Fermilab

TM-899
1738.000
CCI Report No. 390-111

DESIGN EVALUATION OF VALVE ACTUATOR CAMS (FERMILAB RECIPROCATING DESIGN)

PREPARED UNDER FERMILAB SUBCONTRACT NO. 94199
BY CRYOGENIC CONSULTANTS, INC.
ALLENTOWN, PA.

FOR

FERMI NATIONAL ACCELERATOR LABORATORY
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1. INTRODUCTION:

This report summarizes a design evaluation of the valve actuators on both the wet and gas helium expansion engines. Continued reports of noisy cam action on current engines at the higher speeds (500 rpm) prompted a more in-depth study of the valve actuators to determine whether the present cam profile contributes to the noise.

It was concluded that the existing cam profiles with their straight line development from the minor radius to the major radius, together with the small corner blending radius, are not suited for this application. Although low "g" levels are generated during the valve opening cycle, the acceleration is always positive, and at peak opening the cam follower velocity and positive acceleration must be instantaneously opposed by deceleration forces on the order of 114-144 g's. Spring forces incapable of decelerating the follower sufficiently will permit the follower to leave the cam and then slap against the cam causing noise, high shock loads, and premature bearing failure.[1]

Cam profiles are presented that produce constant acceleration and deceleration with no radial velocity of the follower at the peak valve opening position.

2. WET ENGINE CAM (ORIGINAL PROFILE); (Ref. Dwg. No. 1820-MB-111123):

An enlarged view of the cam profile is shown in Figure 1. For purposes of calculation, the angle from point A to point G (35°) was divided into six equal parts of 5.83333° each.

The time interval for the cam to rotate 5.83333° is:

$$t = \frac{1}{500\ \text{rpm}} \times 60\ \text{sec/min} \times \frac{5.83333}{360} = .001944\ \text{sec}$$

[1] Evaluation of Wet and Gas Helium Expansion Engines (Fermilab Reciprocating Design), CCI Report No. 390-110, 10 July 1979.

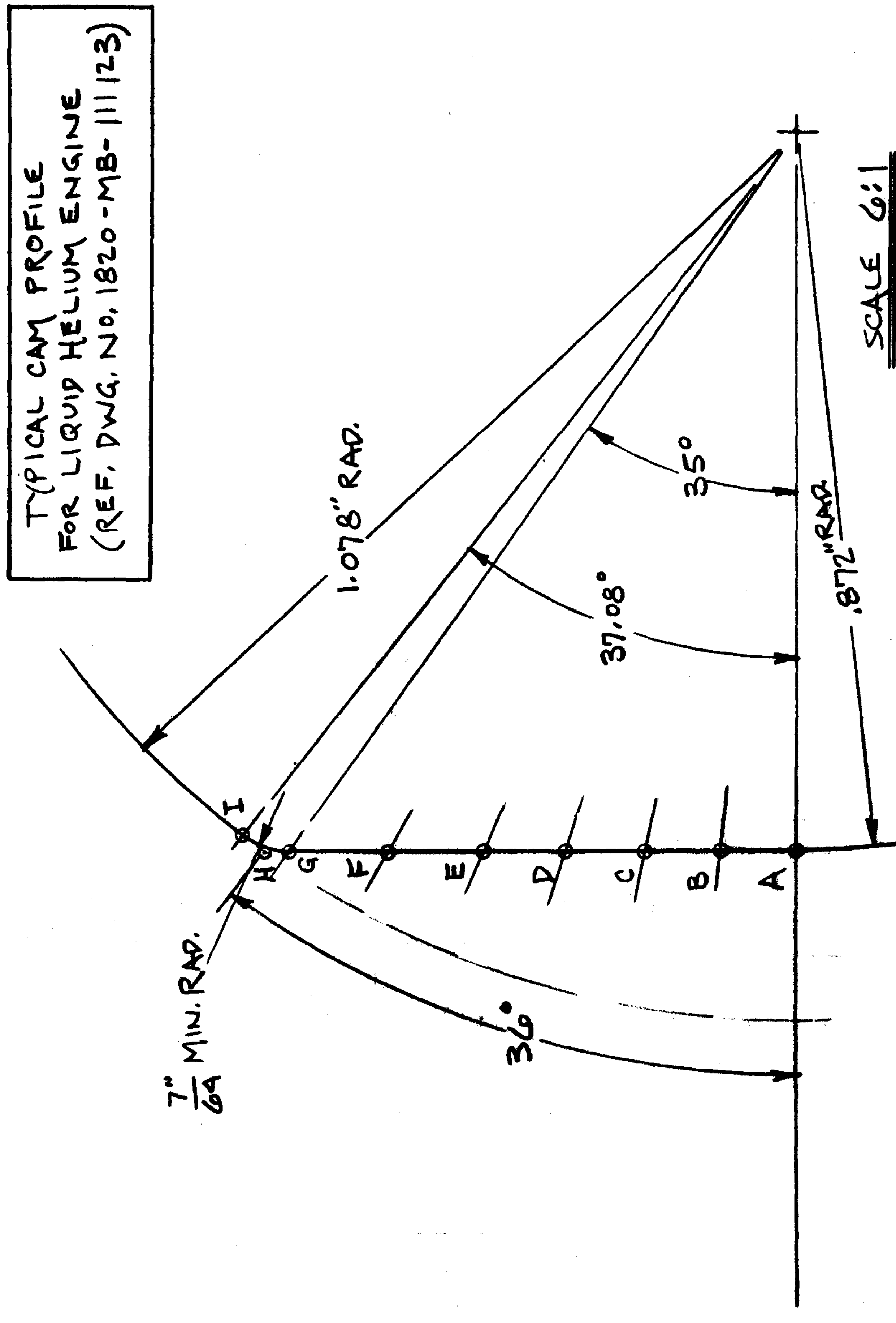
TYPICAL CAM PROFILE
FOR LIQUID HELIUM ENGINE
(REF. DWG. NO. 1820-MB-111123)
1.078" RAD.
35°
37.08°
.872" RAD.
36°
7"/64 MIN. RAD.
A
B
C
D
E
F
G
H
I
SCALE 6:1

