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A Summary of the Characteristics of Ballistic Interplanetary Trajectories, 1962-1977

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ABSTRACT

Within the next decade, considerable national effort will be expended in exploring neighboring planets. For the most part, this exploration will be accomplished with unmanned probes utilizing ballistic trajectories. Ultimately, electric propulsion systems will be used. In the interim, a knowledge of the characteristics of ballistic trajectories will be of considerable value in planning and designing interplanetary missions. This report presents these characteristics (flight times, launch dates, injection energy requirements, etc.) for Mercury, Venus, Mars, and Jupiter trajectories as far ahead as 1977. Only selected trajectories to Mercury and Jupiter are given, the primary emphasis being placed on Venus and Mars trajectories.

I. INTRODUCTION

The planning and design of a space mission is an extremely complex task requiring information from many sources. Some of the primary information required concerns the probe's flight path. A study of feasible trajectories reveals pertinent items as launch dates, injection energy requirements, flight times, and communication distances.

The purpose of this report is to present, in summary form, many of these items as a ready reference for mission planners, those engaged in the early design phase, and other interested persons. A much more extensive and detailed presentation of the same material is given in Ref. 1.

Given below, mostly in tabular form, are the key characteristics of Earth to Mars trajectories from 1962 to 1977, Earth to Venus trajectories from 1962 to 1970, Earth to Mercury trajectories from October 1967 to January 1969, and Earth to Jupiter trajectories from December 1969 to February 1970.

II. GENERAL PROPERTIES OF INTERPLANETARY TRAJECTORIES

A. Launch Opportunities

It is theoretically possible to travel to a target planet on a ballistic trajectory at any time, no matter what the day or year (Ref. 2). In fact, theory shows that there are up to six[1] ballistic paths per launch date (for a given injection energy) from Earth to the target planet for trips of less than one revolution around the Sun. In reality, however, it is possible to launch at only small intervals (1 to 2 months), when the relative positions of the Earth and target planet are such that the energy requirements for ballistic transfer can be reasonably achieved by present boost vehicles. These intervals occur once every synodic period of the planet. (A synodic period is the time between two successive heliocentric conjunctions in celestial longitude.) That is, they are only separated in time by an interval very nearly equal to the synodic period. Thus, favorable launch opportunities may occur every 19.2 months for Venus, every 25.6 months for Mars, every 13 months for Jupiter, and every 3.8 months for Mercury.[2]

B. Classification of Trajectories (see Ref. 3)

As previously stated, there are up to six trajectories per launch date (for a given injection energy) to the target planet for trips of less than one revolution around the Sun. For multiple revolutions there are an infinite number of trips, but we shall treat these as impractical at this writing, and consider only those which take less than one revolution. Within this boundary, there are usually two trajectories, called Type I herein, which travel less than halfway around the Sun. The other two trajectories, called Type II, travel between half and one revolution around the Sun. Because of the greater distance traveled, Type II trajectories have greater flight times than Type I. The faster (shorter flight time) of the two trajectories of each type are called Class I, and the slower are called Class II. Evidently, then, Type I–Class I trajectories have the shortest flight times and exhibit other properties[3] which make them most desirable to employ in interplanetary missions. The existence of two additional Type I trajectories over small intervals has only recently been discovered, yielding up to six trajectories per launch date with the same injection energy. Whether two additional Type II trajectories exist over small intervals is not known at this time. Although the author has never observed them, it would not be surprising if they were found.

The classification of trajectories as given above may be better appreciated by reference to Fig. 1, which is a plot of Venus 1965 flight time vs launch date, with injection energy as a parameter. Here we observe the closed contours of the Type I and II trajectories and, in addition, two small additional loops within the Type I loops occurring, over a small interval, about December 10, 1965. Further investigation of this plot shows that for each energy there are definite fixed intervals (increasing with energy) over which a vehicle may be launched. Also, there are three days on which minimum energy is required for each trajectory type. These days are November 12 for Type I, November 10 for Type II, and December 10 for the small loop which we shall call Type IA.

[1]The existence of six paths is a rare occurrence and is possible only for short (several days) intervals; generally, there are four paths. Actually, there may be even more than six paths, but only a very detailed study would reveal this.

[2]Launchings to Mercury are not desirable every 3.8 months because of rather broad variations in injection energy requirements which are caused by its more elliptical and inclined orbit.

[3]Such as lower error sensitivity and small communication distances.

