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STUDY OF STORED ENERGY SYSTEMS PROPOSED FOR TESTING A PRESSURE-REGULATING VALVE

by

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<p>Two systems using stored mechanical energy, rotational and translational (drop), were proposed for use in testing a high discharge, high-pressure-regulating valve. A computer-based dynamic analysis of those systems indicates the drop test system to be less costly, but near the practical limits of drop height and weight. The rotational system will exercise the valve for one-half of a pump cycle provided the pump begins at the start of a pump output cycle. The rotational system must be able to withstand very large forces. Neither system exercises the valve for enough time, but the rotational system appears to be capable of longer testing time.</p>					
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Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
degrees (angle)	0.01745329	radians
feet	0.3048	metres
foot-pounds (force)	1.355818	joules
gallons (US liquid)	3.785412	cubic decimetres
inches	2.54	centimetres
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.4535924	kilograms

SUMMARY

Two valve test systems were studied. They each use a stored energy approach; one is rotational, the other is translational (drop). An idealized dynamic analysis indicates the rotational system will generate peak forces and torques that will require a massive test fixture. The test fixture needs a thorough design and dynamic analysis to assure it will operate under such severe dynamic forces.

The drop test will almost equal the performance of the rotational system. It also appears to be less costly. However, it is near the practical limits of ball weight, drop height and available reaction structure.

Neither system produces the design discharge for enough time to evaluate the regulating valve's performance. Precise timing of the start of pumping in the rotational test is critical to attaining the desired discharges.

James B. Check, SMO.

The Director of WAB during the investigation and preparation of this report was COL Allen F. Gurn. The Technical Director was Dr. Robert W. Whalin.

PREFACE

This study was conducted in January 1986, by personnel of the US Army Engineer Waterways Experiment Station (WES), under the sponsorship of the Defense Nuclear Agency (DNA) in support of the Silo Test Program-Shock Isolation Systems. The DNA project officer was Mr. James Cooper. Mr. Larry Selzer, Aerospace Corporation, proposed the concept as a means of evaluating a valve for a full-scale shock isolation system.

The investigation was conducted under the supervision of Messrs. Bryant Mather, Chief, Structures Laboratory (SL); James T. Ballard, Assistant Chief, SL; Dr. Jimmy P. Balsara, Chief, Structural Mechanics Division (SMD), SL; and Mr. Robert E. Walker, Project Manager, SMD. This report was prepared by Mr. James B. Cheek, SMD.

The Director of WES during the investigation and preparation of this report was COL Allen F. Grum. The Technical Director was Dr. Robert W. Whalin.

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STUDY OF A PUMPED FOR TESTING A PRESSURE REGULATING VALVE

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STUDY OF STORED ENERGY SYSTEMS

PROPOSED FOR TESTING

A PRESSURE REGULATING VALVE

PART I: INTRODUCTION

1. The analysis documented in this report was accomplished as part of a feasibility study to develop design requirements for a device proposed for testing a hydraulic pressure regulating valve. Because of the valve's high operating pressure and discharge, designing the test device presents many difficult analysis problems. This study looks at but one of those problems in a highly idealized fashion. Nevertheless, the analysis is useful in that it establishes the best performance attainable from a "perfect" system. That performance can be used to see how well it meets test system requirements. From that evaluation, decisions on any changes needed to a practical system can be made and more extensive engineering analysis can be conducted.

PART II: IDEALIZED ANALYSIS, ROTATIONAL

Valve Specification

2. The following analysis was done on a fixture proposed to test a regulating valve at a constant regulating pressure of 4,350 pounds per square inch (psi), at a design maximum flow of 26.4 gallons per second (gps).

Test Fixture Data

3. The Test Fixture consists of two, 30 inch diameter, solid disc flywheels weighting 1,000 pounds (lb). Each is connected to a crankshaft having a one-inch offset (throw) which is in turn linked by a connecting rod to a pump as shown in Figure 1 below. The pump cylinder's ID is 16 inches and the pump shaft's OD is 9 inches.

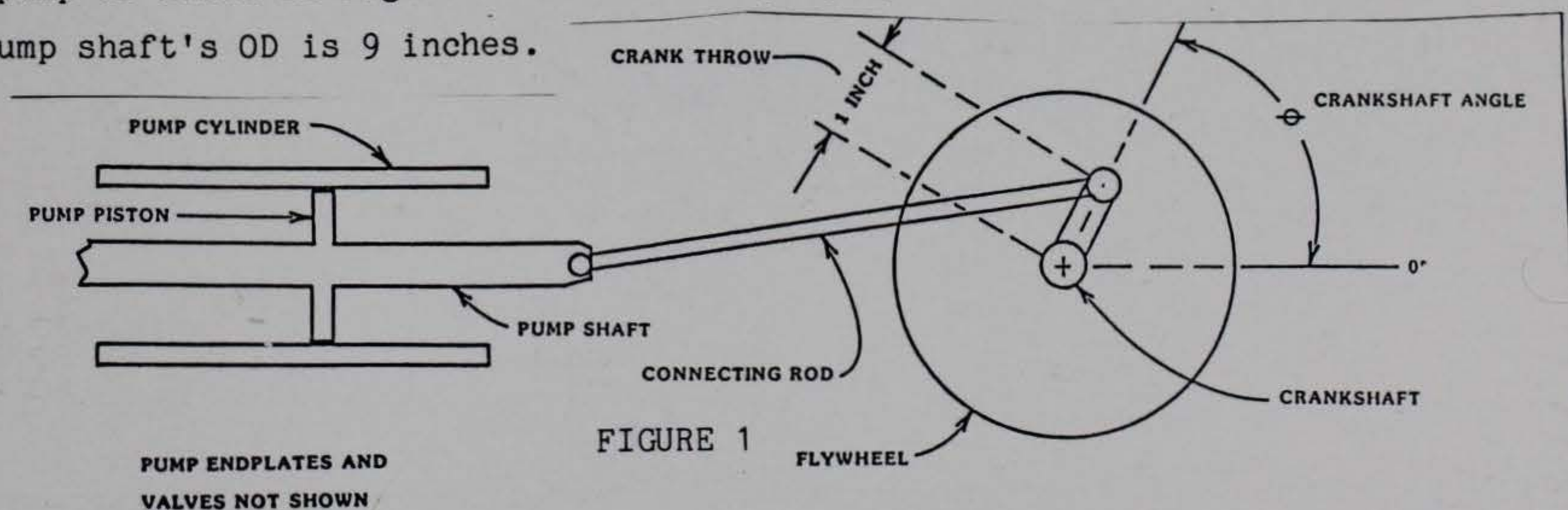


FIGURE 1

Dynamic Analysis

4. The analysis is based on a perfect system (no mechanical or pumping loss). The results, presented in Appendix A, indicate the following:

- a. At 424 revolutions per minute (rpm), the pump will discharge 26.4 gps, peak, provided the pumping starts when the crankshaft angle is 90° . The discharge will decline, as shown in Figure A2, to zero in 71 milliseconds (msec).
- b. Peak torque in the drive is near 50,000 foot-pounds (ft-lbs) (see Figures A1 and A3).
- c. The drive will slow from 424 rpm to zero rpm in 70° of crank rotation which is $70.8^\circ/360^\circ = .197$ revolutions.
- d. The force required to operate the pump shaft is almost 600,000 lb at design pressure.
- e. Operating the system at 577 rpm and starting the test at zero degrees crankshaft angle produces the desired peak discharge and increases the time of regulated discharge (See Figure B7).

5. Appendix B, like Appendix A, graphs the test fixture performance. However, pumping starts at a crank angle of zero degrees. Peak pump output is only 16 gps using 424 rpm as above (see Figures B1 and B2).

6. A second series of calculations was made keeping all conditions the same except the shaft speed which was changed to 577 rpm in order to raise the peak pump discharge to near the design specification (26.4 gps). The results of those calculations are presented on Figures B7 through B12.

7. Those calculations indicate a longer discharge time at a higher discharge. However, the total discharge time of a single cycle system such as this is unlikely to be long enough to thoroughly exercise the test valve.

8. The computer program used for the rotational system analysis is presented in Appendix C.

9. Appendix D presents the calculations upon which the dynamic analysis is based. It also outlines the program logic used in modeling the slowdown of the drive system.

PART III. IDEALIZED ANALYSIS, DROP TEST

Drop Test System

10. For comparison purposes, a swinging ball test fixture was evaluated. The system consisted of a ball suspended by a sling from a fixed point. When directly below the suspension point, the ball will impact the piston of a hydraulic cylinder connected to the regulating valve. Energy is stored in the ball by raising it to height H as shown in Figure 2.

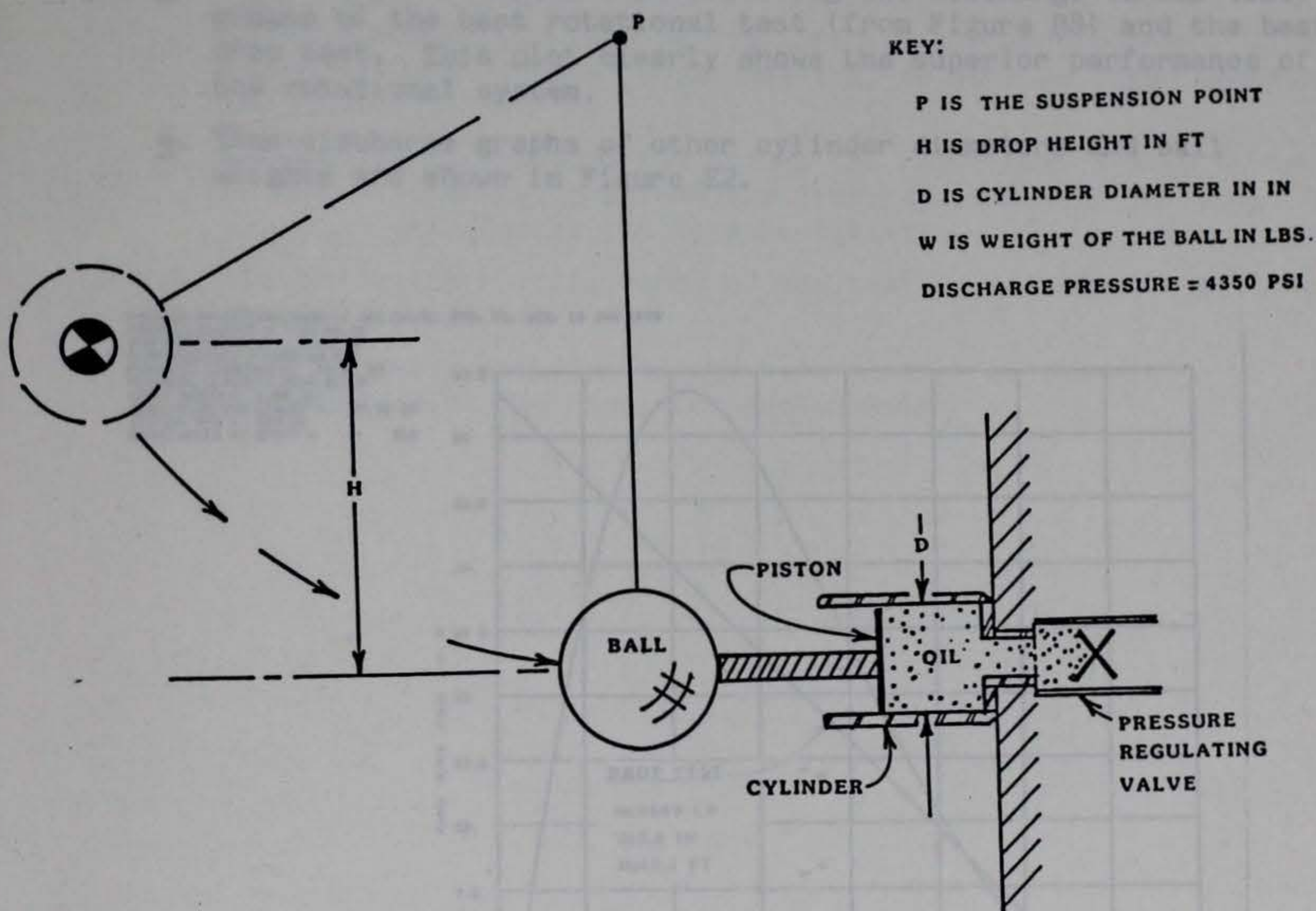


FIGURE 2

Dynamic Analysis, Drop

11. The dynamic analysis calculations and the computer program, shown in Appendix E, are based on total transfer of momentum from the ball to the pump system, ie., the ball does not rebound. The results show the following:

- a. The drop height controls the peak flow rate. Consequently, for a given cylinder diameter, H is fixed in order to attain the valve's design flow.
- b. For a given cylinder diameter (thus drop height) increasing the weight of the ball increases the discharge time of the cylinder.
- c. A 3.5 inch diameter cylinder, a 43.1 foot drop height, and a 2,000 lb ball will produce the design peak flow followed by a linear decline to zero flow for 78 msec.
- d. Figure 3 is a composite plot showing the discharge versus time graphs of the best rotational test (from Figure B8) and the best drop test. This plot clearly shows the superior performance of the rotational system.
- e. Time-discharge graphs of other cylinder diameters and ball weights are shown in Figure E2.