FIGURE 1

From point A to point B the acceleration can be expressed as:

$$a = \frac{2s}{t^2} = \frac{2 \times .00454}{12 \times .001944^2}$$

$$= 200.2 \text{ Ft/sec}^2$$

$$= 6.2 \text{ g}$$

The velocity at point B can be expressed as:

$$V_B = at = 200.2 \times .001944$$

$$= .38923 \text{ Ft/sec}$$

For subsequent points along the cam profile (C through G), the relationships are as follows:

$$a = \frac{2\,(s - V_o t)}{t^2}$$

$$V_f = V_o + at$$

The values of "a" and "V_f" are tabulated in Table I.

At 35° the velocity of the cam follower is +3.23216 Ft/sec, and the acceleration is +419.0 Ft/sec. In order to decrease the velocity of the follower to zero in the remaining cam height of 0.01348", the decleration must be -4650 Ft/sec^2 or -144g.

$$a = \frac{(V_f^2 - V_o^2)}{2\,s}$$

$$= \frac{(0 - 3.23216^2)}{2 \times \frac{.01348}{12}}$$

$$= -4650 \text{ Ft/sec}^2$$

$$= -144 \text{ g}$$

The time to decelerate the cam follower is:

$$t = \frac{V_f - V_o}{a}$$

$$= \frac{0 - 3.23216}{-4650}$$

$$= .0006951 \text{ sec}$$

The cam rotates n degrees from point G to point I where:

$$n = \frac{360\ t}{.12 \text{ sec/rev.}}$$

TABLE I

Ø	L (in.)	L-0.872 (in.)	Δ(in.)	t (sec)	a (ft/sec^2)	a (g)	V_o (ft/sec)	V_f (ft/sec)
-0-	.87200	-0-						
			.00454	.001944	+200.2	+6.2	-0-	.38923
5.83333	.87654	.00454						
			.01386	.001944	+210.8	+6.5	.38923	.79904
.66667	.89040	.01840						
			.02392	.001944	+232.8	+7.2	.79904	1.25172
17.50000	.91432	.04232						
			.03535	.001944	+271.2	+8.4	1.25172	1.77898
23.3333	.94967	.07767						
			.04895	.001944	+328.6	+10.2	1.77898	2.41770
29.16667	.99862	.12662						
			.06590	.001944	+419.0	+13.0	2.41770	3.23216
35.00000	1.06452	.19252						
			.01348	.000695	-4650	-144	3.23216	-0-
37.08526	1.07800	.20600						