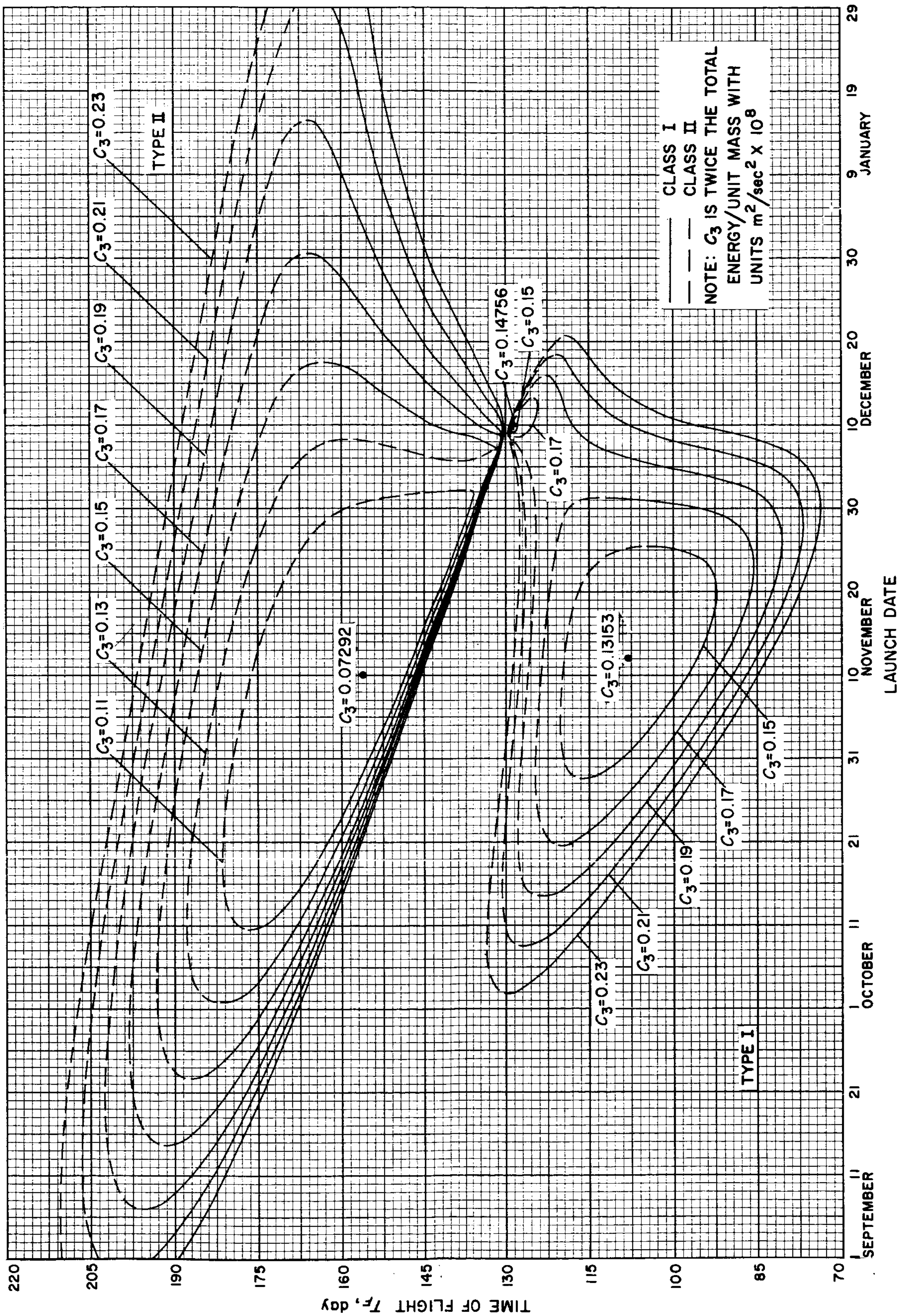

Fig. 1. Venus 1965: Time of flight vs launch date

III. MINIMUM ENERGY TRANSFERS

The existence of minimum energy transfers within the realistic launch intervals provides useful information on the lower bounds of energy requirements and gives a first approximation of launch dates, flight times, and communication distances. This information, relative to Venus, Mars, Mercury, and Jupiter, is given in Table 1. Inspection of this table reveals several interesting phenomena. First, we note the cyclic recurrence of trajectory characteristics for each planet. For example, the characteristics of the 1962 Venus trajectories are very similar to the 1970 Venus trajectories. Less marked similarities exist for Mars in 1962 and 1977 and Mercury in November 1967 and November 1968. These similarities reflect the approximate cyclic recurrence of the same absolute space-fixed geom-

Table 1. Characteristics of minimum–energy transfer

Planet	Trajectory Type	Launch date	Flight time days	Geocentric injection energy[a] $m^2/s^2 \times 10^8$	Heliocentric central angle[b] deg	Sun–planet distance at arrival 10^6 km	Earth–planet distance at arrival 10^6 km	Celestial latitude of planet at arrival deg
Venus	I	8-23-62	114	0.087	132.4	107.5	58	1.46
	II	9-19-62	166	0.104	234.0	108 2	145	1.53
	I	3-30-64	112	0.123	126.8	108.9	61	−2.93
	II	4-9-64	170	0.081	225.4	107.8	137	−0.698
	I	11-12-65	108	0.132	129.5	107.6	60	3.31
	IA	12-10-65	128	0.148	178.2	108.6	114	0.030
	II	11-10-65	156	0.073	205.3	108.5	112	0.218
	I	6-11-67	142	0.065	175.6	107.7	92	−0.082
	II	5-30-67	156	0.059	190.4	107.7	94	0.110
	I	1-13-69	126	0.077	150.5	108.6	70	−0.393
	II	2-12-69	174	0.125	243.7	108.3	161	−2.59
	I	8-19-70	116	0.085	134.5	107.5	58	1.35
	II	9-16-70	165	0.106	233.6	108.2	145	1.71
Mars	I	10-30-62	232	0.151	158.2	243.5	246	1.06
	I	11-19-64	244	0.090	174.1	231.2	222	−0.047
	I	1-5-67	202	0.091	152.2	221.9	160	−0.833
	I	3-2-69	178	0.088	139.3	209.7	177	−1.75
	I	5-24-71	210	0.079	156	216.6	164	−0.352
	I	7-30-73	192	0.146	141.4	234.2	179	1.16
	I	9-15-75	206	0.187	144.7	247.6	221	1.85
	I	10-19-77	224	0.170	152.9	247.1	244	1.44
Mercury	I	11-23-67	107	0.412	169.6	67.8	130	−0.163
	II	11-7-67	121	0.464	183.7	69.5	130	−0.163
	I	4-4-68	92	0.832	123.3	61.6	108	−6.98
	II	4-12-68	102	0.857	199.3	47.5	168	−0.849
	I	7-30-68	89	1.044	144.2	46.8	130	4.7
	II	7-30-68	109	0.820	244.6	62.0	197	4.25
	I	11-12-68	103	0.448	177.4	67.5	143	0.107
	II	11-2-68	113	0.441	187.4	67.5	143	0.107
Jupiter	I	1-3-70	985	0.753	177.9	778.5	744	0.004
	II	12-30-69	995	0.754	182.5	778.2	757	−0.007

[a]Actually, twice the total energy per unit mass, or vis viva integral.
[b]The heliocentric central angle is the angle subtended at the Sun between the Sun–Earth line at launch time and the Sun–planet line at arrival time.

etry of the Earth and target planet. These cycles, known as metonic[4] cycles, are related to the synodic period. The cycle for Venus is very nearly 8 years or 5 synodic periods. For Mars it is about 15 years or 7 synodic periods. For Mercury it is about 1 year or 3 synodic periods. With varying degrees of approximation, then (least for Venus), the same trajectory characteristics would recur every 8 years for Venus, every 15 years for Mars, and every year for Mercury. Thus, the calculation of all feasible trajectories within each of these cycles would be nearly sufficient to describe the trajectories in succeeding cycles, but with degraded accuracy. This calculation has been done and the extensive results presented in Ref. 1.

[4]Actually, the metonic cycle refers to the 19-year cycle recurrence of the phases of the Moon. We have adopted this title for the present study.

IV. PROPERTIES OF INTERPLANETARY TRAJECTORIES

A close inspection of Table 1 reveals some interesting properties of interplanetary trajectories. First, we note that the minimum energy for Type I transfers to Venus steadily increases from 1962 to 1965, then drops abruptly in 1967. From that point it steadily increases again. The reverse is true for Mars, with the energy steadily decreasing until 1971, then abruptly increasing in 1973. Also, the energy required to reach Venus in 1964-65 is greater than that required to reach Mars in the period 1964-71 for Type I transfers. This result is surprising, but can be explained by observing two key quantities: the celestial latitude and the Sun–planet distance at arrival. Although Venus's orbit is fairly circular (eccentricity = 0.0068) compared to that of Mars (eccentricity = 0.0934), it is more inclined (3.39 deg) than that of Mars (1.85 deg). In 1964–65, the probe encounters Venus when it is relatively far above (or below) the ecliptic, causing the energy requirement to rise. In 1967, however, the probe encounters Venus when it is very nearly in the ecliptic, resulting in a near Hohmann transfer and low energy requirements. Thus, for Venus, energy requirements are closely correlated with the celestial latitude at encounter only, the small variation of Sun–planet distance having little effect. For Mars, the effect of Sun–planet distance is more pronounced. From Table 1, we note that as Sun–planet distance decreases, the energy stays about constant in the interval 1964–69, as the celestial latitude increases. This increase in latitude tends to offset any reduction in energy requirements caused by decreased Sun–planet distance. In 1971, however, both latitude and distance are small, resulting in lower energy requirements. From 1973 on, both quantities increase with a subsequent steep rise in energy.

Similar pronounced energy variations (more than 2 to 1) for Mercury transfers are caused by large variations in celestial latitude and Sun–planet distance. For Jupiter, the Sun–planet distance is the chief cause of high injection energy requirements.

In summary, we see that the position of the planet at arrival, both in distance from the Sun and normal to the ecliptic, is very important in determining energy requirements.

