MIDLAND AND O'BANNON

WATER CYLINDER PUMP TEST

SUBMITTED TO:

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NOMNECLATURE

A	Cross-sectional area of the sucker rod
Amps	Amperage drawn by the motor
D	Diameter in inches of the inside cylinder
D	Diameter in inches of the outside cylinder
E	Young's modulas of elasticity of the sucker rod
F	Force on sucker rod in pounds
h	Height the water was pumped
l	Stroke length in inches
mV	Millivolts reading on the oscilliscope
N	Number of pumping strokes per minute
P	Power into the motor
P	Power out of the motor
s	General displacement
t	Time of pump run (20 minutes in all cases)
W	Weight of water pumped in pounds
W	Work being put into the cylinder
W	Work being put into the system by the motor
W	Work out of the system
w	Thickness of a rod
$\Delta \epsilon$	Change in strain
η_m	Mechanical efficiency
η_{motor}	Motor efficiency
η_o	Overall efficiency
η_v	Volumetric efficiency
ν	Poisson's ratio of the sucker rod
τ	Time in seconds for one cycle

I. SUMMARY

The purpose of this experiment is to compare the efficiencies of two water well cylinders so that the relative costs of the pumping systems, when powered by photovoltaic cells, can be compared. The efficiencies which were found are; the motor efficiency, the overall efficiencies of the cylinders, the volumetric efficiencies of the cylinders and the overall efficiencies of the systems.

The first cylinder is a Midland conventional brass cylinder with leather sealing rings. The rings of the inner cylinder make a tight seal with the outer cylinder which causes friction forces which lowers the mechanical efficiency of the cylinder.

The second cylinder is an O'Bannon cylinder which is composed of a close fitting piston and cylinder combination. This cylinder costs about five times more than the conventional brass cylinder, but it is thought that it may be sufficiently more efficient than the cost of the entire photovoltaic pumping system would be less.

This experiment deals only with the efficiencies of the cylinders and will not examine the costs of the systems. The experiment was sponsored by the U.S. Forest Service and conducted by the University of Arizona Water Resources Research Center with cooperation from the Aerospace and Mechanical and the Electrical Engineering Department of the College of Engineering.

II. INTRODUCTION

Many people involved in range or forestry management have found a need to perfect remote watering systems. With the cost of photovoltaic cells rapidly decreasing, they have now become a candidate for powering remote pumping sites. The U.S. Forest Service contracted the Water Resources Research Center at the University of Arizona to find which of two water well pumping systems, powered by photovoltaic cells, would be cheaper to build and run. The Water Resources Research Center then contacted the Departments of Aerospace and Mechanical Engineering and Electrical Engineering to help perform efficiency testing on the two proposed pumping cylinders.

A number of objectives which have been specified to be met require the measurement of certain quantities. The quantities which will be measured are:

The number of strokes per minute
The force on the sucker rod
The run time
The weight of water pumped
The power into the system
The power out of the motor
The stroke length
The diameter of the cylinder
The height the water is raised
The rate of water pumped

From these measured quantities the following will be calculated:

The work into the cylinder
The work into the system
The work out of the system
The overall efficiencies of the cylinders
The volumetric efficiencies of the cylinders
The motor efficiencies
The overall efficiencies

Analysis will be performed for two different cylinders, each with and without a flywheel mounted on the motor. The first cylinder is a Midland conventional brass cylinder with leather fitting rings making a seal with the outer cylinder. The second cylinder is an O'Bannon close fitting cylinder which is machined to precise dimensions to make the seal with the outer cylinder. The pumping system is shown as Figure 1.1. The O'Bannon and Midland cylinders are compared in Figure 1.2.

This experiment has been separated into three important milestones; the motor calibration, the strain gage calibration, and the completion of the experiment.

A. MOTOR CALIBRATION

The purpose of the motor calibration is to obtain a relationship between the power a motor draws in, to the power the motor puts out. The power the motor draws will be measured during the experiment and from this the power the motor puts out, and therefore the efficiency of the motor, can be found from the calibration curve.

In the lab the motor is loaded with known loads while the input power and speed of the motor are measured. The output power is the load times the speed. The calibration curve is then the input power plotted against the output power.

A 1/2 HP Dayton A.C. motor was supplied by the U.S. Forest Service and calibrated; later, tests on the water well showed that the power required to run the pump was on the lower end of the calibration curve

