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ESL-TR-88-17

AD-A200 801

FUEL-ADDITIVE SYSTEM FOR TEST CELLS

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AUGUST 1988

FINAL REPORT

AUGUST 1987 - FEBRUARY 1988

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UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE:

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for Public Release Distribution Unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S):

5. MONITORING ORGANIZATION REPORT NUMBER(S): ESL-TR-88-17

6a. NAME OF PERFORMING ORGANIZATION: Battelle, Columbus Division

6b. OFFICE SYMBOL (If applicable):

7a. NAME OF MONITORING ORGANIZATION: Air Force Engineering and Services Center

6c. ADDRESS (City, State, and ZIP Code): 505 King Avenue, Columbus, Ohio 43201-2693

7b. ADDRESS (City, State, and ZIP Code): HQ AFESC/RDVS, Tyndall Air Force Base, Florida 32403-6001

8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Air Force Engineering and Service Center

8b. OFFICE SYMBOL (If applicable): HQ AFESC/RDVS

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F08635-85-C-0122

8c. ADDRESS (City, State, and ZIP Code): Tyndall AFB, Florida 32403-6001

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
2103	70	32	

11. TITLE (Include Security Classification): Fuel-Additive System for Test Cells

12. PERSONAL AUTHOR(S): Folsom, Dale W.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 87-08-05 TO 88-02-25	August 1988	30

16. SUPPLEMENTARY NOTATION: Availability of this report is specified on reverse of front cover.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
	21	05
	21	02

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Test Cell; Emission Control; Fuel-Additive; Cerium Octoate; Opacity

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This research study was to design, build, and test a prototype fuel-additive system to reduce opacity of turbine engine test cell emissions. The prototype fuel-additive system is capable of delivering 0.0 to 0.5 gallons per minute (0.0 - 1890 milliliters per minute) at up to 50 psig. The system was demonstrated at McClellan AFB, Sacramento, California, during November, 1987.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
Major Paul E. Kerch	904-283-4234	RDVS

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

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PREFACE

This report was prepared by Battelle Columbus Division, 505 King Avenue, Columbus, Ohio 43201-2693, under Contract Number F08635-C-0122, Subtask 1.08. This work was sponsored by the Air Force Engineering and Services Center, Engineering and Services Laboratory (AFESC/RDVS), Tyndall Air Force Base FL 32403-6001. The report documents work performed between August, 1987 and February, 1988. The Air Force Project Officer was Major Paul E. Kerch.

Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the Air Force, nor can the report be used for advertising products.

The author wishes to acknowledge the contribution of Mr. Harry K. Nuzum for his help in the design and construction of the fuel-additive system, Mr. Vincent Brown for editing, and Mrs. Joyce A. Danford for text processing.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

A. OBJECTIVE

The purpose of this project was to provide the U.S. Air Force with design data and a prototype of a fuel-additive system capable of reducing plume opacity during testing of a jet engine in a test cell.

B. BACKGROUND

Jet engines are tested in a test cell after servicing and before placement in an aircraft. Certain jet engines, J-57, J-79, and TF-33 in particular, generate soot which exits the test cell in a plume of greater than 20 percent opacity (Ringelmann number of 1 or greater). This opacity exceeds the opacity limit (20 percent) set by the Environmental Protection Agency (EPA). The U.S. Air Force has previously funded projects that found two jet fuel additives, ferrocene and cerium octoate, that reduce the plume opacity.

C. SCOPE

The scope of this project included the design, construction, and testing of a prototype fuel-additive system. The following report describes the fuel-additive system requirements, design parameters, design, fabrication, and testing of the prototype system. The prototype fuel-additive system, properly built and operated, will provide the U.S. Air Force a means of testing jet engines in test cells while staying within EPA opacity limits. The fuel-additive system is simple and easy to construct and operate.

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SECTION II

FUEL-ADDITIVE SYSTEM REQUIREMENTS

A. FLOW RATE

The purpose of the fuel-additive system is to provide a means of injecting a metered amount of fuel additive into the jet fuel line just before it enters the jet engine. The additive is injected into the fuel line as close to the engine as possible to reduce the time required for the additive to physically reach the engine. The additives are expensive and are required only at specific times for certain engines; premixing the additive in he fuel tank is thus, impractical. Based on the past studies, the highest fuel additive flow rate was 0.4 gal/min for ferrocene and the lowest was 0.04 gal/min for cerium octoate (Reference 1). The fuel-additive system flow rate range requirement was set at 0.0 to 0.5 gal/min for the prototype system design. The flow should be adjustable and should be able to remain constant during changes in the fuel system pressure.

B. PRESSURE

The jet engine fuel line pressure typically is 35 to 40 pounds per square inch, gauge (psig). The fuel-additive system should exceed this pressure to inject the additive into the fuel line. The pressure requirement for the prototype fuel-additive system was set at 50 psig. This value ensures sufficient pump capacity for the additive system.

C. HARDWARE

The system design requirements included other considerations, such as material compatibility with the additives, additive viscosity, and system features including automation, ease of use, system condition readouts, and environment and location of the system. The active ingredients in the additives are carried by organic solvents which deteriorated seals and gaskets. Viton® was shown to be an acceptable elastomer and seal material in a past study (Reference 1). Stainless steel and Teflon® have been shown to be acceptable construction materials.

The viscosity of the additives is important in sizing the pump, filters, and fuel-additive lines. Correct sizing eliminates excessive pressure drop. The past studies by the Aircraft Environmental Support Office and the Naval Air Propulsion Center recommended a minimum line size of 3/8-inch (References 1 and 2).

The location of the fuel-additive system dictates the type of electrical equipment required for safe operation of the system. The system was to be located indoors in an environment that did not require the electrical equipment to be explosion-proof.

SECTION III

FUEL-ADDITIVE SYSTEM DESIGN

A simplified fuel-additive system schematic is shown in Figure 1, which shows the major components and interfaces of the system. The fuel-additive system meters fuel additives from a 55-gallon drum to the jet fuel line of the engine being tested. Additive flow and pressure are monitored. A flowmeter provides input to a process controller, which in turn regulates the fuel-additive pump.

The metering pump is the heart of the fuel-additive system. The pump can be a positive displacement pump with variable speed to regulate flow or it can be a centrifugal pump with a flow control valve to regulate flow. At the desired low 0.01-0.4 gal/min flow range of the fuel-additive system and the wide turn-down ratio of 40 (0.4/0.01), the most flexibility and ease of operation is achieved by use of a variable speed positive displacement pump. To eliminate pulsed flow, a gear pump was coupled with a variable speed motor accepting a 4-20 mA control signal. The pump was a Tuthill DCM 9045-MC seal-less high torque magnetic drive gear pump with a flow range of 0-40 gal/hr (0.67 gal/min) for 70°F water at a differential pressure of 140 psi. The pump is a 316 stainless steel body with nickel alloy stainless driving gear and carbon/Teflon® filled Ryton® driven gear. O-rings are Teflon® and the bearings are carbon/Teflon® filled Ryton®. The inlet and outlet pump connections are 1/8-inch pipe threads.

The flow sensor selected was a positive displacement flowmeter. A positive displacement flowmeter was selected due to the low flow rates expected and the results of past studies with fuel additives using the same type of flowmeter (Reference 1). The flowmeter selected was a series 214-301 "Max" positive displacement flowmeter, equipped with a 276-525 analog flowmeter transmitter. The transmitter generates a 4-20 mA signal for input to a process controller.

