperatures were lowered ignition occurred with leaner mixtures. The explanation of this phenomenon is not readily apparent, however two possible hypotheses may be drawn.

The first is that in the vicinity of the spark plug an air-fuel vapor ratio in the neighborhood of 16:1 to 20:1 was established and combustion started at this point and continued for a short period of time until the flame spread into an area where combustion could not longer be supported. In this case, an analysis of the resulting products of combustion might show an extremely lean mixture.

It is more probable, however, that the small volumes of combustible mixtures would occur at positions remote from the spark plug and consequently no combustion would take place. This is contrary to the observed data (Tables VIII and IX) which shows consistent combustion after a definite number of intake strokes. In view of this data and the low probability of consistently building up combustible mixtures at the spark plug, this first hypothesis does not adequately explain the phenomenon.

The second hypothesis is that combustion can occur at extremely lean mixtures. If the leanest mixture at which combustion can occur (designated as air-fuel ratio "X") or richer is exposed to the spark, it will be ignited. With this assumption, it may be postulated that if on

the first intake stroke the air-fuel ratio does not equal "X", no combustion will occur and most of the unburned mixture will pass out on the exhaust stroke and a new charge will be drawn in on the second intake stroke. Once again the spark occurs and if the mixture has reached the value of "X" or richer, combustion will occur; if not, the cycle must be repeated until the critical air-fuel ratio or richer is finally established.

This hypothesis does not conflict with the data of Figure 22. In the case of the higher temperatures, such as 0 or -20°F., ignition occurred on the first or second strokes. At the close-in nozzle positions, if the charge drawn in by the first intake stroke did not ignite, the second charge was so much richer that it always exceeded the critical ratio "X", hence the exhaust gas analysis, as could be expected, showed a comparatively rich mixture to have existed at the time of combustion. It is important to note that as the nozzle was withdrawn to the positions further removed from the cylinder block, where the amount of fuel vaporized or vapor inducted on each intake stroke was less, the mixture ratios indicated by exhaust gas analysis show slightly leaner conditions to have existed. At the lower temperatures where the amount of fuel evaporated at each intake stroke was much less, it was found that the air-fuel ratio at the time of combustion was much leaner, indicating that the critical air-fuel ratio "X" was being approached by a process of integration.

This hypothesis dictates that to secure a start (or at least a power stroke) it is necessary to establish an air-fuel ratio within the cylinder of about 16:1 on a single intake stroke.

The contention of some experimenters that such a ratio can be built-up primarily by the action of successive intake strokes enriching the charge remaining in the clearance volume does not fit this hypothesis since such a gradual enrichment would result in combustion as soon as the critical ratio "X" was established and the process would repeat "ad infinitum" without ever attaining the air-fuel ratio necessary for a power stroke.

To validate the second hypothesis outlined above, the following experiments were conducted:

A. To insure that combustion did not occur before the stroke indicated in the data, the engine was allowed to make one stroke, followed by the taking of a gas sample from the cylinder to determine if there had been any combustion. The engine was then purged and the process repeated, this time making two strokes before drawing a gas sample. The process was repeated, increasing the number of intake strokes by one each time until combustion occurred.* Table VIII presents the results of these tests.

*This test was performed at various nozzle positions and temperature levels where more than one stroke was required to secure an indication of combustion on the test apparatus.

TEST ENGINE EXHAUST GAS ANALYSIS
(Non-Combustion)

Temp. °F.	Nozzle Position	Intake Strokes at 1st Comb.	A/F Ratio at 1st Comb.	Intake Stroke Investigated	A/F Ratio Investigated Stroke	Times Data Reprod.
0	2"	2	23.6	1st	No Comb.	5
0	6"	2	24.3	1st	No Comb.	5
-20	8"	2	43.0	1st	No Comb.	5
-40	2"	3(min.)	82	1st	No Comb.	5
-40	2"	3(min.)	82	2nd	No Comb.	5

NOTE: Fuel injection at each intake stroke = 2.5 + or - 0.1 cc.

TABLE VIII

This experiment established the fact that no combustion took place until the required number of intake strokes had been made as indicated in the Summary of Data. It also served to prove that the combustion indicating device used with the test apparatus was giving accurate results.

B. To determine, if, under a given set of conditions, firing would occur consistently, the following experiment was performed:

(1) A nozzle position was selected where firing occurred consistently on a given stroke.

(2) Cranking was started and the speed adjusted to give 60 to 100 rpm during the intake stroke, the range of constant volumetric efficiency.

(3) The priming system was activated and the engine allowed to crank until combustion occurred.

(4) At the first combustion the engine stopped automatically and an exhaust gas sample was withdrawn from the cylinder.

(5) The test apparatus was then purged and the

process repeated with the exception that the engine was allowed to crank until the second combustion occurred.

(6) The experiment was repeated analyzing successive combustion strokes.

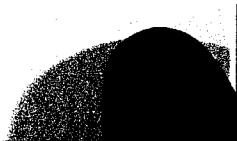
Table IX presents the results of these tests.

An examination of the data reveals that for the 0 and -40°F. temperature levels, combustion occurred consistently and that the air-fuel ratio as indicated by analysis of the products of combustion was the same for each combustion stroke. At 0°F. combustion occurred every two intake strokes; at -40°F., combustion occurred on every sixth stroke; at -60°F., approximately every twenty-five intake strokes resulted in combustion.

At -60°F. the test was confined to investigating only the first and second combustions due to the fact that the cranking motors became dangerously hot after 50 intake strokes (approximately 2 minutes of cranking).

It will be noted also in the data that for 0°F. the test was conducted in the manner described above up to the fifth firing, then to check for longer cranking periods, the engine was allowed to make twenty intake strokes (until 10th firing occurred) before the exhaust gas analysis was made. This confirmed the fact that the firing and air-fuel ratios remained constant for an almost indefinite cranking period.

C. In conjunction with the low temperature testing of an



TEST ENGINE EXHAUST GAS ANALYSIS
(Combustion Strokes)

Temp. °F.	Nozzle Position	Intake Strokes for first Combustion	Intake Stroke Investigated, Stroke	A/F Ratio of Investigated Stroke	Times Test Repeated
0	2"	2	2 (1st fire)	23.6	5
			4 (2nd fire)	23.6	5
			6 (3rd fire)	23.6	5
			8 (4th fire)	23.6	5
			10 (5th fire)	23.6	5
			20 (10th fire)	23.6	5
-40	2"	6	6 (1st fire)	82.2	5
			12 (2nd fire)	82.2	5
			18 (3rd fire)	82.2	5
			24 (4th fire)	81.6	5
-60	0"	25	25 (1st fire)	170.6	1
			51 (2nd fire)	170.6	1
			54 (2nd fire)	172.4	1
			53 (2nd fire)	170.6	1

NOTE: Fuel injection at each intake stroke = 2.5 + or - 0.1 cc.

TABLE IX

AV-1790 tank engine, an 800 horsepower, 12 cylinder engine equipped with open manifolds (no choke), it was found that at -20°F. conditions could be established which would permit the engine to be cranked indefinitely without starting, even though regular combustion was occurring as evidenced by regular, faintly audible explosions in the cylinders. The mixture being supplied to the engine was varied by regulating the amount of heat applied to the manifold hot spot and the audible explosions could be made to die out; or by increasing the rate of heat application and hence enriching the mixture being supplied by the manifold, the engine could be made to start. During the course of these tests it was found that continued cranking with lean mixtures (rich enough to cause audible explosions, but too lean to furnish enough power to turn the engine)would result in ice forming on the spark plugs and thus shorting them out. This indicates that in cold starting the air-fuel ratio within the region of power combustion must be established quickly if spark plug icing is to be avoided.

Figure 23 has been devised to illustrate the foregoing hypothesis. The arrows in sector A indicate three successive intake strokes with combustion occurring on each stroke. In each case the build-up of the fuel vapor must take place in the manifold and as the cranking continues and more fuel is admitted to the manifold, the air-fuel ratio approaches that required for power-producing combustion.

Line B illustrates a case that might be typical of a very low temperature operation. Here five strokes are made, and since the

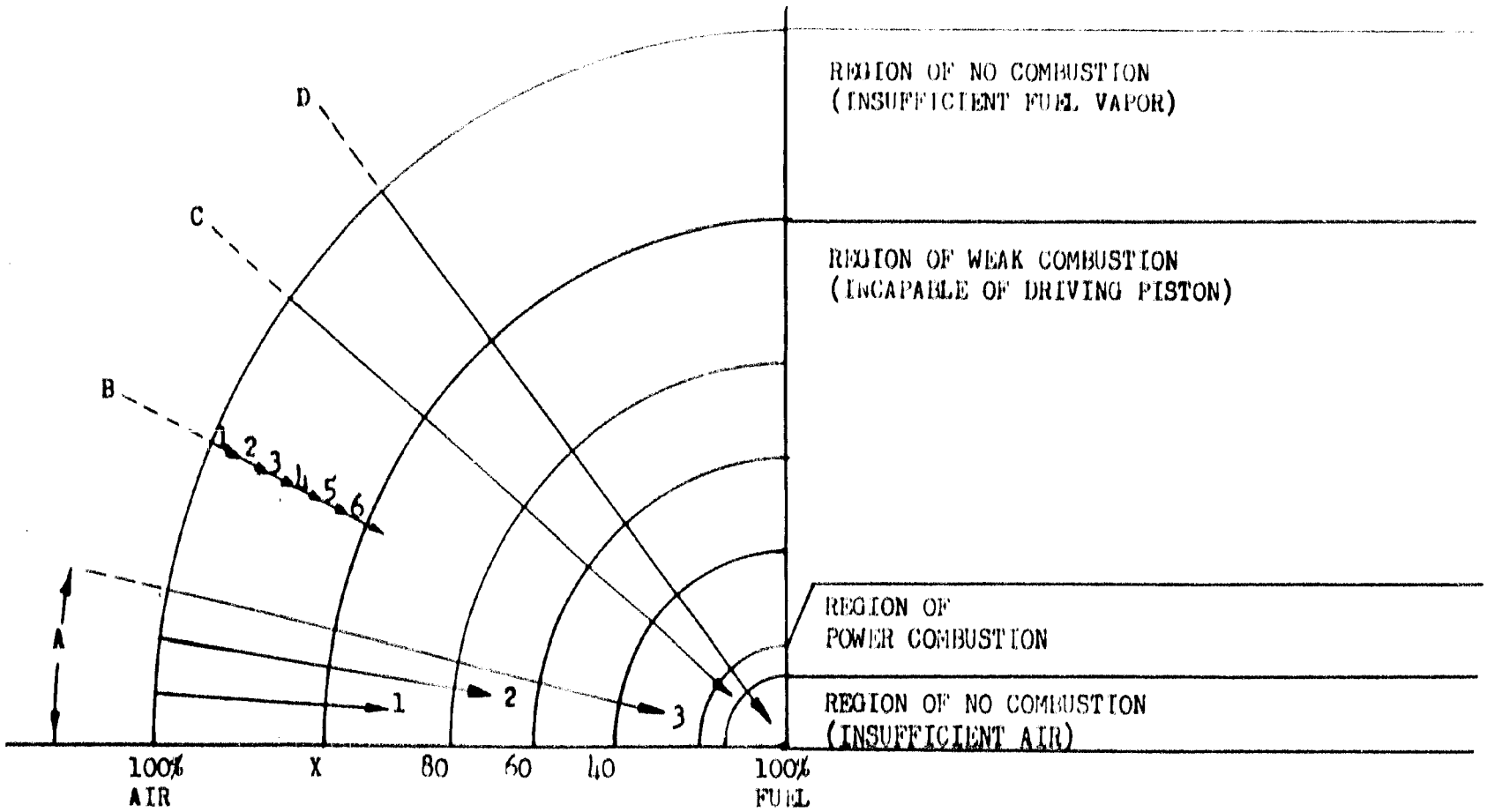


Fig. 23

AIR-VAPOR RATIOS

Note: The arrow tips indicate the magnitude of the air-vapor ratios.

STARTING POWER AND THE AIR - VAPOR RATIO

air-fuel ratio is leaner than the critical ratio "X", no combustion occurs. In this case the air-fuel ratio is building up in the manifold and the clearance volume of the cylinder, however, on the sixth stroke the air-fuel ratio moves into the zone of weak combustion, ignition takes place and the whole process begins anew. In the case of the combustion illustrated by line B, the probability is that no start will be made regardless of the duration of cranking.

Line C represents the case of a typical quick start, the proper air-fuel vapor mixture ratio is established within the cylinder and is ignited on the first stroke, producing power.

Line D represents the case of a flooded engine where the air-fuel vapor ratio established is too rich to ignite.

Figure 23, while not to scale, serves to graphically illustrate one reason why cold starting is such a problem - a very small target must be hit and the means of controlling the process are rather inaccurate.

These experiments lead only to the conclusion that the fuel intake system must be so designed that sufficient fuel can be vaporized to permit the intake of a power producing air-vapor mixture on a single intake stroke, and then to continue to furnish this air-vapor ratio to each succeeding stroke, if starting is to be successful.

CONCLUSIONS

From the results of the experimental work the following conclusions may be drawn:

1. Priming pressures above 50 pounds per square inch do not increase the effectiveness of the standard Ordnance primer nozzle.
2. In the test engine, a simple pipe leading into the manifold is as effective as the Ordnance primer nozzle in securing ignitable mixtures.
3. The effectiveness of the primer nozzle increases as it is moved closer to the intake valve. This increase is particularly great at the lower temperatures.
4. With timed priming, as the temperature is lowered and the number of intake strokes required to secure combustion increases, the percentage of the fuel primed on each stroke that is actually utilized by the engine increases.
5. Evidences of combustion (as indicated by products of combustion and temperature rise) occur at low temperatures with overall air-fuel vapor ratios leaner than 170:1.



6. If a constant quantity and quality of fuel is primed on each intake stroke, combustion will occur consistently after a given number of intake strokes are accomplished, depending upon the quantity of fuel being primed and the temperature.

APPENDIX

THE

TEST EQUIPMENT

I

THE TEST ENGINE

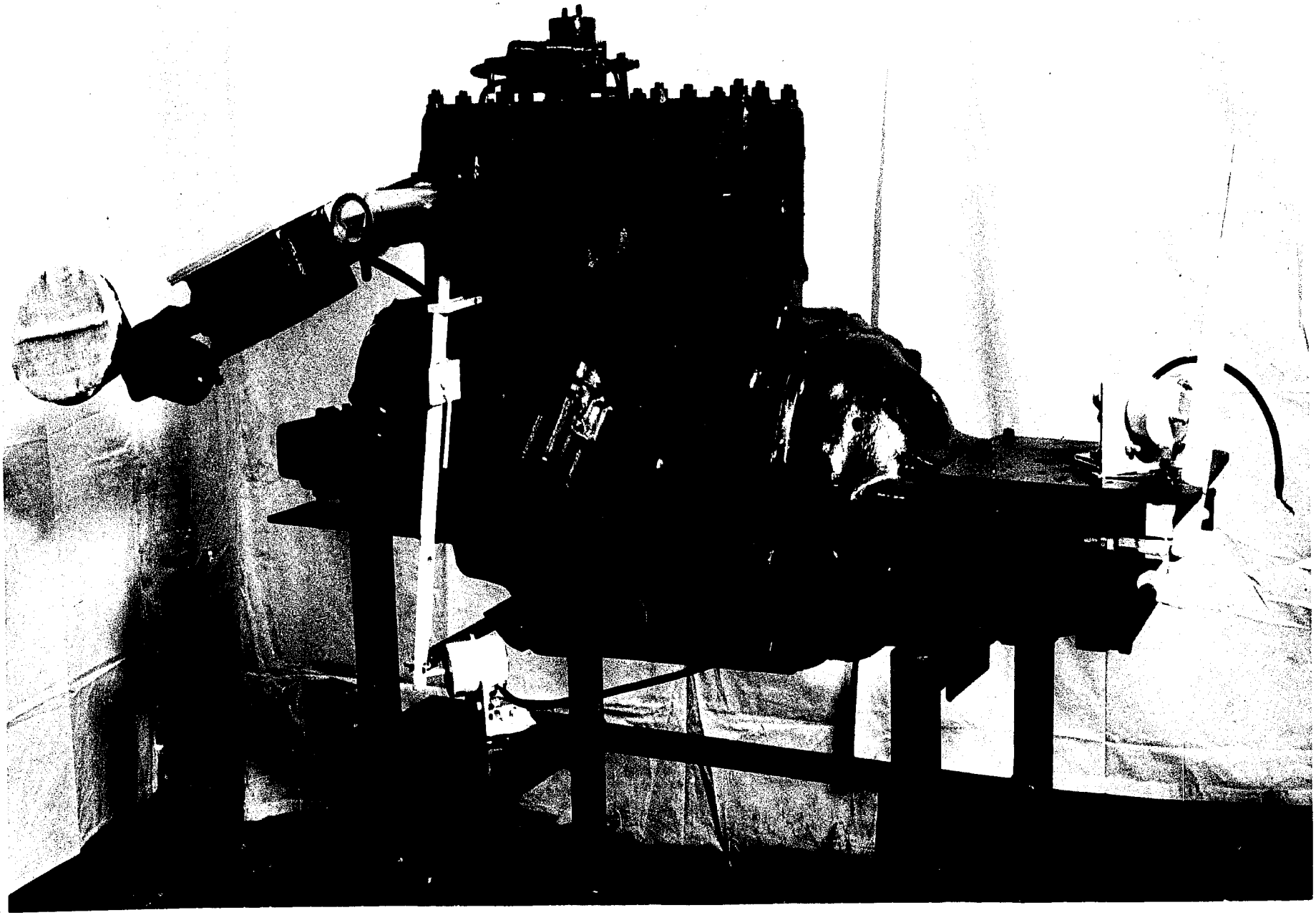
The basic test cylinder was obtained by modifying a standard Ordnance Corps 1/4 ton truck engine (Willys Model MB). The cylinder characteristics are as follows:*

Bore----------3.125 inches
Stroke----------4.375 inches
Clearance Volume----------97.59 cc.
Piston Displacement----------549.8 cc.