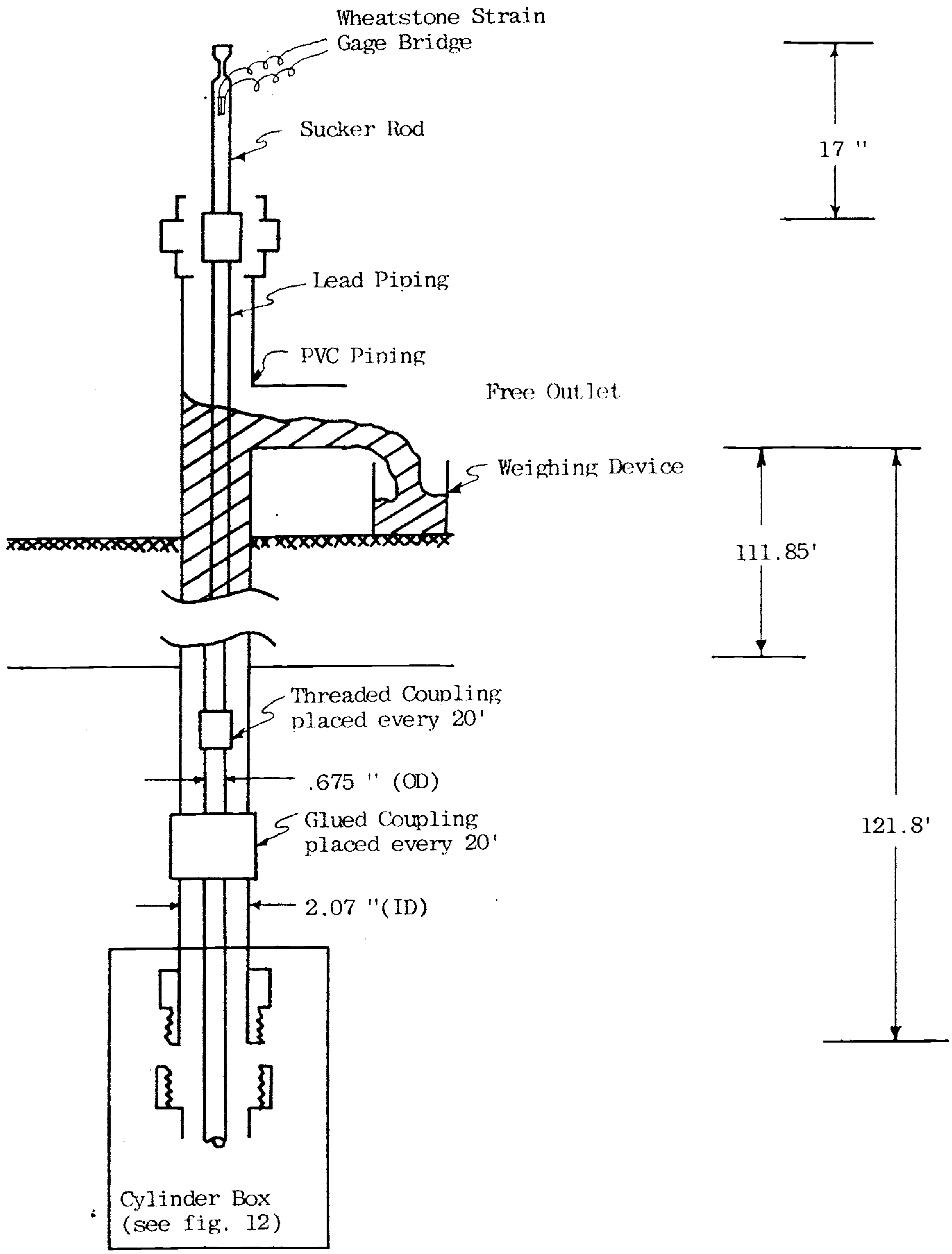


Figure 1.1 : Pumping System Layout

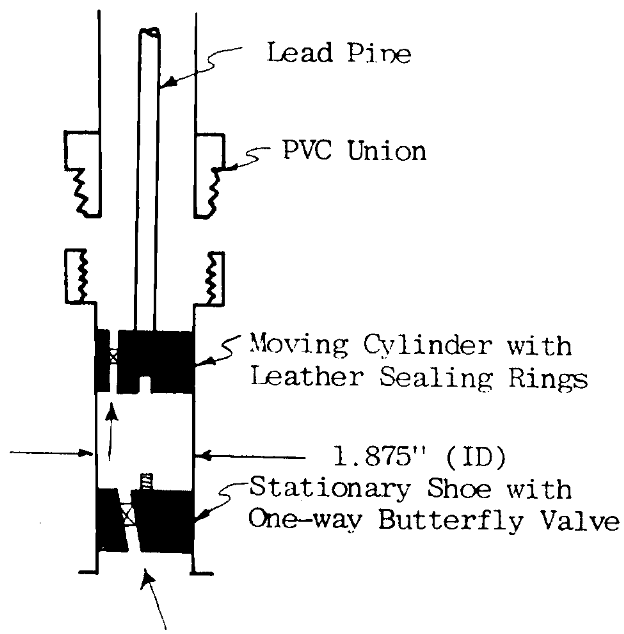


Figure 1.2 A : Midland Cylinder

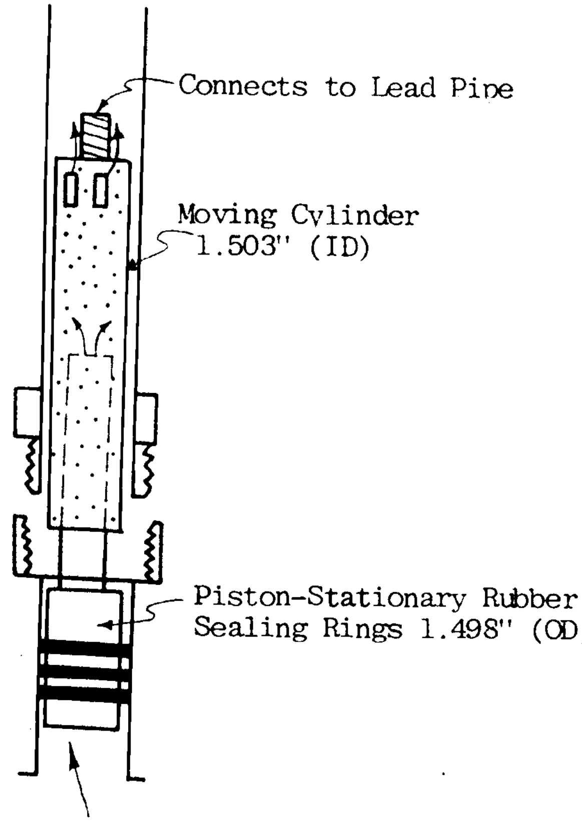


Figure 1.2 B : O'Bannon Cylinder

Figure 1.2 : The Midland and O'Bannon Cylinders

leading to inaccuracies in the power supplied reading. The reason for the errors can be seen in the general shape of the calibration curve.

The general shape of the calibration curve is shown in Figure 1.3 below. If the input power to the motor is known to a degree of accuracy of ϵ ($W_{in} \pm \epsilon$), the output power of the motor is known within the range of ΔW_{out}. As shown in Figure 1.3, a motor loaded on the lower end (subscript l) of the calibration curve causes a larger range of W_{out} than a motor loaded on the higher end (subscript h) which has a lower range of W_{out} and is therefore more accurate for the limits of W_{in}. This shows that where accuracy is needed it is better to have heavily loaded motors. Therefore a 1/6 HP A.C. motor was obtained from the University of Arizona Electrical Engineering Department and used in the experiment.

For greater accuracy in measuring the input power a digital oscilliscope with hold and storage ability was obtained. This scope will measure input amperage referenced to an amperage shunt. For this a current curve was added to the calibration curve. To find the input and output watts from the input amperage go to the current curve at the input amperage and read the output watts from the outputs axis, follow the graph up to the power curve and read the input watts off of the input axis. The calibration curve is shown in the results section of Figure 2.1.

B. STRAIN GAGE CALIBRATION

The purpose of the strain gage calibration curve is to obtain a

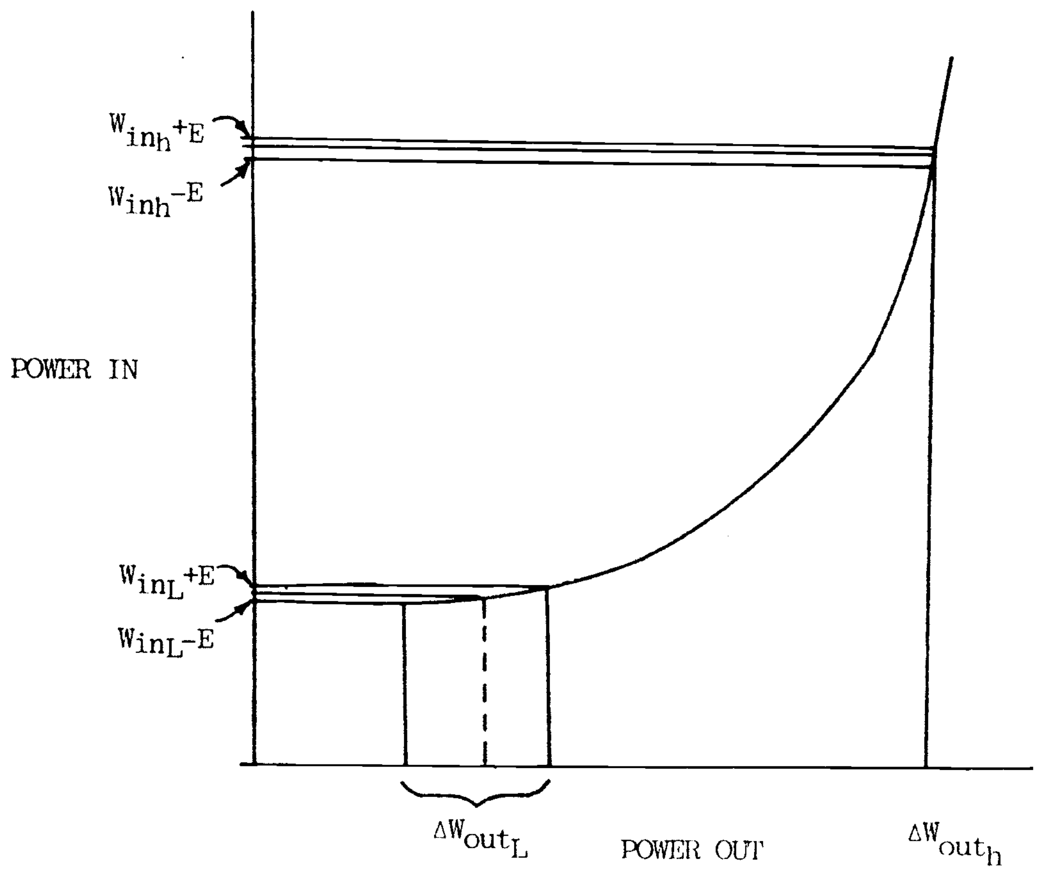


Figure 1.3: General Shape of a Motor Calibration

relationship between the strain reading on a strain gage to the force on the sucker rod which connects the gear system to the cylinder shaft. At the time the experiment began there was a single strain gage applied to the round surface of the sucker rod. Various experiments were performed on the strain gage to test it's quality.

With the strain at zero pressure applied directly on the gage caused a strain reading. A moist atmosphere also caused a strain reading. By the design of the circuit the gage was not temperature compensating; and since the calibration would take place in the lab and the experiment would take place over several weeks in the field, the strain gage would cause many preventable errors. The gage would also be used in a moist atmosphere (directly over a well opening) which would cause more errors. Because of these errors the strain gage was considered inappropriate for the experiment. This strain gage was removed and the upper end of the sucker rod (polish rod) was squared-off at the spot where the new strain gage circuit would be placed.

The new strain gage circuit is four identical strain gages arranged in a wheatstone bridge with four active arms as shown in Figure 1.4. These strain gages are temperature compensating and arranged in a temperature compensating bridge. The gages are coated with a polyethelyne waterproof coating to be moisture proof and arranged so that bending forces will not affect the strain reading. By reference one the change in strain for each strain gage is given by equation 1.1:

$$\Delta\epsilon_1 = \frac{F}{EA} + \frac{Mh}{2EI} = -\nu\Delta\epsilon_2$$
$$\Delta\epsilon_3 = \frac{F}{EA} - \frac{Mh}{2EI} = -\nu\Delta\epsilon_4 \qquad (1.1)$$

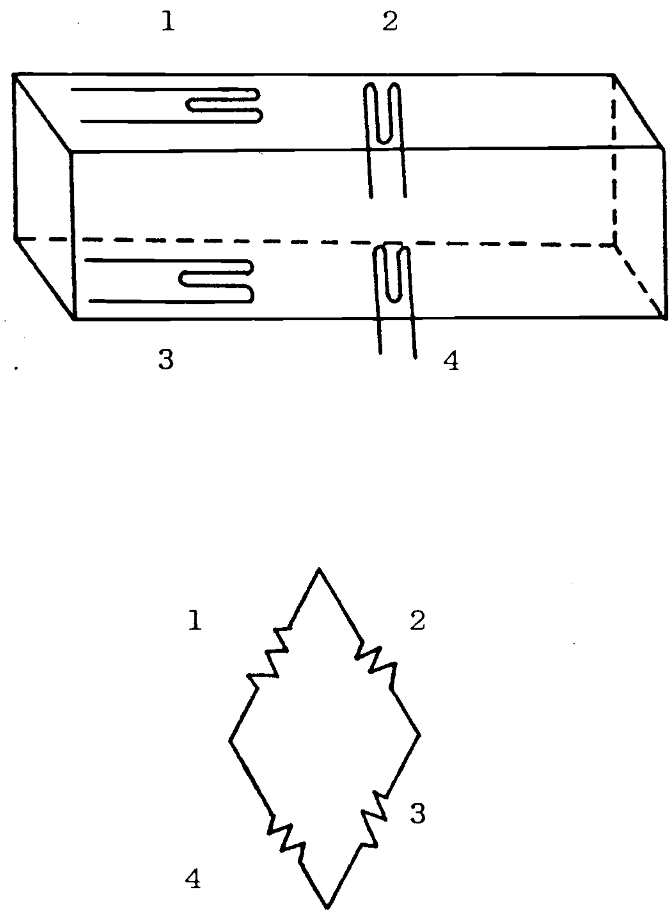


Figure 1.4: Strain Gage Placement and Circuit

The measured strain reading will be:

$$\Delta\epsilon_{inst} = \Delta\epsilon_1 - \Delta\epsilon_2 + \Delta\epsilon_3 - \Delta\epsilon_4 \qquad (1.2)$$

Substituting equations 1.1 into equation 1.2 the strain becomes:

$$\Delta\epsilon_{inst} = \frac{2(1+\nu)F}{EA} \qquad (1.3)$$

The calibration curve will be a straight line with a slope of $\frac{2(1+\nu)F}{EA}$. A dynamic sanborn strain recorder with a paper output was used to record the strain with time. The strain was then converted to force and a force-time plot was made. The force time was related to displacement so a force-displacement curve could be made. These curves are shown in the results section and explained under "Data Recording and Reduction".