The process controller takes a 4-20 mA signal from the flowmeter and generates 4-20 mA signal in relation to the flowmeter input to control the variable speed gear pump. The controller selected was the Honeywell UDC-3000, a microprocessor-based stand alone controller. It offered flexibility and ease of use. It was ordered with a secondary input option to allow for either ratio

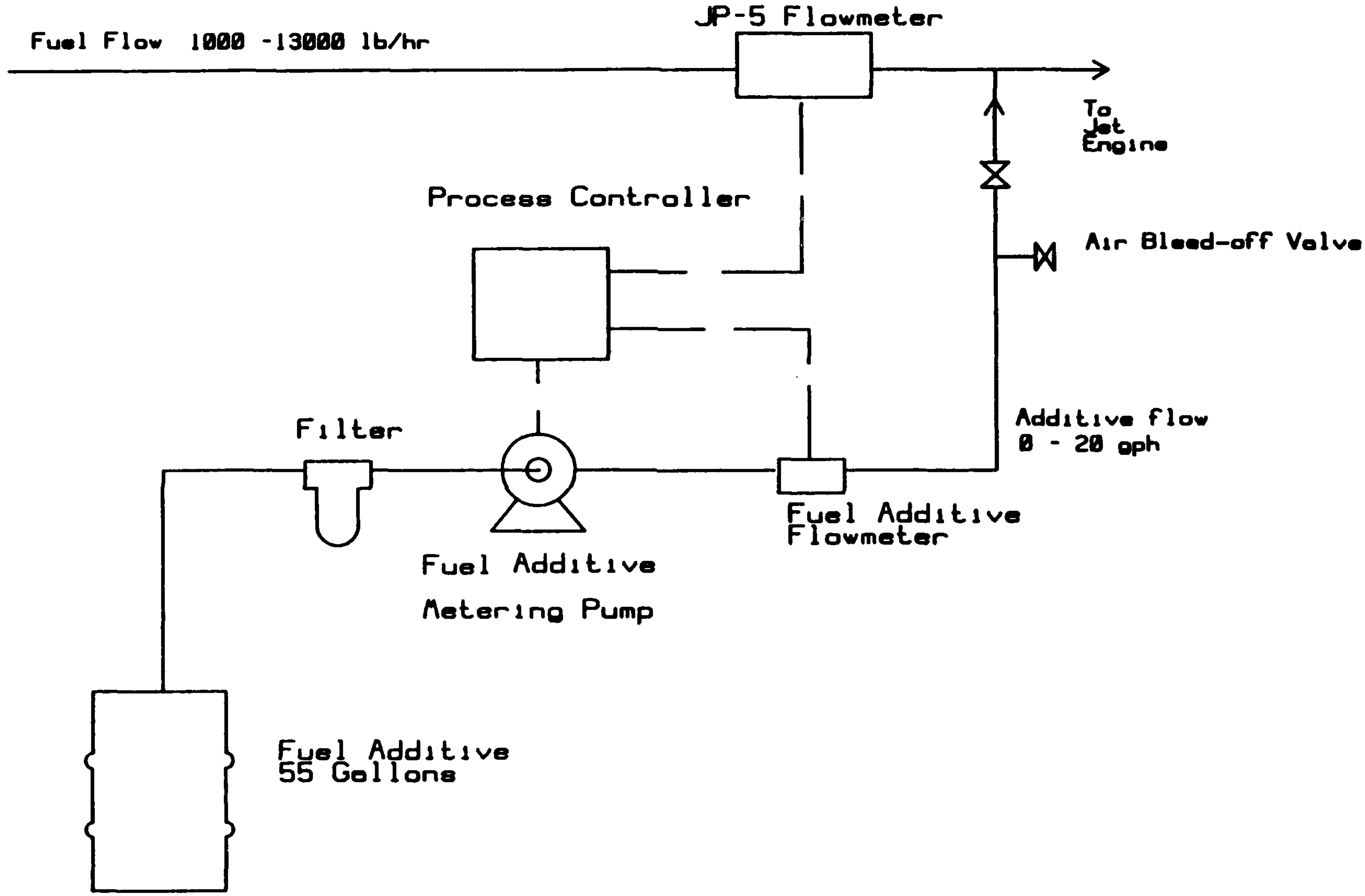

Figure 1. Fuel-Additive System Concept.

control in relation to the amount of fuel flowing to the engine or for interface with the test cell controls. The secondary input option was not used in this project.

The remainder of system design consisted of selecting materials to plumb the pump and flowmeter to the fuel-additive drum and the jet fuel line. A check valve was placed in the fuel-additive line, near its connection to the jet fuel line to keep jet fuel from flowing back into the fuel-additive system. Valves were placed in the fuel-additive system to allow servicing. The valves, check valve, and other plumbing fittings are shown in Figure 2. A bypass line around the flowmeter was installed to prevent damage to the flowmeter during priming of the pump and flushing of air from the system. Filters were installed in front of the pump and flowmeter to protect and remove particulate material coming from the fuel additive. The filter element sizes were based on the clearances of the gears in the pump and flowmeter. The flowmeter clearances between the piston and the cylinder bore are typically 0.0002-0.0004 inches, and the manufacturer recommends a 10 micrometer filter be installed upstream of the flowmeter to protect it from particulate matter. The seven (7) micrometer filter was selected for the preflowmeter filter because of its availability. The prepump filter was sized at 15 micrometers to protect the pump from particulate matter that may be in the fuel additive. Sixty (60) micrometer filter elements were ordered if problems developed form the use of the smaller filter element sizes.

The line sizes used were based on the flow rates desired, liquid viscosity, and sizes readily available. One-half inch tubing and fittings were used up to the pump inlet. Three-eighths-inch tubing and fittings were used downstream of the pump, except for the flex line, which was 1/4 inch. The flex lines were available locally only in 1/4-inch or 1/2-inch diameters; otherwise, 3/8-inch lines would have been used.

The process controller was placed in a separate metal box, along with the variable speed motor control unit and the required switches and power supplies. The wiring diagram for the fuel-additive system control box is shown in Figure 3.

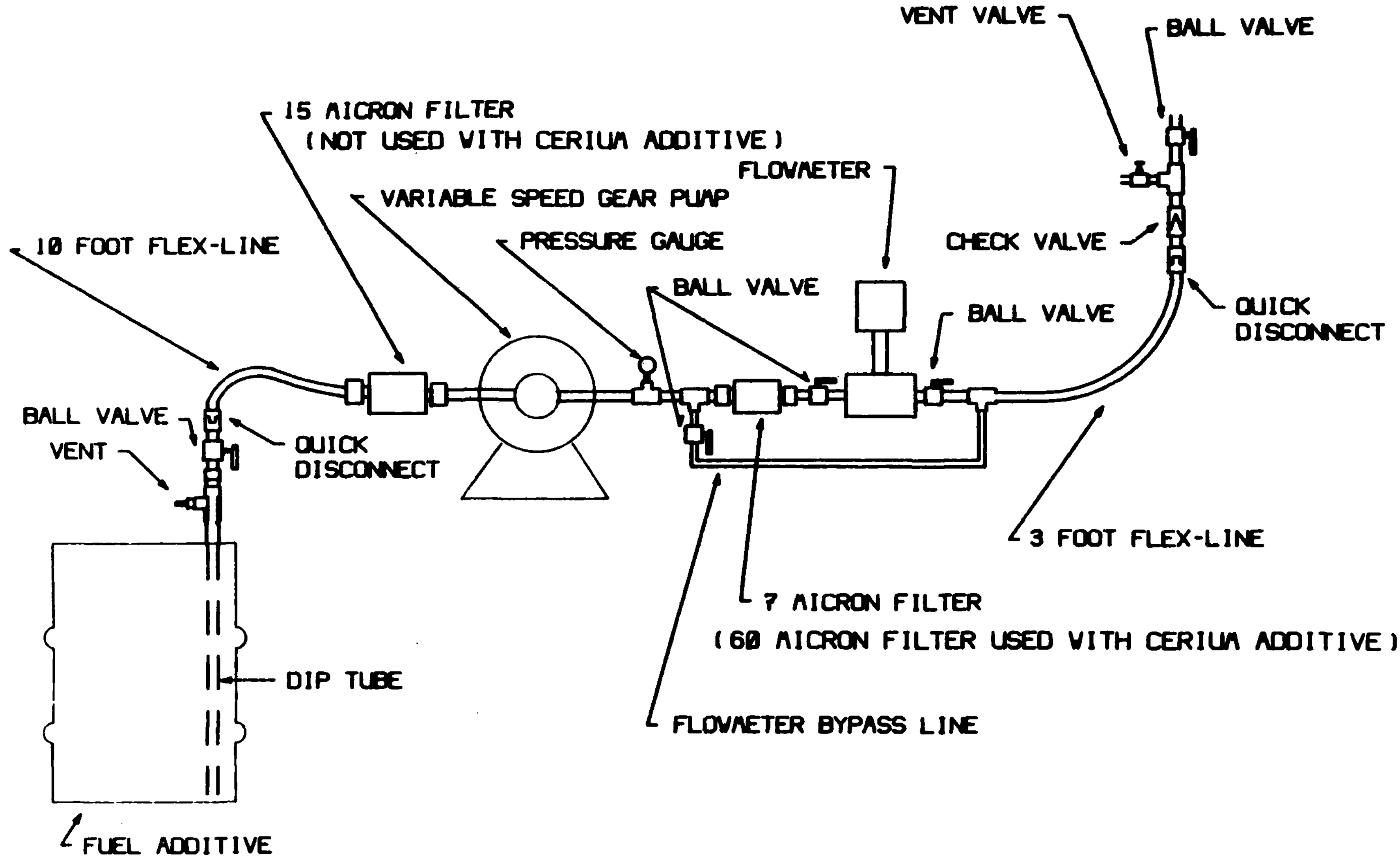

Figure 2. Fuel-Additive System Diagram.

