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WATERTOWN ARSENAL LABORATORY

EXPERIMENTAL REPORT

NO. WAL 710/263-1

AIRCRAFT ARMOR

Perforation Resistance Characteristics of Magnesium Alloys, Dowmetal (Type FS, J-1)

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BY

J. H. SULLIVAN
Asst. Engineer

DATE 21 July 1944

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WATERTOWN, MASS.

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Watertown Arsenal Laboratory
Report Number WAL 710/265-1
Problem Number B-3.1

21 July 1944

AIRCRAFT ARMOR

Perforation Resistance Characteristics of Magnesium Alloys, Dowmetal (Type FS, J-1)

OBJECT

To investigate the feasibility of using Dowmetal as armor in aircraft.

CONCLUSIONS

1. Dowmetal, while affording resistance to perforation by small arms projectiles comparable, on a weight-per-weight basis, to that of good quality non-magnetic steel, nevertheless exhibits severe tendencies toward spalling which militate against its use as armor.

2. The resistance to perforation of Dowmetal by cal. .30 AP M2, cal. .50 AP M2 or 20 MM. AP M75 projectiles at normal incidence and throughout the entire range of obliquities investigated (0° to 70°) is well represented by the following equation:

$$V_n = \frac{1535\,(e_1/d)^{.5}}{\cos\theta}$$

where V_n is the Navy ballistic limit in feet-per-second, e_1 is the thickness (in feet) of a piece of steel equivalent in weight per unit surface area to the subject thickness of Dowmetal, d is the diameter of the projectile (core) in feet, and θ is the angle of obliquity from the normal.

J. F. Sullivan
J. F. SULLIVAN
Asst. Engineer

APPROVED:

H. H. ZORNIG
Colonel, Ordnance Dept.
Director of Laboratory

INTRODUCTION

As an aid to the designer and fabricator of aircraft armor, a study of the perforation resistance characteristics of various types of materials which might be used as aircraft armor has recently been completed at this arsenal[1].

This study has shown that duralumin (24 ST), an aluminum alloy, exhibits high resistance to perforation by small arms projectiles and, on a weight-for-weight basis, at high obliquities affords even greater resistance than steel armor. It is reasonable to attribute the weight-for-weight superiority of duralumin over steel at high obliquity to the greater thickness-per-unit-weight of the lighter alloy.

Since Dowmetal has even greater thickness-per-unit-weight than duralumin and has wide use in the aircraft industry, samples of this magnesium alloy have been studied concurrently.

In an earlier report[2] the results of firing at Dowmetal (FS) were set forth. This report reviews and corrects those data and integrates with them the results of firing at the J-1 alloy of the same material.

TEST PROCEDURE

Ballistic tests at normal incidence and at nominal obliquities of 30°, 45°, 60° and 75° from the normal were conducted on a one-hundred yard ~~under~~ indoor firing range, utilizing a cal. .50 Browning Machine Gun barrel and a cal. .30 Mann barrel mounted in a machine rest which permits horizontal and vertical orientation of the gun to control the placement of shots on the target and to compensate for any fluctuation in trajectory incidental to a variation in velocity. A 20 MM. gun mounted in a 3' field piece permitting similar maneuverability was used for heavier fire.

(Upon checking, the nominal obliquities of 30°, 45°, 60° and 75° were found to be actually 32°, 45°, 59° and 69°27', respectively.)

Striking velocities were determined by the use of a pair of Aberdeen Chronographs connected to screens of metal foil mounted on wooden frames. By such a device the average velocity of the projectile over the distance between the screens was determined from which the striking velocity was computed from prepared correction tables.

1. Watertown Arsenal Laboratory Report No. WAL 710/506, "Aircraft Armor - An Empirical Approach to the Efficient Design of Armor for Aircraft", dated 31 January 1944.

2. Watertown Arsenal Laboratory Report No. WAL 710/265, "Aircraft Armor - Ballistic Characteristics of a Magnesium Alloy, Dowmetal (Type FS)", dated 22 October 1943.

Before firing, powder charges were estimated to produce the required striking velocity for each round and rounds were accordingly assembled from appropriate components.

RESULTS

The results of the ballistic tests have been summarized in Tables I to X and graphically represented in Figures 1 to 10. Values of e and e_1 in these tables are listed in terms of inches, although e_1/d values have been completed with both e_1 and d in terms of feet.

The estimated resistance to perforation of several armor materials equivalent on a weight-for-weight basis to steel whose thickness equals the diameter of the attacking projectile (core) is listed in Table XI and illustrated in Figure 11.

The detailed records of firing are maintained in the files of the Armor Section of this laboratory and in the interests of conservation of materials have not been reproduced herein.

DISCUSSION

In order to facilitate a comparison of the perforation resistance efficiency of Dowmetal with that of other armor materials, its performance at the various obliquities investigated has been evaluated in terms of the Thompson coefficient[3] and plotted against $e_1/d \cos\theta$ in Figures 1 to 10. From these figures there has been estimated the resistance at

3. The Thompson coefficient (F) is a measure of the ballistic efficiency of armor and is obtainable from the following:

$$F^2 = \frac{m V^2 \cos^2\theta}{e\, d^2}$$

where m is the weight of the projectile in pounds, V is the limit velocity in feet-per-second, θ is the angle of obliquity from the normal, e is the thickness of the plate in feet and d is the diameter of the projectile (core) in feet.

For the purpose of comparing the efficiency of materials of different density with that of steel on the basis of protection afforded per unit-weight used to protect a unit of area perpendicular to the line of fire e_1 may be substituted for e in this equation e_1 being that thickness of steel which is equivalent in weight to the subject thickness (e) of the material whose efficiency is being evaluated. In this report $e_1 = \frac{e}{4.4}$ for Dowmetal;

$e_1 = \frac{e}{2.8}$ for duralumin;

various obliquities of a thickness of Dowmetal equivalent in weight-per-unit-surface-area to a thickness of steel equal to the diameter of the attacking projectile (core), and these values have been listed in Table XI and plotted in Figure 11 against typical values for other armor materials.

It will be noted that over the range of obliquities where data is available, the resistance of Dowmetal is greater on a weight-for-weight basis than that of non-magnetic steel armor. However, the inherent spalling tendency characteristic of Dowmetal in this condition militates against its substitution for austenitic steel in installations requiring armor with non-magnetic properties. Duralumin affords much greater resistance with less tendency toward spalling and is thus a more favorable substitute.

In the earlier report calculations of the F function were based on the presumption that the nominal obliquities were accurate. As a result of these calculations it was concluded that the value of that figure of merit, substantially constant over a wide range of obliquity, apparently fell off at obliquities greater than 60°. Precise measurement of the obliquities, however, discloses that the nominal obliquities were not accurate and in the case of the assumed 75° obliquity, the angle at which the testing was actually performed was 69°27'. Recalculation of the Thompson Coefficient on the basis of the corrected values resulted in substantial constancy of their values throughout the entire range of obliquities observed.

Thus the formula: $$Vn = \frac{1535\,(e_1/d)^{.5}}{\cos\theta}$$

considered in the previous work to be applicable only up to 60° now appears to be valid over the entire range of observation (0° to 70°).