The strain gage calibration curve is shown in the results section as Figure 2.2.

C. DATA RECORDING AND REDUCTION

During the experiment the pumping system remained the same with only the cylinders being changed. Each cylinder was run for 20 minutes, then a flywheel was placed on the motor and another 20 minute run was performed. During the run the sucker rod force, the weight of the water and the input power were measured. From these quantities the objectives can be calculated.

The number of strokes per minute was measured by counting the strokes on a one minute run of the paper strain recorder, for both cylinders. The water pumped was captured in a barrel and weighed on a weight balance scale. The rate of water pumped is the weight of water pumped divided by the time. The distance from the water outlet to the top of the water table was measured with a marked plumb-bob type steel tape, this is the distance the pump raises the water. The draw down (the change in height of the water table due to pumping) is assumed to be zero since the water table is large and the pump is small.

The inside diameter of the Midland cylinder was measured and the diameter of the O'Bannon cylinder was measured. From these diameters the cross-sectional areas can be found. The stroke length was marked on the sucker rod by a stationary grease marker as the pump was ran and the resulting line was measured after the rod was removed from the system.

The strain in the sucker rod was dynamically recorded on paper by sanborn dynamic strain recorder. The output was expected to be approximately a square wave function (this is shown in the results section as Figure 2.3). Using the strain gage calibration curve the strain-time recording could be converted to a force-time recording where:

$$F = \frac{C}{K}$$

where K = the slope of the strain gage calibration curve. The force-time curves are shown in the results section for each pump run. Force could be found as a function of displacement since the cycle of the pump is known as a function of time this could be related to the force-time curve such that a force-displacement curve could be found. This is shown in the results section.

The work into the cylinder is equal to the area under the force-displacement curve or:

$$W_{inc} = Nt\int F \cdot ds \qquad (1.5)$$

The output work is the product of the weight of water pumped and the height the water is raised or:

$$W_{out} = Wh \qquad (1.6)$$

The input amperage, as referenced to an amperage shunt, is dynamically recorded by a digital oscilliscope capable of holding and storing sampled data (some sample recordings are shown in the results section in Figure 2.3). The amperage shunt was referenced as 50mV's for 2Amps, so the average amperage could be found from

$$Amps_{ave} = \frac{2}{50}\ (.707)R \qquad (1.7)$$

where R is the oscilliscope reading in mV. To find the work into the system; first find the area under the watts input curve in the results section, then divide this by the time of one cycle and multiply by the total time or:

$$W_{ins} = \frac{60 \cdot t}{T} \int P_{in} \cdot dt \qquad (1.8)$$

The objectives of this experiment may now be calculated from the measured quantities.

The overall efficiency of the cylinders is defined as the work out of the cylinders divided by the work put into the cylinders. This can be found by finding the area under the force-displacement curve times the number of strokes over the time period divided by the product of the weight of water pumped and the height the water was raised or:

$$\eta_m = \frac{Wh}{N + \int F.ds} \qquad (1.9)$$

The volumetric efficiency of the cylinders is defined as the volume of water pumped divided by the volume displaced by the cylinder during pumping. This can be found by:

$$v = \frac{26.916 \cdot W}{A \cdot N \cdot t \cdot 1} \qquad (1.10)$$

The motor efficiency is defined as the power output of the motor divided by the input power to the motor. This can be found by finding the area under the watts out curve in the results section divided by the area under the watts in curve shown in the results section or:

$$\text{motor} = \frac{P_{out} \cdot dt}{P_{in} \cdot dt} \qquad (1.11)$$

The overall efficiency of the pumping system is defined as the power out of the system divided by the power in the system. The power into the system can be found from the area under the watts in curve divided by the product of the time for one cycle and the run time of the experiment. The power out of the system is the weight of water times the distance the water was raised divided by the run time of the experiment or:

$$P_{out} = \frac{W \cdot h \cdot N \cdot t}{W_{ins}} \qquad (1.12)$$

These quantities are calculated and presented in the results section.

III. RESULTS

The motor calibration curve is given as Figure 2.1.

The strain gage calibration curve is given as Figure 2.2.

Example strain-time and amperage-time recordings are shown in Figure 2.3. The strain is found off the strain recording, then by finding this on the calibration curve the force is found. Using Equation 1.7 the amperage is found and the watts in and out can be found from the motor calibration curve.

A. MIDLAND CYLINDER

The following qualities of the Midland cylinder were found:

1. The stroke length was 6.875 inches.
2. The number of strokes per minute were 35.5.
3. The height the water was raised was 111.85 feet.
4. The diameter of the outside cylinder was 1.875 inches.
5. The diameter of the inside cylinder was .675 inches.
6. Run time was 20 minutes.

A1. Midland Cylinder Without the Flywheel;

1. Weight of the water pumped was 441 pounds.
2. Rate of water pumped was 2.65 gal/min.
3. The dynamic load on the sucker rod is shown in Figure 2.4.
4. The work into the cylinder from Equation 1.5, where the force displacement curve is Figure 2.4, was 86,123.0 ft/lb.
5. The work out of the system from Equation 1.6 was 49,325.9 ft/lb.
6. The work into the system is found from Figure 2.5 and Equation 1.8 and was 207,900 ft/lb.
7. The average power into the system is found from Figure 2.5 and was 227.2 watts.
8. The average power out of the motor is found from Figure 2.5 and was 120.0 watts.
9. The overall efficiency of the cylinder is found from Equation 1.9 and was 57.3%.
10. The volumetric efficiency of the cylinder is found from Equation 1.10 and was 90.5%.
11. The motor efficiency is found from Equation 1.11 and was 52.8%.
12. The overall efficiency of the system is found from Equation 1.12 and was 23.7%.

A2. Midland Cylinder With Flywheel;

The effect of the flywheel was to smooth out the power curves, it raised the motor efficiency and the overall efficiency a little.

1. Weight of water pumped was 438 pounds.
2. Rate of water pumped was 2.63 gal/min.
3. The dynamic loading on the sucker rod is shown in Figure 2.4 (same).
4. The work into the cylinder stayed the same.
5. The work out of the system was 48,990 ft/lb.
6. The work into the system from Figure 2.6 was 201,008 ft/lb.
7. The average power into the motor found from Figure 2.6

was 228.3 watts.

8. The average power out of the motor found from Figure 2.6 was 127.2 watts.
9. The overall efficiency of the cylinder was 56.9%.
10. The volumetric efficiency of the cylinder was 90.5%.
11. The motor efficiency was 55.7%.
12. The overall efficiency of the system was 24.4%.

The data for the Midland cylinder is presented in table form in Table 2.1.

B. O'BANNON CYLINDER:

The following qualities of the O'Bannon cylinder were found:

1. The stroke length was 6.875 inches.
2. The number of strokes per minute were 35.4.
3. The height the water was raised was 111.85 feet.
4. The diameter of the outer cylinder was 1.503 inches.
5. There was no restrictive inside cylinder.
6. Run time was 20 minutes.

B1. O'Bannon Cylinder Without the Flywheel;

1. Weight of water pumped was 282 pounds.
2. Rate of water pumped was 1.69 gal/min.
3. The dynamic load on the sucker rod is shown in Figure 2.7.
4. The work into the cylinder from Equation 1.5, where the force displacement curve is Figure 2.7 was 68,463.6 ft/lb.
5. The work out of the system from Equation 1.6 was 31,541.7 ft/lb.
6. The work into the system is found from Figure 2.8 and Equation 1.8 and was 148,685.8 ft/lb.
7. The average power into the system is found from Figure 2.8 and was 168 watts.
8. The average power out of the motor is found from Figure 2.8 and was 87.5 watts.
9. The overall efficiency of the cylinder is found from Equation 1.9 and was 53.4%.
10. The volumetric efficiency of the cylinder is found from Equation 1.10 and was 90.5%.
11. The motor efficiency is found from Equation 1.11 and was 52.1%.
12. The overall efficiency of the system is found from Equation 1.12 and was 21.2%.

B2. O'Bannon Cylinder With the Flywheel;

1. Weight of water pumped was 284 pounds.
2. Rate of water pumped was 1.70 gal/min.
3. The dynamic load on the sucker rod is shown in Figure 2.7 (same).