V. LAUNCH PERIODS

Although the properties of minimum energy trajectories provide much useful information, they only put us in the "ballpark." Of some interest is the relationship between launch period[5] and energy requirements. Such a relationship can be derived from a graph of flight time vs launch date as shown in Fig. 2. Here we see that, for a fixed injection energy, there is a definite limited interval over which launching is possible. Or, if a launch interval is chosen, there is a corresponding required injection energy. These energies are given in Tables 2–6 for launch intervals of 15, 30, 45, and 60 days along with their corresponding launch dates. In addition, trajectory parameters such as flight times, communication distances, asymptotic speeds relative to the target planet, and geocentric asymptotic declination are tabulated for each interval. For these parameters, the maximum and minimum values are given for Classes I and II separately. Careful interpretation of these maxima and minima is necessary. They correspond to the largest and smallest values of these parameters under the conditions that the vehicle would be launched within the prescribed launch interval and would have an injection energy lying between the minimum value and the one corresponding to the launch interval. For example, according to Table 2 (Venus Type I trajectories), if a probe is launched in the 15-day interval, August 13–28, 1962, and has an injection energy between $0.087 \times 10^8 m^2/s^2$ (the minimum possible) and $0.090 \times 10^8 m^2/s^2$ (the energy necessary for a 15-day launch interval) it can have, for Class I transfer, maximum and minimum flight times of 123 and 110 days, maximum and minimum communication distances of 59- and 53-million km, maximum and minimum hyperbolic approach speeds to Venus of 5.92 and 5.37 km/sec, and maximum and minimum geocentric asymptotic declinations of -0.3 and -7.9 degrees. Similar boundary values of these parameters for Class II transfers are given also.

The geocentric asymptotic declination is included in Tables 2–6 because it is an important parameter in determining the injection location (Ref. 4) over the Earth's surface. Acceptable values for this parameter lie between -34 and $+34$ deg. Values outside this range result in severe launch restrictions from Cape Canaveral.

As a further aid in determining energy-launch period relationships different from those tabulated above, Fig. 3—19 show curves of injection energy vs launch date for Venus, Mars, Mercury, and Jupiter. By treating the energy as the independent variable in these figures, we may find two launch dates corresponding to a chosen energy (above the minimum energy, of course). The difference between the two launch dates is the permissible launch period for that chosen energy.

[5] Defined as the number of launch days. Launch "window" is the number of launch hours during a launch day.