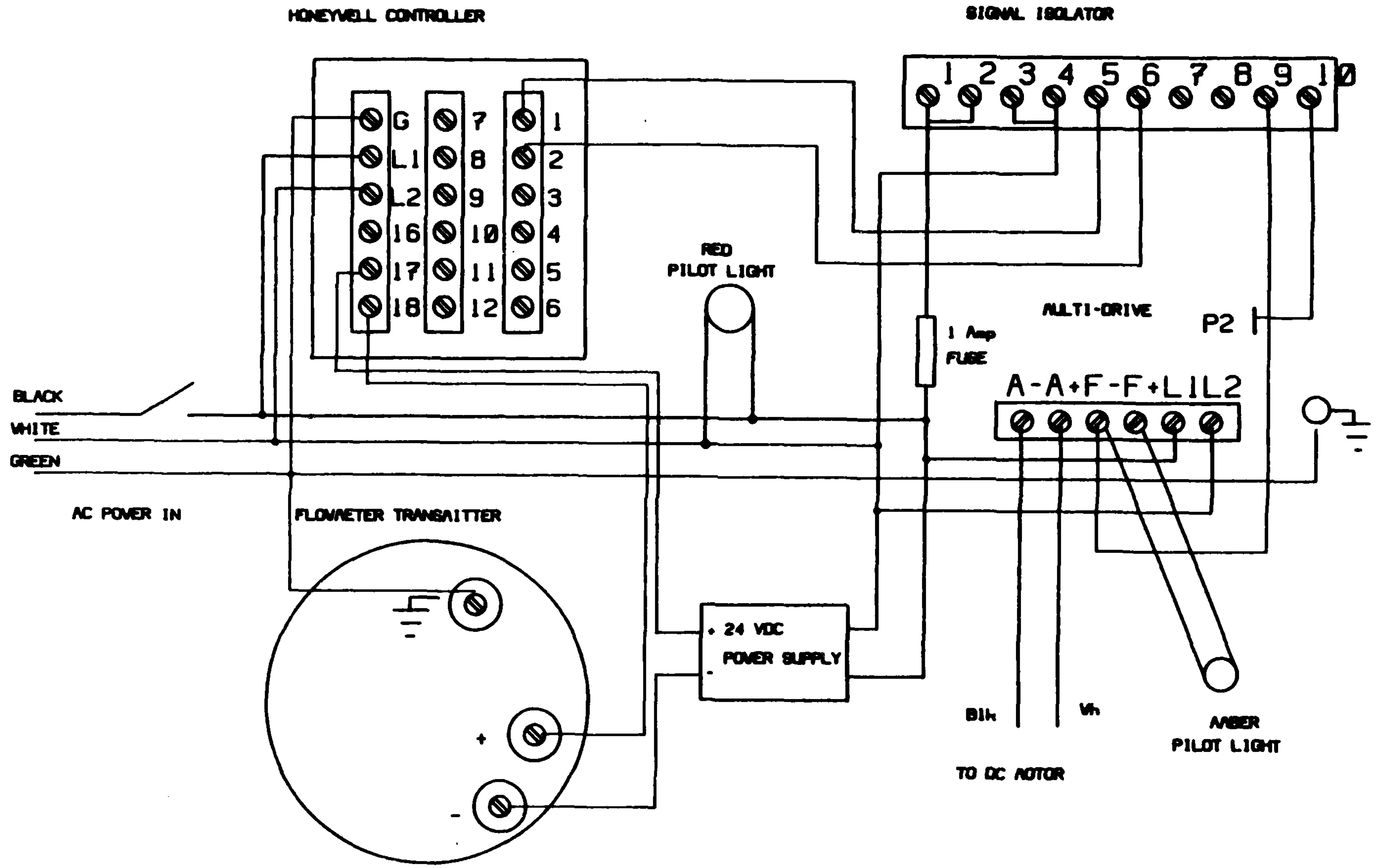

Figure 3. Fuel-Additive System Wiring Diagram.

TABLE 1. FUEL-ADDITIVE SYSTEM MAJOR EQUIPMENT LIST

ITEM	MANUFACTURER	CATALOG #	PRICE
PUMPING UNIT			
Quick Connect 1/2" T Deso Stem	Swagelok	SS-QC8-D-810	$ 37.07
Flexhose Teflon Lined 1/2" x 10' w/Tubing Ends	Cajon	SS-8BHT-120	$ 165.36
Pump Inlet Filter 1/2" 15 micron Sintered Element	Nupro	SS-8F-15	$ 69.19
Spare Sintered Elements 15 micron	Nupro	SS-8F-K4-15	$ 4.73
Fract. Tube Adapter 3/8" T x 1/8" MNPT (2)	Cajon	SS-6-TA-1-2	$ 3.36
Variable Speed Pump with Motor	Tuthill	DMC-9045-MCV	$ 750.00
Female Branch Tee 3/8" T x 1/4" FNPT (2)	Swagelok	SS-600-3TTF	$ 23.42
Snubber Adapter 1/4" NPT	Cajon	SS-4-SA-EW	$ 10.40
Pressure Gauge 0-100psig 2 1/2" Dial SS Oil Filled 1/4" NPT	--------	------------	$ 38.00
Flowmeter Inlet Filter 7 micron Sintered Element 3/8" T	Nupro	SS-6F-7	$ 55.23
Spare Sintered Element 7 micron	Nupro	SS-8F-K4-7	$ 4.73
Spare Sintered Element 60 micron	Nupro	SS-8F-K4-60	$ 4.73
Flowmeter	Max Peters	214-301	$1,100.00
Transmitter	Max Peters	276-525	$ 700.00
Conv. Fitting Adapter 3/8" T x 3/8" MNPT (2)	Cajon	SS-6-TA-1-6	$ 5.46
Ball Valves 3/8" (4)	Whitey	SS-44S6	$ 84.21
Tubing Reducer 3/8" T to 1/4" T (2)	Swagelok	SS-400-R-6	$ 6.35
Flexhose Teflon Lined 1/4" D. x 3' w/Tubing Ends	Cajon	SS-4BHT-36	$ 42.11
Quick-Connect 3/8" SS Deso Stem	Swagelok	SS-QC6-D-600	$ 24.98
Quick-Connect 3/8" SS Body	Swagelok	SS-QC6-B-600	$ 30.24
Shutoff Valve (Vent Valve)	Whitey	SS-OKF2	$ 35.28
1/8" T to 1/8" FNPT Connector	Swagelok	SS-200-1-2	$ 5.09
Union Tee 3/8" T (2)	Swagelok	SS-600-3	$ 20.53
Check Valve with 25 psi spring 3/8" T	Nupro	SS-6C-25	$ 56.18
Tubing 3/8" O.D. x 5' L. SS	--------	------------	$ 5.00
Misc. (Base Plate, Bolts, etc.)	--------	------------	$ 25.00
		Total	$3,618.40

TABLE 1. FUEL-ADDITIVE SYSTEM MAJOR EQUIPMENT LIST (CONCLUDED)

ITEM	MANUFACTURER	CATALOG #	PRICE
DIP TUBE ASSEMBLY (2 MADE)			
Dip Tube 1/2" O.D. x 4" L. SS	-------	------------	$ 5.00
Pipe Nipple 3/4" D. x 4" L. SS	-------	------------	$ 7.70
Pipe Tee 3/4" SS	-------	------------	$ 9.15
Pipe Bushing 3/4" x 1/4" SS	-------	------------	$ 3.92
Check Valve 1/4" (vent)	Nupro	SS-4CP2-1	$ 17.85
Deflector Cap	Nupro	P-4CP4-K12-RD	$ 2.31
Ball Valve 1/2" T	Whitey	SS-45S8	$ 129.36
1/2" T x 3/4" MNPT	Swagelok	SS-810-1-12	$ 14.65
Quick Connect 1/2" T Body	Swagelok	SS-QC8-B-810	$ 47.85
		Total	**$ 475.58**
CONTROL UNIT			
Motor Speed Pump for Variable Speed Pump	Tuthill	7400	$ 300.00
Signal Isolator for Variable Speed Pump	Tuthill	7414	$ 240.00
Digital Process Controller	Honeywell	DC3002-0-01A-2-00	$ 595.00
Portacab Instrument Cabinet, Aluminum	Hughes Peters	WA1542	$ 40.00
24 V DC Power Supply	-------	------------	$ 37.00
Switch	-------	------------	$ 4.00
Pilot Light, Terminal Strip, Wiring, Plugs	-------	------------	$ 8.00
Misc. (Sheet Aluminum, Screws, etc.)	-------	------------	$ 20.00
		Total	**$ 1,244.00**
		GRAND TOTAL	**$ 5,337.98**

Table 1 lists the equipment used in the fuel-additive system, along with model numbers, part numbers, and costs. The manufacturers listed are not necessarily the recommended manufacturers, but those who either had the equipment in stock, or could produce it quickly. The schedule for the project required that the fuel-additive system be designed and fabricated in 8 weeks, resulting in the selection of in-stock equipment items.