The following modifications were made:

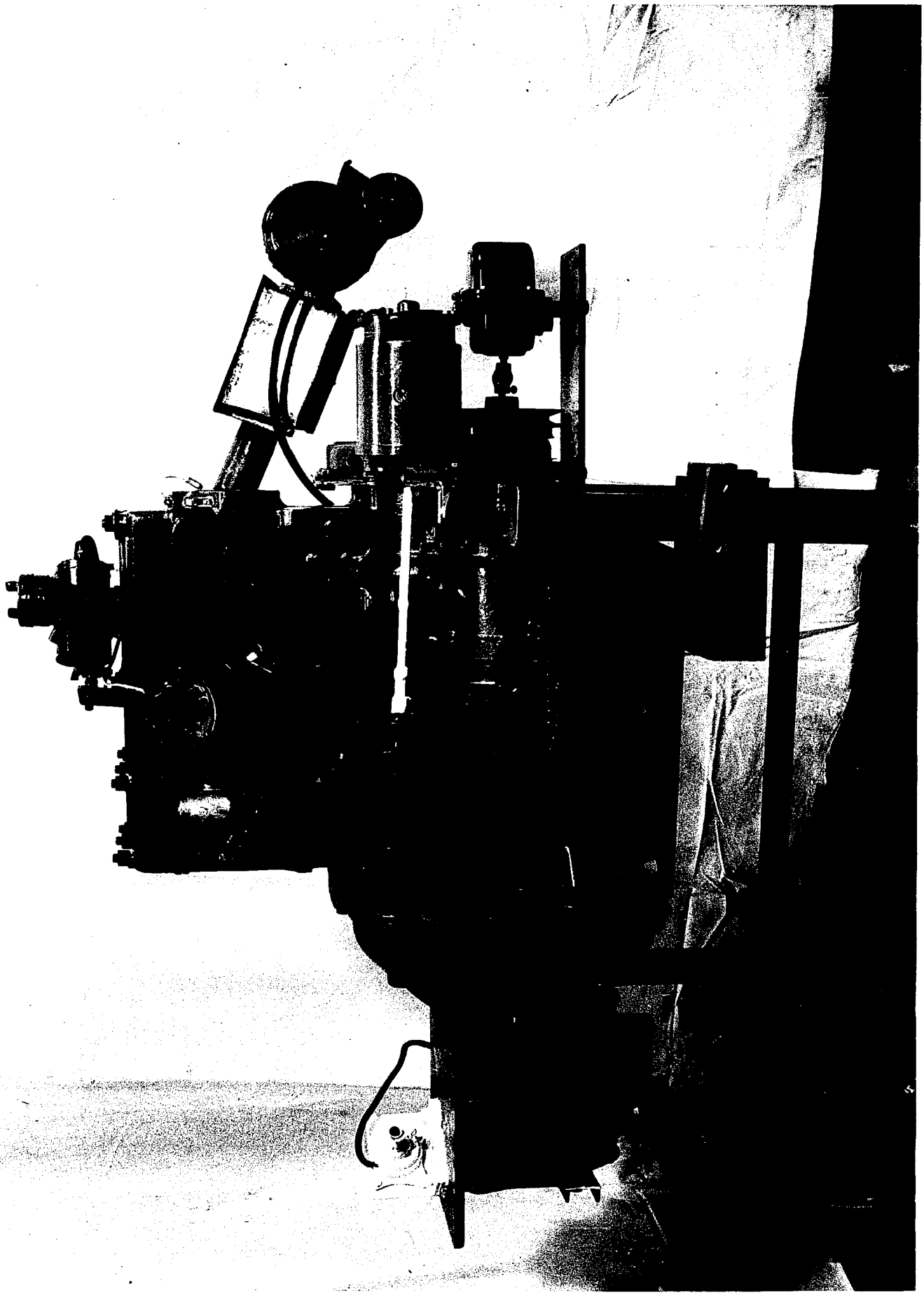
1. The valve lifters were removed from all valves except those of cylinder number one, thus allowing the valves to remain closed under normal valve spring action.
2. The spark plugs were removed from cylinders three and four and the spark plug holes left open.
3. The spark plug in cylinder number two was removed and replaced with a plug. Through this plug a 1/8 inch O.D. tube was run into cylinder number two and through a small hole in the cylinder head wall into cylinder number one to permit the withdrawal of gas samples from the test cylinder. See Figure No. 27. Cylinder number two, with both valves closed under the action of the valve springs and

* See Figure 26



—DETROIT ARSENAL—
NEG. NO. 27977 DATE 26 Oct 1951 DEVELOPMENT & ENGINEERING
Primer Effectiveness Test under Extreme Low Temperature Conditions. Right side of test engine.

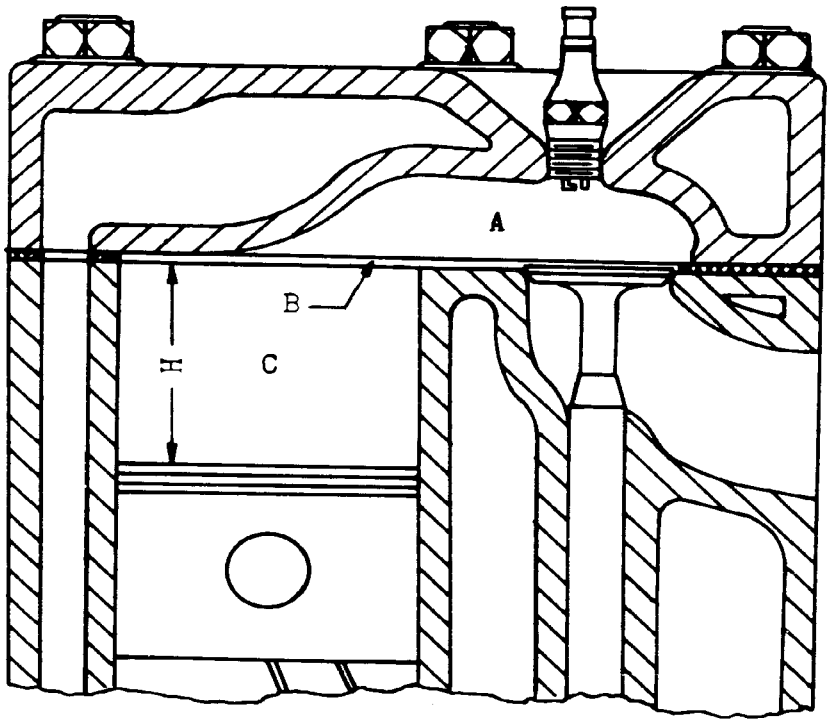
Fig. 24



—DETROIT ARSENAL—
NEG. NO. 27978 DATE 26 Oct 1951 DEVELOPMENT & ENGINEERING
Primer Effectiveness Test Under Extreme Low Temperature Conditions. Left side of test engine.

Fig. 25

Determination Of Clearance Volume



Bore..... 3.125 in.
Stroke..... 4.375 in.
Piston displacement..... 549.98 cc

1. Volume contained in cylinder head cavity with spark plug installed (A)..... 84.70 cc
(Determined by measuring fluid to fill cavity)

2. Volume created by gasket (B)..... 12.89 cc
Method: Area of gasket opening by planimeter = 14.84 in.^{2}
Thickness of compressed gasket by gage = 0.053 in.
(The gasket had a $\frac{1}{8}$ inch section cut from the outside edge to the cylinder wall. The cylinder head bolts were tightened to the manufacturers specifications and the head to block clearance was measured.)

3. Total clearance with piston at top dead center (A + B).... 97.59 cc

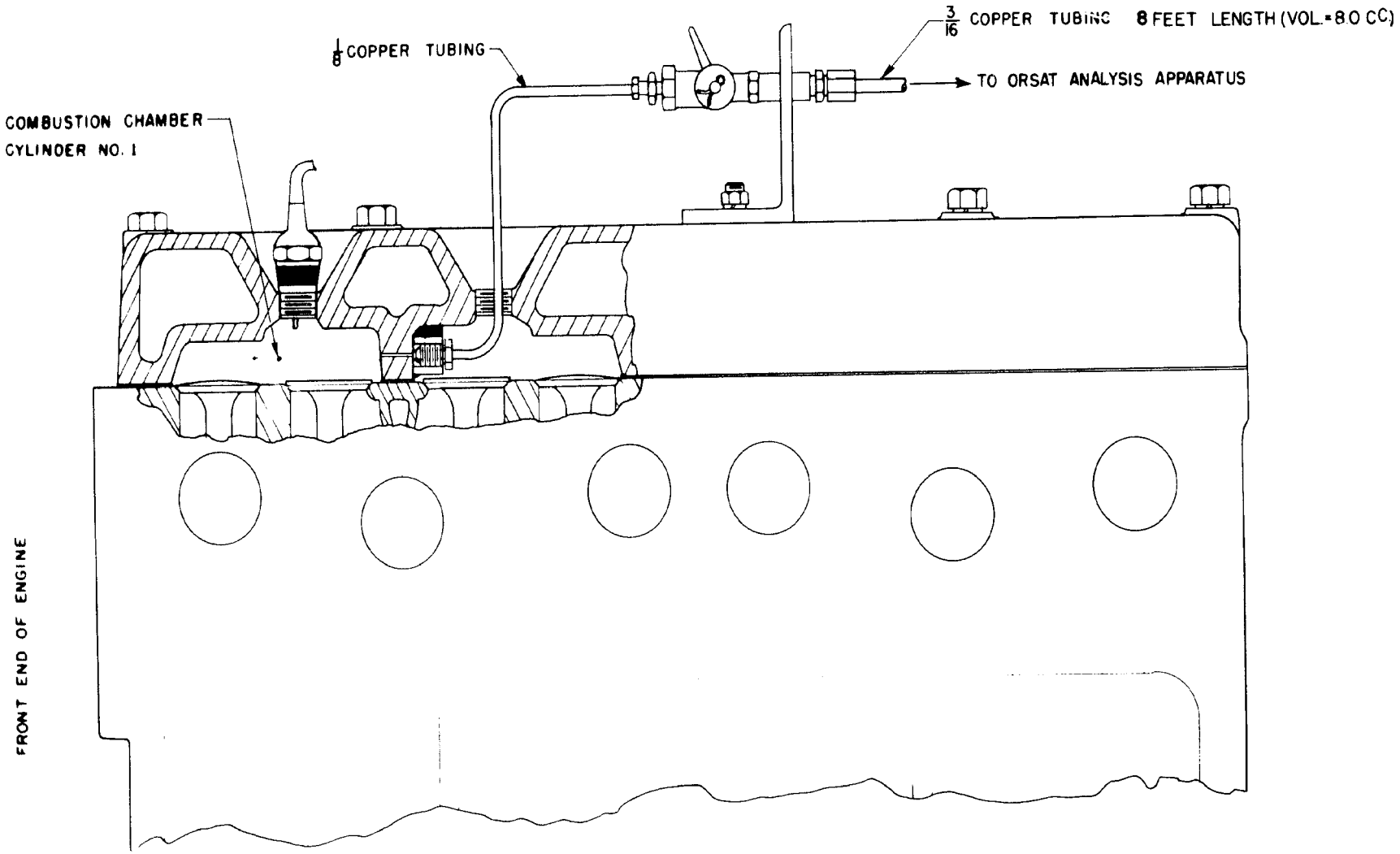
4. Volume above piston when intake valve seats (A + B + C).. 487.29 cc

$H = 3.1$ in.; $C = 549.98 \times \frac{3.1}{4.375} = 389.70$ cc

5. Volume at gas sampling position (A + B + C)..... 411.86 cc

$H = 2.5$ in.; $C = 549.98 \times \frac{2.5}{4.375} = 314.27$ cc

Fig. 26



METHOD OF OBTAINING
COMBUSTION GAS SAMPLES
-SAMPLING TUBE-

Fig. 27

Fig. 27

with the spark plug hole plugged, exerted a cushioning effect upon the cranking characteristics of the engine by decreasing the variations in cranking speed that occurred when the test cylinder piston was coming up on the compression stroke. Extensive experimentation was carried out in an effort to secure constant cranking speeds by removing various pistons, installing throttling valves in the spark plug holes, and by adjusting the valve timing, however, the best results were obtained with the arrangement described above.

4. The original engine starter was modified to enable the coupling of another starter motor in tandem and thus apply additional power at the lower temperatures. (See Figure 25) Cranking speed was varied by controlling the voltage to the starter motors.
5. The distributor of the engine was modified by replacing the four lobe cam with a single lobe cam for ignition and adding a second cam which controlled the action of the electric primer valve through a set of breaker points mounted in a special distributor cap. (See Figure 28)
6. The standard ignition coil was connected directly to the spark plug by a short two inch high tension lead.

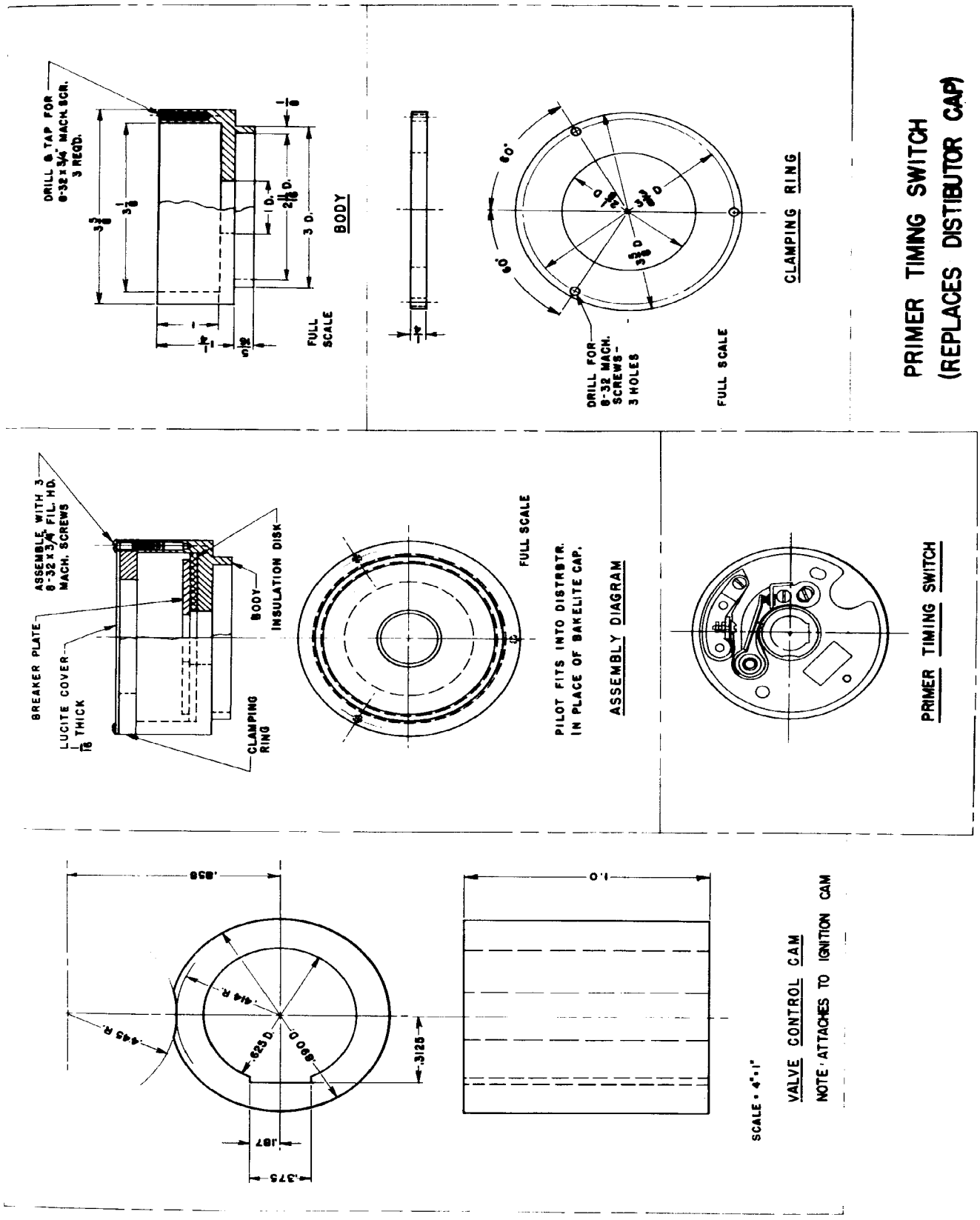

PRIMER TIMING SWITCH
(REPLACES DISTIBUTOR CAP)
BODY
CLAMPING RING
PRIMER TIMING SWITCH
ASSEMBLY DIAGRAM
VALVE CONTROL CAM
NOTE: ATTACHES TO IGNITION CAM
FULL SCALE
SCALE - 4":1"
BREAKER PLATE
LUCITE COVER
INSULATION DISK
CLAMPING RING
PILOT FITS INTO DISTRTR. IN PLACE OF BAKELITE CAP.

Fig. 28

7. The standard exhaust and intake manifolds were removed. The exhaust manifold was replaced with a short nipple and elbow leading into a glass topped baffle box designed to trap entrained fuel. Attached to the baffle box was a small blower designed to give reversed air flow for purging the apparatus between runs. The intake manifold was replaced with an eleven inch lucite tube (1 1/2 inch I. D.) with a drain port at the outer end. (See Figures 29 & 30)

8. The exhaust tappet of cylinder number one was modified to permit the insertion of a lifting wedge between the tappet and the valve stem. This wedge was automatically removed at the first detected combustion, thus allowing the exhaust valve to close, trapping the products of combustion. (See Figure 31)

9. The transmission of the engine was locked solidly and an automatic trip installed in the clutch linkage to engage the clutch at the first detected combustion, stopping the engine and trapping the products of combustion. (See Figure 32)

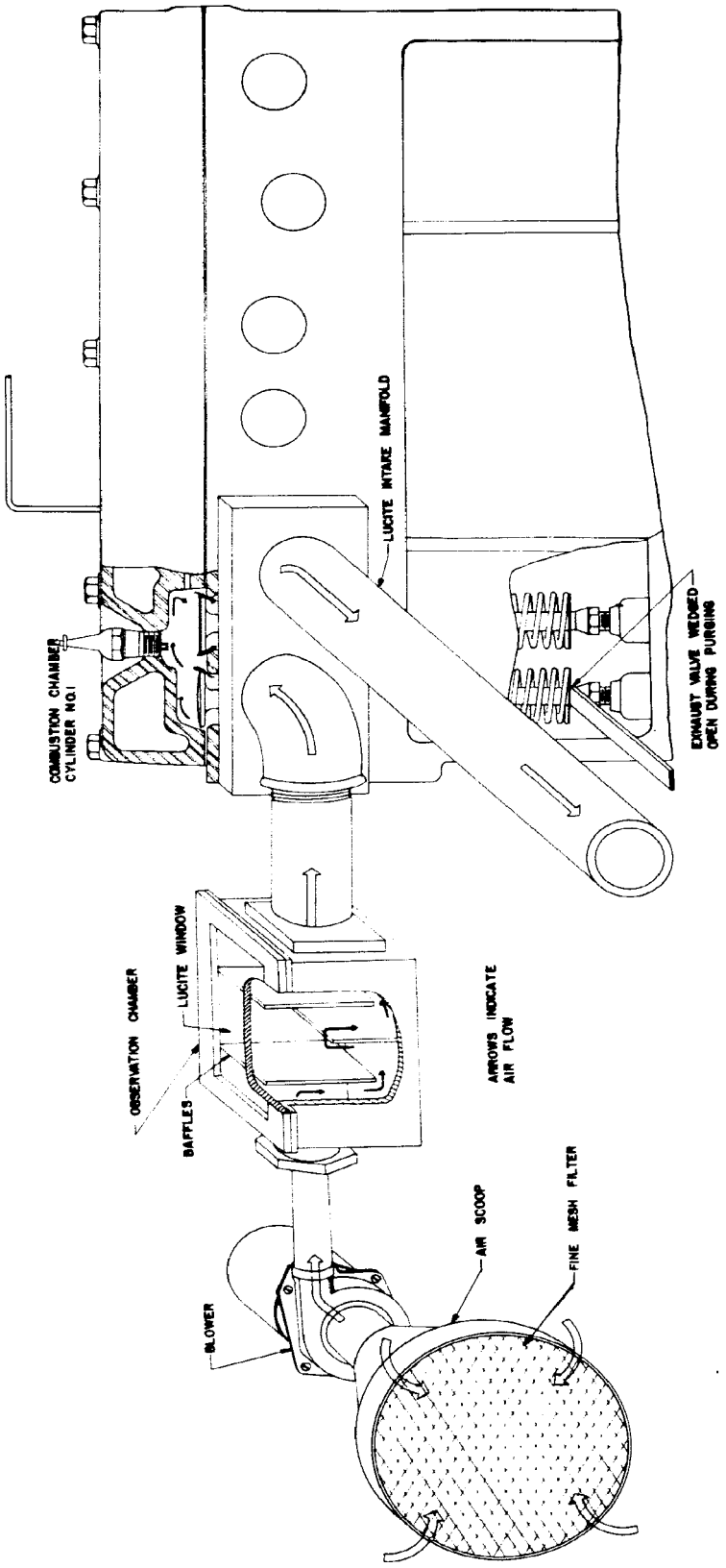

COMBUSTION CHAMBER
CYLINDER NO.1
LUCITE INTAKE MANIFOLD
EXHAUST VALVE WEDGED
OPEN DURING PURGING
OBSERVATION CHAMBER
LUCITE WINDOW
BAFFLES
ARROWS INDICATE
AIR FLOW
AIR SCOOP
FINE MESH FILTER
BLOWER
PURGING SYSTEM