PROGRAM ROSSCOBRA/JUMP -- JAY CHEEK, SHD. SL. VES. 16 JAN 1988
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 577.00
CRANK ANGLE AT START = 0. DEG

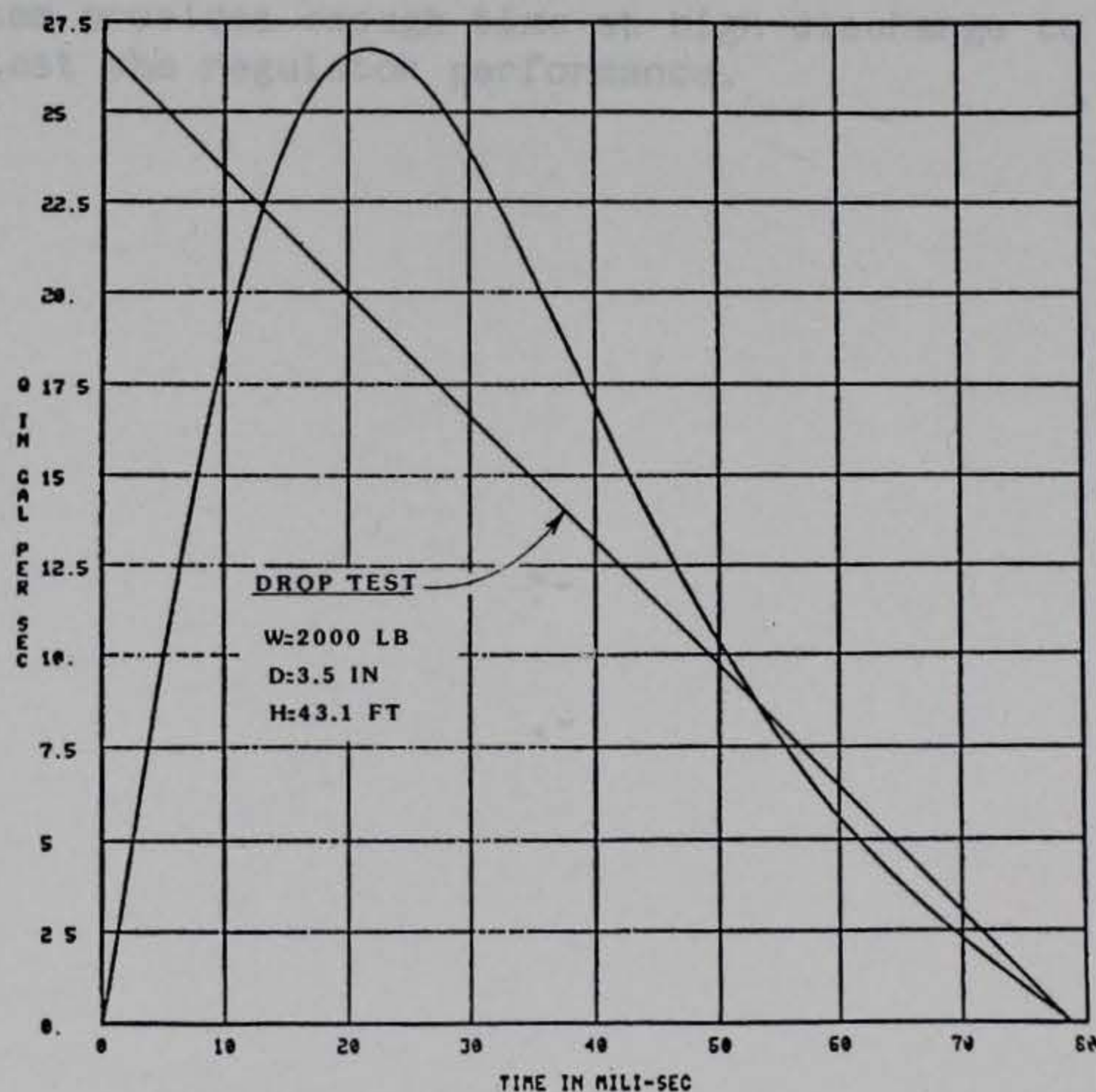


FIGURE 3

PART IV: CONCLUSIONS

12. The following conclusions are based on the idealized analysis of the two systems.

- a. Provided the initial rpm of the rotational test is increased from 424 to 577, the Drop Test will do an inferior job of exercising the regulating valve because of the Drop Test's linear decline in discharge. However, the drop test will cost less.
- b. The drop test is near the practical limits of ball weight and drop height. Going beyond the design discharge requires a four fold increase in drop height to double the peak discharge. Changing to a larger cylinder diameter increases discharge directly with the square of D , but decreases flow time with D^4 .
- c. The very short test time of the rotating system produces extremely large forces in the bearings as well as other parts of the mechanism.
- d. The ability to increase rpm allows the rotational system to test at high discharges, provided the fixture can handle the peak forces. Consequently, it is more flexible.
- e. Precise timing for the start of the test is critical to getting meaningful results.
- f. Neither system provides enough time at high discharge to thoroughly test the regulator performance.

APPENDIX A: ROTATIONAL TEST RESULTS

1. The figures presented in this appendix show the rotational testing system's performance at the design shaft speed of 424 rpm. Other analysis (not presented) showed that the design discharge (26.4 gps) would be attained only when pumping action starts at a shaft angle of ninety degrees. This analysis shows the system's performance under those conditions.

2. Figure A1 provides a tabulation of various system parameters versus time. Figures A2 through A6 are plots of those same parameters versus time.

500	0.0222	132.44	224.6	13653.	10.65	-27467.
600	0.0286	136.27	195.3	10153.	8.33	-31989.
700	0.0311	143.09	167.1	7427.	6.43	-30721.
800	0.0353	147.39	141.3	5330.	4.92	-27754.
900	0.0400	152.54	118.4	3733.	3.74	-25134.
1000	0.0444	153.51	97.3	2529.	2.80	-23083.
1100	0.0483	151.85	78.3	1633.	2.07	-21004.
1200	0.0533	157.20	60.7	929.	1.48	-19492.
1300	0.0572	159.69	44.2	519.	1.01	-18336.
1400	0.0622	160.05	28.5	211.	0.63	-17531.
1500	0.0666	160.61	13.4	48.	0.29	-17064.
PUMPING ENDS AT 0.071 SEC.						
PUMP CUTOFF ANGLE = 70.0 DEGREES						
NUMBER OF TIME STEPS = 1591						

TEST START ANGLE, RPM =?
=90 424

N	T(SEC)	THETA	RPM	KE (FT-LB)	Q (GAL/SEC)	TORQ (FT-LB)
0	0.	90.00	424.0	47833.	26.49	-49824.
100	0.0044	100.71	380.6	38539.	23.51	-49259.
200	0.0089	110.28	338.3	30454.	20.06	-47276.
300	0.0133	118.74	298.2	23661.	16.60	-44384.
400	0.0178	126.18	260.9	18106.	13.42	-41007.
500	0.0222	132.66	226.6	13658.	10.65	-37467.
600	0.0266	138.27	195.3	10153.	8.33	-33988.
700	0.0311	143.09	167.1	7427.	6.43	-30721.
800	0.0355	147.19	141.5	5330.	4.92	-27754.
900	0.0400	150.64	118.4	3733.	3.74	-25134.
1000	0.0444	153.51	97.5	2529.	2.80	-22883.
1100	0.0488	155.85	78.3	1633.	2.07	-21004.
1200	0.0533	157.70	60.7	979.	1.48	-19492.
1300	0.0577	159.09	44.2	519.	1.01	-18338.
1400	0.0622	160.05	28.5	216.	0.63	-17531.
1500	0.0666	160.61	13.4	48.	0.29	-17064.

PUMPING ENDS AT 0.071 SEC.

PUMP CUTOFF ANGLE = 70.8 DEGREES

NUMBER OF TIME STEPS = 1591

FIGURE A1

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK. SMD, SL, WES, 16 JAN 1986
 PISTON DIAMETER = 16.00 IN
 SHAFT DIAMETER = 9.00 IN
 PUMP PRESSURE = 4350.00 PSI
 FLYWHEEL DIAMETER = 30.00 IN
 FLYWHEEL WEIGHT = 2000.00 LB
 CRANK THROW = 1.00 IN
 CONNECTING ROD LENGTH = 30.00 IN
 INITIAL RPM = 424.00
 CRANK ANGLE AT START = 90.00 DEG

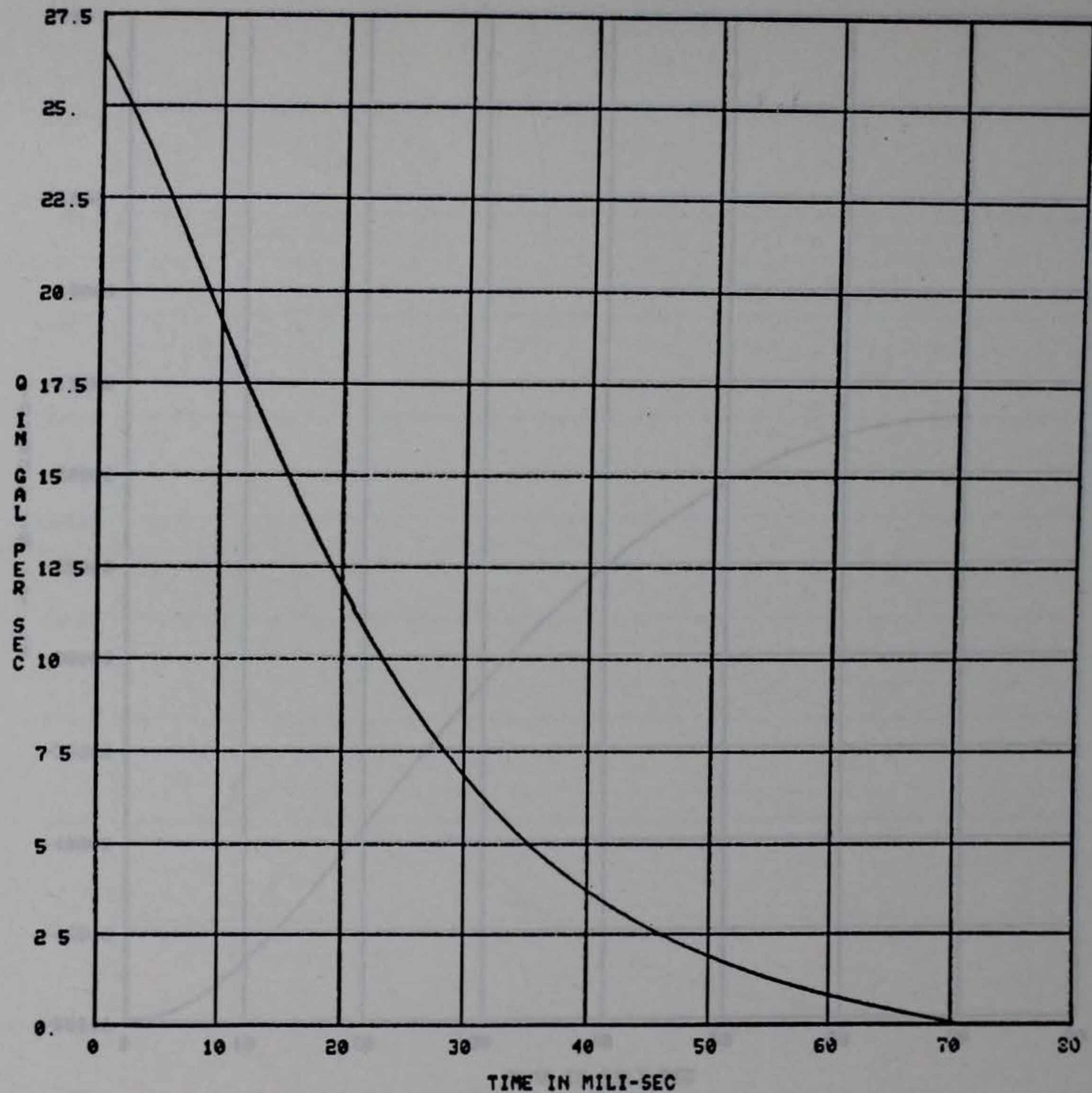


FIGURE A2

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD, SL, WES, 16 JAN 1986
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 90.00 DEG



FIGURE A3

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD, SL. UES, 16 JAN 1986
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 90.00 DEG

