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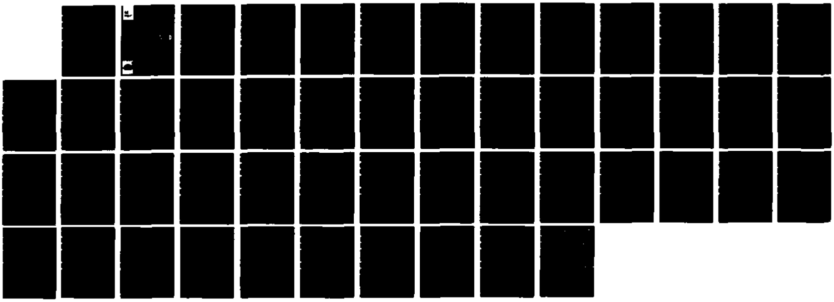

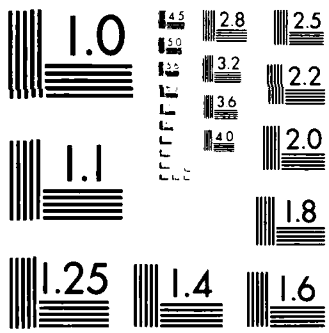
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MISCELLANEOUS PAPER SL-86-6

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

by

James B. Cheek

Structures Laboratory

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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.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
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.

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 evaluatiing 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.

CONTENTS

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 cf 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.

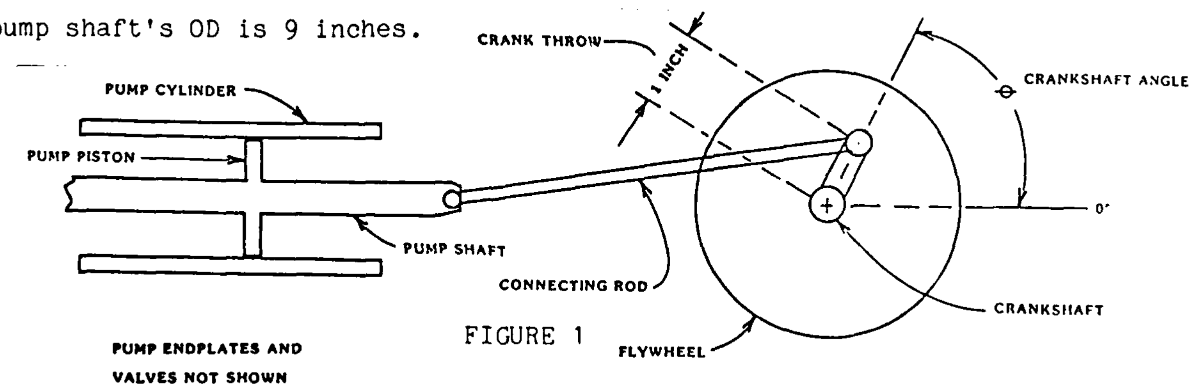


FIGURE 1

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°/360° = .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 t' ; 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 has shown in Figure 2.

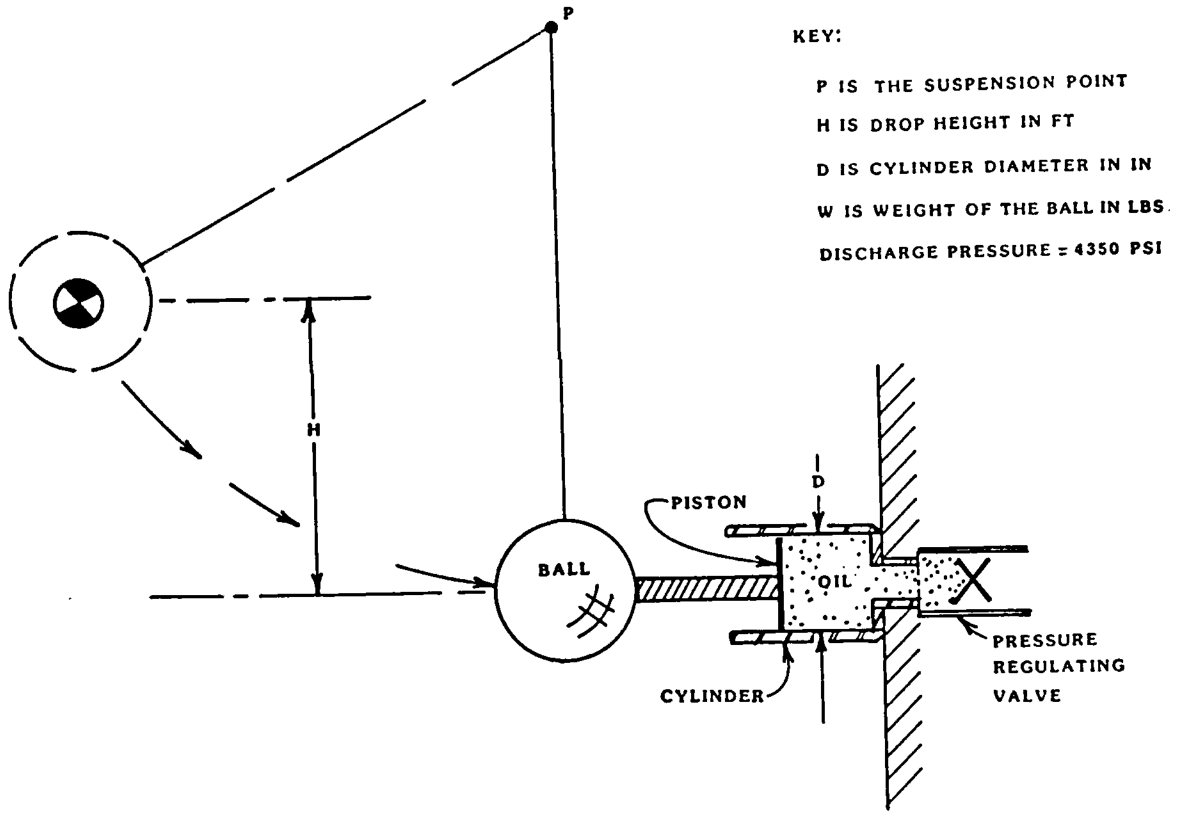


FIGURE 2

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.

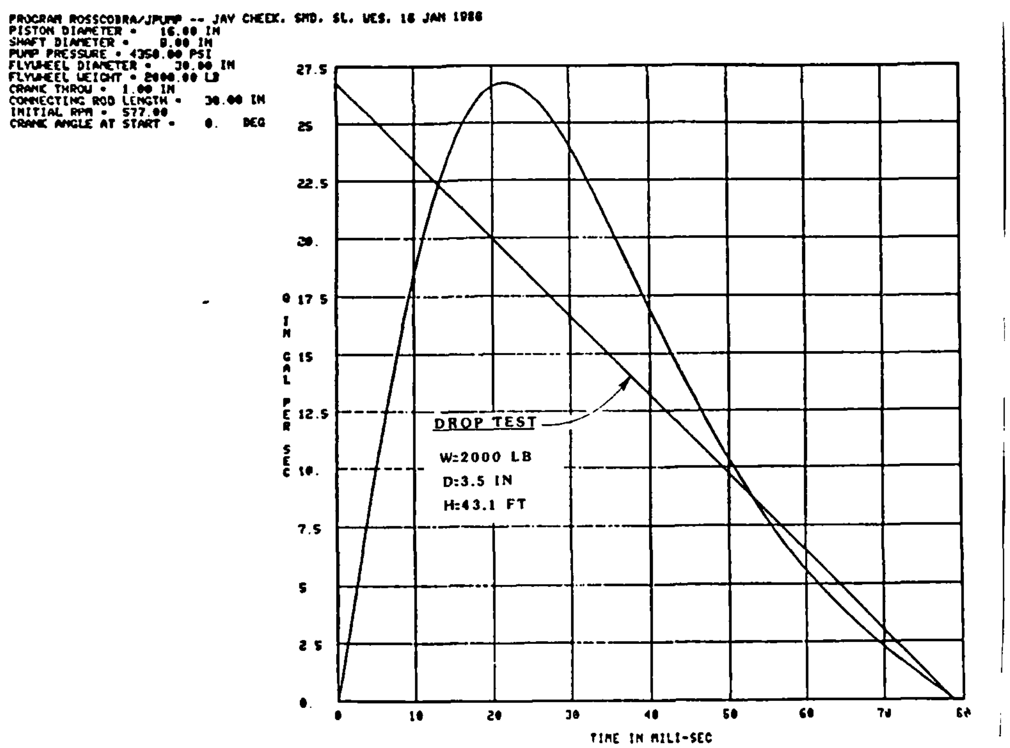


FIGURE 3

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.

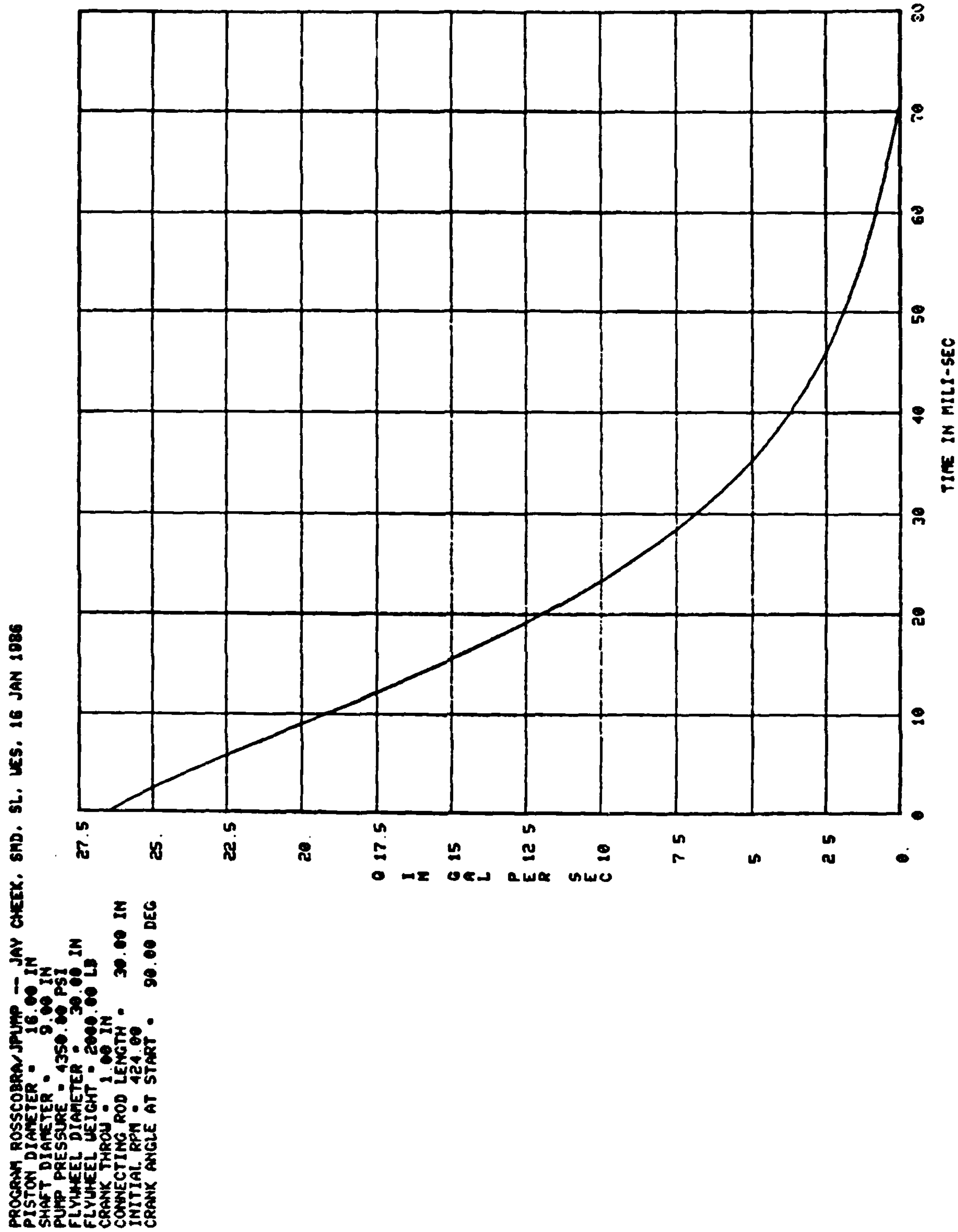
2. Figure A1 provides a tabulation of various system parameters versus time. Figures A2 through A6 are plots of those same parameters versus time.