Fig. 29

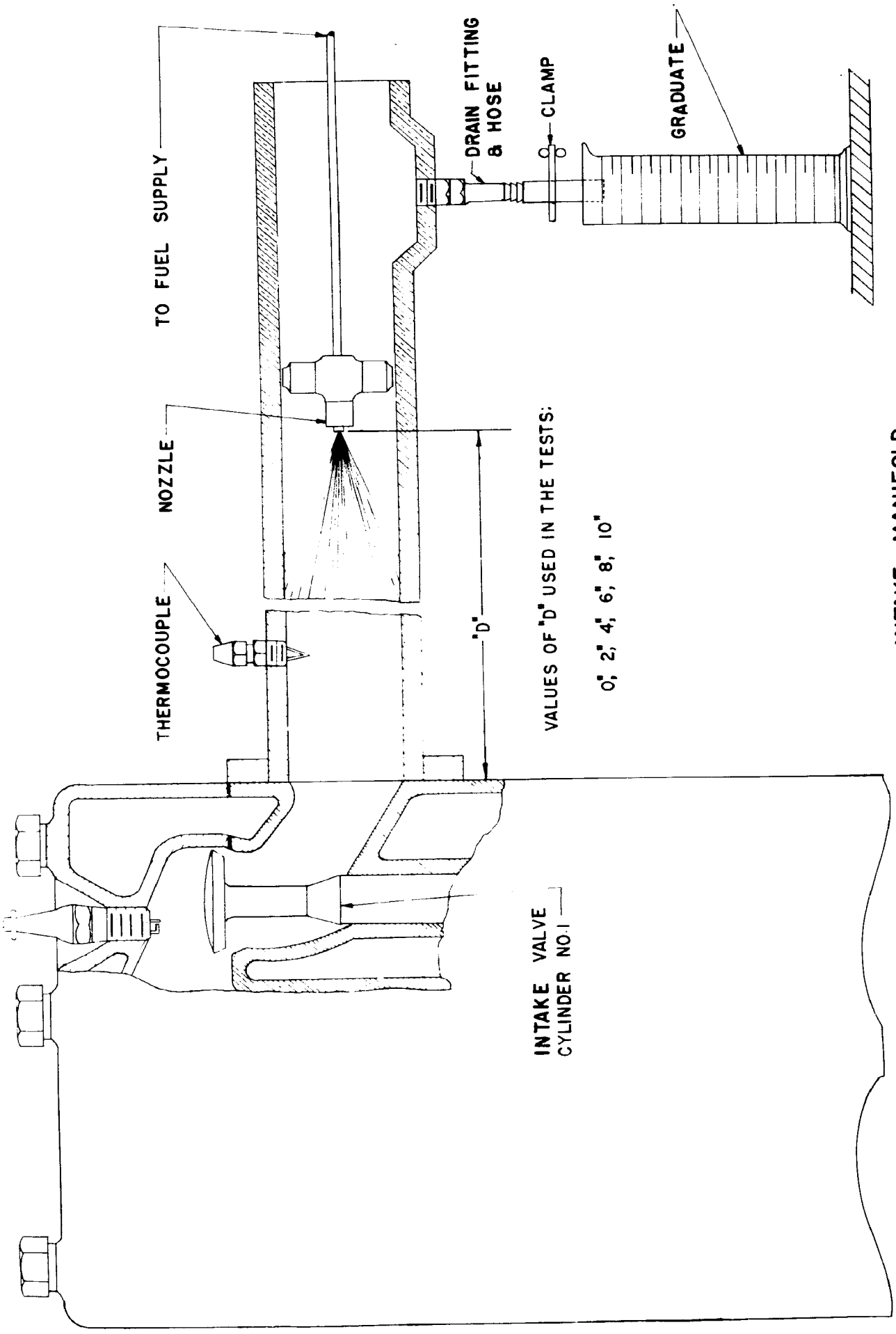
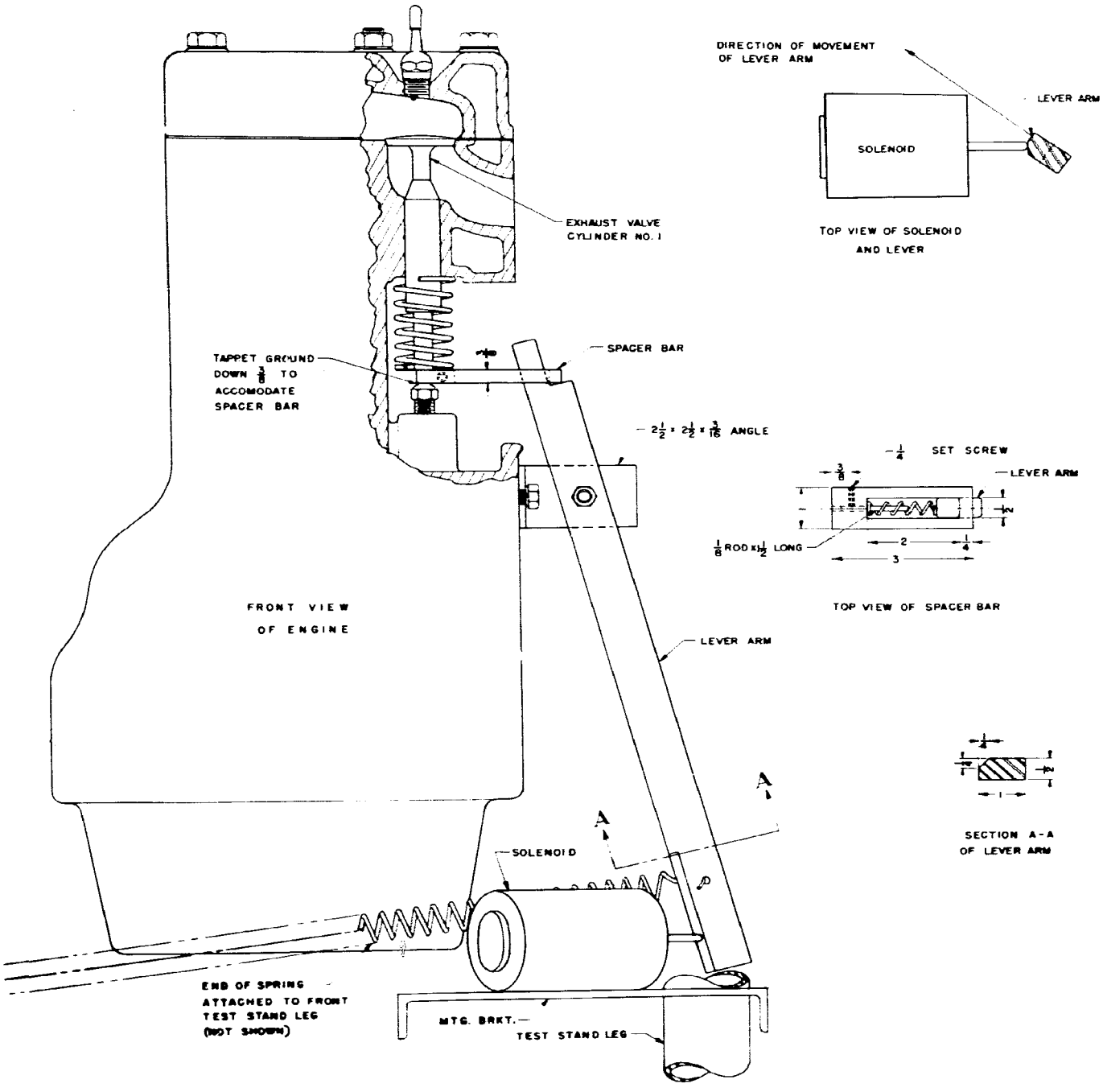
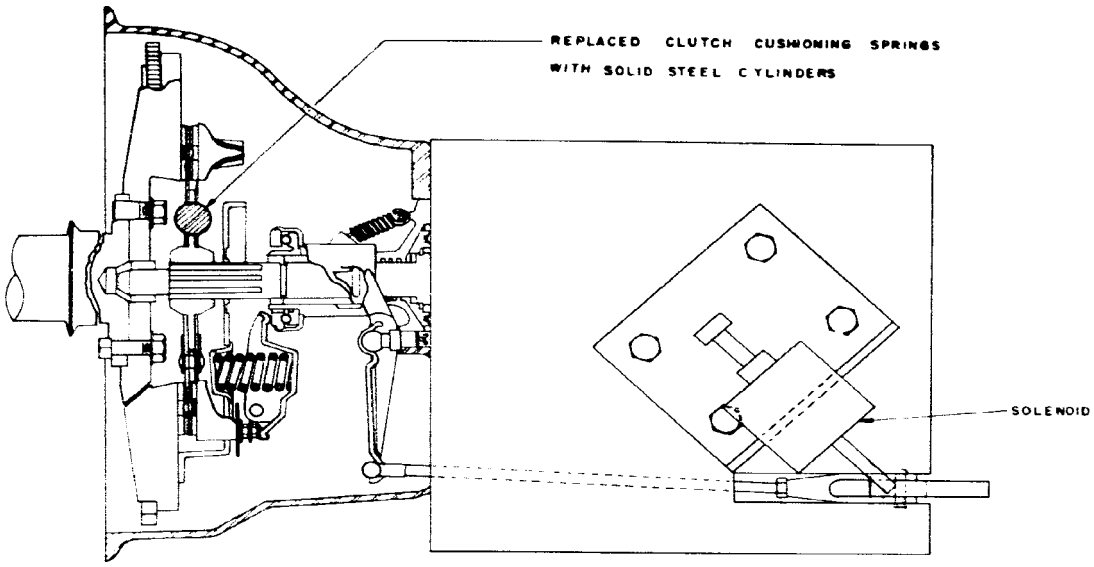

TO FUEL SUPPLY
NOZZLE
THERMOCOUPLE
DRAIN FITTING & HOSE
CLAMP
GRADUATE
"D"
VALUES OF "D" USED IN THE TESTS:
0"; 2"; 4"; 6"; 8"; 10"
INTAKE VALVE CYLINDER NO.1
INTAKE MANIFOLD SCHEMATIC

Fig. 30

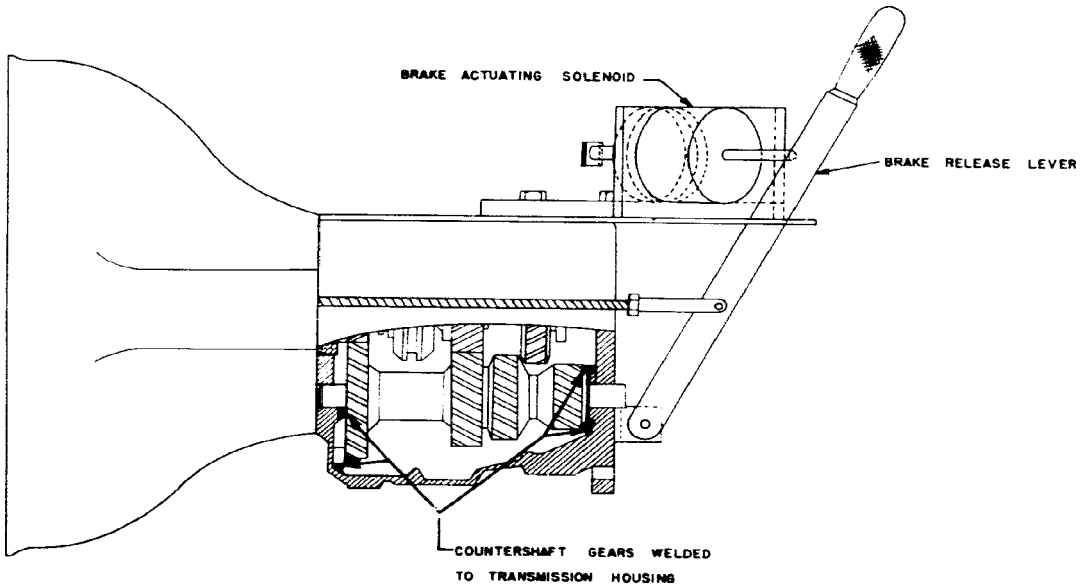


METHOD OF OBTAINING
COMBUSTION GAS SAMPLES
EXHAUST VALVE DISCONNECT SYSTEM

Fig. 31



METHOD OF OBTAINING
COMBUSTION GAS SAMPLES
ENGINE BRAKE
(TOP VIEW)



METHOD OF OBTAINING
COMBUSTION GAS SAMPLES
-ENGINE BRAKE-
(SIDE VIEW)

Fig. 32

10. The Siamese intake port between cylinder No. 1 & 2 was modified by plugging the opening to cylinder No. 2 to provide a smooth contour into cylinder No. 1.

II

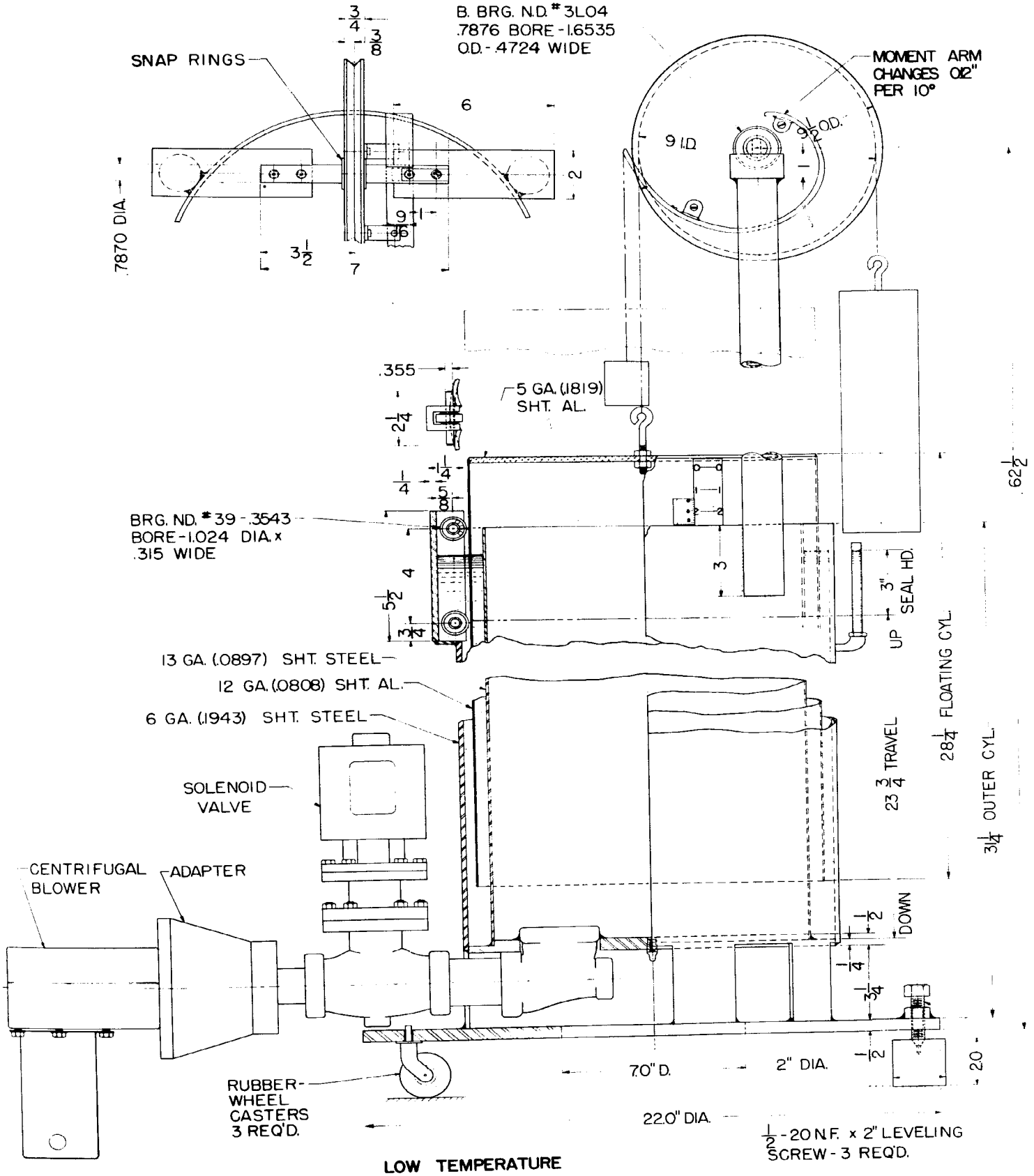
AIR MEASURING EQUIPMENT

To permit measurement of the quantity of air consumed by the engine at low temperatures, a special gasometer was designed and constructed. (See Figures 33 & 34)

When the gasometer was designed, the availability of a suitable sealing fluid was in doubt. The main design considerations were to achieve a seal with a minimum of seal surface exposed to the air inside the gasometer in order to minimize the possible effects of vapor from the seal, to secure reasonable movement of the air bell for each intake stroke, to achieve a perfect balance in order to prevent pressure differentials in the manifold, and to hold the unit to such a size that it would fit in the cold room and still have sufficient capacity for a reasonable test run.

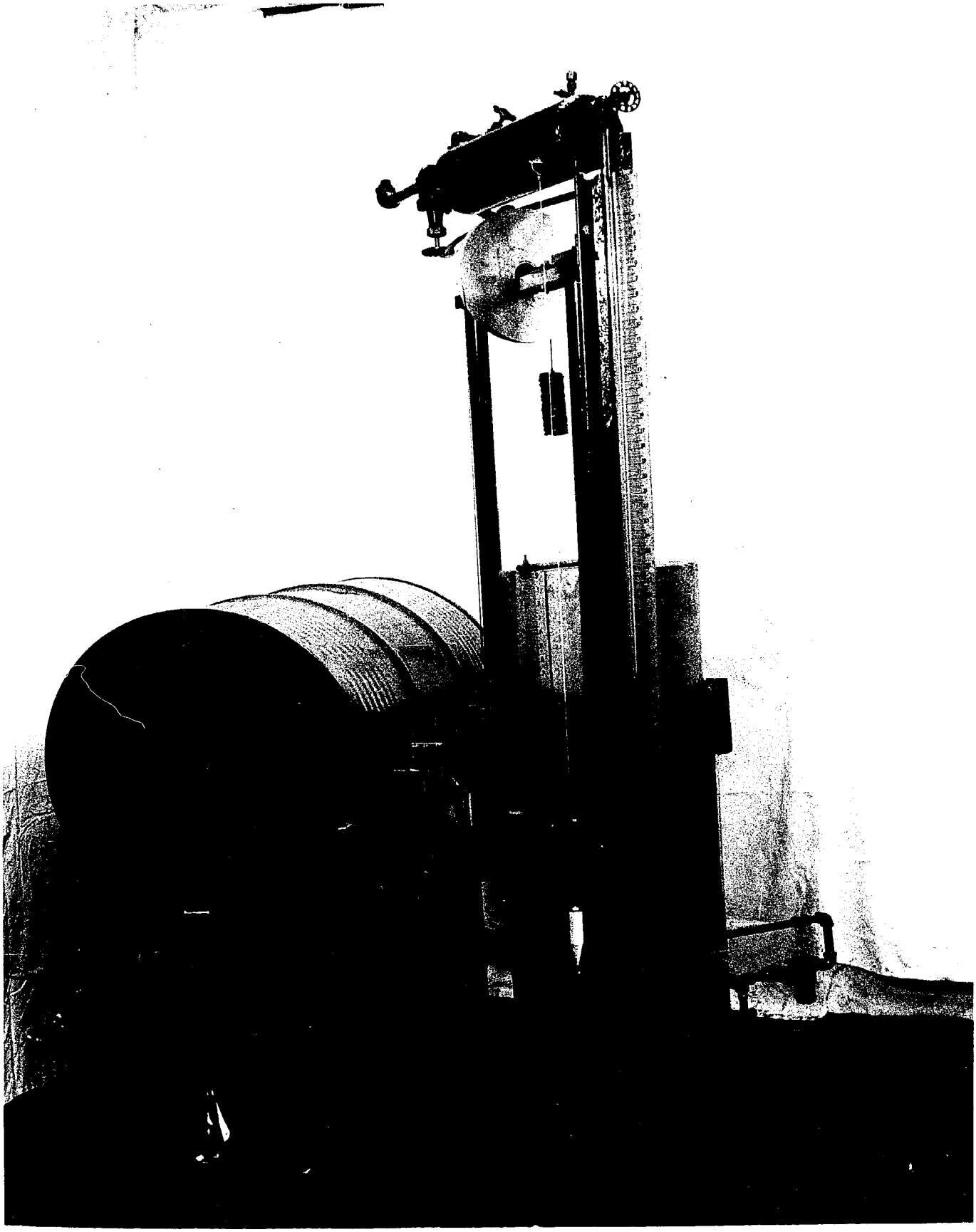
The design considerations have been attained with this unit and its functioning has been eminently satisfactory at all temperatures down to $-70^{\circ}F$.

