THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Automotive Engineering Laboratory

Final Report

AIR-FUEL METER DEVELOPMENT

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Air-Fuel Meter Project Final Report

Introduction:

The goal of this investigation was to develop a method for measuring the ratio of the mass flow rates of air and fuel in an air-fuel mixture in the manifolding of an automotive reciprocating engine. Further, such a method should involve equipment sufficiently small such that the air-fuel ratio (A/F) can be measured for individual cylinders. Typical values of A/F to be measured lie within the range of 10 to 20, therefore the mass flow rate of the fuel is some 5 to 10% of the total mass flow rate of the mixture. This relatively small fuel mass flow rate eliminates the use of optical or electrical methods as a basis for determining A/F.

The location of the instrument also influences its configuration and accuracy; installation in the inlet manifolding of the engine requires that the instrumentation must sense the several forms in which fuel is found: vapor, droplets, and a liquid film on the manifold walls. These different forms complicate the measurement problem since their densities, as well as their velocities, are different.

However, if the instrument is located in the exhaust manifolding, the products of combustion (which still provide an index of the fuel mass flow rate) exist in the vapor phase only, which tends to simplify the problem. Disadvantages of this location are the higher operating temperatures as well as corrosion and exhaust products deposition.

The method used to solve the above problems and to measure the A/F involved the use of a radioactive gas, Krypton 85, dissolved in the fuel to provide a fuel density signal regardless of the form of the fuel; whether it was in the form of vapor, droplets, liquid film for inlet manifold measurements or in the form of products of combustion as was the case for exhaust manifold measurements.

This report covers the basis of the A/F measurement method, the experimental apparatus and techniques, results, discussion, and applications. Details of special velocity measurement techniques, fuel preparation, droplet investigation are included in the appendix.

Basis of A/F Measurement Method:

The basis for using a radioactive fuel density signal for determination of A/F rests on the following assumptions:

1. One-dimensional, steady, continuum flow.
2. The radioactive gas is uniformly mixed with the fuel, and remains with the fuel in a uniform

concentration whether the fuel is in liquid or vapor phases or in products of combustion.

3. Instrumentation can be so located that a true integrated or average fuel density signal is obtained.

The mass flow rate of the air, $\dot{m}_a$, is the product of the air density, ρ_a; the mixture velocity, V; and the flow area, A, as

$$\dot{m}_a = \rho_a A V$$

And similarly the mass flow rate of the fuel, $\dot{m}_f$, is the product of the fuel density, ρ_f, the mixture velocity V, and the flow area A, as

$$\dot{m}_f = \rho_f A V$$

Now the ratio of the mass flow rate of the air, $\dot{m}_a$, to the mass flow rate of the fuel, $\dot{m}_f$ is the air-fuel ratio (A/F) and is

$$\frac{A}{F} = \frac{\dot{m}_a}{\dot{m}_f} = \frac{\rho_a V A}{\rho_f V A} = \frac{\rho_a}{\rho_f}$$

Under the above assumptions the problem of measuring the A/F reduces to a problem of measuring the ratio of the densities of the air to fuel.

The air-fuel mixture is some 90 to 95% air; therefore use of the ideal gas equation of state in the determination of the air density should involve an error of less than 5%. This equation of state relates the density, ρ, to the temperature, T, the absolute pressure, P, and the gas constant, R, as

$$\rho = \frac{P}{RT}$$

The only variables in the above equation are temperature and pressure which are readily measured; therefore the problem of synthesizing the A/F meter essentially depends on the development of a fuel density meter.

If a radioactive gas is thoroughly mixed with the fuel and remains either with the fuel or in the close proximity of the fuel regardless of the condition of the fuel - whether in the form of droplets, vapor, liquid film, or products of combustion - the radioactivity level, as measured in counts per minute, will then furnish an index of the quantity of fuel present at or near the measuring location and it is this radioactivity signal which furnishes a fuel density signal. As discussed previously, the combination of the air density and "fuel density" signals provide the A/F signal.

Experimental work:

1. General. The experimental work involved the development of a technique for mixing and handling the radioactive gas, Krypton 85, with commercial gasoline; the development of a fuel measurement technique and apparatus, operating a CFR single-cylinder engine with the radioactive or "hot" fuel fitted with this instrumentation to compare the "test" or interval A/F signal with the

Calibration or external A/F signal.

2. Equipment. The CFR engine installation for the inlet manifold configuration is shown in Figs. 1 and 2.

Airflow to the Fiat carburetor was metered through sonic orifices and delivered to the carburetor at atmospheric pressure.

The radiation signal from the "hot" fuel was obtained by surrounding the flow duct with several Geiger-Muller tubes. These G-M tubes provide an electrical pulse for each passage of Beta radiation. Mass of any sort attentuates the radiation signal, in order to minimize this signal attenuation a special duct test section was fabricated using 0.005 in. thick aluminum, as shown in Figs. 3, 4, 5, 6. The internal flow geometry of the special section was identical with the duct geometry on both the upstream and downstream sides.

Fuel storage, delivery, and metering posed a problem since if the "hot" fuel were vented, the Krypton 85 gas would tend to come out of solution with the gasoline. Commercial pneumatic cylinders were used as fuel containers, by placing the appropriate pressure or vacuum on one side of the piston, the fuel would flow into or out of the cylinder. Measurement of the rate of travel of the piston rod, by means of a dial indicator and a stop watch, provided a calibration fuel volume flow

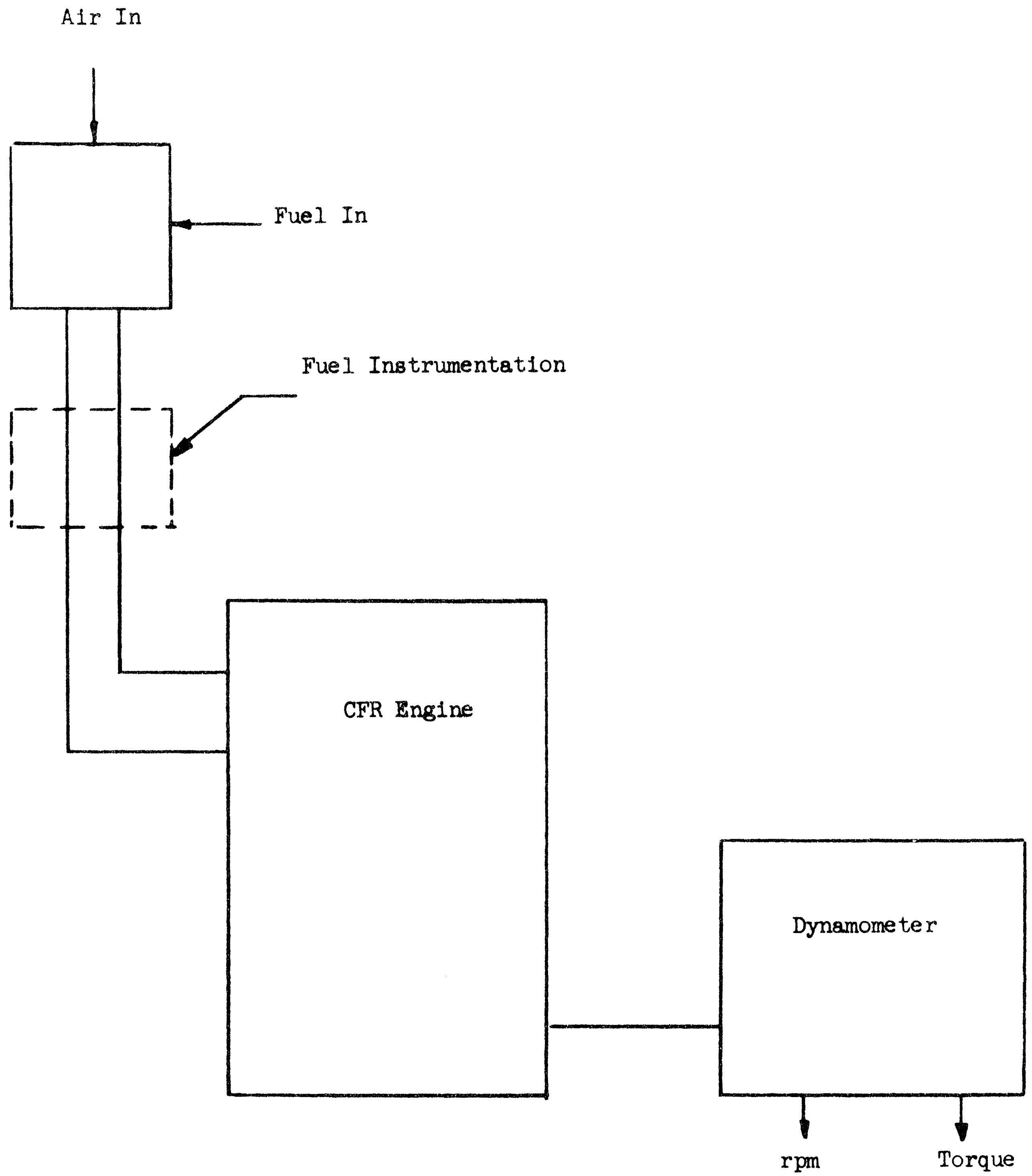

Fig. 1. Schematic diagram of test apparatus.

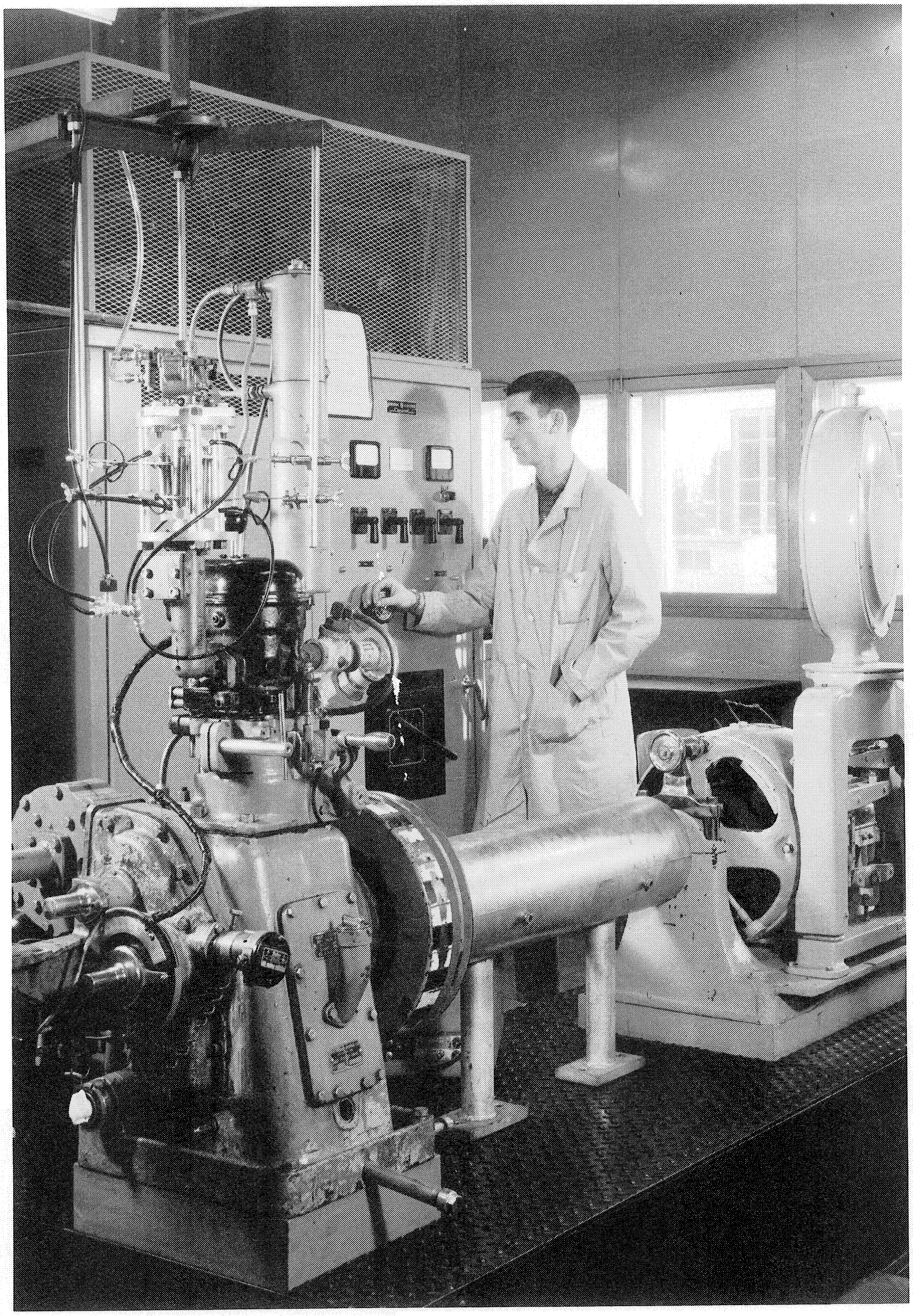

Figure 2. General view of CFR engine, dynamometer, and carburetor.