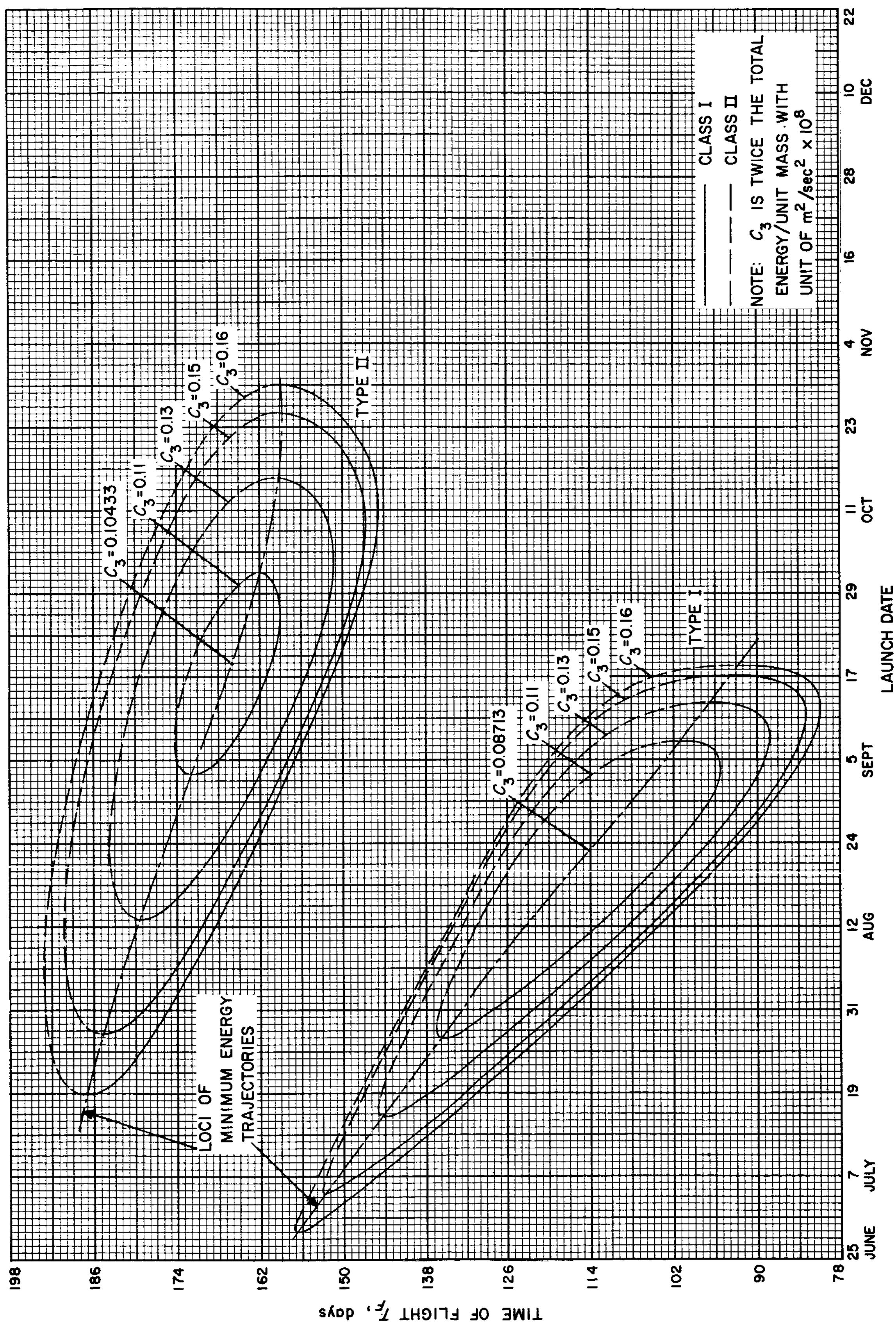

Fig. 2. Venus 1962: Time of flight vs launch date

Table 2. Venus Type I transfer characteristics

Launch dates	Launch period, days	Geocentric injection energy, meters^2/sec^2 × 10^8	Class I trajectories								Class II trajectories							
			Flight time, days		Communication distance, 10^6 km		Planetocentric asymptotic speed, km/sec		Declination of the geocentric asymptote, deg		Flight time, days		Communication distance, 10^6 km		Planetocentric asymptotic speed, km/sec		Declination of the geocentric asymptote, deg	
			Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Aug 13–Aug 28 1962	15	0.09	108	122	54	59	5.40	5.92	−7.8	−0.6	110	123	57	62	5.20	5.58	−1.5	5.9
Aug 4–Sept 3 1962	30	0.0985	101	127	50	59	5.41	6.49	−13.5	−1.7	106	130	56	66	4.98	5.63	0.2	12.6
July 26–Sept 9 1962	45	0.112	94	135	47	57	5.62	7.18	−18.0	−4.2	104	138	53	69	4.78	5.79	−4.1	18.3
July 15–Sept 13 1962	60	0.1295	88	143	45	59	5.36	7.91	−21.4	−2.5	99	145	51	73	4.61	6.03	−5.1	23.0
March 22–April 6 1964	15	0.128	104	115	55	60	6.06	6.82	−3.6	0.7	108	119	60	66	5.39	6.12	−11.1	−5.2
March 14–April 13 1964	30	0.142	96	122	51	59	6.30	7.74	−3.6	5.8	106	125	57	72	4.82	6.50	−17.1	−5.7
March 5–April 19 1964	45	0.1645	88	128	48	60	6.19	8.71	−1.2	9.8	102	132	55	78	4.34	6.79	−22.2	−3.8
Feb 24–April 24 1964	60	0.19475	81	134	46	60	6.30	9.72	0.8	13.0	102	138	52	84	3.98	7.15	−26.5	−3.7
Nov 5–Nov 20 1965	15	0.1370	99	108	54	58	5.05	5.75	9.2	13.7	111	115	60	69	3.73	4.70	13.9	19.0
Oct 27–Nov 26 1965	30	0.1537	91	115	48	63	4.33	6.94	4.9	15.8	111	121	55	81	3.02	5.49	9.6	24.1
Oct 19–Dec 3 1965	45	0.1750	84	121	45	89	2.99	7.92	2.0	16.7	118	126	51	96	2.99	6.03	7.2	27.8
Oct 16–Dec 15 1965	60	0.183	82	123	44	114	2.91	8.23	−17.8	13.3	123	129	51	116	3.18	5.99	−41.1	28.9
June 8–June 23 1967	15	0.0842	128	144	81	91	2.81	3.42	−18.5	9.1	133	146	93	96	2.96	4.90	−16.0	35.9
May 30–June 29 1967	30	0.1065	110	127	60	93	3.31	5.15	−23.7	15.2	127	145	72	98	2.88	5.61	−27.3	44.4
May 21–July 5 1967	45	0.1344	96	132	51	96	3.45	6.96	−27.4	20.0	122	146	61	100	3.13	6.27	−33.7	48.0
May 12–July 11 1967	60	0.1700	86	134	47	88	3.62	8.48	−26.6	11.7	123	146	56	103	3.54	6.82	−38.2	52.0
Jan 4 1969–Jan 19 1969	15	0.0805	119	132	66	69	4.53	4.73	2.2	8.8	123	134	70	74	4.49	4.62	−8.4	−0.4
Dec 27 1968–Jan 26 1969	30	0,0894	111	140	61	68	4.45	5.22	2.5	15.4	119	141	68	78	4.44	4.88	−16.3	3.5
Dec 17 1968–Jan 31 1969	45	0.1035	103	148	56	70	4.26	5.92	−0.9	20.3	113	149	67	82	4.39	5.26	−23.1	3.7
Dec 9 1968–Feb 7 1969	60	0.1315	93	156	51	66	3.63	7.12	2.3	26.2	112	157	66	86	4.10	5.88	−30.6	14.6
Aug 9 1970–Aug 24 1970	15	0.088	109	120	54	58	5.51	5.88	−8.2	−2.8	112	124	59	62	5.17	5.44	1.8	6.3
Aug 1–Aug 31 1970	30	0.0965	102	126	51	58	5.47	6.42	−13.6	−2.7	107	131	57	66	4.98	5.57	1.5	12.4
July 23–Sept 6 1970	45	0.1105	95	134	48	54	5.87	7.13	−18.3	−8.1	109	139	55	70	4.79	5.73	0	18.6
July 12–Sept 10 1970	60	0.1272	89	142	45	58	5.55	7.84	−21.5	−3.9	101	146	53	73	4.63	6.00	−1.6	23.1

Table 3. Venus Type II transfer characteristics

Launch dates	Launch period, days	Geocentric injection energy, meters²/sec² × 10⁸	Class I trajectories								Class II trajectories							
			Flight time, days		Communication distance, 10⁶ km		Planetocentric asymptotic speed, km/sec		Declination of the geocentric asymptote, deg		Flight time, days		Communication distance, 10⁶ km		Planetocentric asymptotic speed, km/sec		Declination of the geocentric asymptote, deg	
			Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Sept 10–Sept 25 1962	15	0.106	162	168	138	149	6.02	6.52	−45.8	−35.6	164	171	140	151	6.12	6.58	−42.8	−34.0
Sept 2–Oct 2 1962	30	0.1103	159	172	132	153	5.78	6.67	−50.6	−32.7	164	174	133	156	5.83	6.84	−47.4	−28.9
Aug 24–Oct 8 1962	45	0.118	155	173	125	159	5.48	6.92	−55.3	−27.4	155	179	130	163	5.69	7.16	−47.6	−23.3
Aug 15–Oct 14 1962	60	0.1275	152	176	118	162	5.17	7.13	−59.0	−23.4	161	183	124	169	5.40	7.45	−49.8	−18.6
March 31–April 15 1964	15	0.0835	165	174	130	139	5.20	5.49	29.8	41.3	168	176	132	142	5.25	5.62	24.6	36.2
March 23–April 22 1964	30	0.090	160	175	124	143	5.06	5.63	25.1	48.7	166	181	130	149	5.22	5.96	17.0	35.9
March 15–April 29 1964	45	0.1007	155	181	119	149	4.92	5.88	18.6	55.4	165	187	124	157	5.02	6.38	10.1	40.9
March 7–May 6 1964	60	0.114	151	185	113	152	4.78	6.08	15.0	60.7	168	191	119	164	4.86	6.84	4.4	43.5
Nov 3–Nov 18 1965	15	0.0761	150	159	108	114	4.18	4.43	−29.4	−18.6	150	163	113	118	4.17	4.27	−17.7	−10.0
Oct 25–Nov 24 1965	30	0.0850	144	163	103	114	4.22	4.76	−39.2	−20.8	147	170	112	126	4.10	4.47	−16.7	−0.8
Oct 16–Nov 30 1965	45	0.0993	138	170	99	113	4.51	5.19	−46.5	−28.1	151	177	107	136	4.31	4.88	−20.9	6.8
Oct 6–Dec 5 1965	60	0.1197	133	175	93	115	4.32	5.68	−52.5	−21.3	159	185	103	149	4.50	5.53	−22.9	13.6
May 23–June 7 1967	15	0.0614	147	160	92	93	3.31	4.02	2.0	19.3	147	161	93	96	3.22	3.66	−3.0	7.3
May 9–June 8 1967	30	0.078	147	171	87	93	3.89	4.88	10.0	34.6	150	176	94	107	2.92	3.73	−18.2	3.4
April 28–June 12 1967	45	0.0978	147	181	83	109	2.98	5.49	−24.7	41.8	166	187	90	122	3.89	4.38	−25.5	9.0
April 21–June 20 1967	60	0.1125	147	183	81	125	3.00	5.88	−28.2	45.7	170	193	91	134	4.01	5.14	−28.9	7.9
Feb 6–Feb 21 1969	15	0.126	170	174	154	168	6.00	6.91	37.0	43.1	172	176	156	168	6.11	6.93	37.0	42.4
Jan 28–Feb 27 1969	30	0.1292	167	175	145	172	5.47	7.13	35.0	45.7	172	179	147	175	5.57	7.33	33.6	44.8
Jan 19–March 5 1969	45	0.1332	165	176	136	177	4.91	7.52	31.7	47.5	170	181	138	179	5.02	7.67	30.8	46.1
Jan 9–March 10 1969	60	0.138	163	176	124	179	4.25	7.64	30.4	48.8	171	184	128	183	4.43	7.95	28.4	46.0
Sept 8–Sept 23 1970	15	0.1075	162	168	138	147	6.04	6.47	−46.4	−38.6	166	171	141	152	6.19	6.66	−42.4	−34.2
Aug 31–Sept 30 1970	30	0.1115	160	171	132	151	5.80	6.64	−50.6	−35.5	165	175	135	157	5.91	6.91	−46.6	−29.6
Aug 22–Oct 6 1970	45	0.1190	156	172	125	159	5.48	6.98	−55.2	−28.4	163	179	131	164	5.75	7.23	−47.1	−24.1
Aug 13–Oct 12 1970	60	0.1276	153	175	119	166	5.17	7.28	−58.4	−22.9	160	183	126	169	5.52	7.50	−48.4	−19.8