TABLE I

Summary of Results of Ballistic Tests of Dowmetal (Type FS)

at Normal Incidence

(See also Figure 1)

Cal.	m/d^3	θ	V_n	e	e_1	e_1/d	$e_1/d \cos \theta$	F	Data Source
.50	1275	0°	1230	1.110	.255	.595	.595	56,900	W.A. - R2455
.50	1275	0°	1218	1.118	.257	.600	.600	56,100	W.A. - R2415
.30	1355	0°	1307	.741	.170	.691	.691	57,900	W.A. - R2420
.50	1275	0°	1307	1.305	.300	.700	.700	55,800	W.A. - R2414
.50	1275	0°	1311	1.313	.301	.702	.702	55,900	W.A. - R2454
.30	1355	0°	1325	.766	.176	.715	.715	57,700	W.A. - R2439
.50	1275	0°	1433	1.495	.343	.800	.800	57,200	W.A. - R2413
.50	1275	0°	1415	1.499	.344	.803	.803	56,400	W.A. - R2453
.30	1355	0°	1541	.998	.229	.931	.931	58,800	W.A. - R2419
.30	1355	0°	1605	1.110	.255	1.037	1.037	58,000	W.A. - R2438
.30	1355	0°	1598	1.118	.257	1.045	1.045	57,500	W.A. - R2418
.30	1355	0°	1794	1.305	.300	1.220	1.220	59,800	W.A. - R2419
.30	1355	0°	1793	1.313	.301	1.224	1.224	59,700	W.A. - R2437
.30	1355	0°	1895	1.495	.343	1.394	1.394	59,100	W.A. - R2416
.30	1355	0°	1820	1.499	.344	1.398	1.398	56,700	W.A. - R2436

TABLE II

Summary of Results of Ballistic Tests of Dowmetal (Type FS)

at 32° Obliquity

(See also Figure 2)

Cal.	m/d^3	θ	V_n	e	e_1	e_1/d	$e_1/d \cos\theta$	F	Data Source
.50	1275	32°	1154	.766	.176	.411	.485	54,400	W.A. - R2405
.50	1275	32°	1273	.998	.229	.534	.630	52,800	W.A. - R2452
.30	1355	32°	1343	.635	.146	.593	.700	54,500	W.A. - R2413
.50	1275	32°	1371	1.110	.255	.595	.702	53,900	W.A. - R2411
.50	1275	32°	1392	1.118	.257	.600	.708	54,400	W.A. - R2403
.50	1275	32°	1363	1.118	.257	.600	.708	53,300	W.A. - R2451
.30	1355	32°	1352	.675	.155	.630	.742	53,200	W.A. - R2412
.30	1355	32°	1371	.741	.170	.691	.815	51,500	W.A. - R2404
.50	1275	32°	1426	1.305	.300	.700	.825	51,600	W.A. - R2450
.50	1275	32°	1395	1.313	.301	.702	.828	50,400	W.A. - R2402
.30	1355	32°	1495	.766	.176	.715	.844	55,100	W.A. - R2410
.50	1275	32°	1511	1.499	.344	.803	.947	51,000	W.A. - R2401
.30	1355	32°	1656	.998	.229	.931	1.098	53,600	W.A. - R2446
.30	1355	32°	1776	1.110	.255	1.037	1.222	54,400	W.A. - R2409
.30	1355	32°	1832	1.118	.257	1.045	1.233	55,900	W.A. - R2408
.30	1355	32°	1989	1.305	.300	1.220	1.439	56,200	W.A. - R2445
.30	1355	32°	2084	1.313	.301	1.224	1.443	58,800	W.A. - R2407
.30	1355	32°	2124	1.499	.344	1.398	1.648	56,100	W.A. - R2406

TABLE III

Summary of Results of Ballistic Tests of Dowmetal (Type FS)

at 45° Obliquity

(See also Figure 3)

Cal.	m/d3	θ	V_n	e	e1	e1/d	e1/d cos θ	F	Data Source
20 MM.	1295	45°	1100	1.118	.257	.328	.464	48,900	W.A. - R2377
20 MM.	1295	45°	1250	1.313	.301	.384	.543	51,300	W.A. - R2378
.50	1275	45°	1334	.741	.170	.397	.561	53,500	W.A. - R2392
.30	1355	45°	1364	.425	.098	.398	.563	56,300	W.A. - R2400
20 MM.	1295	45°	1397	1.499	.344	.439	.621	53,600	W.A. - R2379
.30	1355	45°	1536	.635	.146	.593	.839	51,900	W.A. - R2399
.50	1275	45°	1744	1.110	.255	.595	.841	57,100	W.A. - R2391
.50	1275	45°	1763	1.118	.257	.600	.849	57,400	W.A. - R2390
.30	1355	45°	1675	.675	.155	.630	.891	54,900	W.A. - R2398
.50	1275	45°	1949	1.305	.300	.700	.990	58,800	W.A. - R2389
.30	1355	45°	1704	.766	.176	.715	1.011	52,500	W.A. - R2397
.50	1275	45°	1903	1.499	.344	.803	1.136	53,600	W.A. - R2384
.30	1355	45°	2149	1.110	.255	1.037	1.467	54,900	W.A. - R2396
.30	1355	45°	2108	1.118	.257	1.045	1.478	53,700	W.A. - R2395,R2448
.30	1355	45°	2614	1.313	.301	1.224	1.731	61,500	W.A. - R2394
.30	1355	45°	2477	1.499	.344	1.398	1.977	54,500	W.A. - R2393

TABLE IV

Summary of Results of Ballistic Tests of Dowmetal (Type FS)

at 59° Ol iquity

(See also Figure 4)

Cal.	m/d^3	θ	V_n	e	e_1	e_1/d	$e_1/d\cos\theta$	F	Data Source
20 MM.	1295	59°	1200	.675	.155	.198	.384	50,000	W.A. - R2376
.50	1275	59°	1367	.425	.098	.229	.445	52,500	W.A. - R2353
20 MM.	1295	59°	1729	.998	.229	.292	.567	59,300	W.A. - R2369
20 MM.	1295	59°	1716	1.118	.257	.328	.637	55,500	W.A. - R2375
.50	1275	59°	1696	.675	.155	.362	.703	51,800	W.A. - R2354
20 MM.	1295	59°	1994	1.305	.300	.383	.744	59,700	W.A. - R2374
.50	1275	59°	1938	.741	.170	.397	.771	56,600	W.A. - R2355
.30	1355	59°	1933	.425	.098	.398	.773	58,100	W.A. - R2353
20 MM.	1295	59°	1936	1.495	.343	.438	.850	54,300	W.A. - R2350
.50	1275	59°	2377	.998	.229	.534	1.037	59,800	W.A. - R2352
.50	1275	59°	2177	1.118	.257	.600	1.165	51,700	W.A. - R2380
.30	1355	59°	2393	.675	.155	.630	1.223	57,200	W.A. - R2354
.50	1275	59°	2702	1.313	.301	.702	1.363	59,300	W.A. - R2381
.30	1355	59°	2632	.766	.176	.715	1.388	59,000	W.A. - R2383
.50	1275	59°	2810	1.495	.343	.800	1.553	57,800	W.A. - R2351
.30	1355	59°	2913	1.110	.255	1.037	2.013	54,200	W.A. - R2382

TABLE V

Summary of Results of Ballistic Tests of Dowmetal (Type FS)

at 69°27' Obliquity

(See also Figure 5)

Cal.	m/d^3	θ	V_n	e	e_1	e_1/d	$e_1/d \cos \theta$	F	Data Source
20 MM.	1295	69°27'	1298	.425	.098	.125	.356	46,400	W.A. - R2360
20 MM.	1295	69°27'	1748	.741	.170	.217	.618	47,500	W.A. - R2356
.50	1275	69°27'	1990	.425	.098	.229	.653	52,100	W.A. - R2348
20 MM.	1295	69°27'	2389	.998	.229	.292	.832	55,900	W.A. - R2368
.50	1275	69°27'	2541	.635	.146	.341	.972	54,500	W.A. - R2346
.50	1275	69°27'	2441	.675	.155	.362	1.032	50,900	W.A. - R2347
.30	1355	69°27'	2787	.425	.098	.398	1.134	57,100	W.A. - R2348
.50	1275	69°27'	2643	.766	.176	.411	1.171	51,700	W.A. - R2358

TABLE VI

Summary of Results of Ballistic Tests of Dowmetal (Type J-1)

at 0° Obliquity

(See also Figure 6)

Cal.	m/d3	O	Vn	e	e^1	e1/d	e1/d cos θ	F
.50	1275	0°	1188	1.122	.2550	.5951	.5951	55000
.50	1275	0°	1242	1.137	.2584	.6030	.6030	57100
.50	1275	0°	1384	1.515	.3443	.8035	.8035	55100
.50	1275	0°	1448	1.518	.3450	.8050	.8059	57600
.30	1355	0°	1660	1.138	.2586	1.0513	1.0513	59600
.30	1355	0°	1735	1.142	.2595	1.0550	1.0550	62200

TABLE VII

Summary of Results of Ballistic Tests of Downetal (Type J-1)

at 32° Obliquity

(See also Figure 7)