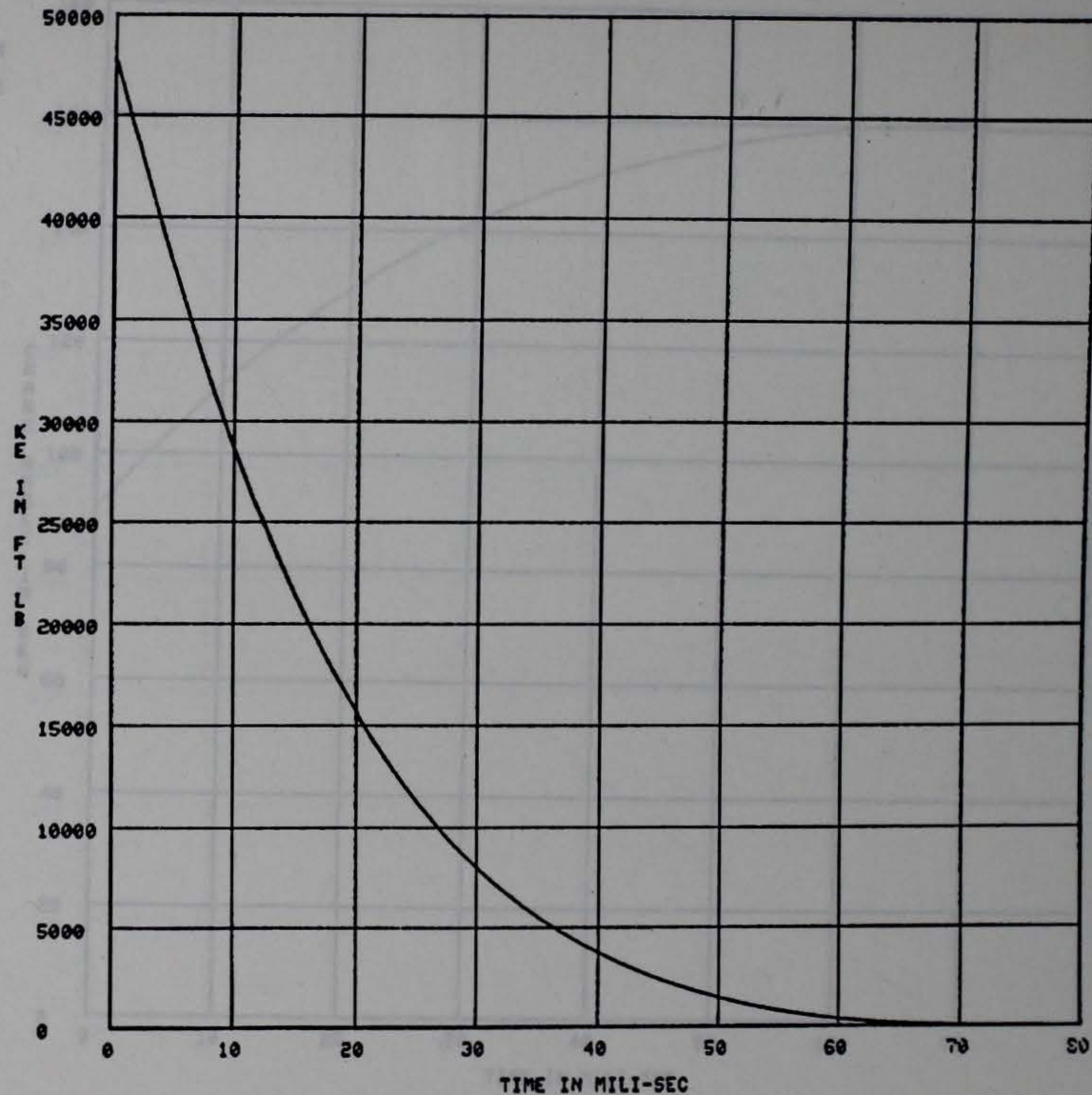


FIGURE A4

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD, SL, WES, 16 JAN 1986
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 90.00 DEG



FIGURE A5

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD, SL, UES, 16 JAN 1986
 PISTON DIAMETER = 16.00 IN
 SHAFT DIAMETER = 9.00 IN
 PUMP PRESSURE = 4350.00 PSI
 FLYWHEEL DIAMETER = 30.00 IN
 FLYWHEEL WEIGHT = 2000.00 LB
 CRANK THROW = 1.00 IN
 CONNECTING ROD LENGTH = 30.00 IN
 INITIAL RPM = 424.00
 CRANK ANGLE AT START = 90.00 DEG

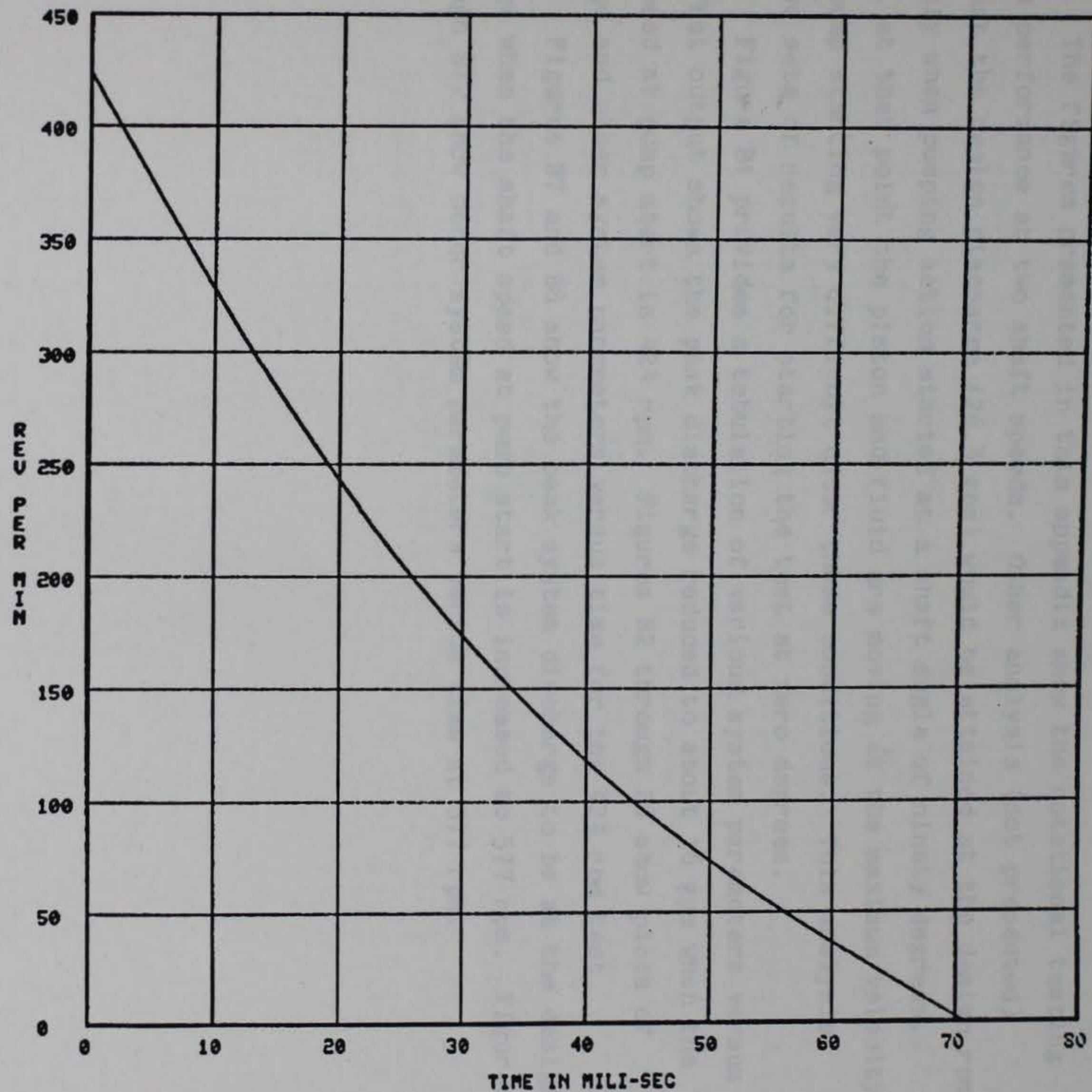


FIGURE A6

APPENDIX B: ROTATIONAL TEST RESULTS, PUMP START AT ZERO DEGREES

1. The figures presented in this appendix show the rotational testing system's performance at two shaft speeds. Other analysis (not presented) shows that the design discharge (26.4 gpm) would be attained at the design rpm (424) only when pumping action started at a shaft angle of ninety degrees. However, at that point the piston and fluid are moving at the maximum velocity making pump starting very difficult under those conditions. This analysis shows two sets of results for starting the test at zero degrees.

2. Figure B1 provides a tabulation of various system parameters versus time. That output shows the peak discharge reduced to about 16 gpm when the shaft speed at pump start is 424 rpm. Figures B2 through B6 show plots of discharge and other system parameters versus time for the 424 rpm test.

3. Figures B7 and B8 show the peak system discharge to be at the design discharge when the shaft speed at pump start is increased to 577 rpm. Figures B9 through B12 show other system parameters versus time at 577 rpm.

TEST START ANGLE, RPM =?
=0 424

N	T(SEC)	THETA	RPM	KE (FT-LB)	Q (GAL/SEC)	TORQ (FT-LB)
0	0.	0.	424.0	47833.	0.03	0.
100	0.0044	11.26	419.9	46914.	4.93	-9410.
200	0.0089	22.30	407.8	44243.	9.35	-18323.
300	0.0133	32.92	388.2	40103.	12.79	-26317.
400	0.0178	42.92	362.2	34907.	15.02	-33101.
500	0.0222	52.16	330.8	29121.	15.98	-38542.
600	0.0266	60.50	295.3	23199.	15.78	-42654.
700	0.0311	67.86	256.7	17529.	14.66	-45569.
800	0.0355	74.15	216.0	12409.	12.85	-47493.
900	0.0400	79.34	173.9	8047.	10.61	-48662.
1000	0.0444	83.40	131.1	4572.	8.10	-49304.
1100	0.0488	86.31	87.9	2053.	5.46	-49614.
1200	0.0533	88.07	44.4	525.	2.77	-49739.
1300	0.0577	88.66	1.0	0.	0.06	-49771.

PUMPING ENDS AT 0.058 SEC.

PUMP CUTOUT ANGLE = 88.7 DEGREES

NUMBER OF TIME STEPS = 1303

FIGURE B1

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD, SL, UES, 16 JAN 1986
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 0. DEG