$$= \frac{360 \times .0006951}{.12}$$

$$= 2.0852°$$

3. WET ENGINE CAM (RECOMMENDED PROFILE)

It is desirable to both reduce the deceleration force necessary to restrain the cam follower and eliminate the radial velocity component of the follower when the peak deflection is reached. In order to accomplish this, a constant acceleration - constant deceleration cam is recommended.

This type of cam profile is shown in figure 2. With this cam the peak g-loading is as low as possible for the given lift, speed, and percent rotation to obtain full lift. The radial velocity component of the follower is zero at both the minor and major radii inflection points.

For a uniformly accelerated motion, the distances passed through by the follower during equal periods of time increase uniformly in the proportion 1:3:5:7:9 etc.

Angular increments of 6° were assumed giving six equal time periods. The distance proportion for this assumption was 1:3:5:5:3:1, or fractions of the total lift of 1/18, 3/18, 5/18, 5/18, 3/18, 1/18. Values of "a" and "V" for this profile are tabulated in Table II. Note that "a" is constant at an absolute value of 14.8 g.

The theoretical cam profile can be approximated almost precisely by using the two radii shown in figure 2. Using the 7/8" radius ramp rather than the straight line ramp is optional. More important is that no less than 3/8" radius is used to blend the ramp to the major dia.

The spring must be selected to provide an acceleration force of 15 g minimum on the cam follower.

4. GAS ENGINE CAM (ORIGINAL PROFILE)
(Ref. Dwg. No. 1820-MB-111505)

An enlarged view of the cam profile is shown in Figure 3. This cam was analyzed similarly as the cam for the wet engine. For purposes of calculation the angle from point A to point H was divided into 6 equal parts of 4.80266° each.