4. The work into the cylinder stayed the same.
5. The work out of the system was 31,765.4 ft/lb.
6. The work into the system from Figure 2.9 was 147,694.9 ft/lb.
7. The average power into the motor is found from Figure 2.9 was 166.9 watts.
8. The average power out of the motor found from Figure 2.9 was 90.6 watts.
9. The overall efficiency of the cylinder was 53.4%.
10. The volumetric efficiency of the cylinder was 90.5%.
11. The motor efficiency was 54.3%.
12. The overall efficiency of the system was 21.5%.

The data for the O'Bannon cylinder is presented in table form in Table 2.2. A comparison between the four runs is presented in table form in Table 2.3 and discussed in the discussion section.

TABLE 2.1: POWER DATA FOR MIDLAND CYLINDER

TABLE 2.1A: MIDLAND CYLINDER WITHOUT FLYWHEEL

TIME (sec)	AMPERAGE	WATTS IN	WATTS OUT
0	3.68	325	175
.1	3.50	295	155
.2	2.88	235	120
.3	2.60	180	90
.4	2.50	155	80
.5	2.46	150	75
.6	2.55	160	80
.7	2.60	180	100
.8	2.88	235	130
.9	3.64	320	160
1.0	3.70	330	175
1.1	3.30	280	155
1.2	3.00	240	130
1.3	2.65	185	105
1.4	2.42	140	80
1.5	2.38	130	60
1.6	2.86	230	130
1.7	3.64	320	170

TABLE 2.1B: MIDLAND CYLINDER WITH FLYWHEEL

TIME (sec)	AMPERAGE	WATTS IN	WATTS OUT
0	3.00	240	130
.1	2.88	235	130
.2	2.86	230	125
.3	2.84	220	125
.4	2.82	215	120
.5	2.80	210	120
.6	2.84	215	120
.7	2.85	225	125
.8	2.88	235	130
.9	3.00	240	130
1.0	3.02	245	135
1.1	3.00	240	135
1.2	2.86	230	125
1.3	2.84	220	120
1.4	2.83	215	120
1.5	2.84	220	120
1.6	2.88	235	135
1.7	3.00	240	140

TABLE 2.2: POWER DATA FOR THE O'BANNON CYLINDER

TABLE 2.2A: THE O'BANNON CYLINDER WITHOUT FLYWHEEL

TIME (sec)	AMPERAGE	WATTS IN	WATTS OUT
0	2.46	150	75
.1	2.54	165	85
.2	2.66	190	105
.3	2.78	205	120
.4	2.78	205	120
.5	2.56	170	95
.6	2.46	150	75
.7	2.40	130	55
.8	2.38	120	40
.9	2.38	120	60
1.0	2.40	130	80
1.1	2.54	165	90
1.2	2.66	190	105
1.3	2.78	205	115
1.4	2.78	205	120
1.5	2.68	195	110
1.6	2.58	175	95
1.7	2.48	155	80

TABLE 2.2B: THE O'BANNON CYLINDER WITH FLYWHEEL

TIME(sec)	AMPERAGE	WATTS IN	WATTS OUT
0	2.50	170	90
.1	2.60	175	95
.2	2.60	175	100
.3	2.62	180	100
.4	2.62	180	100
.5	2.60	175	95
.6	2.50	170	90
.7	2.48	165	90
.8	2.46	160	85
.9	2.46	160	80
1.0	2.44	155	80
1.1	2.46	160	80
1.2	2.48	165	90
1.3	2.48	165	95
1.4	2.50	170	95
1.5	2.48	165	90
1.6	2.46	160	90
1.7	2.44	155	85

TABLE 2.3: A Comparison of the Midland and O'Bannon Cylinders

		Midland Cylinder	O'Bannon Cylinder
1.	Stroke length in inches	6.875	6.875
2.	Number of strokes per min.	35.5	35.5
3.	Height the water was raised in feet	111.85	111.85
4.	Diameter of the outer cylinder in inches	1.875	1.503
5.	Diameter of sucker rod in inches	.675	.675
6.	Run time in minutes	20	20

		w/Flywheel	wo/Flywheel	w/Flywheel	wo/Flywheel
1.	Weight of water pumped (lb)	438	441	284	282
2.	Rate of water pumped in gallons per minute	2.63	2.65	1.7	1.69
3.	Dynamic load on sucker rod	Figure 2.4	Figure 2.4	Figure 2.7	Figure 2.7
4.	Work into the cylinder in foot pounds	86,123	86,123	68,464	68,464
5.	Work out of system (ft/lb)	48,990	49,326	31,765	31,542
6.	Work into the system (ft/lb)	201,008	207,900	147,695	148,686
7.	Average power into the motor in watts	228.5	227.2	166.9	168.0
8.	Average power out of the motor in watts	127.2	120.0	90.6	87.5
9.	Overall efficiency of the cylinder (percent)	57.8	58.0	53.4	53.4
10.	Volumetric efficiency of the cylinder (percent)	90.5	90.5	90.5	90.5
11.	Motor efficiency (percent)	55.7	52.8	54.3	52.1
12.	Overall efficiency (percent)	24.4	23.7	21.5	21.2

TABLE 2.4: Test Results for Flywheel and Pumpjack Losses in Wattts

	Power In	Motor Losses	Flywheel and Pump-jack Losses	Cylinder Losses	Useful Work
O'Bannon Pumping* (1.69 GPM) (with flywheel, oil level 40%)	173	79.1	26.7	31.3	35.9
Midland Pumping* (2.63 GPM) (with flywheel, oil level 40%)	228.3	101.1	31.4	40.3	55.5
O'Bannon Pumping* (1.69 GPM) (with flywheel, oil level 100%)	174	79.1	27.7	31.3	35.9
without pump (with flywheel oil level = 100% and counterbalance of 60 lbs weight at 19 1/2 inches)	118.5	68.5	50.0	---	---
without pump (with flywheel without counterbalance oil level = 100%)	96.5	68.9	27.6	---	---
without pump, flywheel and counterbalance oil level = 100%	93.0	68.4	24.6**	---	---
motor and pully only	74.0	74.0	---	---	---

* Pumping data summarized from previous tables.
** Pumpjack losses only.

Subsequent to obtaining the information summarized in the proceding tables and figures, one remaining test was made to obtain additional information about the flywheel and pumpjack losses. These losses were characterized by dropping loads one at a time ad finding the resulting input wattage to the motor. The output from the motor could be determined from Figure 2.2. The motor losses and other losses could then be computed.

It was found in this test program that putting oil in the pumpjack completely up to the fill point increased the losses in the pumpjack by approximately 1 watt. The complete results of this test is shown in Table 2.4.

IV. DISCUSSIONS AND CONCLUSIONS

The results indicate the overall efficiency of the Midland Cylinder (51.8%) was little better than the efficiency of the O'Bannon (53.4%).

The flow rate of the Midland was 35.8% greater which was expected because of the difference in cylinder sizes.

There was a 27% higher input to the motor on the Midland to produce 35.8% more water.

The volumetric efficiency of the Midland Cylinder was the same, 90.5%.

The overall efficiency of the Midland (24.4%) was slightly higher than the overall efficiency of the O'Bannon (21.5%). The overall efficiency of the Midland would have been higher if the losses in the pumpjack had not been considerably higher for the Midland Pump. See Table 2.4.

These losses were even higher when the O'Bannon Pump was disconnected and the pumpjack operated in an unbalanced condition with 60 lbs of weight whose center of gravity was 19.5 inches from the pivot point of the pumpjack.

This indicates that the efficiency of both cylinders might be improved if the pumps were precisely balanced. However the higher loading of the Midland (80+ lbs of counterbalance at 19.5 inches) appears to greatly increase pumpjack losses.

The flywheel had the effect of smoothing out the power and force curves. However, it should not be used with a small motor unless a centrifugal clutch is also used. Otherwise the starting windings of a motor are used too long while waiting for the flywheel to get up to speed. A centrifugal clutch would solve this problem and allow the use of a relatively small D. C. motor powered by photovoltaic panels.

Both cylinders were found to be relatively leak free so that each would start pumping almost immediately when the motor was turned on. This is an important characteristic when intermittant solar pumping is used.

There were no significant differences in the starting force needed to start the Midland Pump when started after six hours, 12 hours and 24 hours. This test was not repeated on the all metal O'Bannon since the starting force would characteristically be much more independent of time than the Midland Cylinder.

On the basis of this testing program there appears to be no justification in purchasing the more expensive O'Bannon cylinders instead of the Midland unless a smaller amount of water is needed. The O'Bannon is reported to have a much larger installed life.

There does appear to be justification to try to reduce pumpjack losses when the system is more heavily loaded. It would be helpful to repeat the same test using a deeper pumping level to load the pumpjack more heavily to find out what the overall efficiencies would be then.

In looking for reasons as to why the O'Bannon was not more efficient it was suggested that this cylinder had a much greater friction area than the Midland cylinder even though it was smaller in diameter. The O'Bannon cylinder has a metal to metal contact which would have a lower friction per unit area than the leather to metal contact of the Midland. However, evidently the friction surface of the O'Bannon was enough greater to offset the lower unit friction.