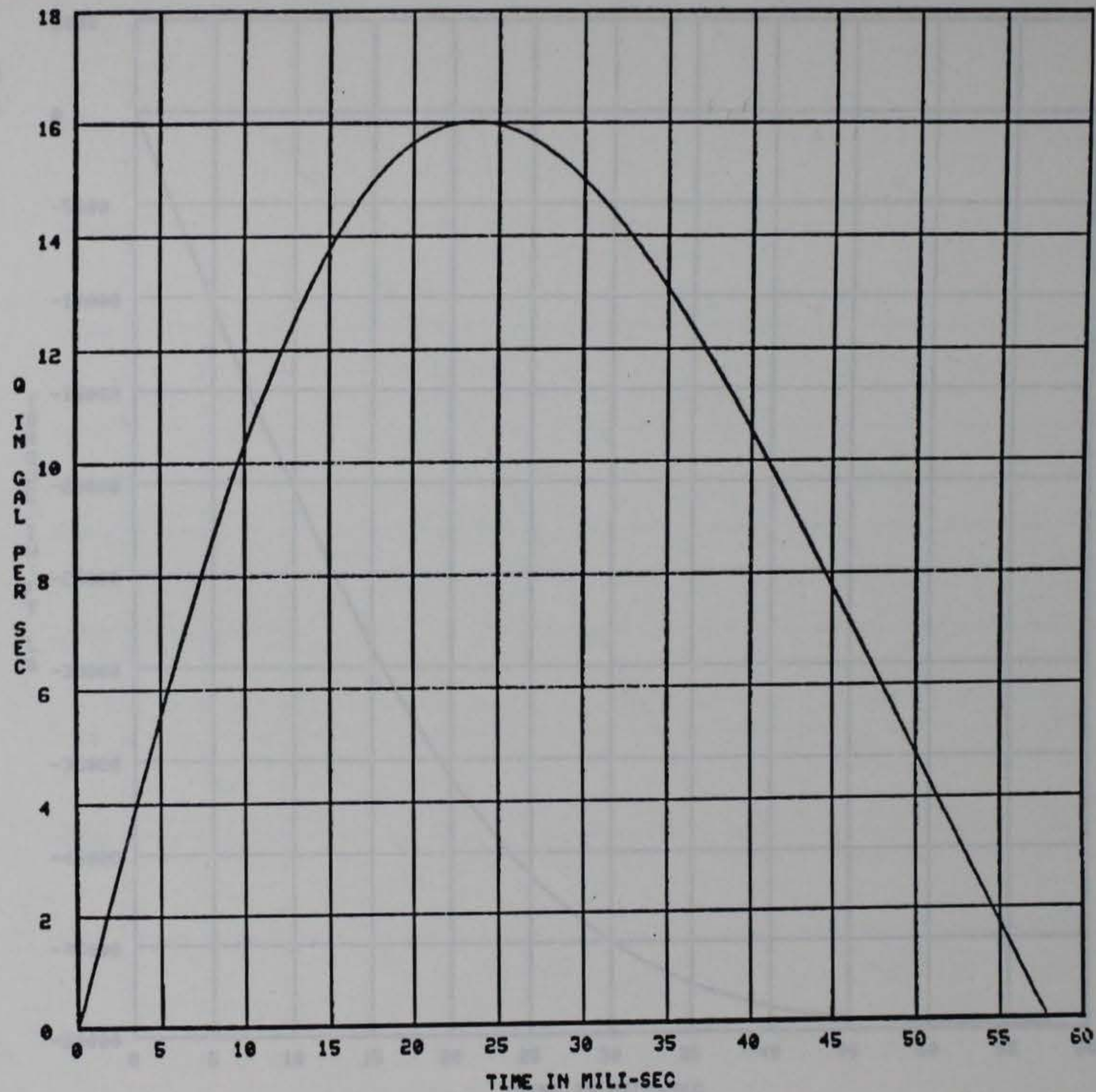


FIGURE B2

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD, SL, WES, 16 JAN 1986

PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 0. DEG

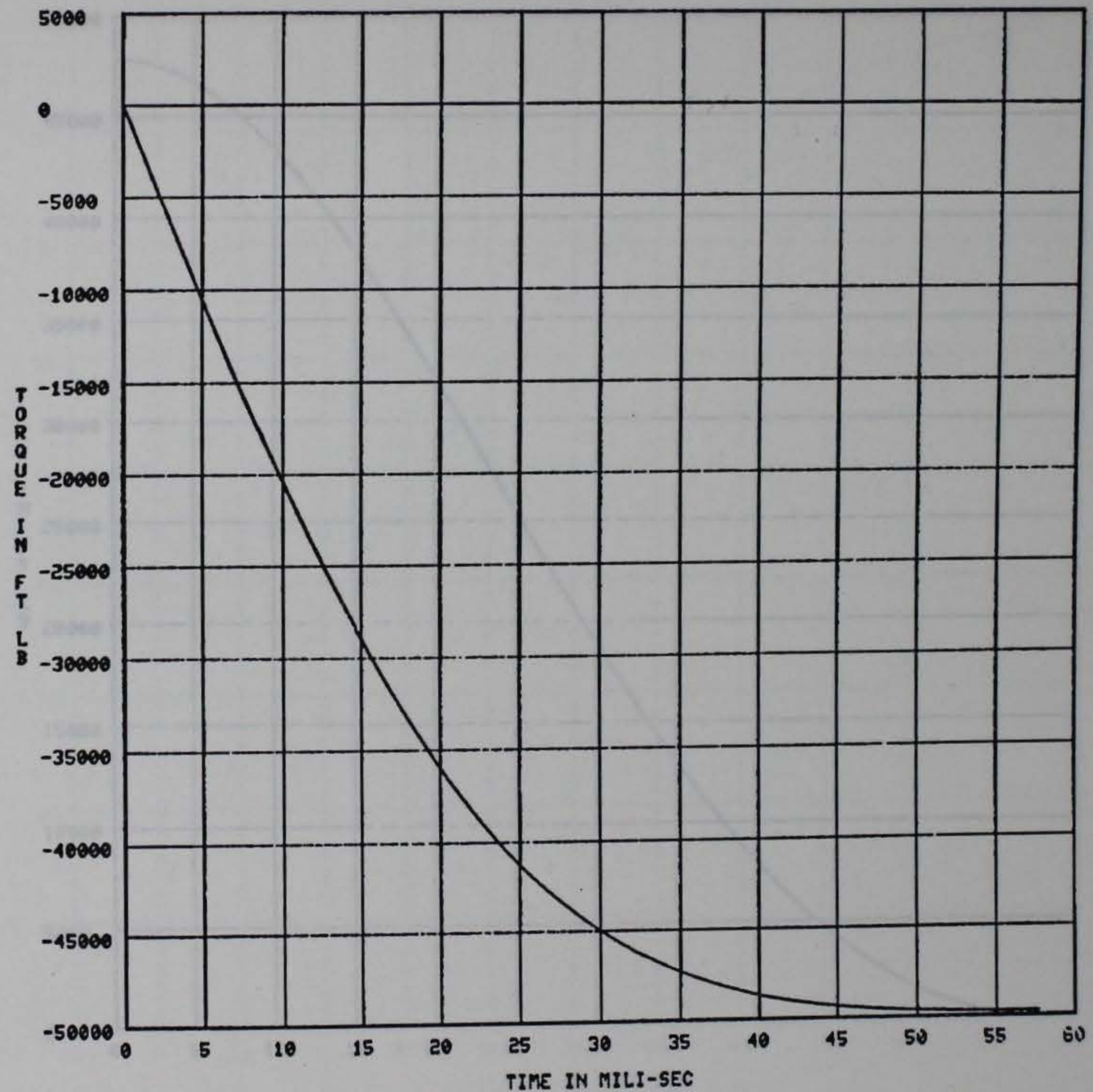


FIGURE B3

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD, SL, WES, 16 JAN 1986
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 0. DEG

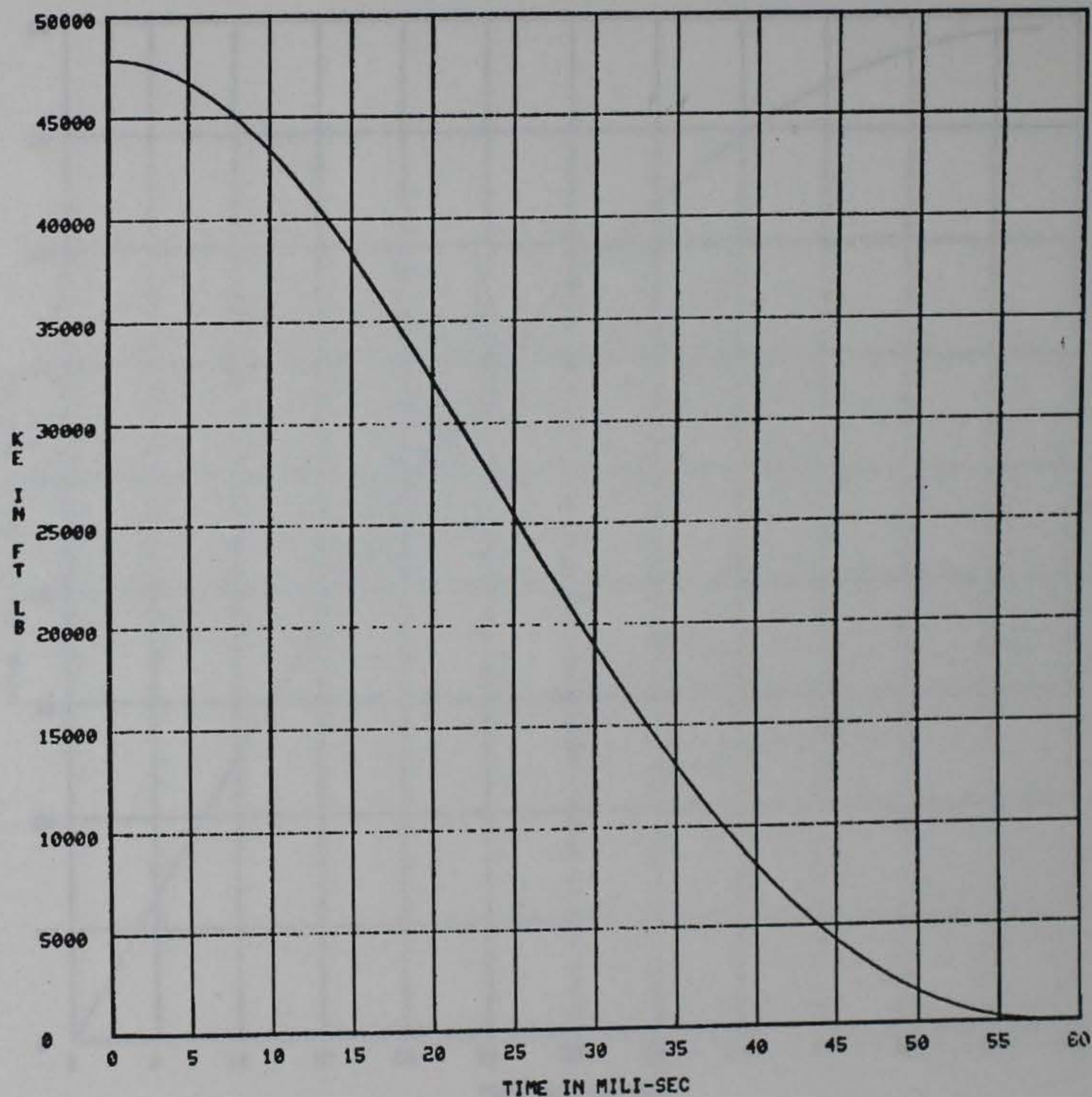


FIGURE B4

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD, SL, UES, 16 JAN 1986
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 0. DEG



FIGURE B5

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD, SL, UES, 16 JAN 1986
 PISTON DIAMETER = 16.00 IN
 SHAFT DIAMETER = 9.00 IN
 PUMP PRESSURE = 4350.00 PSI
 FLYWHEEL DIAMETER = 30.00 IN
 FLYWHEEL WEIGHT = 2000.00 LB
 CRANK THROW = 1.00 IN
 CONNECTING ROD LENGTH = 30.00 IN
 INITIAL RPM = 424.00
 CRANK ANGLE AT START = 0. DEG

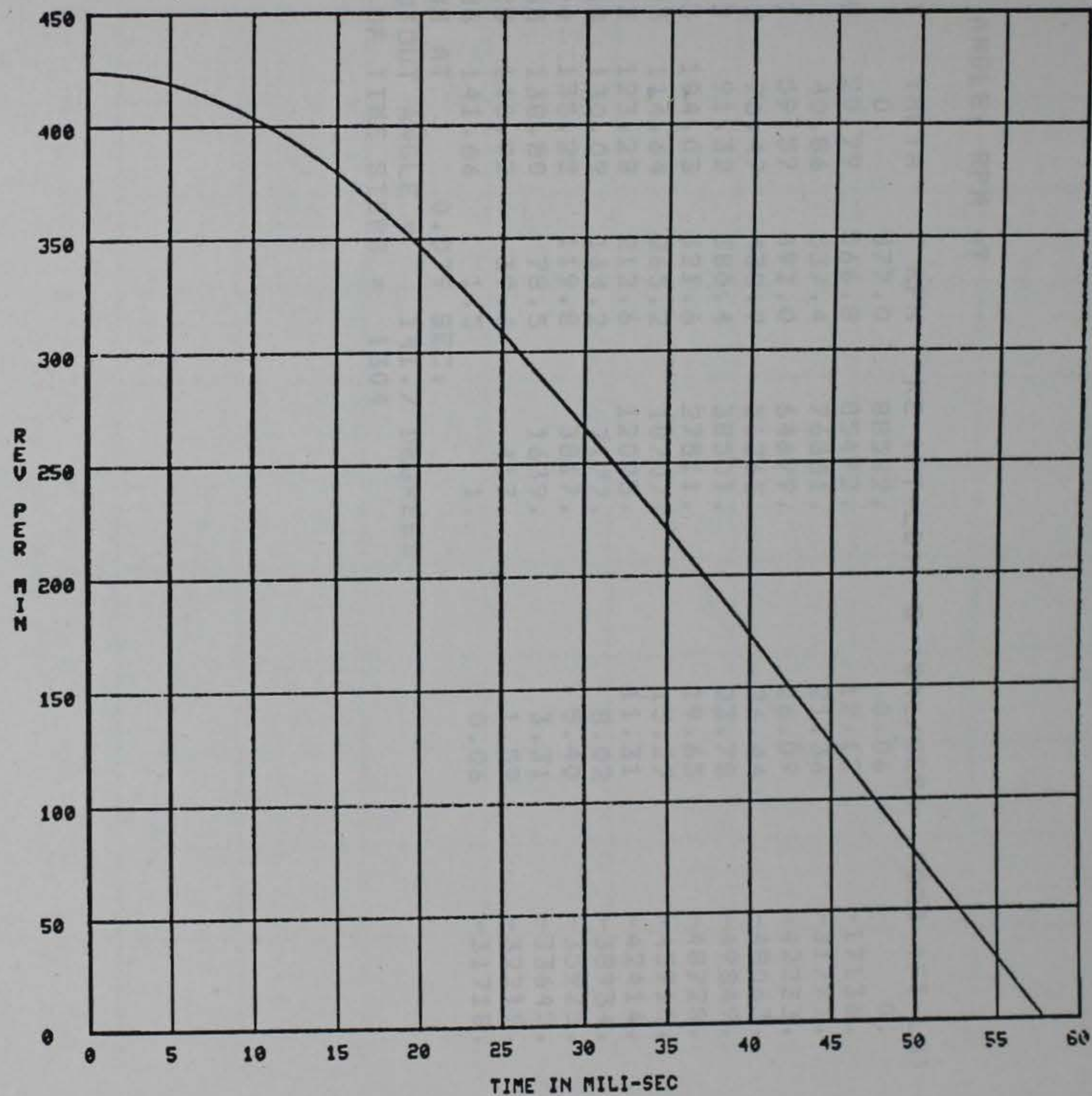


FIGURE B6

TEST START ANGLE, RPM =?
=0 577

N	T (SEC)	THETA	RPM	KE (FT-LB)	Q (GAL/SEC)	TORQ (FT-LB)
0	0.	0.	577.0	88582.	0.06	0.
100	0.0060	20.79	566.8	85472.	12.12	-17136.
200	0.0121	40.86	537.4	76851.	21.36	-31771.
300	0.0181	59.57	493.0	64679.	26.09	-42233.
400	0.0242	76.47	438.9	51265.	26.44	-48063.
500	0.0302	91.32	380.4	38501.	23.78	-49849.
600	0.0363	104.03	321.6	27511.	19.65	-48728.
700	0.0423	114.64	265.2	18707.	15.27	-45915.
800	0.0483	123.28	212.6	12025.	11.31	-42414.
900	0.0544	130.09	164.2	7177.	8.02	-38934.
1000	0.0604	135.22	119.8	3817.	5.40	-35925.
1100	0.0665	138.80	78.5	1639.	3.31	-33642.
1200	0.0725	140.92	39.4	413.	1.59	-32219.
1300	0.0786	141.66	1.5	1.	0.06	-31718.

