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DETAILED COMBUSTION STUDIES FOR STRATIFIED CHARGE ROTARY ENGINES

Final Report, April 1, 1976—September 30, 1978

By
R. L. Steinberger
F. V. Bracco

September 1978

Work Performed Under Contract No. EY-76-S-02-2943

Princeton University
Princeton, New Jersey

MASTER

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COO-2943-1
Distribution Category UC-96

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R. L. Steinberger and F. V. Bracco

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Prepared For

THE U. S. ENERGY RESEARCH AND DEVEOPMENT
ADMINISTRATION UNDER CONTRACT NO.
EY-76-S-02-2943

Princeton University
Princeton, New Jersey 08540

ABSTRACT

The objective of the research is to aid the development of stratified charge rotary engines by experimentally implementing and testing concepts for optimal charge stratification. To that end a rotary engine test facility has been built. This facility includes an RC1-60 rotary engine built by Curtiss Wright which was coupled to a GE 60 hp dynamometer the external wiring of which had to be mostly reconstructed. Separate rotor lubrication and cooling systems and engine housing cooling systems were designed and built. Intake and exhaust systems were planned and constructed. And a fuel injection system was chosen, purchased, and installed. Once these systems were all installed and operating, engine test data was taken to compare with data taken by Curtiss Wright under similar conditions and found to be in reasonable agreement. The data indicates that the performance of the Curtiss Wright direct injection stratified charge rotary engine is comparable to that of its reciprocating counterpart.

OBJECTIVE

The objective of this project has been to aid the development of stratified charge rotary engines by experimentally implementing and testing concepts for optimal charge stratification which have evolved in years of theoretical research. To implement these concepts, precise control of the fuel injection process is necessary. Efforts have been concentrated on the nozzles and the fuel injection systems. A comprehensive report of this research follows.

COMPREHENSIVE EVALUATION OF PROGRESS

The Engine and Dynamometer

The engine used in this research was supplied by Curtiss Wright and is an RC1-60 single rotor model and has rotor housing SK10565. The rotor utilizes a "deep" pocket and Curtiss Wright's test results for this engine (Engine 701-85) are reported in Reference 1. To achieve charge stratification this engine uses a direct fuel injection system closely coupled to the spark plug. A modified (ground electrode removed) spark plug fires from the plug center electrode to the injector tip itself through a gap of 0.018 to 0.026 inches. All shower-head nozzle tip designs used in the engine employ a "light-off spray" hole which directs one fuel jet near the spark plug to achieve ignition. A summary of the engine parameters is given in Table 1.

Table 1

The RC1-60 Engine Parameters

Compression Ratio: 8.5:1

Displacement: 60.959 in^3

Minimum Volume: 4.730 in^3

Eccentricity: 0.750

Generating Radius: 5.175 in

The dynamometer for this work was also supplied by Curtiss Wright. It is a General Electric Type TLC 2352 with automatic speed control to within 1/2% and capable of absorbing 60 hp at speeds up to 6000 rpm.

This project was begun in June, 1976 and at that time only the dynamometer was available. The engine was received in July, 1976 and being a research engine lacked all auxiliary systems. The following sections describe work done in six distinct areas: the dynamometer and its controls, the exhaust and intake systems, the rotor cooling system, the engine housing cooling system, the ignition system and the fuel system.

Dynamometer and Its Controls

The dynamometer system consists of the dynamometer, the controls, the amplidyne units, and the motor generator set. At the beginning of the project, the interior wiring of the dynamometer controls was relatively complete, while exterior wiring linking the motor generator set, the amplidynes, and the control system was largely missing. Therefore, these interconnections were supplied in a systematic way with all physical connections being made in a single junction box each wire being checked for continuity and individually labeled.

Following the completion of this rewiring a trouble shooting period of several weeks began. During this time numerous problems including missing wires, cracked and grossly maladjusted resistors, and broken fuses and tubes, were discovered and repaired.

At the end of this period the dynamometer was operated successfully within its specifications and continues to do so at present.

Before the engine could be operated a coupling between the dynamometer and engine had to be designed and fabricated. The design had to provide positive and safe coupling to 5000 rpm while still providing some flexibility to allow for small misalignments. The design also included a torsional analysis so that possible resonances in the operating speed range could be avoided. The coupling has now been in use for a year with no problems having arisen.

Intake and Exhaust Systems

Air is inducted by the engine through a 55 gallon drum which provides a settling chamber to steady the flow and through an Autotronic Controls Corp. Series 100 air flow transducer to measure the air flowrate. The airflow transducer and its associated pulse shaping circuitry, shown in Figure 1, provide an output waveform whose frequency is proportional to the volume flow of air according to the calibration data supplied by Autotronic. This signal is then changed to a voltage by a Potter Aeronautical Corporation Model 41A frequency to voltage converter.

Calibration of the Potter frequency converter was accomplished by supplying it with a wave train signal from a Tektronix FG501 Function Generator of appropriate magnitude and range of frequencies. Thus air flow rate could be measured as a voltage from the Frequency Converter. The calibration curve is shown in Figure 2.

The intake system was also equipped with an oil dripping mechanism near the intake port which provides lube oil for the rotor housing interior wall at the rate of 1% of the fuel mass flow rate as specified by Curtiss Wright. Intake air temperature is monitored with a thermocouple in the surge tank.

The exhaust port of the engine was initially connected to a 30 gallon (6930 in^3) surge tank and then to the building exhaust lines. Eventually the engine noise was found to be intolerable and this tank was replaced with a large truck muffler. A gas sampling tube was mounted at the exhaust port so that exhaust gases could be extracted for pollutant analysis.

Rotor Cooling System

The rotor cooling system had to be designed and built to provide a continuous flow of lube oil from a reservoir to the engine, and a return path to to the reservoir. It had to supply the engine with 25-30 lbs of lube oil per minute at a pressure of 55-60 psi. The resulting system is shown in schematic form in Figure 3.

Cooling of the oil is accomplished by varying the flow of cooling water to the heat exchanger. Thus temperature control of the oil is possible without variation of oil pressure or flow rate. Input and output oil temperatures are monitored with thermocouples.

Oil flow rate is measured with a Pottermeter S/N PU-5 Flowmeter used in conjunction withthe Potter Frequency Converter previously described. The calibration for this meter was carried out in the lab by counting the turns of the vanes in the Pottermeter as a known volume of oil was passed through the meter. The Frequency Converter was calibrated for the appropriate frequency range as also previously described. Oil flowrate can now be read as a voltage output according to the curve shown in Figure 4.

Engine Housing Cooling System

The housing cooling system also had to be designed and built to provide continuous coolant (44% Prestone and water by volume) flow through the housing at flow rates to 50 gallons per minute.

The system is shown in schematic form in Figure 5. Temperature is controlled again by controlling the flow of cooling water to the heat exchanger. Input and output temperatures are monitored with thermocouples. Coolant flow rate is measured with a Pottermeter S/N PU-1-3 Flowmeter and the Frequency Converter, again having calibrated the meter with a known volume of coolant. The calibration graph for the converter is shown in Figure 6.

Fuel System

The fuel injection system consists of a fuel injection pump, the fuel injector and nozzle, a fuel measurement reservoir and the engine-pump coupling including a timing device.

The injection pump originally used by Curtiss Wright could not be duplicated. An American Bosch APE1B-70P-5078A injection pump with similar characteristics was purchased and used. Injection pump rack setting is controlled by a micrometer.

The fuel injector was supplied by Curtiss Wright and is an American Bosch AKB-35S-362A nozzle holder used in conjunction with a Bendix #10-27877-6 valve and Bendix L-31771 nozzle blanks. These blanks could then be drilled with a variety of showerhead hole configurations. The nozzle tip used with best results by Curtiss Wright was designated SK10720N-12 and the spray configuration was that shown in Figure 7. This was also the tip employed in our preliminary tests to repeat some of Curtiss Wright's data.

Improved performance over this engine test data was predicted by Bracco and Reitz in Reference 2 through the use of a particular charge stratification scheme. This scheme requires the use of different showerhead nozzle orifice designs corresponding to particular speed-load ranges. These orifice arrangments are illustrated in Figures 8, 9, 10, and 11. Presently the drilling of these holes in nozzle blanks has been ordered from Bendix for the first three designs. Upon their arrival the tips will be implemented and engine test data will be taken to determine if the predicted improvements are borne out.

Fuel, which in all tests was JP-5, is delivered to the injection pump from a reservoir which is pressurized with nitrogen to 20 psi. The sightglass of the reservoir is calibrated in volume units. During each engine test the initial fuel level was noted once the engine had reached operating conditions. The consumed volume was then measured during a period of elapsed time measured with a stop watch. Thus an average fuel flow rate was measured and with knowledge of engine speed the delivery characteristics of the pump could be obtained. Typical results are shown in Figure 12.