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 CUTOUT ANGLE = 70.8 DEGREES
NUMBER OF TIME STEPS = 1591

FIGURE A1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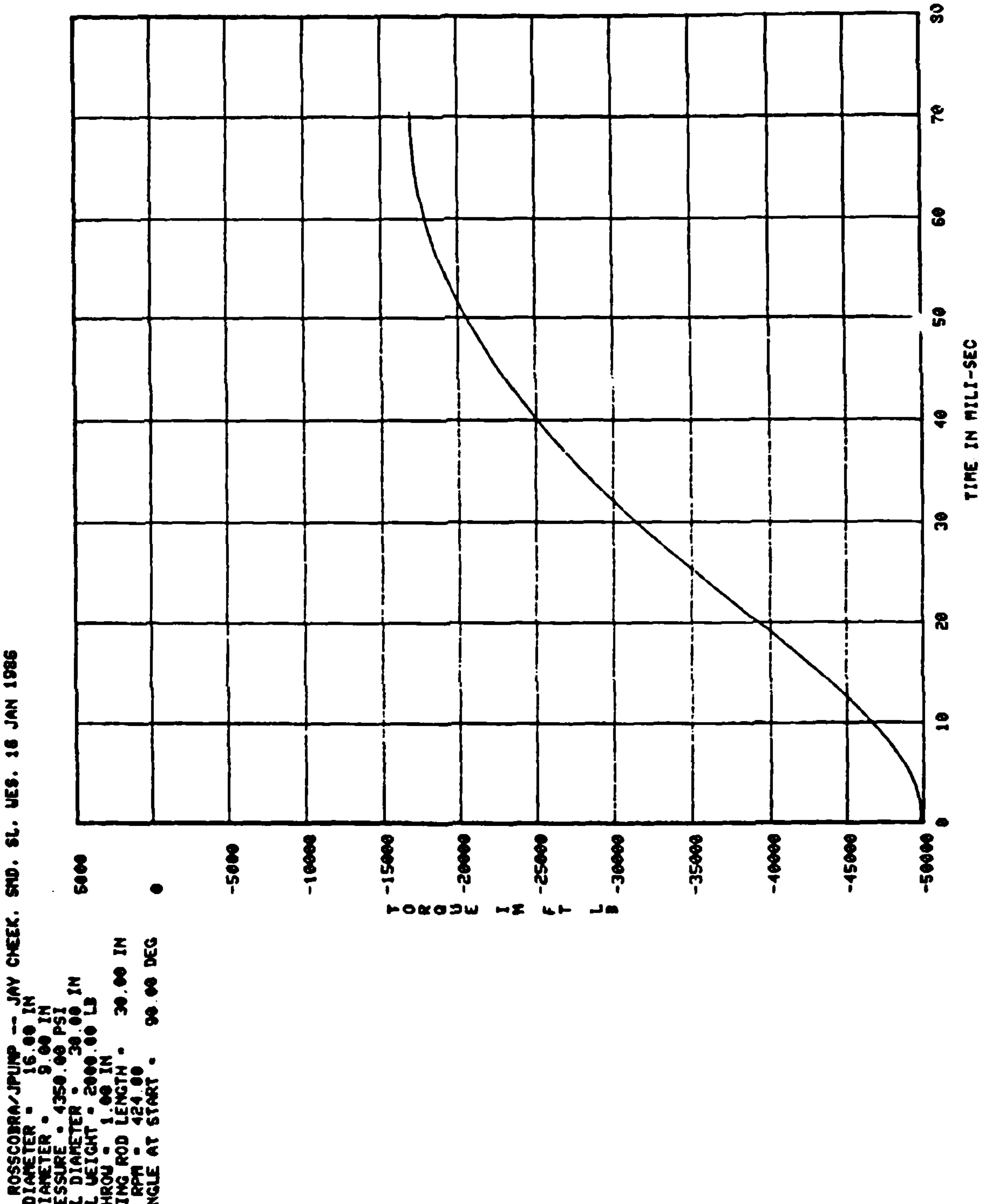
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 90.00 DEG
Q IN GAL PER SEC
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
27.5
TIME IN MILI-SEC
0
10
20
30
40
50
60
70
80

FIGURE A2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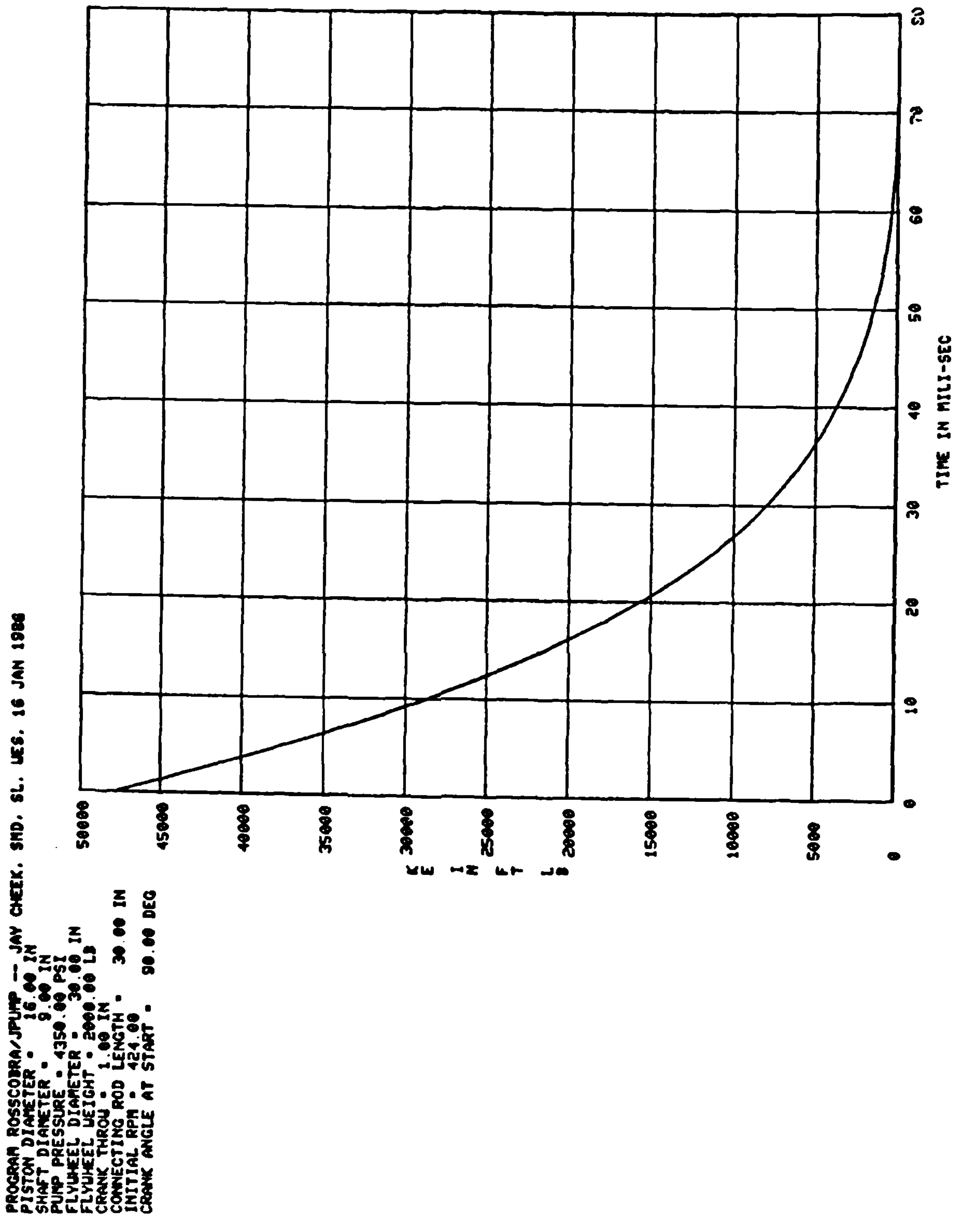
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 90.00 DEG
TORQUE IN FT LB
5000
0
-5000
-10000
-15000
-20000
-25000
-30000
-35000
-40000
-45000
-50000
TIME IN MILI-SEC
0
10
20
30
40
50
60
70
80
90