Cal.	n/d3	θ	Vn	e	e1	e1/d	e1/d cos θ	F
.50	1275	32°	1037	.755	.1716	.4004	.4721	49600
.50	1275	32°	1316	1.122	.2550	.5951	.7017	51700
.50	1275	32°	1379	1.137	.2584	.6030	.7110	53400
.30	1355	32°	1406	.755	.1716	.6976	.8226	52600
.50	1275	32°	1556	1.515	.3443	.8035	.9463	52600
.50	1275	32°	1604	1.518	.3450	.8050	.9492	54100
.30	1355	32°	1887	1.138	.2586	1.0513	1.2397	57600
.30	1355	32°	1908	1.142	.2595	1.0550	1.2440	58000

TABLE VIII

Summary of Results of Ballistic Tests of Dowmetal (Type J-1)

at 45° Obliquity

(See also Figure 8)

Cal.	m/d3	θ	Vn	e	e1	e1/d	e1/d cos θ	F
.50	1275	45°	1064	.496	.1127	.2630	.3719	52400
.50	1275	45°	1097	.506	.1150	.2683	.3794	53500
.50	1275	45°	1148	.570	.1295	.3023	.4275	52700
.50	1275	45°	1164	.570	.1295	.3023	.4275	53500
.30	1355	45°	1216	.376	.0855	.3473	.4912	53700
.50	1275	45°	1340	.755	.1716	.4004	.5662	53500
.50	1275	45°	1757	1.122	.2550	.5951	.8416	57500
.50	1275	45°	1739	1.137	.2584	.6030	.8528	56500
.30	1355	45°	1670	.755	.1716	.6976	.9866	52000
.50	1275	45°	1949	1.515	.3443	.8035	1.1363	54900
.50	1275	45°	2039	1.518	.3450	.8050	1.1384	57400
.30	1355	45°	2289	1.138	.2586	1.0513	1.4868	58100
.30	1355	45°	2329	1.142	.2595	1.0550	1.4920	59000

TABLE IX

Summary of Results of Ballistic Tests of Dowmetal (Type J-1)

at 59° Obliquity

(See also Figure 9)

Cal.	m/d^3	θ	Vn	e	e_1	e_1/d	$e_1/d \cos θ$	F
.50	1275	59°	1580	.496	.1127	.2630	.5106	56700
.50	1275	59°	1707	.506	.1150	.2683	.5209	60600
.50	1275	59°	1669	.570	.1295	.3023	.5868	55800
.50	1275	59°	1755	.570	.1295	.3023	.5869	58700
.30	1355	59°	1839	.376	.0855	.3473	.6745	59200
.50	1275	59°	1912	.755	.1716	.4004	.7774	55300
.50	1275	59°	2382	1.122	.2550	.5951	1.1554	56800
.50	1275	59°	2593	1.137	.2584	.6030	1.1708	61400
.50	1275	59°	2510	1.142	.2595	.6057	1.1760	59300
.30	1355	59°	2648	.755	.1716	.6976	1.3545	60100
.50	1275	59°	2647	1.515	.3443	.8035	1.5601	54300
.50	1275	59°	2932	1.518	.3450	.8050	1.5632	60100
.30	1355	59°	2934	1.138	.2586	1.0513	2.0412	54300
.30	1355	[illegible]	3041	1.142	.2595	1.0550	2.0484	[illegible]

TABLE X

Summary of Results of Ballistic Tests of Dowmetal (Type J-1)

at 69°27' Obliquity

(See also Figure 10)

Cal.	m/d^3	θ	Vn	e	e_1	e_1/d	$e_1/d \cos \theta$	F
.50	1275	69°27'	2057	.496	.1127	.2630	.7492	50300
.50	1275	69°27'	2392	.506	.1150	.2683	.7643	57900
.50	1275	69°27'	2318	.570	.1295	.3023	.8612	52900
.50	1275	69°27'	2329	.570	.1295	.3023	.8612	53100
.30	1355	69°27'	2261	.376	.0855	.3474	.9897	57900
.50	1275	69°27'	2919	.755	.1716	.4004	1.1407	57900

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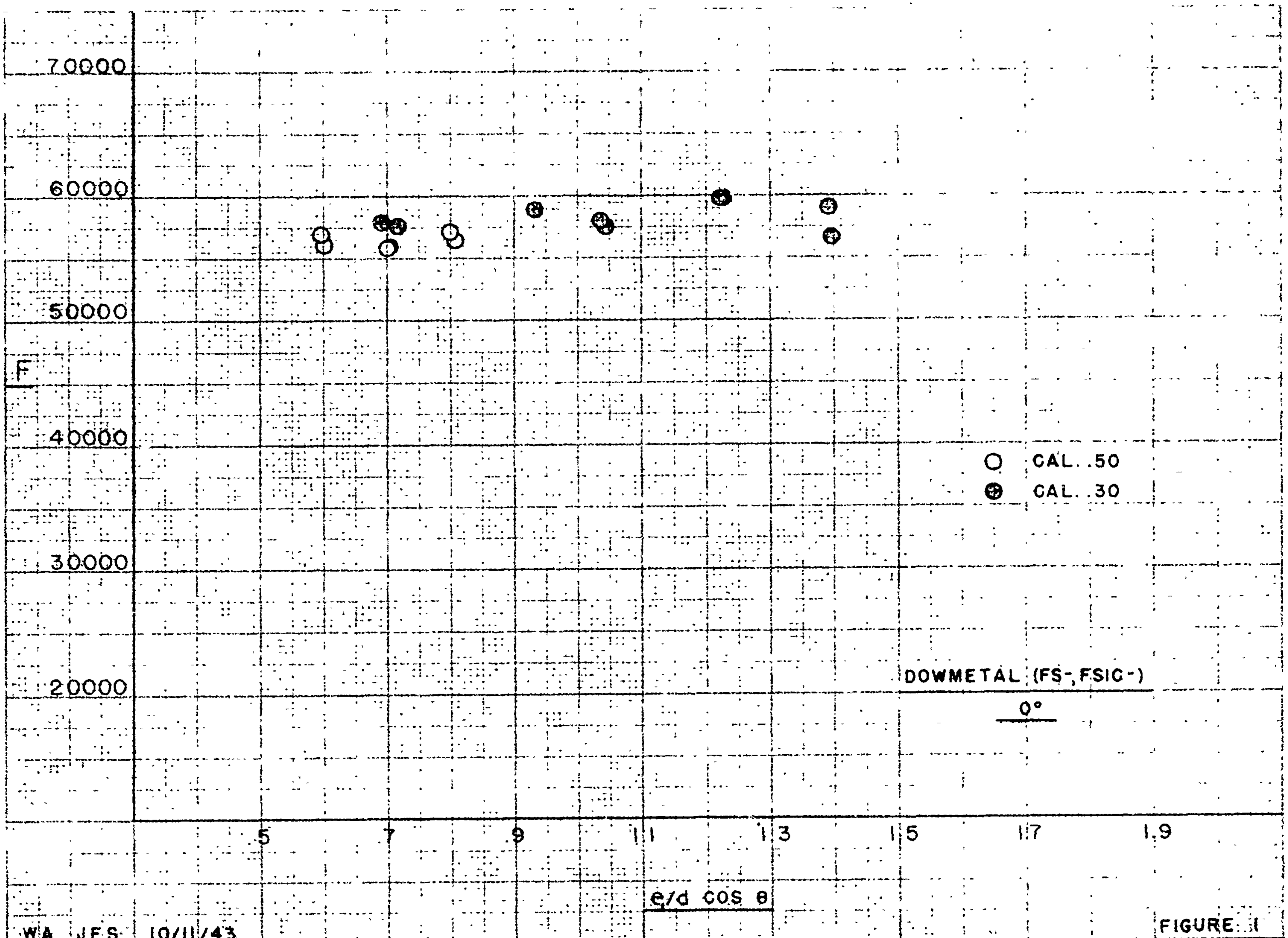
TABLE XI

Navy Ballistic Limits (Estimated) at Various Obliquities of Different Armor Materials Equivalent on a Weight-for-Weight Basis to Steel Whose Thickness Equals the Diameter of the Attacking Projectile (Core)