The pump was coupled to the engine in such a way that gross timing adjustments could be made at the coupling. An American Bosch TMB-12A2 Timing Device then allows 12 degrees of timing control while the engine is operating. Initially, timing of injection was set by observing the first instant of injection into a small chamber external to the engine by triggering a stroboscopic light at that instant. A delay unit with the strobe allowed observation of various stages of the spray process so that duration could also be measured. Later, a Bentley Nevada proximity pickup was used to monitor the valve motion within the injector. By observing this signal and a pulse per degree signal from a shaft encoder on an oscilloscope, the injection timing could be monitored while the engine was operating.

Ignition

An ignition system was purchased and installed based on suggestions from Curtiss Wright. The unit is an Autotronic Controls MSD 404B which is a multiple spark discharge type. The signal from the breaker points initiates the first spark and the unit's trigger and duration control circuits continue the firing for 20 degrees of rotation. The number of discharges actually fired is a function of engine speed and varies from about 30 at 500 rpm to 3 at 5000 rpm.

With the installation and operation of these subsystems the engine could be run and its performance checked. The goal of the test runs was to repeat as nearly as possible previously obtained Curtiss Wright data so that confidence could be obtained in the correct operation of all measurement devices and equipment in this newly constructed engine facility.

Engine Test Parameters and Method of Measurement

In all engine tests the following parameters were measured:

Parameter	Method
Engine speed	Tach generator on dynamometer and Standard Electric Time Tachometer
Engine Torque and Brake Horsepower	Dynamometer attached Toledo scale, 1/10 lb. graduations Torque arm = 1.313 ft. $HP = \frac{\text{Indicated Force x RPM}}{4000}$
Fuel Flow	Volume measurement during timed interval of test
Temperatures Intake air Coolant oil Coolant fluid	Chromel Alumel thermocouples
Flow rates	
Coolant oil	Pottermeter PU-5
Coolant fluid	Pottermeter PU-1-3
Intake air	Autotronic Flow Transducer
Injection Timing	Stroboscopic visualization and Valve motion monitoring
Spark Timing	Inductive pickup display on oscilloscope

Test Results and Discussion

The individual test data is shown in Table 2. Test result data obtained by Curtiss Wright for Brake Horsepower vs. Specific Fuel Consumption is shown in Figures 13 and 14 for 1000 and 2000 rpm. Displayed on the same Figures is the test data using the same nozzle tip obtained in the present work.

The data obtained to date shows considerable scatter. However the general trend of the data is comparable to that obtained by Curtiss Wright. The data obtained was considered close enough to the Curtiss Wright data to make the reasonable conclusion that the engine systems were functioning properly. The scatter can be attributed to the considerably deteriorated condition of the nozzle tip (due to spark errosion) which also contributed to rough running. Further verification would await obtaining another N-12 nozzle tip.

TABLE 2

RC1-60 ENGINE TEST DATA

Fuel: JP-5

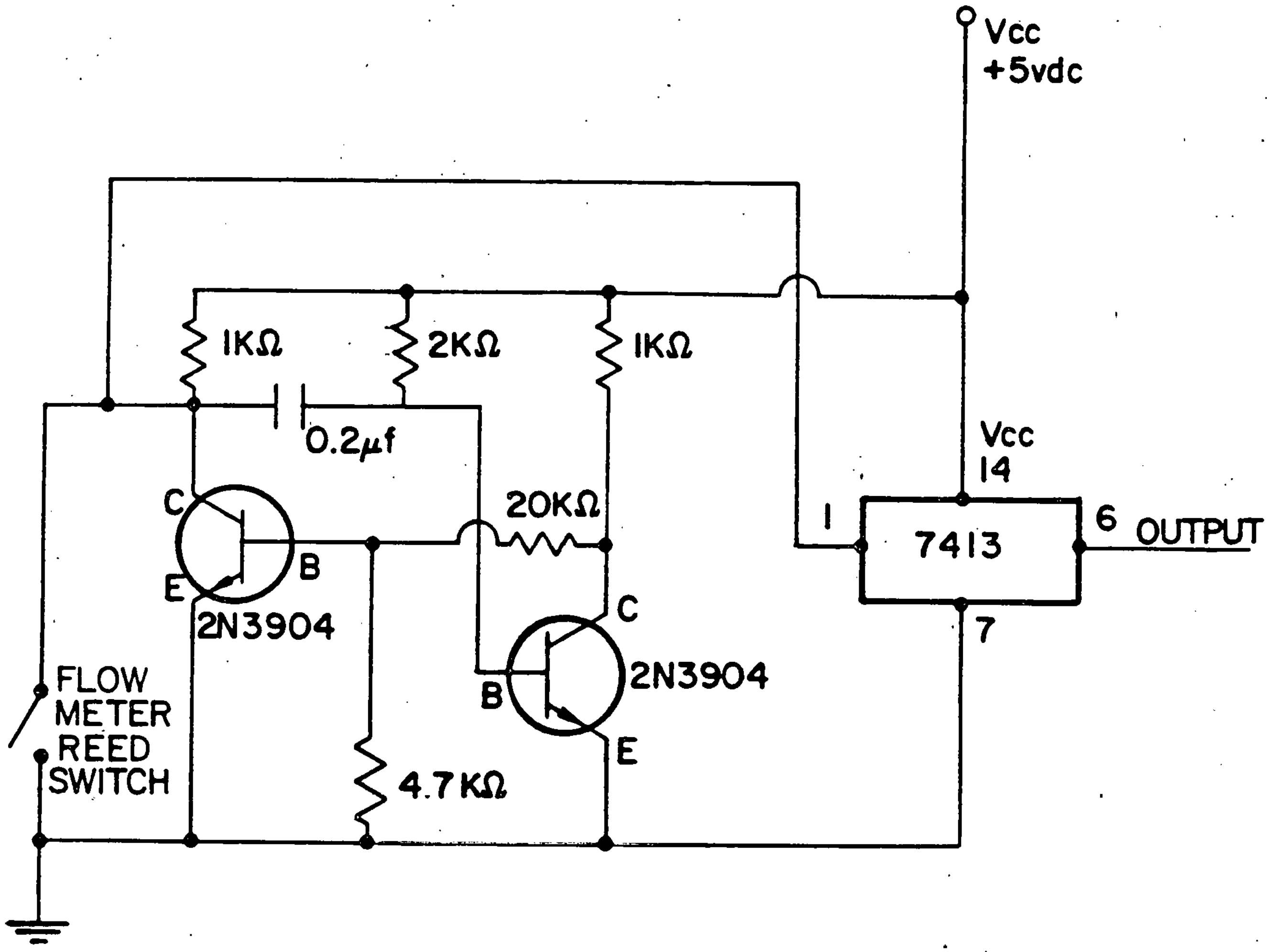
Tip: N-12

Date	Run No.	Speed (rpm)	Dyno Indic. Force (lb)	HP	Volume Injected (ml)	Flow Rate (lb/hr)	Fuel Micrometer	BSFC lb/(bhp-hr)	Injection Start (°BTDC)	Temperatures: Coolant In (°F)	Temperatures: Coolant Out (°F)	Temperatures: Oil Out (°F)	Temperatures: Oil In (°F)	Temperatures: Air (°F)	Flowrates: Oil (GPM)	Flowrates: Coolant (GPM)	Flowrates: Air (CFM)	Ignition Timing (°BTDC)
9/7/77	12	2000	23.0	11.5	100	9.02	--	0.78	32									24
	13	2000	12.0	6.0	100	4.82	--	0.80	32									24
	14	2000	31.0	15.5	100	8.64	--	0.56	32									24
	15	2000	48.0	24.0	100	16.8	--	0.70	32									24
	16	2000	40.0	20.0	100	9.44	--	0.47	32									24
	17	2000	42.0	21.0	100	14.9	--	0.71	32									24
6/29/78	1	1000	37.0	9.25	220	7.16	0.400	0.77	34							~16,7		24
	2	1000	41.5	10.5	291	9.94	0.500	0.95	34							~15,9		24
	3	1000	43.0	10.8	283	12.3	0.600	1.14	34							~15,9		24
7/14/78	1	1000	29.0	7.38	201	4.37	0.345	0.59	34	118	121	126	9[illegible]	74	0,5	4,5	4,40	24
	2	1000	30.0	7.5	206	5.54	0.360	0.74	34	118	123	126	94	80	0,5	4,5	4,40	24
	3	1000	36.0	9.0	197	6.57	0.380	0.73	34	100	106	112	86	80	0,5	4,45	4,70	24
	4	1000	40.0	10.0	237	7.39	0.400	0.74	34	120	123	129	94	81	0,5	4,45	4,45	24
	5	2000	35.0	17.5	261	11.0	0.325	0.63	34	113	120	137	94	81	0,7	4,5	7,45	23
	6	2000	38.5	19.25	382	12.0	0.350	0.62	34	140	149	157	109	87	0,7	4,5	7,8	23

REFERENCES

1. Lamping, R., "Exploratory Program to Evaluate a Deep Pocket Rotor in Two Close-Coupled Spark Plug/Fuel Injector Rotor Housings in the Stratified Charge Rotating Combustion Engine Using the RC1-60 Test Rig", Curtiss Wright Corporation Report #CW-WR-73-010, January, 1973.