FIGURE A3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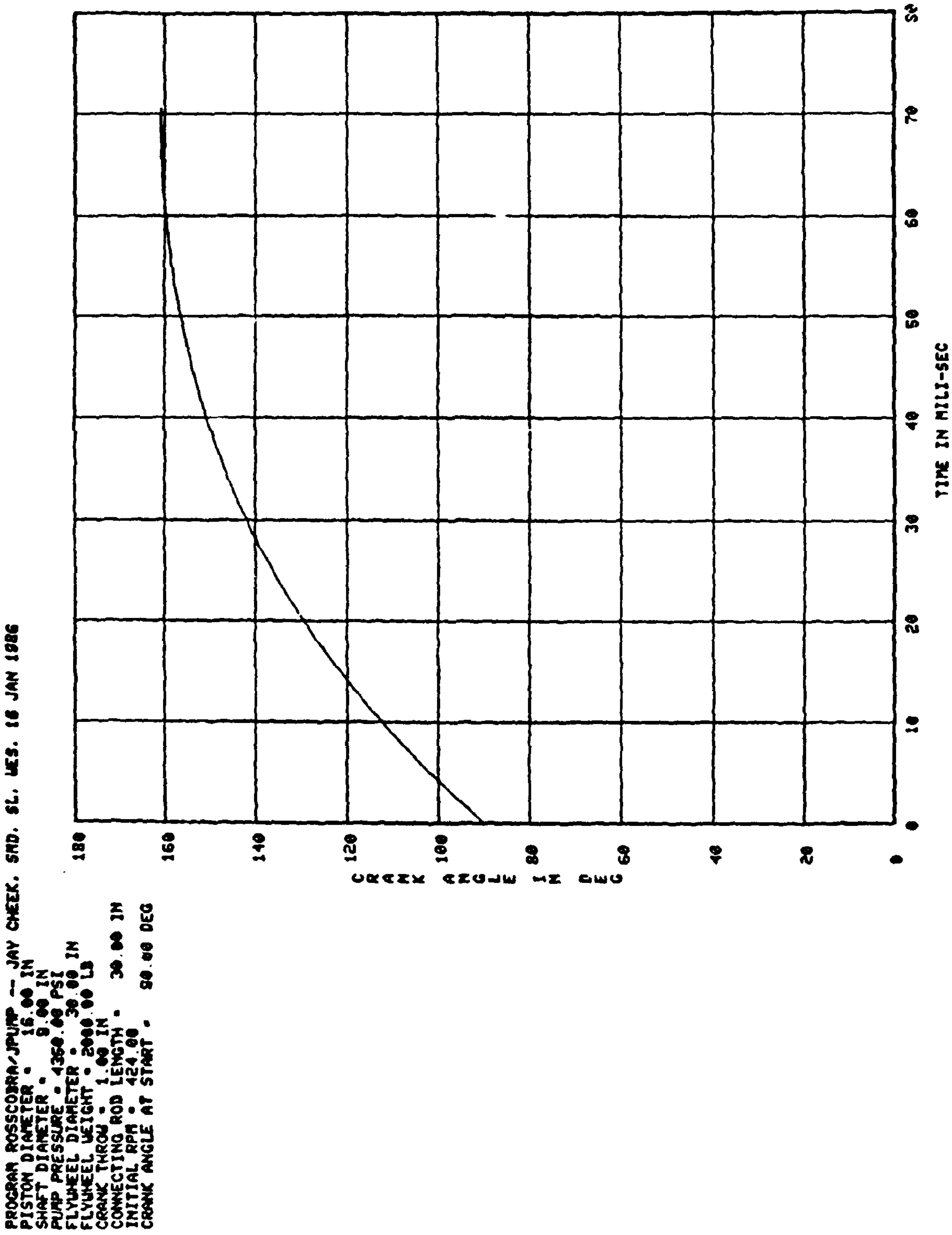
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 90.00 DEG
KE IN FT LB
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
TIME IN MILI-SEC
0
10
20
30
40
50
60
70
80

FIGURE A4



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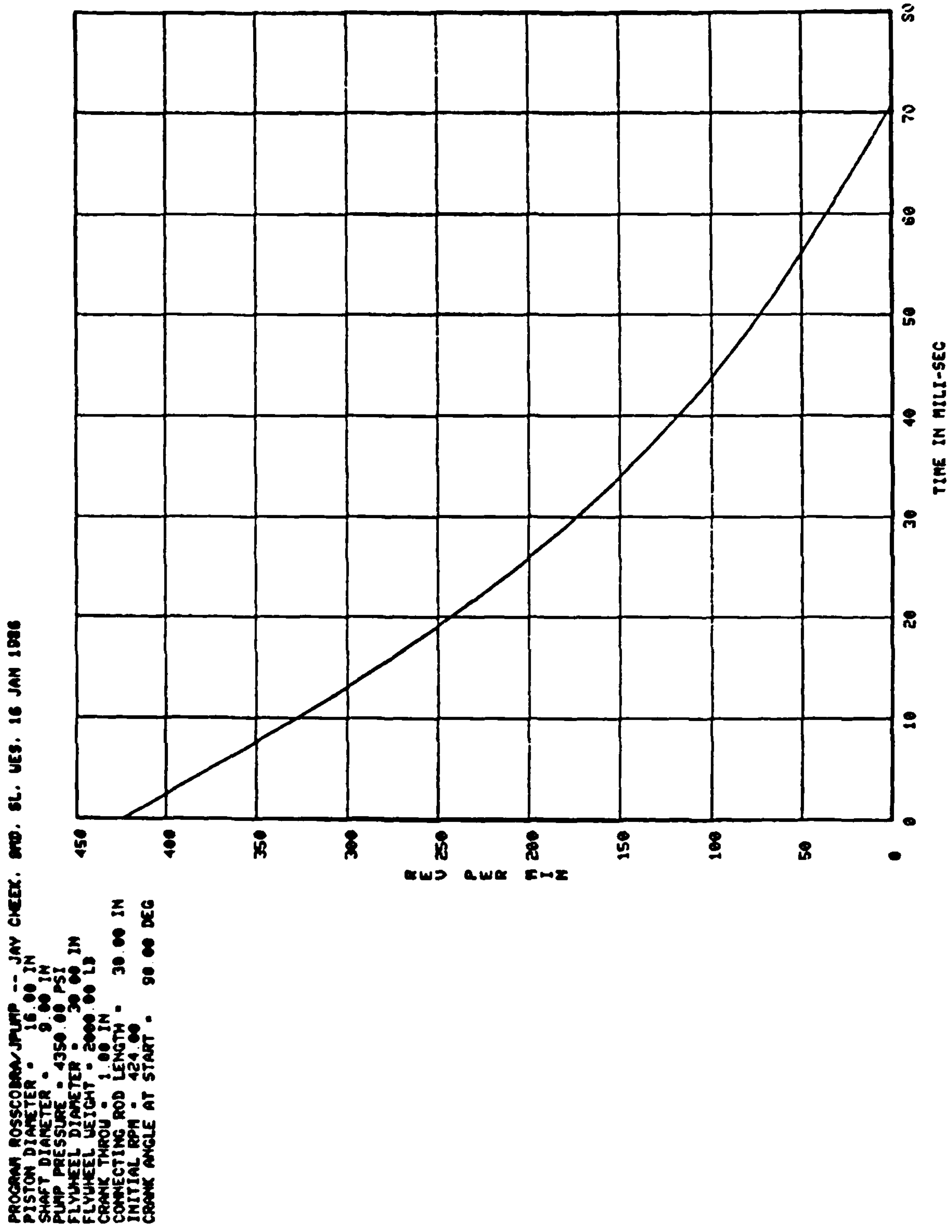
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 90.00 DEG
CRANK ANGLE IN DEG
0
20
40
60
80
100
120
140
160
180
TIME IN MILI-SEC
0
10
20
30
40
50
60
70
80

FIGURE A5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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
REV PER MIN
0
50
100
150
200
250
300
350
400
450
0
10
20
30
40
50
60
70
80
TIME IN MILI-SEC

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 gps) 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 gps 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.