The fuel-additive system, as built, is shown in Figure 4, which shows the pump in the foreground and the dip tube into the 55 gallon drum of additive in the background. Figure 5 shows a side view of the pump and flowmeter. A closeup of the dip tube assembly is shown in Figure 6. The vent valve is located on the side of the pipe tee below the ball valve. The quick-disconnect fitting is located above the ball valve. Figure 7 shows a closeup of the connecting end of the fuel-additive system. The ball valve used to isolate the fuel-additive system from the fuel line is the end item of the fuel-additive system. The air-bleed-off valve is located before the ball valve and after the check valve. The quick disconnect fitting is located between the check valve and the flex-line. The control box which contains the main power switch and the process controller is shown in Figure 8. The control box is equipped with two pilot lights: one indicating power to the system, and one indicating power to the pump.

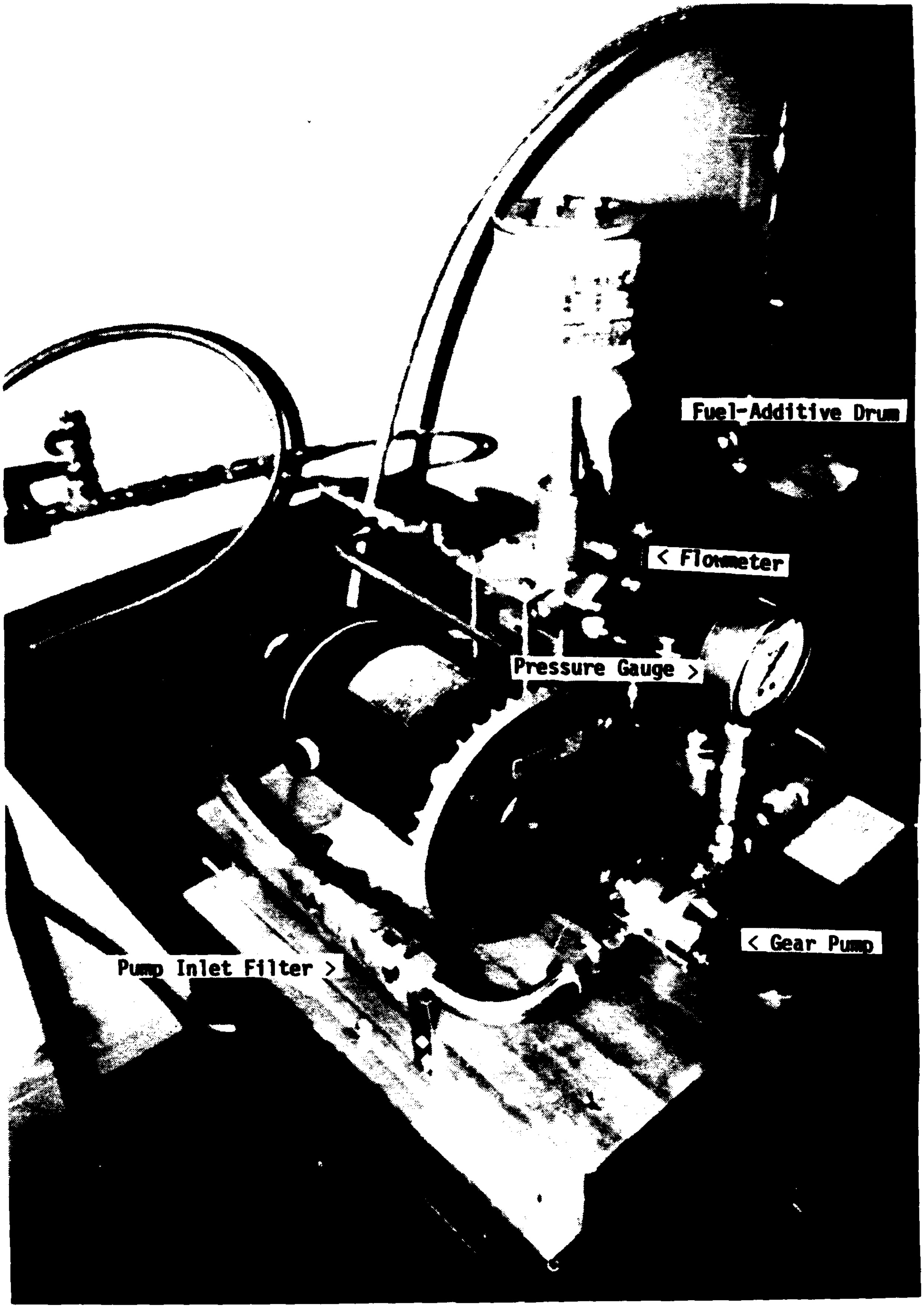

Figure 4. Fuel-Additive System Pumping Unit.

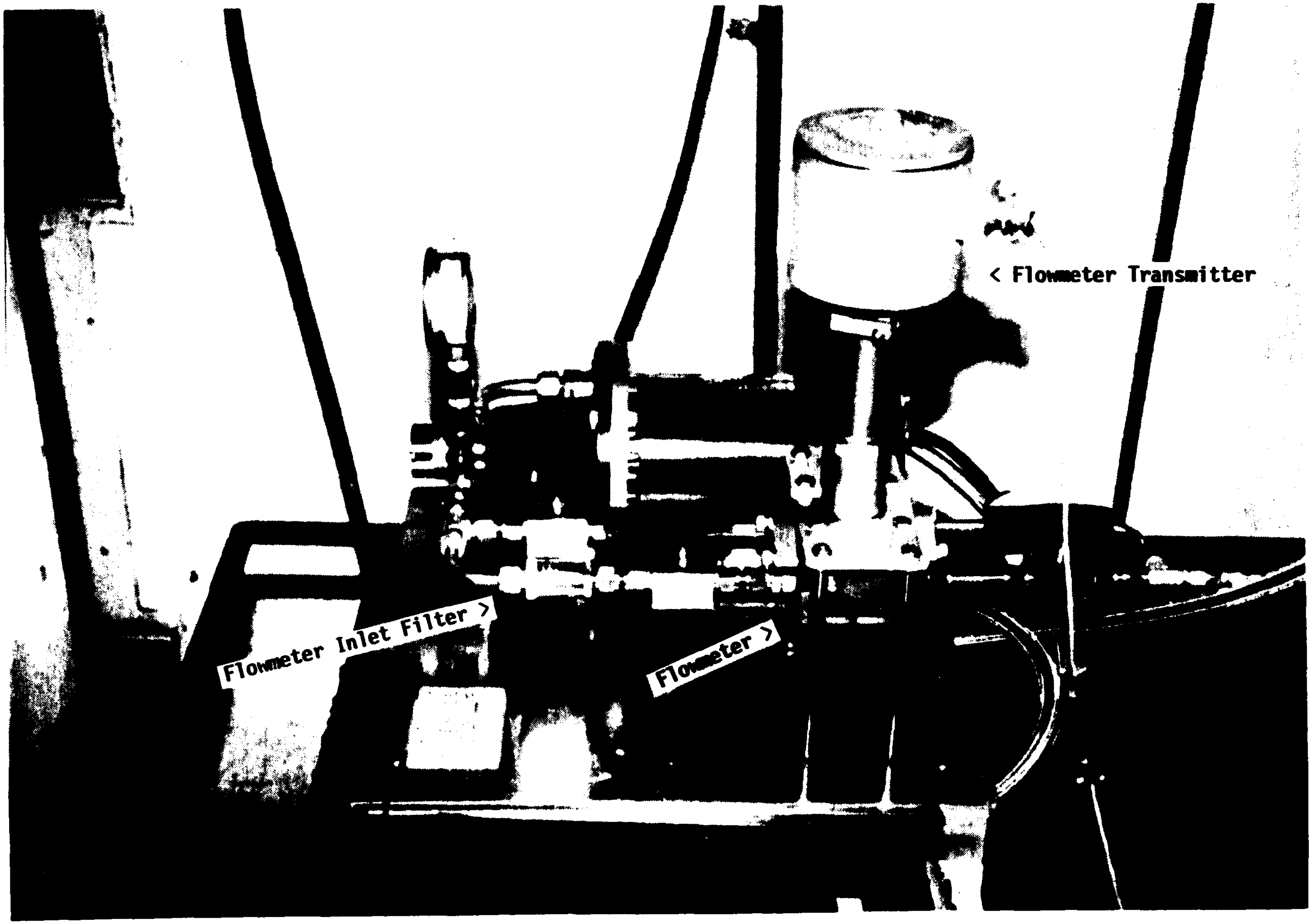

Figure 5. Side View of Fuel-Additive Pumping Unit.