2. Reitz, R. D., and Bracco, F. V., "Studies Toward Optimal Charge Stratification in a Rotary Engine", Stratified Charge Engines, Second Special Issue, Combustion Science and Technology, v. 12, p. 63-74, 1976.



AUTOTRONIC FLOW TRANSDUCER
SIGNAL CONDITIONING CIRCUIT

FIGURE 1

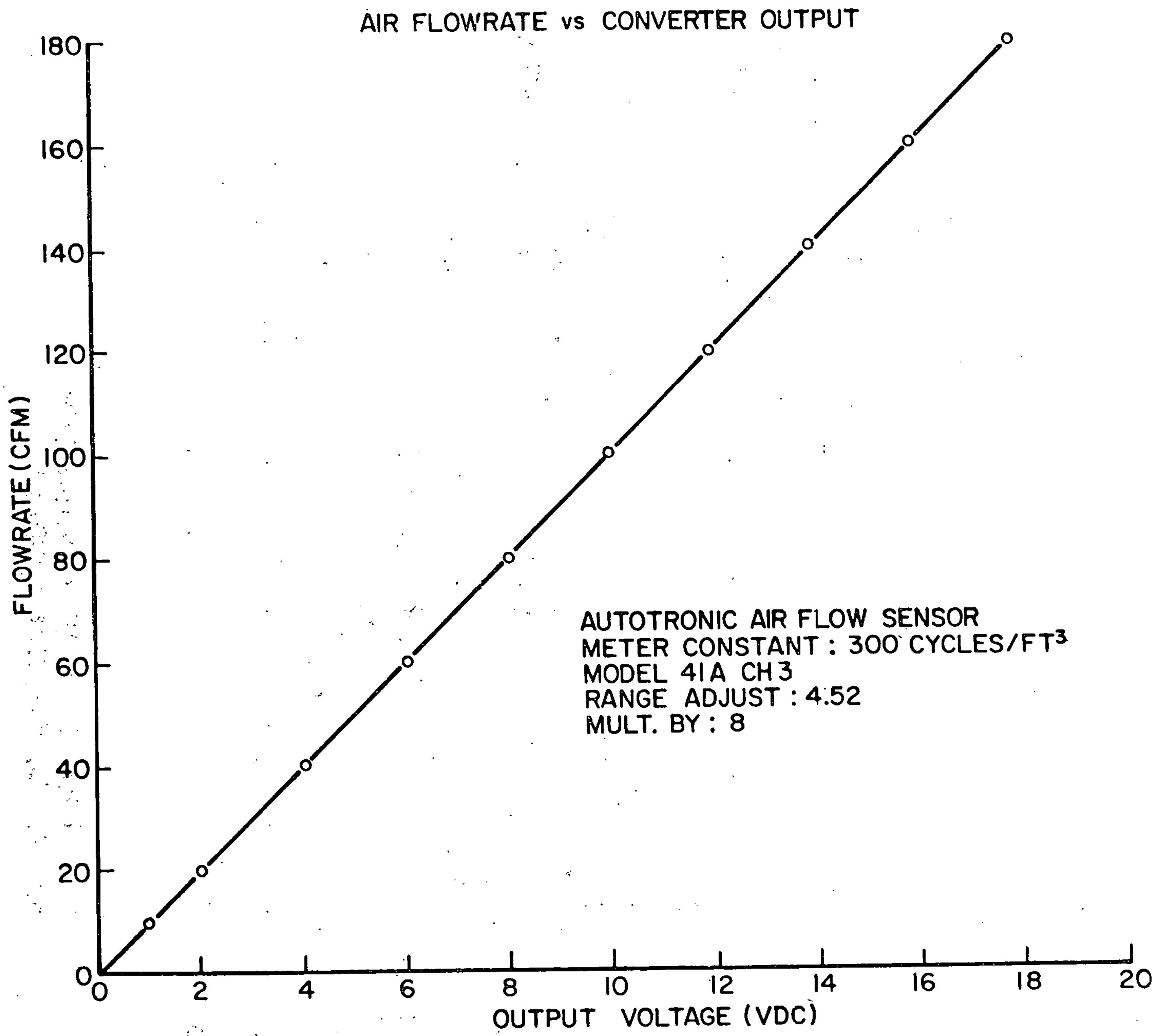
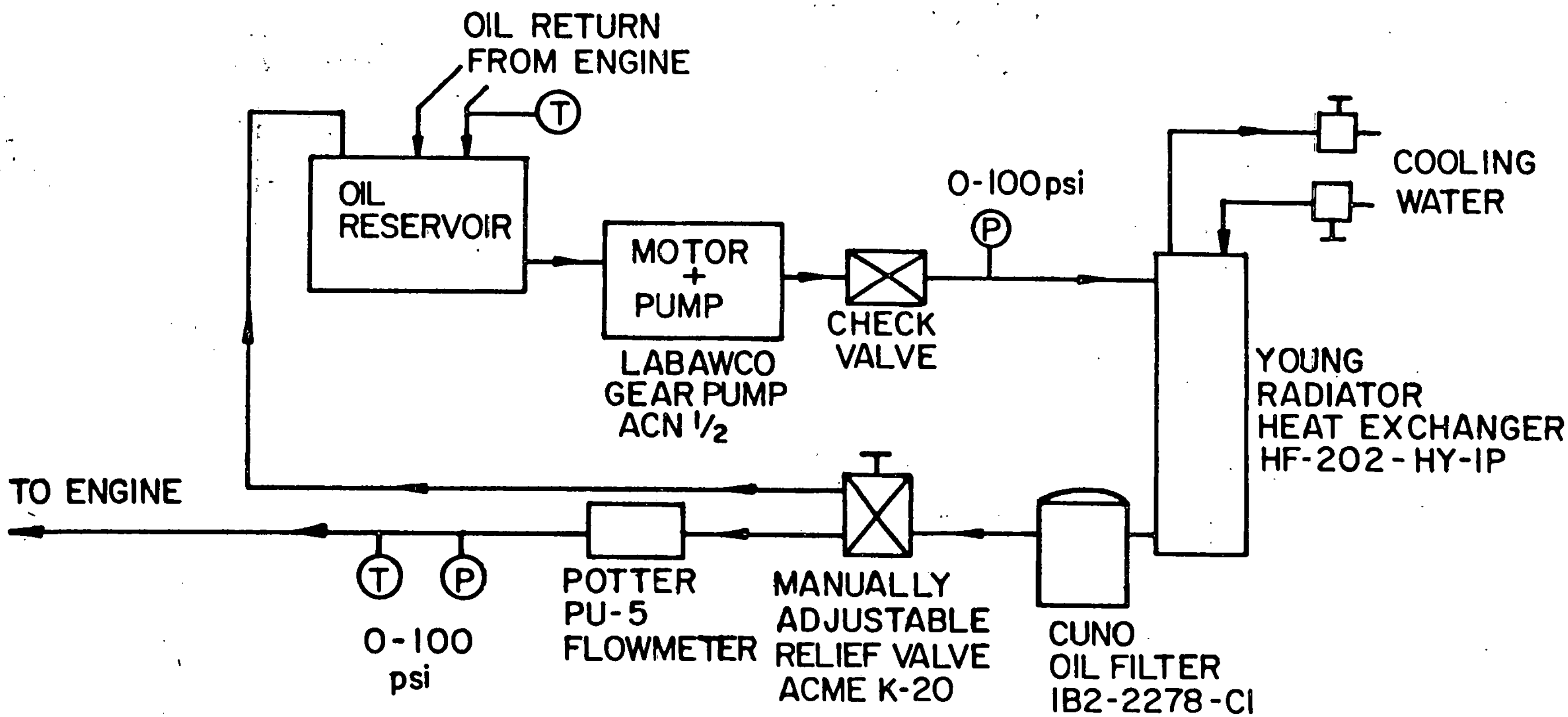