Table 4. Mars Type I transfer characteristics

Launch dates	Launch period, days	Geocentric injection energy, meters²/sec² × 10⁸	Class I trajectories: Flight time, days		Class I: Communication distance, 10⁶ km		Class I: Planetocentric asymptotic speed, km/sec		Class I: Declination of the geocentric asymptote, deg		Class II trajectories: Flight time, days		Class II: Communication distance, 10⁶ km		Class II: Planetocentric asymptotic speed, km/sec		Class II: Declination of the geocentric asymptote, deg	
			Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Oct 23–Nov 7 1962	15	0.1612	206	224	214	244	4.03	5.24	40.2	45.7	235	260	242	281	2.88	4.11	45.4	54.8
Oct 18–Nov 17 1962	30	0.1821	188	288	193	313	2.55	6.30	21.3	49.1	224	292	221	315	2.53	4.88	6.6	61.5
Oct 11–Nov 25 1962	45	0.232	163	279	167	312	2.66	7.94	23.3	46.1	221	294	208	320	2.80	5.40	−5.2	70.4
Oct 4–Dec 3 1962	60	0.3004	144	203	148	321	2.77	9.52	17.0	42.2	229	298	215	325	3.13	5.30	−14.8	77.2
Nov 12–Nov 27 1964	15	0.094	233	246	214	225	4.05	4.46	9.7	16.2	240	248	220	229	3.95	4.20	−1.8	8.5
Nov 10–Dec 10 1964	30	0.1257	196	243	182	213	4.39	6.24	17.8	35.9	243	253	216	244	3.59	4.56	−20.9	37.8
Nov 5–Dec 20 1964	45	0.1759	167	224	157	199	5.37	8.16	14.9	30.4	226	259	189	257	3.41	5.54	−32.1	50.1
Oct 31–Dec 30 1964	60	0.24350	146	223	139	240	3.60	9.96	11.7	24.4	226	265	183	270	3.54	5.89	−38.1	54.2
Dec 28 1966–Jan 12 1967	15	0.0962	189	201	149	159	5.58	6.25	−23.1	−14.3	202	212	159	171	4.87	5.53	−29.3	−17.8
Dec 21 1966–Jan 20 1967	30	0.1120	173	206	138	155	5.86	7.23	−27.1	−9.3	203	220	152	182	4.38	5.98	−37.7	−14.6
Dec 13 1966–Jan 27 1967	45	0.1397	158	203	127	164	5.25	8.41	−24.3	−5.6	194	227	148	194	4.01	6.23	−44.6	−8.4
Dec 6 1966–Feb 4 1967	60	0.178	143	206	118	170	4.89	9.64	−25.4	−3.1	209	233	138	206	3.81	6.82	−51.3	−11.6
Feb 24–March 11 1969	15	0.092	165	178	108	119	4.92	5.88	−51.9	−43.6	180	189	115	129	4.34	5.22	−56.1	−46.7
Feb 16–March 18 1969	30	0.1049	151	181	98	128	4.40	6.91	−55.1	−38.1	183	201	109	145	3.79	5.70	−63.3	−43.3
Feb 9–March 26 1969	45	0.1235	140	193	92	151	3.66	7.86	−51.5	−34.3	188	212	109	163	3.62	5.72	−68.9	−44.2
Feb 3–April 4 1969	60	0.1433	131	201	87	165	3.64	8.64	−53.9	−31.8	186	224	102	185	3.87	6.27	−72.8	−52.0
May 16–May 31 1971	15	0.0815	186	212	130	175	2.83	2.99	−27.2	−15.6	214	230	160	191	2.82	3.04	−22.5	−6.7
May 8–June 7 1971	30	0.0896	164	201	106	169	2.86	3.64	−30.0	−18.0	203	240	137	208	2.84	3.24	−29.5	5.8
May 1–June 15 1971	45	0.1033	147	208	90	188	2.91	4.52	−30.6	−13.3	208	242	135	223	2.88	3.51	−33.6	16.2
April 24–June 23 1971	60	0.1222	132	218	79	212	2.95	5.47	−31.7	−7.2	199	246	117	240	2.95	3.75	−38.5	24.4
July 21–Aug 5 1973	15	0.1507	176	186	154	169	3.22	3.53	23.8	38.0	202	209	184	206	2.71	2.97	30.9	35.6
July 13–Aug 12 1973	30	0.166	159	185	132	184	2.96	4.26	19.9	27.8	204	223	176	233	2.54	3.11	27.2	42.6
July 5–Aug 19 1973	45	0.1903	143	194	114	185	2.96	5.10	16.9	30.9	199	235	153	259	2.45	3.44	28.1	49.1
June 26–Aug 25 1973	60	0.2228	130	189	100	201	2.75	5.98	14.7	27.1	204	246	148	283	2.48	3.57	29.5	54.9
Sept 7–Sept 22 1975	15	0.1964	186	226	191	209	4.17	4.68	41.7	47.0	216	226	227	254	3.10	3.68	47.3	54.9
Aug 31–Sept 30 1975	30	0.2237	165	194	164	215	4.01	5.78	37.2	47.5	215	245	214	285	2.62	4.03	42.4	62.6
Aug 23–Oct 7 1975	45	0.2683	147	192	143	198	4.64	6.99	33.7	47.3	212	264	198	315	2.39	4.46	45.0	69.7
Aug 15–Oct 14 1975	60	0.3263	132	211	126	268	2.78	8.18	31.3	47.7	206	283	177	342	2.54	4.98	45.4	75.6
Oct 11–Oct 26 1977	15	0.1806	198	216	209	230	4.54	5.33	42.5	50.8	223	247	232	275	3.10	4.42	48.5	57.7
Oct 4–Nov 3 1977	30	0.2122	176	207	182	240	4.18	6.66	38.0	47.6	226	273	228	308	2.49	4.59	45.7	66.0
Sept 30–Nov 4 1977	45	0.2376	164	306	170	339	2.46	7.44	25.1	47.6	222	309	218	340	2.51	4.95	12.2	70.2
Sept 23–Nov 22 1977	60	0.301	145	298	149	339	2.56	8.94	23.7	43.8	221	309	208	344	2.92	5.34	−4.9	77.7