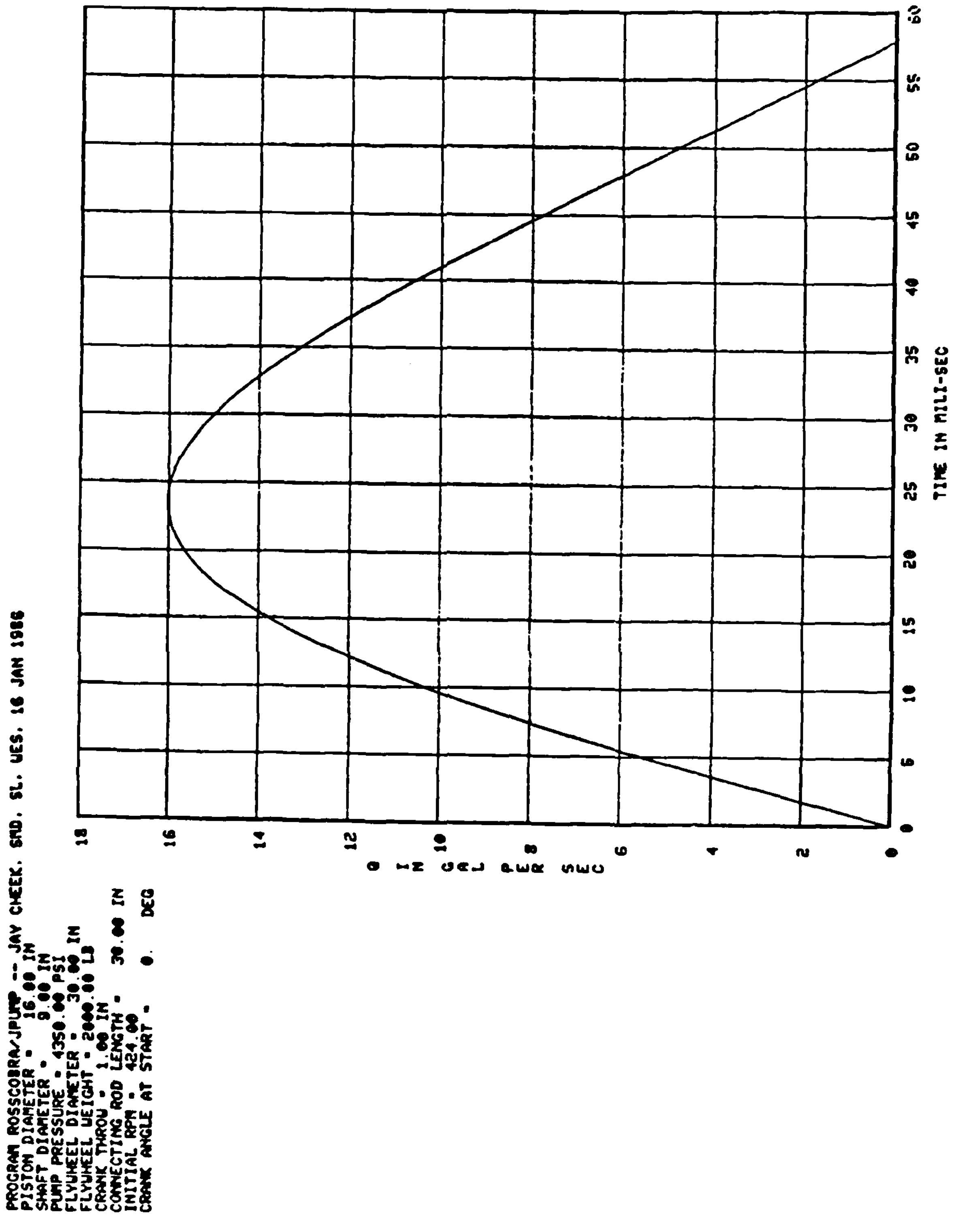
3. Figures B7 and B8 show the peak system discharge to be at the design discharge when the shaft speed at pump start is increased to 577 rpm. Figures B9 through B12 show other system parameters versus time at 577 rpm.

```
 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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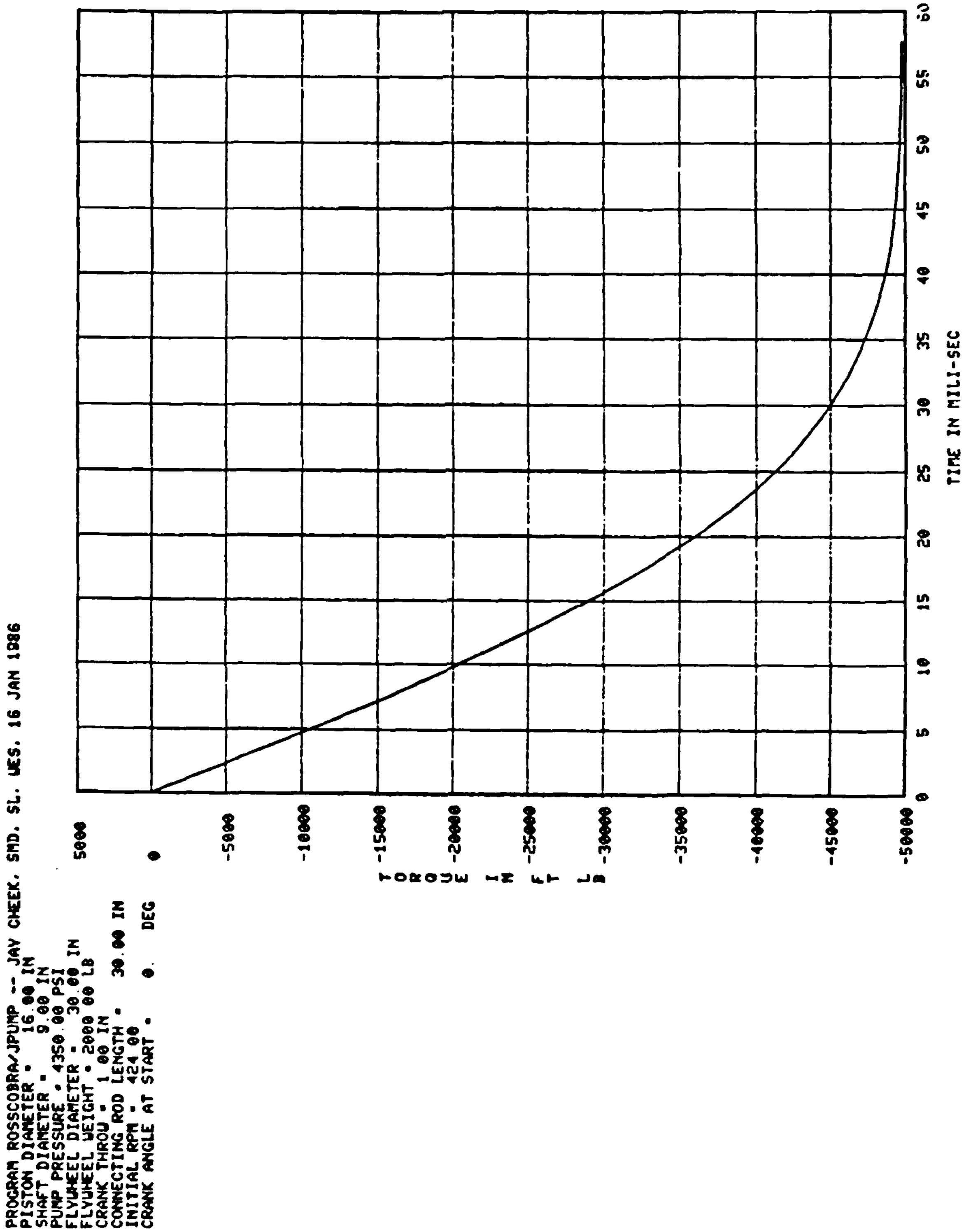
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 0. DEG
Q IN GAL PER SEC
0
2
4
6
8
10
12
14
16
18
TIME IN MILI-SEC
0
5
10
15
20
25
30
35
40
45
50
55
60

FIGURE B2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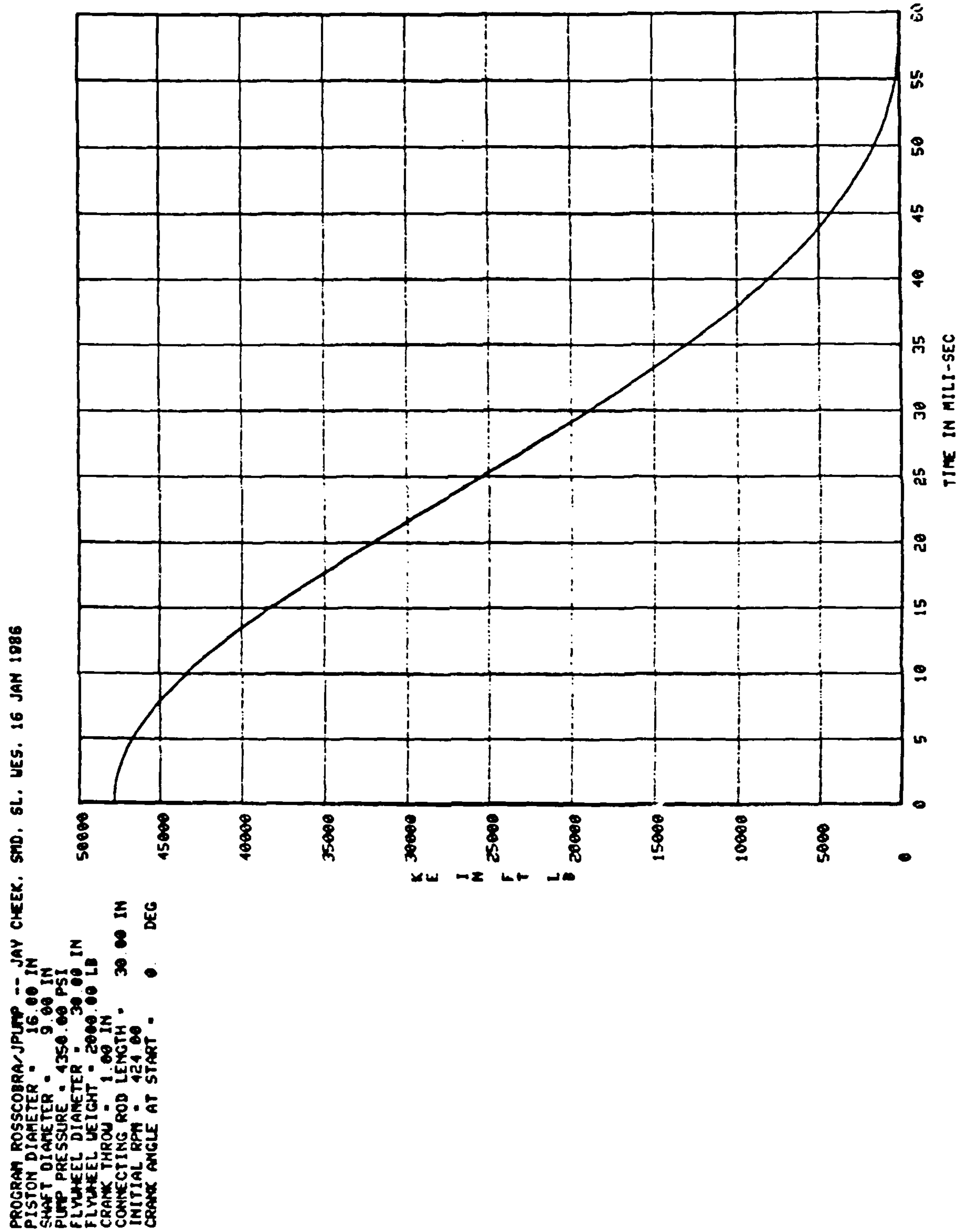
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 0. DEG
TORQUE IN FT LB
5000
0
-5000
-10000
-15000
-20000
-25000
-30000
-35000
-40000
-45000
-50000
TIME IN MILI-SEC
0
5
10
15
20
25
30
35
40
45
50
55
60

FIGURE B3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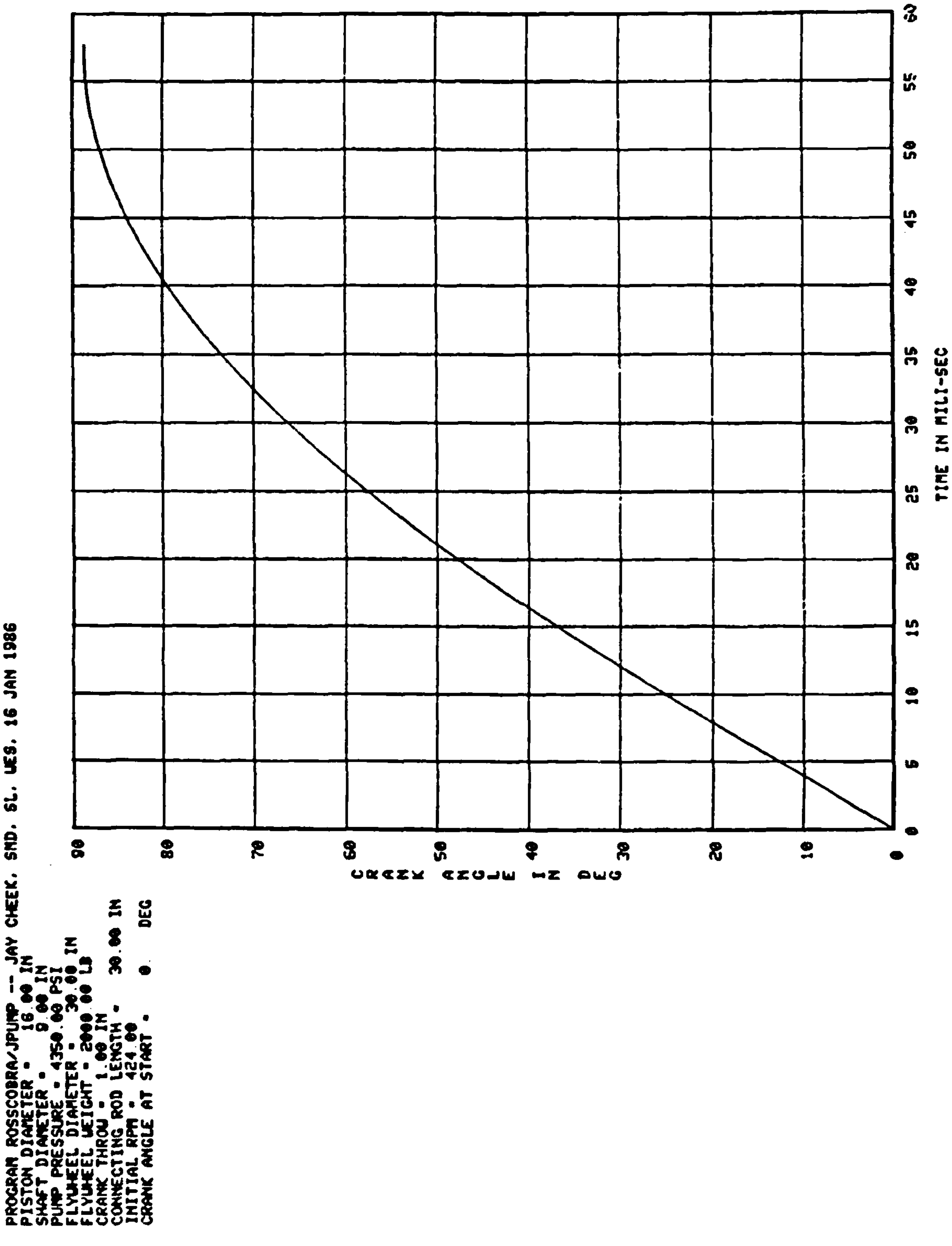
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 0. DEG
KE IN FT LB
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
TIME IN MILI-SEC
0
5
10
15
20
25
30
35
40
45
50
55
60

FIGURE B4



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CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 0 DEG
CRANK ANGLE IN DEG
0
10
20
30
40
50
60
70
80
90
TIME IN MILI-SEC
0
5
10
15
20
25
30
35
40
45
50
55
60

FIGURE B5

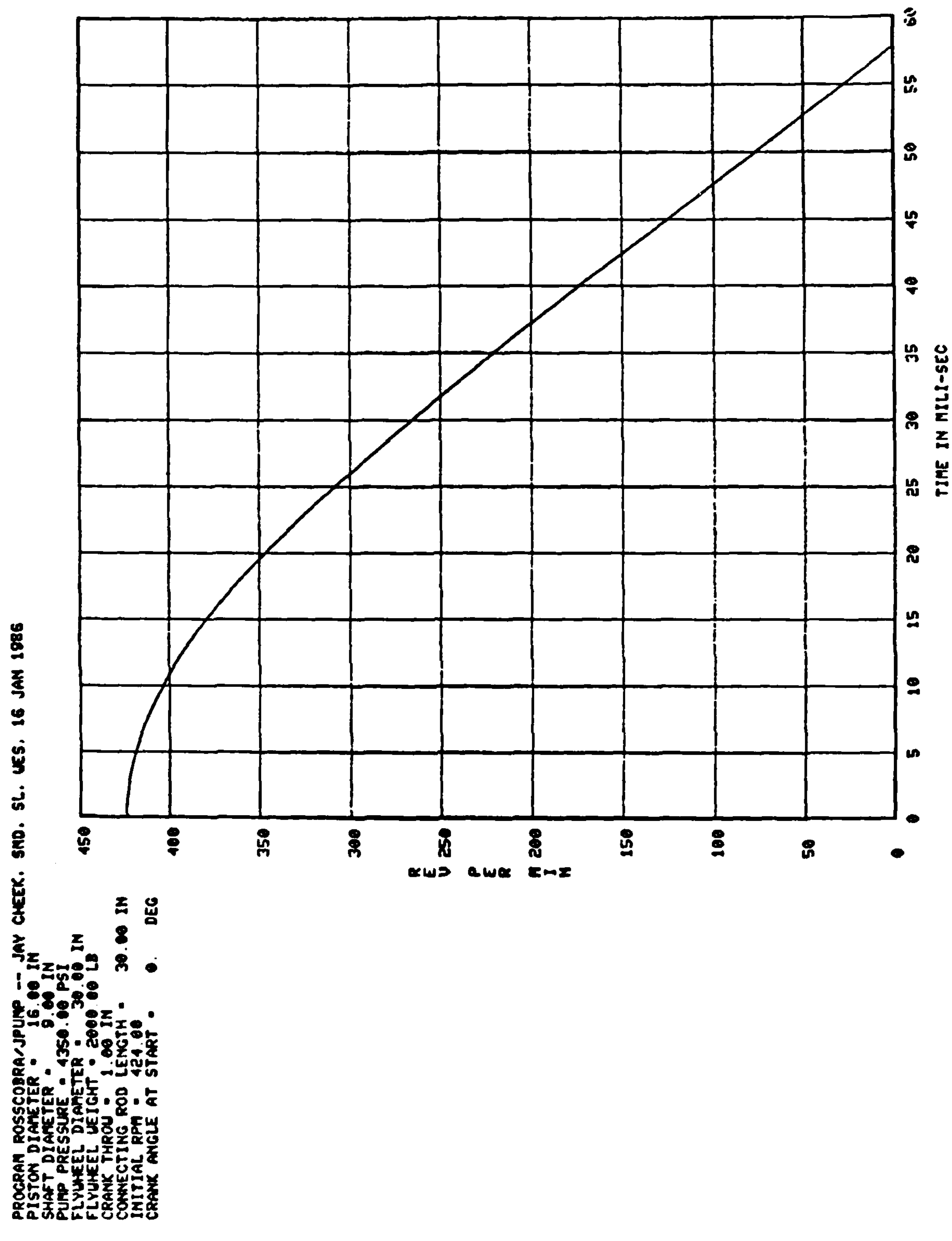

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK. SND. SL. WES. 16 JAN 1986
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 424.00
CRANK ANGLE AT START = 0. DEG
REV PER MIN
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
35
40
45
50
55
60
TIME IN MILI-SEC

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

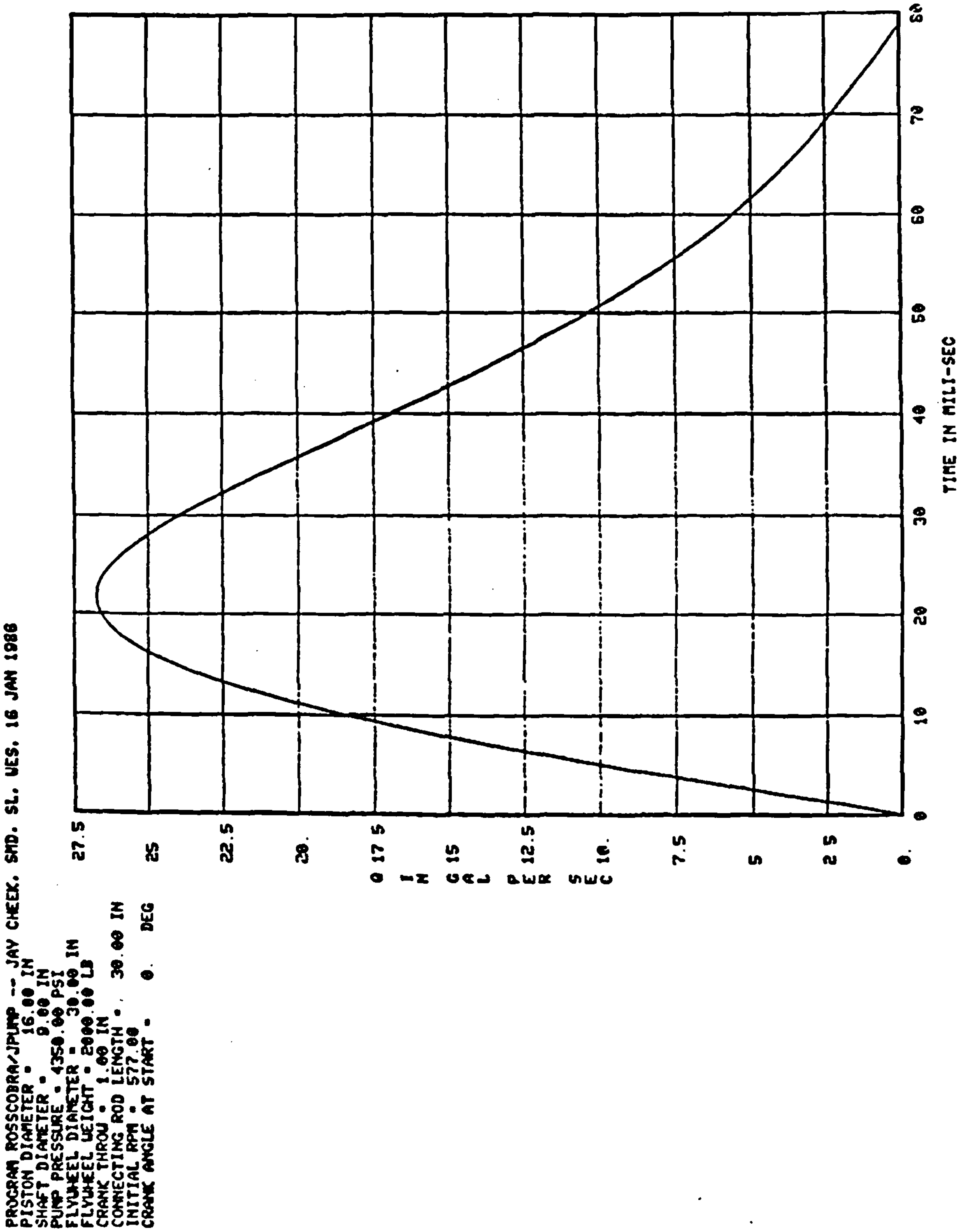

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD. SL. WES. 16 JAN 1988
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 577.00
CRANK ANGLE AT START = 0. DEG
Q IN GAL PER SEC
TIME IN MILI-SEC

FIGURE B8

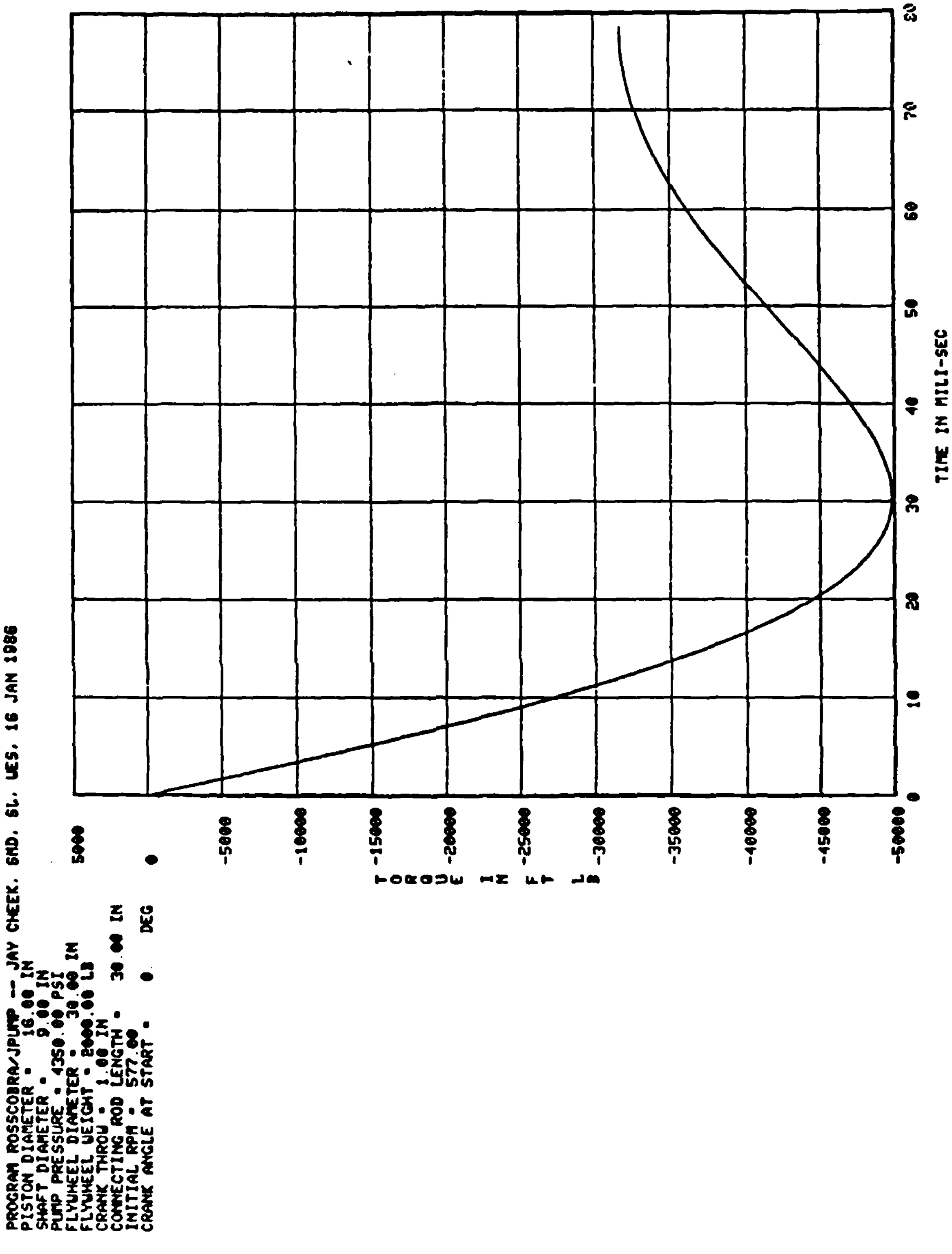

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK. GND. GL. WES. 16 JAN 1986
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 577.00
CRANK ANGLE AT START = 0 DEG
5000
0
-5000
-10000
-15000
-20000
-25000
-30000
-35000
-40000
-45000
-50000
TORQUE IN FT LB
0
10
20
30
40
50
60
70
80
TIME IN MILI-SEC

FIGURE B9

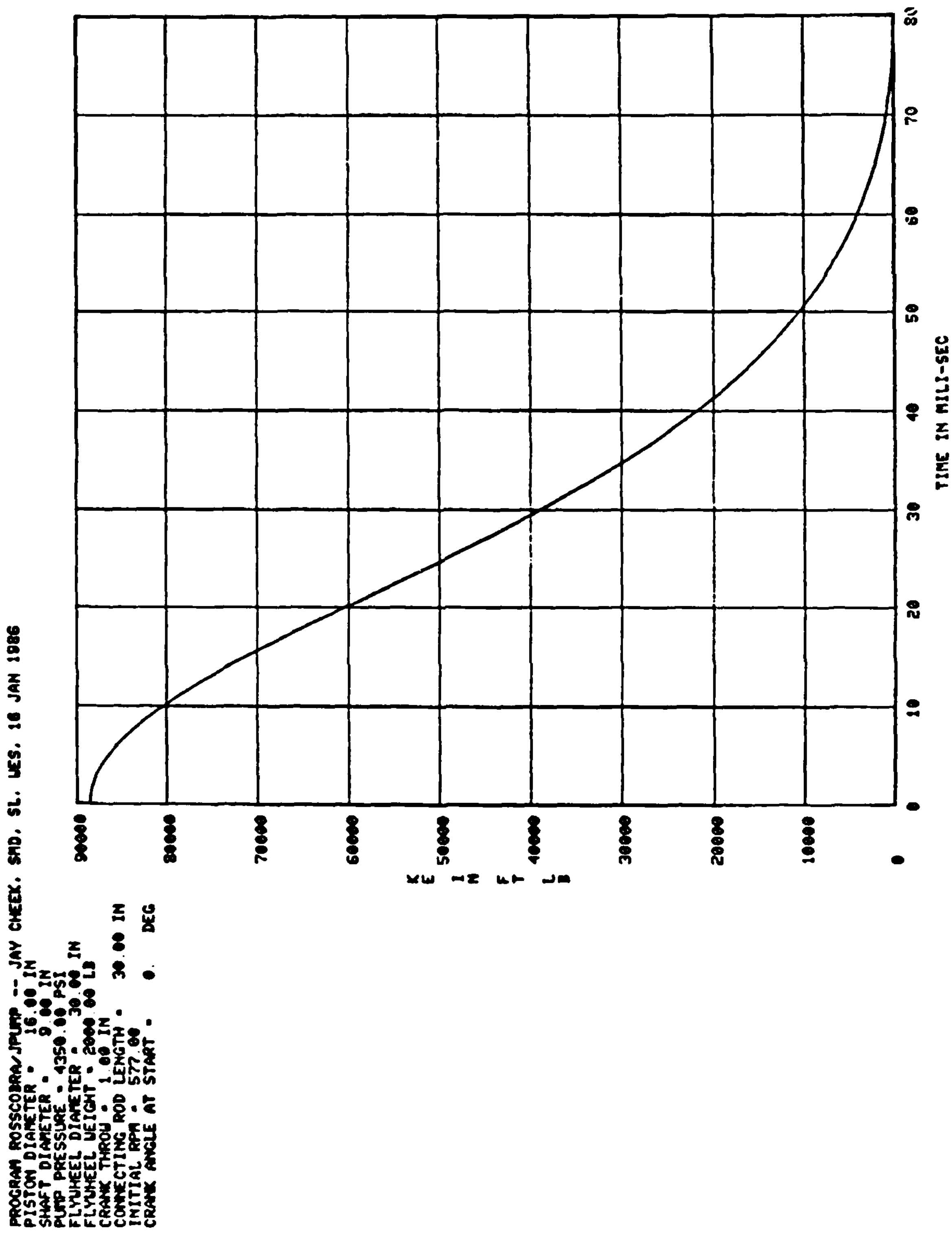

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD, SL, WES, 18 JAN 1986
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 577.00
CRANK ANGLE AT START = 0. DEG
KE IN FT LB
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
TIME IN MILI-SEC
0
10
20
30
40
50
60
70
80

FIGURE B10

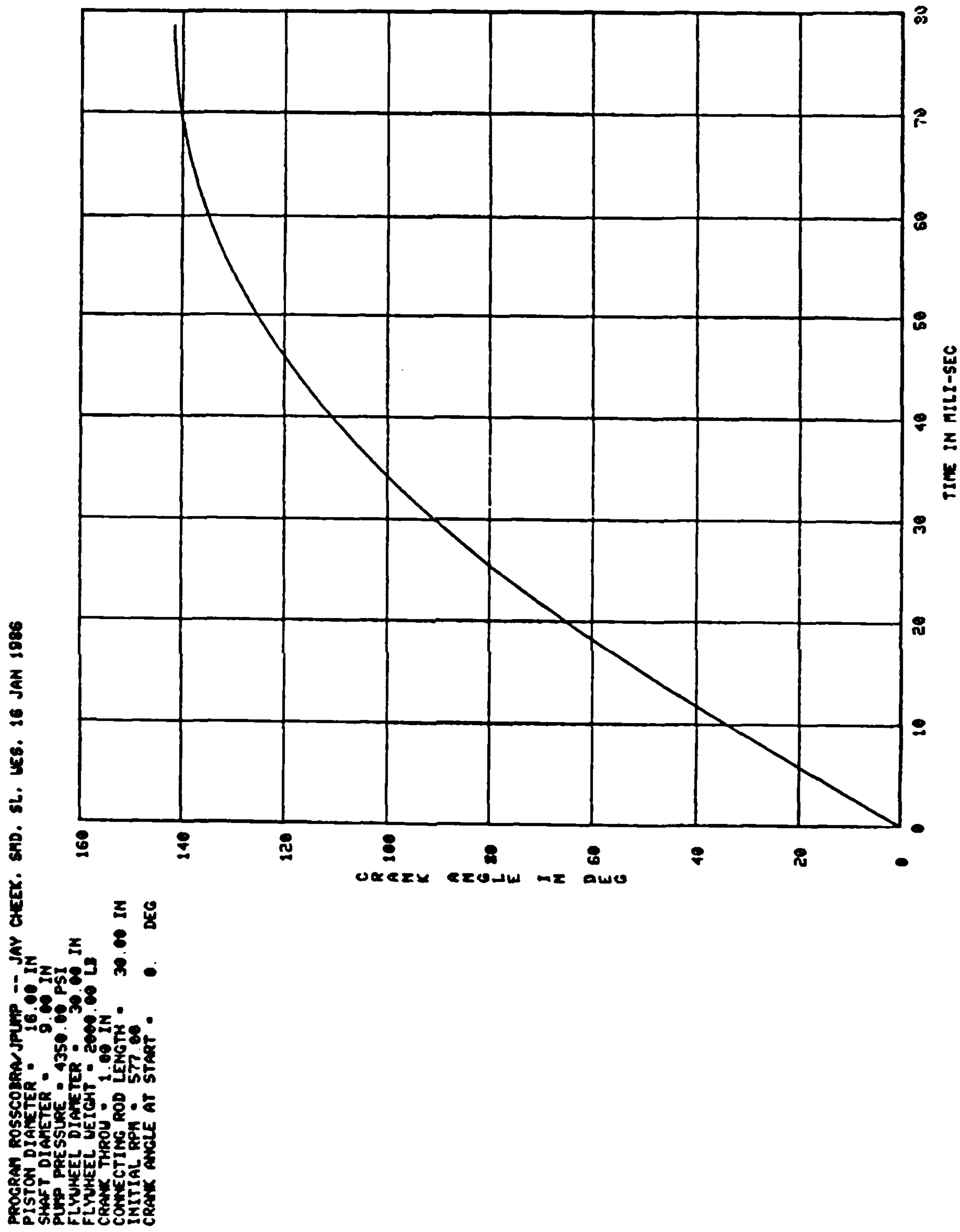

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK. SMD. SL. WES. 16 JAN 1986
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 577.00
CRANK ANGLE AT START = 0. DEG
CRANK ANGLE IN DEG
0
20
40
60
80
100
120
140
160
TIME IN MILI-SEC
0
10
20
30
40
50
60
70
80

FIGURE B11

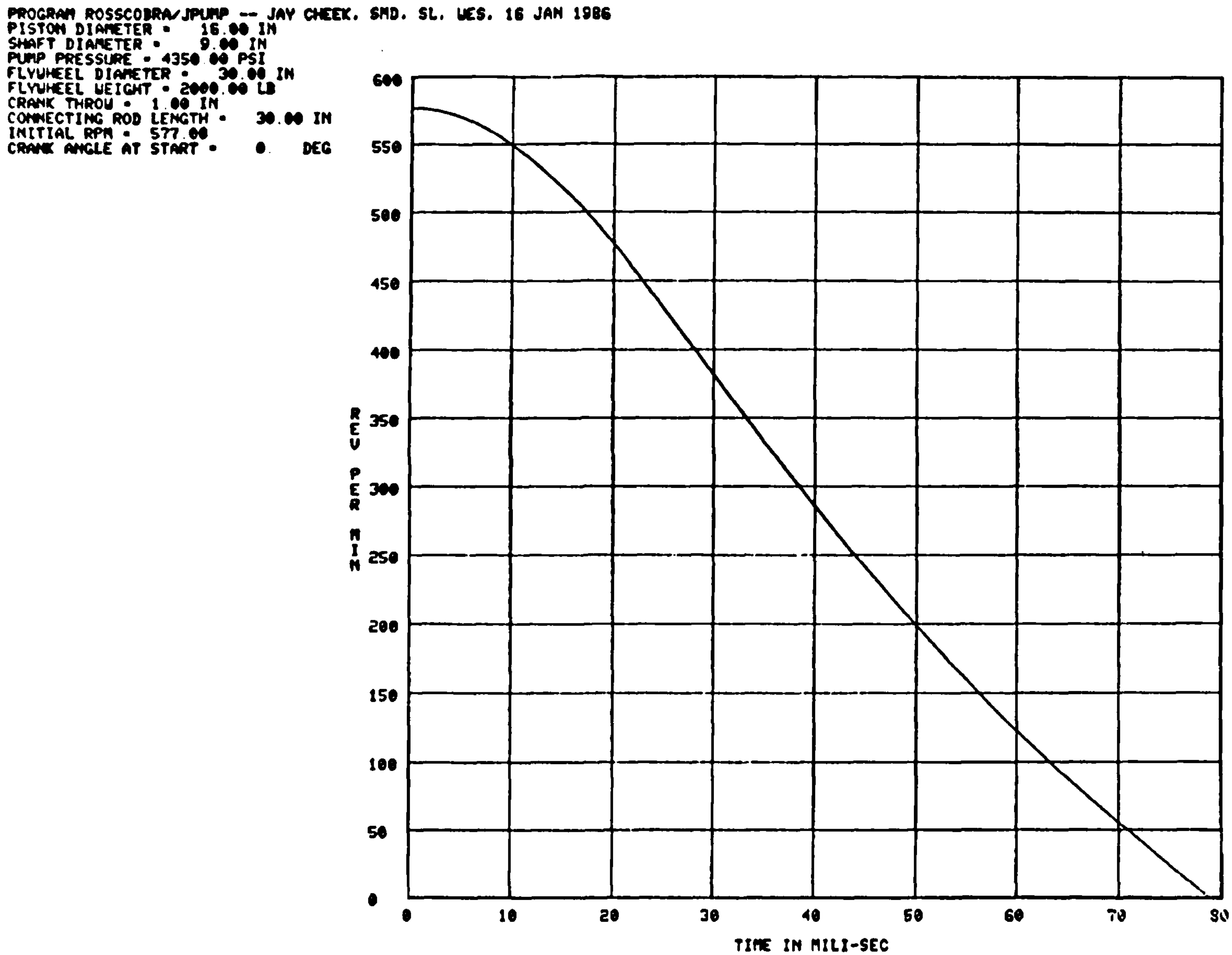

PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK. SMD. SL. WES. 16 JAN 1986
PISTON DIAMETER = 16.00 IN
SHAFT DIAMETER = 9.00 IN
PUMP PRESSURE = 4350.00 PSI
FLYWHEEL DIAMETER = 30.00 IN
FLYWHEEL WEIGHT = 2000.00 LB
CRANK THROW = 1.00 IN
CONNECTING ROD LENGTH = 30.00 IN
INITIAL RPM = 577.00
CRANK ANGLE AT START = 0. DEG
REV PER MIN
600
550
500
450
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
TIME IN MILI-SEC

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.