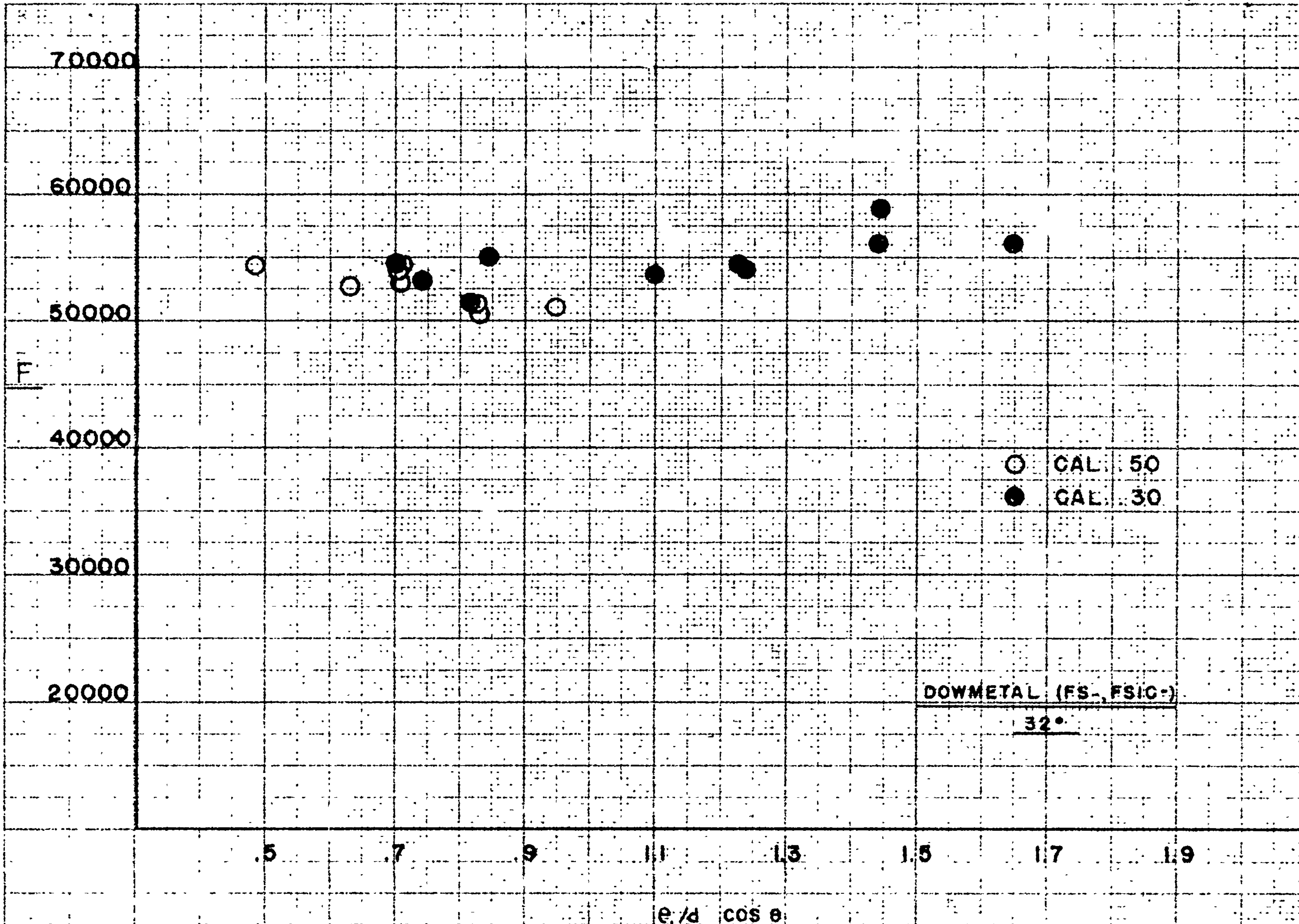
(See also Figure 11)

	0°	30°	45°	60°
Face-Hardened Steel	2130	2390	2870	3920
Homogeneous Steel (BHN 340-360)	1650	2040	2670	3530
Non-Magnetic Steel (Spec. ANOS-3)	1300	1725	—	—
Duralumin (24ST)	1820	1940	2610	4025
Dowmetal (FS)	1600	1780	2170	3045



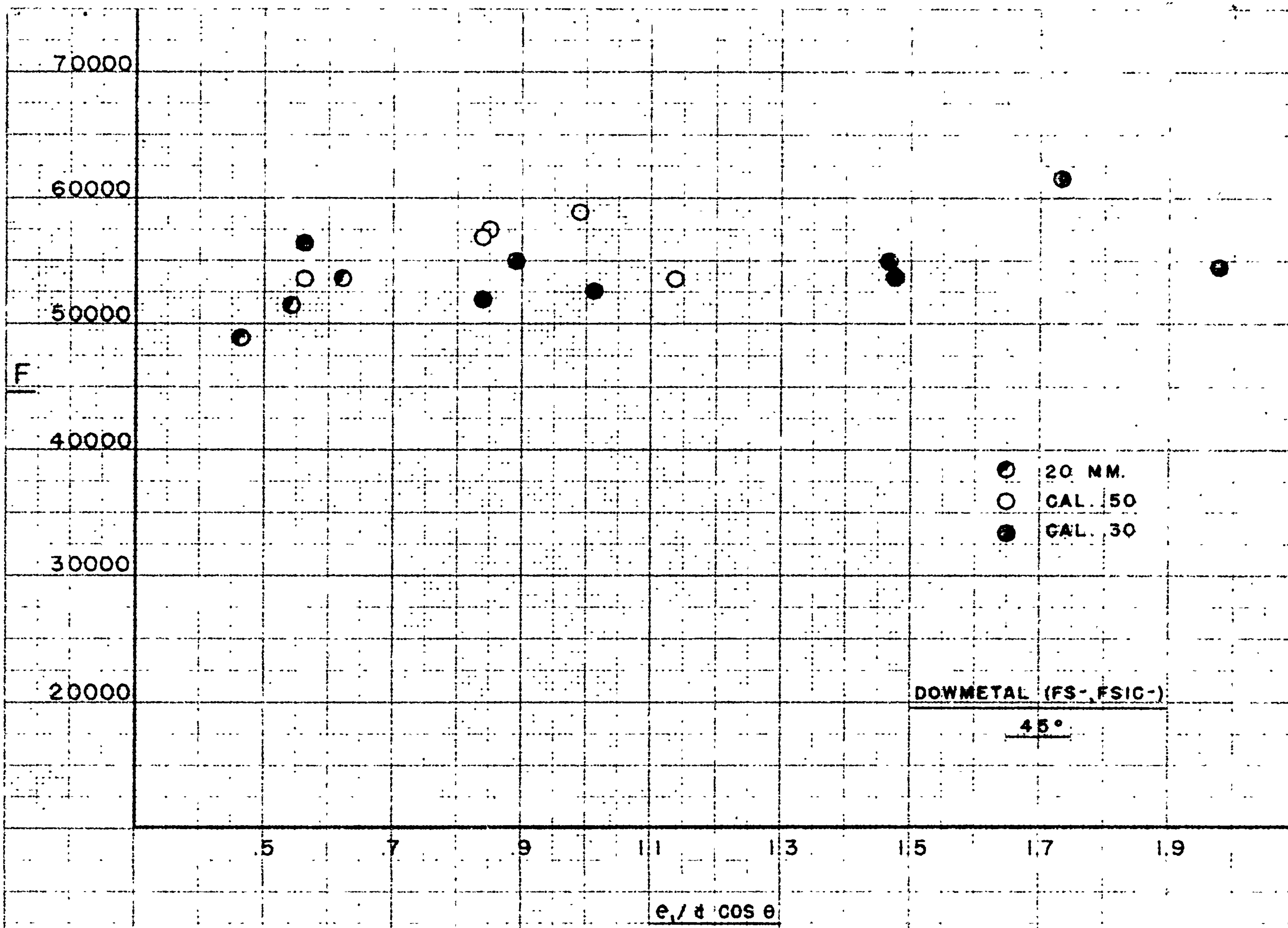
70000
60000
50000
40000
30000
20000
F
.5
.7
.9
1.1
1.3
1.5
1.7
1.9
e/d COS θ
CAL. .50
CAL. .30
DOWMETAL (FS-, FSIC-)
0°
W.A. J.E.S. 10/11/43