AIR FLOWRATE vs CONVERTER OUTPUT
FLOWRATE (CFM)
0
20
40
60
80
100
120
140
160
180
0
2
4
6
8
10
12
14
16
18
20
OUTPUT VOLTAGE (VDC)
AUTOTRONIC AIR FLOW SENSOR
METER CONSTANT : 300 CYCLES/FT³
MODEL 41A CH3
RANGE ADJUST : 4.52
MULT. BY : 8

FIGURE 2



ROTOR COOLING OIL SUPPLY SYSTEM

FIGURE 3

ROTOR COOLING FLOW RATE vs CONVERTER OUTPUT

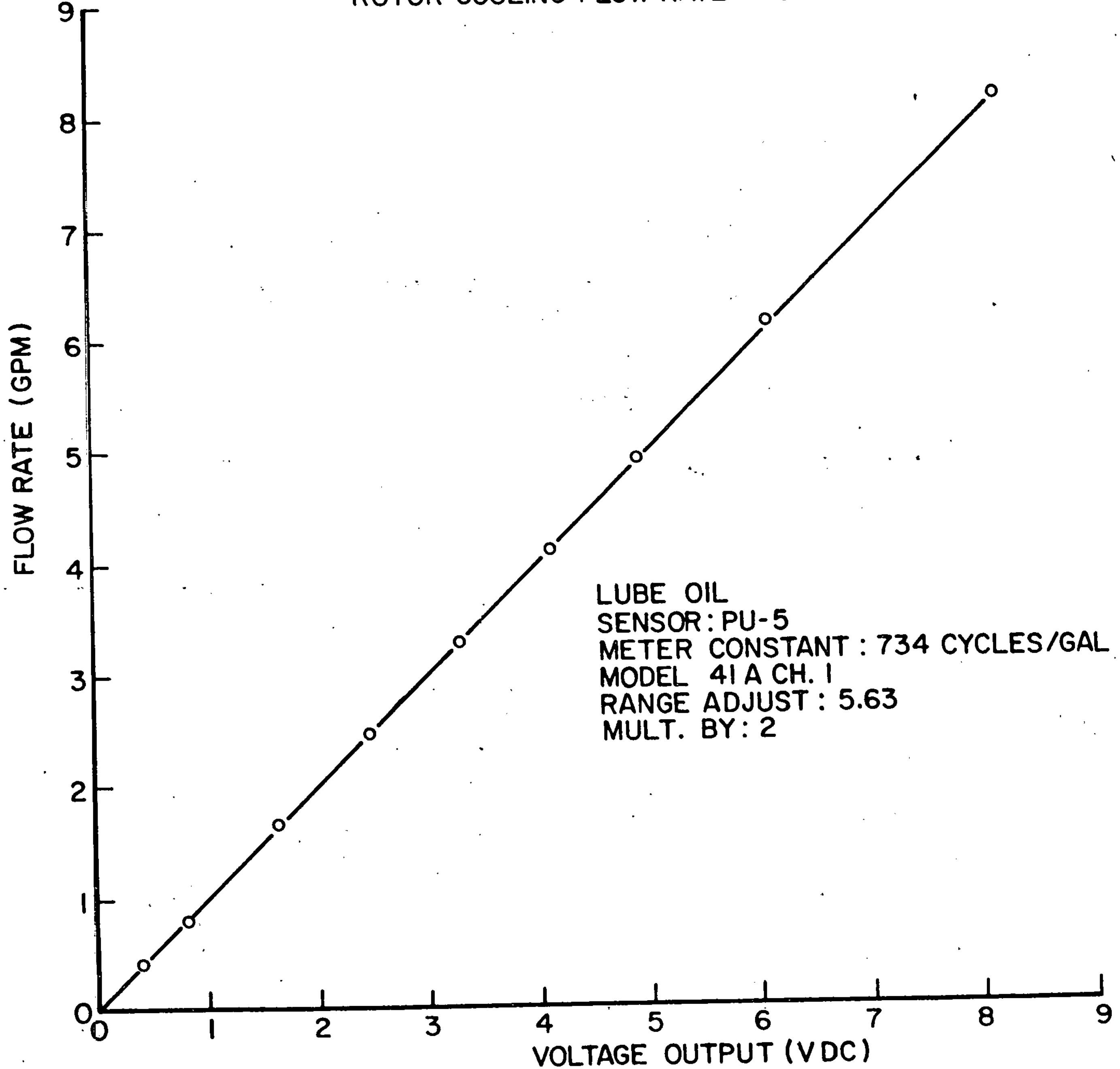
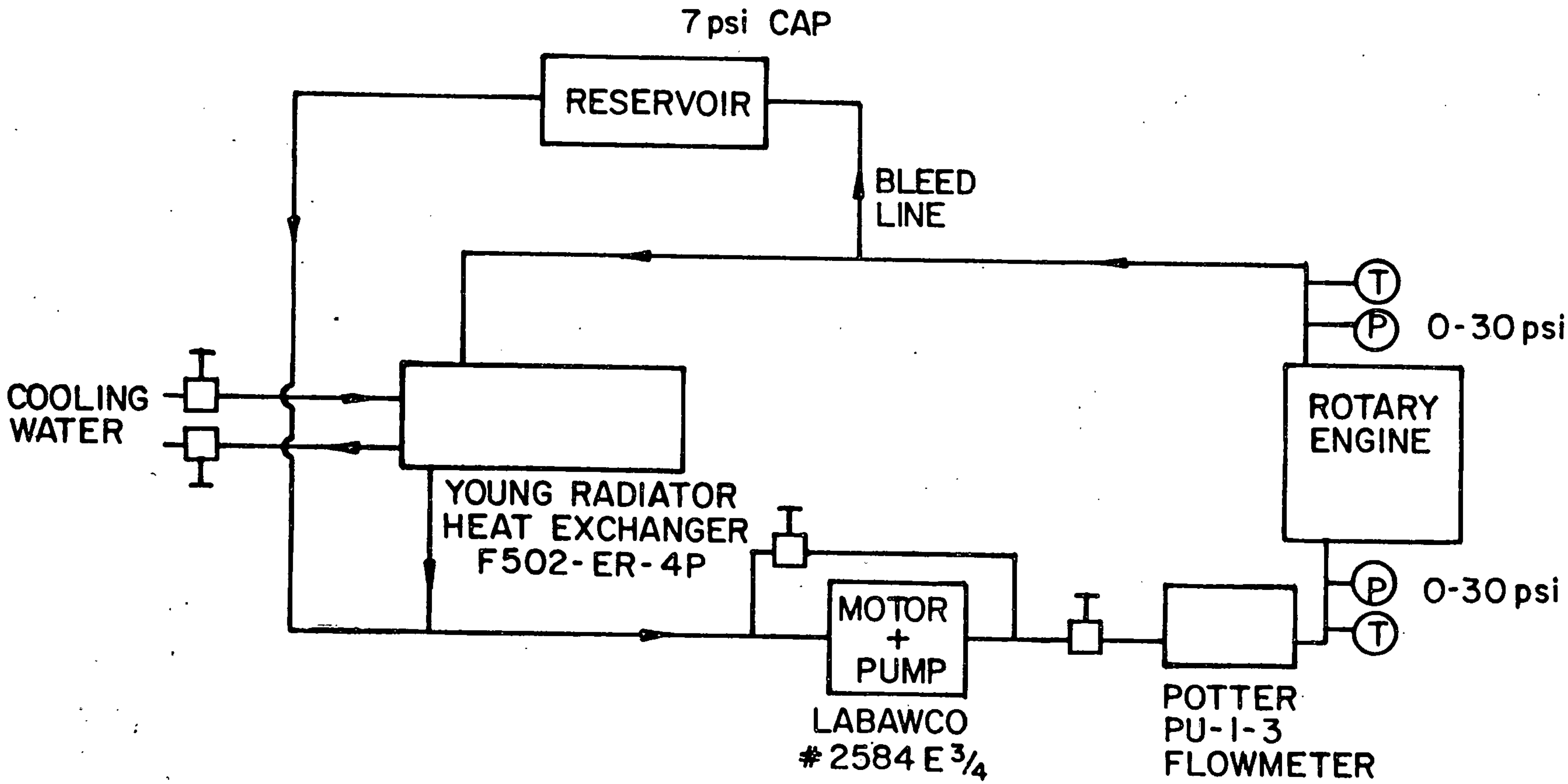