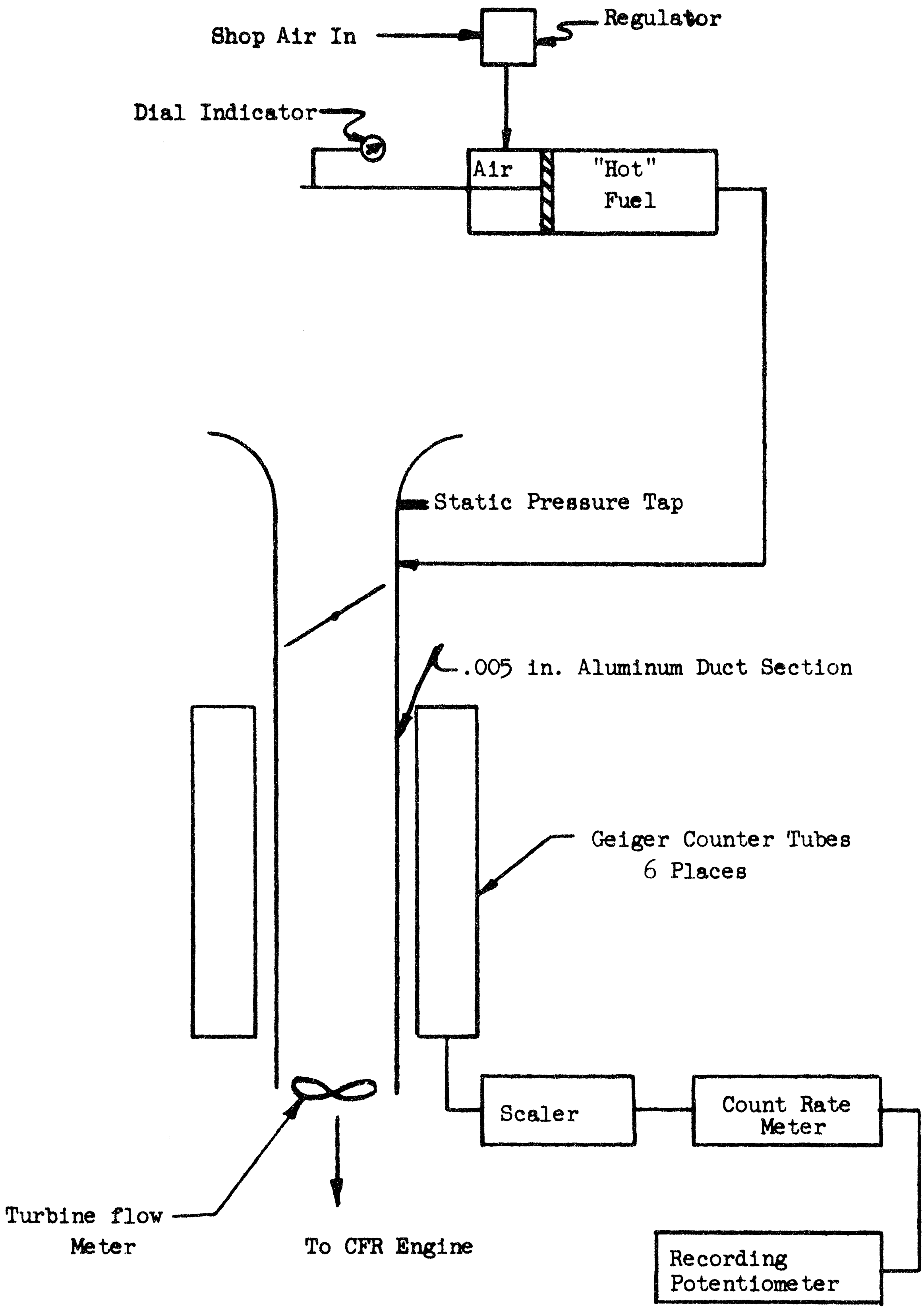

Fig. 3. Schematic diagram of fuel system and instrumentation.

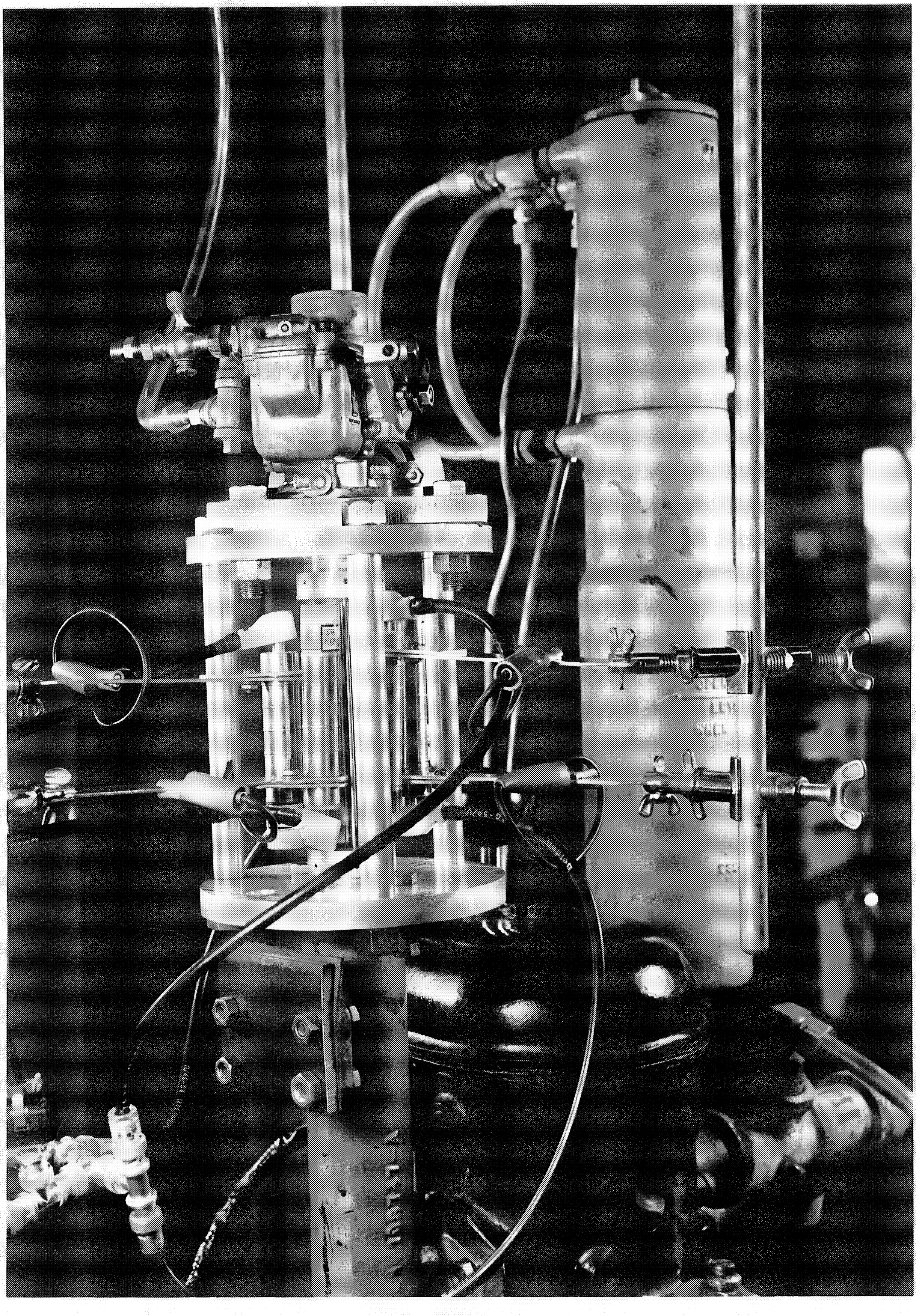

Figure 4. View of carburetor, manifold, thin wall duct section with six Geiger pickups.

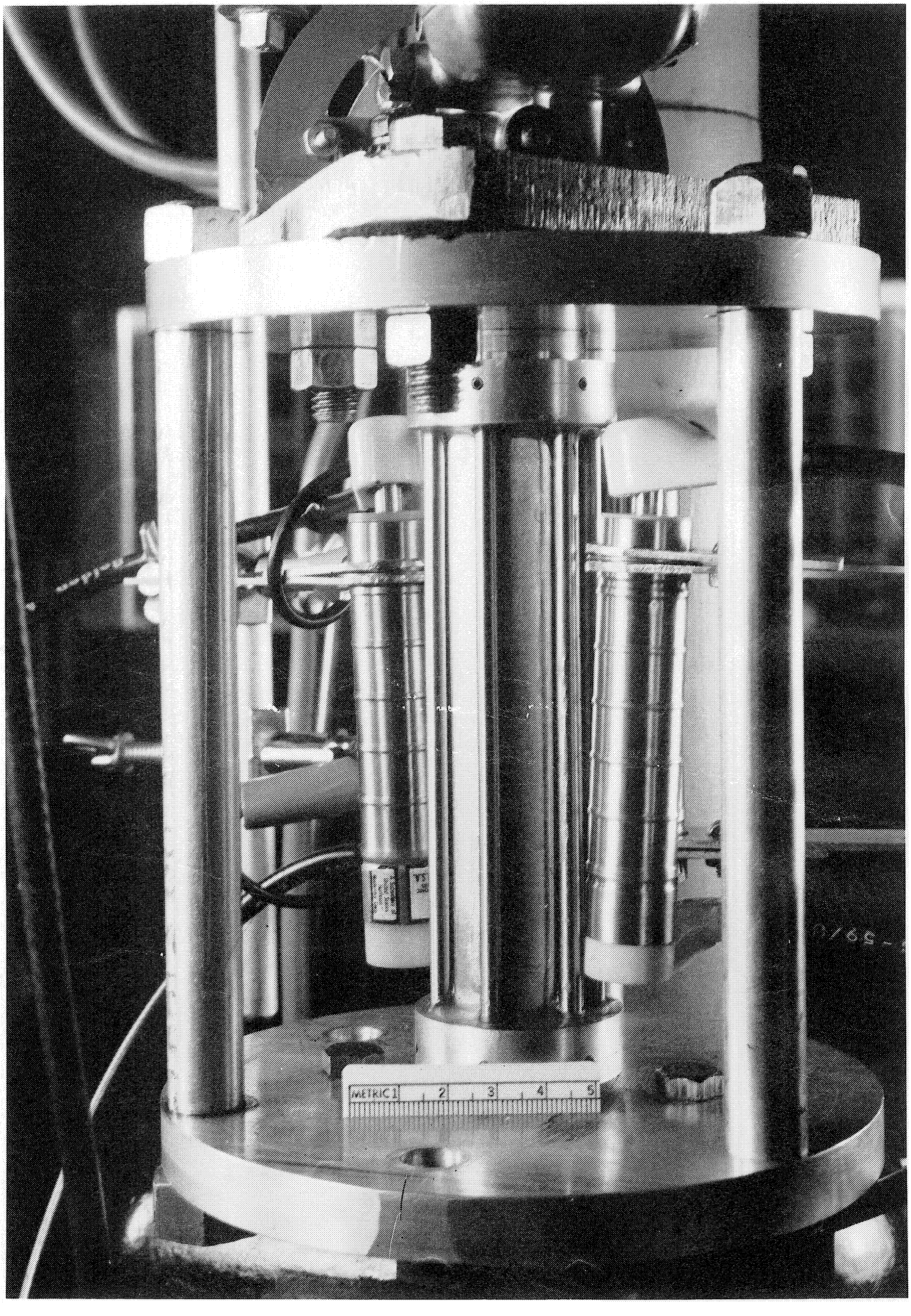

Figure 5. Close-up of thin wall duct section with two Geiger pickups removed.

Figure 6. Flowmeter-transparent tube assembly on left, thin wall duct section on the right.

rate. A typical fuel cylinder is shown in Fig. 7.

A check on the volume flow rate of the fuel was provided by a tapered tube-float flowmeter in the latter tests.

The signal from the G-M tubes is fed to a pulse counter and also to a count rate meter and then to a recording potentiometer, which displays a signal which is proportional to the count rate from the G-M tubes.

3. Test Configurations. The initial configuration had the duct test section installed between the carburetor and the engine, the second and final test configuration, as shown in Figs. 8, 9, 10 consisted of the test section downstream of the engine with a simple heat exchanger used to maintain exhaust gas temperature within required limits.

4. Range of test variables. Speed requirements of the CFR engine set the engine operating range from 1000 to 1600 RPM, four throttle settings were used: 1/4, 1/2, 3/4, and WOT. In the latter tests, an air bypass around the carburetor was used to produce values of A/F higher than available from normal carburetor operation.

5. Test Results and Discussion.

A. Inlet Manifold Configuration

1. Run 12/21/62. This was the first run with

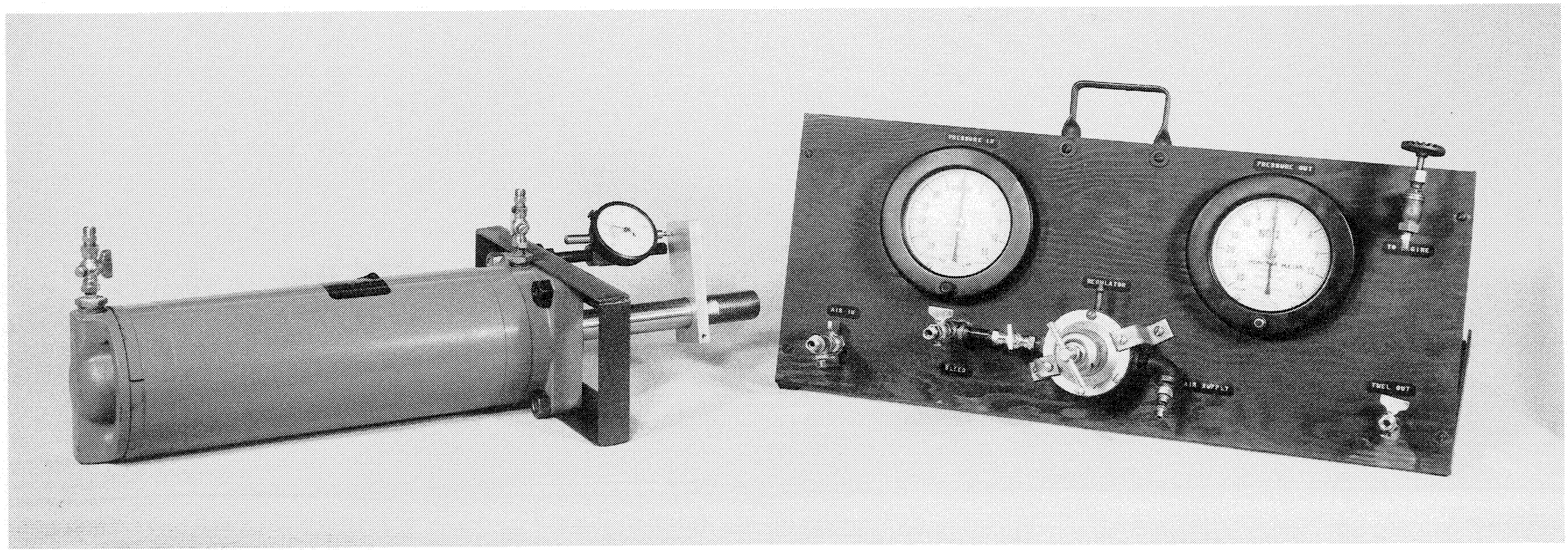

Figure 7. Fuel cylinder assembly with dial indication attached and pressurizing panel.