Figure 2.1: Motor Calibration Curve

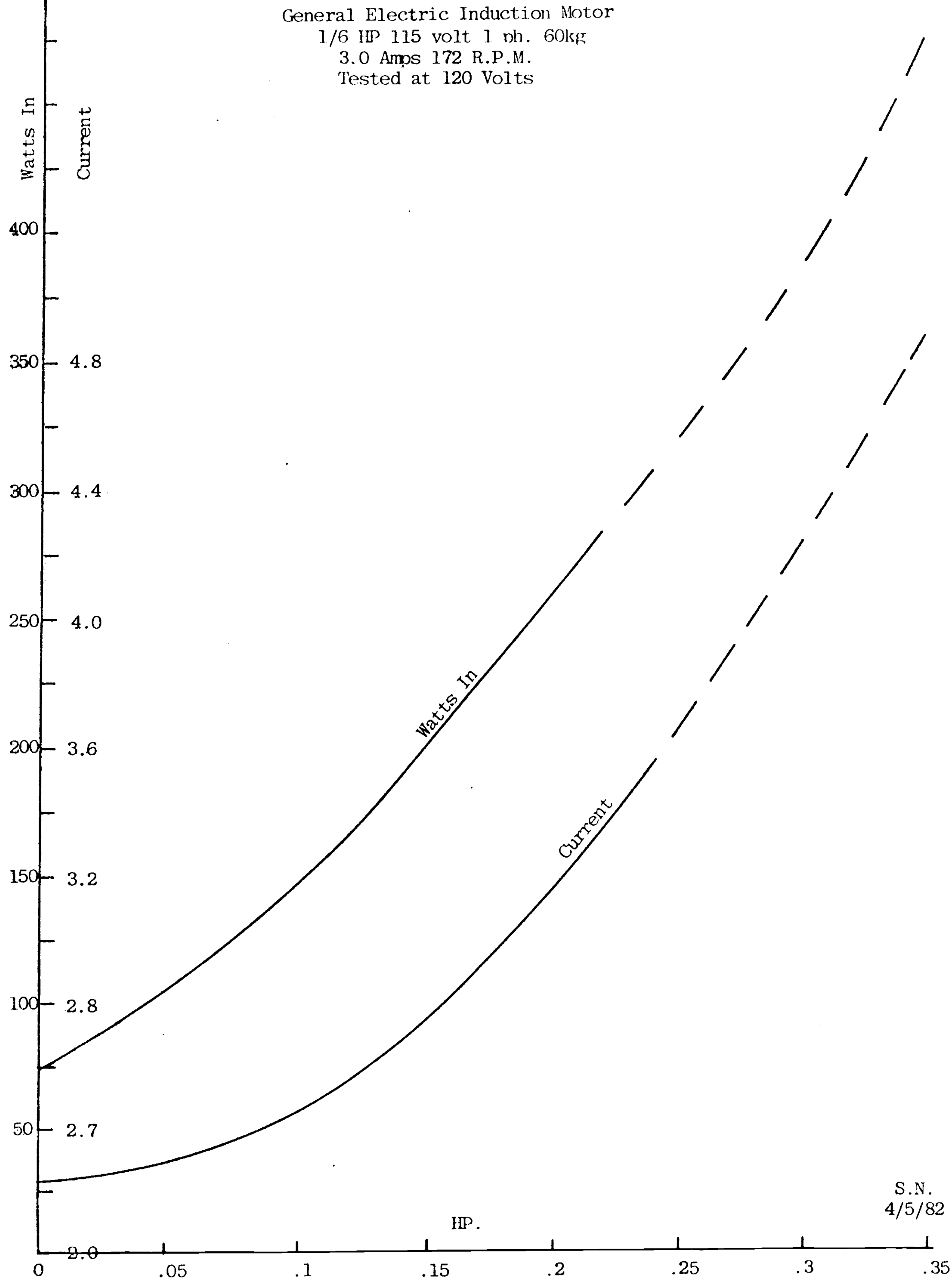


Figure 2.2: Strain-Gage Calibration Curve

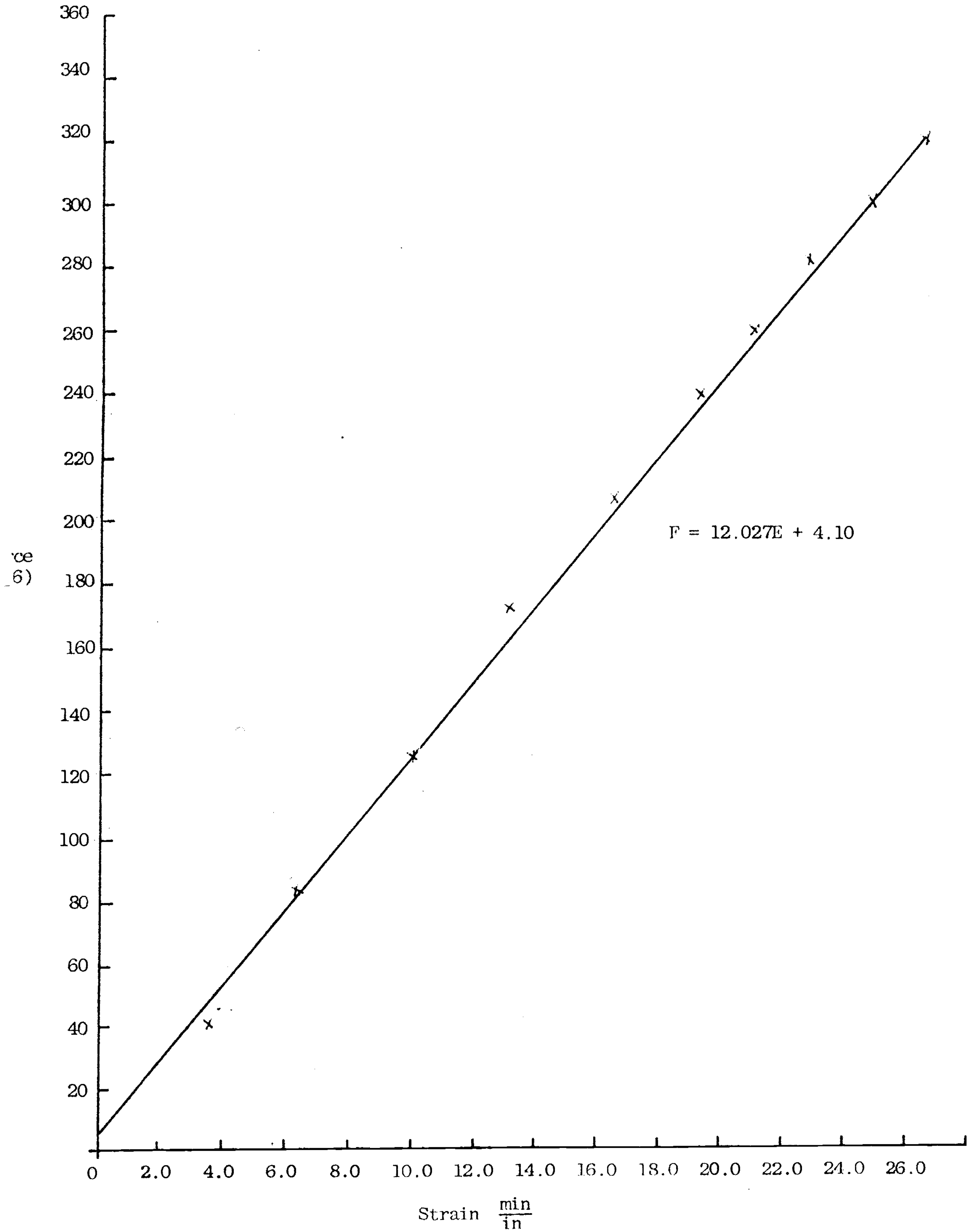
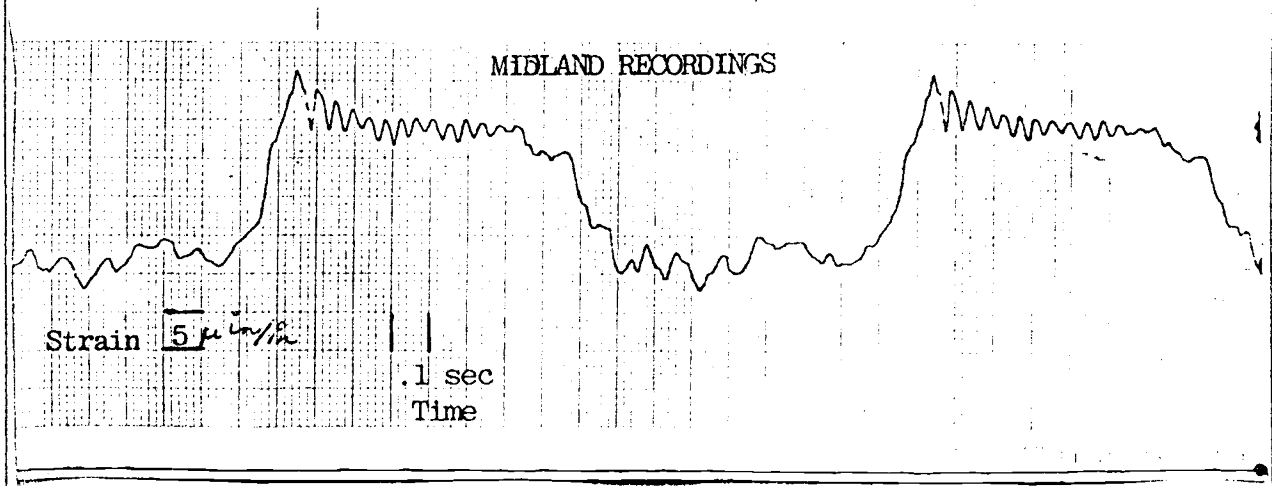
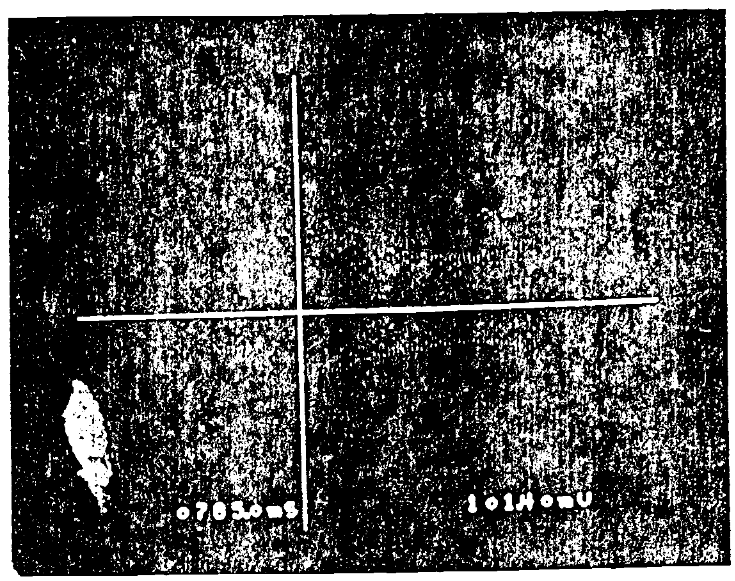
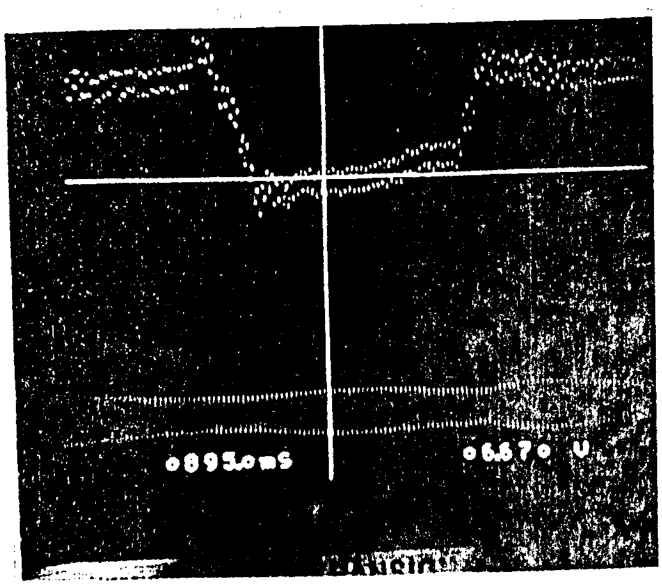