FIGURE 4



ENGINE COOLANT SUPPLY SYSTEM

FIGURE 5

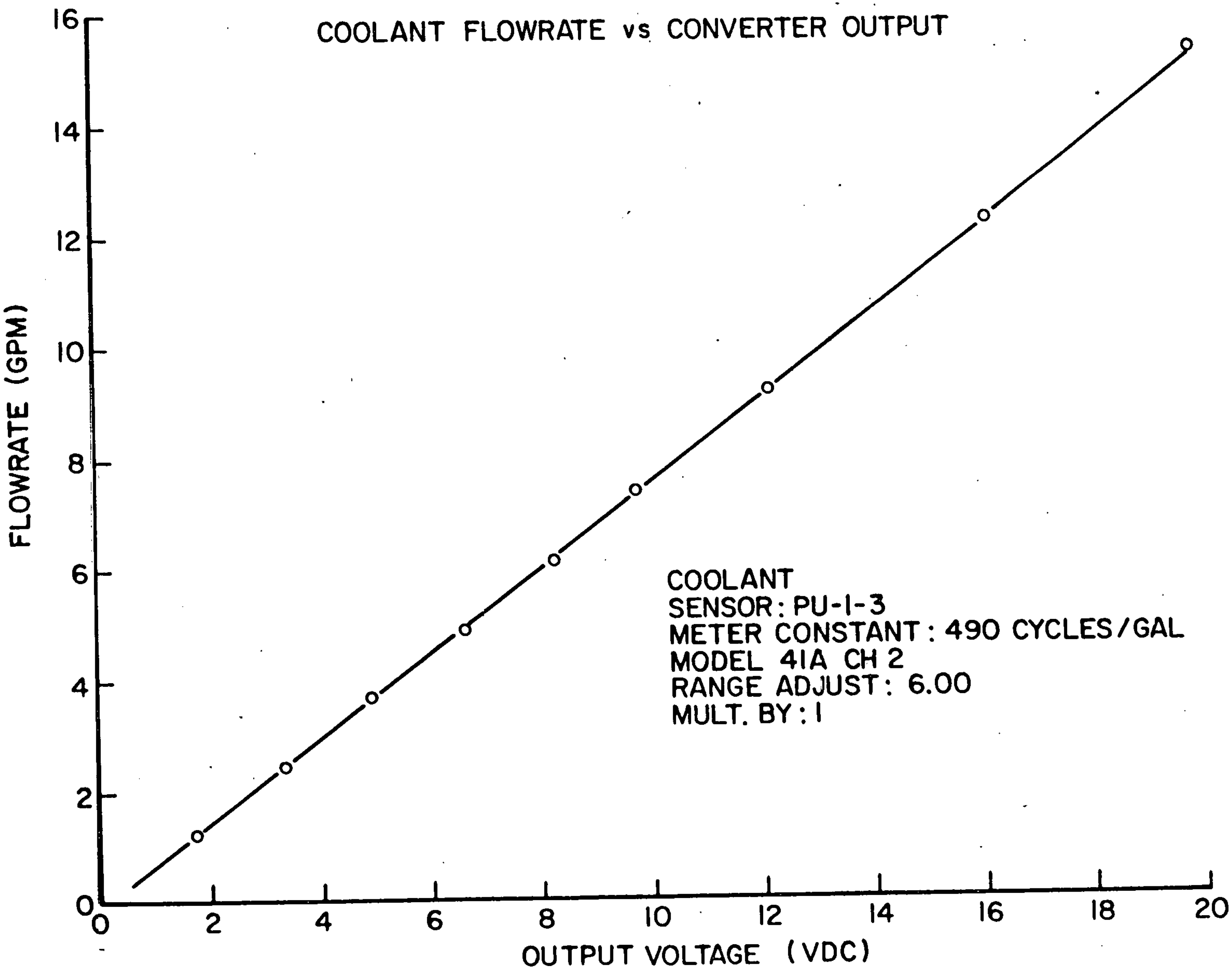
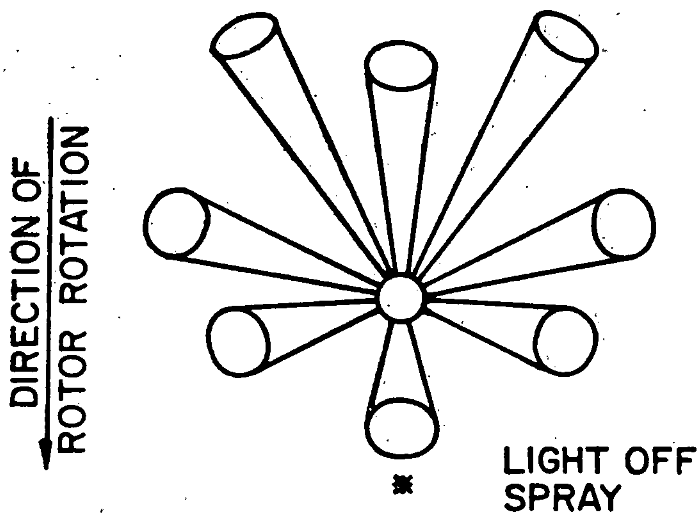

COOLANT FLOWRATE vs CONVERTER OUTPUT
FLOWRATE (GPM)
OUTPUT VOLTAGE (VDC)
0
2
4
6
8
10
12
14
16
18
20
COOLANT
SENSOR: PU-1-3
METER CONSTANT: 490 CYCLES/GAL
MODEL 41A CH 2
RANGE ADJUST: 6.00
MULT. BY: 1

FIGURE 6



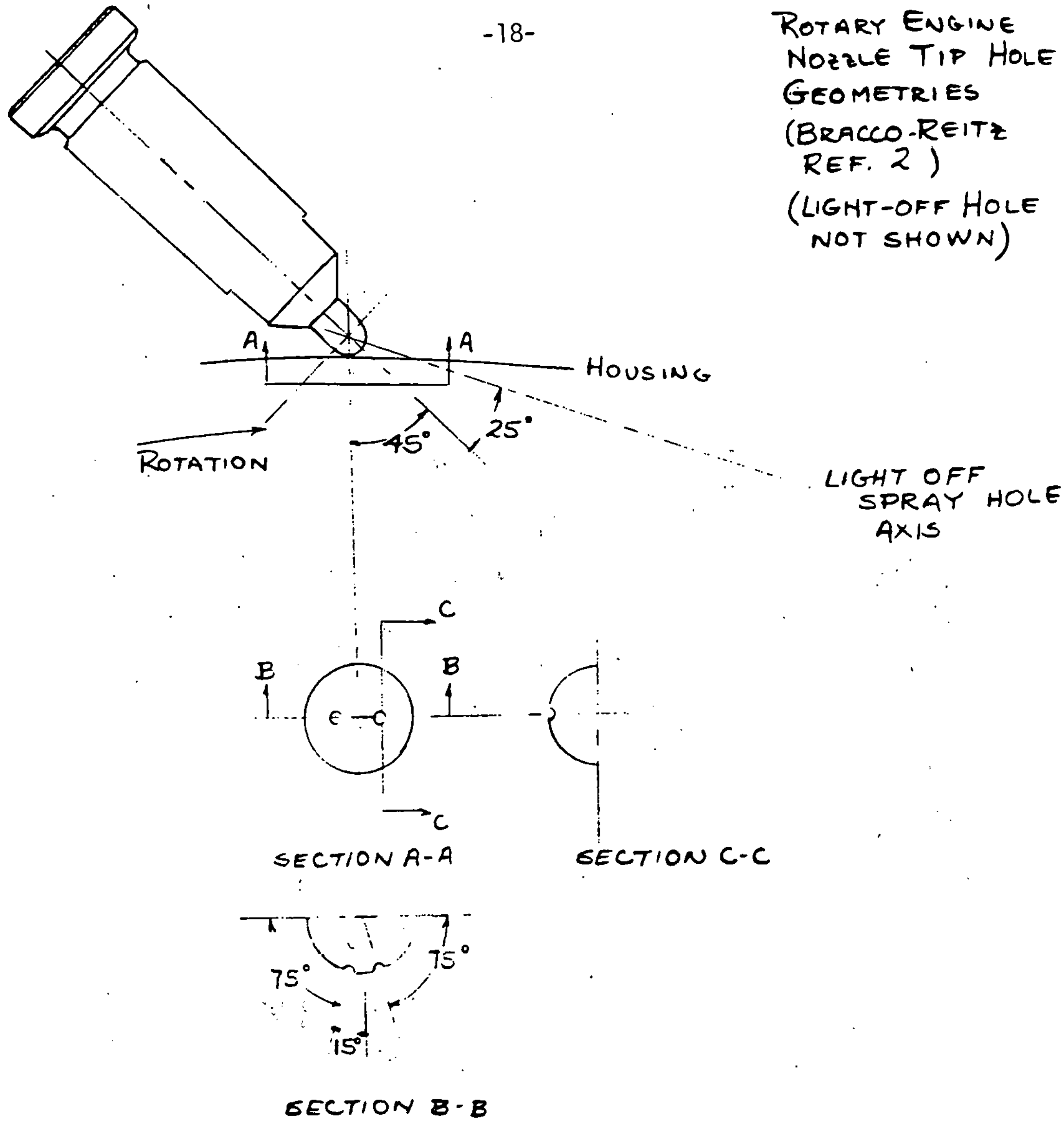
SK10720N -
N12 - 0.006 DIA.