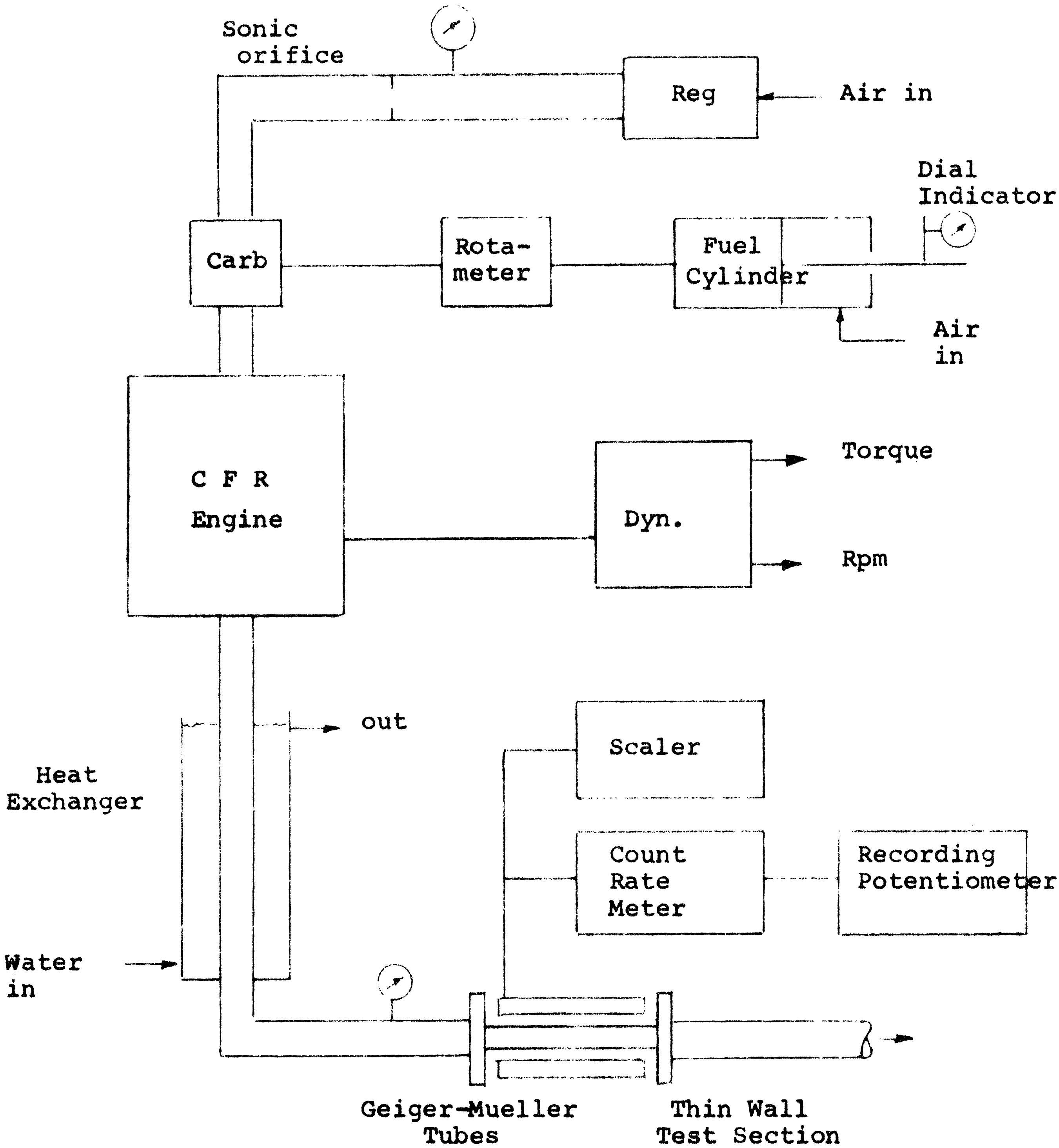

Figure 8   Schematic of Test Configuration with Instrumentation in Exhaust Duct

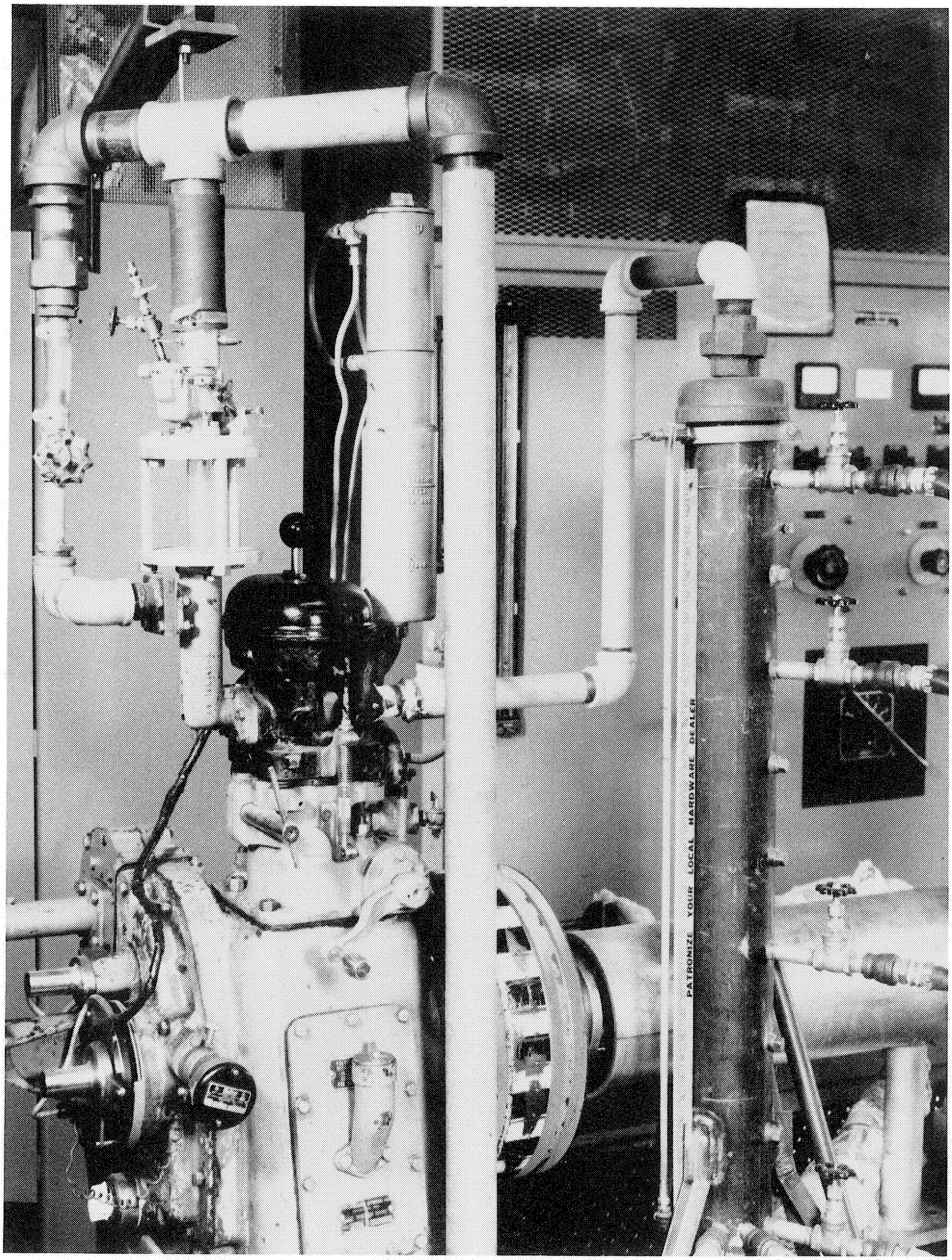

Figure 9. General view of exhaust-located instrumentation configuration showing carburetor bypass and exhaust gas heat exchanger.

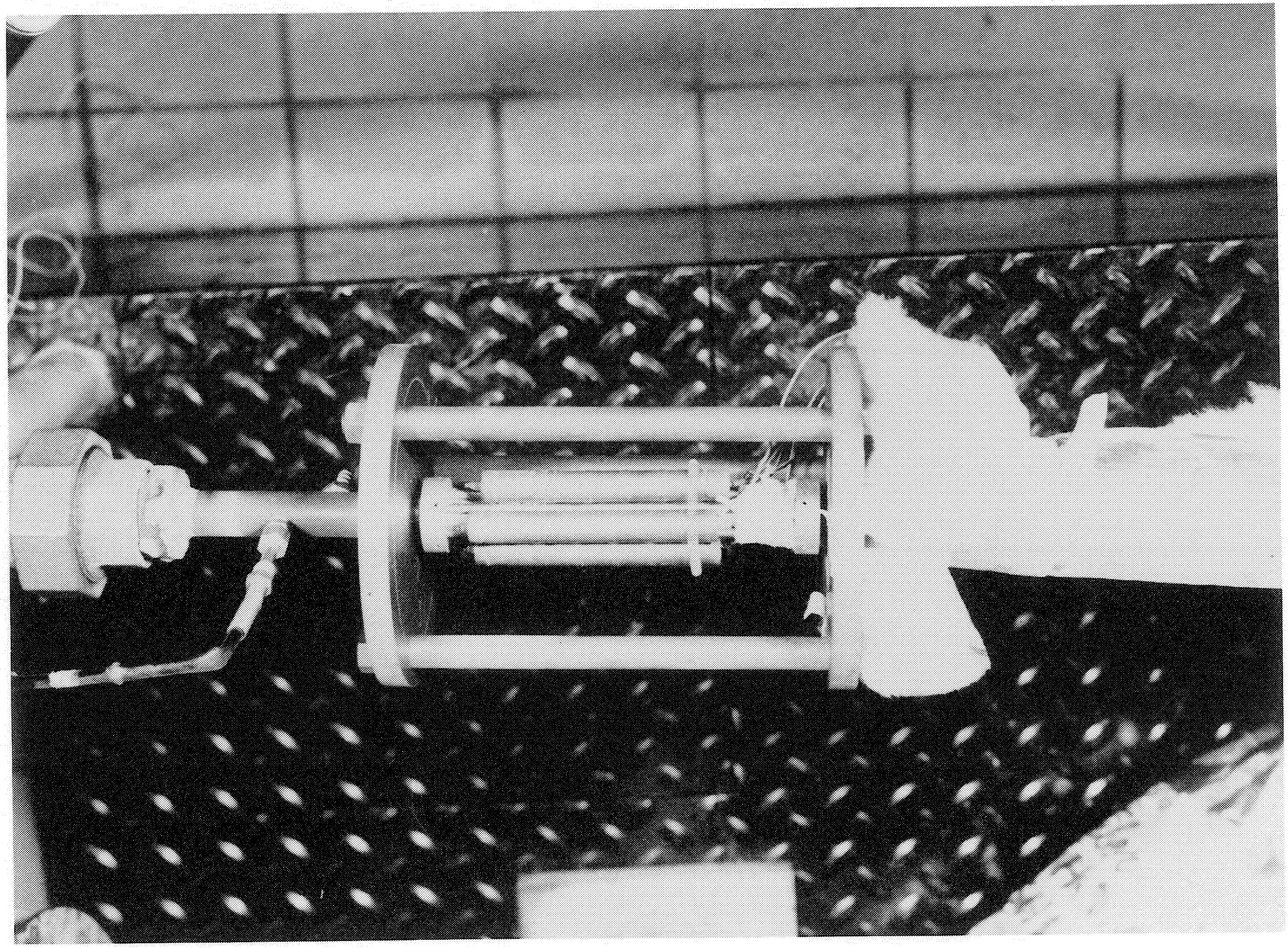

Figure 10. View of G-M tubes surrounding 5/8 in. dia. thin wall test section for exhaust instrumentation configuration.

"hot" fuel. Aside from inconclusive results, it was decided to replace a neoprene fuel bag with the piston-cylinder type container.

2. Run 1/10/63. These tests indicated that improved G-M tube mounting, carburetor float bowl shielding, an improved throttle quadrant, and a fuel flow rate measurement were required.