The search for a sealing fluid that would be nonvolatile and have a fairly constant viscosity down to $-70^{\circ}F$. was long and disappointing. During the spring of 1950 the John B. Pierce Foundation developed a silicate compound known as EC - 170 which had the following characteristics:



LOW TEMPERATURE GASOMETER
(SEALING FLUID: EC-170)

Fig. 33



—DETROIT ARSENAL—
NEG. NO. 27936 DATE 31 Oct 1951 DEVELOPMENT & ENGINEERING
Low Temperature Gasometer and Fuel Gage. Calibration set-up.

Fig. 34

EC 170*

Iso-propyl-iso-butyl silicate

Pour Point	130°F.
Boiling Point	423°F.
Avg. Molecular Wt.	286.5
% Vol. expansion/°F.	0.0618
Specific Gravity	0.887 (60°F.)
	0.817 (200°F.)
Viscosity, centipoises	2.00 (60°F.)
	0.67 (200°F.)
Vapor Pressure, mm Hg.	less than 1.0 at 60°F.
	11.2 (200°F.)
Specific Heat, BTU/lb. °F. (C_p)	0.387 (60°F.)
	0.504 (200°F.)

In the fall of 1950, the Pierce Foundation donated eight gallons of EC-170 which proved to be the perfect solution to the problem of liquid seals at low temperatures. The compound has been in use at normal temperatures and extreme low temperatures for over a year and a half with no evidence of deterioration or loss of characteristics.

The gasometer, using EC-170 as a seal, required a maximum of 0.02 inches of water pressure differential to start the movement of the bell and balanced out with no detectible pressure differential.

The instrument provides a direct reading with vernier scale to 0.01 inches. A change of 0.01 inches in height represents a volume of 22 cubic centimeters. The gasometer was calibrated over its entire range by the displacement method. In conducting this calibration the setup shown in Figure 34 was used and the

*John B. Pierce Foundation, Raritan, N. J., Report No. RR-HT-8

calibration carried out at $0^{\circ}F$, $-30^{\circ}F$ and $-65^{\circ}F$. using stoddard solvent as a displacement fluid. The calibration data for the test temperatures is presented in Tables X, XI, & XII.

Since this calibration over the test temperatures showed variations no larger than the accuracy of reading, the calibration data was used to construct a calibration curve for the gasometer which eliminated the necessity for interpolation.

Due to the fact that there was a possibility of gasoline or its vapor escaping from the manifold and contaminating the air in the gasometer, the volume of air inducted per intake stroke at the various cranking speeds was determined prior to starting the tests and these figures were used in the computations for the weight of air inducted on the starting tests. To reduce the errors that might be encountered in reading the gasometer scale, the air tests were started with the gasometer against a physical stop and the quantity of air for ten intake strokes determined. In this manner, the accuracy of the measurement was within 0.5%. Since the results obtained were consistent, this averaging method is considered sufficiently accurate. Figure 35 and Tables XIII,XIV, and XV present this data.

See Table XVI for sample calculations.

GASOMETER CALIBRATION AT - 0 °F

Air Withdrawn from Gasometer (Litres)	Reading in Inches #1	#2	#3	Average Reading (Inches)	Drop in inches per 2 Litres
0	20.00	20.00	20.00	20.00	0.00
2	19.13	19.12	19.12	19.12	0.88
4	18.23	18.24	18.23	18.23	0.89
6	17.33	17.35	17.34	17.34	0.89
8	16.46	16.47	16.47	16.47	0.87
10	15.57	15.58	15.56	15.57	0.90
12	14.69	14.68	14.68	14.68	0.89
14	13.78	13.77	13.78	13.78	0.90
16	12.89	12.88	12.89	12.89	0.89
18	12.01	12.00	12.00	12.00	0.89
20	11.12	11.12	11.11	11.12	0.88
22	10.23	10.24	10.23	10.23	0.89
24	9.33	9.34	9.33	9.33	0.90
26	8.47	8.47	8.47	8.47	0.86
28	7.59	7.59	7.58	7.59	0.88
30	6.72	6.72	6.72	6.72	0.87
32	5.83	5.82	5.83	5.83	0.89
34	4.93	4.93	4.94	4.93	0.90
36	4.01	4.02	4.02	4.02	0.91
38	3.12	3.12	3.12	3.12	0.90
40	2.22	2.22	2.23	2.22	0.90
42	1.33	1.33	1.34	1.33	0.89

Date of Calibration - March 30, 1951

TABLE X

GASOMETER CALIBRATION AT - 35 °F

Air Withdrawn from Gasometer (Litres)	Reading in Inches #1	#2	#3	Average Reading (Inches)	Drop in inches per 2 Litres
0	20.00	20.00	20.00	20.00	0.00
2	19.13	19.12	19.12	19.12	0.88
4	18.23	18.23	18.23	18.23	0.89
6	17.34	17.34	17.34	17.34	0.89
8	16.47	16.46	16.46	16.46	0.88
10	15.56	15.57	15.57	15.57	0.89
12	14.69	14.69	14.68	14.69	0.88
14	13.78	13.79	13.78	13.78	0.91
16	12.89	12.89	12.88	12.89	0.89
18	12.00	12.00	12.00	12.00	0.89
20	11.12	11.11	11.12	11.12	0.88
22	10.23	10.23	10.23	10.23	0.89
24	9.34	9.34	9.34	9.34	0.89
26	8.47	8.47	8.47	8.47	0.87
28	7.59	7.59	7.59	7.59	0.88
30	6.72	6.72	6.72	6.72	0.87
32	5.83	5.82	5.82	5.82	0.90
34	4.93	4.93	4.93	4.93	0.89
36	4.02	4.02	4.01	4.02	0.91
38	3.12	3.12	3.13	3.12	0.90
40	2.23	2.23	2.24	2.23	0.89
42	1.33	1.33	1.34	1.33	0.90

Date of Calibration - April 2, 1951

TABLE XI

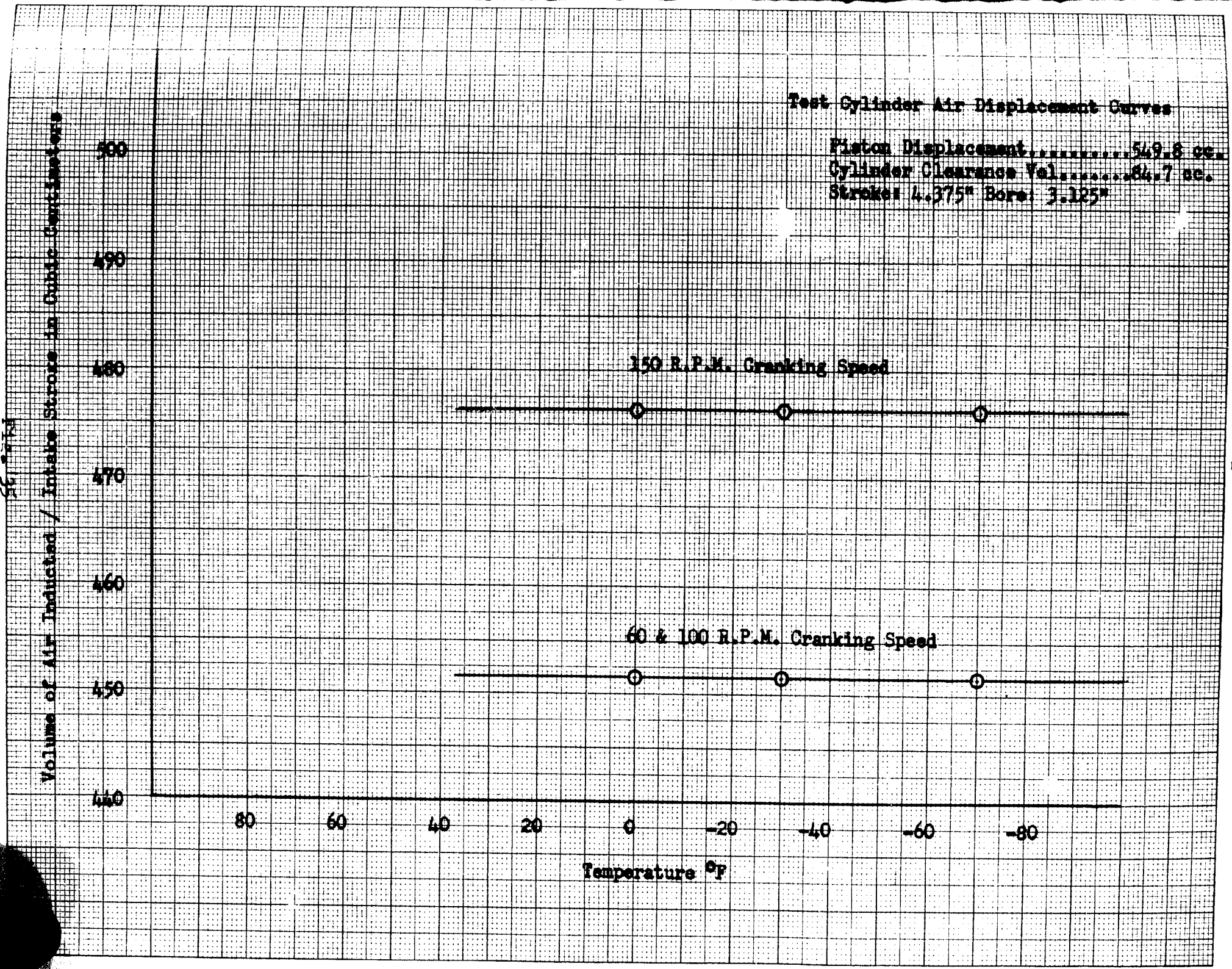
GASOMETER CALIBRATION AT - 65 ° F

Air Withdrawn from Gasometer (Litres)	Reading in Inches #1	#2	#3	#4	#5	Average Reading (Inches)	Drop in inches per 2 Litres
0	20.00	20.00	20.00	20.00	20.00	20.00	
2	19.13	19.12	19.12	19.12	19.13	19.12	.88
4	18.24	18.23	18.23	18.23	18.24	18.23	.89
6	17.34	17.33	17.33	17.34	17.34	17.34	.89
8	16.47	16.46	16.46	16.47	16.47	16.46	.88
10	15.57	15.57	15.57	15.57	15.57	15.57	.89
12	14.69	14.69	14.69	14.69	14.69	14.69	.88
14	13.78	13.77	13.77	13.78	13.78	13.78	.91
16	12.89	12.88	12.89	12.89	12.89	12.89	.89
18	12.00	11.99	12.00	12.00	12.00	12.00	.89
20	11.12	11.12	11.12	11.12	11.12	11.12	.88
22	10.23	10.23	10.23	10.23	10.23	10.23	.89
24	9.34	9.33	9.33	9.34	9.34	9.34	.89
26	8.48	8.47	8.48	8.47	8.47	8.47	.87
28	7.59	7.59	7.59	7.59	7.59	7.59	.88
30	6.73	6.73	6.72	6.72	6.72	6.72	.87
32	5.83	5.83	5.82	5.82	5.82	5.82	.90
34	4.94	4.93	4.93	4.94	4.93	4.93	.89
36	4.01	4.03	4.03	4.02	4.02	4.02	.91
38	3.12	3.13	3.11	3.12	3.12	3.12	.90
40	2.22	2.23	2.22	2.23	2.24	2.23	.89
42	1.33	1.33	1.33	1.34	1.34	1.33	.90

Date of Calibration - March 2, 1951

TABLE XII




Test Cylinder Air Displacement Curves
Piston Displacement.....549.8 cc.
Cylinder Clearance Vol.....84.7 cc.
Stroke: 4.375" Bore: 3.125"
150 R.P.M. Cranking Speed
60 & 100 R.P.M. Cranking Speed
Volume of Air Inducted / Intake Stroke in Cubic Centimeters
500
490
480
470
460
450
440
80
60
40
20
0
-20
-40
-60
-80
Temperature °F

ENGINE DISPLACEMENT CALIBRATION

Calibration Temperature: 0° F.

Trial No.	Scale Reading, Inches Start	End	Total Air/ 10 Strokes, cc.	Air/Intake Stroke, cc.
		Cranking RPM: 50		
1	20.00	18.00	-	-
2	20.00	18.01	-	-
3	20.00	18.00	-	-
4	20.00	18.00	-	-
5	20.00	18.00	-	-
Average	20.00	18.002	4516	451.6
		Cranking RPM: 100		
1	20.00	18.00	-	-
2	20.00	18.00	-	-
3	20.00	18.01	-	-
4	20.00	18.01	-	-
5	20.00	18.00	-	-
Average	20.00	18.004	4516	451.6
		Cranking RPM: 150		
1	20.00	17.89	-	-
2	20.00	17.90	-	-
3	20.00	17.89	-	-
4	20.00	17.89	-	-
5	20.00	17.90	-	-
Average	20.00	17.894	4764	476.4

TABLE XIII

ENGINE DISPLACEMENT CALIBRATION

Calibration Temperature: -30° F.

Trial No.	Scale Reading, Inches Start	End	Total Air/10 Strokes, cc.	Air/Intake Stroke, cc.
		Cranking RPM: 60		
1	20.00	17.99	-	-
2	20.00	18.00	-	-
3	20.00	18.01	-	-
4	20.00	18.00	-	-
5	20.00	17.99	-	-
Average	20.00	17.998	4516	451.6
		Cranking RPM: 100		
1	20.00	17.98	-	-
2	20.00	17.99	-	-
3	20.00	18.00	-	-
4	20.00	18.01	-	-
5	20.00	18.00	-	-
Average	20.00	17.996	4516	451.6
		Cranking RPM: 150		
1	20.00	17.89	-	-
2	20.00	17.89	-	-
3	20.00	17.90	-	-
4	20.00	17.90	-	-
5	20.00	17.89	-	-
Average	20.00	17.894	4764	476.4

TABLE XIV

ENGINE DISPLACEMENT CALIBRATION

Calibration Temperature: -70° F.

Trial No.	Scale Reading, Inches Start	End	Total Air/10 Strokes, cc.	Air/Intake Stroke, cc.
		Cranking RPM: 60		
1	20.00	18.00	-	-
2	20.00	18.01	-	-
3	20.00	18.01	-	-
4	20.00	18.00	-	-
5	20.00	18.00	-	-
Average	20.00	18.002	4516	451.6
		Cranking RPM: 100		
1	20.00	18.01	-	-
2	20.00	18.00	-	-
3	20.00	17.99	-	-
4	20.00	18.00	-	-
5	20.00	18.00	-	-
Average	20.00	18.00	4516	451.6
		Cranking RPM: 150		
1	20.00	17.88	-	-
2	20.00	17.89	-	-
3	20.00	17.89	-	-
4	20.00	17.90	-	-
5	20.00	17.89	-	-
Average	20.00	17.89	4764	476.4

TABLE XV

SAMPLE CALCULATIONS
for
ENGINE DISPLACEMENT CALIBRATION

Using Tabulated Calibration Data for $0^{\circ}F.$
(Table X)

Scale reading of 20 inches = 0 liters of air withdrawn
Scale reading of 18.23 inches = 4 liters of air withdrawn
Scale reading of 17.34 inches = 6 liters of air withdrawn

A change of 0.89 inches from
18.23 to 17.34 = 2 liters of air withdrawn

A change of 0.66 inches from
18.00 to 17.34 = X liters of air withdrawn

Therefore:

$$.89/2 = .66/X$$

$$X = (.66)(2)/0.89 = 1.4842 \text{ liters}$$

Hence:

The change in scale readings from 20 to 18 inches

= 6.0000 - 1.4842 = 4.5158 liters for ten strokes

or

= 451.6 cc. per intake stroke

TABLE XVI

III

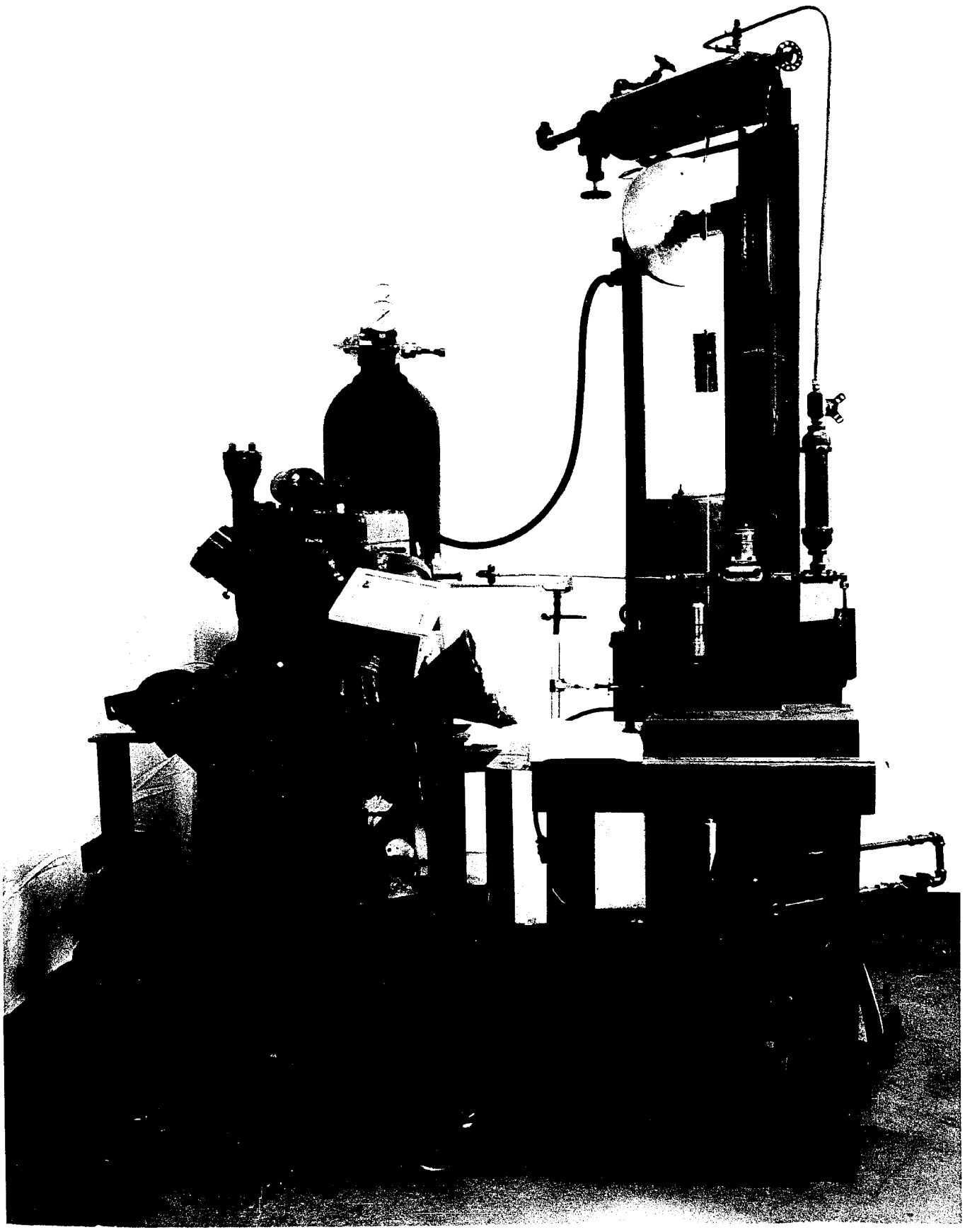
FUEL MEASURING EQUIPMENT

Since the fuel supply system (See Figure 36) is an integral part of the pressurized primer system a method was devised to permit measurement of the fuel primed without the necessity of releasing the pressure on the system. Figure 37 is a schematic diagram of the complete fuel system.

The measuring element consists of a boiler gage glass (0.419" nominal dia., 5' length) which was found to withstand over 400 psi pressure. This tube was mounted over a scale and equipped with a sliding vernier which permitted reading fuel levels to 0.01 inches (See Figure 38). To correct for any variations in the bore of the tube, the gage was calibrated over its entire length. The calibration figures are presented in Tables XVII, XVIII & XIX. The gage was calibrated at 0°, -35° and -65°F. and it was found that temperature had no detectible effect upon its accuracy. By recording fuel levels before and after each trial and referring to a curve plotted from Tables XVII, XVIII & XIX the fuel primed can be determined to within ≠ or - 0.02 cc.