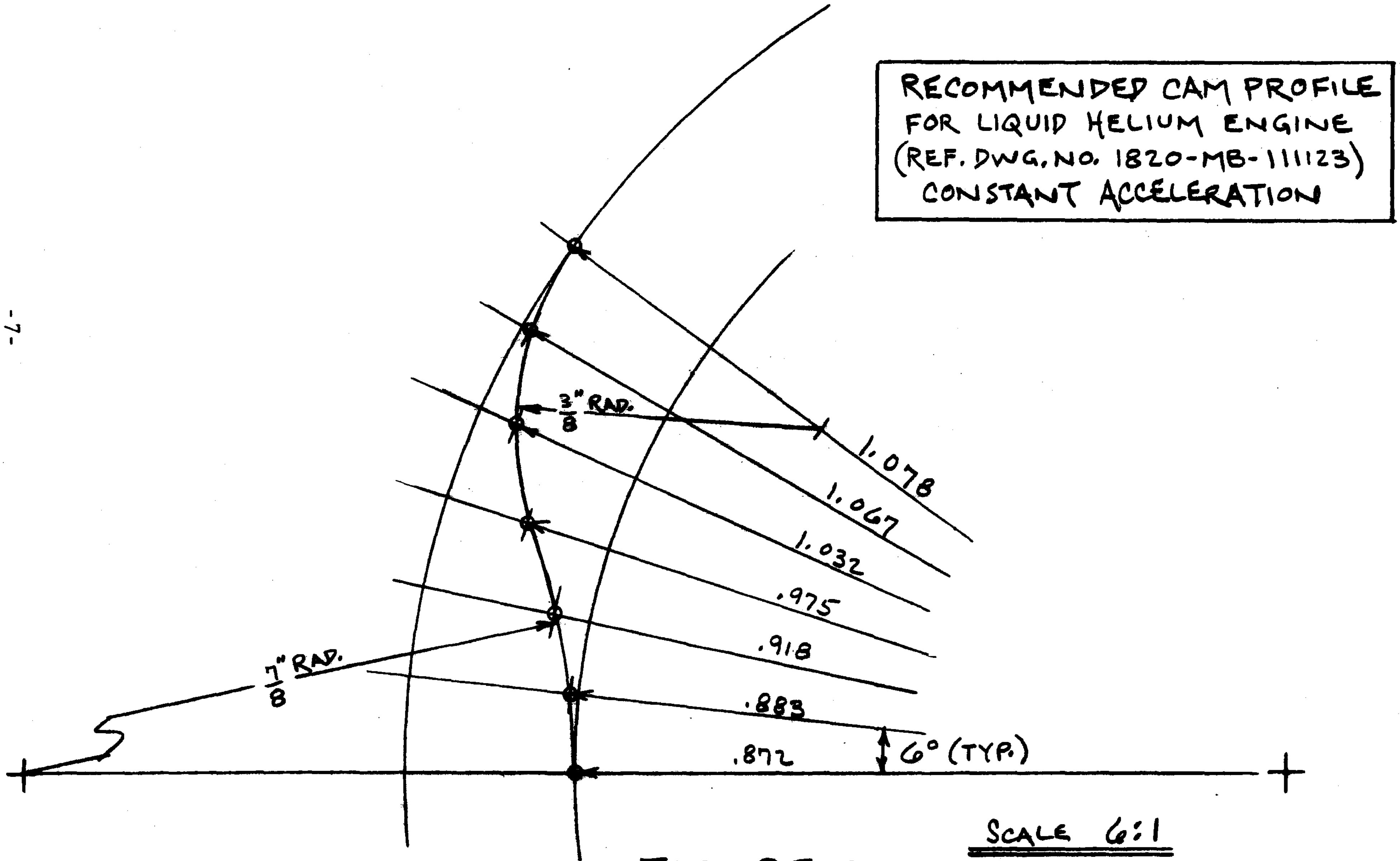
RECOMMENDED CAM PROFILE
FOR LIQUID HELIUM ENGINE
(REF. DWG. NO. 1820-MB-111123)
CONSTANT ACCELERATION
3/8" RAD.
7/8" RAD.
1.078
1.067
1.032
.975
.918
.883
.872
6° (TYP.)
SCALE 6:1

FIGURE 2

TABLE II

∅	Δ(in.)	a(ft/sec^2)	a (g)	V_o(ft/sec)	V_f(ft/sec)
0					
	.011444	+476.83	+14.8	-0-	.95367
6					
	.034333	+476.88	+14.8	.95367	1.90741
12					
	.057222	+476.84	+14.8	1.90741	2.86108
18					
	.057222	-476.83	-14.8	2.86108	1.90741
24					
	.034333	-476.88	-14.8	1.90741	.95367
30					
	.011444	-476.83	-14.8	.95367	-0-
36					