3. Run 2/20/63. Inconclusive data.

4. Run 3/6/63. Results of this testing are shown in Figure 11, in which the test results, called the "Test F/A" is only an index of the F/A as measured by the instrumentation at the thin wall duct section. As mentioned earlier, the A/F is based on the ratio of the densities of the air and fuel; however the air density is proportional to the ratio of the absolute pressure to the absolute temperature, while the fuel density is a function of the radioactive count rate. Since the amount of Krypton 85 mixed with the gasoline varied from test to test, this count rate furnishes a relative index of the density of the fuel; therefore it was felt that using the following definition of the "Test F/A" would adequately describe the usefulness of this approach to F/A measurement:

$$\text{"Test F/A"} = \frac{\text{Net Radioactive Count Rate (counts/minute)}}{\text{Absolute pressure/abs. temp. (psia/}^{\circ}\text{R)}}$$

The calibration F/A is simply the F/A measured by

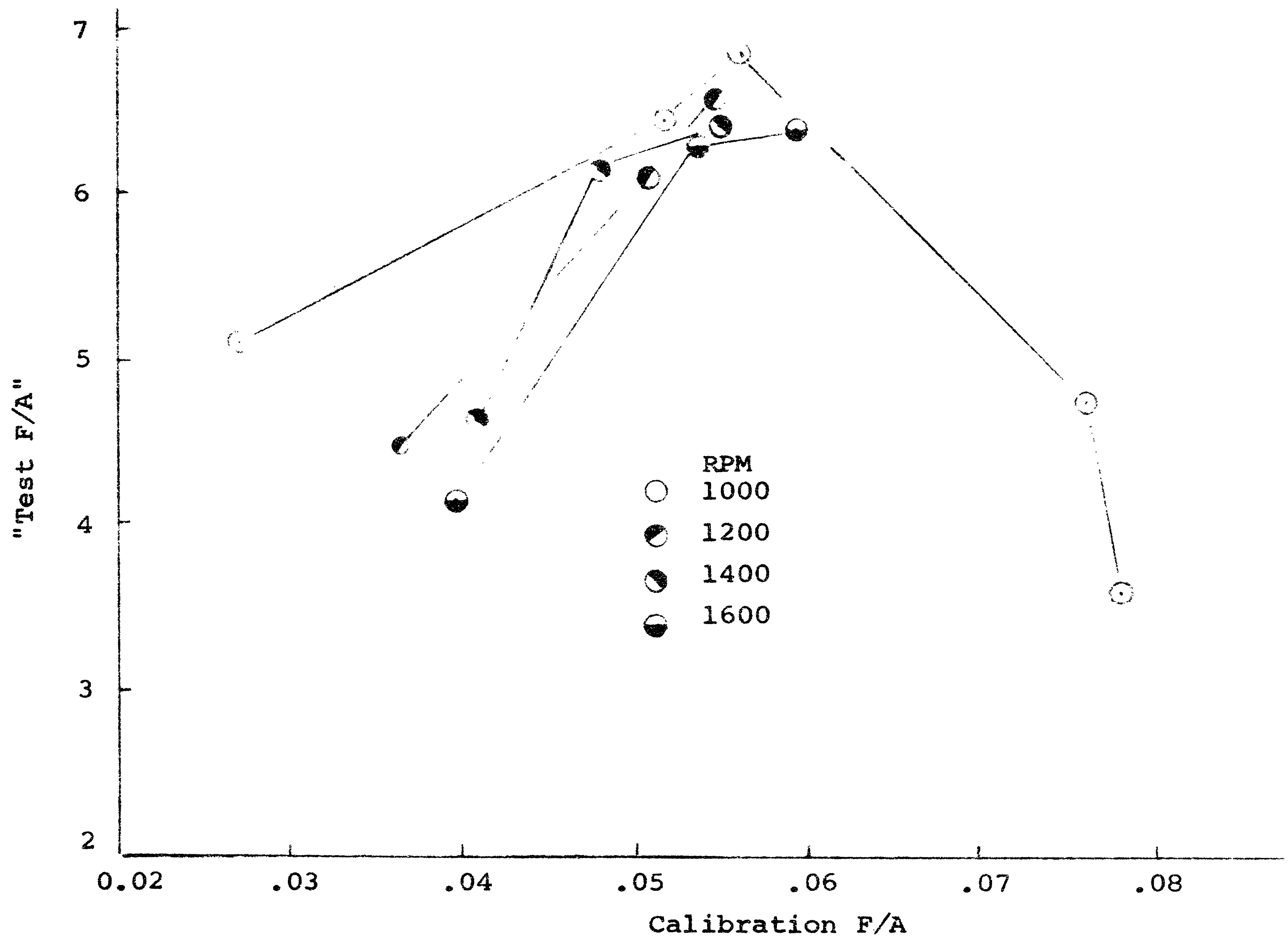

Figure 11 Comparison of "Test F/A" with Calibration F/A for 3-6-63 Tests

external means; fuel flow rate/air flow rate. The effectiveness of the use of a radioactive fuel for determining F/A will then be shown by the comparison of the "Test F/A" and the Calibration F/A; the correlation between the two F/A will be evident from the plot. The results of 3/6/63 tests were both encouraging and inadequate.

5. Run 4/16/63. The critical flow orifice was used for the first time, engine was warmed up for 3 hours prior to operation with "hot" fuel. Results, shown in Figure 12 appear to have a scatter of about 1 unit of A/F.

While the first runs were mostly for learning about the system, the run of 4/16/63 gave results which were indicative of the level of accuracy from this test configuration. Further since this level of accuracy was undesirable and it was felt that the errors or "scatter" derived from the lack of consistency of the fuel forms (vapor, droplets, and liquid film) from one operating condition to the next it was decided that placing the test section downstream of the cylinder in the engine exhaust duct would eliminate the major disadvantage by keeping the exhaust products in a single phase. The Krypton 85 gas, which probably would now be separated from the fuel through the mixing, heating and

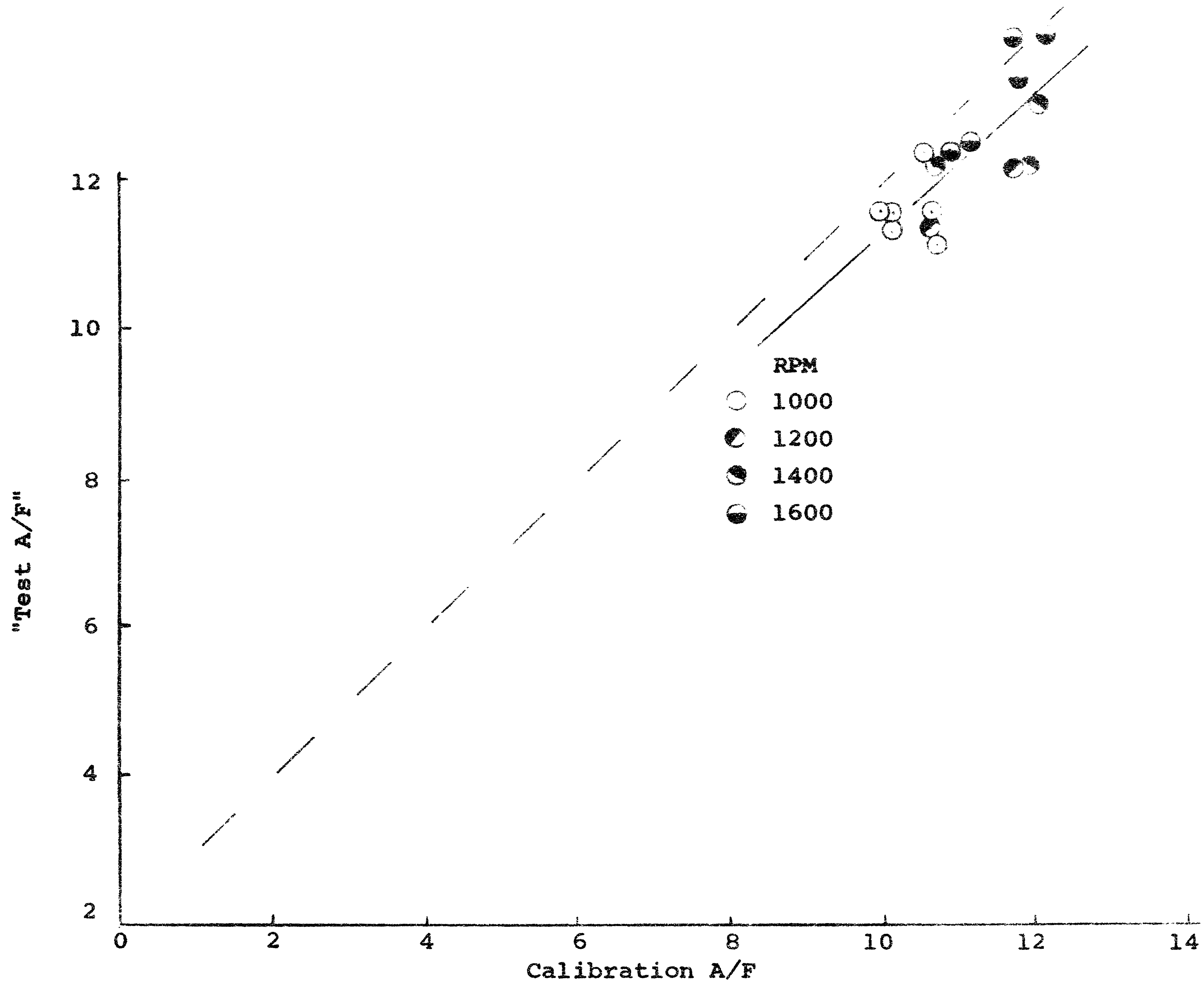

Figure 12 Comparison between "Test A/F" and Calibration A/F for 4-16-63 Tests

combustion processes should still furnish a measure of the fuel density since it does not readily form chemical compounds.

A heat exchanger was installed between the cylinder and the test section to maintain the exhaust temperature within the temperature limits of the test section and the saturation temperature of the constituents in the exhaust gases.

B. Exhaust Manifold Configuration

1. Run 6/19/63. With the exception of three test points, all of which, interestingly enough, were at the 1000 RPM condition, a good correlation was obtained between test and calibration A/F as shown in Figure 13.

2. Run 7/10/63. The carburetor bypass was used during this run to extend the A/F range, further test section temperature was some 50° higher than for the previous run. As shown in Figure 14, data scatter was quite large; further, a well-defined shift with time was noticed in the data.

Vibration effects were considered as a possible factor in the poor readings from the G-M tubes, but checks showed that this was not the case. Then, operating the engine with conventional fuel and with insulation around the G-M tubes, the count rate, which