FIGURE I



70000
60000
50000
40000
30000
20000
F
.5
.7
.9
1.1
1.3
1.5
1.7
1.9
e/d cos θ
CAL .50
CAL .30
DOWMETAL (FS-, FSIC-)
32°

FIGURE 2



70000
60000
50000
40000
30000
20000
F
.5
.7
.9
1.1
1.3
1.5
1.7
1.9
e,/d COS θ
20 MM.
CAL. 50
CAL. 30
DOWMETAL (FS-, FSIC-)
45°
WA JFS 10/11/43

FIGURE 3

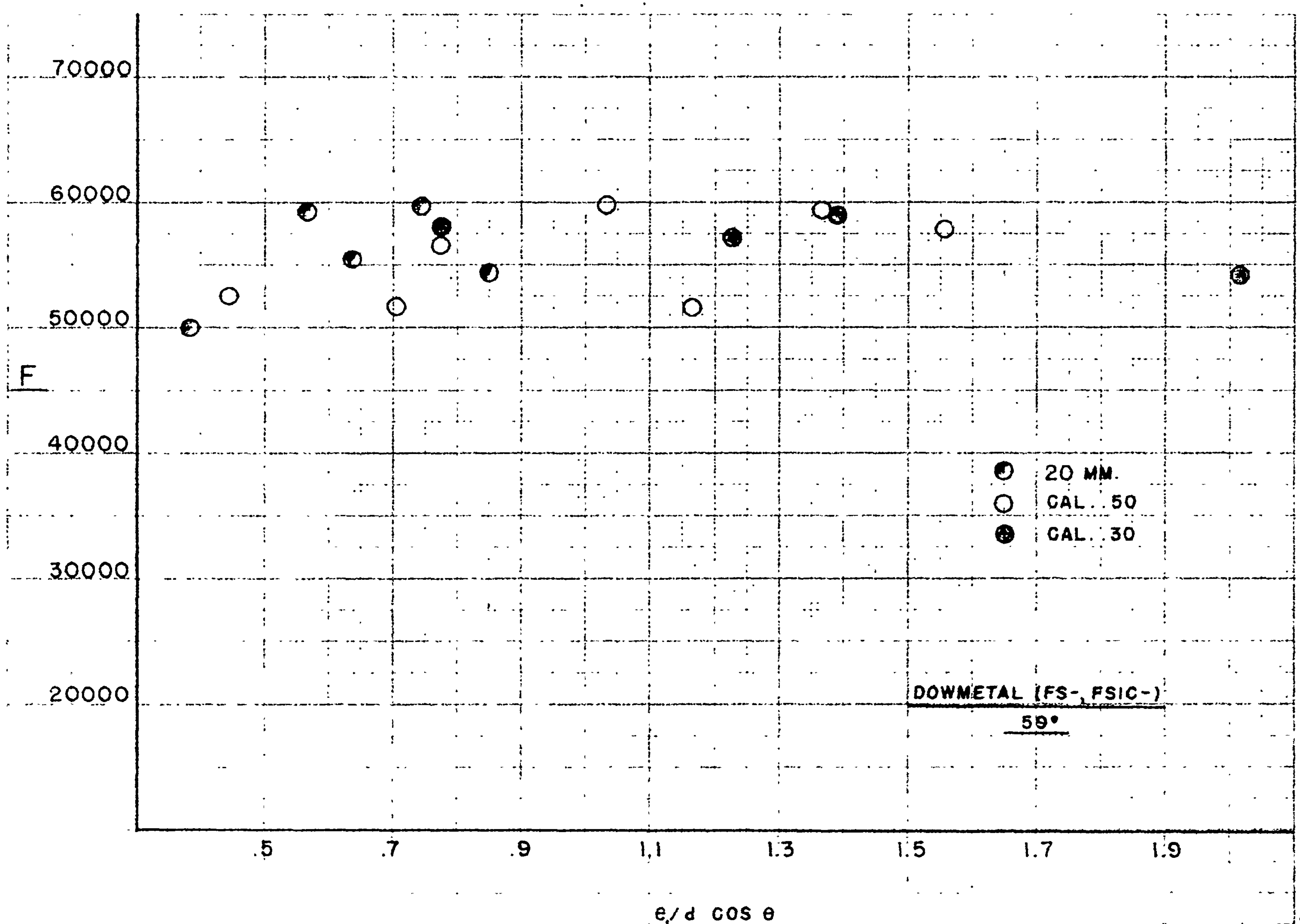

70000
60000
50000
40000
30000
20000
F
.5
.7
.9
1.1
1.3
1.5
1.7
1.9
e/d COS θ
20 MM.
CAL. .50
CAL. .30
DOWMETAL (FS-, FSIC-)
59°

FIGURE 4

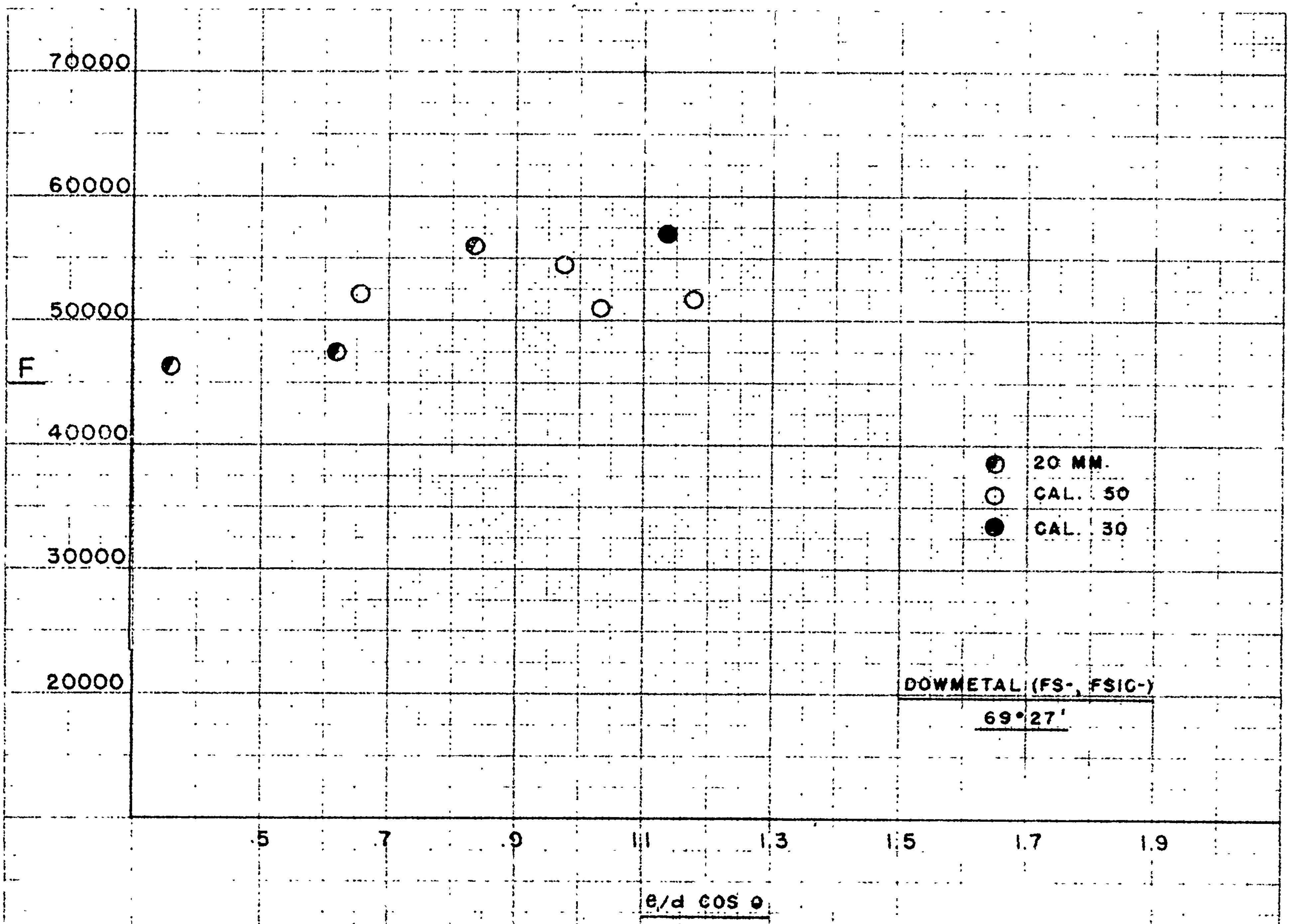

F
70000
60000
50000
40000
30000
20000
.5
.7
.9
1.1
1.3
1.5
1.7
1.9
e/d COS θ
20 MM.
CAL. 50
CAL. 30
DOWMETAL (FS-, FSIC-)
69°27'