PUMPING ENDS AT 0.079 SEC.

PUMP CUTOUT ANGLE = 141.7 DEGREES

NUMBER OF TIME STEPS = 1304

FIGURE B7

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD, SL, UES, 16 JAN 1986
 PISTON DIAMETER = 16.00 IN
 SHAFT DIAMETER = 9.00 IN
 PUMP PRESSURE = 4350.00 PSI
 FLYWHEEL DIAMETER = 30.00 IN
 FLYWHEEL WEIGHT = 2000.00 LB
 CRANK THROW = 1.00 IN
 CONNECTING ROD LENGTH = 30.00 IN
 INITIAL RPM = 577.00
 CRANK ANGLE AT START = 0. DEG

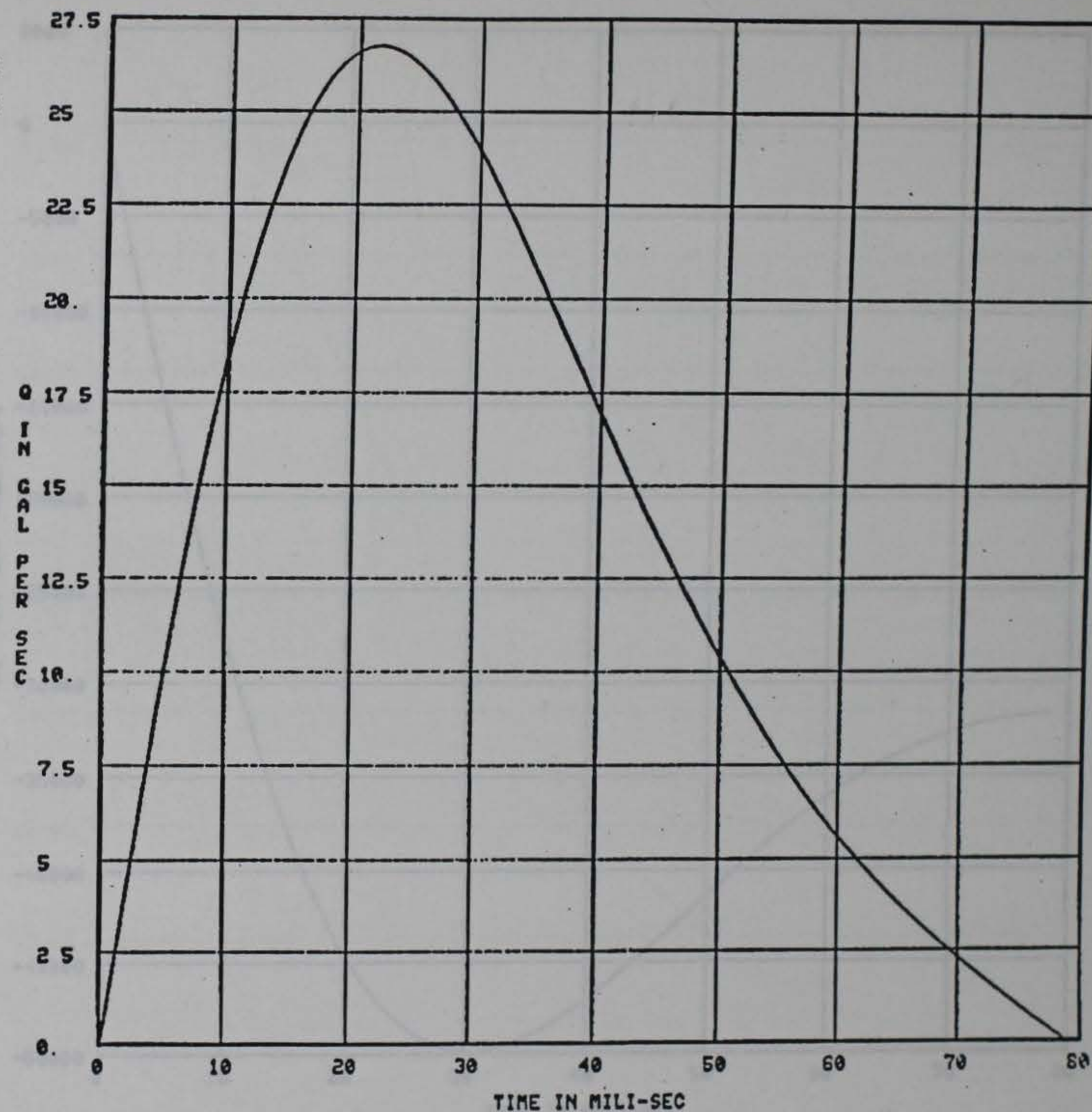


FIGURE B8

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, 6ND, SL, WES, 16 JAN 1986
 PISTON DIAMETER = 16.00 IN
 SHAFT DIAMETER = 9.00 IN
 PUMP PRESSURE = 4350.00 PSI
 FLYWHEEL DIAMETER = 30.00 IN
 FLYWHEEL WEIGHT = 2000.00 LB
 CRANK THROW = 1.00 IN
 CONNECTING ROD LENGTH = 30.00 IN
 INITIAL RPM = 577.00
 CRANK ANGLE AT START = 0. DEG

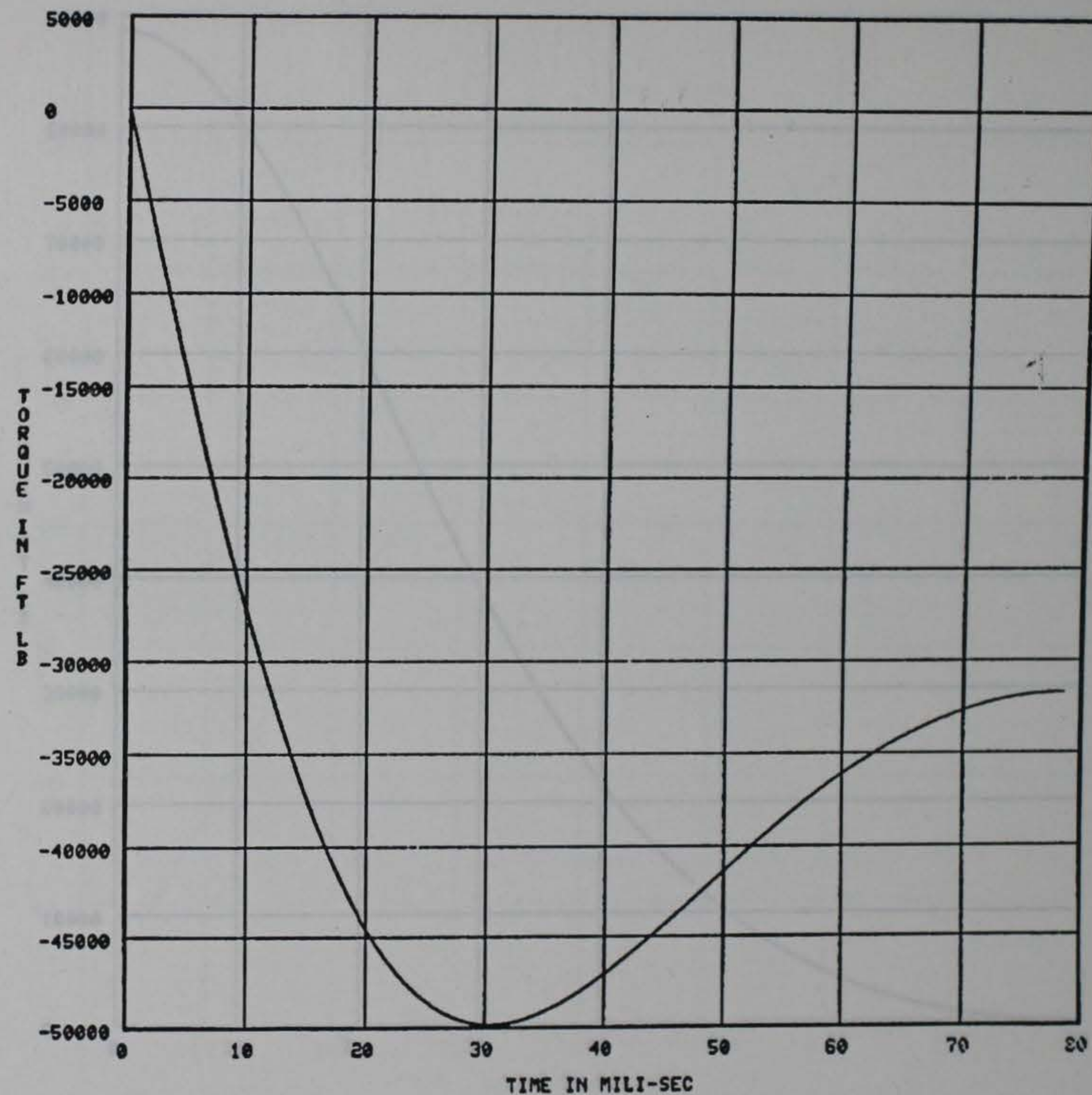


FIGURE B9

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD, SL, WES, 16 JAN 1986
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 577.00
CRANK ANGLE AT START = 0. DEG

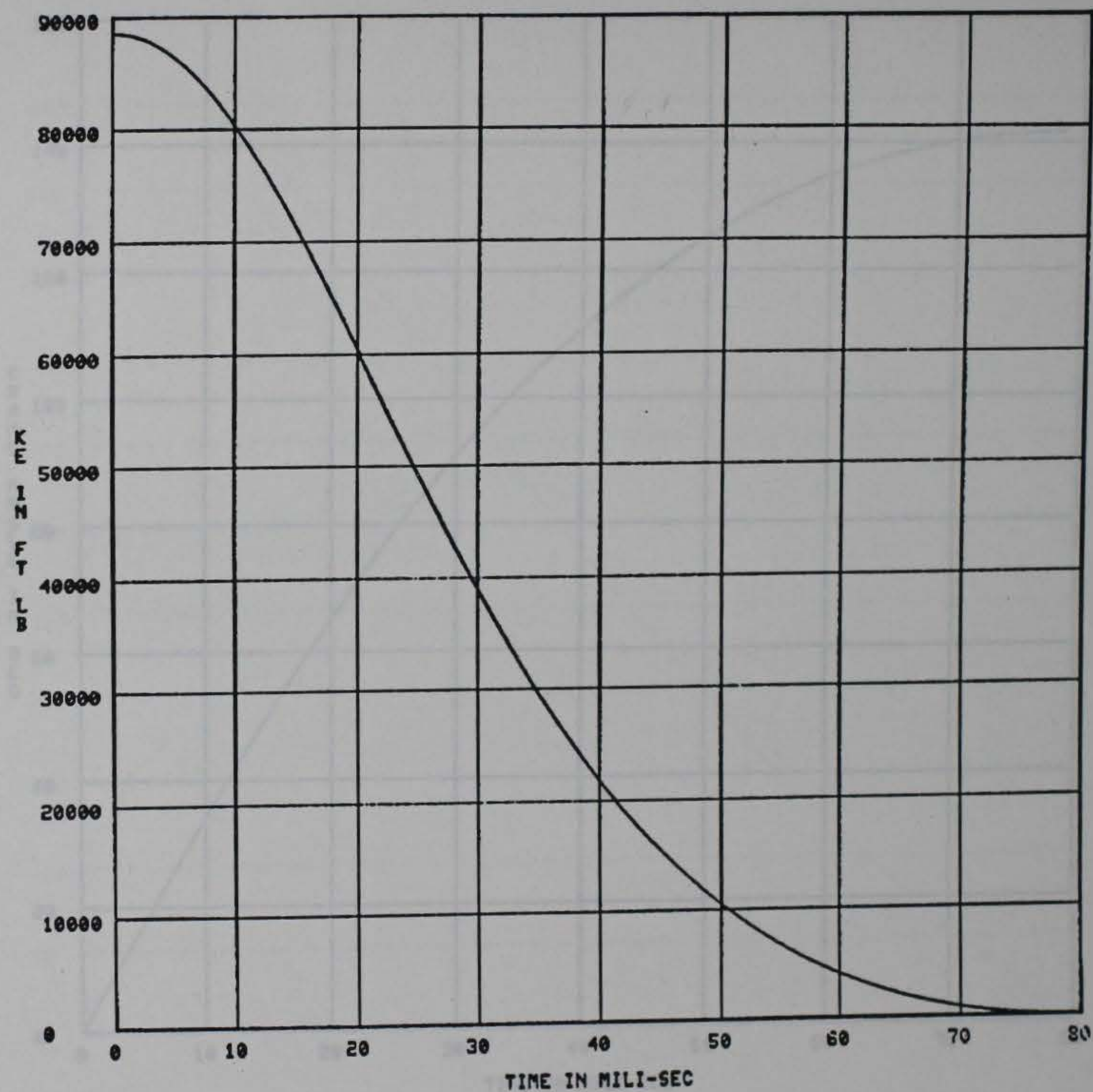


FIGURE B10

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK. SMD. SL. WES. 16 JAN 1986
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 577.00
CRANK ANGLE AT START = 0. DEG