TOTAL AREA
0.0002262

CURTISS WRIGHT DATA FUEL INJECTOR
NOZZLE SPRAY PATTERN

FIGURE 7

ROTARY ENGINE NOZZLE TIP HOLE GEOMETRIES
(BRACCO-REITZ REF. 2)
(LIGHT-OFF HOLE NOT SHOWN)



NOZZLE TIP S2-75

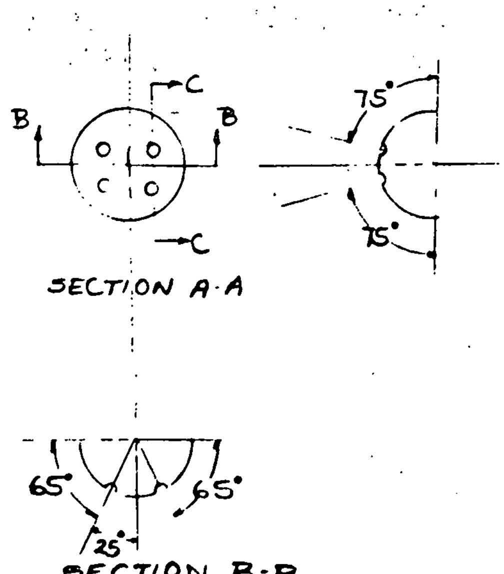
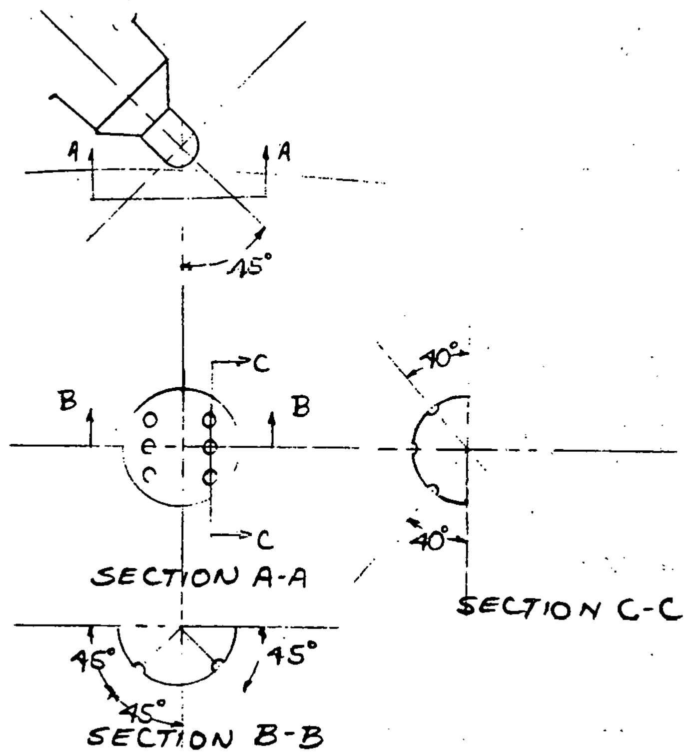


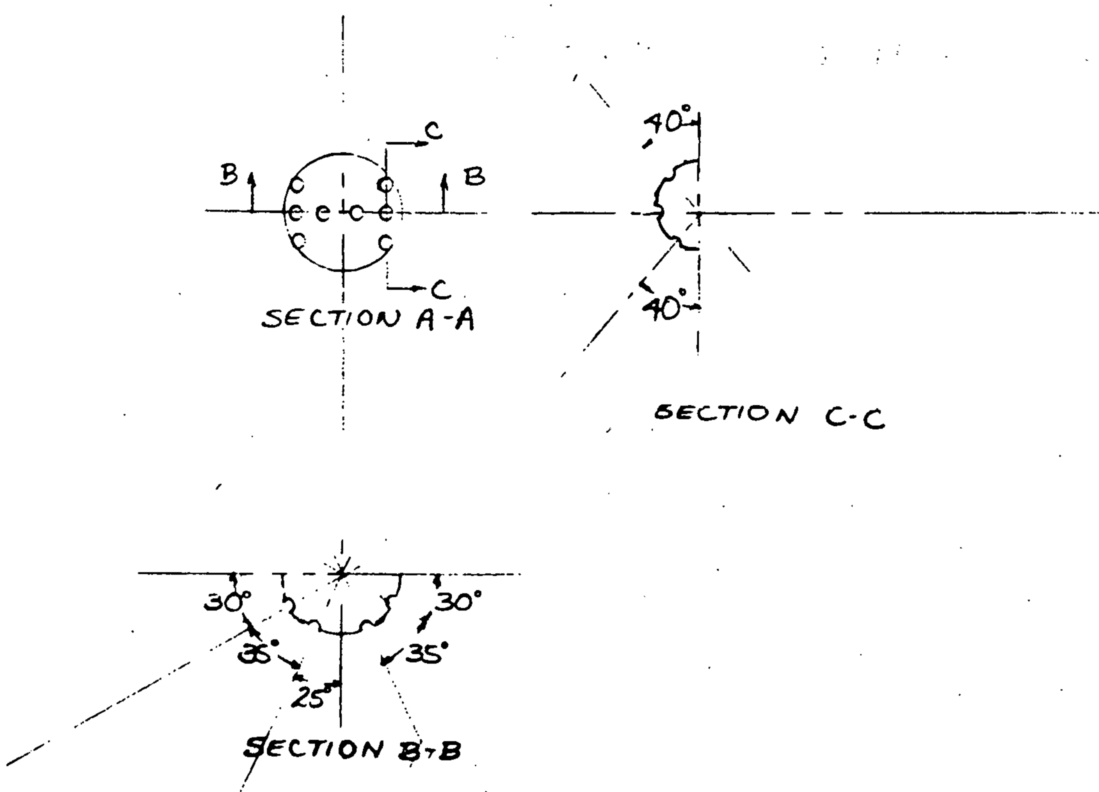
FIGURE 8

NOZZLE TIP S4-65

ROTARY ENGINE
NOZZLE TIPS
(BRACCO - REITZ)