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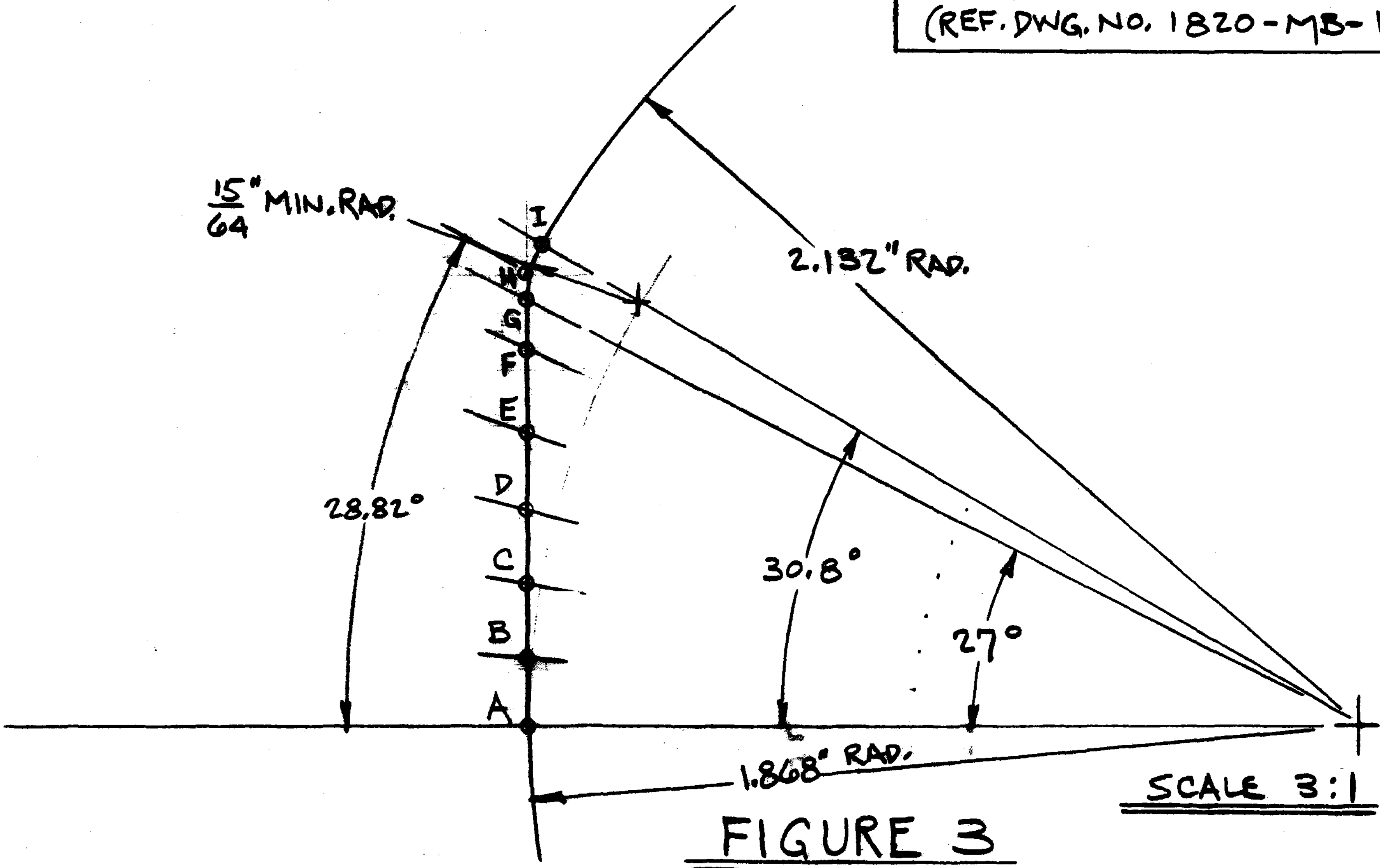
TYPICAL CAM PROFILE
FOR GAS EXPANSION ENGINE
(REF. DWG. NO. 1820-MB-111505)



SCALE 3:1

FIGURE 3

The time interval for the cam to rotate 4.80266° is:

$$t = \frac{1}{500 \text{ RPM}} \times \frac{60 \text{ sec}}{\text{Min.}} \times \frac{4.80266}{360} = .0016 \text{ sec.}$$

From point A to point B the acceleration can be expressed as:

$$a = \frac{2s}{t^2} = \frac{2 \times .00658}{.0016^2 \times 12}$$

$$= 428.38 \text{ Ft/sec}^2$$

$$= 13.3 \text{ g}$$

The velocity at point B can be expressed as:

$$V_B = at = 428.38 \times .0016$$

$$= 0.68541 \text{ Ft/sec}$$

For subsequent points along the cam profile (C through G), the relationships are as follows:

$$a = \frac{2\,(s - V_o t)}{t^2}$$

$$V_f = V_o = at$$

The values of "a" and "V_f" are tabulated in Table III.