```
JPUMP
  10C$TITLE FILED IN ROSSCOBRA/JPUMP
  20C   PUMP RUN-TIME TEST PROGRAM
  30C   JAY CHEEK, SMD, SL, WES, 14 JAN 1986
  40C
  50C   DP        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 FLYWHEL
  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

```
C  GET INITIAL CONDITIONS
   100 WRITE (6,110) ' TEST START ANGLE, RPM =?'
   110 FORMAT (V)
       READ (5,110) THETAI, RPM
C  PISTON AREA
       AP = PI * (DP * DP - DS * DS) / 576.0
C  MASS OF THE TWO FLYWHEELS
       FM = WF * 2.0 / G
C  ROTATIONAL MOMENT OF INERTIA
       RMI = FM * DF * DF / 1152.0
C  INITIAL ANGULAR VELOCITY
       AVFI = RPM * PI / 30.0
C
C  CALC CONSTANTS FOR THE INTEGRATION LOOP.
C  CRANK ARM LENGTH IN FT
       TH = SP / 24.0
C  SQUARE OF THE CONNECTING ROD LENGTH
       CLS = CL * CL / 144.0
C  TIME STEP IN SEC.
       TDEL = AVFI / 1000000.0
C  PUMP FORCE TIMES CRANK ARM LENGTH
       FR = AP * P * TH * 144.0
C  STEP COUNTER
       N = 0
C  INITIAL ANGULAR VELOCITY OF THE CRANKSHAFT (RADIANS/SEC)
       AVF = AVFI
C  CRANKSHAFT ANGLE AT START OF PUMPING (0 DEG IS
C  TOP DEAD CENTER OF STROKE)
       THETA = THETAI
C  NUMBER OF POINTS TO BE PLOTTED
       NVP = 0
C
C  HEADING.
       WRITE (6,120)
   120 FORMAT ('   N   T(SEC)    THETA      RPM    KE (FT-LB)   Q '
      &      , '(GAL/SEC)  TORQ (FT-LB)')
C
C  START THE PUMP TEST LOOP
C  ELAPSED TIME IN SEC
   130 TI = N * TDEL
C  CURRENT CRANKSHAFT ANGLE IN RADIANS
       TR = THETA / DTR
C  KINETIC ENERGY IN FT LBS
       EK = RMI * AVF * AVF / 2.0
C  TEST FOR SPECIAL CALCULATION FOR Q AT START
       IF (N .NE. 0) GO TO 140
C  CALC PUMP POSITION JUST BEFORE THE FIRST STEP.
       TRR = TR - AVF * TDEL
       ST = SIN(TRR)
        TEMP1 = TH * COS(TRR)
```