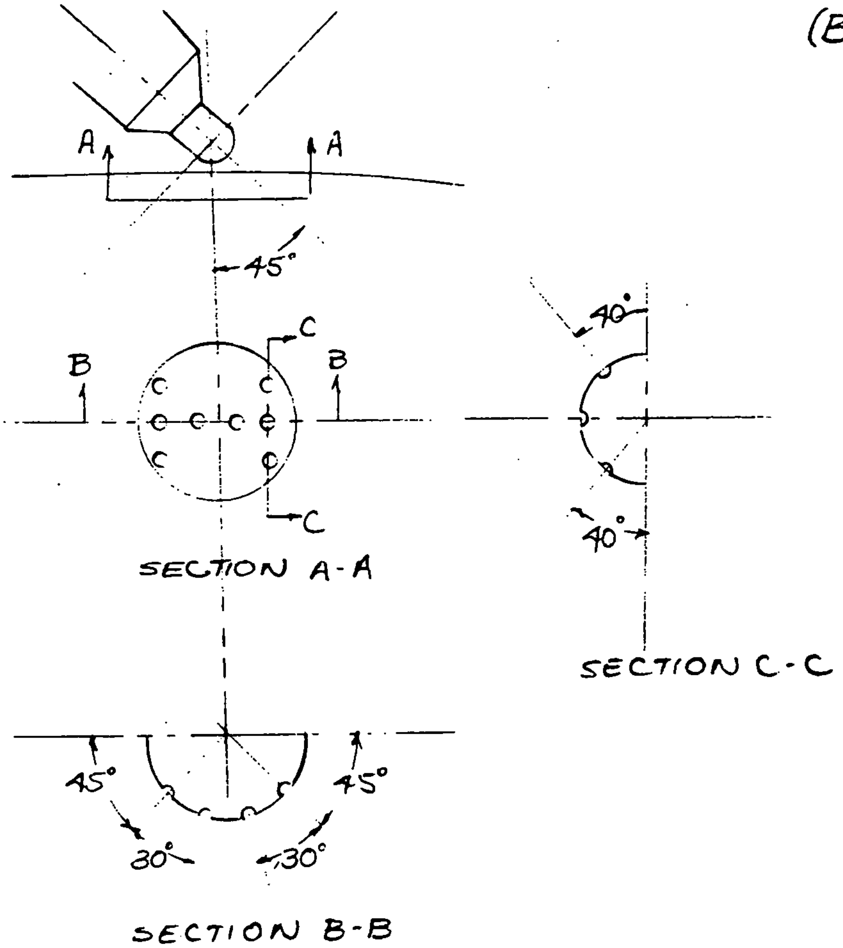
NOZZLE TIP S6-45



NOZZLE TIP S8-30

FIGURE 9

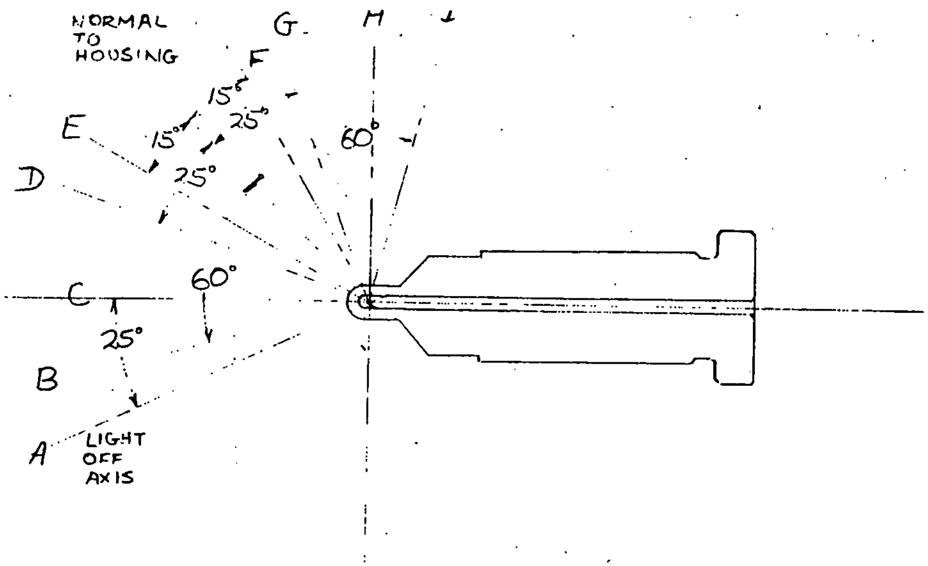
ROTARY ENGINE
NOZZLE TIPS
(BRACCO - REITZ)

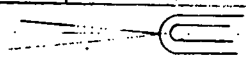


NOZZLE TIP 58-30,45

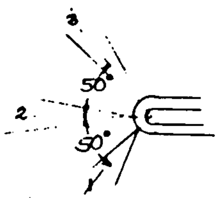
FIGURE 10

PLANE		TIP S-NO. 2-75	4-65	6-45	8-30	8-30,45
A		✓	✓	✓	✓	✓
B	1				✓	
	2				✓	
	3				✓	
C	1			✓		✓
	2			✓		✓
	3			✓		✓
D	1		✓			
	2				✓	
	3		✓			
E		✓				✓
F		✓				✓
G	1		✓			
	2				✓	
	3		✓			
H	1			✓		✓
	2			✓		✓
	3			✓		✓
I	1				✓	
	2				✓	
	3				✓	