The fuel system, as originally designed, incorporated a remote reading and refilling system which was abandoned due to the unreliability of the automatic equipment at low temperatures.

Referring to Figure 37, in operation during a test the following valve positions are used:



—DETROIT ARSENAL—
NEG. NO. 27975 DATE 26 Oct 1951 DEVELOPMENT & ENGINEERING
Primer Effectiveness Test under Extreme Low Temperatur
Conditions. Fuel system.

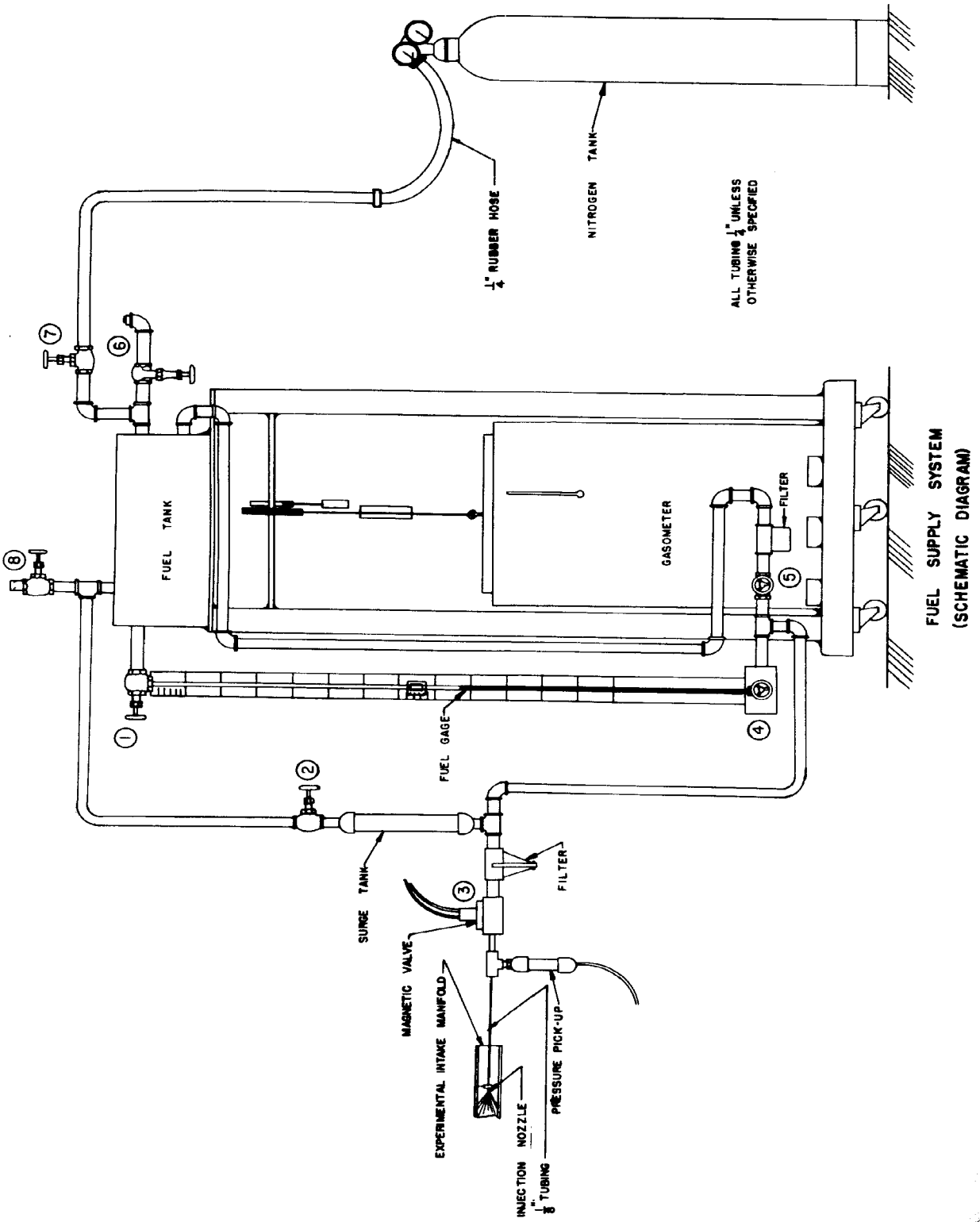
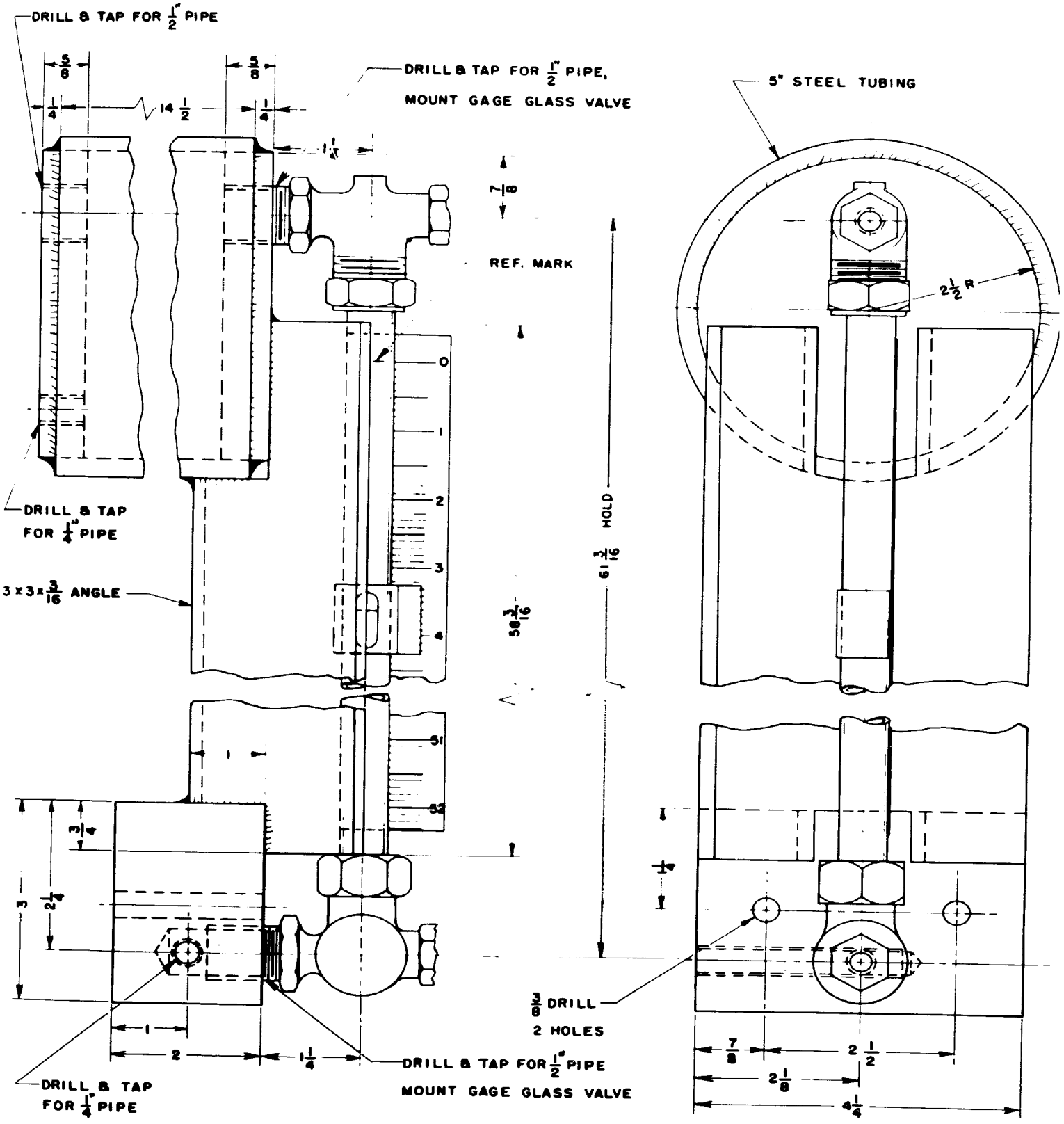

FUEL SUPPLY SYSTEM
(SCHEMATIC DIAGRAM)
ALL TUBING 1/4" UNLESS OTHERWISE SPECIFIED
1/4" RUBBER HOSE
NITROGEN TANK
FUEL TANK
GASOMETER
FILTER
FUEL GAGE
SURGE TANK
FILTER
MAGNETIC VALVE
EXPERIMENTAL INTAKE MANIFOLD
INJECTION NOZZLE
1/8" TUBING
PRESSURE PICK-UP

Fig. 37



FUEL GAGE

Fig. 38

FUEL GAGE CALIBRATION AT 0 °F

Gasoline Withdrawn from Gage (cc)	Scale Readings in inches			Average Scale Reading (inches)	Drop in inches per 5cc	Fuel in Gage (cc)
	#1	#2	#3			
0	0	0	0	0	0	120
5	2.20	2.19	2.19	2.19	2.19	115
10	4.40	4.39	4.39	4.39	2.20	110
15	6.58	6.55	6.57	6.57	2.18	105
20	8.74	8.73	8.74	8.74	2.17	100
25	10.93	10.91	10.92	10.92	2.18	95
30	13.10	13.10	13.11	13.10	2.18	90
35	15.29	15.30	15.30	15.30	2.20	85
40	17.47	17.47	17.46	17.47	2.17	80
45	19.66	19.67	19.67	19.67	2.20	75
50	21.83	21.82	21.83	21.83	2.16	70
55	24.01	24.01	24.00	24.01	2.18	65
60	26.20	26.20	26.19	26.20	2.19	60
65	28.40	28.40	28.39	28.40	2.20	55
70	30.57	30.57	30.58	30.57	2.17	50
75	32.76	32.76	32.76	32.76	2.29	45
80	34.92	34.93	34.92	34.92	2.16	40
85	37.09	37.09	37.09	37.09	2.17	35
90	39.27	39.28	39.28	39.28	2.19	30
95	41.45	41.46	41.47	41.46	2.18	25
100	43.60	43.61	43.61	43.61	2.15	20
105	45.73	45.73	45.73	45.73	2.12	15
110	47.86	47.85	47.84	47.85	2.12	10
115	49.95	49.95	49.95	49.95	2.10	5
120	52.05	52.04	52.04	52.04	2.09	0

Date of Calibration - March 30, 1951

TABLE XVII

FUEL GAGE CALIBRATION AT - 35 °F

Gasoline Withdrawn from Gage (cc)	Scale Readings in inches #1	#2	#3	Average Scale Reading (inches)	Drop in inches per 5cc	Fuel in Gage (cc)
0	0	0	0	0	0	120
5	2.20	2.20	2.19	2.20	2.20	115
10	4.38	4.40	4.40	4.39	2.19	110
15	6.56	6.57	6.56	6.56	2.17	105
20	8.74	8.73	8.74	8.74	2.18	100
25	10.93	10.92	10.92	10.92	2.18	95
30	13.10	13.10	13.11	13.10	2.18	90
35	15.29	15.29	15.29	15.29	2.19	85
40	17.48	17.47	17.47	17.47	2.18	80
45	19.66	19.66	19.66	19.66	2.19	75
50	21.84	21.82	21.83	21.83	2.17	70
55	24.01	24.00	24.00	24.00	2.17	65
60	26.18	26.21	26.20	26.20	2.20	60
65	28.39	28.40	28.41	28.40	2.20	55
70	30.58	30.58	30.57	30.58	2.18	50
75	32.75	32.76	32.76	32.76	2.18	45
80	34.92	34.92	34.93	34.92	2.16	40
85	37.10	37.09	37.10	37.10	2.18	35
90	39.27	39.27	39.27	39.27	2.17	30
95	41.46	41.44	41.45	41.45	2.18	25
100	43.60	43.60	43.61	43.60	2.15	20
105	45.73	45.75	45.74	45.74	2.14	15
110	47.85	47.84	47.84	47.84	2.10	10
115	49.95	49.95	49.94	49.95	2.11	5
120	52.05	52.05	52.04	52.05	2.10	0

Date of Calibration - April 2, 1951

TABLE XVIII

FUEL GAGE CALIBRATION AT - 65 °F

Gasoline Withdrawn from Gage (cc)	Scale Readings in inches					Average Scale Reading (inches)	Drop in inches per 5cc	Fuel in Gage (cc)
	#1	#2	#3	#4	#5			
0	0	0	0	0	0	0	0	120
5	2.20	2.19	2.20	2.20	2.20	2.20	2.20	115
10	4.40	4.39	4.40	4.38	4.40	4.39	2.19	110
15	6.57	6.56	6.57	6.56	6.57	6.57	2.18	105
20	8.74	8.73	8.74	8.72	8.75	8.74	2.17	100
25	10.93	10.89	10.92	10.93	10.93	10.92	2.18	95
30	13.10	13.10	13.10	13.11	13.10	13.10	2.18	90
35	15.29	15.28	15.29	15.30	15.29	15.29	2.19	85
40	17.47	17.46	17.47	17.48	17.47	17.47	2.18	80
45	19.66	19.66	19.67	19.67	19.66	19.66	2.19	75
50	21.83	21.82	21.83	21.84	21.82	21.83	2.17	70
55	24.01	24.01	24.01	24.01	24.00	24.01	2.18	65
60	26.20	26.19	26.20	26.20	26.19	26.20	2.19	60
65	28.40	28.39	28.40	28.40	28.40	28.40	2.20	55
70	30.58	30.58	30.58	30.57	30.58	30.58	2.18	50
75	32.75	32.75	32.75	32.75	32.76	32.75	2.17	45
80	34.92	34.93	34.92	34.92	34.92	34.92	2.17	40
85	37.09	37.09	37.09	37.10	37.10	37.09	2.17	35
90	39.27	39.28	39.28	39.27	39.27	39.27	2.18	30
95	41.45	41.46	41.47	41.45	41.45	41.45	2.18	25
100	43.61	43.61	43.61	43.61	43.60	43.61	2.16	20
105	45.74	45.74	45.74	45.74	45.74	45.74	2.13	15
110	47.85	47.86	47.86	47.85	47.85	47.85	2.11	10
115	49.95	49.95	49.95	49.94	49.94	49.95	2.10	5
120	52.05	52.05	52.05	52.04	52.04	52.05	2.10	0

Date of Calibration - Feb 21, 1951

TABLE XIX

OPEN	CLOSED
Valve No. 1	Valve No. 8
Valve No. 4	Valve No. 6
Valve No. 7	Valve No. 5
	Valve No. 2

IMPORTANT: Close valves indicated before opening others. Valve No. 3 operates under control of the injection timing circuit. The desired pressure is applied through the regulator from the nitrogen cylinder.

To reflill the sight gage, the following valve positions are used:

OPEN	CLOSED
Valve No. 1	Valve No. 8
Valve No. 4	Valve No. 6
Valve No. 7	Valve No. 2

IMPORTANT: Close valves indicated before opening others. Valve No. 3 is normally closed when the injection circuit is not energized. Valve No. 5 is opened slightly and the fuel is allowed to rise in the sight gage to the desired height and then Valve No. 5 is closed. The system is then ready for the next trial.

To replenish the fuel supply in the main fuel tank the pressure must be released from part of the system. The following valve positions are used:

OPEN	CLOSED
Valve No. 8	Valve No. 1
Valve No. 6	Valve No. 2
	Valve No. 3 (Normal)
	Valve No. 5
	Valve No. 7

IMPORTANT: Close valves indicated before opening others. Fuel must be added through Valve No. 6, Valve No. 8 serves as a vent. The tank is filled half full (not over one-half gallon). The valves are then returned to the following positions:

OPEN	CLOSED
Valve No. 7	Valve No. 8
	Valve No. 6

IMPORTANT: Close valves indicated before opening No. 7. The remaining valves may now be set to the positions indicated for conducting tests.

During the course of testing it was discovered that the rapid opening of the electric valve caused momentary pressure rises or surges* far in excess of the applied pressures. To eliminate these pressure waves which might have some effect upon nozzle performance, the surge tank was added to the fuel system. The level of the gasoline in the surge tank was checked between tests, however it is believed that this precaution was unnecessary. The only cause

*Surges of over 400 psi. were found with priming pressures of 200 psi. The explanation of these surges and the theory is explained in detail by Prof. N. Joukovsky as quoted in "Hydraulics for Engineers" by R. W. Angus, 3rd Edition, P.284-286, Sir Isaac Pitman & Sons, Toronto, Canada, publishers. In this application the column of fluid

for the level changing was the absorption of nitrogen by the gasoline or the loss of gas through slow leaks in the piping. To charge the surge tank the following valve positions are used:

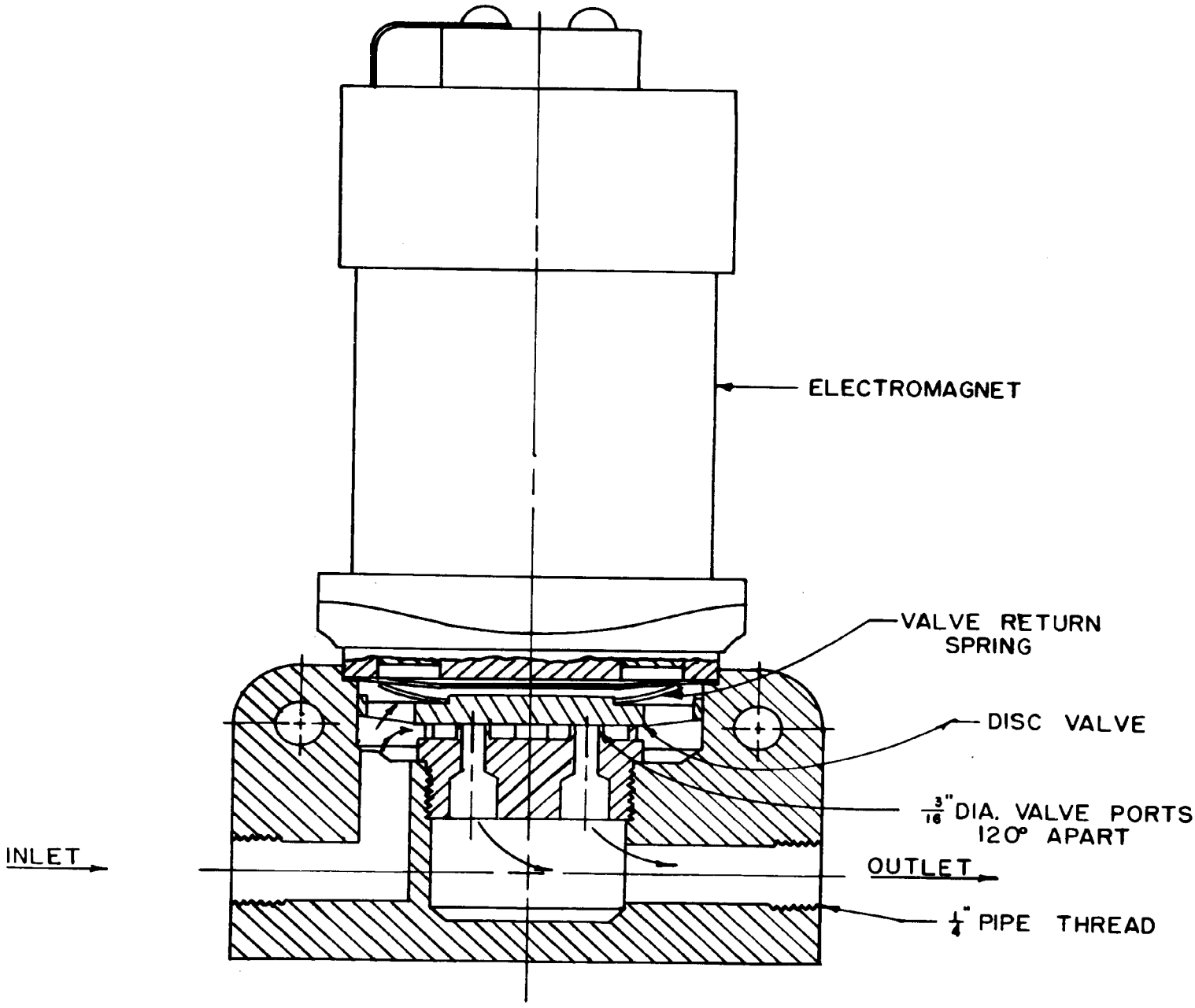
OPEN	CLOSED
Valve No. 7	Valve No. 8
Valve No. 1	Valve No. 6
Valve No. 4	Valve No. 3 (Normal)
Valve No. 2	

Valve No. 5 is opened and the fuel allowed to rise in the sight gage until it is standing half way up the surge tank body. At this time Valve No. 2 is closed and the fuel permitted to rise to the desired level in the gage glass. All valves are then returned to test position.