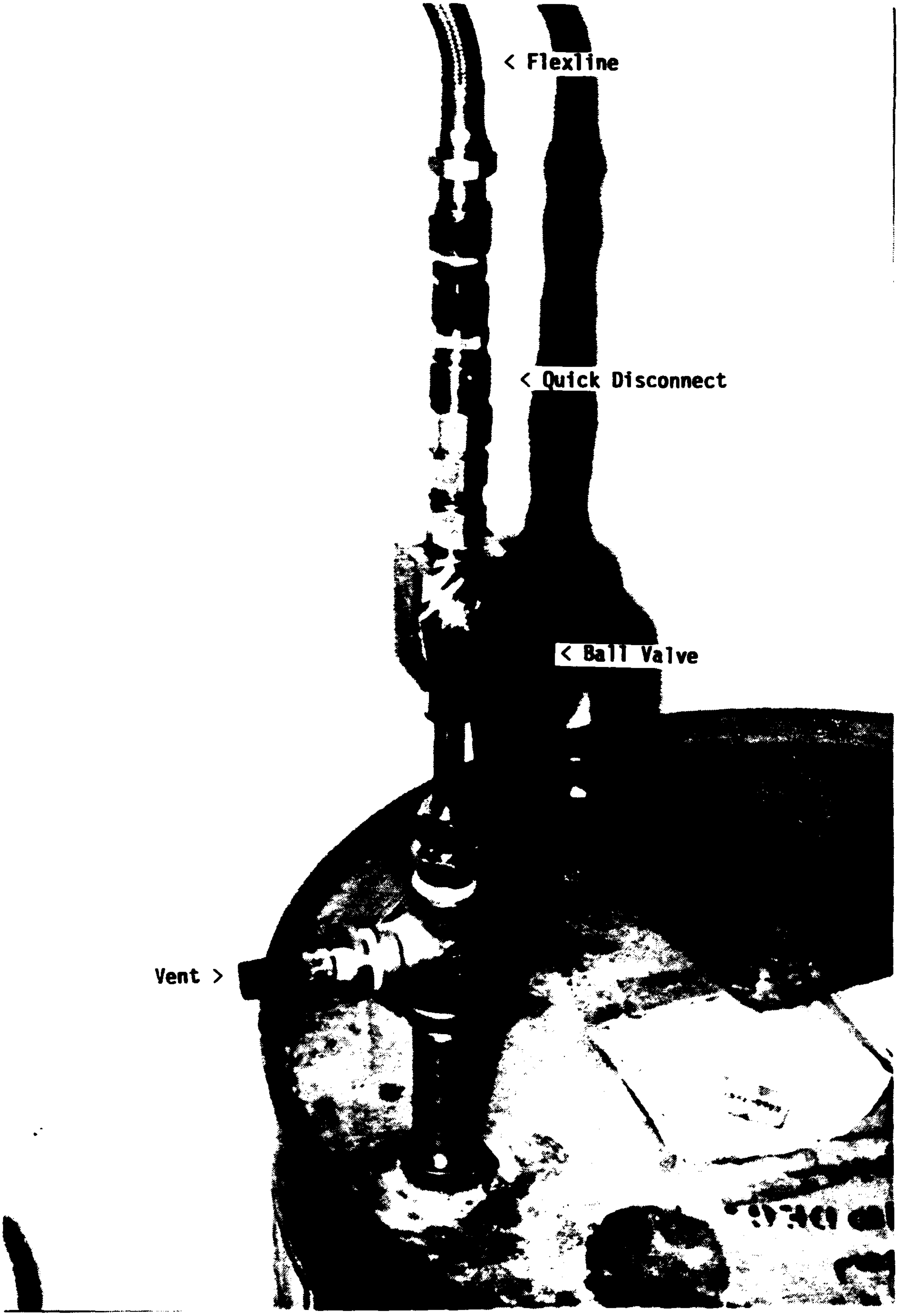

Figure 6. Fuel-Additive System Dip Tube Assembly.

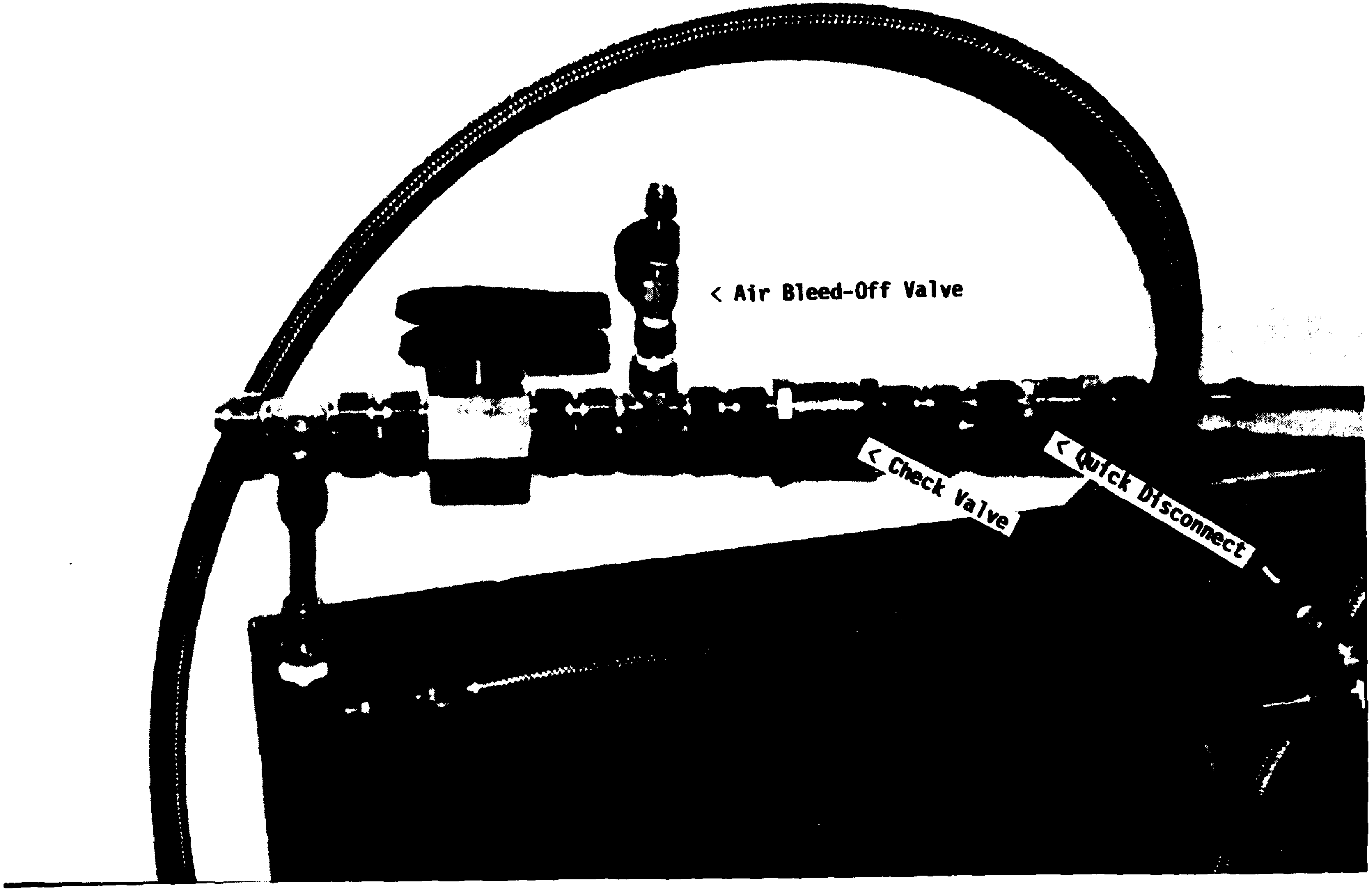

Figure 7. Fuel-Additive Connecting End.