At 27° the velocity of the cam follower is +4.66109 Ft/sec and the acceleration is +710.31 Ft/sec^2. In order to decrease the velocity of the follower to zero in the remaining cam height of .03549", the deceleration must be -3673 Ft/sec^2 or -114 g.

$$a = \frac{(V_f^2 - V_o^2)}{2\,s}$$

$$= \frac{(0 - 4.66109^2)}{2 \times \frac{.03549}{12}}$$

$$= -3673 \text{ Ft/sec}^2$$

$$= -114 \text{ g}$$

The time to decelerate the cam follower is:

$$t = \frac{(V_f - V_o)}{a}$$

TABLE III

Ø	L (in.)	L-1.868 (in.)	Δ(in.)	t(sec)	a(ft/sec^2)	a (g)	V_o(ft/sec)	V_f(ft/sec)
-0-	1.86800	-0-						
			.00658	.0016	+428.38	+13.3	-0-	.68541
4.80266	1.87458	.00658						
			.01998	.0016	+444.02	+13.8	.68541	1.39584
9.60531	1.89456	.02656						
			.03410	.0016	+475.25	+14.8	1.39584	2.15624
14.40797	1.92866	.06066						
			.04949	.0016	+526.71	+16.4	2.15624	2.99898
19.21063	1.97815	.11015						
			.06684	.0016	+602.84	+18.7	2.99898	3.96352
24.01328	2.04499	.17699						
			.05152	.0010	+700.66	+21.8	3.96352	4.66109
27.00000	2.09651	.22851						
			.03549	.00127	-3673.0	-114.0	4.66109	-0-
30.80704	2.13200	.264						

$$= \frac{0 - 4.66109}{-3673}$$

$$= .00127 \text{ sec.}$$

The cam rotates n degrees from point G to point I.

$$n = \frac{360\ t}{.12\ \text{sec/rev}}$$

$$= \frac{360 \times .00127}{.12}$$

$$= 3.80704°$$

5. GAS ENGINE CAM (RECOMMENDED PROFILE)

A constant acceleration cam profile for the gas engine is shown is figure 4.

The theoretical profile can be approximated by using the two radii shown. Again, the curved (2" Rad.) ramp is optional but the blend radius of 3/4" minimum must be used.

The spring selected must provide a deceleration force of 30 g minimum on the cam follower.

Values of "a" and "V" for this profile are tabulated in Table IV. Note that "a" is constant at 29.7 g.

6. GENERAL COMMENTS

In order to develop the constant acceleration cam profile, it was assumed that the original minor and major radii were correct and that the degree rotation of the cam to cause maximum lift was correct. The "g"-levels were calculated at 500 RPM which is the anticipated top speed of the engines.

If another lift and/or rotational degree is desired, the cam profile can readilly be developed assuming equal angular increments and lift proportions of 1:3:5:7:9 etc.

By comparing the original cam profile with the recommended profile it can be seen that the original profile develops a lower but constantly increasing acceleration (6.2g to 13.0g vs. 14.8g for the wet engine and 13.3g to 21.8g vs. 29.7g for the gas engine.).

However, at peak lift the original profile requires exceedingly high acceleration forces to hold the follower against the cam. This is true both at the end of the opening stroke and at the start of the closing stroke. For either case, insufficient spring force will not hold the follower against the cam.