FIGURE 5

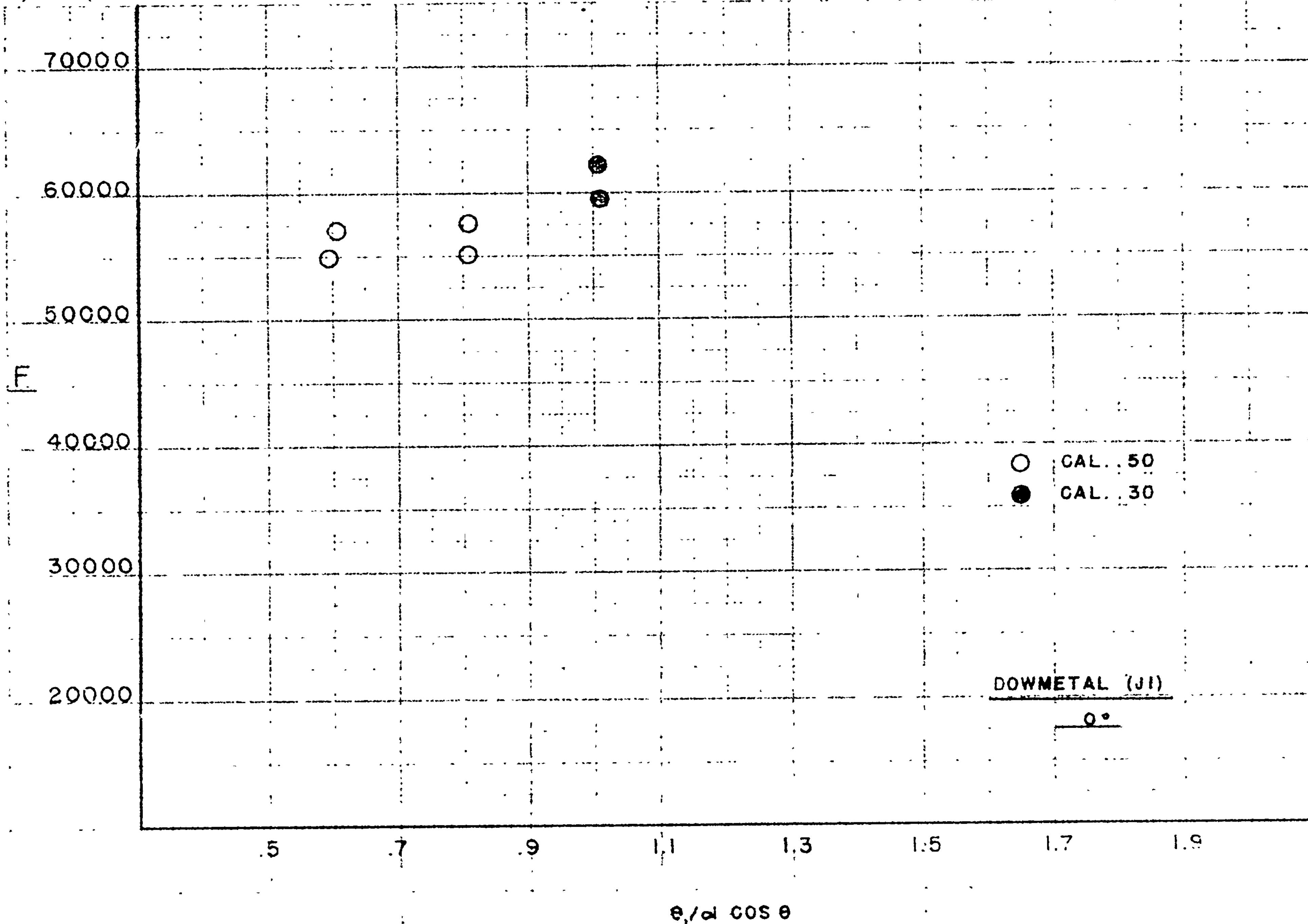
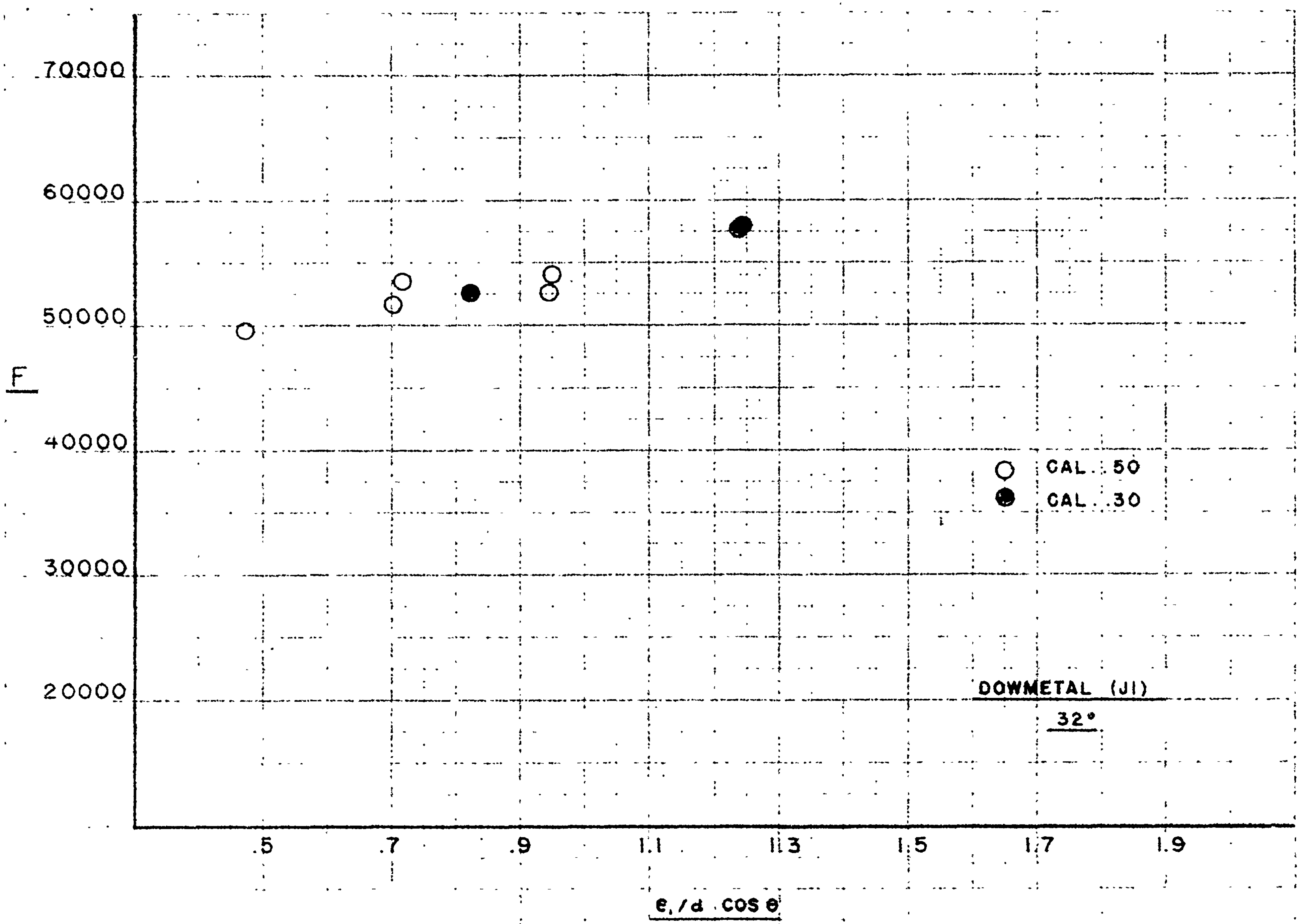
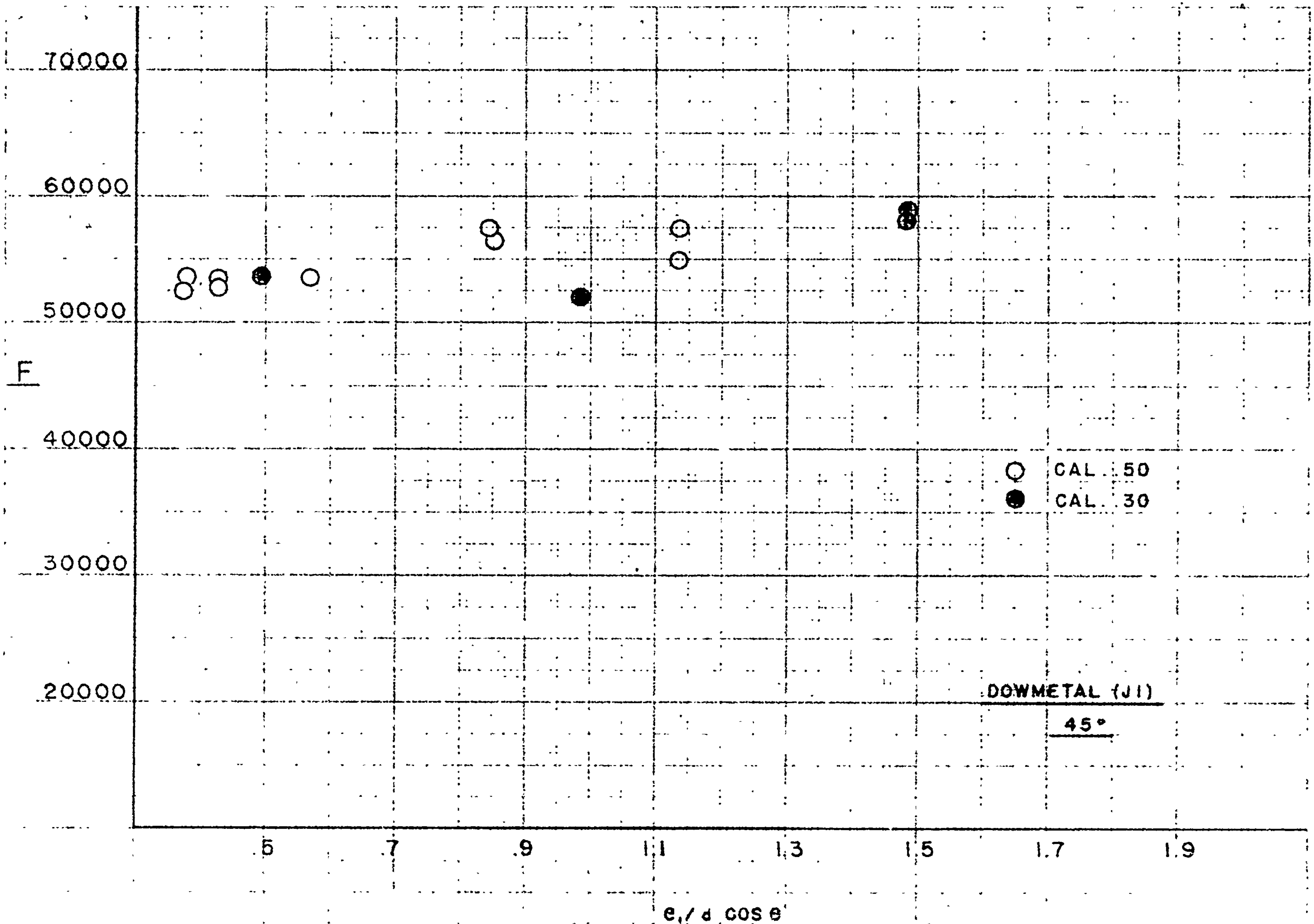