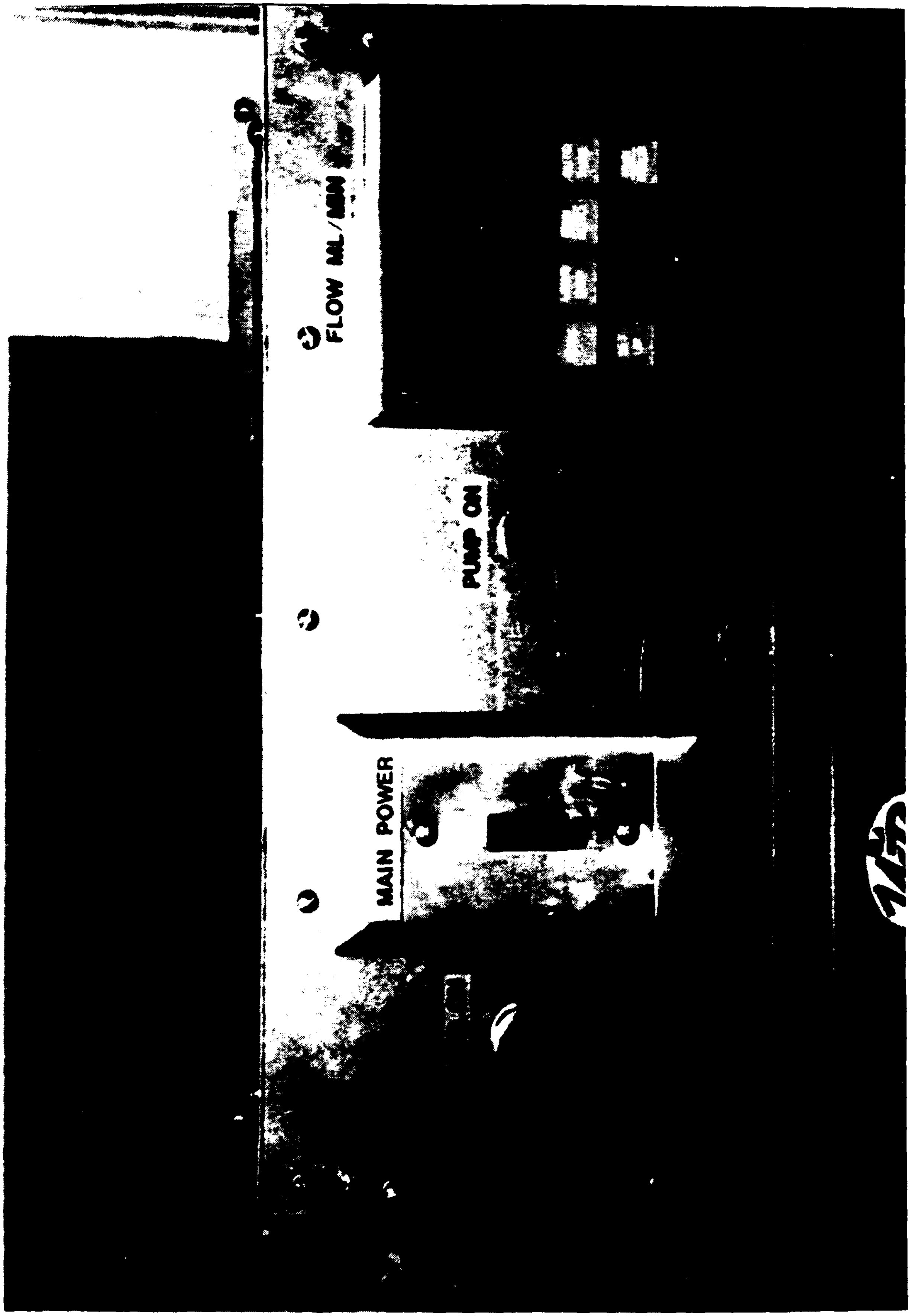

Figure 8. Fuel-Additive System Control Unit.

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SECTION IV

FUEL-ADDITIVE SYSTEM TESTING

A. SYSTEM CONTROL AND CALIBRATION

The positive displacement flowmeter was flow calibrated by the factory to provide a 4-20 mA signal for 0.0 to 1.0 gal/min. The data sheets are attached in Appendix A. The Honeywell controller was also factory calibrated. After the fuel-additive system was assembled and installed in test cell 3 at McClellan AFB, Sacramento, California, the flow readout on the flow controller was checked against the injected fuel additive flow by collecting the cerium fuel additive in a graduated cylinder. The reading on the controller agreed with the amount in the graduated cylinder, within the $\pm$2 mL reading accuracy of the cylinder. The controller was set to read out in units of milliliters per minute (mL/min), which provided a higher degree of accuracy for the controller than if it had been set up to operate in units of gallons per minute (gal/min).

The controller was installed with an initial set point of 151.4 mL/min (0.04 gal/min) and in the automatic mode of operation when the fuel-additive system was turned on. The controller response was such that the fuel additive flow reached greater than 90 percent of the set point value of the fuel additive flow within a minute after the system was turned on. This made operation of the system simple for the test cell operators. After initial testing, the set point was changed to 568 mL/min (0.15 gal/min).

1. Startup

The fuel-additive system was very difficult to prime. This was because the filters in the system were sized for a nonviscous solution and the cerium additive was about the consistency of motor oil. The cerium additive was much more viscous than anticipated and is also very dependent on temperature. To prime the pump, the inlet filter element was removed and additive was poured into the filter element chamber. The fuel-additive system was then able to prime itself and flush the system of air. The 7-micrometer filter element was replaced with a 60-micrometer filter element to reduce the pressure drop. This permitted the pump to achieve an output of near 0.5 gal/min. For the balance of the cerium additive tests, a 60-micrometer filter element was installed before the flowmeter with no filter element before the pump. Since the fuel additive tested did not contain particulate matter, the filters were not needed. The pump inlet filter and the flowmeter filter should be replaced with the original filter elements when testing the ferrocene fuel additive, which has a much lower viscosity and has been known to have crystallized matter contained in aged additive.

2. Power Level vs Opacity

The initial step of the fuel-additive system test was to get baseline opacity readings on the TF-33 model P-5 jet engine at various power settings. The baseline readings were made by Mr. Don Detwiler, a civilian employee at McClellan AFB who is certified to make opacity readings. The power level was then set at the highest opacity-producing level and the fuel additive varied until the opacity was reduced significantly. This additive level was 568 ml/min (0.15 gal/min). Instead of a Ringelmann number of 2.5 or greater, the opacity was reduced to 0.25 or below.

The Ringelmann numbers versus power settings with and without the cerium fuel additive are shown in Figure 9 for the TF-33 jet engine. The highest opacity occurs at about 95 percent power level (parked power) for the TF-33 engine. The addition of the cerium fuel additive reduced the opacity at all levels greater than 80 percent to near zero for additive amounts over 379 ml/min (0.10 gal/min).

3. Economics

A jet engine is ground tested after it has been rebuilt and before it is installed in an airplane. This engine test is performed in a test cell where the engine is mounted on a stationary frame. This test is called an engine trim run. During an engine trim run the power settings are varied frequently. An average time at each power setting is listed in Table 2 (Reference 3).