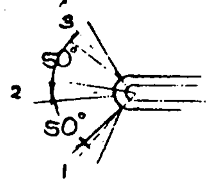




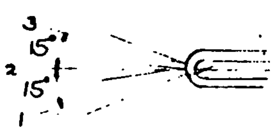
PLANE A



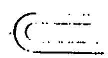
PLANE B



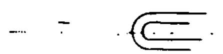
PLANE C



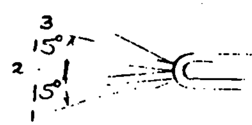
PLANE D



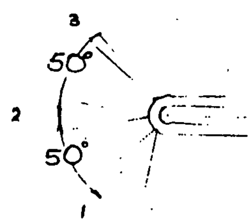
PLANE E



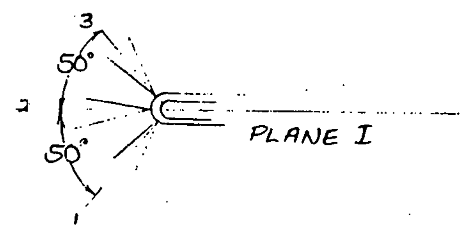
PLANE F



PLANE G



PLANE H



PLANE I

FIGURE 11

ROTARY ENGINE
NOZLE TIPS
(BRACCO-REITZ)
ALL HOLES: 0.006" DIA

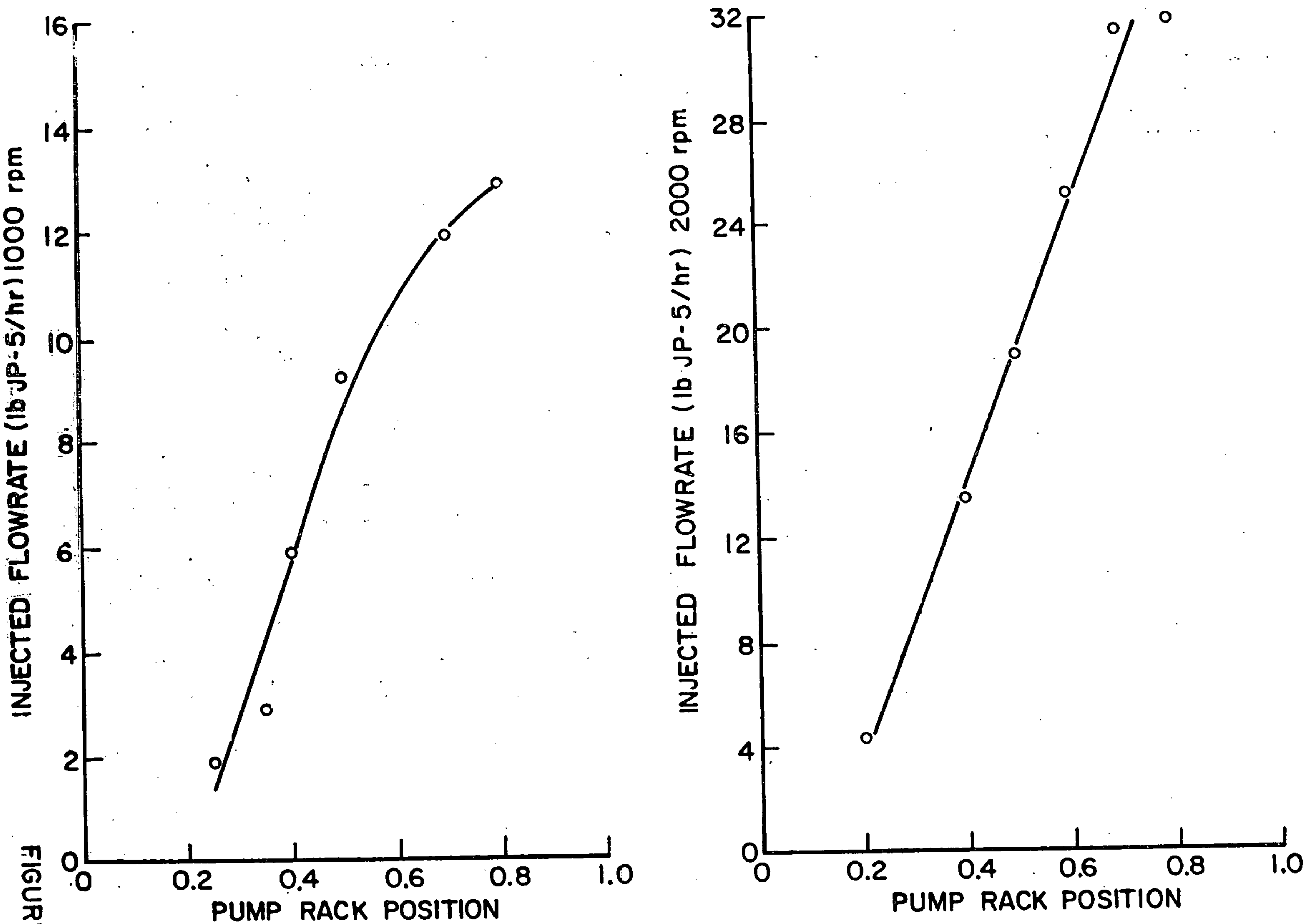


FIGURE 12

FUEL PUMP (APE IB-70P-5078A)+ INJECTOR DELIVERY CHARACTERISTICS

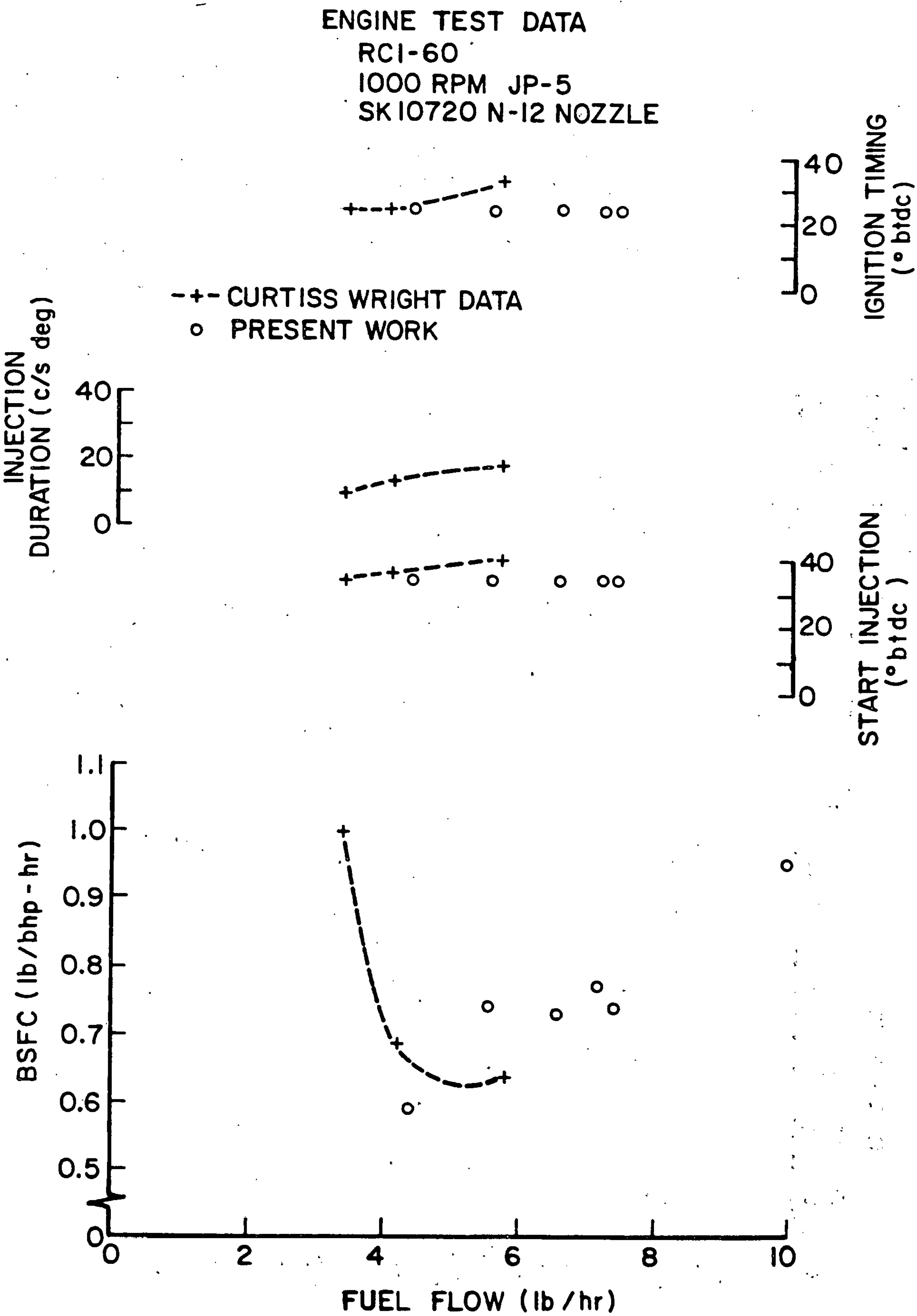

ENGINE TEST DATA
RC1-60
1000 RPM JP-5
SK 10720 N-12 NOZZLE
-+- CURTISS WRIGHT DATA
o PRESENT WORK
IGNITION TIMING (° btdc)
40
20
0
INJECTION DURATION (c/s deg)
40
20
0
START INJECTION (° btdc)
40
20
0
BSFC (lb/bhp-hr)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0
0
2
4
6
8
10
FUEL FLOW (lb/hr)

FIGURE 13

ENGINE TEST DATA
RCI-60
2000 RPM JP-5
SK 10720 N-12 NOZZLE

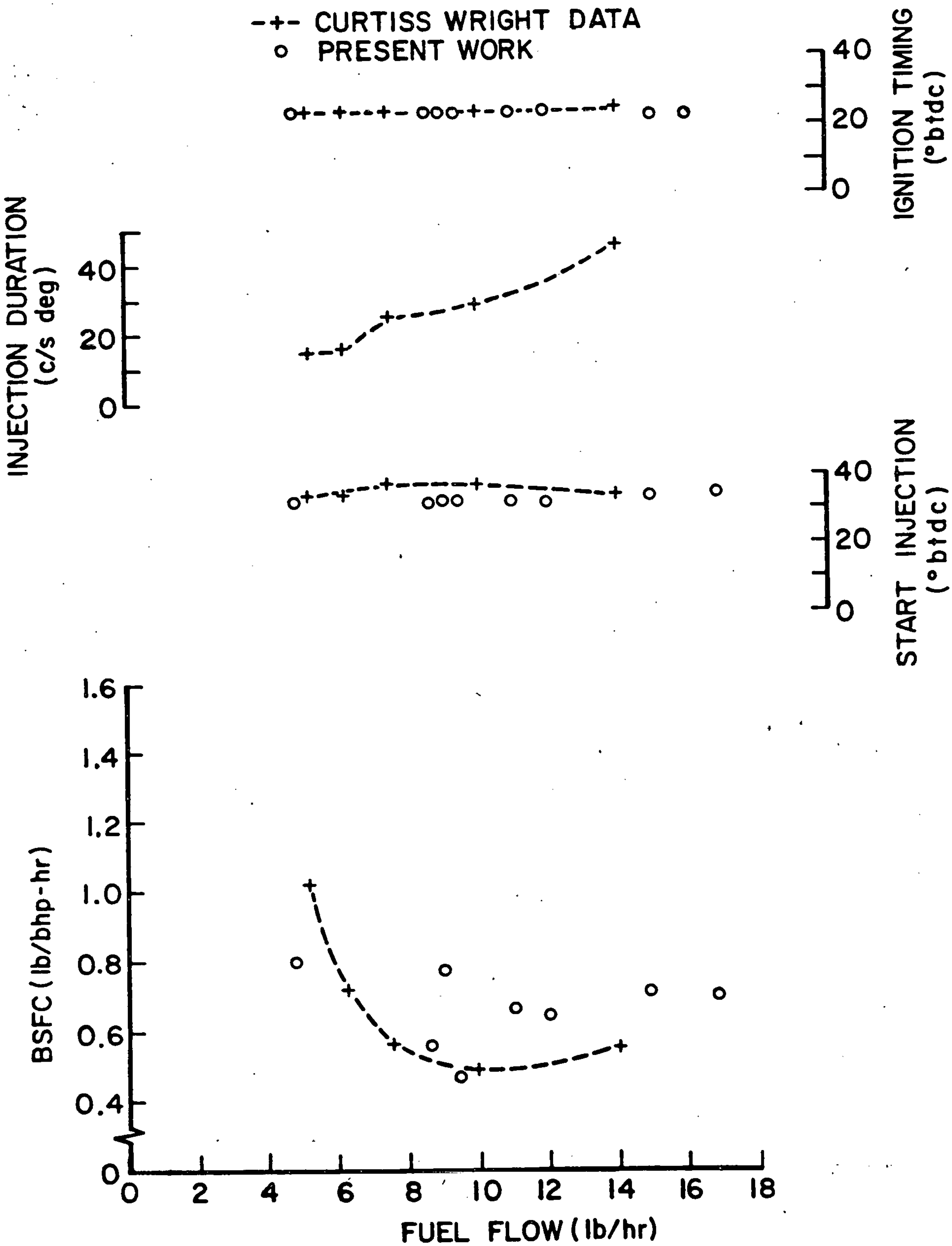


FIGURE 14

*U.S. GOVERNMENT PRINTING OFFICE: 1979-640-014/4599. Region 4.