70000
60000
50000
F
40000
30000
20000
.5
.7
.9
1.1
1.3
1.5
1.7
1.9
e/d cos θ
CAL. .50
CAL. .30
DOWMETAL (J1)
0°

FIGURE 6



70000
60000
50000
40000
30000
20000
F
.5
.7
.9
1.1
1.3
1.5
1.7
1.9
e, /d COS θ
CAL. 50
CAL. 30
DOWMETAL (JI)
32°

FIGURE 7



70000
60000
50000
40000
30000
20000
F
.5
.7
.9
1.1
1.3
1.5
1.7
1.9
$e_1/d \cos\theta$
CAL. .50
CAL. .30
DOWMETAL (J1)
45°

FIGURE 8

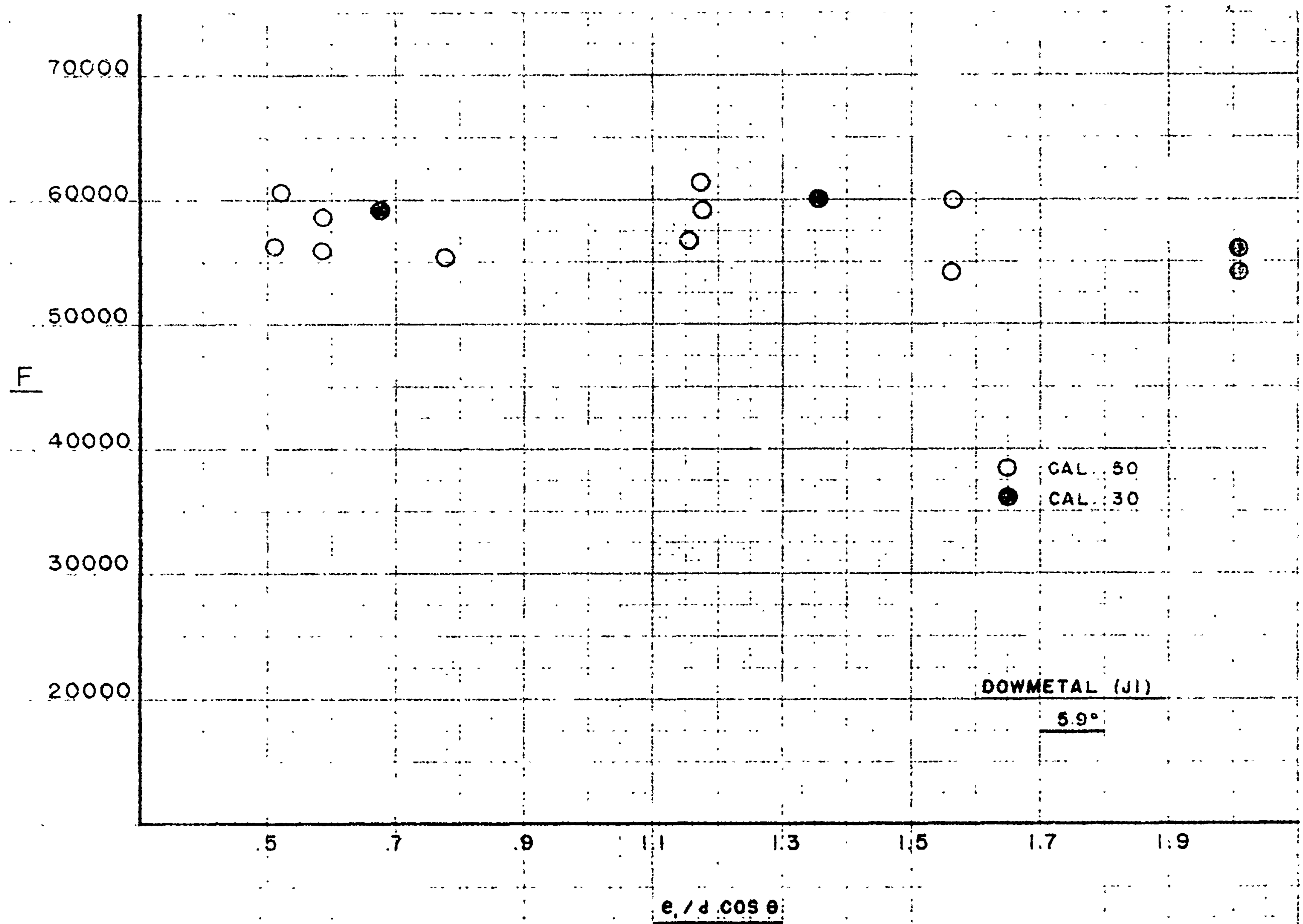