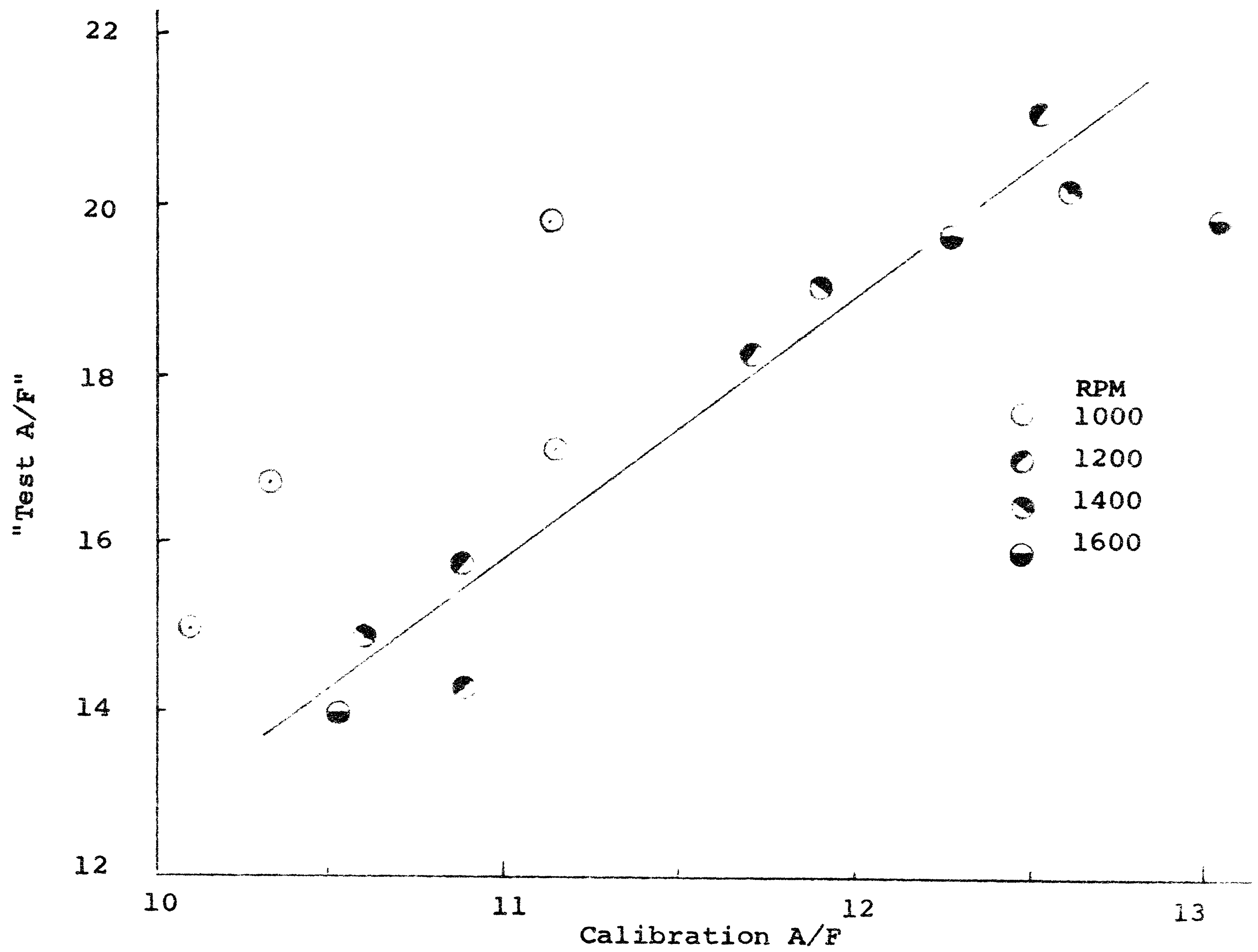

Figure 13 Comparison of "Test A/F" with Calibration A/F for 6-19-63 tests

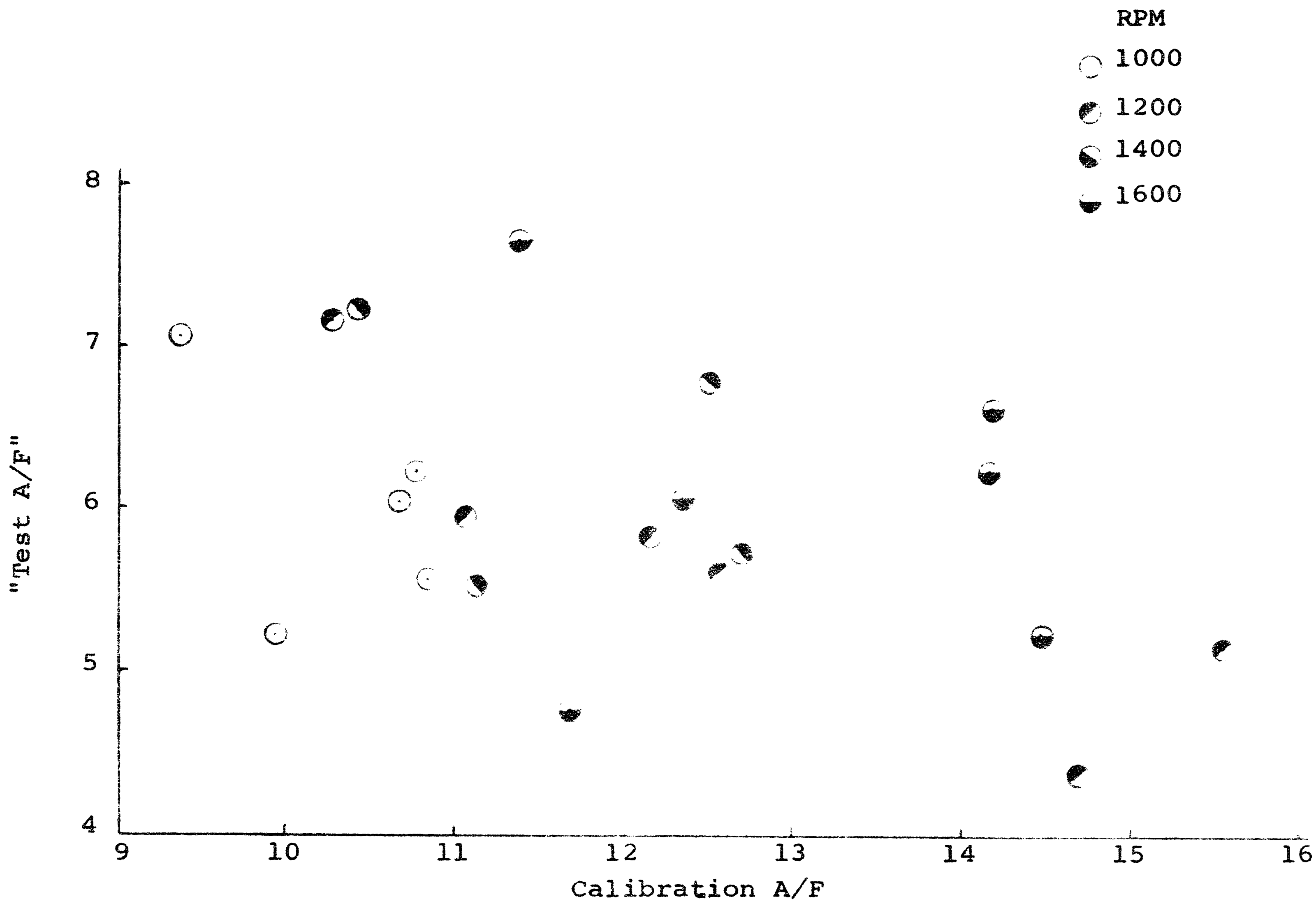

Figure 14 Comparison of "Test A/F" and Calibration A/F for Test of 7-10-63

should have been constant due to normal background radiation, steadily increased with time. Controlled checks of the G-M performance showed that the elevated temperature (180F) performance of the tubes was extremely temperature sensitive and individual tubes varied considerably from the norm.

3. Run 8/1/63. A final check with the standard G-M tubes showed inconclusive data as given in Figure 15.

4. Run 8/9/63. High temperature G-M tubes were used for the first time. Results, as shown in Figure 16, are still not good. When early data points were repeated the correlation was improved. It would appear that a warm-up or similar transient effect was present. Further, the part-throttle data points seem to have the greatest error. It was conjectured that the boundary layer of the duct and hence test section wall may be undergoing transition from turbulent to laminar flow as the throttle setting and hence mass flow rate is decreased. A special small (5/8 in. I.D.) test section was fabricated for use on the next run.

5. Run 8/15/63. Test results, shown in Figure 17, with the smaller diameter test section showed improvement. Scatter in the data was probably due to either poor fuel flow measurement or air leakage past the piston of the hot fuel cylinder.