Figure 2.3: Strain and Amperage Recordings





O'BANNON RECORDINGS



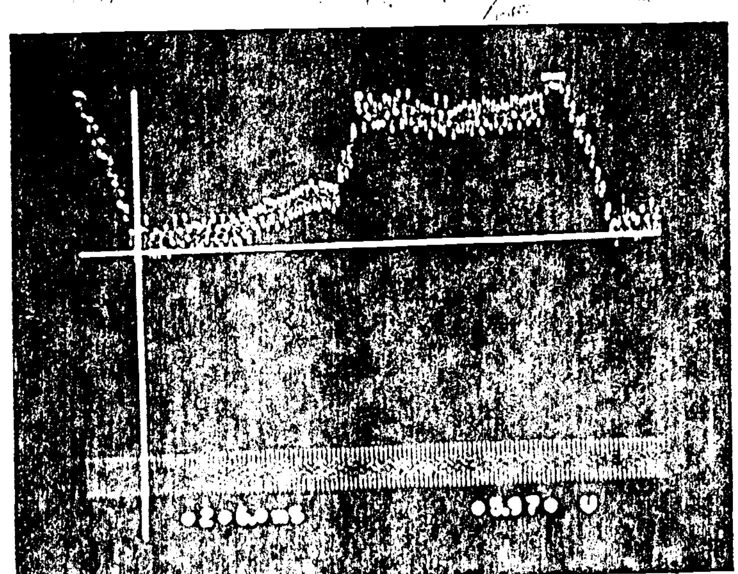
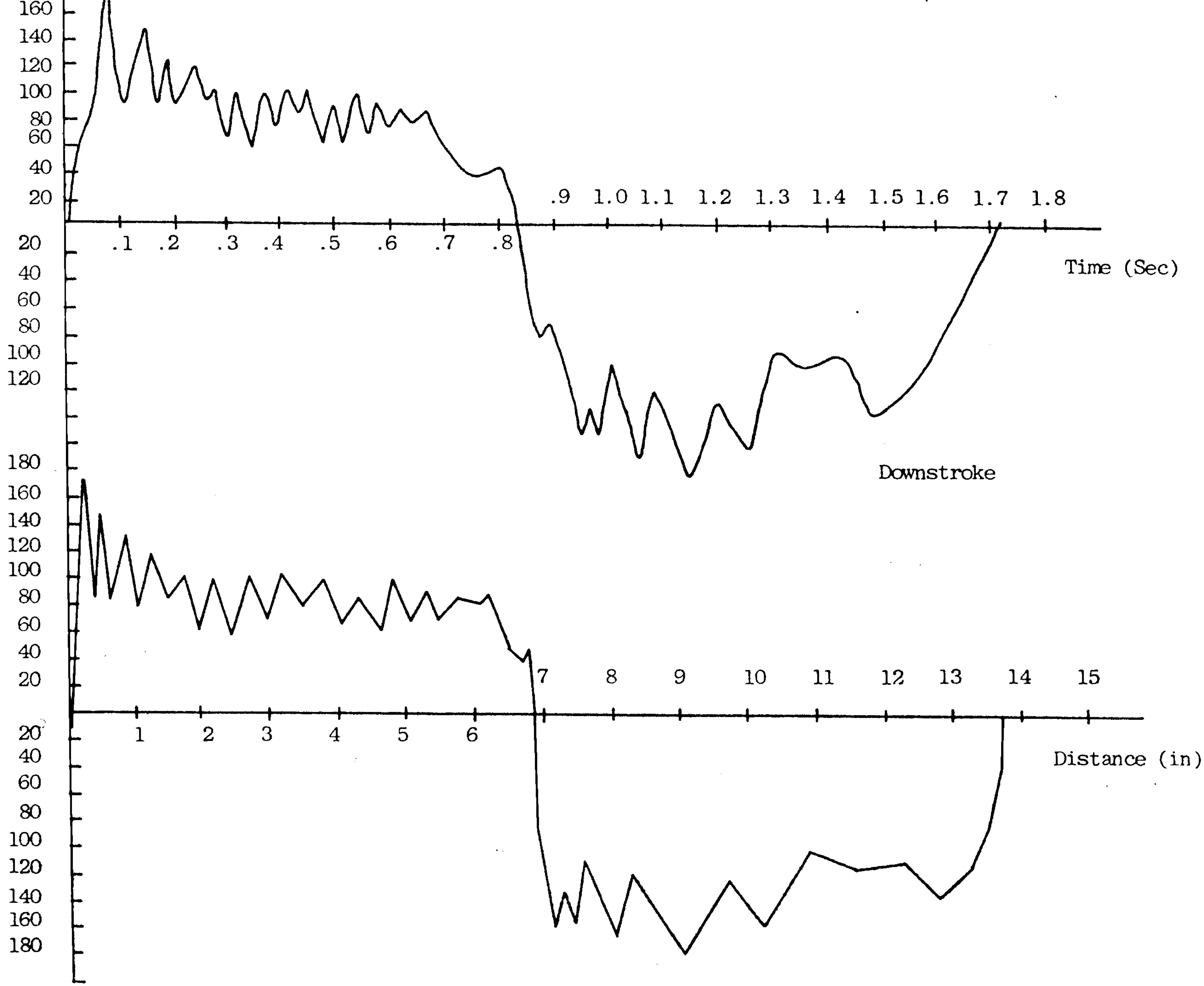