Table 5. Mercury transfer characteristics

Launch dates	Launch period, days	Geocentric injection energy, meters²/sec² × 10⁸	Class I trajectories								Class II trajectories							
			Flight time, days		Communication distance, 10⁶ km		Planetocentric asymptotic speed, km/sec		Declination of the geocentric asymptote, deg		Flight time, days		Communication distance, 10⁶ km		Planetocentric asymptotic speed, km/sec		Declination of the geocentric asymptote, deg	
			Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Type I																		
Nov 16–Dec 1 1967	15	0.4415	99	112	125	130	15.04	15.62	−15.6	−3.9	99	113	130	132	15.02	15.44	−21.6	−16.4
Nov 11–Dec 11 1967	30	0.5685	88	118	114	131	13.52	20.15	−18.6	12.3	91	131	128	156	13.78	17.81	−39.0	12.3
Nov 5–Dec 20 1967	45	0.8195	76	114	103	124	16.88	27.96	−14.9	11.2	87	119	121	144	15.10	20.07	−48.2	22.0
Nov 8–Nov 23 1968	15	0.5902	91	103	127	139	13.90	16.74	−13.7	7.0	94	105	134	147	12.52	16.93	−43.8	8.0
Oct 31–Nov 30 1968	30	0.7825	81	105	112	145	13.93	25.00	−23.3	9.3	87	107	123	151	13.81	18.86	−51.2	16.7
Type II																		
Oct 29–Nov 13 1967	15	0.5367	119	130	127	146	12.02	16.08	−20.8	14.0	124	134	138	150	12.02	12.52	1.1	14.0
Oct 23–Nov 22 1967	30	0.5957	118	136	125	155	12.09	17.10	−25.2	18.4	124	141	140	162	12.48	15.10	−0.5	17.1
Oct 16–Nov 30 1967	45	0.668	117	141	123	164	12.37	18.36	−31.2	21.9	121	148	141	172	12.76	18.31	−2.1	18.6
Oct 23–Nov 7 1968	15	0.443	108	121	141	145	13.52	14.81	−27.8	−17.9	108	124	147	155	11.90	12.31	−7.6	−1.9
Oct 12–Nov 11 1968	30	0.5305	106	132	137	145	12.15	16.68	−37.1	3.5	117	136	149	171	12.68	15.15	−11.0	5.6
Oct 4–Nov 18 1968	45	0.6188	105	139	134	171	11.96	18.10	−44.5	10.1	115	143	148	181	12.88	18.86	−12.7	7.9

Table 6. Jupiter transfer characteristics

Launch dates	Launch period, days	Geocentric injection energy, meters²/sec² × 10⁸	Class I trajectories								Class II trajectories							
			Flight time, days		Communication distance, 10⁶ km		Planetocentric asymptotic speed, km/sec		Declination of the geocentric asymptote, deg		Flight time, days		Communication distance, 10⁶ km		Planetocentric asymptotic speed, km/sec		Declination of the geocentric asymptote, deg	
			Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Type I																		
Dec 27–Jan 11 1969	15	0.7882	810	1035	641	866	5.72	6.65	−7.7	4.4	902	1043	633	876	5.72	6.00	−16.1	8.6
Dec 21–Jan 20 1969	30	0.8612	675	1077	638	940	5.74	8.69	−7.1	4.7	820	1122	636	920	5.81	6.64	−24.6	16.9
Type II																		
Dec 25–Jan 9 1969	15	0.7758	955	1192	667	910	5.70	6.01	−13.9	6.1	1011	1198	779	874	5.71	6.03	−5.7	1.0
Dec 21–Jan 20 1969	30	0.8039	929	1327	612	918	5.71	6.57	−18.6	11.0	984	1390	610	914	5.71	6.84	−7.7	−2.7