FIGURE B11

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD. SL. UES. 16 JAN 1986
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 577.00
CRANK ANGLE AT START = 0. DEG



FIGURE B12

APPENDIX C: ROTATIONAL SYSTEM PROGRAM "JPUMP"

1. This appendix presents a listing of program JPUMP that was used for the idealized dynamic analysis of the rotational test system. This program produced the tabulations and plots presented in Appendixes A and B.

```

600  DS      PUMP SHAFT DIAMETER (IN.)
700  AP      EFFECTIVE AREA OF PISTON (FT**2)
800  SP      STROKE OF THE PISTON (IN)
900  DP      FLYWHEEL DIAMETER (IN.)
1000 WF      FLYWHEEL WEIGHT (LBS.)
1100 PI      3.1415927
1200 DTA     FACTOR TO CONVERT DEGREES TO RADIANS
1300 G       32.2
1400 P       WORKING PRESSURE IN THE PUMP (P/IN**2)
1500 FM      FLYWHEEL MASS
1600 RMI     ROTATIONAL MOMENT OF THE FLYWHEEL
1700 RPH     INITIAL REV. PER MIN. OF THE FLYWHEEL
1800 AWF     CURRENT ANGULAR VELOCITY OF THE FLYWHEEL (RAD./SEC)
1900 AWF1     INITIAL ANGULAR VELOCITY OF THE FLYWHEEL (RAD./SEC)
2000 EK      KINETIC ENERGY OF THE FLYWHEEL
2100 THETA1  SHAFT ANGLE WHEN PUMPING TEST STARTS (DEG)
2200 THETA   CURRENT SHAFT ANGLE DURING PUMP TEST
2300 ZMI     INITIAL MOMENTUM OF THE FLYWHEEL
2400 ZM      CURRENT MOMENTUM OF THE FLYWHEEL
2500 ZIMP     TOTAL IMPULSE ON FLYWHEEL FROM PUMP ACTION
2600 TDEL     TIME STEP (SEC)
2700 TI      CURRENT TIME SINCE START OF THE TEST
2800 CL      CONNECTING ROD LENGTH
2900 TOR      TORQUE APPLIED DURING ONE TIME STEP
3000 ALPHA   ANGULAR DECELERATION DURING ONE TIME STEP
3100 Q       DISCHARGE OF THE PUMP IN GAL/SEC.
3200 XP      DIST. FROM CL OF CRANK TO PUMP AT STEP N
3300 XPM      DIST. FROM CL OF CRANK TO PUMP AT STEP N-1
3400
3500
3600 DIMENSION M(1500.0)
3700 DATA PI/3.1415927/, G/32.2/, DP/18.0/, DS/9.0/,
3800  P/18.0/, DTA/57.295780/, WF/1000.0/, SP/2.0/, F/4350.0/,
3900  RMI/30.0/, CL/39.0/
4000
4100 PLOT SETUP
4200 CALL USTART
4300 CALL UPSET('SPEED',130.)
4400 CALL USET('SCALE')
4500 CALL USET('VECTRLABELS')
4600 CALL USET('BOTHLABELS')
4700 CALL UERASE
4800 CALL UMORE
4900 CALL UALPHA
5000

```


JPUMP

```

10C$TITLE FILED IN ROSSCOBRA/JPUMP
20C PUMP RUN-TIME TEST PROGRAM
30C JAY CHEEK, SMD, SL, WES, 14 JAN 1986
40C
50C DF PISTON DAMETER (IN.)
60C DS PUMP SHAFT DIAMETER(IN.)
70C AP EFFECTIVE AREA OF PISTON (FT**2)
80C SP STROKE OF THE PISTON (IN)
90C DF FLYWHEEL DIAMETER (IN.)
100C WF FLYWHEEL WEIGHT (LBS.)
110C PI 3.1415927
120C DTR FACTOR TO CONVERT DEGREES TO RADIANS
130C G 32.2
140C P WORKING PRESSURE IN THE PUMP (P/IN**2)
150C FM FLYWHEEL MASS
160C RMI ROTATIONAL MOMENT OF THE FLYWHEEL
170C RPM INITIAL REV. PER MIN. OF THE FLYWHEEL
180C AVF CURRENT ANGULAR VELOCITY OF THE FLYWHEEL (RAD./SEC)
190C AVFI INITIAL ANGULAR VELOCITY OF THE FLYWHEEL (RAD./SEC)
200C EK KINETIC ENERGY OF THE FLYWHEEL
210C THETAI SHAFT ANGLE WHEN PUMPING TEST STARTS (DEG)
220C THETA CURRENT SHAFT ANGLE DURING PUMP TEST
230C ZMI INITIAL MOMENTUM OF THE FLYWHEEL
240C ZM CURRENT MOMENTUM OF THE FLYWHEEL
250C ZIMP TOTAL IMPULSE ON FLYWHEEL FROM PUMP ACTION
260C TDEL TIME STEP(SEC)
270C TI CURRENT TIME SINCE START OF THE TEST.
280C CL CONNECTING ROD LENGTH.
290C TOR TORQUE APPLIED DURING ONE TIME STEP
300C ALPHA ANGULAR DECELERATION DURING ONE TIME STEP.
310C Q DISCHARGE OF THE PUMP IN GAL/SEC.
320C XP DIST. FROM CL OF CRANK TO PUMP AT STEP N
330C XPL DIST. FROM CL OF CRANK TO PUMP AT STEP N-1
340C
350C
360 DIMENSION V(1500,6)
370 DATA PI/3.1415927/, G/32.2/, DP/16.0/, DS/9.0/,
380 & DTR/57.295780/, WF/1000.0/, SP/2.0/, P/4350.0/,
390 & DF/30.0/, CL/30.0/
400C
410C PLOT SETUP
420 CALL USTART
430 CALL UPSET('SPEED', 120.)
440 CALL USET('SMALL')
450 CALL USET('XBOTHLABELS')
460 CALL USET('YBOTHLABELS')
470 CALL UERASE
480 CALL UHOME
490 CALL UALPHA
500C

```



```

JPUMP
510C  GET INITIAL CONDITIONS
520  100 WRITE (6,110) ' TEST START ANGLE, RPM =?'
530  110 FORMAT (V)
540      READ (5,110) THETA1, RPM
550C  PISTON AREA
560      AP = PI * (DP * DP - DS * DS) / 576.0
570C  MASS OF THE TWO FLYWHEELS
580      FM = WF * 2.0 / G
590C  ROTATIONAL MOMENT OF INERTIA
600      RMI = FM * DF * DF / 1152.0
610C  INITIAL ANGULAR VELOCITY
620      AVFI = RPM * PI / 30.0
630C
640C  CALC CONSTANTS FOR THE INTEGRATION LOOP.
650C  CRANK ARM LENGTH IN FT
660      TH = SP / 24.0
670C  SQUARE OF THE CONNECTING ROD LENGTH
680      CLS = CL * CL / 144.0
690C  TIME STEP IN SEC.
700      TDEL = AVFI / 1000000.0
710C  PUMP FORCE TIMES CRANK ARM LENGTH
720      FR = AP * P * TH * 144.0
730C  STEP COUNTER
740      N = 0
750C  INITIAL ANGULAR VELOCITY OF THE CRANKSHAFT (RAD/SEC)
760      AVF = AVFI
770C  CRANKSHAFT ANGLE AT START OF PUMPING (0 DEG IS
780C  TOP DEAD CENTER OF STROKE)
790      THETA = THETA1
800C  NUMBER OF POINTS TO BE PLOTTED
810      NVP = 0
820C
830C  HEADING.
840      WRITE (6,120)
850  120 FORMAT ('      N      T(SEC)      THETA      RPM      KE (FT-LB)      Q '
860      &      , '(GAL/SEC)      TORQ (FT-LB)')
870C
880C  START THE PUMP TEST LOOP
890C  ELAPSED TIME IN SEC
900  130 TI = N * TDEL
910C  CURRENT CRANKSHAFT ANGLE IN RADIAN
920      TR = THETA / DTR
930C  KINETIC ENERGY IN FT LBS
940      EK = RMI * AVF * AVF / 2.0
950C  TEST FOR SPECIAL CALCULATION FOR Q AT START
960      IF (N .NE. 0) GO TO 140
970C  CALC PUMP POSITION JUST BEFORE THE FIRST STEP.
980      TRR = TR - AVF * TDEL
990      ST = SIN(TRR)
1000     TEMP1 = TH * COS(TRR)

```



```

JPUMP
1010      TEMP2 = SQRT(CLS-(TH*ST)**2)
1020      XPL = TEMP2 - TEMP1
1030      140 ST = SIN(TR)
1040C    X COMPONENT OF THE CRANK ARM
1050      TEMP1 = TH * COS(TR)
1060C    PROJECTION OF CONN. ROD ON X AXIS
1070      TEMP2 = SQRT(CLS-(TH*ST)**2)
1080C    POSITION OF THE PUMP AT STEP N
1090      XP = TEMP2 - TEMP1
1100C    PUMP DISCHARGE DURING THIS STEP
1110      Q = ABS(XP-XPL) * AP * 7.5 / TDEL
1120      XPL = XP
1130C    SLOWDOWN TORQUE ON CRANK DUE TO PUMPING FORCE
1140      TOR = - ABS(FR*ST*(1.0-TEMP1/TEMP2))
1150C    ANGULAR DECELERATION
1160      ALPHA = TOR / RMI
1170      IF (MOD(N,100) .EQ. 0) WRITE (6,150) N, TI, THETA, AVF /
1180      &      2. / PI * 60, EK, Q, TOR
1190      150 FORMAT (1X, I4, F8.4, F8.2, F8.1, F10.0, F14.2, F14.0)
1200C
1210C    SAVE EVERY FIFTH POINT FOR PLOTTING
1220      IF (MOD(N,5) .NE. 0) GO TO 160
1230      NVP = NVP + 1
1240      V(NVP,1) = TI * 1000.0
1250      V(NVP,2) = Q
1260      V(NVP,3) = TOR
1270      V(NVP,4) = EK
1280      V(NVP,5) = THETA
1290      V(NVP,6) = AVF / 2.0 / PI * 60.0
1300C    NEW ANGULAR VELOCITY DUE TO SLOWDOWN TORQUE
1310      160 AVF = AVF + ALPHA * TDEL
1320C    COUNT STEP
1330      N = N + 1
1340C    STILL ROTATING?
1350      IF (AVF .LT. 0.0) GO TO 170
1360C    YES. ADVANCE TO NEXT CRANK ANGLE
1370      THETA = THETA + AVF * TDEL * DTR
1380      GO TO 130
1390C
1400C    DONE
1410      170 WRITE (6,180) TI, THETA - THETA1, N
1420      180 FORMAT (' PUMPING ENDS AT ', F10.3, ' SEC.' /
1430      &      ' PUMP CUTOFF ANGLE = ', F8.1, ' DEGREES' /
1440      &      ' NUMBER OF TIME STEPS = ', I5 '//// ')
1450      CALL UPAUSE
1460C
1470C    PLOT THE CURVES
1480      CALL PLOTFU(V, NVP, DP, DS, P, DF, WF, SP, CL, RPM, THETA1)
1490      GO TO 100
1500      END