Figure 2.4: Force-Time and Force-Distance Curves for the Midland Cylinder



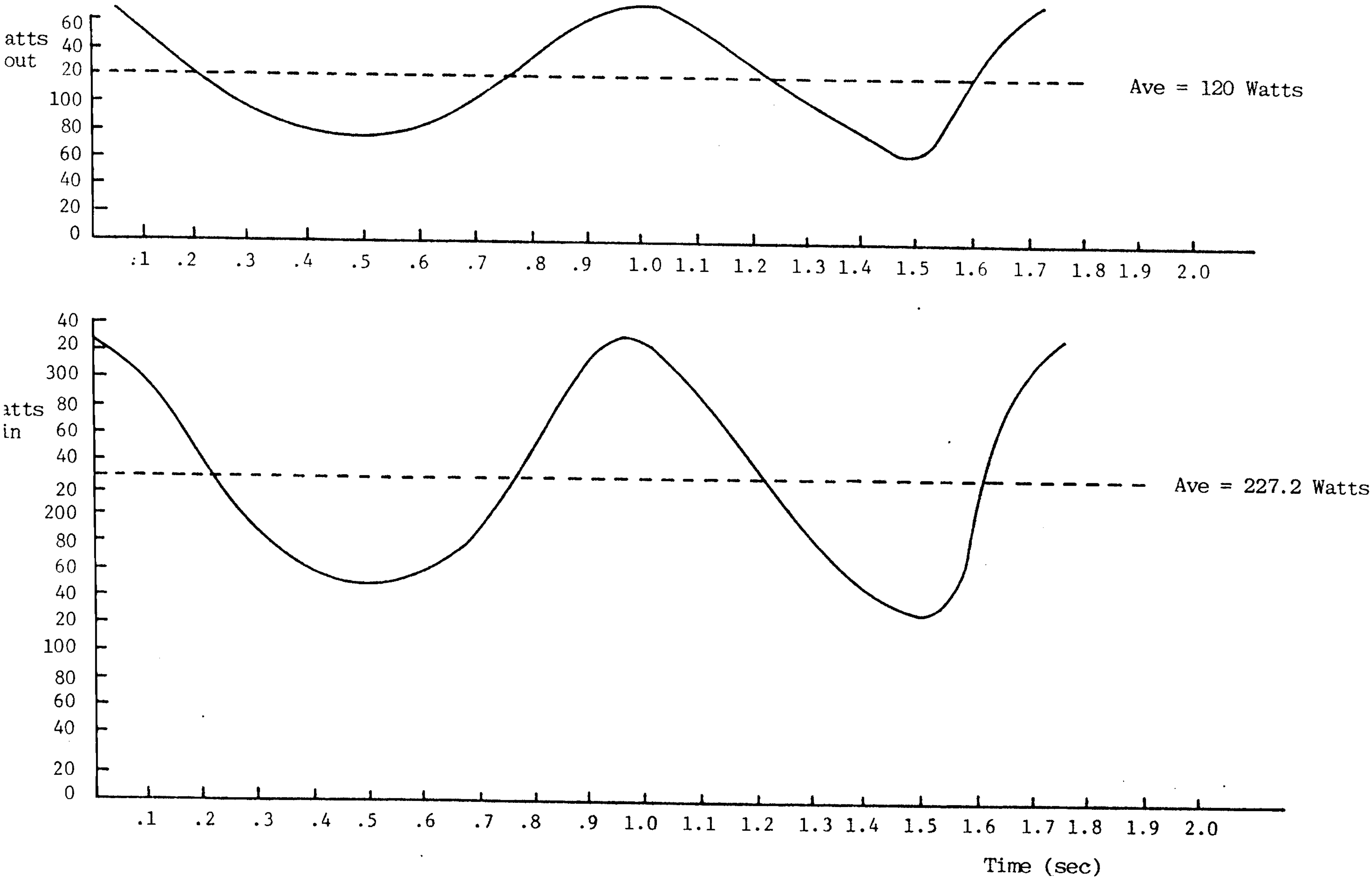


Figure 2.5: Power Out and Power in for Midland Cylinder without Flywheel

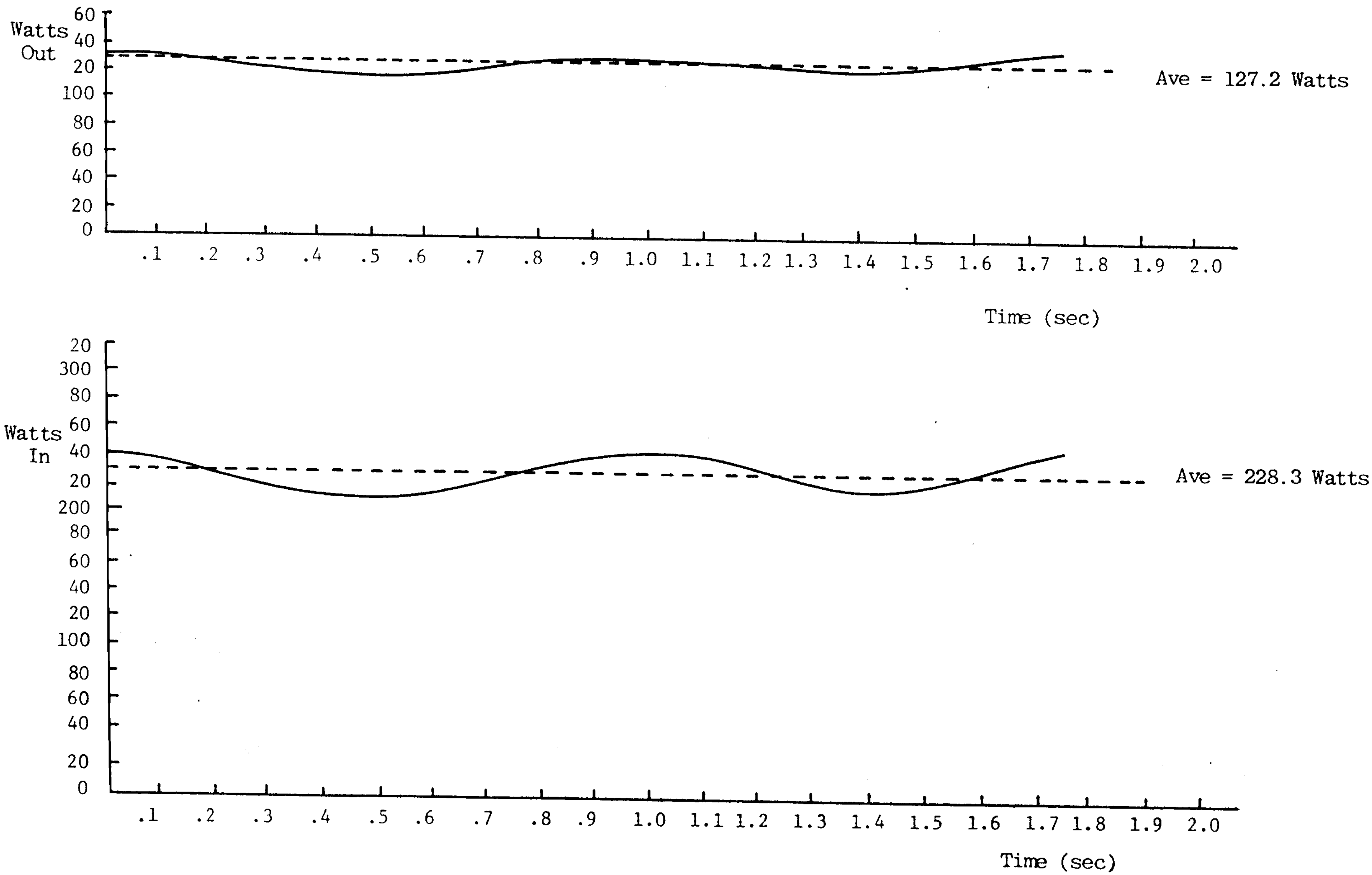
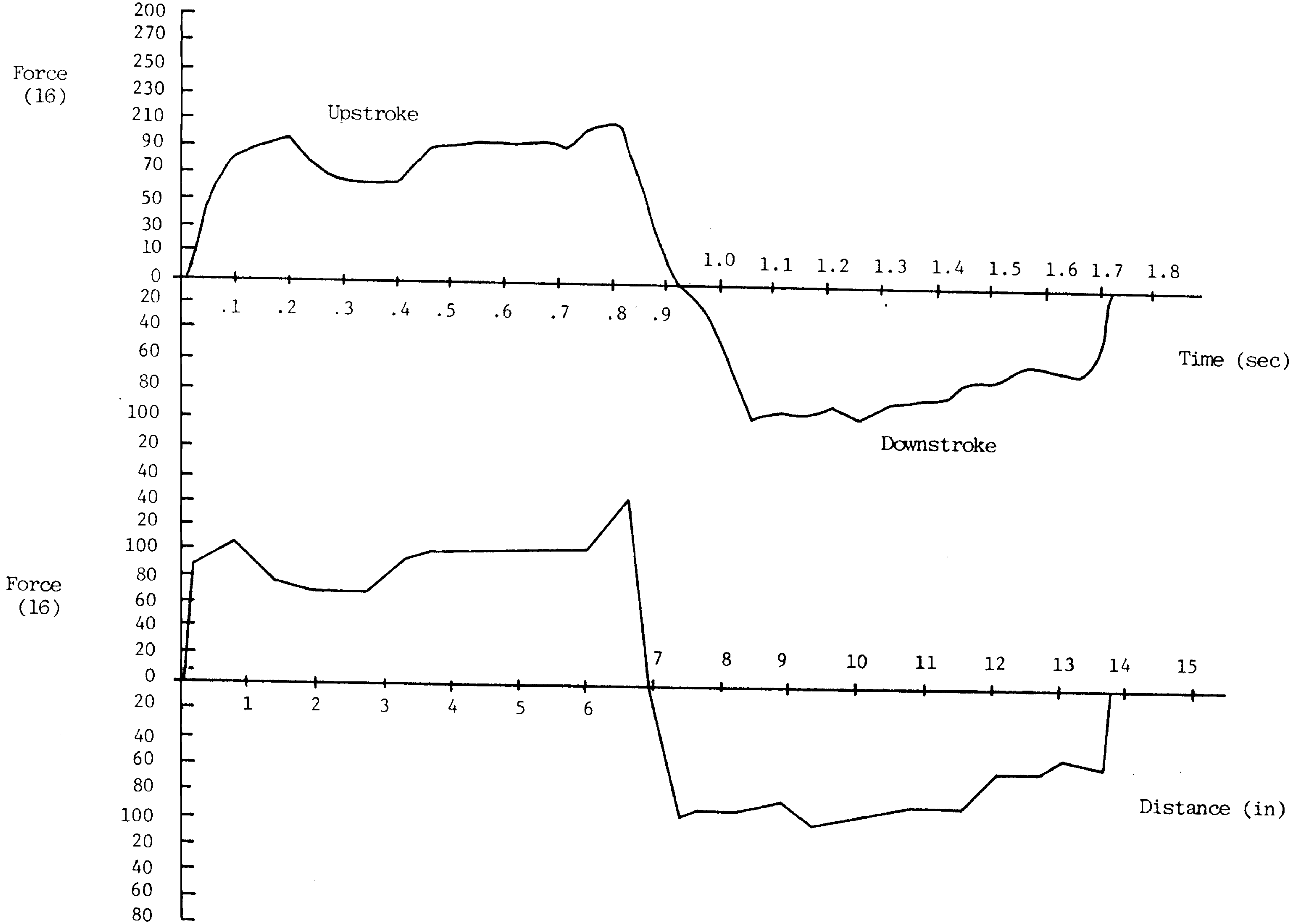