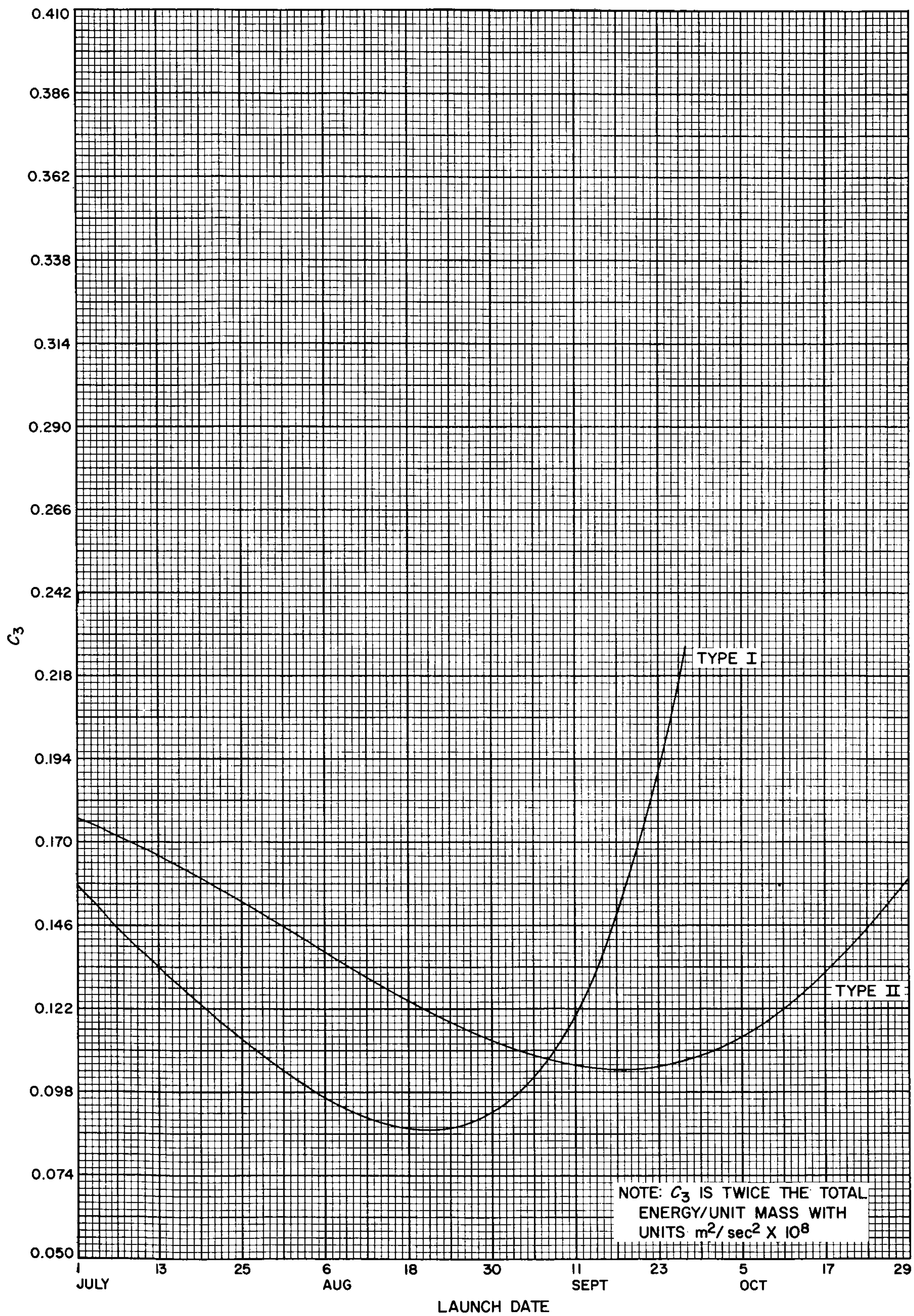

Fig. 3. Venus 1962: Minimum injection energy vs launch date

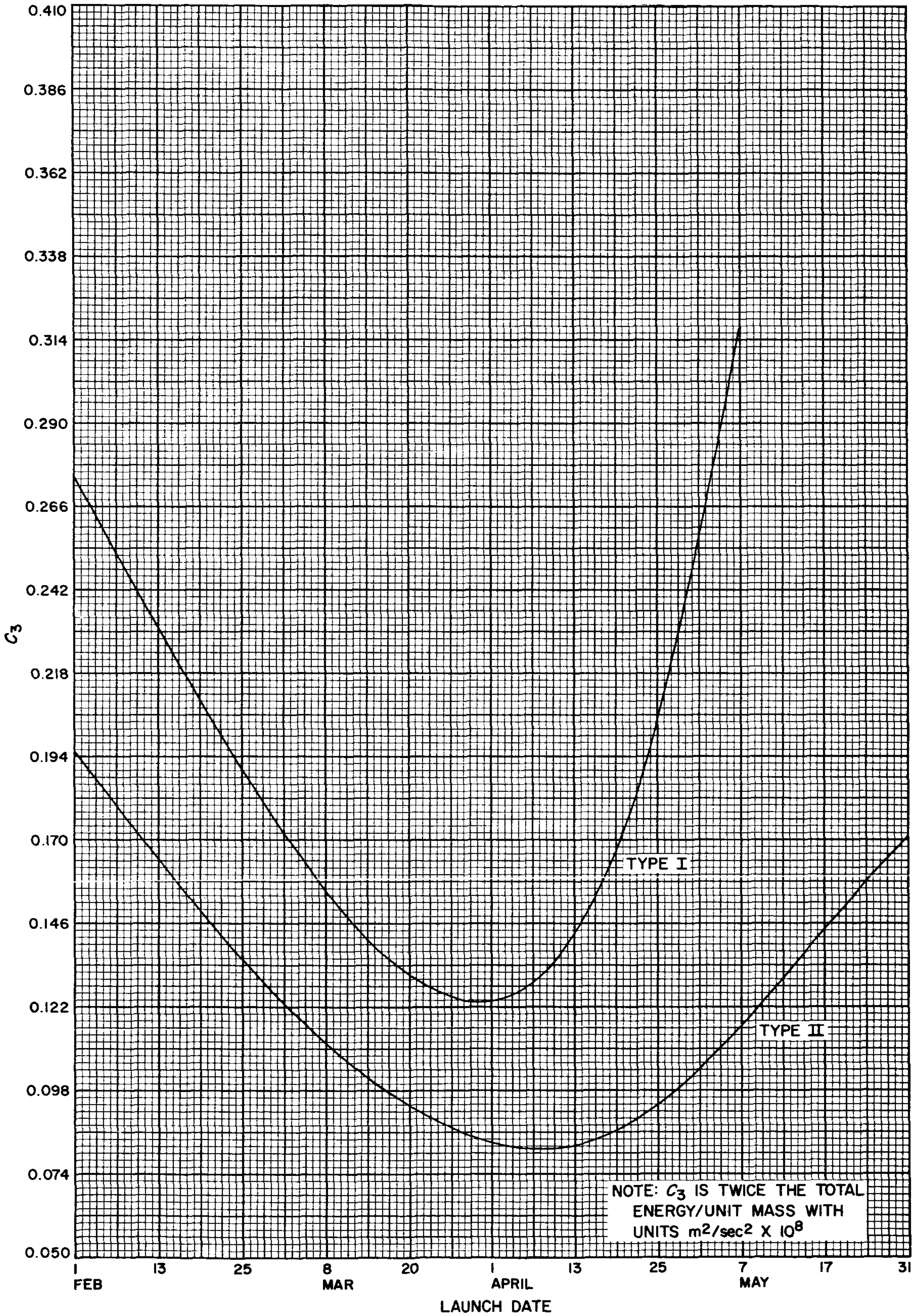

Fig. 4. Venus 1964: Minimum injection energy vs launch date

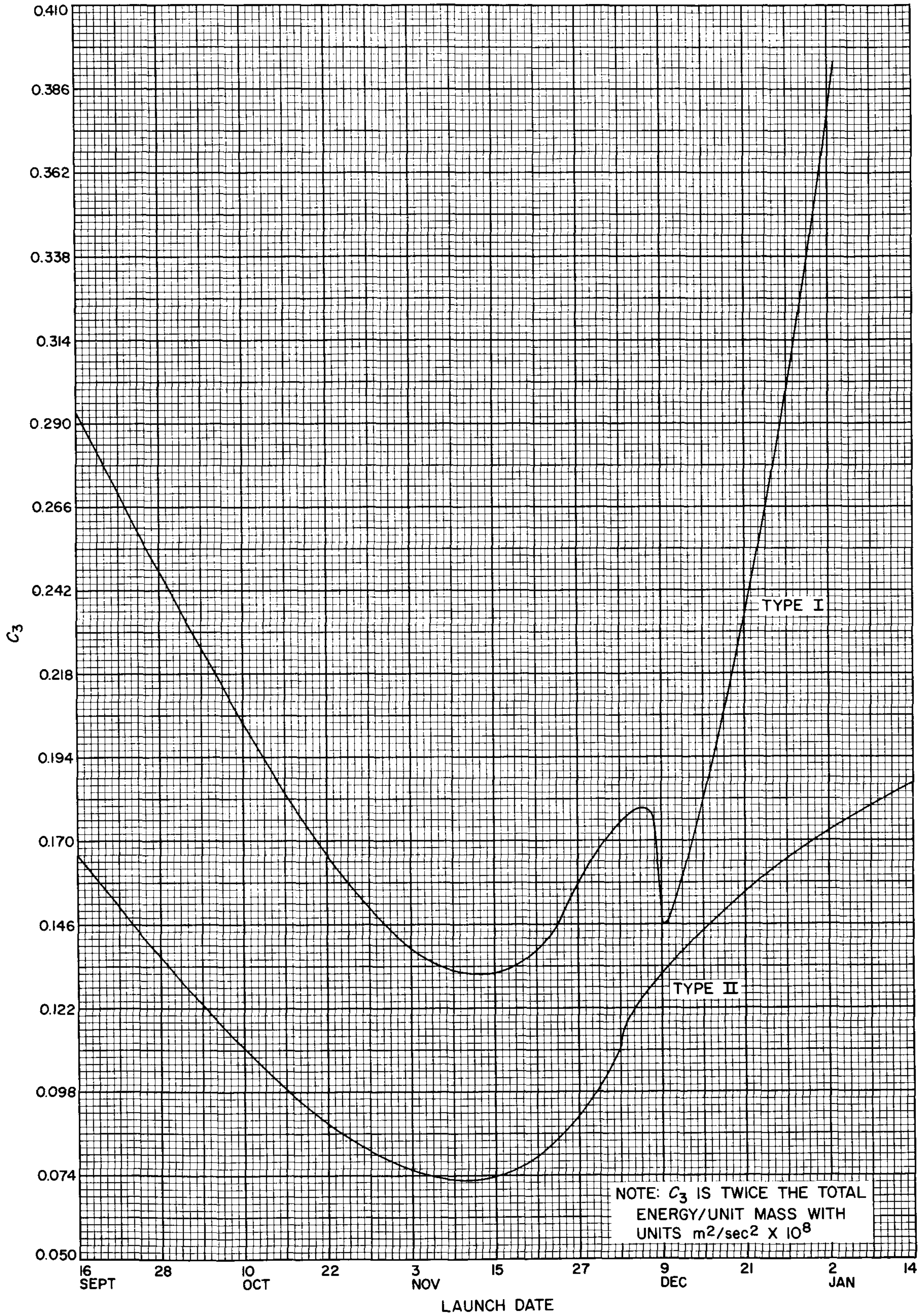