JPUMP

```
       TEMP2 = SQRT(CLS-(TH*ST)**2)
       XPL = TEMP2 - TEMP1
 140 ST = SIN(TR)
C  X COMPONENT OF THE CRANK ARM
       TEMP1 = TH * COS(TR)
C  PROJECTION OF CONN. ROD ON X AXIS
       TEMP2 = SQRT(CLS-(TH*ST)**2)
C  POSITION OF THE PUMP AT STEP N
       XP = TEMP2 - TEMP1
C  PUMP DISCHARGE DURING THIS STEP
       Q = ABS(XP-XPL) * AP * 7.5 / TDEL
       XPL = XP
C  SLOWDOWN TORQUE ON CRANK DUE TO PUMPING FORCE
       TOR =  - ABS(FR*ST*(1.0-TEMP1/TEMP2))
C  ANGULAR DECELERATION
       ALPHA = TOR / RMI
       IF (MOD(N,100) .EQ. 0) WRITE (6,150) N, TI, THETA, AVF /
      &     2. / PI * 60, EK, Q, TOR
 150 FORMAT (1X, I4, F8.4, F8.2, F8.1, F10.0, F14.2, F14.0)
C
C  SAVE EVERY FIFTH POINT FOR PLOTTING
       IF (MOD(N,5) .NE. 0) GO TO 160
       NVP = NVP + 1
       V(NVP,1) = TI * 1000.0
       V(NVP,2) = Q
       V(NVP,3) = TOR
       V(NVP,4) = EK
       V(NVP,5) = THETA
       V(NVP,6) = AVF / 2.0 / PI * 60.0
C  NEW ANGULAR VELOCITY DUE TO SLOWDOWN TORQUE
 160 AVF = AVF + ALPHA * TDEL
C  COUNT STEP
       N = N + 1
C  STILL ROTATING?
       IF (AVF .LT. 0.0) GO TO 170
C  YES.  ADVANCE TO NEXT CRANK ANGLE
       THETA = THETA + AVF * TDEL * DTR
       GO TO 130
C
C  DONE
 170 WRITE (6,180) TI, THETA - THETAI, N
 180 FORMAT (' PUMPING ENDS AT ', F10.3, ' SEC.' /
      &     '     PUMP CUTOUT ANGLE = ', F8.1, ' DEGREES' /
      &     '     NUMBER OF TIME STEPS = ', I5 //// )
       CALL UPAUSE
C
C  PLOT THE CURVES
       CALL PLOTPU(V, NVP, DP, DS, P, DF, WF, SP, CL, RPM, THETAI)
       GO TO 100
       END
```