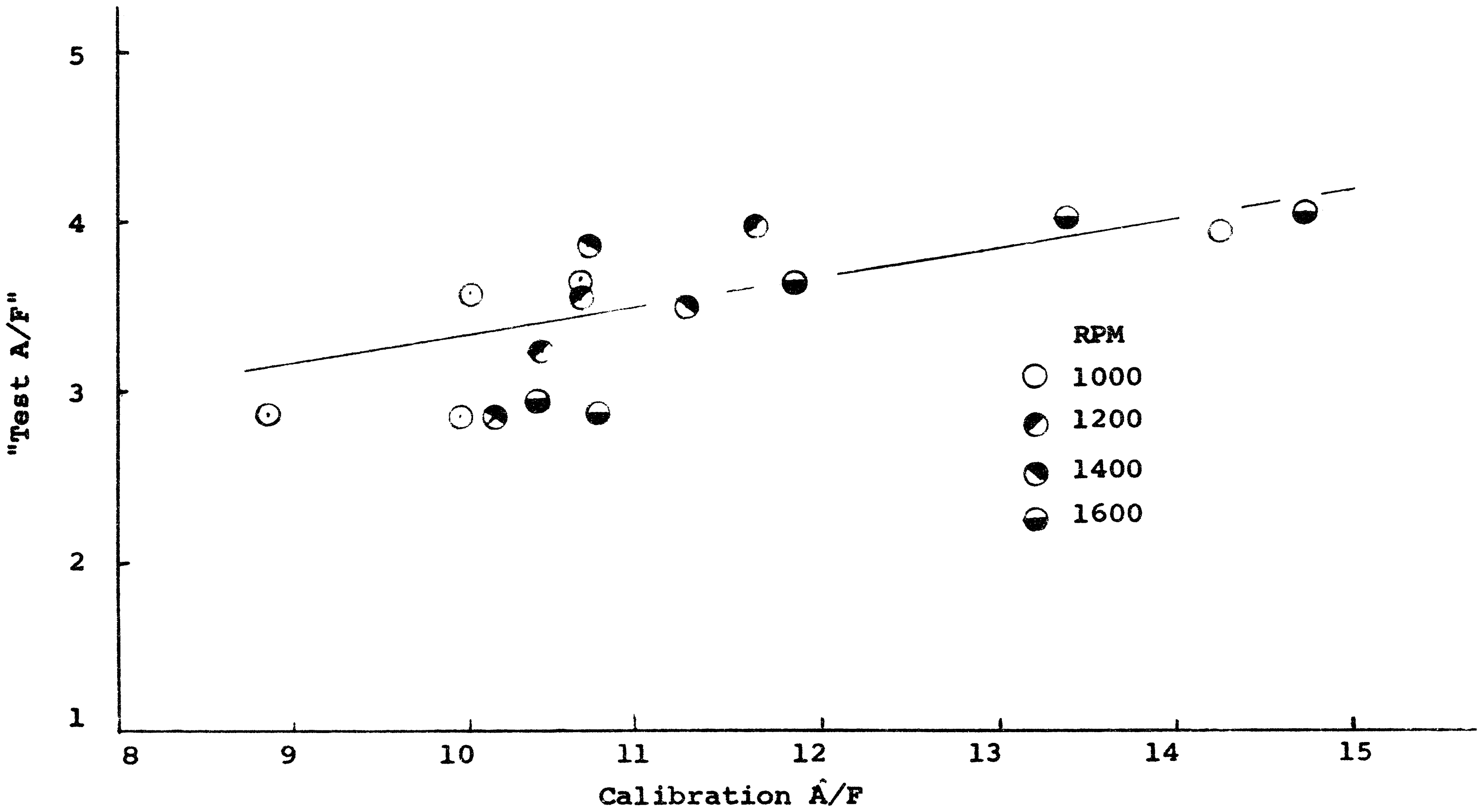

Figure 15 Comparison of "Test A/F" with Calibration A/F for 8-1-63 Tests

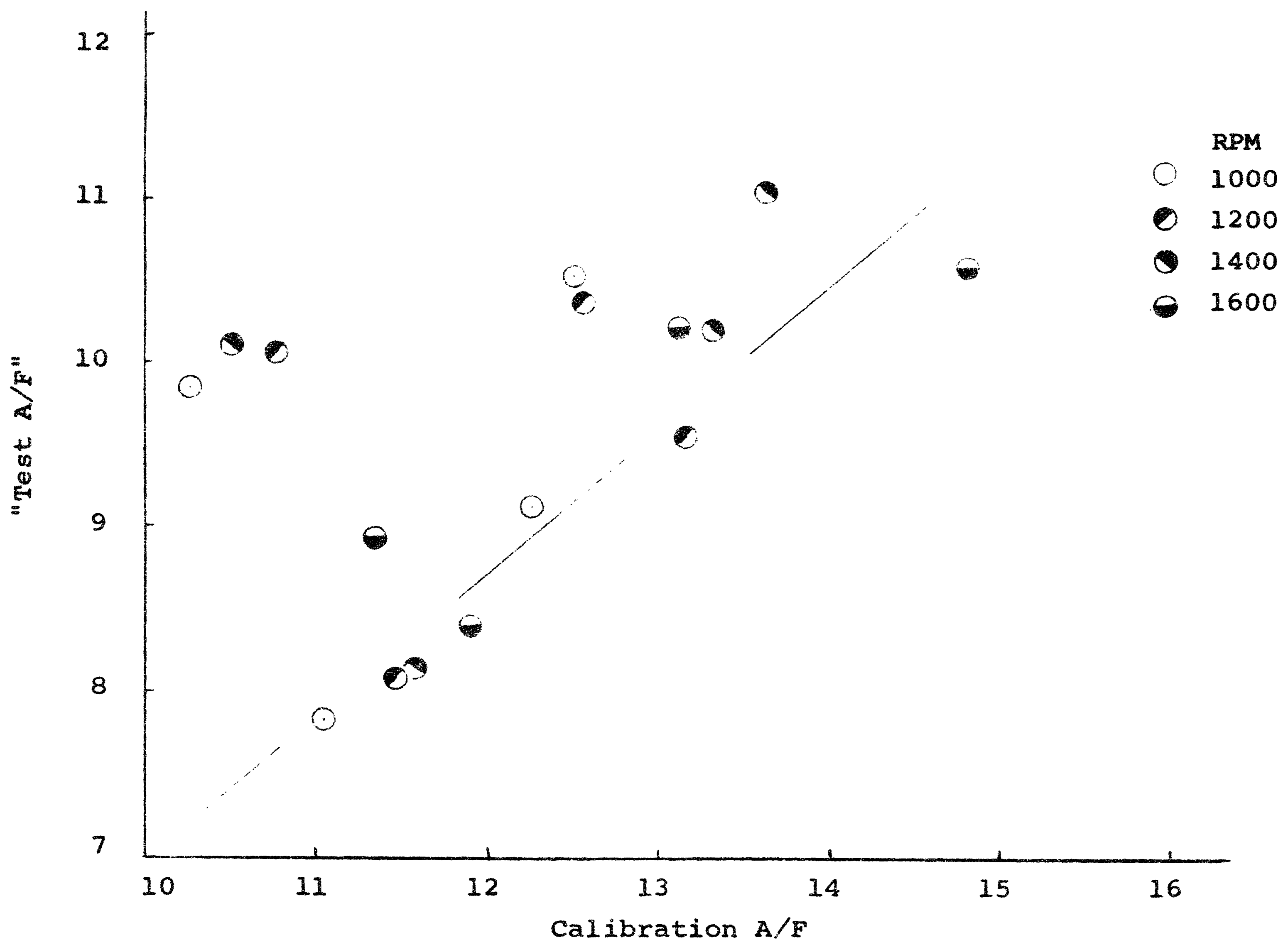

Figure 16 Comparison of "Test A/F" with Calibration A/F for 8-9-63 Tests

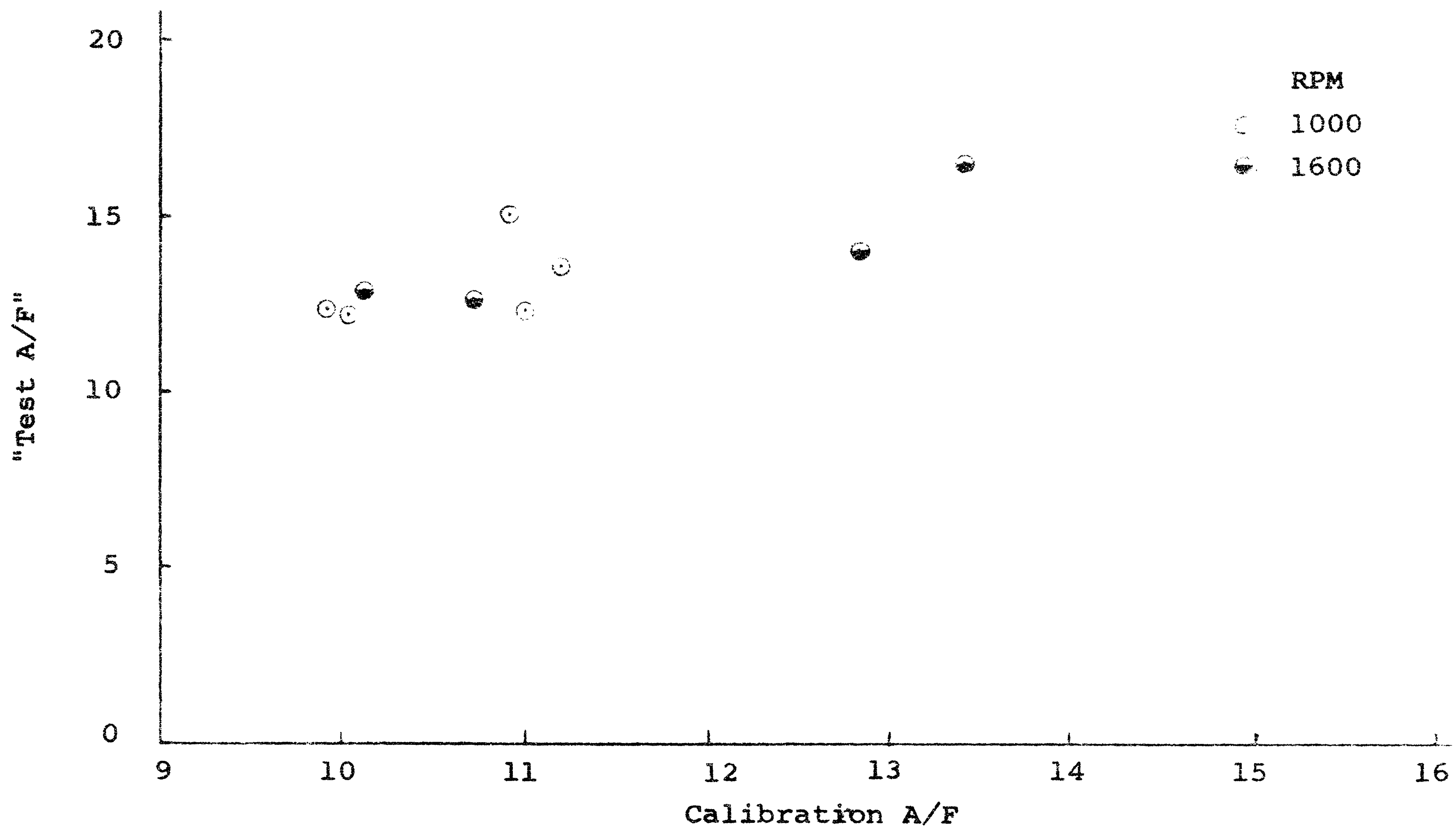

Figure 17 Comparison of "Test A/F" and Calibration A/F for 8-15-63 Tests

6. Run 9/18/63. With the small test section, a tapered tube flow meter for fuel flow measurement, in addition to the usual piston travel method, results, as shown in Figure 18, are good. All runs were made at 1600 RPM, WOT with several bypass settings. The engine rpm counter for runs 1 and 2 was erratic and was replaced before run 3. A nearly linear relationship is obtained between Test A/F and Calibration A/F.

C. Application to Automotive Engine Testing.

1. Steady-state performance. It appears that the use of a radioactively labelled gasoline, together with appropriate instrumentation, would be eminently suitable for use in automotive engine development testing. For the typical multi-cylinder engine, separate test sections and G-M pick-ups would be installed in individual exhaust manifolds. If this testing is done in fixed installation such as a test cell, this added geometry and instrumentation pose little, if any, space problems. Installation in a vehicle would require a certain amount of modification to the exhaust ducting, with possibly the ducting from each cylinder being directed through the baggage compartment of the vehicle and the instrumented test sections located in the trunk. Radiation level of the automobile exhaust would preclude its use on public highways but could easily be used on

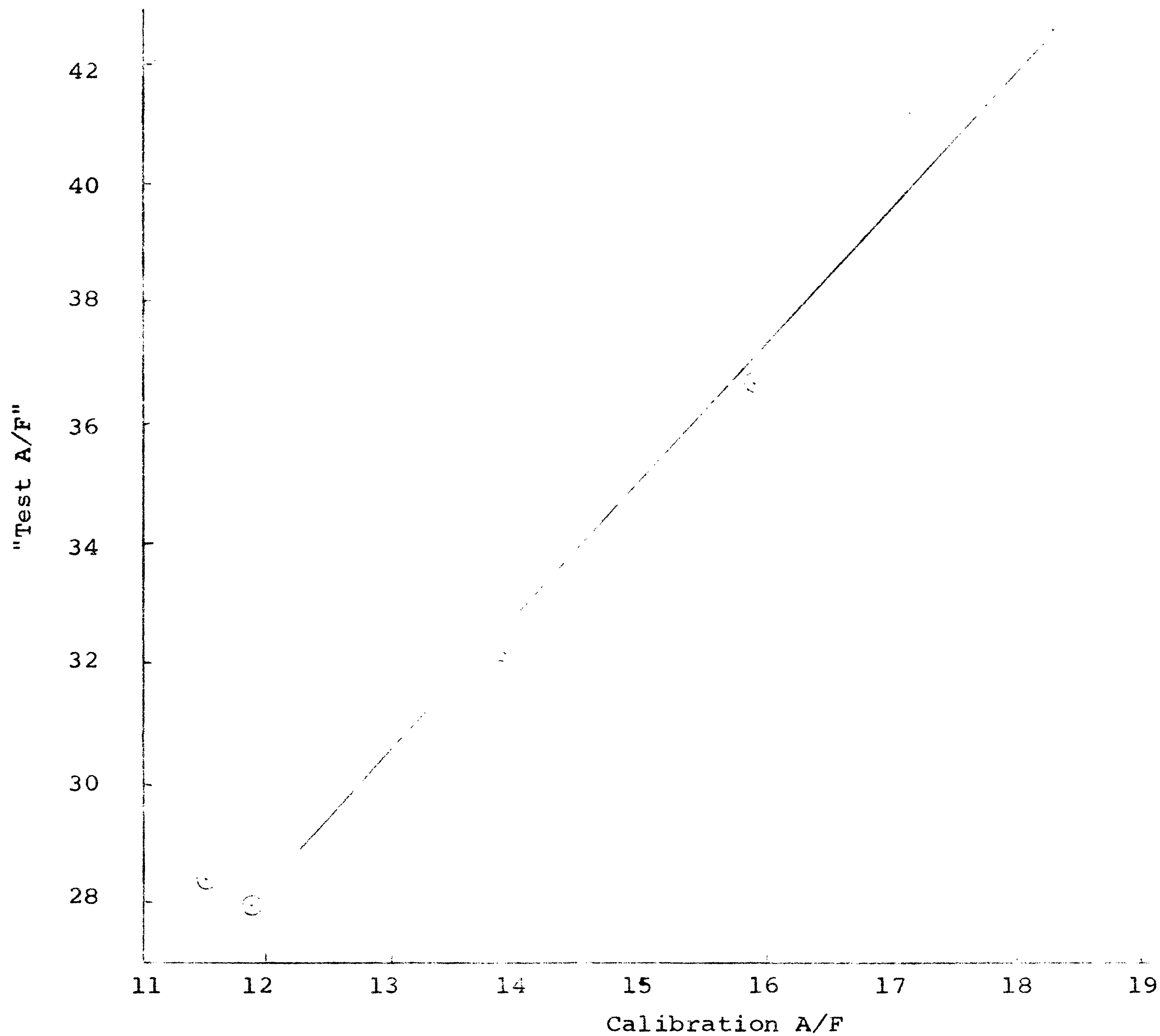

Figure 18 Comparison of "Test A/F" with Calibration A/F for 9-18-63 Tests private roads and test areas. Additional development work would be necessary to evaluate the effects of vehicle operation on the reliability and calibration and accuracy of the device.

2. Transient performance. Each data point represented three to five minutes operating time with three or more radiation counts made during this testing interval. Further, the signal shown on the recording potentiometer output has been highly damped (time constant of 10 sec.). This averaging process is necessary because of the statistical nature of the signal from a radioactive decay process, is truly a random process, and while the average over some period of time can easily be determined (total counts divided by elapsed time), the calculated average count rate and the actual average count rate are in better agreement as the sample time period is increased. A typical signal trace, including a transient resulting from a throttle setting change, is shown in Figure 19.

This A/F measurement procedure could measure a transient occurring over several minutes, but not a transient occurring over seconds or milliseconds. In order to apply this A/F measurement method to a 10 to 100 millisecond transient either the identical transient must be repeated as many as 10 times in order to get

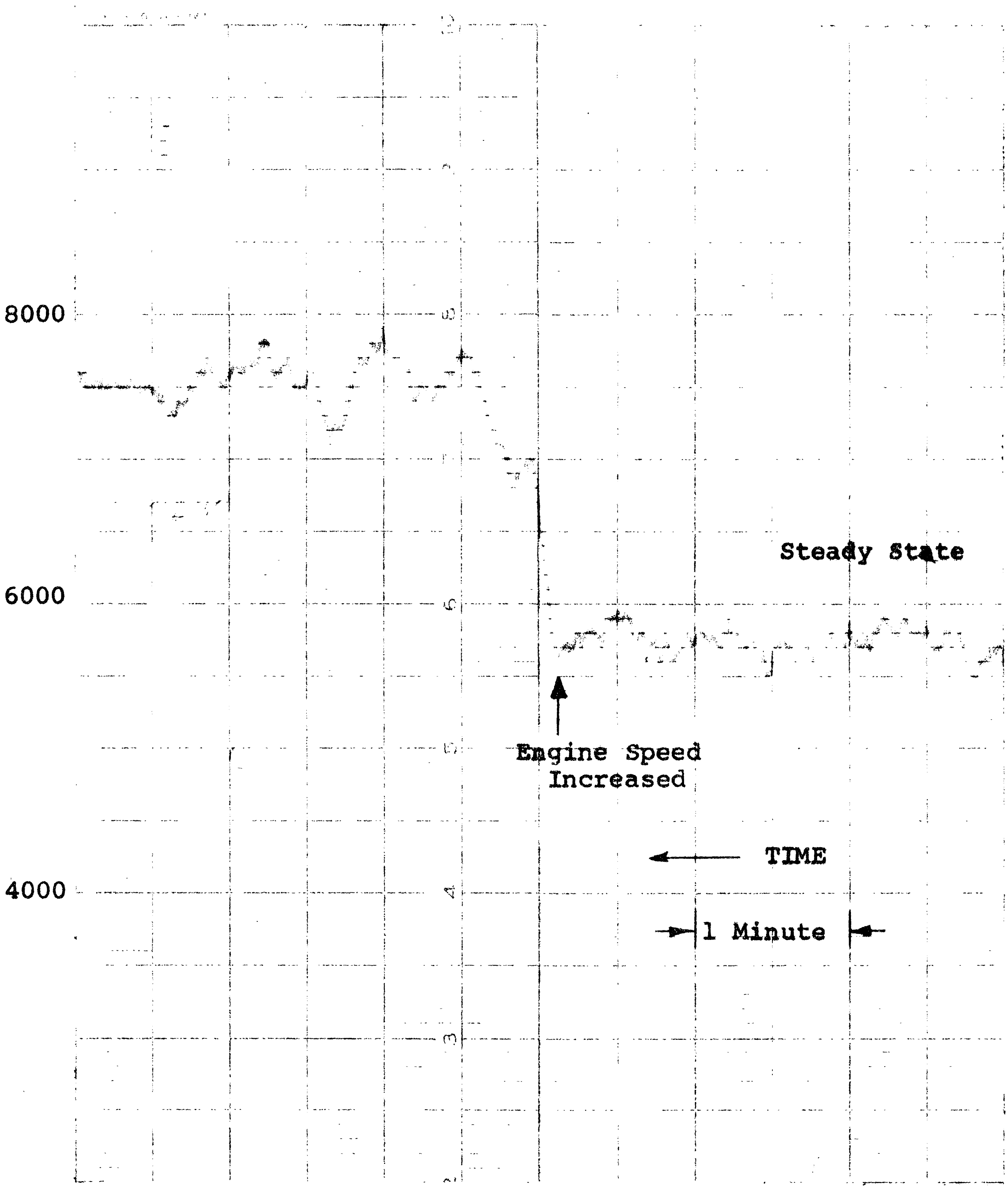

Figure 19 Typical Trace of Fuel Count Rate Signal

enough data such that the signal could be properly smoothed or the data from a single transient must be smoothed mathematically. The former procedure appears to be experimentally difficult while the latter involves a certain amount of electronic equipment.

Conclusions

1. A method has been devised to measure the A/F with an accuracy of 1 A/F unit for steady state operation of an automotive engine.

2. The application of this method to transients in A/F of the order of 10 to 100 milliseconds involves additional experimental operation and data-reduction equipment and procedures.

Appendix A

Equipment Details

1. Geiger-Mueller tubes

   a. Low-temperature (80 - 100F)

      Model 112, Anton Electronic Laboratories

   b. High temperature (80 - 250F)

      Type 90L, Amperex Electronic Corp.