F
70000
60000
50000
40000
30000
20000
.5
.7
.9
1.1
1.3
1.5
1.7
1.9
e, / d COS θ
CAL. 50
CAL. 30
DOWMETAL (J1)
5.9°

FIGURE 9

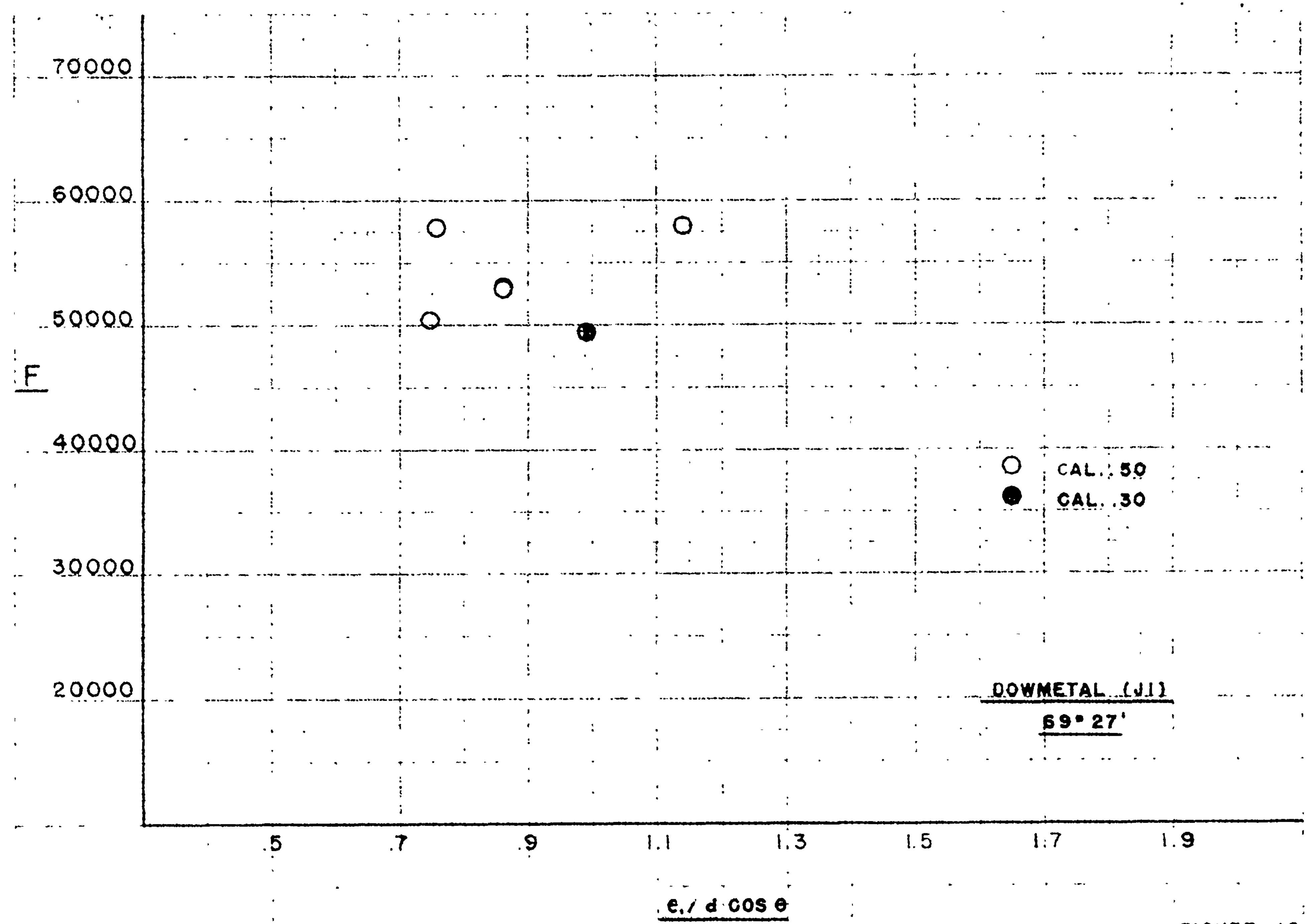

70000
60000
50000
40000
30000
20000
F
.5
.7
.9
1.1
1.3
1.5
1.7
1.9
e,/ d COS θ
CAL. .50
CAL. .30
DOWMETAL (J1)
69° 27'

FIGURE 10

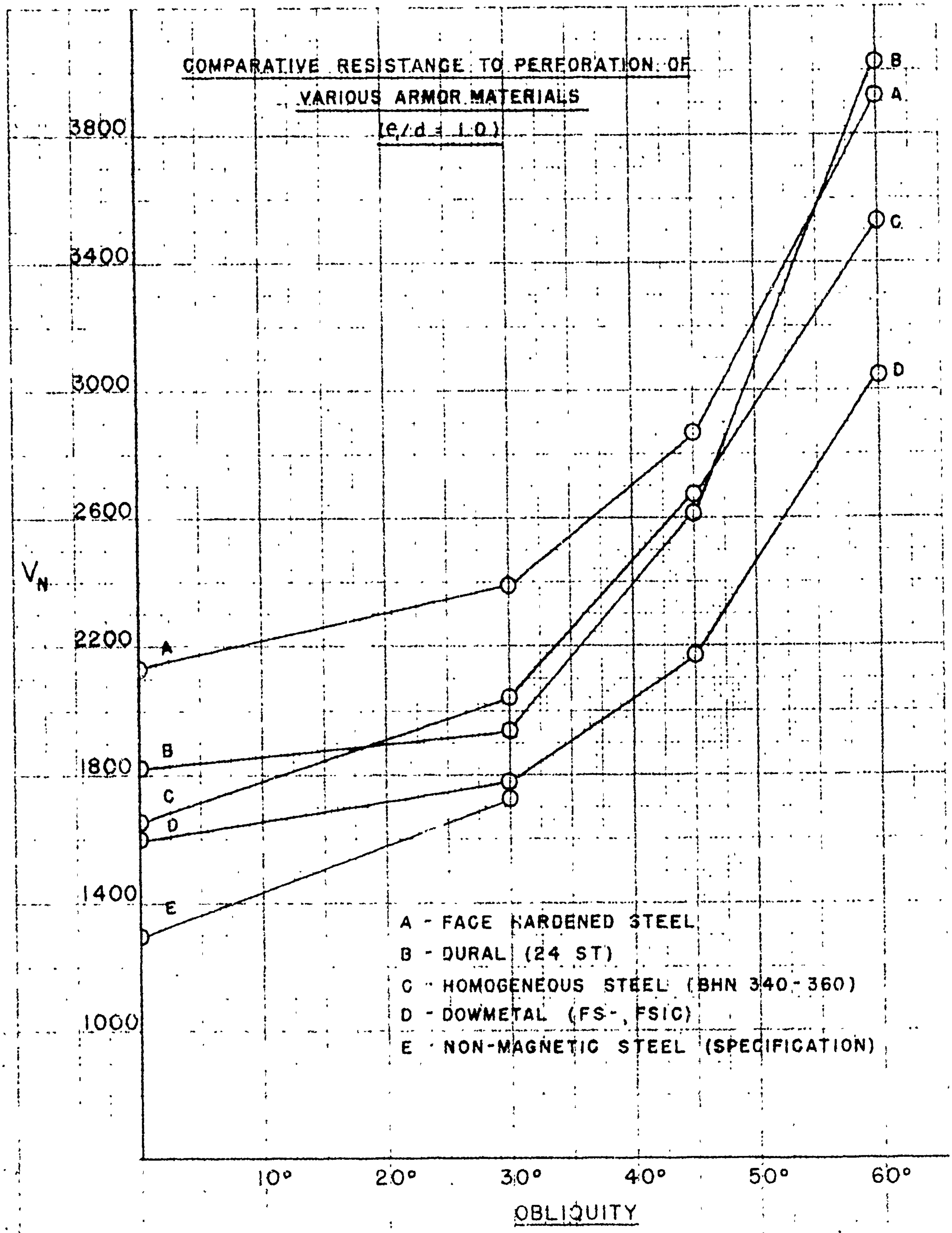


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FIGURE 11