To protect the fuel system and primer nozzle from clogging with ice crystals, two high pressure filters were used. One filter was devised from sintered metal bar stock and the other was a standard Zenith disc type passing particles no larger than 0.003 inches. The filters effectively prevented any troubles due to clogging.

The electric primer valve was a specially constructed magnetic valve built by General Controls Corp. and designed to operate at -65°F. at pressures up to 300 psi. This valve worked reliably at all test temperatures. Figure 39 illustrates the principles of this valve.

released by the opening of the magnetic valve is rapidly accelerated and then strikes the primer nozzle which, due to the restriction presented by the small opening, acts in a manner similar to a quick closing valve or a dead end pipe.



MAGNETIC VALVE SCHEMATIC

Fig. 39

Since nine months were required to obtain the General Controls valve, another type of valve was designed, built and tested (See Figure 40) which failed to give consistent results at low temperatures, primarily due to leakage past the shaft. This valve depended upon the priming pressure to open the valve and the solenoid to close it.

The injection nozzle was a standard Ordnance nozzle (Ordnance Drawing No. A29675, manufactured by Dole Co.) with a 0.020" diameter opening. Figure 5 is a schematic diagram of the nozzle."

Since, during the investigation, the primer nozzle was to be constant, it was decided to select a representative item from issue stock. Five nozzles, selected at random, were measured and flow tested at room temperatures to determine their discharge rates. The nozzles showed fairly uniform construction and the orifice sizes were as shown below:

PRODUCTION
INJECTION NOZZLE ORIFICE SIZE

Nozzle No.	1	2	3	4	5
Orifice Dia. Inches	0.020	0.020	0.019	0.020	0.019

The flow curves for the various pressures at 69°F. are shown on Figure 6. Typical primer nozzle spray patterns at pressures from 25 to 200 psi. are shown in Figures 7 through 14.

Nozzle No. 4 was selected as the test nozzle and was very carefully calibrated with respect to flow at 0°, -35°, and -66°F. It was found that the calibration held over the entire temperature

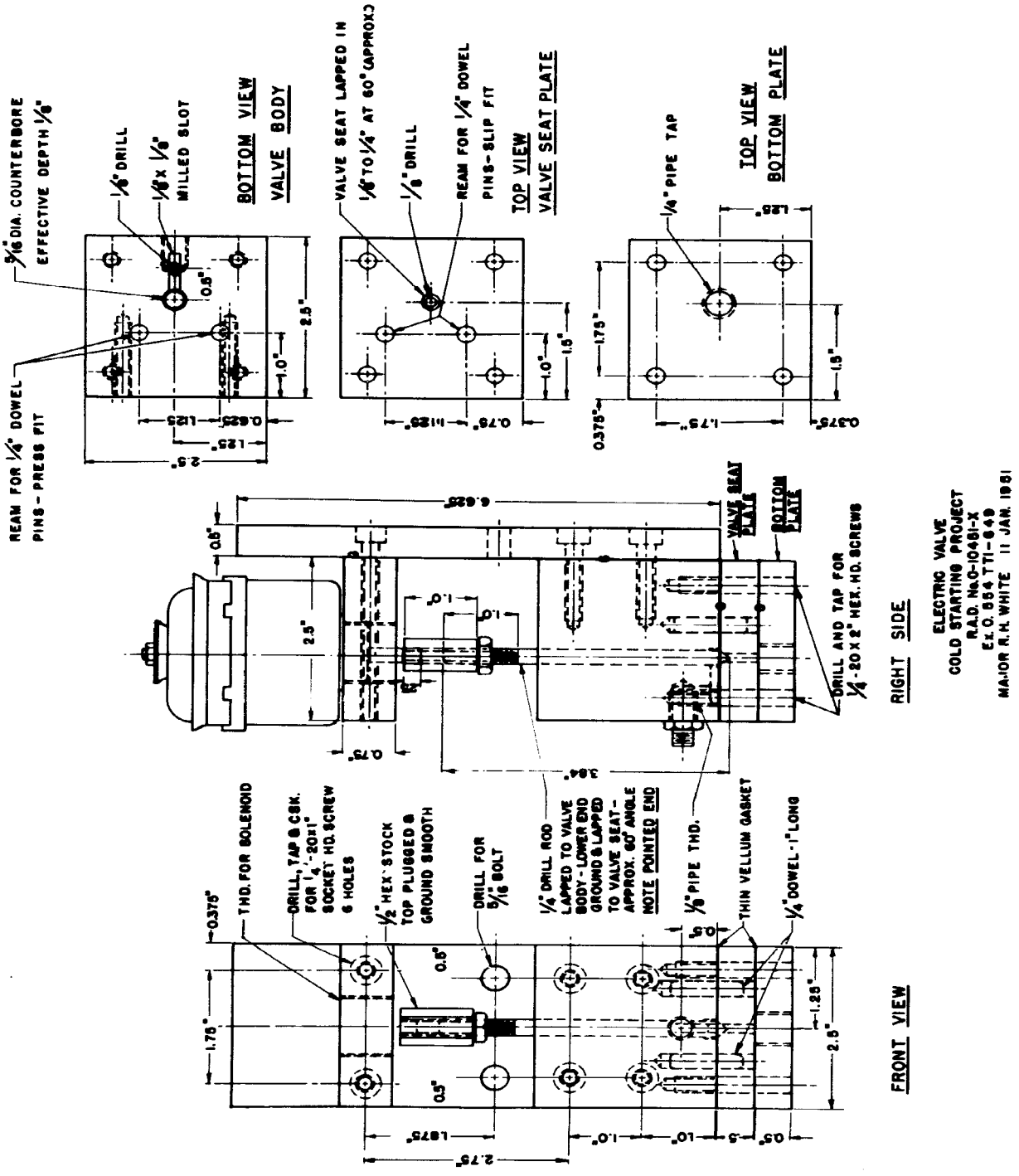

BOTTOM VIEW
VALVE BODY
TOP VIEW
VALVE SEAT PLATE
TOP VIEW
BOTTOM PLATE
RIGHT SIDE
FRONT VIEW
ELECTRIC VALVE
COLD STARTING PROJECT
R.A.D. No.O-10481-X
Ex. O. 854 TTI-649
MAJOR R. H. WHITE 11 JAN. 1951

Fig. 40

range. The results are presented in Table XX and in Figure 15.

DISCHARGE CHARACTERISTICS
Test Primer Nozzle
(0^{o}, -35^{o}, -66^{o}F.)

Priming Pressure psi.	Flow Time (sec.) for 74.9 cc. Trial Number					Ave. Time, Sec.	Discharge Rate cc./sec.
15	52.3	52.4	52.4	52.4	52.4	52.4	1.43
25	43.0	43.0	44.0	43.0	43.0	43.0	1.74
50	31.2	31.2	31.2	31.2	31.3	31.2	2.40
75	25.9	26.0	26.0	26.0	26.0	26.0	2.89
100	22.7	22.6	22.6	22.7	22.7	22.7	3.30
125	20.4	20.4	20.5	20.5	20.4	20.4	3.68
150	19.1	19.0	19.1	19.0	19.0	19.0	3.95
175	17.6	17.7	17.5	17.6	17.6	17.6	4.26
200	16.8	16.8	16.7	16.7	16.8	16.8	4.55

TABLE XX

IV

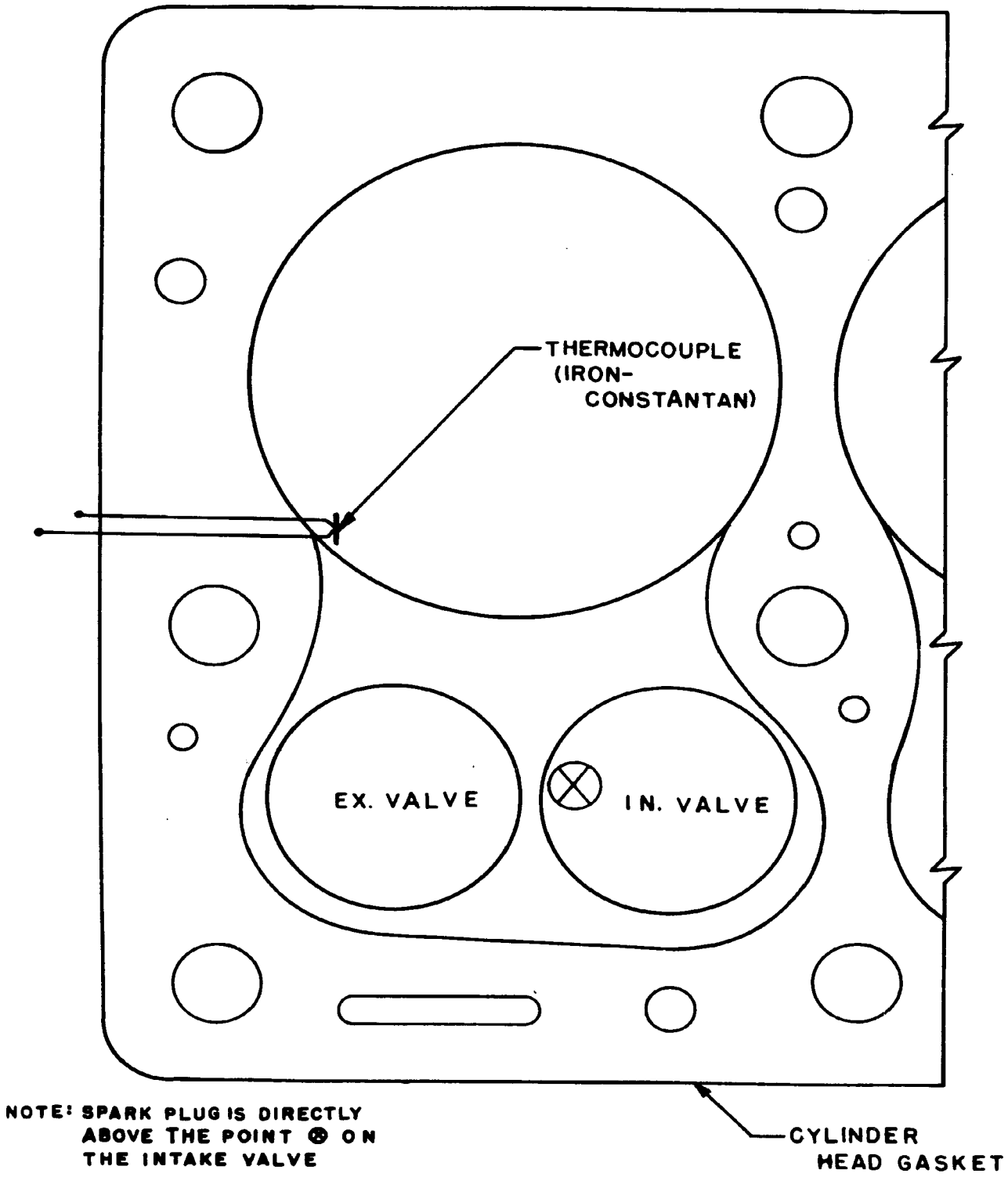
INSTRUMENTATION

1. Combustion Detection Device.

A small iron-constantan thermocouple was introduced into the combustion chamber through an extremely small hole in the cylinder head gasket. Figure 41 shows the location of the thermocouple. The thermocouple, insofar as could be determined, stabilized at its surrounding temperature almost instantaneously. The thermocouple, which would generate an electromotive force of 0.0271 millivolts per degree Fahrenheit (in the range -100 to 0 ^{o}F.), was connected to a D' Arsonval movement with a moving coil resistance of 1.9 ohms. An aluminum foil blade was attached to the moving coil and served to interrupt a photo-electric cell circuit when the coil moved a predetermined distance. At each test temperature the instrument was adjusted so that a temperature rise of 3 ^{o}F. above the rise caused by the compression stroke would cause the moving blade to swing completely across the light source to the photo-electric cell. Through an appropriate circuit, the photo-electric cell was connected to the relays that stopped the test equipment instantaneously.

2. Instruments Employed.

Figure 42 illustrates the instrumentation employed in the course of testing and Figure 43 shows schematically the major instrument connections.



THERMOCOUPLE POSITION IN TEST ENGINE
(FULL SCALE)

Fig. 41



DETROIT ARSENAL

NEG. NO. 27993 DATE 29 Oct 1951 DEVELOPMENT & ENGINEERING

Primer Effectiveness Test Under Extreme Low Temperature Conditions. Instrumentation

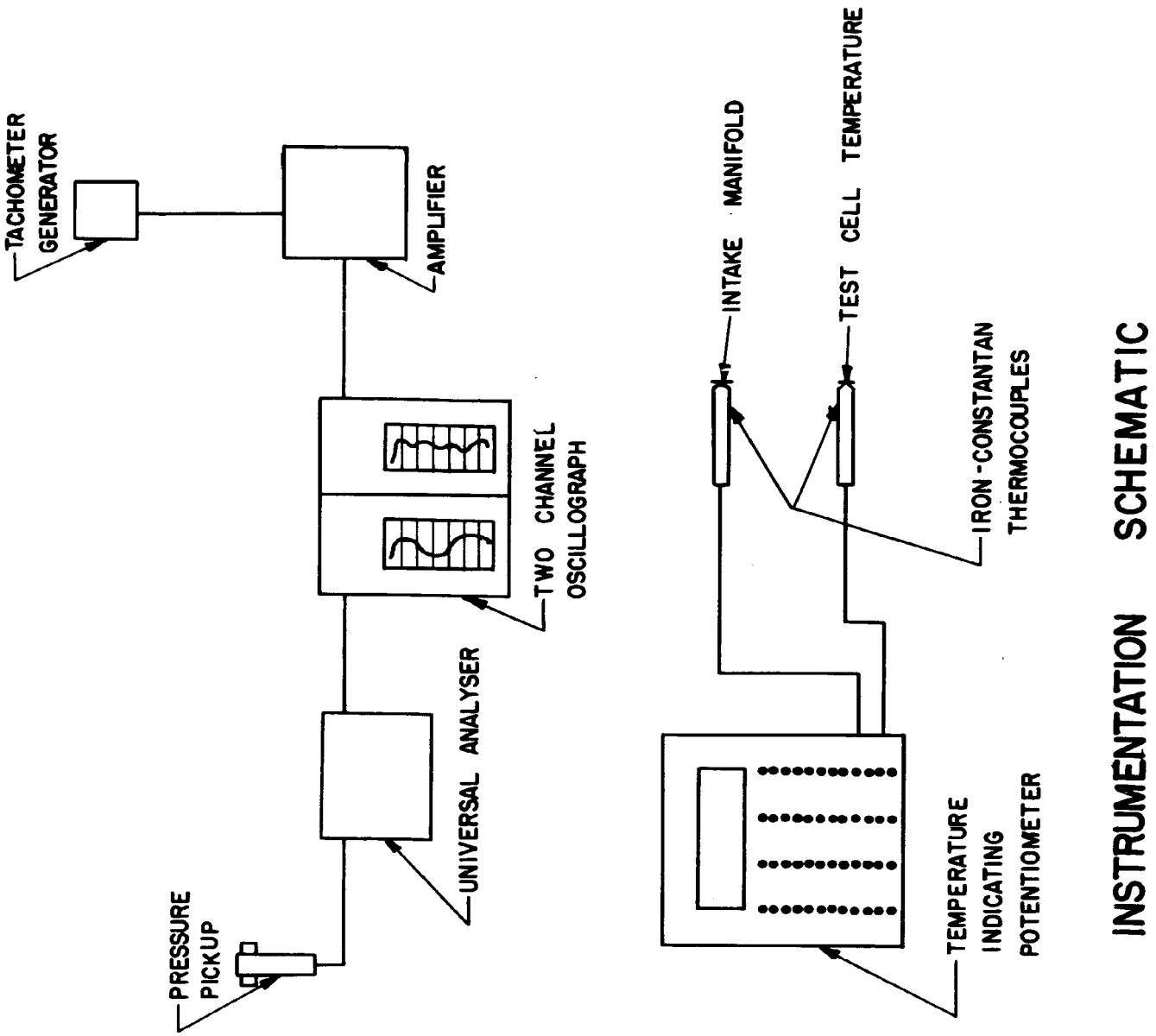

TACHOMETER GENERATOR
AMPLIFIER
TWO CHANNEL OSCILLOGRAPH
UNIVERSAL ANALYSER
PRESSURE PICKUP
INTAKE MANIFOLD
TEST CELL TEMPERATURE
IRON-CONSTANTAN THERMOCOUPLES
TEMPERATURE INDICATING POTENTIOMETER
INSTRUMENTATION SCHEMATIC

Fig. 43

The following major instruments were employed:

A. Tachometer-Generator, Weston, Model 44, 2000 RPM maximum.

B. Pressure Pick-up, Statham Lab., PLO-10MG-350, Strain Gage Type.

C. Two Channel Recording Oscillograph, Brush Dev. Co. Model BL-902, with power source Model BL-320 and D. C. Amplifier, Model BL-962.

D. Temperature Indicating Potentiometer, Brown "Electronik", + 700 to -100 ^{o}F.

E. Compression Pressure Gage, Arsco Mfg. Co.

F. Hand Tachometer, Jones Motorola Corp, 50-500 RPM.

G. Various gages, meters and recording potentiometers installed as part of cold cell.

Since the speed of cranking could not be held constant, the use of the tachometer-generator and oscillograph permitted the determination of cranking speed during the intake stroke. This, in turn, made it possible to adjust the cranking motor voltage to produce the same speed for each intake stroke. Calibration was maintained by checking the tachometer-generator against the hand tachometer.

The strain gage type of pressure pick-up was found to work satisfactorily down to -70 ^{o}F. It was calibrated at each test temperature and checked daily during the course of testing. The pressure pick-up used in conjunction with the oscillograph permitted complete surveillance of the pressure pattern developed at the primer nozzle throughout the injection period.

V

ELECTRICAL CIRCUITS AND THEIR OPERATION

Figure 44 presents the complete electrical system of the test apparatus in schematic form. To simplify the description, the electrical system is discussed under the various circuits which comprise the complete system.

1. The Power Circuit.

The main power circuit appears in the upper left section of Figure 44. Switch (1) is the main power switch controlling the solenoids 1R and 2R which in turn control the starter circuits of the 6, 12, and 24 volt D.C. rectifiers of the cold cell. The three voltages were required since the various relays, motors and instruments could not be obtained for a single voltage.

2. Starter Circuit.

The starter circuit is shown in the upper right section of Figure 44. Switch (2) is the starter switch. Closing it energizes relay 3R which closes contact points 3R and permits current to flow through variable resistor (18) to the starter motors. The starter motors are standard 6 volt units coupled in tandem, and by adjusting resistor (18) any voltage from 0 to 12 may be impressed on the motors, thus providing controls of the engine cranking speed.