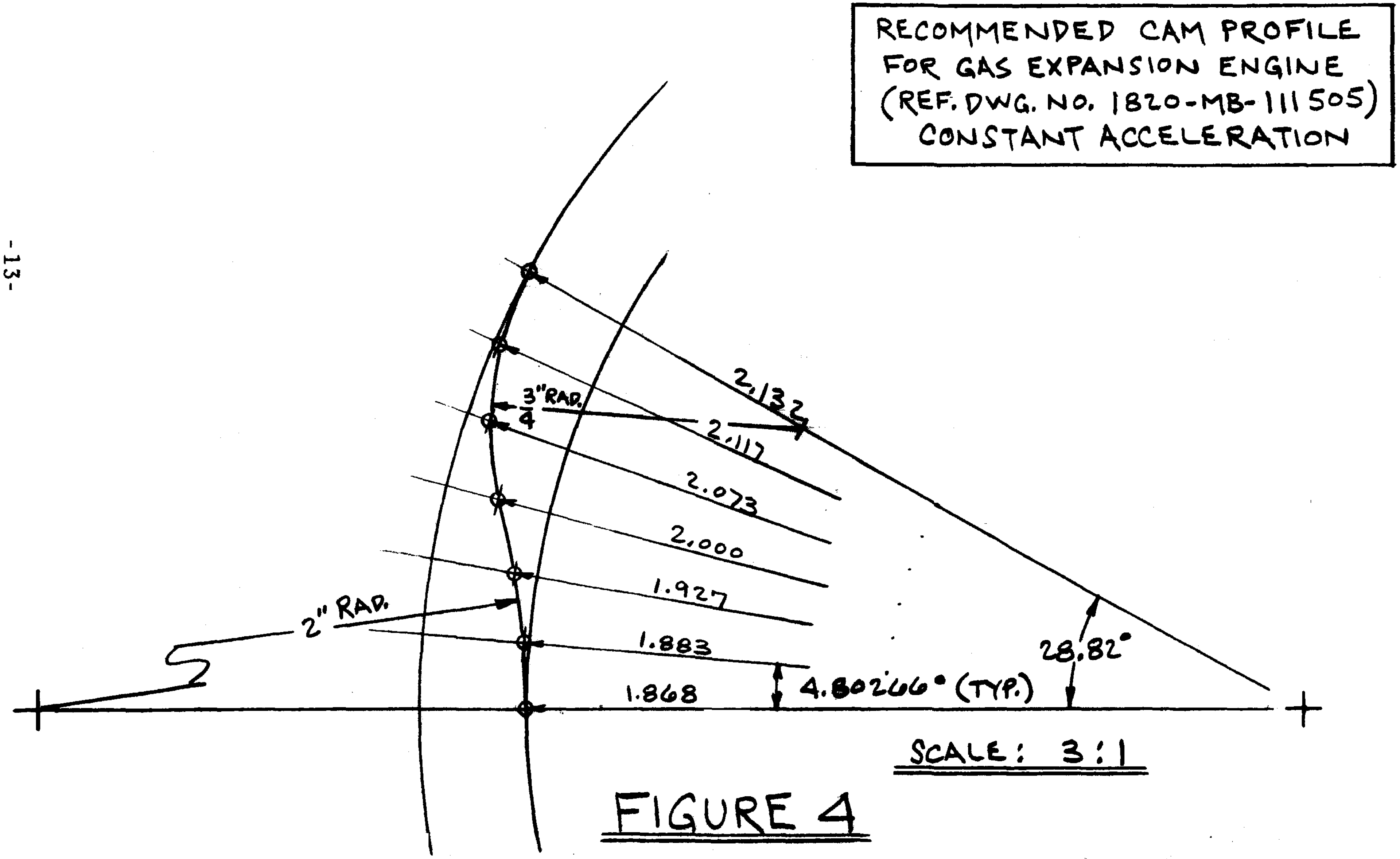

RECOMMENDED CAM PROFILE
FOR GAS EXPANSION ENGINE
(REF. DWG. NO. 1820-MB-111505)
CONSTANT ACCELERATION
2.132
2.117
2.073
2.000
1.927
1.883
1.868
3/4" RAD.
2" RAD.
4.80266° (TYP.)
28.82°
SCALE: 3:1

FIGURE 4

TABLE IV

Ø	Δ(in.)	a (ft/sec^2)	a (g)	V_o(ft/sec)	V_f(ft/sec)
-0-					
	.01467	+955.08	+29.7	-0-	1.52812
4.80266					
	.04400	+954.43	+29.6	1.52812	3.05520
9.60531					
	.07333	+955.08	+29.7	3.05520	4.58334
14.40797					
	.07333	-955.08	-29.7	4.58334	3.05521
19.21063					
	.04400	-954.43	-29.6	3.05521	1.52812
24.01328					
	.01467	-955.07	-29.7	1.52812	-0-
28.81594					

A sufficiently weak spring could permit the follower to leave the cam after the opening stroke and, if the major radius dwell arc is small, the follower may not return to the cam until after the dwell arc is past. As a result, small changes in the cam open-to-close ratio would have no effect on the operation of the engine because the follower return would be a function only of the spring force.

The acceleration produced by both the existing cams and the recommended cams is shown graphically in Figure 5. Keep in mind that due to the sign convention in all the calculations, the positive "g" is the acceleration of the cam follower due to the cam profile while the negative "g" represents the acceleration required from spring forces for the cam follower to remain in contact with the cam during the deceleration of the follower.