```



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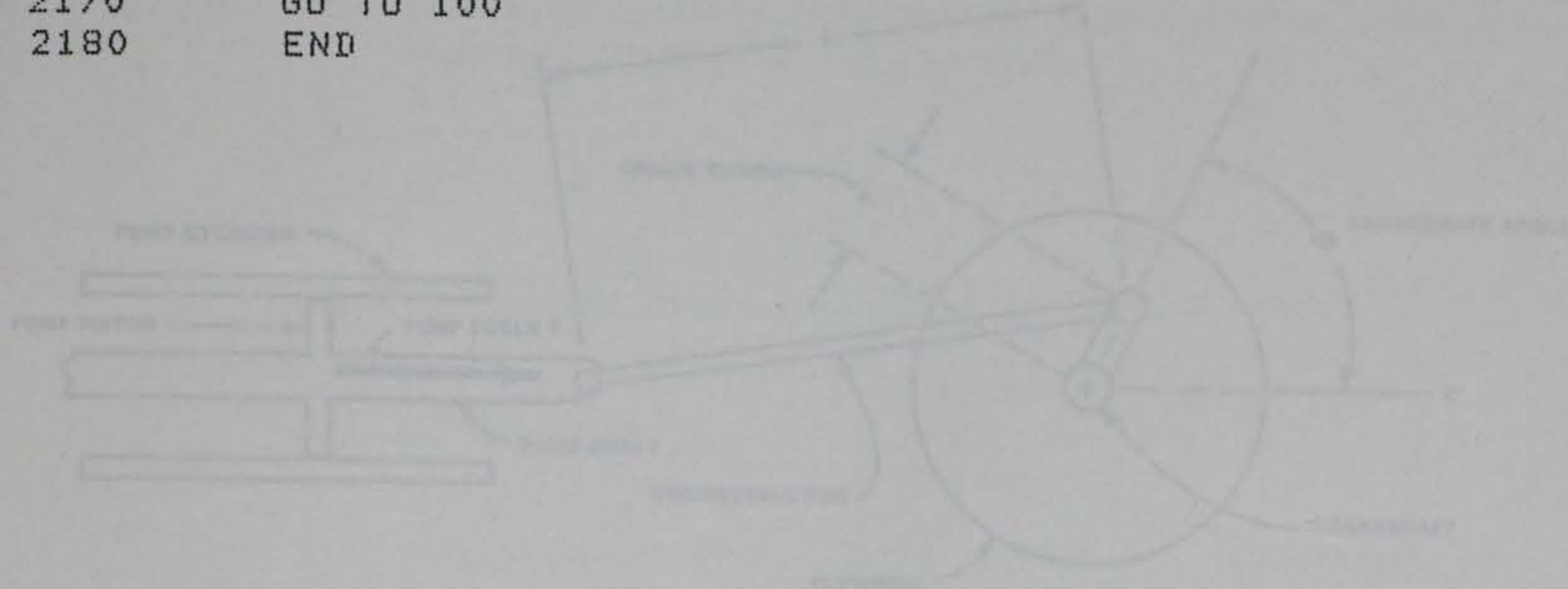
JPUMP
1510      SUBROUTINE PLOTPU(V, NV, DP, DS, P, DF, WF, SP, CL, RPM,
1520      &      THETA1)
1530C
1540C      PLOT ANY OF THE 5 ARRAYS AS A FUNCTION OF TIME (ARRAY1).
1550C      JAY CHEEK, SMD, SL, WES, 16 JAN 1986
1560C
1570      CHARACTER*20 T(20)
1580      DIMENSION V(1500,6)
1590      DATA T(1)/'TIME IN MILI-SEC\      '/, T(2)
1600      &      '/Q IN GAL PER SEC\      '/, T(3)
1610      &      '/TORQUE IN FT LB\      '/, T(4)
1620      &      '/KE IN FT LB\      '/, T(5)
1630      &      '/CRANK ANGLE IN DEG\      '/, T(6)
1640      &      '/REV PER MIN\      '/'
1650C      START PLOTTING
1660      FN = NV
1670      CALL UPSET('XLABEL', T(1))
1680      DO 120 I = 2, 6
1690C
1700C      IS THIS GRAPH NEEDED?
1710      WRITE (6,100) T(I)
1720 100      FORMAT (' PLOT ', A20, '?')
1730      CALL IANSR(IST)
1740      IF (IST .EQ. 0) GO TO 120
1750C
1760C      YES. DO IT.
1770      CALL UPSET('YLABEL', T(I))
1780      CALL UERASE
1790      CALL UDAREA(4.0, 14.0, 0.0, 10.0)
1800      CALL USET('GRIDAXIS')
1810      CALL UPLOT1(V(1, 1), V(1, I), FN)
1820      CALL UHOME
1830      CALL UALPHA
1840      WRITE (6,110) DP, DS, P, DF, WF * 2.0, SP / 2.0, CL, RPM,
1850      &      THETA1
1860 110      FORMAT (' PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD, '
1870      &      , 'SL, WES, 16 JAN 1986' / ' PISTON DIAMETER =',
1880      &      F8.2, ' IN' / ' SHAFT DIAMETER =', F8.2, ' IN' /
1890      &      ' PUMP PRESSURE =', F8.2, ' PSI' /
1900      &      ' FLYWHEEL DIAMETER =', F8.2, ' IN' /
1910      &      ' FLYWHEEL WEIGHT =', F8.2, ' LB' /
1920      &      ' CRANK THROW =', F6.2, ' IN' / ' CONNECTING ROD LENG
1930      &      , F8.2, ' IN' / ' INITIAL RPM ='
1940      &      , F8.2 / ' CRANK ANGLE AT START =', F8.2, ' DEG')
1950      CALL UPAUSE
1960 120      CONTINUE
1970      RETURN
1980      END

```


JFUMP

```

1990      SUBROUTINE IANSR(IWHAT)
2000C     SEE WHETHER THE USER GIVES A Y (OR A CARRIAGE RETURN)
2010C     FOR YES OR A N FOR NO TO A PREVIOUSLY ASKED QUESTION.
2020C
2030C     CODE FILED IN ROSSCOBRA/JHEST-S.
2040C     JAY CHEEK, SMD, SL, WES; DEC 1981
2050C
2060      DATA IBLK/'      '/, IYES/'Y      '/, NO/'N      '/
2070 100  IWHAT = 0
2080      READ (5,110) II
2090 110  FORMAT (A4)
2100      IF (II .EQ. NO) RETURN
2110      IWHAT = 1
2120      IF (II .EQ. IYES) RETURN
2130      IF (II .EQ. IBLK) RETURN
2140      WRITE (6,120)
2150 120  FORMAT ('  ERROR:  ONLY Y OR RETURN (FOR YES)  OR N (FOR '
2160      &      , 'NO)  ALLOWED, RETRY')
2170      GO TO 100
2180      END
    
```



Pump's End Pipes and Valves not shown

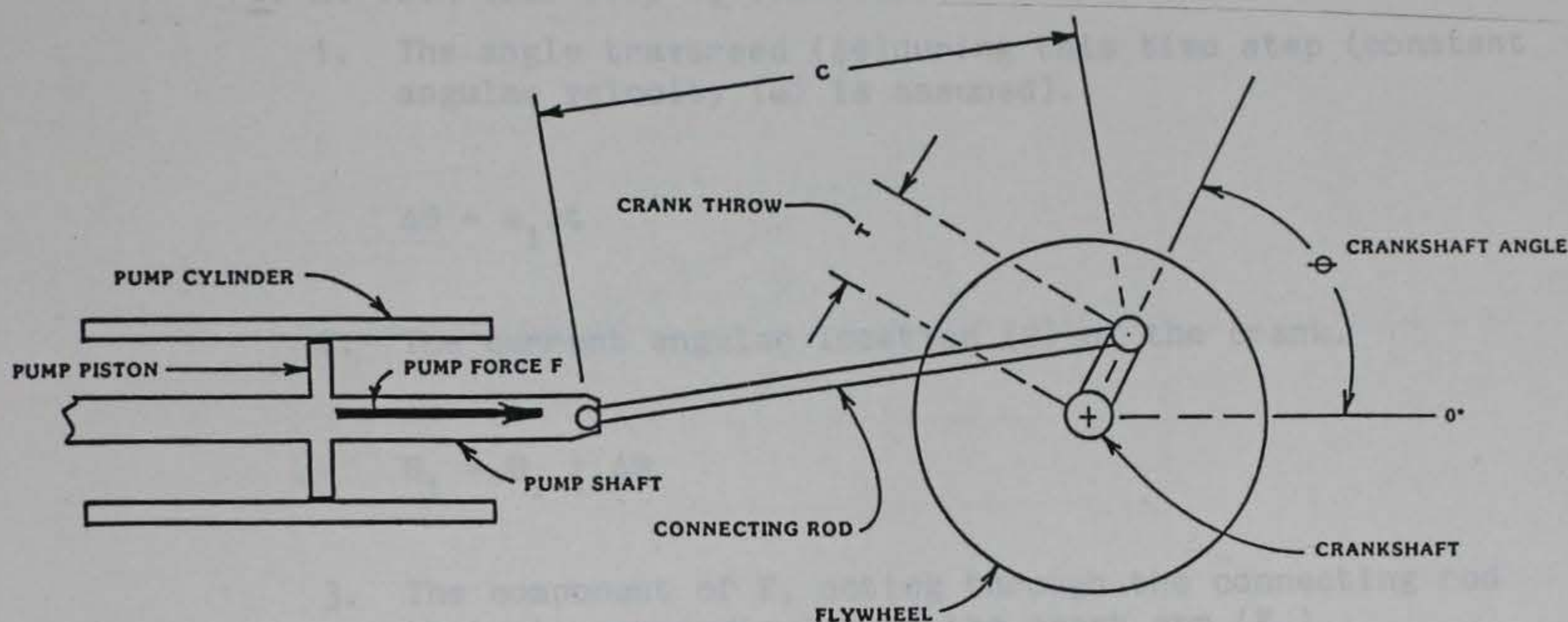
Idealized Pump and Drive System

Figure D1

APPENDIX D: METHOD FOR CALCULATING SLOWDOWN OF FLYWHEEL

Initial Conditions

1. As shown in Figure D1, a flywheel (solid disc) of weight W is rotating at an initial rpm. The flywheel diameter is D . The flywheel is connected to a crankshaft whose offset (throw) is T . A connecting rod of length C connects the crank to the pump that resists motion with a constant force F . That force is directed on a line from the crankshaft center-line through the center-line of the pump shaft.



Pump's End Plates and Valves not shown

Idealized Pump and Drive System

Figure D1

Calculating Procedure For Flywheel Slowdown

2. The following steps are used to calculate the flywheel slowdown:

a. Calculate the Rotational Moment of Inertia (I).

$$I = \frac{W}{g} \left(\frac{D}{2}\right)^2 \frac{1}{2}$$

b. Calculate the Angular Velocity (ω).

$$\omega = 2\pi \frac{(\text{rpm})}{60}$$

and choose a small time step (Δt) so that the wheel will rotate less than $.1^\circ$ at the initial rpm during time Δt .

c. At each time Step i, Calculate:

1. The angle traversed ($\Delta\theta$) during this time step (constant angular velocity (ω) is assumed).

$$\Delta\theta = \omega_i \Delta t$$

2. The current angular location (θ) of the crank.

$$\theta_i = \theta_{i-1} + \Delta\theta$$

3. The component of F, acting through the connecting rod that is perpendicular to the crank arm (F_M).

4. The torque (Γ) at angle θ .

$$\Gamma = F_M r$$

5. The angular deceleration (α) produced by this constant torque.

$$\alpha = - \Gamma / I$$

6. The new angular velocity due to the slowdown torque from the pumping force.

$$\omega_i = \omega_{i-1} + \alpha \Delta t$$

7. Add 1 to i and repeat steps C1 through C7 until $\omega_i \leq 0$.

8. Done.

Calculating Moment Applied To The Crankshaft

3. As illustrated in Figure D2: T is crankshaft throw, F is force to operate the pump, C is connecting rod length, E is the moment arm, θ is crankshaft angle, and G is the force normal to E.

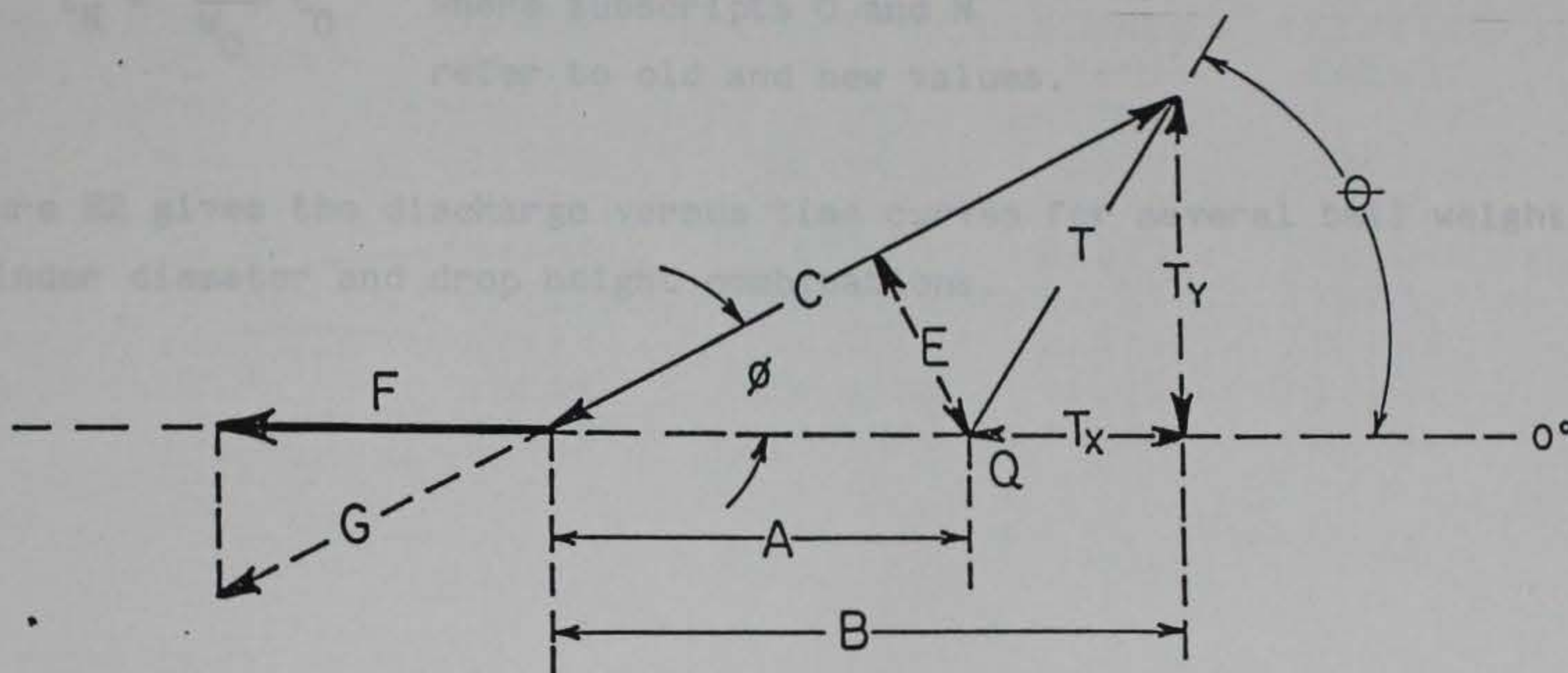


Figure D2

Calculating the Torque (Γ) about point Q.

$$\Gamma = G E$$

$$E = A \sin \phi$$

$$A = B - T_x$$

$$B = (C^2 - T_y^2)^{1/2}$$

$$T_y = T \sin \theta$$

$$T_x = T \cos \theta$$

$$\sin \phi = \frac{T_y}{C} = \frac{T \sin \theta}{C}$$

$$G = \frac{F}{\cos \phi}$$

$$\cos \phi = \frac{B}{C}$$

$$\Gamma = \frac{F}{\frac{B}{C}} (B - T_x) \frac{T_y}{C} = F T_y \left(1 - \frac{T_x}{B}\right)$$

$$\Gamma = F T \sin \theta \left[1 - \frac{T \cos \theta}{(C^2 - T^2 \sin^2 \theta)^{1/2}} \right] \text{ for } C > T$$

APPENDIX E: ANALYSIS OF THE DROP TEST SYSTEM

1. This appendix contains the output of the drop test analysis program, JPEND (Figure E1), the listing of the program (E3), and the development of the equations used (E4 and E5). The output is given for both 1,000 and 2,000 pound balls impacting on the pistons of various diameter cylinders. The drop height is paired with the cylinder diameter to produce the rated discharge peak of 26.4 gps. Discharge pressure is assumed to be constant at 4,350 psi. Note that an increase in ball weight, holding other parameters constant, serves to increase the test time (t) directly as the ratio of the new weight to the old

$$t_N = \frac{W_N}{W_O} t_O \quad \text{where subscripts O and N refer to old and new values.}$$

Figure E2 gives the discharge versus time curves for several ball weight, cylinder diameter and drop height combinations.

DROP TEST OF VALVE
FOR BALL WEIGHT OF 1000. LB PEAK DISCHARGE OF 26.4 GAL / SEC
AND DISCHARGE PRESSURE OF 4350. PSI

CYLINDER DIAMETER (INCHES)	DROP HEIGHT (FEET)	RETARD FORCE (POUNDS)	IMPACT VELOCITY (FT / SEC)	DISCHARGE TIME (SECONDS)	KINETIC ENERGY (FT - LB)
3.50	43.10	41852.	52.48	0.078	86201.
3.75	31.21	40044.	43.89	0.059	65412.
4.00	23.34	34334.	40.34	0.044	30530.
4.25	19.82	41710.	35.73	0.036	39447.
4.50	15.77	47184.	31.37	0.029	21545.
4.75	12.21	77084.	28.60	0.023	25410.
5.00	10.23	85412.	32.02	0.019	20497.

Output of the Drop Test Analysis Program "JPEND"

DROP TEST OF VALVE
 FOR BALL WEIGHT OF 1000. LB PEAK DISCHARGE OF 26.4 GAL / SEC
 AND DISCHARGE PRESSURE OF 4350. PSI

CYLINDER DIAMETER (INCHES)	DROP HEIGHT (FEET)	RETARD FORCE (POUNDS)	IMPACT VELOCITY (FT / SEC)	DISCHARGE TIME (SECONDS)	KINETIC ENERGY (FT - LBS)
3.50	43.10	41852.	52.68	0.039	43101.
3.75	32.71	48044.	45.89	0.030	32706.
4.00	25.26	54664.	40.34	0.023	25265.
4.25	19.82	61710.	35.73	0.018	19824.
4.50	15.77	69184.	31.87	0.014	15773.
4.75	12.71	77084.	28.60	0.012	12705.
5.00	10.35	85412.	25.82	0.009	10348.

DROP TEST OF VALVE
 FOR BALL WEIGHT OF 2000. LB PEAK DISCHARGE OF 26.4 GAL / SEC
 AND DISCHARGE PRESSURE OF 4350. PSI

CYLINDER DIAMETER (INCHES)	DROP HEIGHT (FEET)	RETARD FORCE (POUNDS)	IMPACT VELOCITY (FT / SEC)	DISCHARGE TIME (SECONDS)	KINETIC ENERGY (FT - LBS)
3.50	43.10	41852.	52.68	0.078	86201.
3.75	32.71	48044.	45.89	0.059	65413.
4.00	25.26	54664.	40.34	0.046	50530.
4.25	19.82	61710.	35.73	0.036	39649.
4.50	15.77	69184.	31.87	0.029	31545.
4.75	12.71	77084.	28.60	0.023	25410.
5.00	10.35	85412.	25.82	0.019	20697.

FIGURE E2

Listing of the Drop Test Analysis Program "JPEND"

JPEND