2. Counter (scaler)

   Model N-221, Hamner Electronics Co., Inc.

3. Count rate meter

   Model 441A, Baird Atomic Co.

4. Recording Potentiometer

   Leeds and Northrup, Speedomax Type G

5. Counter (engine rpm)

   Model 521A, Hewlett-Packard

6. Flowmeter

   Model MU-3/8-3, Potter Aeronautical Co.

5. Throttle setting. Read directly from throttle quadrant.

6. Test section pressure. Read directly from micromanometer.

7. Test section temperature. Read from copper constantan thermocouple on potentiometer, reading directly in degrees F.

8. Background radiation count rate. With the "hot" fuel in position, but not being supplied to the engine, a reading was taken of the count rate from the G-M tubes installed in the test configuration. The procedure is to display the number of counts in a one or two minute count period on the scaler.

9. Total count rate. The total count rate, as measured by the scale during a hot fuel run, is reduced by the background rate.

10. Test on internally measured A/F signal

$$\text{Test A/F} = \frac{\text{net count rate (counts/min)}}{\text{test section pressure (psia)/temperature (}^{\circ}\text{R)}}$$

Appendix B

Inlet Manifold Flow Distribution Measurements

The velocity distribution in the inlet manifold was measured using a turbine flowmeter. The flowmeter is shown installed in a section of transparent (Plexiglas) duct and was placed in the identical position of the test section shown in Figs. 5 and 6. The duct could be rotated through 360°, also the flowmeter position could be varied radially. The flowmeter case diameter of 9/16 inch is not small as compared with the I.D. of the transparent duct; hence some blockage effects are probably present, even though the frontal area of the flowmeter is not large as compared with the total flow area of the duct.

In any case, the readings of the flowmeter in terms of average velocities through the flowmeter geometry, should be within 10% or so of the actual velocities found in the duct at a point 3 inches downstream of the carburetor base as shown in Figure 20.

Two conclusions can be immediately drawn from these data:

(1) If a representative duct flow velocity is required, it must be based on an integrated or average velocity of the entire duct.

(2) The presence of fuel appears to alter the velocity signal obtained from the turbine flowmeter.

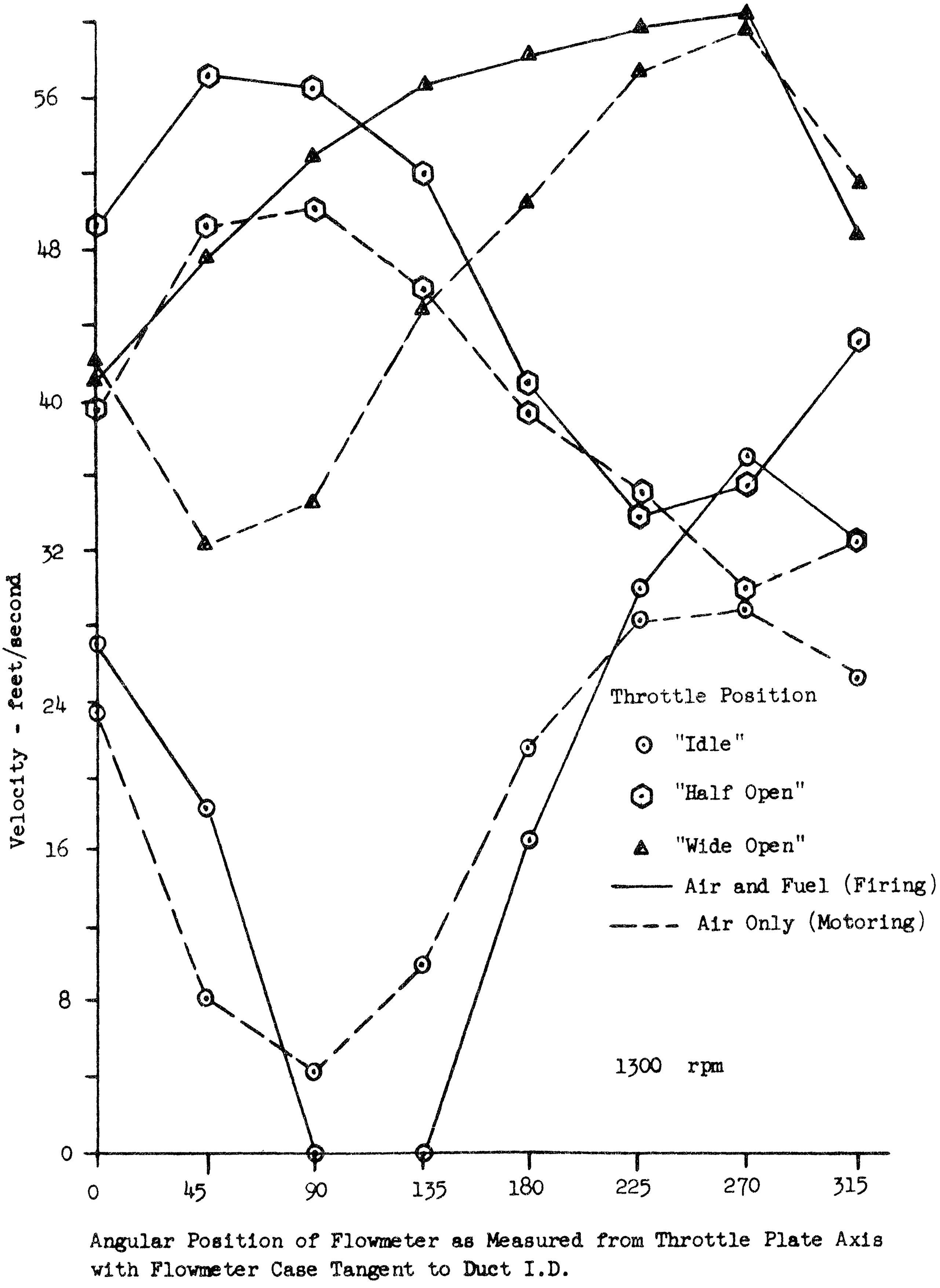

Fig. 20. Manifold velocities 3 inches downstream of carburetor base.

Appendix C

Development of a Manifold Flowmeter - the "Dragmeter"

This account is a brief summary of a portion of Mr. David C. Hoselton's Fifth Year Report entitled, "Air-Fuel Measurement" and is included here from a standpoint of completeness.

The results of the velocity distribution in the inlet manifold indicated that any instrumentation installed in the duct must produce a minimum effect on the flow and also must produce a signal which represents average or integrated conditions over the entire duct.

With these requirements in mind, a circular grid was devised composed of 0.005 inch diameter wire, and supported by two cantilever struts, on which strain gages were mounted. By proper spacing of the grid wires a drag signal should be obtained which represents the average or integrated aerodynamic conditions existing across the manifold at the measuring station. Further the strain gage signal should then be proportional to this total drag and hence furnish a flow signal. If the density of the flow is constant, the drag on the grid should be proportional to the square of the velocity.

Typical results are shown in Figure 21; it would appear that this would be a very useful instrument for measuring average manifold flow velocities in the presence of fuel vapor and droplets.

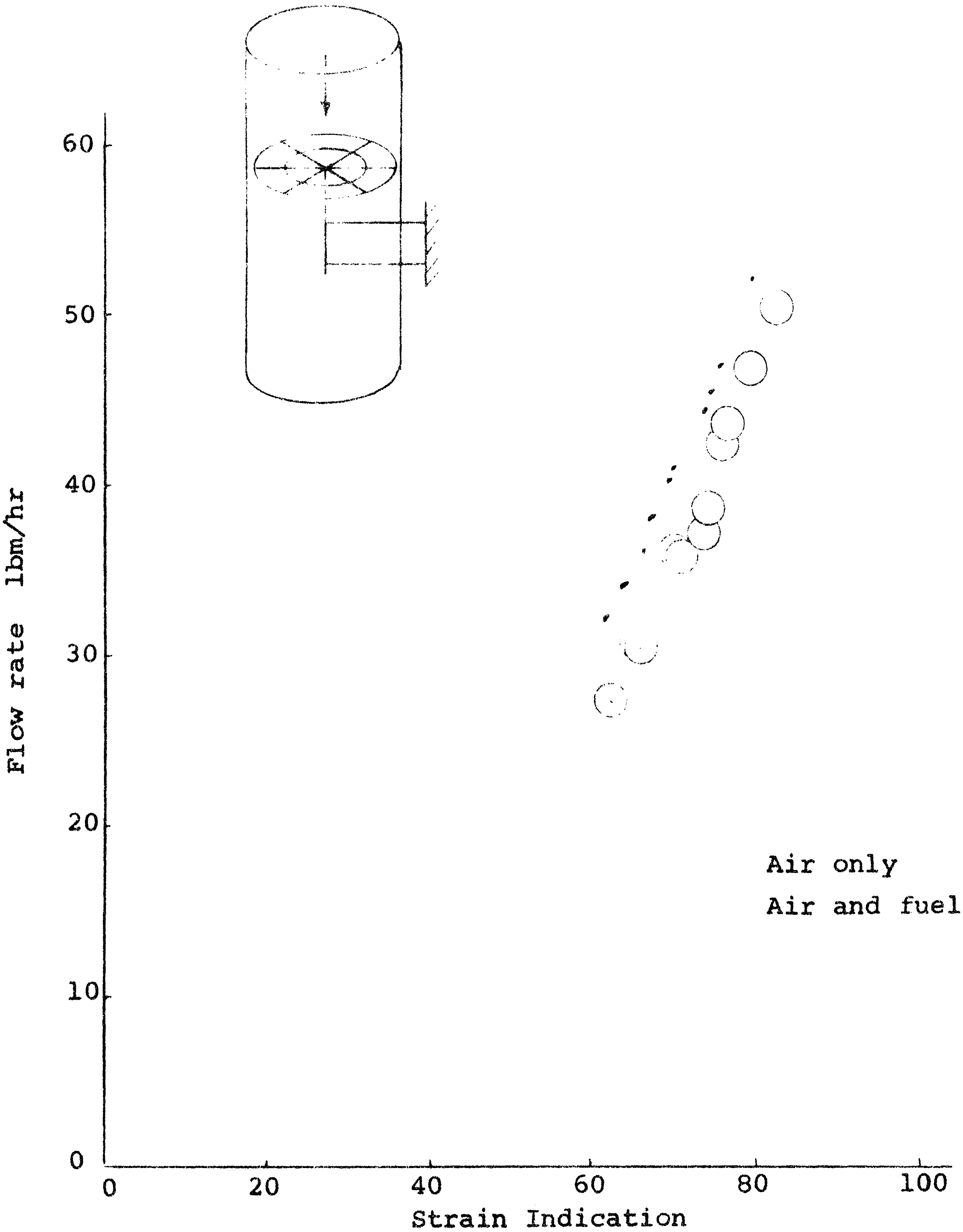

Figure 21 Air and air-fuel mixture flow rates and Strain Measurements compared

Appendix D

Data Reduction Procedures

1. Calibration or external air flow rate. Pressure and temperature upstream of the orifice was measured along with the total area of the orifices used was known and substituted in the following equation

$$\dot{m}_a = \frac{K_n P}{\sqrt{T}}$$

where

$\dot{m}_a$ = air mass flow rate LBM/HR

P = nozzle pressure, psia

T = air temperature, ^{o}R

K_n = nozzle constant

2. Calibration or external fuel flow rate. Measurement of the time required for a given translation deflection of the piston rod of the fuel cylinder as measured by a conventional dial indicator reading to 0.001 inch produced a displacement velocity; which when combined with the cross-sectional cylinder bore, gave a volume flow rate. Measurement of the fuel density with a hydrometer then gave a mass flow rate of fuel.

3. Engine Torque. Read directly from dynamometer balance.

4. Engine RPM. Read directly from counter.

Appendix E

Fuel Preparation Procedures

This procedure involves two main steps: first, the dilution of the Krypton 85 with common Krypton gas; and second, the degassing of the fuel and the introduction of the diluted Krypton 85 mixture into the fuel.

1. Krypton-85 Dilution. The radioactive or "hot" Krypton, as received from Oak Ridge National Laboratories, has a concentration of about 80 microcuries/cc which is too high for both legal and safety reasons and must be diluted with common Krypton to about 2 microcuries/cc. This dilution is accomplished by placing the common Krypton bottle, initially at 300 psi, in a liquid nitrogen bath which liquifies the Krypton and reduces the tank pressure to about 1 atmosphere. Then "hot" Krypton gas is fed to the cold tank; the tank is removed from the liquid nitrogen, brought to room temperature where the tank pressure rises to approximately 300 psi. This dilute "hot" mixture is then transferred to smaller bottles for handling ease.