JPUMP

```
      SUBROUTINE PLOTPU(V, NV, DP, DS, P, DF, WF, SP, CL, RPM,
     &      THETAI)
C
C  PLOT ANY OF THE 5 ARRAYS AS A FUNCTION OF TIME (ARRAY1).
C  JAY CHEEK, SMD, SL, WES, 16 JAN 1986
C
      CHARACTER*20 T(20)
      DIMENSION V(1500,6)
      DATA T(1)/'TIME IN MILI-SEC\    '/, T(2)
     &      /'Q IN GAL PER SEC\    '/, T(3)
     &      /'TORQUE IN FT LB\     '/, T(4)
     &      /'KE IN FT LB\         '/, T(5)
     &      /'CRANK ANGLE IN DEG\ '/, T(6)
     &      /'REV PER MIN\         '/
C  START PLOTTING
      FN = NV
      CALL UPSET('XLABEL', T(1))
      DO 120 I = 2, 6
C
C  IS THIS GRAPH NEEDED?
         WRITE (6,100) T(I)
 100     FORMAT ('  PLOT ', A20, '?')
         CALL IANSR(IST)
         IF (IST .EQ. 0) GO TO 120
C
C  YES.  DO IT.
         CALL UPSET('YLABEL', T(I))
         CALL UERASE
         CALL UDAREA(4.0, 14.0, 0.0, 10.0)
         CALL USET('GRIDAXIS')
         CALL UPLOT1(V(1, 1), V(1, I), FN)
         CALL UHOME
         CALL UALPHA
         WRITE (6,110) DP, DS, P, DF, WF * 2.0, SP / 2.0, CL, RPM,
     &          THETAI
 110     FORMAT ('  PROGRAM ROSSCOBRA/JPUMP -- JAY CHEEK, SMD, '
     &          , 'SL, WES, 16 JAN 1986' / '  PISTON DIAMETER =',
     &          F8.2, ' IN' / '  SHAFT DIAMETER =', F8.2, ' IN' /
     &          '  PUMP PRESSURE =', F8.2, ' PSI' /
     &          '  FLYWHEEL DIAMETER =', F8.2, ' IN' /
     &          '  FLYWHEEL WEIGHT =', F8.2, ' LB' /
     &          '  CRANK THROW =', F6.2, ' IN' / '  CONNECTING ROD LENGT
     &        , F8.2, ' IN' / '  INITIAL RPM ='
     &          , F8.2 / '  CRANK ANGLE AT START =', F8.2, ' DEG')
         CALL UPAUSE
 120  CONTINUE
      RETURN
      END
```