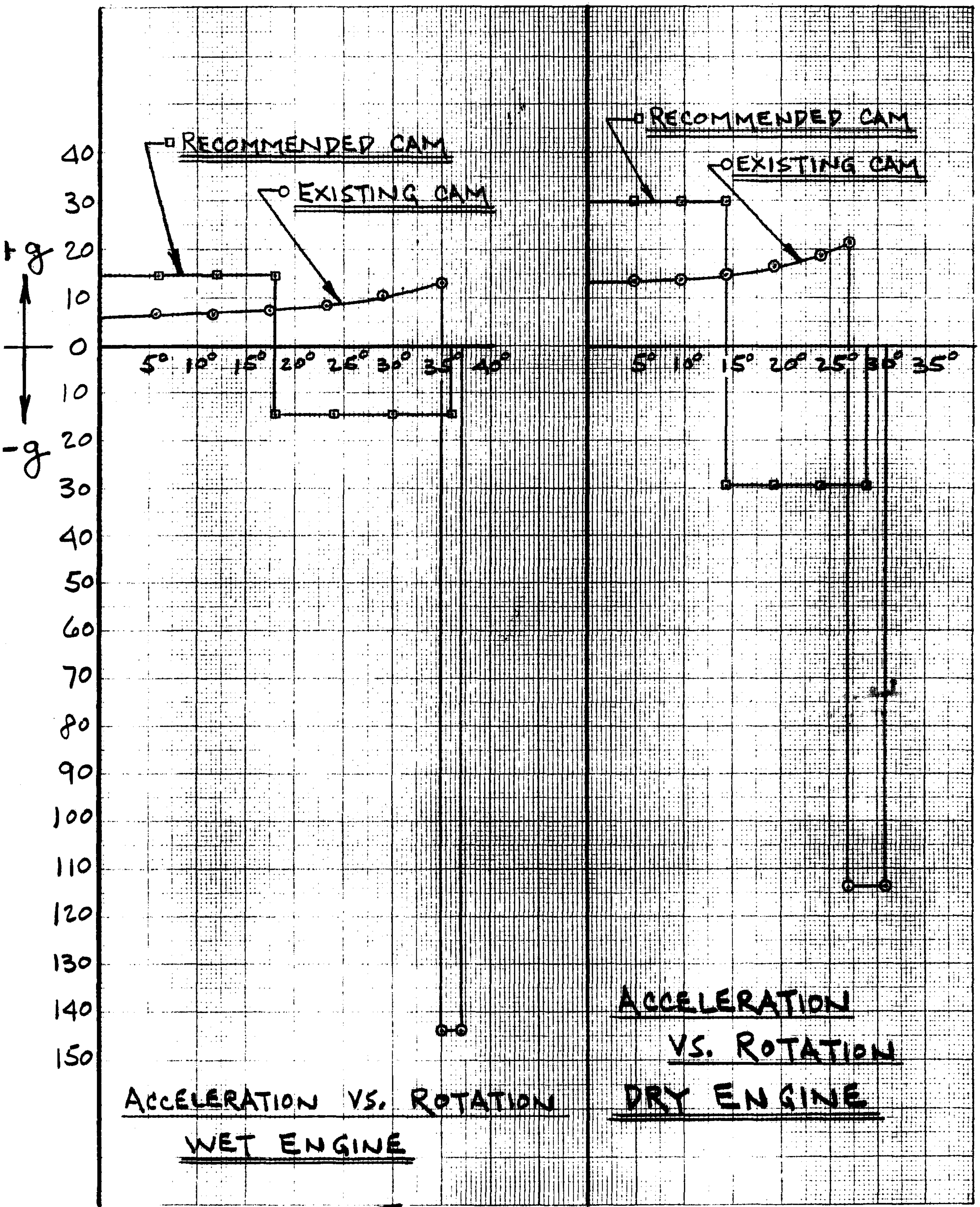

RECOMMENDED CAM
EXISTING CAM
+g
-g
40
30
20
10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
5° 10° 15° 20° 25° 30° 35° 40°
5° 10° 15° 20° 25° 30° 35°
ACCELERATION VS. ROTATION
WET ENGINE
ACCELERATION
VS. ROTATION
DRY ENGINE

FIGURE 5