2. Fuel Mixing. The apparatus shown in Figure 22 for mixing the "hot" Krypton with the gasoline consists of a mixing flask, a bottle of "hot" Krypton, a fuel cylinder, and a vacuum source, interconnected with

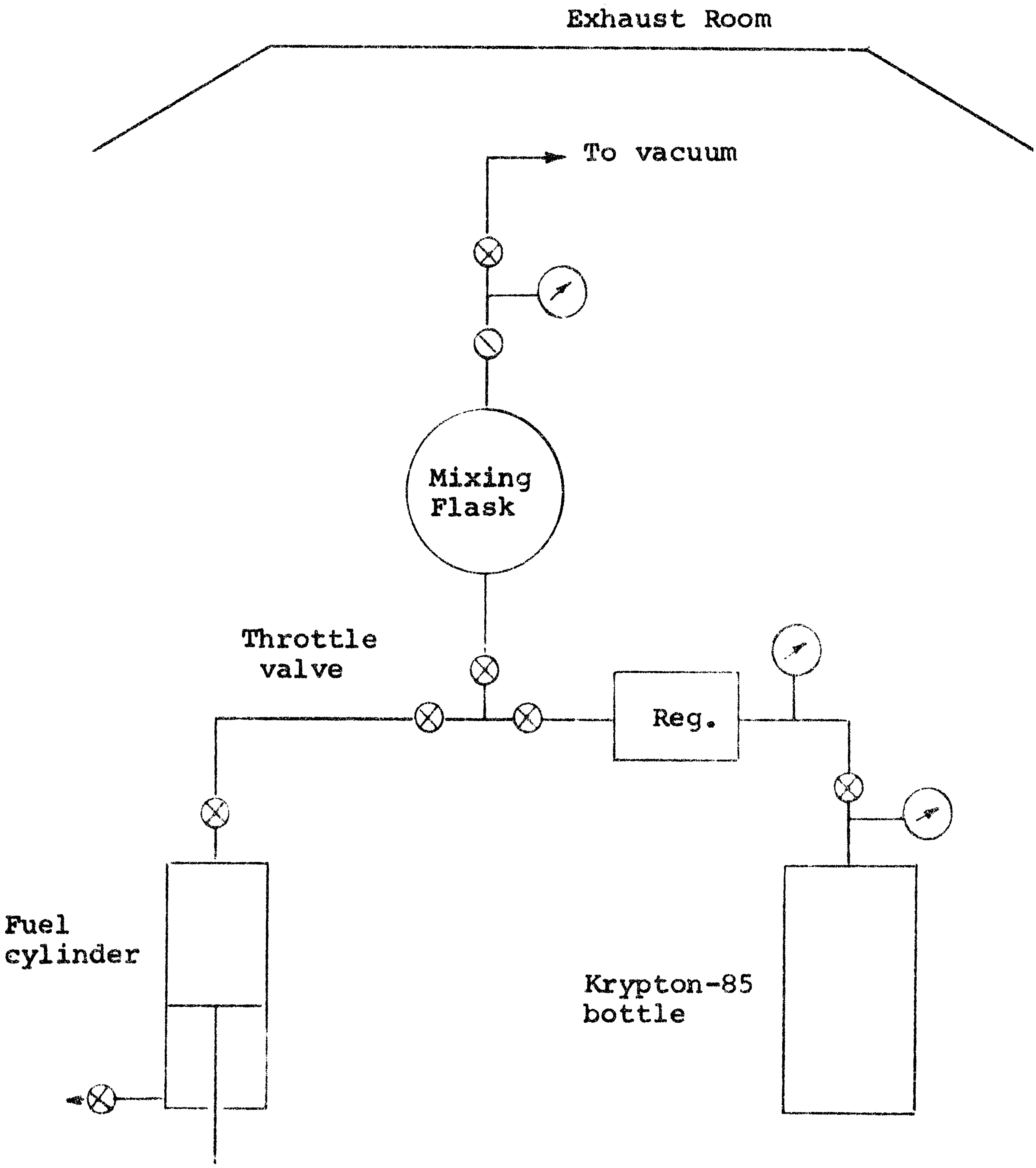

Figure 22 Fuel Preparation Apparatus

valving. The entire procedure takes place under an exhaust hood for safety reasons.

Initially the full fuel cylinder and the Krypton bottle containing "hot" diluted Krypton are connected to the apparatus while the mixing flask is empty.

With all valves in the Krypton line closed, valves are opened in the fuel, mixing flask, and vacuum lines so that a slight vacuum will bring the fuel from the fuel cylinder into the mixing flask. When the flask is full, valves between the mixing flask and the fuel cylinder are closed.

Applying a vacuum of 0.1 atmosphere to the fuel contained in the mixing flask removes a large part of the gases (mostly air) dissolved in the fuel. Now valves in the vacuum line are closed and the valves in the Krypton line are opened with the regulator remaining closed. When the pressure on the Krypton or upstream side of the regulator reaches 50 psi, the Krypton supply valve is closed. Now the regulator is set for 3 to 5 psi discharge pressure with the bubbling of Krypton gas through the fuel controlled by the Krypton throttle (needle) valve. As Krypton gas is bubbled through the fuel, the pressure in the Krypton supply line falls and must be replenished by temporarily opening the Krypton supply valve until the Krypton supply pressure again reaches 50 psi. As a safety precaution, the shut-off valve downstream of the regulator is closed when this is done.

The Krypton is assumed to be in equilibrium with the fuel if, with the Krypton, fuel, and vacuum valves closed, the pressure over the Krypton-impregnated fuel remains constant. The "hot" fuel can now be replaced in the fuel cylinder by venting the vacuum line and pulling a slight vacuum on the air side of the piston of the fuel cylinder.

Appendix F

Analytical Study of Droplet Characteristics

Analytical studies were made of the acceleration and vaporization rates of the droplets of liquid fuel flowing in a manifold. Using the assumptions of steady, one-dimensional flow in the duct, along with the assumption of a spherical droplet, with a drag coefficient, C_D expressed as

$$C_D = 27 (R_e)^{-0.84}$$

where the Reynolds number, R_e, is based on the relative velocity V, between the droplet and gas velocities, the droplet diameter, d, and the kinematic viscosity of the gas, ν, the drag force, F is written as

$$F = \frac{C_D A \rho_g V^2}{2 g_o}$$

and the acceleration, $\frac{dV}{d\theta}$, is then

$$\frac{dV}{d\theta} = \frac{3}{8} C_D \frac{\rho_g}{\rho_l} \frac{V^2}{r}$$

for a spherical droplet.

The energy equation written for an evaporating droplet is

$$\frac{dm}{d\theta} = \frac{h A_s \Delta T}{H_v}$$

where

m = droplet mass

θ = time

h = heat transfer coefficient at the droplet surface

A_s = surface area

ΔT = temperature difference between the droplet and the gas

H_v = latent heat of vaporization of the droplet liquid

Solving the combined energy and motion equations by numerical integration results in the data shown in Figs. 23 and 24.

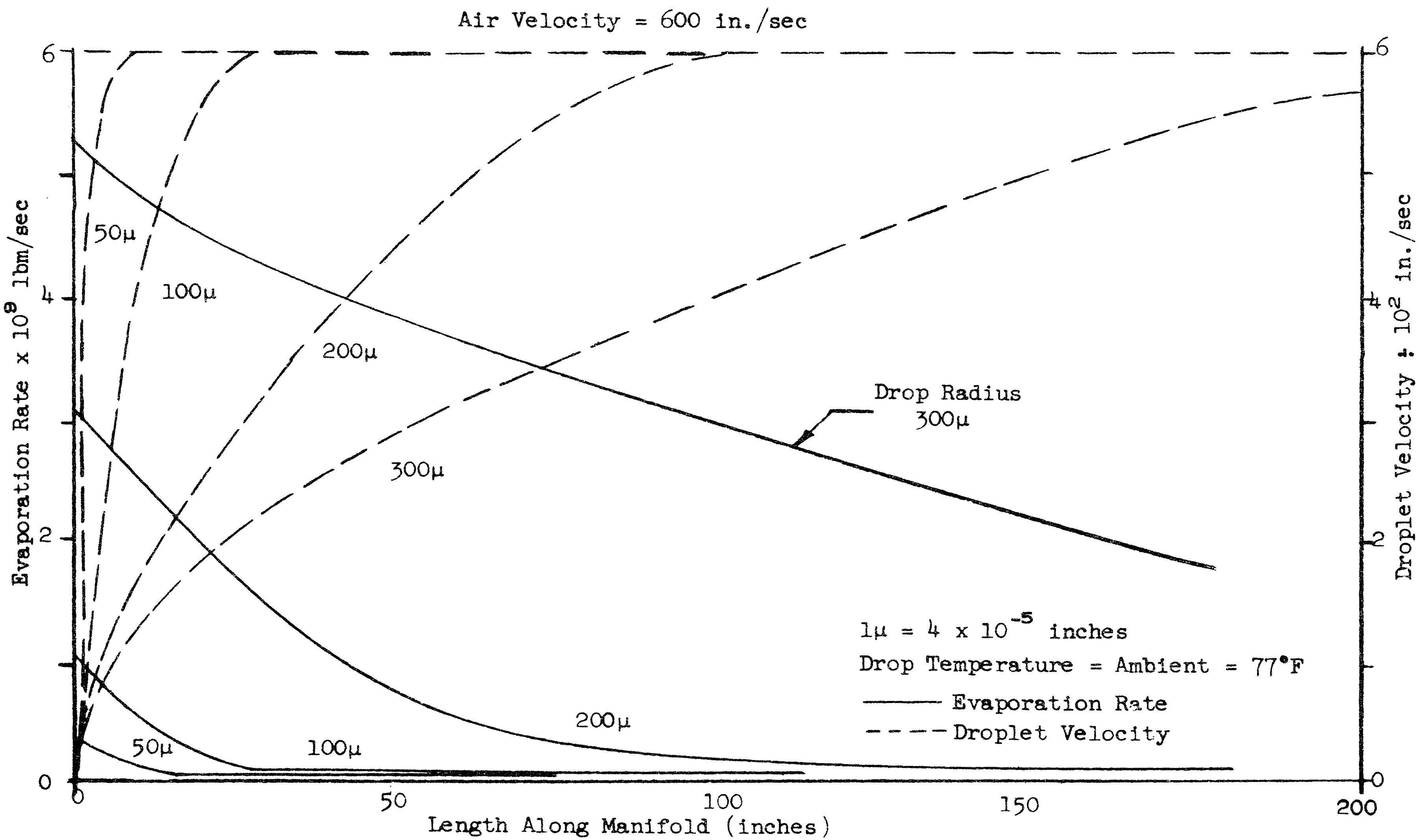

Fig. 23. Predicted droplet performance.

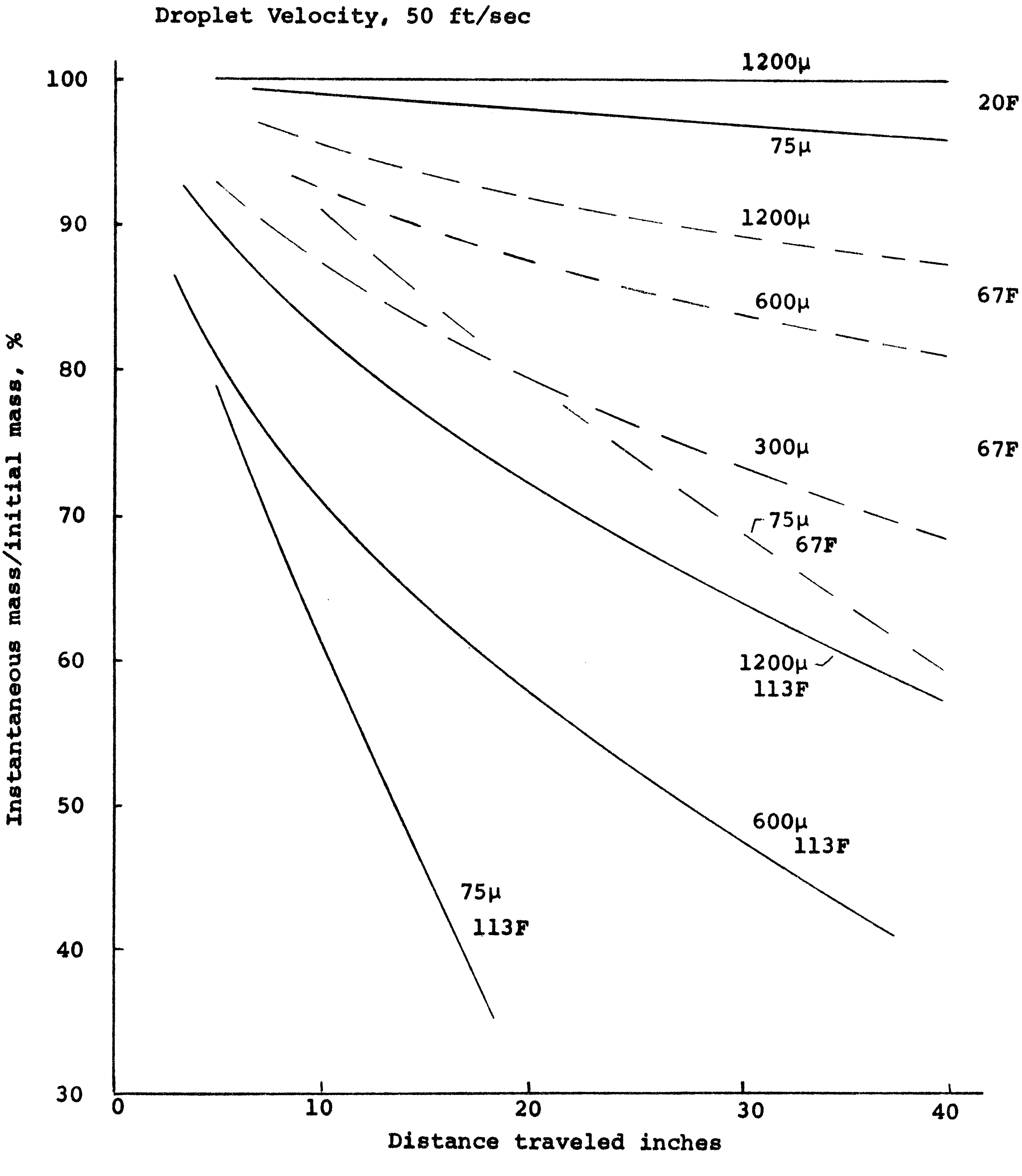

Figure 24 Variation in Droplet Mass as a function of initial radius, ambient temperature, and distance traveled