Figure 2.6: Power in and Power out for Midland Cylinder with Flywheel

Figure 2.7: Force - Time and Force - Distance Curves for The O'Bannon Cylinder



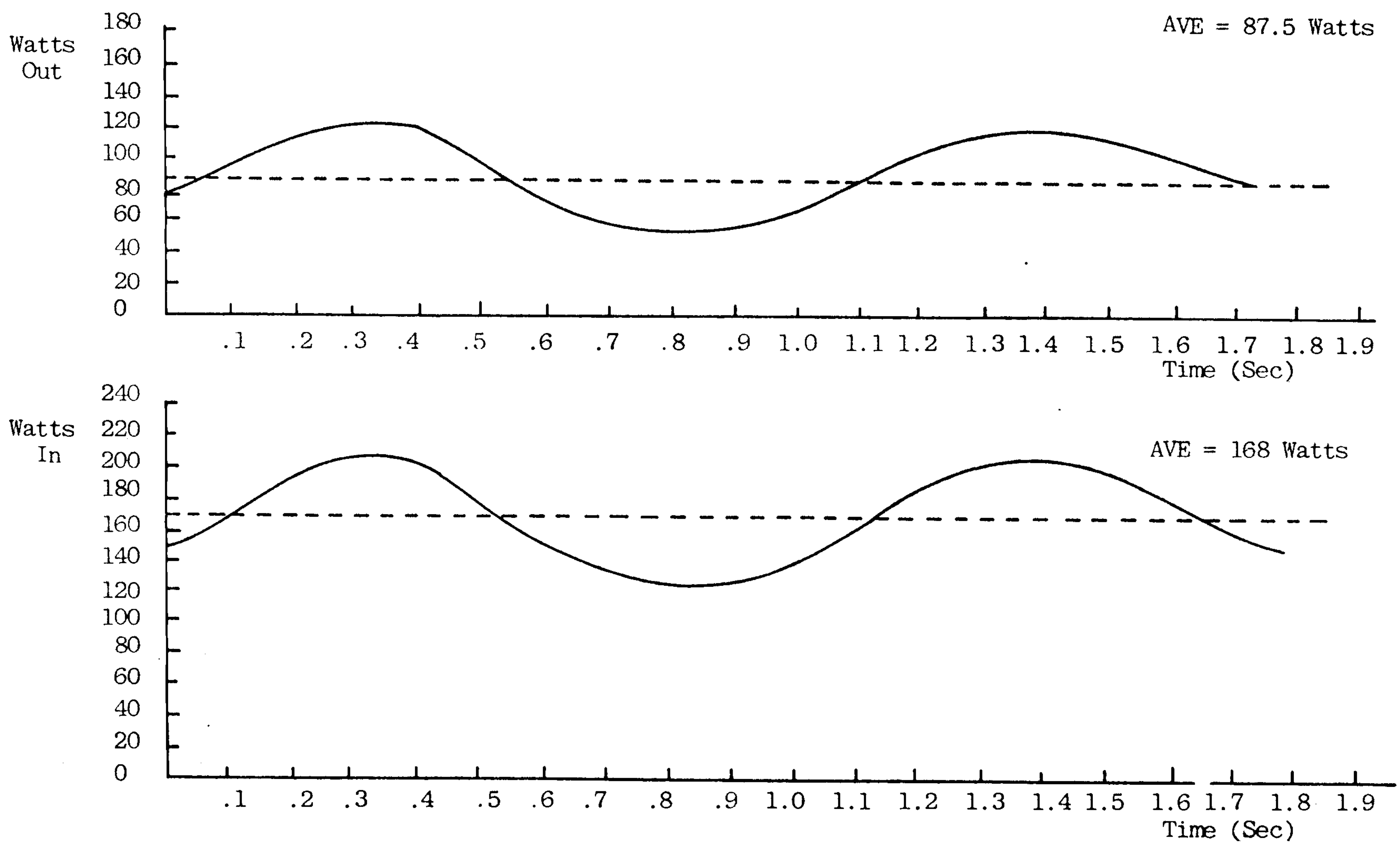


Figure 2.8: Power in and Power out for O'Bannon Cylinder without Flywheel

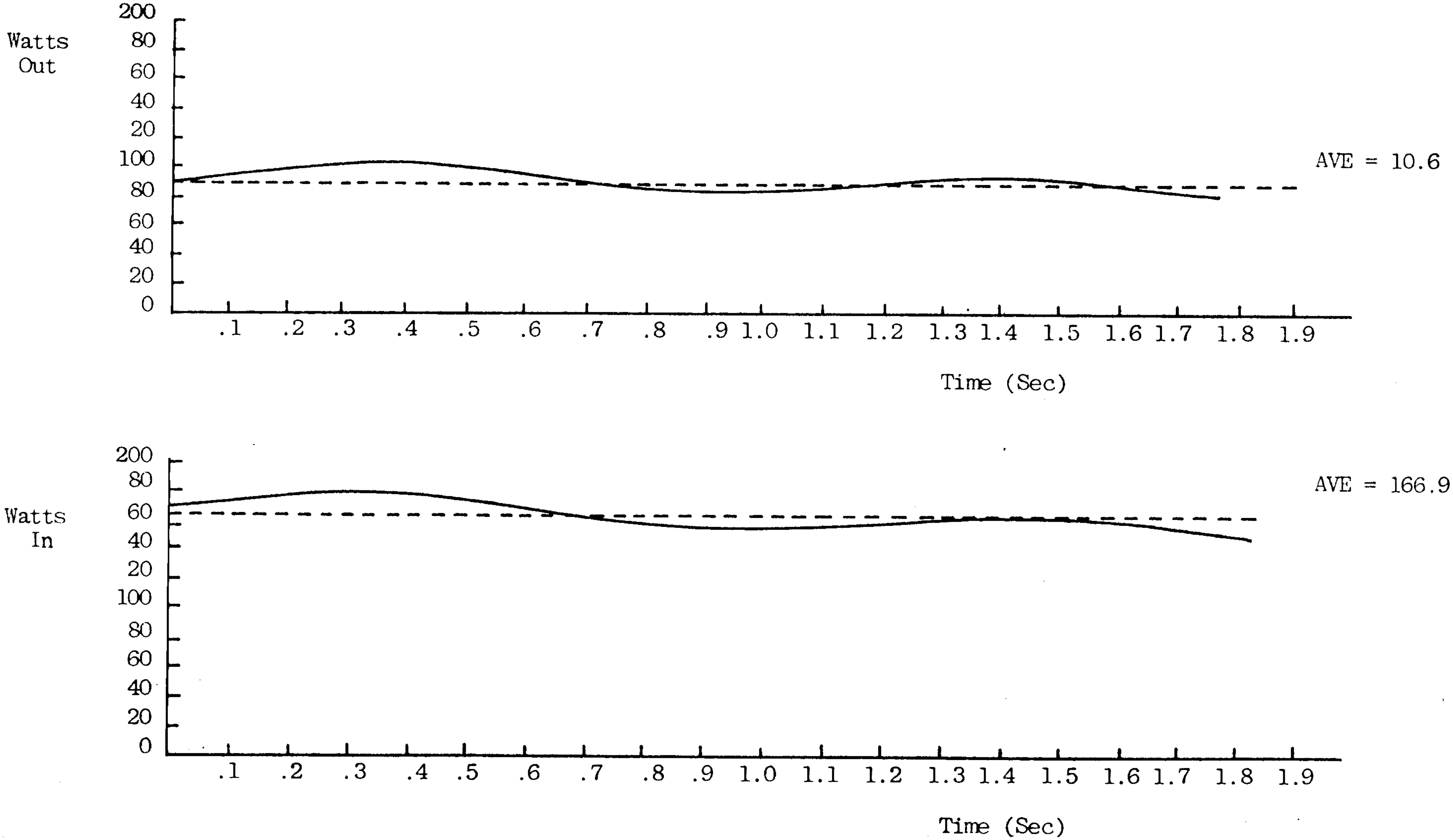


Figure 2.9: Power in and Power out for O'Bannon Cylinder with Flywheel