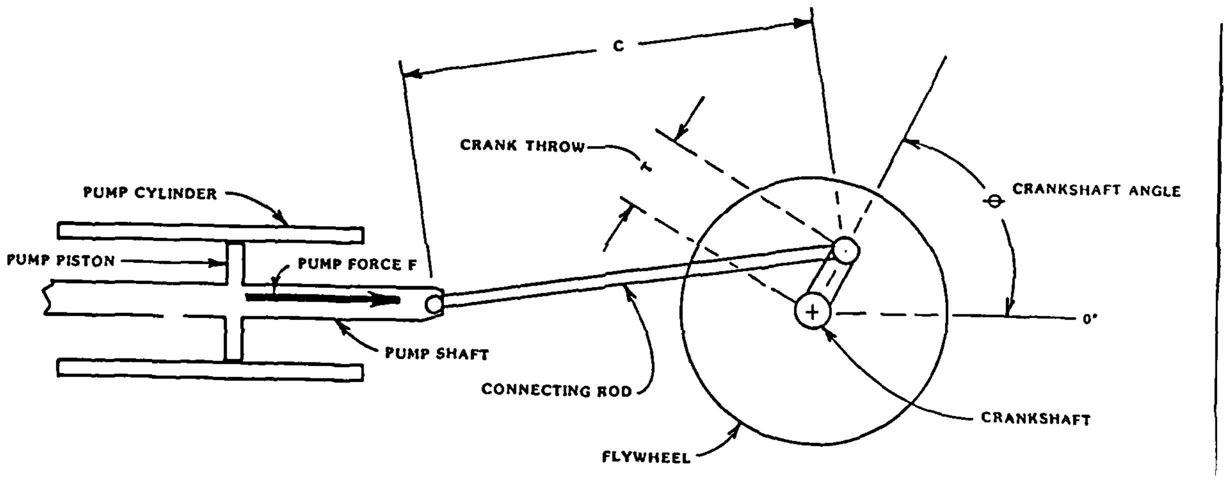
JPUMP

```
      SUBROUTINE IANSR(IWHAT)
C  SEE WHETHER THE USER GIVES A Y (OR A CARRIAGE RETURN)
C  FOR YES OR A N FOR NO TO A PREVIOUSLY ASKED QUESTION.
C
C  CODE FILED IN ROSSCOBRA/JHEST-S.
C  JAY CHEEK, SMD, SL, WES; DEC 1981
C
      DATA IBLK/'    '/, IYES/'Y   '/, NO/'N   '/
  100 IWHAT = 0
      READ (5,110) II
  110 FORMAT (A4)
      IF (II .EQ. NO) RETURN
      IWHAT = 1
      IF (II .EQ. IYES) RETURN
      IF (II .EQ. IBLK) RETURN
      WRITE (6,120)
  120 FORMAT ('  ERROR:  ONLY Y OR RETURN (FOR YES)  OR N (FOR '
     &       , 'NO)   ALLOWED, RETRY')
      GO TO 100
      END
```

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).

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

and choose a small time step (Δt) so that the wheel will rotate less than .1° 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.

$$\Gamma = F_M T$$

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.

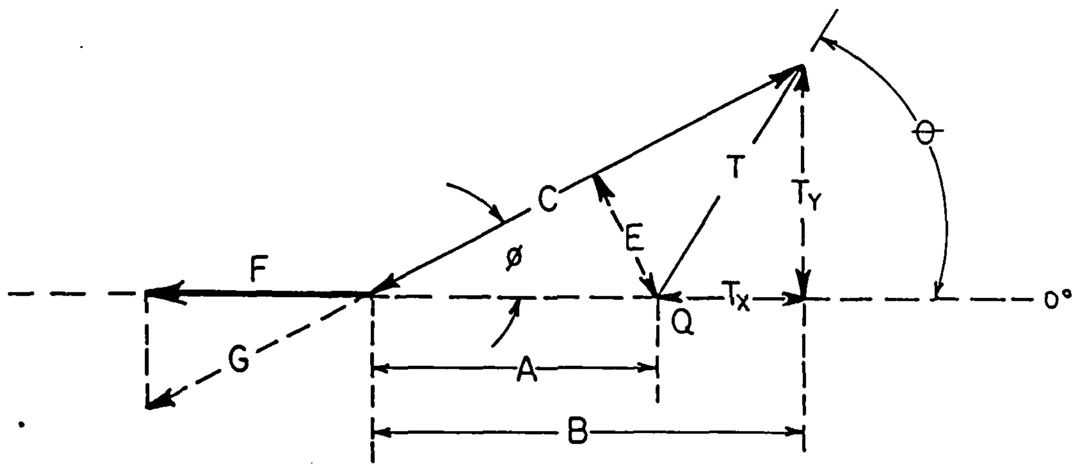


Figure D2

Calculating the Torque (Γ) about point Q.

$\Gamma = G E$

$E = A \sin \phi$

$A = B - T_x$

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

$T_y = T \sin \Theta$

$T_x = T \cos \Theta$

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

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

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

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

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

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

$$t_N = \frac{W_N}{W_O} t_O$$

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.

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
C$TITLE FILED IN ROSSCOBRA/JPEND
C  CALC OF PENDULUM TEST OF VALVE PERFORMANCE.
C  JAY CHEEK SMD, SL, WES, 17 JAN 1986
C
        DATA PI/3.1415926/, P/4350.0/, Q/26.4/
C
        DO 130 J = 1, 2
C  WEIGHT OF BALL
          WT = J * 1000.0
C DIAMETER OF HYDRAULIC CYLINDER (ONE STROKE PUMP)
           D = 3.250
           WRITE (6,100) WT, Q, P
   100     FORMAT ( //// '          DROP TEST OF VALVE' /
     &          '  FOR BALL WEIGHT OF', F6.0,
     &          ' LB   PEAK DISCHARGE OF', F5.1, ' GAL / SEC' /
     &          '  AND DISCHARGE PRESSURE OF', F6.0, ' PSI' //
     &          ' CYLINDER    DROP       RETARD      IMPACT    '
     &          , 'DISCHARGE   KINETIC' /
     &          ' DIAMETER    HEIGHT      FORCE    VELOCITY      TIME '
     &          , '      ENERGY' /
     &          ' (INCHES)    (FEET)     (POUNDS)   (FT / SEC) '
     &          , '(SECONDS) (FT - LBS)')
C
C   CALC FOR SEVERAL CYL. DIAMETERS
           DO 120 I = 1, 7
C   DIAMETER
             DI = D + I * .25
C   PISTON (CYLINDER) AREA
             A = PI * DI * DI / 4.0
C   MASS OF THE BALL
             ZMASS = WT / 32.2
C   DROP HEIGHT TO PRODUCE PEAK DISCHARGE
             H = 9.280 * Q * Q / DI ** 4
C   IMPACT VELOCITY
             V = SQRT(2.0*32.2*H)
C   RETARDING FORCE OF THE CYLINDER
             F = P * A
C   TIME OF DISCHARGE
             TI = ZMASS * V / F
C   KINETIC ENERGY
             EK = ZMASS * V * V / 2.0
C
C   RESULTS
             WRITE (6,110) DI, H, F, V, TI, EK
   110       FORMAT (1X, F7.2, F10.2, F12.0, F10.2, F10.3, F10.0)
   120     CONTINUE
   130 CONTINUE
         STOP
         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/sec^2

b. Discharge = $Q = \frac{V}{\Delta t}$ where V is volume in ft^3.

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

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

D is cylinder diameter in ft

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

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

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

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

Total discharge time (t) is

$$t = \frac{MU_I}{F} = \frac{\frac{W}{g}(2gH)^{\frac{1}{2}}}{\frac{\pi}{4}D^2 P} = \frac{\frac{W}{g}\left(\frac{2g9.280Q_I^2}{D^4}\right)^{\frac{1}{2}}}{\frac{\pi}{4}D^2 P} = .9667\,\frac{W}{P}\,\frac{Q_I}{D^4}$$

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

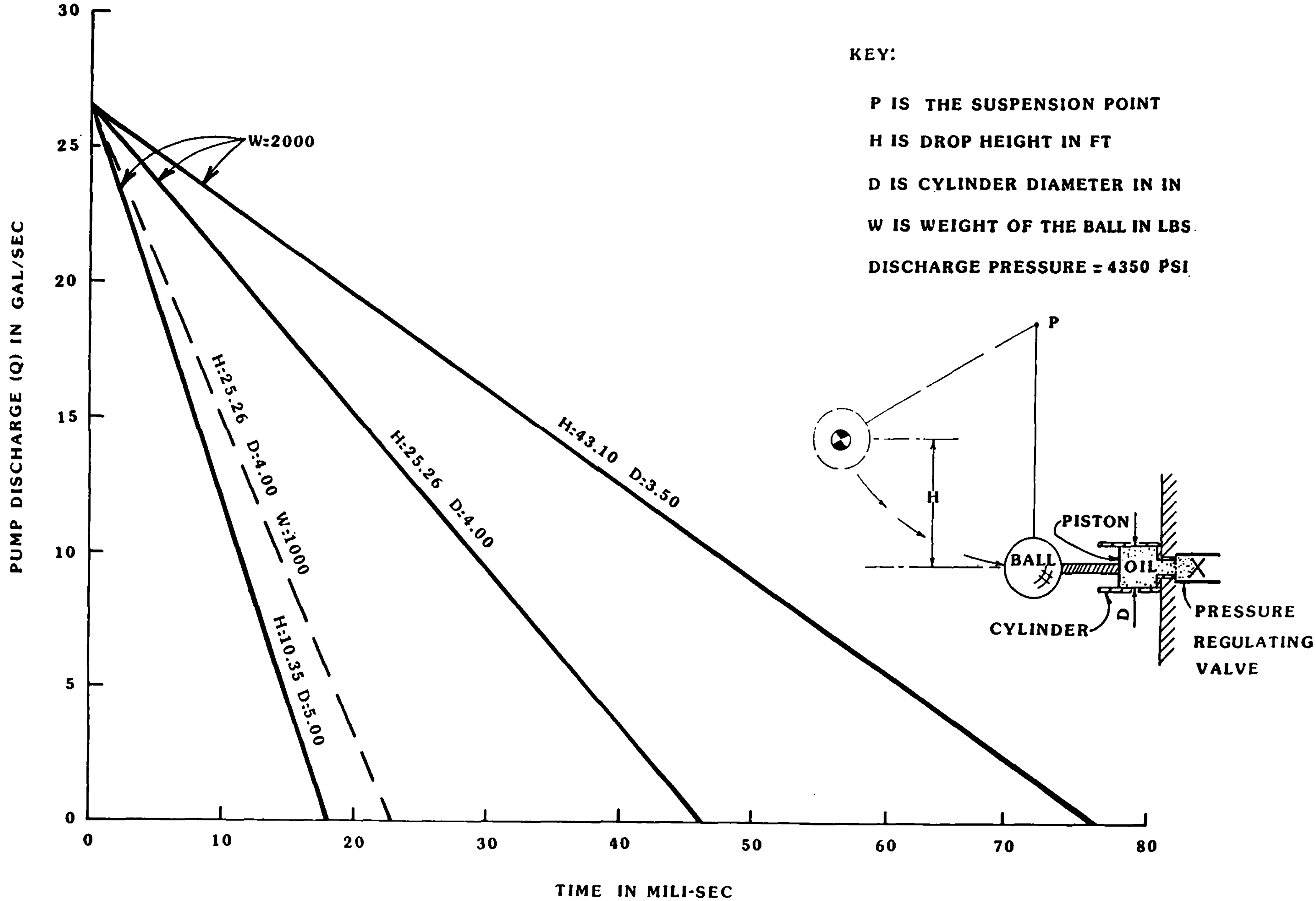


Figure E2

END
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