3. Ignition Circuit.

The ignition circuit appears at center left in Figure 44. Switch

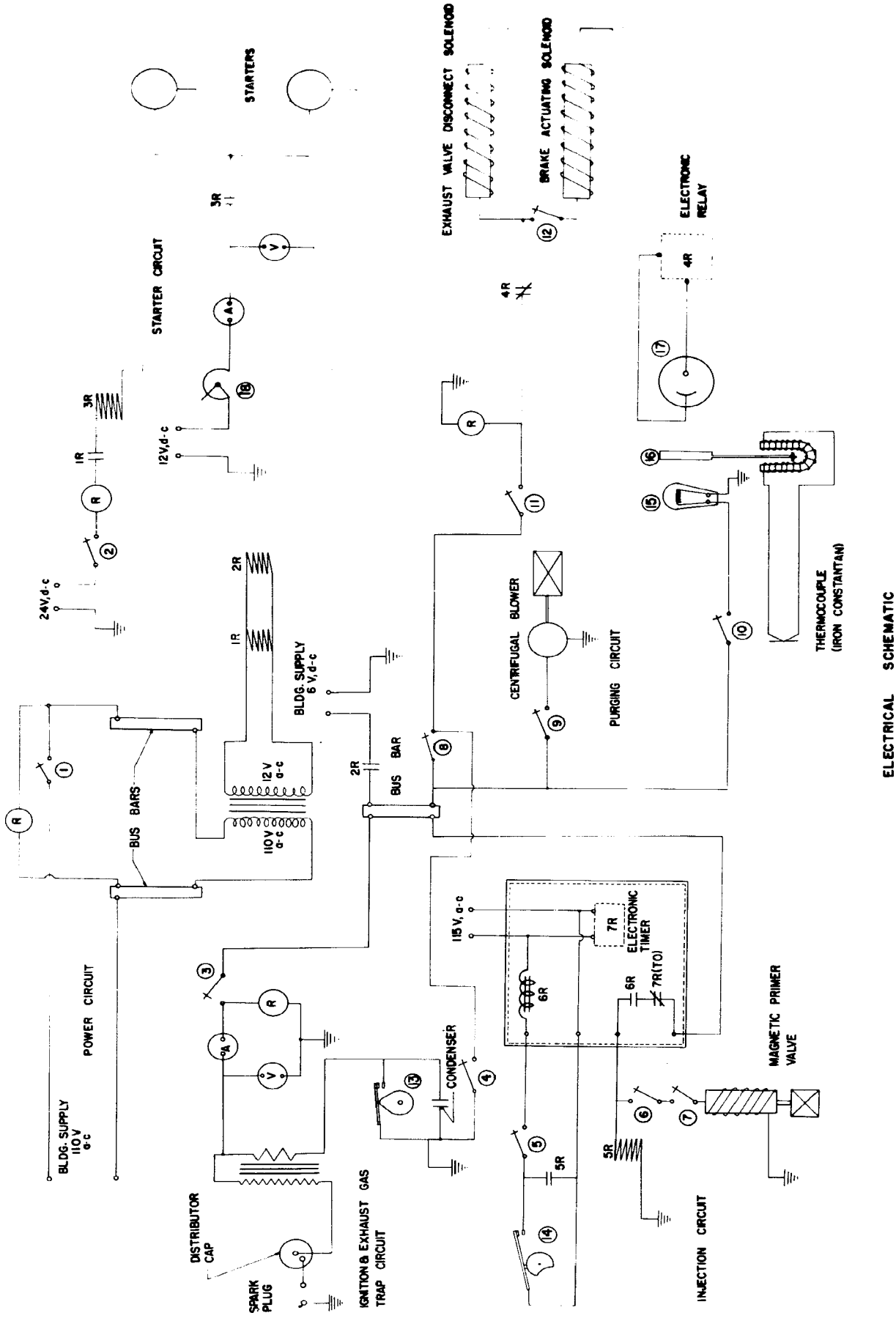

STARTERS
EXHAUST VALVE DISCONNECT SOLENOID
BRAKE ACTUATING SOLENOID
ELECTRONIC RELAY
STARTER CIRCUIT
3R
1R
2R
4R
5R
6R
7R
7R(TO)
24V,d-c
12V,d-c
110V a-c
12 V a-c
BLDG. SUPPLY 6 V,d-c
BLDG. SUPPLY 110 V a-c
BUS BARS
BUS BAR
POWER CIRCUIT
CENTRIFUGAL BLOWER
PURGING CIRCUIT
THERMOCOUPLE (IRON CONSTANTAN)
115 V, a-c
ELECTRONIC TIMER
CONDENSER
MAGNETIC PRIMER VALVE
DISTRIBUTOR CAP
SPARK PLUG
IGNITION & EXHAUST GAS TRAP CIRCUIT
INJECTION CIRCUIT
ELECTRICAL SCHEMATIC

Fig. 44

(3) is the primary ignition switch. The distributor has been modified to include a single lobe cam and the high tension lead from the spark coil is connected directly to the single spark plug. (No distributor rotor is used. See Figure 45) The ignition circuit operates on 6 volts D. C. and employs a standard automotive type ignition coil. The spark plug is a standard, unshielded, automotive plug.

4. Purging Circuit

The purging circuit appears at the center of Figure 44. Switch (9) controls the 6 volt centrifugal blower attached to the exhaust pipe of the test cylinder. The purging fan, with air intake covered by a snow filter, may be seen at the lower left in Figure 45.

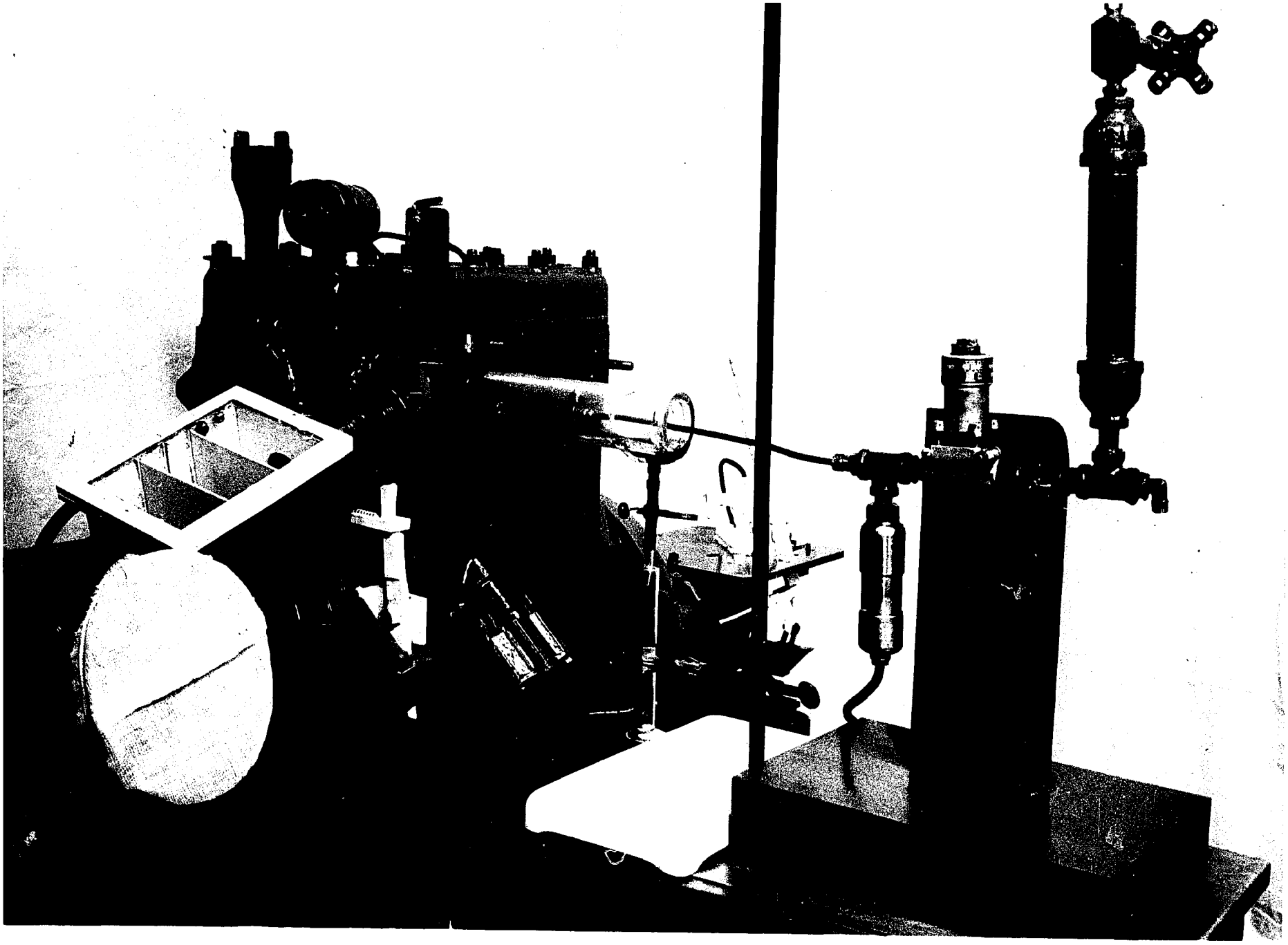
5. The Injection Circuit.

The injection circuit and its allied controls for stopping the test at the first combustion appear across the lower half of Figure 44. The action of the circuit may be explained by following the actual sequence of events in an actual test run.

A. The engine is rotated until the cam operated breaker points (14) are just opened. The cam is timed mechanically with respect to the engine cam shaft so that the contacts close at the point desired for start of injection.

B. Switches (5), (6) and (7) are closed.

C. The electronic timer is set for the time duration desired for injection.



—DETROIT ARSENAL—

NEG. NO. 27976 DATE 26 Oct 1951 DEVELOPMENT & ENGINEERING

Primer Effectiveness Test under Extreme Low Temperature Conditions. Intake manifold and purging system.

D. When cranking starts, breaker points (14) close, energizing coil 6R and closing contacts 6R. This allows current to flow through timed interval contacts 7R. This current flow energizes coil 5R which closes contacts 5R. At this action the magnetic primer valve is opened and contacts 5R constitute a holding device to keep coil 6R energized and thus hold contacts 6R closed even though cam driven switch (14) has opened. At the expiration of the preset time interval, the electronic timer allows contacts 7R to open momentarily, thus breaking the primer valve circuit and allowing the valve to close under the action of its spring and the pressure of the fuel. At the same time contacts 5R and 6R open and contact 7R closes. The entire circuit is then reset automatically and is ready to repeat the cycle at the next closing of the breaker points (14).

6. Combustion Gas Trap Circuit.

The combustion gas trap circuit which permitted the stopping of all motion immediately after combustion occured (to permit the taking of gas samples) is shown in the lower right quarter of Figure 44. The detecting device is described in paragraph IV, 1.

The circuit may be used in two ways, as described below:

A. Investigation of first combustion:

(1) Close switches (8), (10), (11), and (12). This action turns on the photo-electric cell and its light source, activating electronic relay 4R and closing contacts 4R, allowing current to flow through the exhaust valve disconnect solenoid and the brake actuating solenoid.

(2) By use of the two white levers shown in Figure 24, the mechanical linkages are set and held by the energized solenoids. As long as the solenoids are energized the engine is free to rotate and valve action is normal. The engine is now ready for test.

(3) When combustion occurs in the test engine cylinder, a current is generated by the thermocouple which drives the leaf (16) across the beam of light existing between (15) and (17). This action momentarily interrupts the current flow to electronic relay 4R which de-energizes the relay coil and allows contacts 4R to open momentarily. This action interrupts the flow of current to the two main solenoids and the mechanical linkage is tripped, stopping the engine and locking the exhaust valve closed.

B. Investigation of selected combustion:

(1) Block contacts 4R closed with wedge.

(2) Close switches (4), (8), (10) and (11). This will energize the exhaust valve disconnect solenoid and the brake actuating solenoid.

(3) Set mechanical linkages on exhaust valve and engine brake. Engine is now ready for test.

(4) As engine is cranked the movements of blade (16) are counted by the operator. The regular small jumps of the blade indicate compression strokes (large deflections will indicate combustion occurring).

(5) When blade movement has indicated the compression stroke immediately preceding the one it is desired to investigate, switch (8) is opened manually. For example, if it is desired to investigate the results of the tenth intake stroke, switch (8) would be opened after the ninth small deflection of the blade (16).

(6) After switch (8) is opened the circuit is kept energized by current flowing through the primary of the ignition coil. At the next firing of the spark plug (which indicates that the desired intake stroke has been made and afforded the opportunity for combustion) the interruption of the primary current

by the ignition breaker points (13) will cause a momentary break in the circuit to the two solenoids thus releasing the mechanical links, stopping the engine and blocking the exhaust valve.

VI

COMPUTATIONS

1. Engine Data:

Ignition Timing	5° before TDC
Point Gap at ≠ 70°F.	0.020"
Spark Plug Gap at ≠ 70°F.	0.030"
Tappet Clearance at ≠ 70°F.	
Intake Valve	0.014"
Exhaust Valve	0.014"
Compression, ≠ 70°F. & 180 RPM	100 psi.
Compression, *0 to -60°F.	
and 45 RPM, Average	50 psi.
Maximum cranking rate, 0 to -60°F.	74.6 RPM
Minimum cranking rate, 0 to -60°F.	26.1 RPM
Average cranking rate, 0 to -60°F.	
during intake stroke	62.2 RPM
Volumetric Efficiency, 0 to -60°F.	
60 to 100 RPM	82.2%
Displacement of cylinder	549.9 cc.
Lubricating Oil	MIL-O-10295, Sub-Arctic
Technical Manual covering	
basic test engine	TM 9-803

2. Piston Displacement:

Cylinder Bore = 3.125" = 7.94 cm.
Piston Stroke = 4.375" = 11.1 cm.

$$\text{Displacement} = \text{Pi}\,(7.94)^2/4 \times 11.1$$
$$= 549.8 \text{ cc.}$$

3. Volumetric Efficiency:

By actual gasometer measurement, the volume of air inducted at the cranking conditions existing at test temperatures was determined (See Figure 35 and Appendix II) to be 451.6 cubic centimeters.

*Test engine was completely reconditioned prior to tests. Compression pressures at test temperatures were measured while cranking, both before and after applying oil to top of piston. Both tests resulted in same compression pressures, namely, 50 psi.

Vol. Eff. = 451.6/549.8 X 100 = 82.2%

4. Gross Injection.

The total fuel injected during a test could be determined from the data of Tables XVII through XIX. However, another method was developed that permitted the amount of fuel injected on each intake stroke to be recorded. This method, utilizing a pressure-time curve plotted automatically by a Brush oscillograph, was found to be sufficiently accurate and gives promise of providing a technique that will be applicable to future cold starting research. This indirect method eliminates the almost unavoidable errors arising from constant seepage of gasoline at glands and other joints in the fuel system, eliminates the dangers inherent in the use of sight gages at low temperatures, and permits the entire fuel system to be sealed, thus preventing loss of the light ends of the fuel.

To use the indirect fuel measuring method, the primer nozzle must be calibrated for flow throughout the range of pressures and for the test temperatures, the gasoline must be effectively filtered to prevent dirt or ice crystals from partially clogging the nozzle and the pressure pick-up must be properly installed*. Figure 15 represents a typical nozzle calibration curve which, in this case, applies to all test temperatures. Figures 36 and 37 show the installation of the pressure pick-up. The pick-up, in turn, is connected to an

*Vapor pockets at the pick-up connection will cause it to act as an accumulator and will change the pressure pattern at the nozzle.

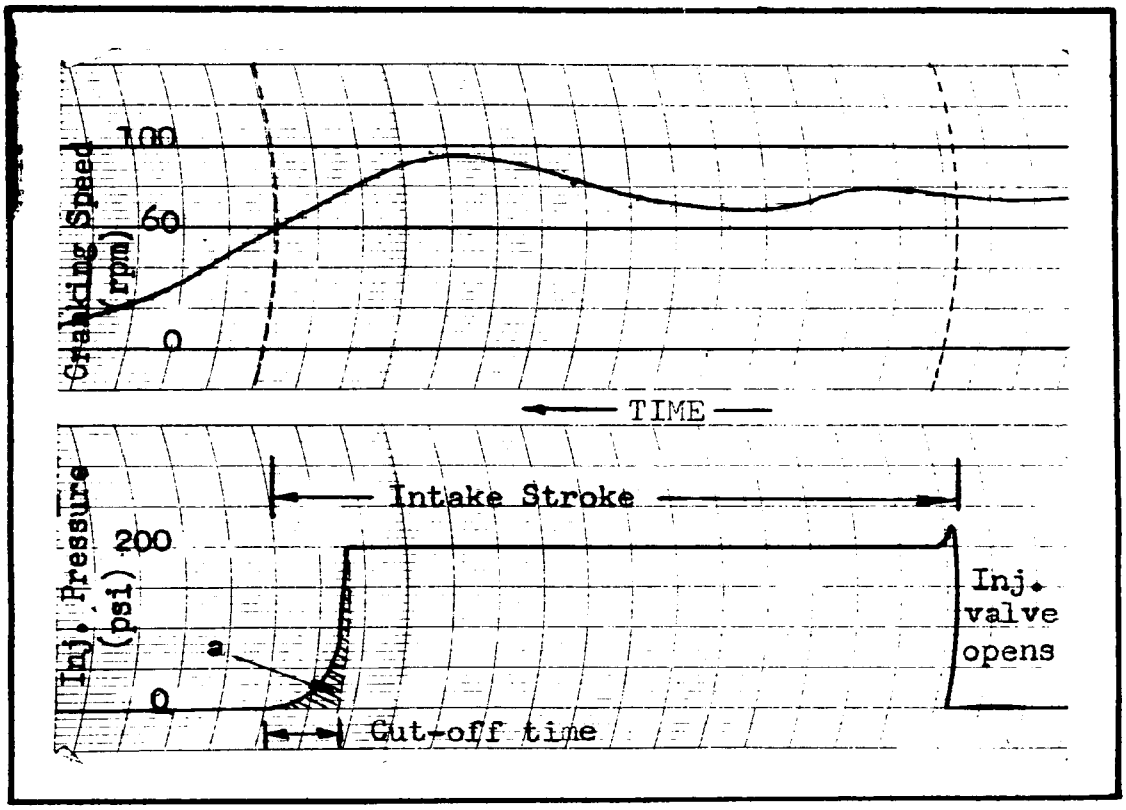
oscillograph as shown in Figure 43.* The installation as shown in Figure 43 will produce a pressure vs. time curve as illustrated by Figure 46 every time the engine makes an intake stroke.

To determine the total fuel injected, the oscillogram must be analyzed in two parts. Examination of the oscillogram reveals that the valve opens instantaneously but that the cutoff is not accomplished as rapidly, hence there is a period of injection at constant pressure followed by injection at a decreasing rate as the pressure on the nozzle decays due to the closing of the valve. The fuel represented by the area from the opening of the valve to the beginning of the cutoff is computed simply by measuring the oscillogram to determine the length of time that injection occurred at constant pressure and to determine the actual pressure during injection; with this information and the data of Figure 15, the flow during constant pressure injection is computed by multiplying the time of injection by the flow rate of the nozzle for the injection pressure.

To determine the quantity discharged by the nozzle during the cutoff period represented by the shaded area "a", a more complicated procedure is required.