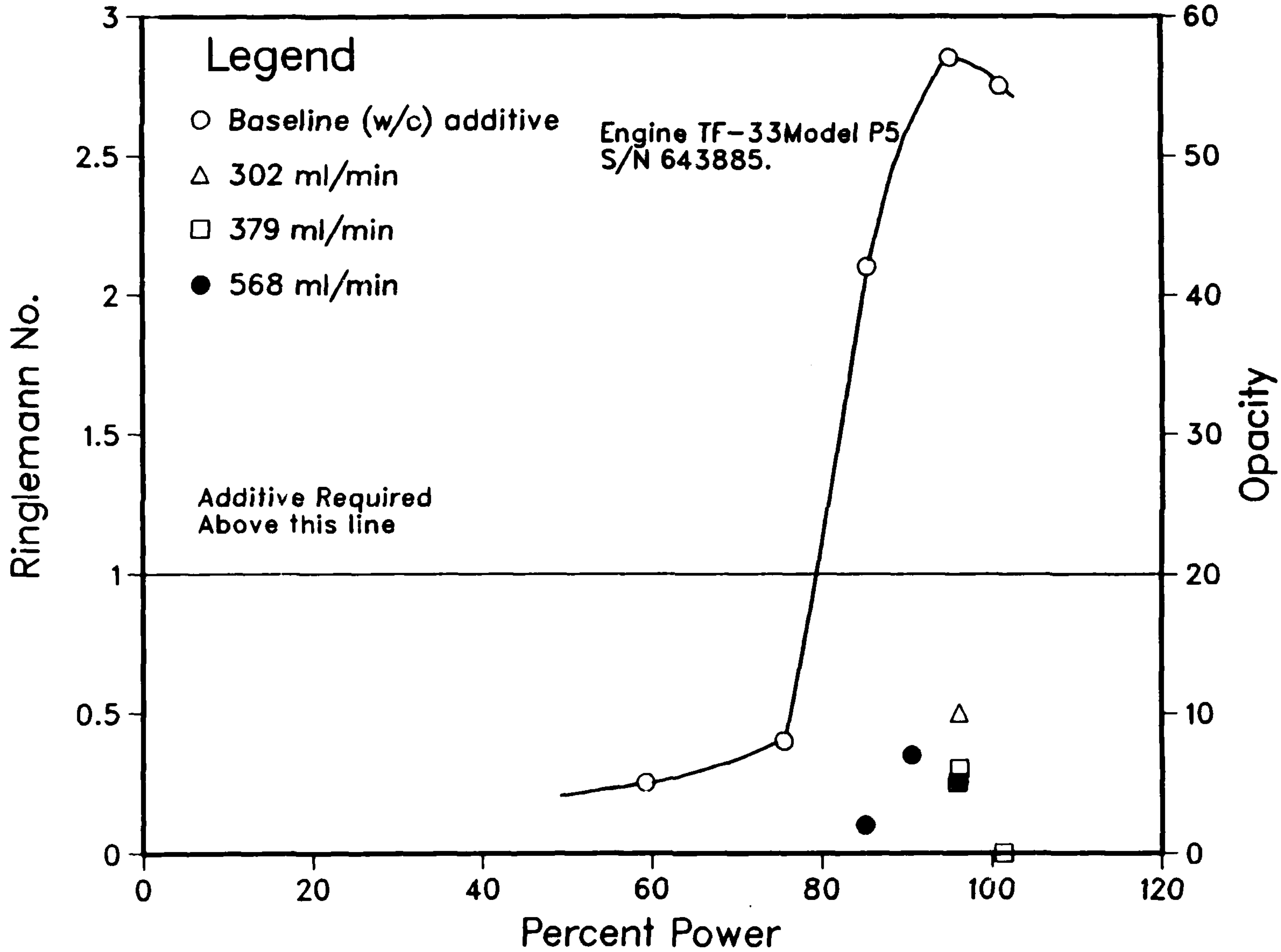

Figure 9. Opacity Readings at Various Power Levels Using Cerium Octoate Fuel Additive.

TABLE 2. REPRESENTATIVE TRIM RUN TIMES AND POWER SETTINGS

Time, Minutes	Power Setting, %	Additive Needed
4	Idle (59)	
1	75	
1	80	X
2	90	X
5	Idle	
2	Parked Power (95)	X
3	Idle	
2	Parked Power	X
2	Data (~95)	X
3	Idle	
1	80	X
1	Take Off (101)	X
5	Idle	

The total engine run time is 32 minutes, 11 minutes of which are at a greater than 80 percent power. During these 11 minutes, opacity readings for the TF-33 engine would exceed limits and require additive use. The additive would be needed for four different intervals. Alternatively, the fuel additive system could be left on after the first 80 percent power setting and turned off after the last high power setting. Additives would then be used for 22 minutes during testing.

The cost of a 55-gallon drum of the cerium octoate additive is $2,200 ($40/gallon). Based on an additive flow rate of 0.15 gal/min, the cost is $6/minute for visible soot suppression, and could range from $66 for 11 minutes to $192 for the complete engine trim run. These costs are based on the fuel additive flow rate used for these tests. At lower additive rates the cost is reduced proportionally.

The fuel-additive system built for this project can be interfaced with the test cell controls, so that the fuel-additive pump could be switched on and off, depending on the power setting of the engine on jet fuel flow rate. This interface was not tried for this project because of engine availability and time constraints.

SECTION V

CONCLUSIONS AND RECOMMENDATION

A. CONCLUSIONS

The prototype fuel-additive system built and tested was successful in delivering the required amounts of jet fuel additive to reduce jet plume opacity to below compliance levels. The process controller controlled the additive flow very accurately. The cost of using the fuel-additive system to reduce opacity was found not to be cost prohibitive. The fuel-additive system controller was equipped with a secondary input option, which was not used in this test. The secondary input can link the fuel-additive system pump to the test-cell control, and control the ratio of fuel additive to jet fuel. If the fuel-additive system were connected to the test-cell control, the test-cell control would in effect operate the additive system, and additive would flow only when needed, reducing the amount used. Ratio control appears unnecessary for two reasons: a set amount of fuel additive is sufficient to maintain plume opacity below limits, and the plume opacity is not proportional to the engine power setting.

The flow rate of the additive needed to reduce plume opacity will vary, depending on differences among engine models or individual engines. To avoid the cost of testing each engine for its required fuel additive level, the flow rate could be set high enough to reduce opacity levels for all engines of a given model. This can only be done onsite by the prospective users of the fuel-additive system.

B. RECOMMENDATIONS

It is recommended that the use of the secondary input option of the process controller to operate the fuel-additive system be tested to determine if its use would be beneficial. A flow totalizer should be added to the system if more testing is to be performed with this unit.

The fuel-additive system piping is recommended to be a minimum of 1/2-inch tubing to the inlet of the pump and a minimum of 3/8-inch tubing after the pump. This is to reduce pressure drop in the system due to the high viscosity of the cerium fuel additive. The pump capacity should be increased if the system is to be used in a cold environment. The cerium fuel additive viscosity is very temperature dependent and may become unpumpable at low temperatures.

The fuel-additive inlet to the jet fuel line is recommended to be as close as practical to the engine to reduce response time of additive reaching the engine.

REFERENCES

1. Aircraft Environmental Support Office, Characteristics of Particulate Emissions from J79-GE-15A Engine, McClellan AFB, AESO Report No. 2-87, April, 1987 (draft report).

2. Loveland, O.M., Klarman, A.F., Tarquinio, J., Stoddart, T.L., The Use of Fuel Additives to Control Plume Opacity of Turbine Engine Test Cells, ESL-TR-83-08, April, 1983.

3. Telephone conversation with Major Paul E. Kerch, January 26, 1988, Tyndall Air Force Base, Florida.

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APPENDIX A

CALIBRATION DATA

CALIBRATION
276 4-20MA TRANSMITTERS

DATE 10/13/87

CUSTOMER BATTELLE CONTROL NO. 61605 CHECKED BY [illegible]

	FLOWMETER	TRANSMITTER
MODEL NO.	214-301	275-525
SERIAL NO.	728164	739017

TEST STAND A1
TEST FLUID Kero.

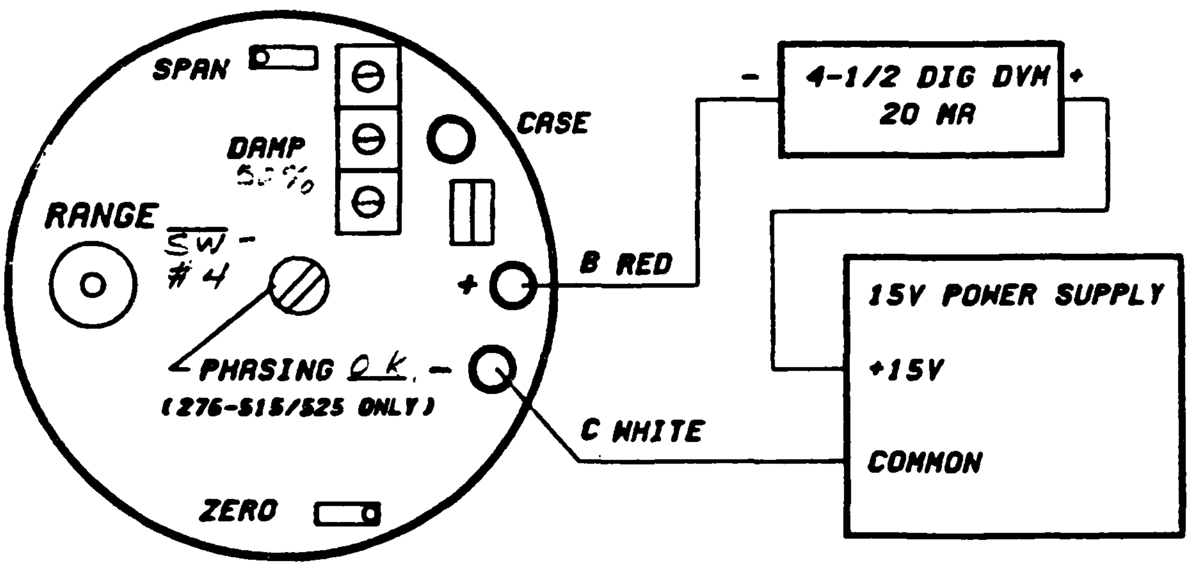
SP. GR.
VISCOSITY 1.8 CPS
AT TEMP. AMB.