```
10C$TITLE FILED IN ROSSCOBRA/JPEND
20C  CALC OF PENDULUM TEST OF VALVE PERFORMANCE.
30C  JAY CHEEK SMD, SL, WES, 17 JAN 1986
40C
50      DATA PI/3.1415926/, P/4350.0/, Q/26.4/
60C
70      DO 130 J = 1, 2
80C  WEIGHT OF BALL
90      WT = J * 1000.0
100C DIAMETER OF HYDRAULIC CYLINDER (ONE STROKE PUMP)
110      D = 3.250
120      WRITE (6,100) WT, Q, P
130 100  FORMAT ( // // '          DROP TEST OF VALVE' /
140      &      ' FOR BALL WEIGHT OF', F6.0,
150      &      ' LB   PEAK DISCHARGE OF', F5.1, ' GAL / SEC' /
160      &      ' AND DISCHARGE PRESSURE OF', F6.0, ' PSI' //
170      &      ' CYLINDER      DROP      RETARD      IMPACT      '
180      &      ' DISCHARGE      KINETIC' /
190      &      ' DIAMETER      HEIGHT      FORCE      VELOCITY      TIME '
200      &      ' ENERGY' /
210      &      ' (INCHES)      (FEET)      (POUNDS)      (FT / SEC) '
220      &      ' (SECONDS) (FT - LBS)' )
230C
240C  CALC FOR SEVERAL CYL. DIAMETERS
250      DO 120 I = 1, 7
260C  DIAMETER
270      DI = D + I * .25
280C  PISTON (CYLINDER) AREA
290      A = PI * DI * DI / 4.0
300C  MASS OF THE BALL
310      ZMASS = WT / 32.2
320C  DROP HEIGHT TO PRODUCE PEAK DISCHARGE
330      H = 9.280 * Q * Q / DI ** 4
340C  IMPACT VELOCITY
350      V = SQRT(2.0*32.2*H)
360C  RETARDING FORCE OF THE CYLINDER
370      F = P * A
380C  TIME OF DISCHARGE
390      TI = ZMASS * V / F
400C  KINETIC ENERGY
410      EK = ZMASS * V * V / 2.0
420C
430C  RESULTS
440      WRITE (6,110) DI, H, F, V, TI, EK
450 110  FORMAT (1X, F7.2, F10.2, F12.0, F10.2, F10.3, F10.0)
460 120  CONTINUE
470 130  CONTINUE
480      STOP
490      END
```


Equation For Drop Height

2. Calculating combinations of cylinder diameter (D) and drop height (H) that yield a specific value of fluid discharge Q.

a. Impact velocity = $U_I = (2gH)^{\frac{1}{2}}$

where U is in ft/sec

H is in ft

g is in ft/sec²

b. Discharge = $Q = \frac{V}{\Delta t}$ where V is volume in ft³.

$$Q = \frac{V}{\Delta t} = \frac{A\Delta x}{\Delta t} = AU_I$$

where A is cylinder area = $\frac{\pi}{4} D^2$

D is cylinder diameter in ft

c. $H = \frac{Q_I^2}{2g \left(\frac{\pi}{4} D^2\right)^2} = \frac{Q_I^2}{1.234gD^4}$

where Q_I is discharge at impact, i.e., peak discharge.

d. Converting for Q in gps, and D in inches.

$$H = \frac{\left(\frac{Q_I}{7.5}\right)^2}{1.234 \left(\frac{D}{12}\right)^4 g} = \frac{9.280 Q_I^2}{D^4}$$

Equation For Total Discharge Time

3. As shown on E4, Drop Weight (H) relates to Peak Discharge (Q_I) and cylinder diameter (D) by:

$$H = \frac{9.280Q_I^2}{D^4}$$

Where Q is in gps, D is in inches.

Conservation of momentum gives $MU_I = Ft$

Where t is the time in seconds that the constant force F exists, M is the ball mass, W is the ball weight and $M = \frac{W}{g}$.

$$F \text{ is the constant piston force} = \frac{\pi D^2 P}{4}$$

Where P is pressure in psi, F is in lbs.

$$U_I = \text{impact velocity} = (2gH)^{\frac{1}{2}}$$

Total discharge time (t) is

$$t = \frac{MU_I}{F} = \frac{\frac{W}{g} (2gH)^{\frac{1}{2}}}{\frac{\pi D^2 P}{4}} = \frac{\frac{W}{g} \left(2g \frac{9.280Q_I^2}{D^4} \right)^{\frac{1}{2}}}{\frac{\pi D^2 P}{4}} = .9667 \frac{W Q_I}{P D^4}$$

Where: W is weight in lb, D is diameter in inches, Q is discharge in gps, P is pressure in psi, and t is time in sec.

For P = 4,350 psi, $Q_I = 26.4$ gps

$$t = .005866 \frac{W}{D^4}$$

DROP TEST OF PRESSURE REGULATING VALVE

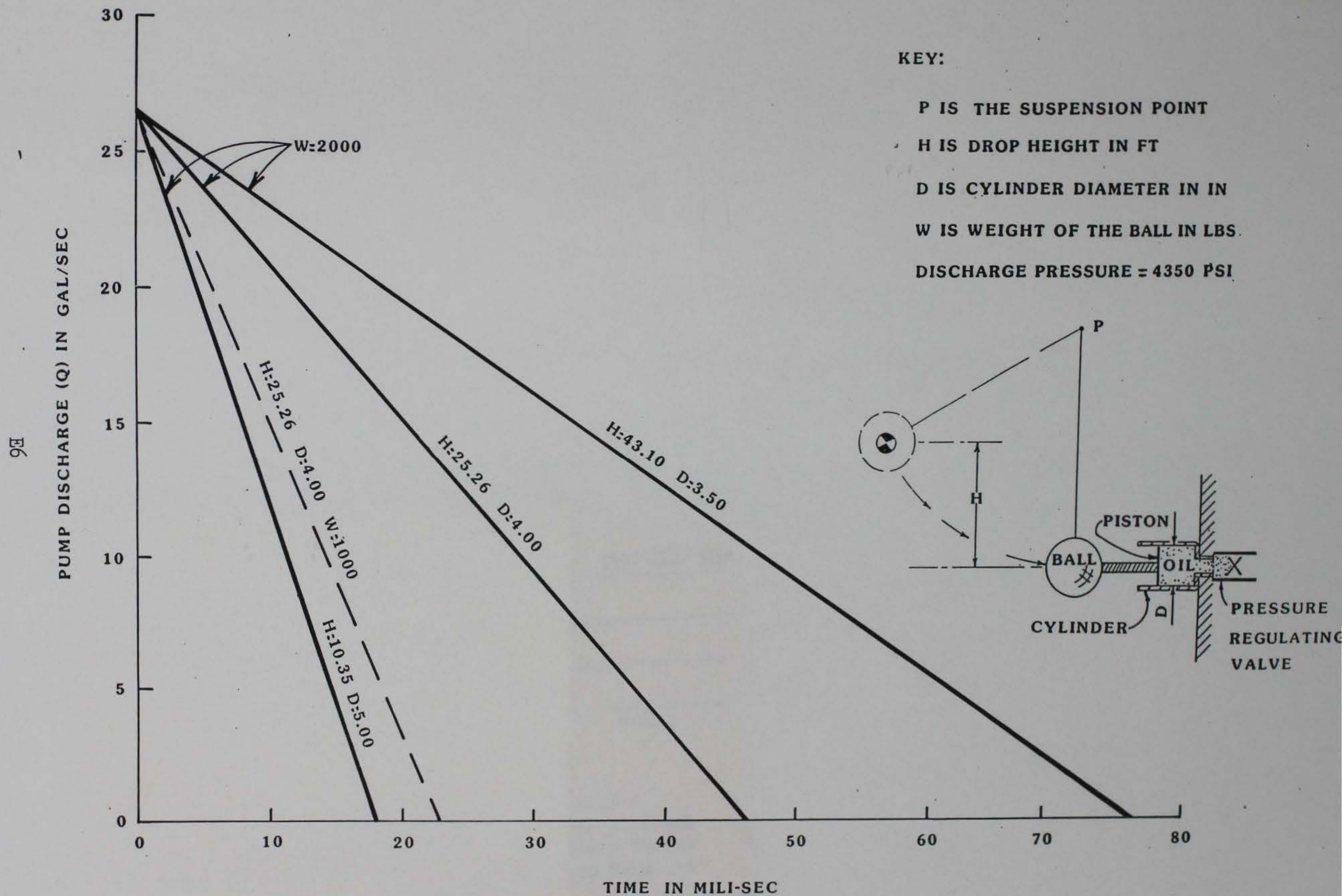


Figure E2