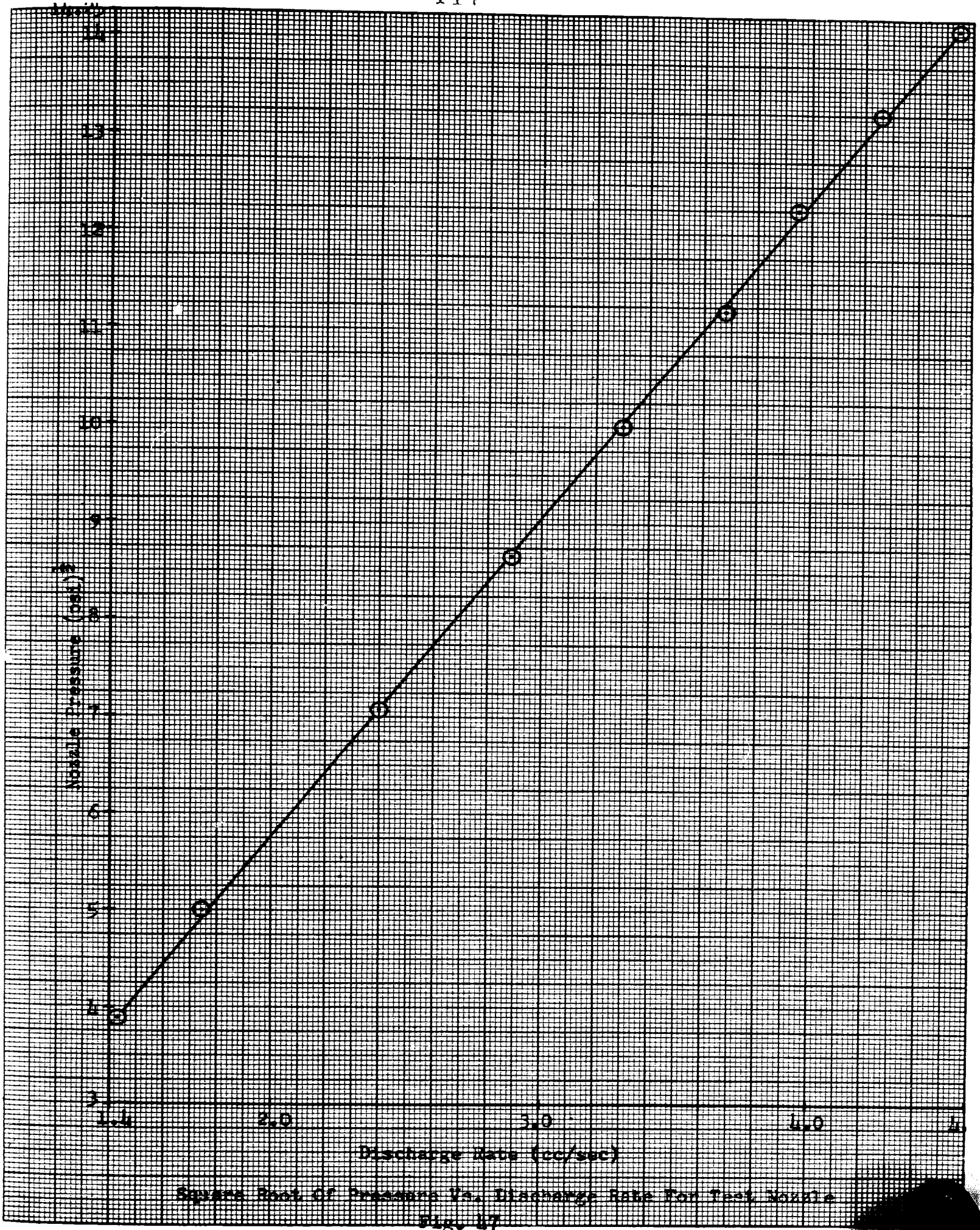
By replotting Figure 15 with the discharge rate vs. the square root of the pressure it is found that the discharge rate varies linearly with the square root of pressure. (See Figure 47) The area of the oscillogram, however, represents the product of pressure multiplied

*The pressure pick-up must be calibrated frequently. Once every four hours was found to suffice for this particular instrument.



Injection Curve, Fuel Measurement

Fig. 46



Square Root Of Pressure Vs. Discharge Rate For Test Nozzle

Fig. 47

by time. A new curve, therefore, is constructed to the same time base by determining the square roots of various pressures along the cutoff curve of the oscillogram. The area of this new curve (See Figure 48) represents the product of time multiplied by the square root of the pressure and the volume discharged may be computed by multiplying the area under the curve by some constant "k".

By plotting the area of constant pressure discharge (where the discharge may be computed from the nozzle calibration curve) the constant "k" for the reconstructed oscilligram may be determined and this same constant used to determine the flow during cutoff.

$$k = \frac{\text{Area of curve at constant pressure}}{\text{Volume discharged at constant pressure}}$$

Therefore:

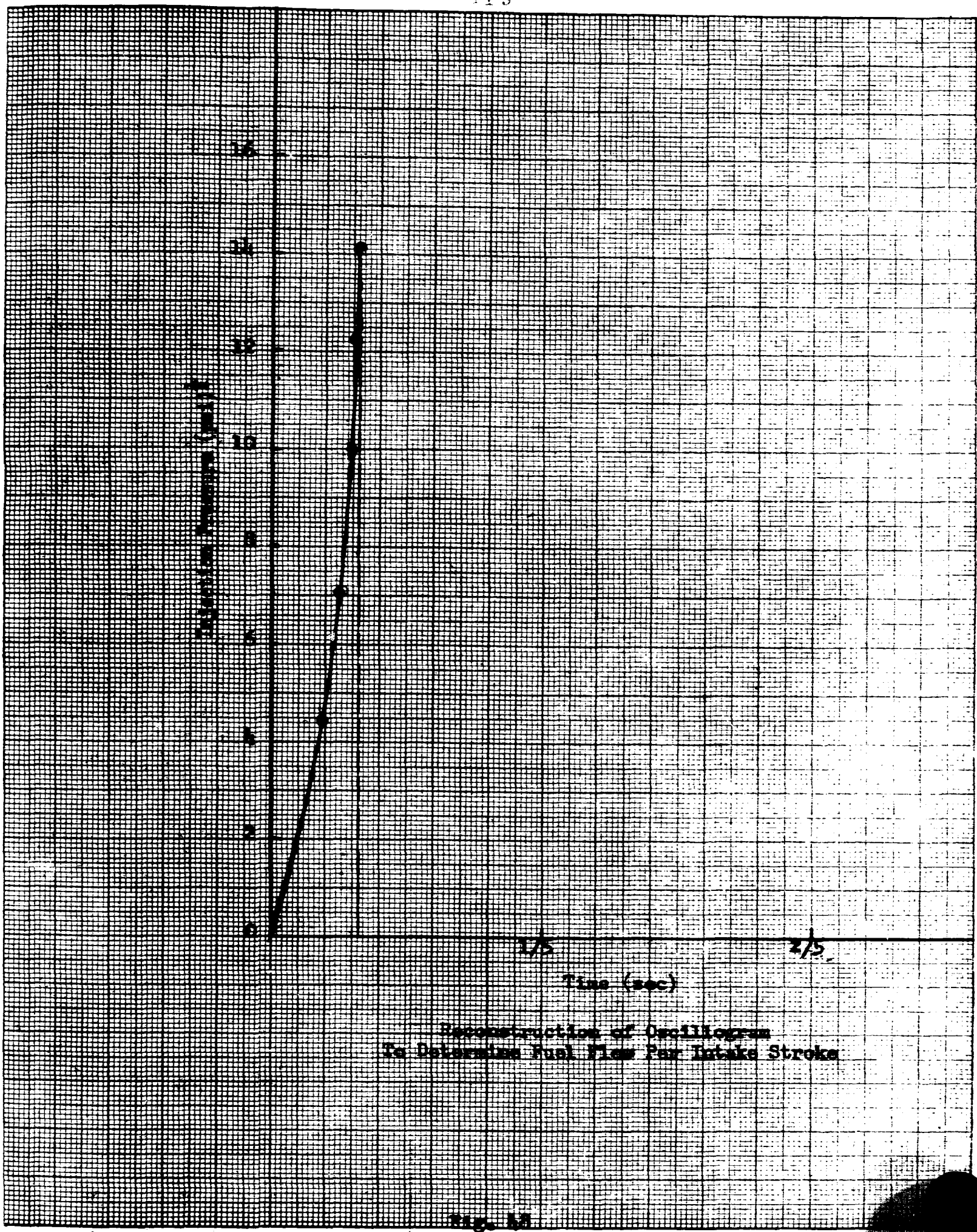
Volume discharged during cutoff = k X area under cutoff curve

From plotting a number of curves, it was determined that the value of k, for this particular set-up, was constant at 0.083 cc/sq. in. of area. Utilizing this value it was then necessary only to plot the cutoff portion of the curve.

To determine the accuracy of this method, the following check was made:

a. With priming system arranged as for a trial run, the primer nozzle was inserted into a covered graduate.

b. The system was activated and various quantities of fuel were allowed to pass through the primer system, with the measurements being made from the fuel gage, the graduate, and by use of the oscillograph.



Reconstruction of Oscillogram
To Determine Fuel Flow Per Intake Stroke

Fig. 43

FUEL MEASUREMENT METHODS
Comparison of Results

Test No.	Method		
	Graduate	Graphic	Fuel Gage
1	4.0 cc.	3.96 cc.	4.55 cc.
2	2.8	2.796	3.4
3	5.55	5.56	5.83
4	2.60	2.596	3.18
5	1.10	1.085	1.40

TABLE XXI

Table XXI indicates a very close agreement between the results of trapping fuel in a graduate and the results obtained by the graphic method (the graduate was graduated to 0.1 cc). In every case the fuel gage indicated a larger flow than the other two methods. Intensive investigation revealed that when the fuel gage was under pressure a continual seepage of gasoline occured at every gland and joint in the fuel system. At temperatures below 0^{o}F. it was found impossible to prevent this seepage. The seepage was never sufficient to cause noticeable dripping, but was characterized by a wet film constantly maintained in the area of every joint. As a result of this observation, an inspection was made of other equipment operating in the cold rooms and it was found that this seepage existed in every case where fuel under pressure came in contact with a pipe or tube fitting. This in-

vestigation leads to the conclusion that the present fittings used on primer and fuel lines are not entirely satisfactory for low temperature applications.

As a result of the tests on fuel measurement methods, the oscilligraph method was adopted for use in this work and the sight glass fuel gage was used only as a check.

5. Residue.

The residue recorded in the Summary of Data represents fuel leaving the manifold in the liquid state. During a test, excess fuel draining from the manifold walls would collect at the bottom of the manifold and then drain eventually into a pocket at the outer end of the manifold, from this pocket or trap it was withdrawn into a graduate after the completion of a test. Figure 45 illustrates this arrangement.

At the completion of a test, the fuel collected in the drain was removed and measured, the end of the manifold plugged and the reverse purging mechanism placed into operation with the air flowing through the trap into the graduate. This procedure deposited any other liquid fuel moved out by the purging air in the graduate. At the end of ten minutes, the graduate was read and the quantity of fuel trapped added to the original quantity to arrive at the total residue. The percent residue was computed by dividing the residue as measured above by the fuel injected. The graduate employed in these measure-

ments had a least reading of 0.1 cc.

6. Net Injection.

Net injection was determined by subtracting the residue from the quantity of fuel injected.

7. C.C. per Intake.

This represents the average volume of fuel inducted on each intake stroke. The value recorded was obtained by dividing the net injection by the number of intake strokes to start. Table XXII illustrates the accuracy of control of the injection cycle.

8. Air per Intake (Lbs.).

From the engine calibration curve the volume of air inducted per stroke was determined for the cranking speed used on the test. This volume was converted into pounds of air per intake stroke at the test conditions by use of the following basic equation:

$$PV = WRT$$

Where:
- P = pressure in lbs./sq. ft. abs.
- V = cubic feet
- W = pounds
- R = constant = 53.34 for air
- T = temperature ^{o}Abs. (460 + ^{o}F.)

9. Fuel per Intake (Lbs.).

From the cubic centimeters of fuel per intake stroke obtained as outlined in paragraph 7 above, the volume of fuel was converted into weight by the following equation:

$$\text{lb fuel/intake} = \frac{\text{cc/stroke}}{16.387(1728)} \times 62.4 \times \text{specific gravity}$$
$$= 0.002205(\text{cc/stroke})(\text{Sp. grav.})$$

ACCURACY OF FUEL INJECTION REGULATION

Trial No.	Temp. °F.	Nozzle Position	Fuel Injected per stroke, cc. 1st	2nd	3rd	4th	5th
1	0	2"	2.70	2.61	---	---	---
2	0	2"	2.66	2.69	---	---	---
3	0	4"	2.68	2.64	---	---	---
4	0	4"	2.65	2.69	---	---	---
5	0	6"	2.73	2.69	---	---	---
6	0	6"	2.71	2.63	---	---	---
7	0	8"	2.69	2.69	---	---	---
8	0	8"	2.60	2.67	---	---	---
9	0	8"	2.64	2.65	---	---	---
10	0	8"	2.69	2.60	---	---	---
11	-40	2"	3.29	3.27	3.24	3.23	3.25
12	-40	2"	3.40	3.19	3.20	3.22	---
13	-40	2"	3.34	3.26	3.23	---	---

Above data, taken from oscillograph records, is presented as typical of the data acquired and to demonstrate that once the injection rate was set for a trial run, it held constant within 0.1 cubic centimeter for each successive stroke.

TABLE XXII

The specific gravity of the fuel was determined by hydrometer to be as follows:

Temp. °F.	Sp. Grav.
0	0.762
-20	0.770
-40	0.777

10. Air/Fuel (Delivery).

The air-fuel ratio of delivery was computed by dividing the air per intake (lbs.) by the fuel per intake (lbs.).

11. Air/Fuel (Comb.).

The air-fuel ratio at combustion was determined from the results of Orsat analysis of the products of combustion remaining in the cylinder after ignition occurred. From the General Motors Research Laboratories Division, GMC Report No. OC-73, "The Analysis of Engine Exhaust Gas", the following equation for determining air-fuel ratios was obtained:

$$A/F = \frac{77(100 - 3(CO_2 + O_2) - 2\,CO)}{(11.9 + R + 15.9r)(CO_2 + CO)} - \frac{38.5(R - 2r)}{11.9 + R + 15.9r}$$

Where: CO_2 = % carbon dioxide by Orsat

O_2 = % oxygen by Orsat

CO = % carbon monoxide by Orsat

R = constant for fuel as determined from carbon-hydrogen ratio = 1.94

r = oxygen in fuel = 0 for this fuel.

The chemical composition of the fuel may be represented

by the general formula $(CH_RO_r)_x$. When r = 0, the fuel is a hydrocarbon or a mixture of various hydrocarbons. When r is not zero the fuel may be an oxygenated derivative of a hydrocarbon (e.g., alcohol or ether) or a mixture of hydrocarbon and oxygen compounds. Through the courtesy of the Ethyl Corporation, the carbon-hydrogen ratio by weight of the test fuel was determined to be 6.17 and R is computed as follows:

$$C/HR = 6.17$$

$$R = C/6.17 \times H = 12/6.17 \times 1 = 1.94$$

Where: C = atomic weight of carbon = 12
H = atomic weight of hydrogen = 1
R = a constant

Substituting, the equation reduces to the following:

$$A/F = \frac{5.56(100 - 3(CO_2 \neq CO) - 2\,CO)}{CO_2 \neq CO} - 5.40$$

12. % Fuel Evaporated.

% fuel evaported is the percentage of the fuel actually inducted which apparently was burned, as indicated by Orsat analysis.

It is computed as follows:

Air/Fuel Ratio (delivery) = 1.07
Air/Fuel Ratio (comb.) = 24
Fuel (delivery) = Air (delivery)/1.07
Fuel (comb.) = Air (comb.)/24
% Fuel evap. = Fuel(comb.)/Fuel(delivery)
= 1.07/24 = 4.5

NOTE: Air of combustion is assumed equal to the air delivered.

VII

TEST FUEL

The fuel used for all tests was manufactured to meet the lowest limits of the military specification for Gasoline, Automotive, Combat, Type C, Specification MIL-G-3056, dated 30 September 1949. Type C gasoline is the type commonly known as winter grade gasoline and is normally sold in Michigan and other northern states from November through March.

The test fuel, when tested in accordance with ASTM procedures, had the following characteristics:

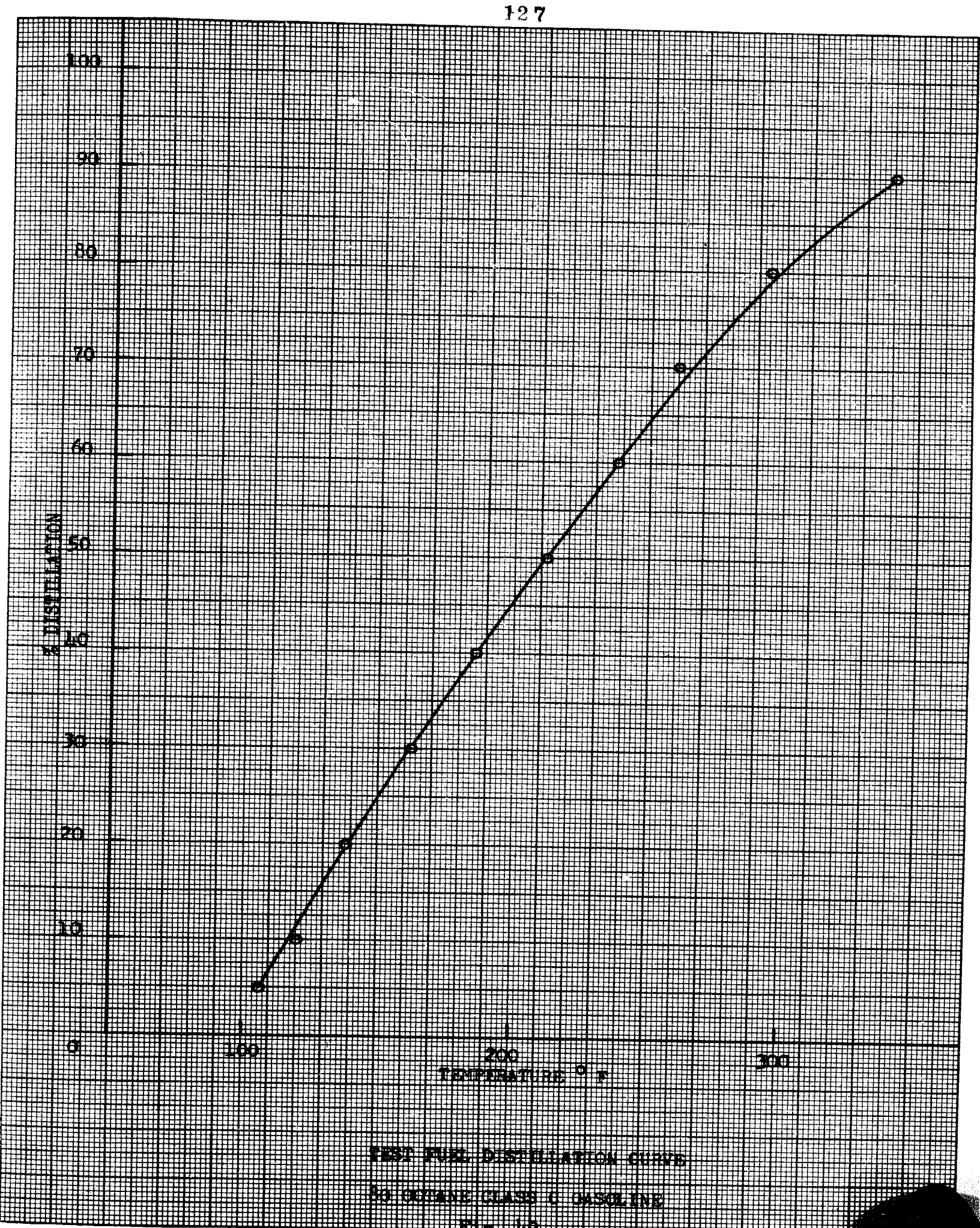
	Test Fuel	Spec.
Reid Vapor Pressure	11.8	12 (min.)
Initial Boiling Point	91° F.	--
Residue	0.35%	2% (max.)
10% Evaporated	120°F.	122°F.
50% Evaporated	212°F.	203°F.
90% Evaporated	340°F.	302°F.
End Point	402°F.	--

Figure 49 presents the distillation curve for the test fuel. The carbon-hydrogen ratio (by weight) of the fuel was determined by the Ethyl Corp. Laboratory to be 6.17.

For use in weight conversions, the specific gravity of the fuel was determined at test temperatures and found to be as follows:

Temp. °F.	Sp. Grav.	A.P.I.
0	0.762	54.4
-20	0.770	52.2
-40	0.777	50.5
-60	0.787	48.3

The fuel was received from the refinery in sealed 55 gallon drums



TEST FUEL DISTILLATION CURVE

90 OCTANE CLASS C GASOLINE

Fig. 49

and was immediately placed in refrigerated storage at 0°F. Fuel removed from the storage drum was immediately placed in the test apparatus where it was stored under pressure at the test temperature until consumed. In no case was fuel handled at temperatures above 0°F. No detectible change in vapor pressure or ASTM distillation results were found during a storage period of sixteen months at -65°F.

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