O-RINGS VITON

PRESSURE CHECK 100 PSI

FLOWRATE G.P.M.	OUTPUT 4-20MA	% ERROR
.9985	19.98	Ø
.7977	16.77	+.04
.5506	12.83	+.16
.2859	8.59	+.17
.1385	6.23	+.23
.0521	4.84	+.14
.0270	4.43	−.05
Ø	4.00	Ø

276



PRECISION FLOWMETER CALIBRATION

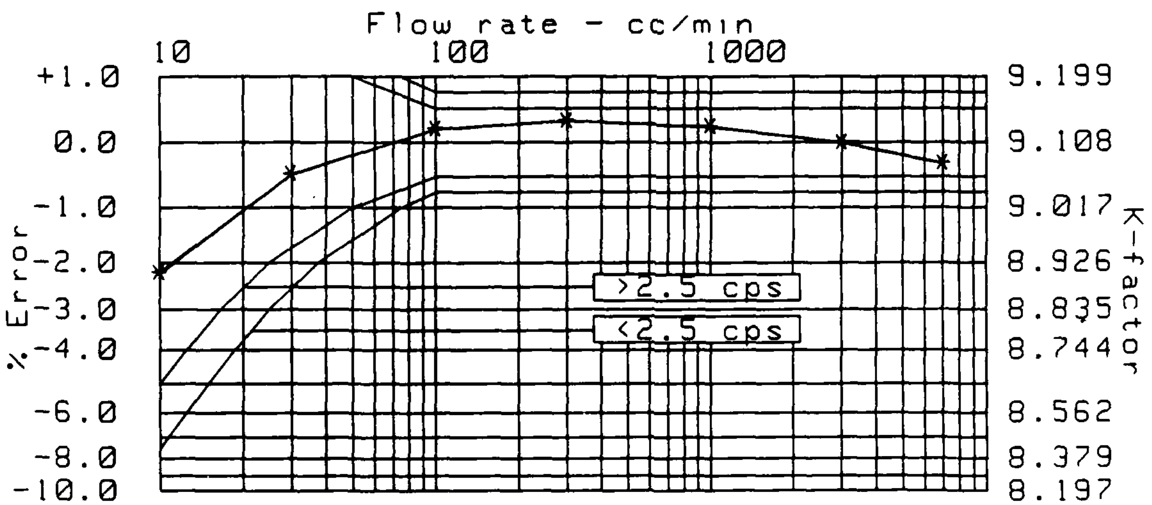
FLOWMETER		TRANSMITTER	
Model #	214-301	Model #	TEST
Serial #	728164	Serial #	LAB

cc/min	volts/cc	% Error	Limits
7000	9.08	-.31	.5
3000	9.107	-.01	.5
1000	9.128	.22	.5
300	9.136	.31	.5
100	9.125	.19	.5
30	9.065	-.47	1.67
10	8.907	-2.21	5

Control # 61605
Customer: BATTELLE
Date: 13 Oct 1987
Time: 12:38
Stand # 401A
Tested By: mso
Test Fluid: Kerosene
Viscosity: 1.83cps
Temp(°C): 21
Leak Test(psi): 100 PSI
Switch Setting: NONE

K-Factor: 9.108

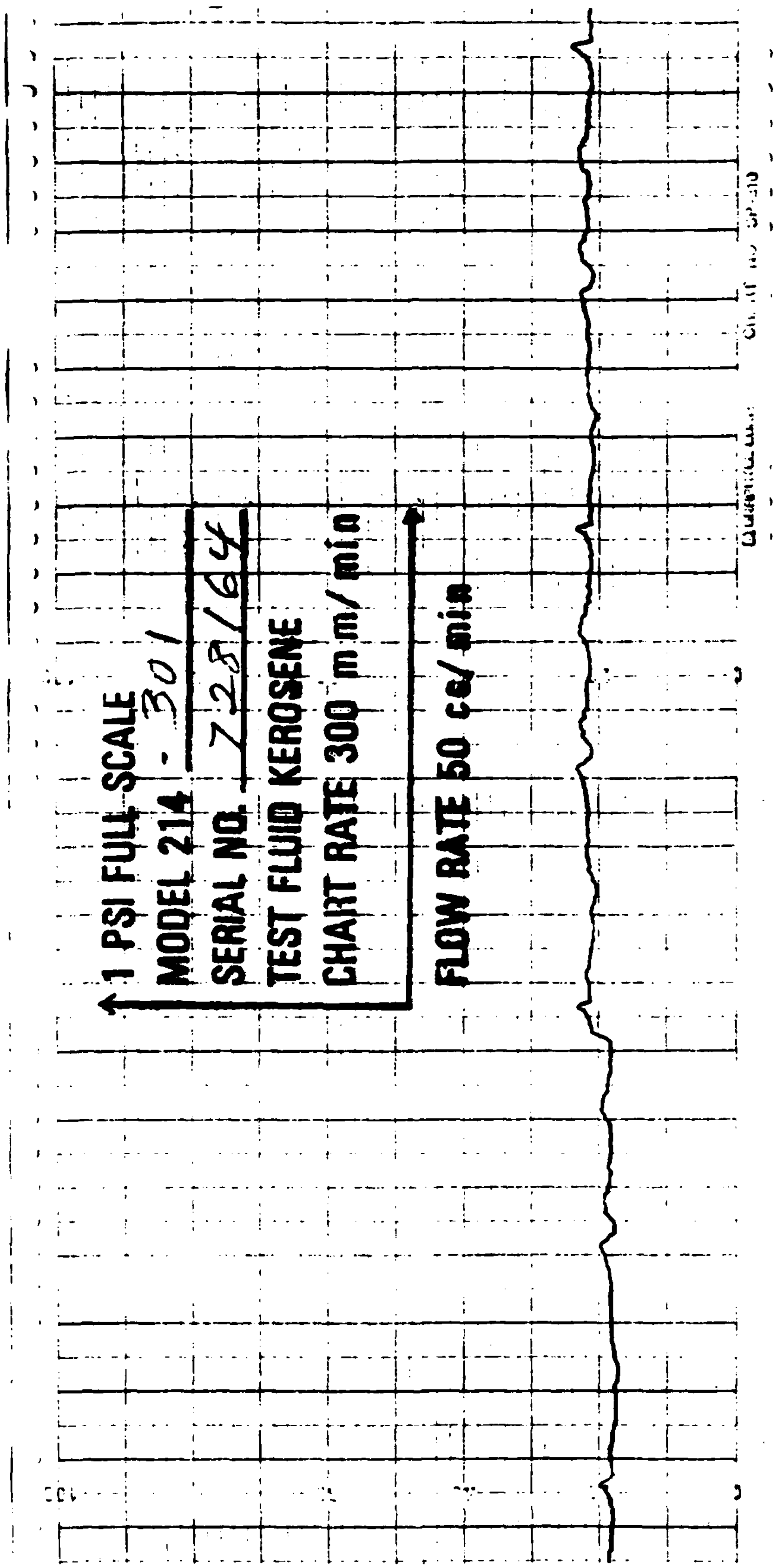
LINEARITY CURVE



-- SEE NEXT PAGE FOR PRESSURE DROP GRAPH --

NOTE: Flowmeter filled with 20W OIL before shipping

MAX MACHINERY INC. HEALDSBURG CALIFORNIA 95448 USA


1 PSI FULL SCALE
MODEL 214 - 301
SERIAL NO. 728/64
TEST FLUID KEROSENE
CHART RATE 300 m m/ min
FLOW RATE 50 cc/ min