Fig. 5. Venus 1965: Minimum injection energy vs launch date

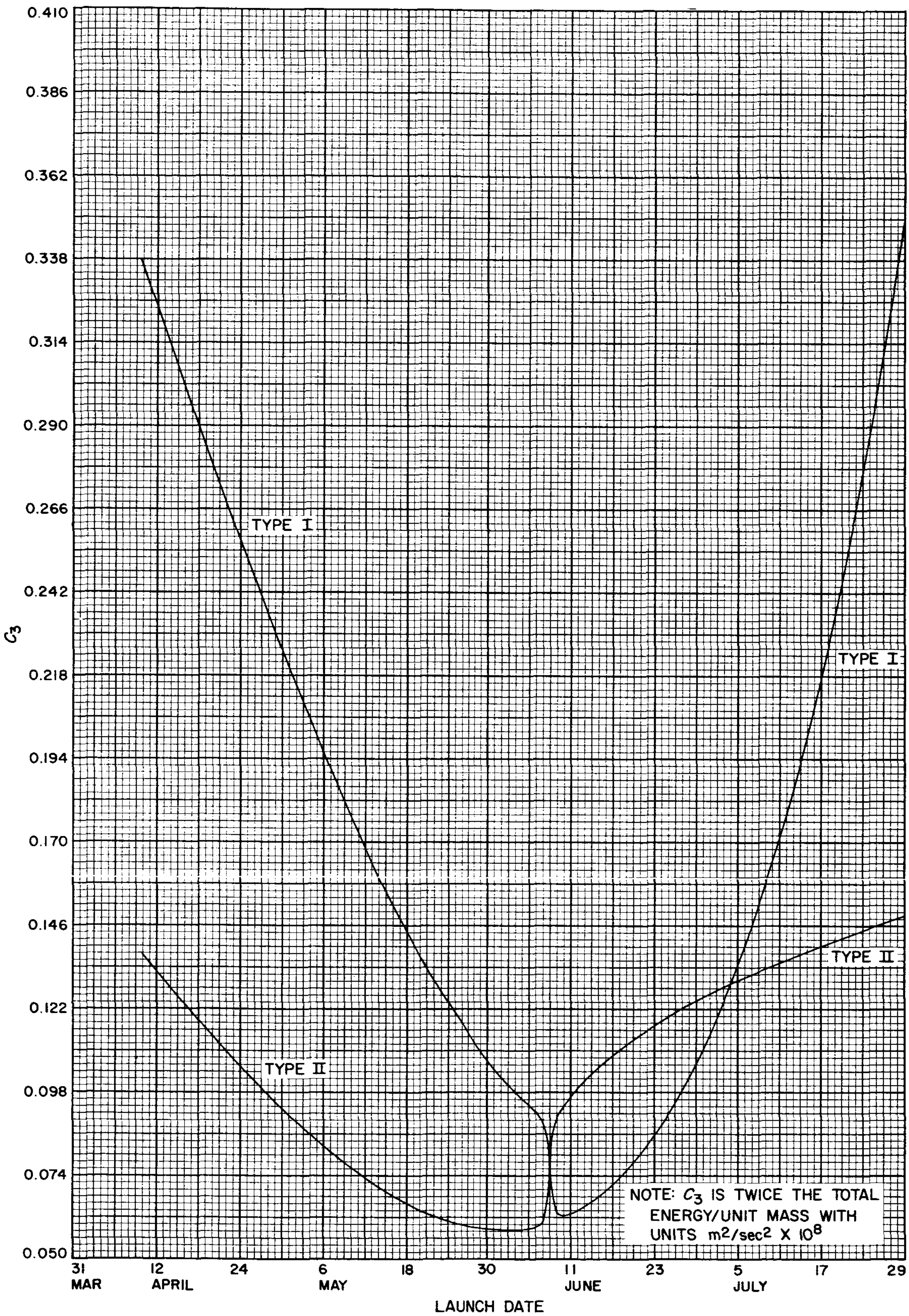

Fig. 6. Venus 1967: Minimum injection energy vs launch date

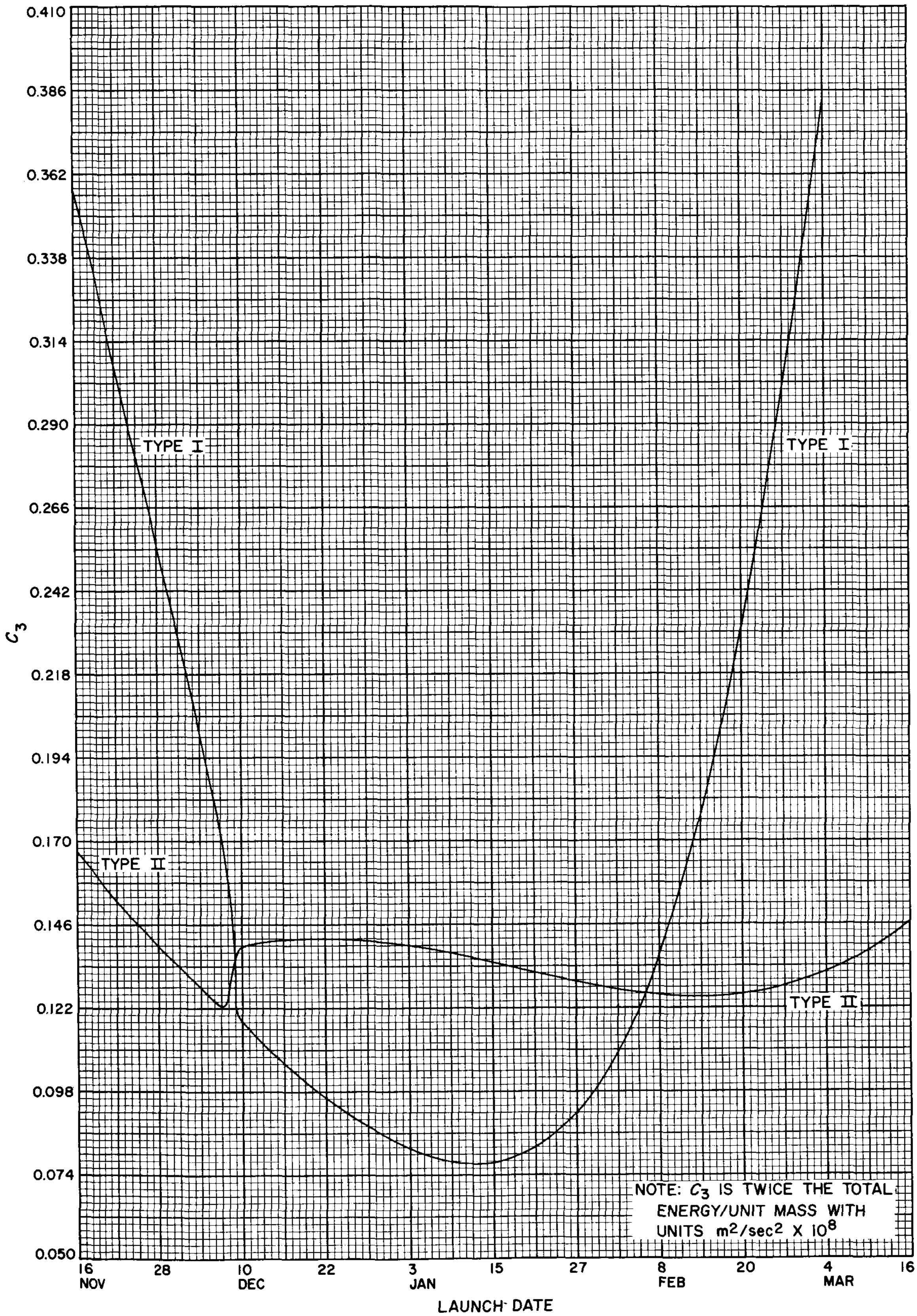

Fig. 7. Venus 1968–1969: Minimum injection energy vs launch date

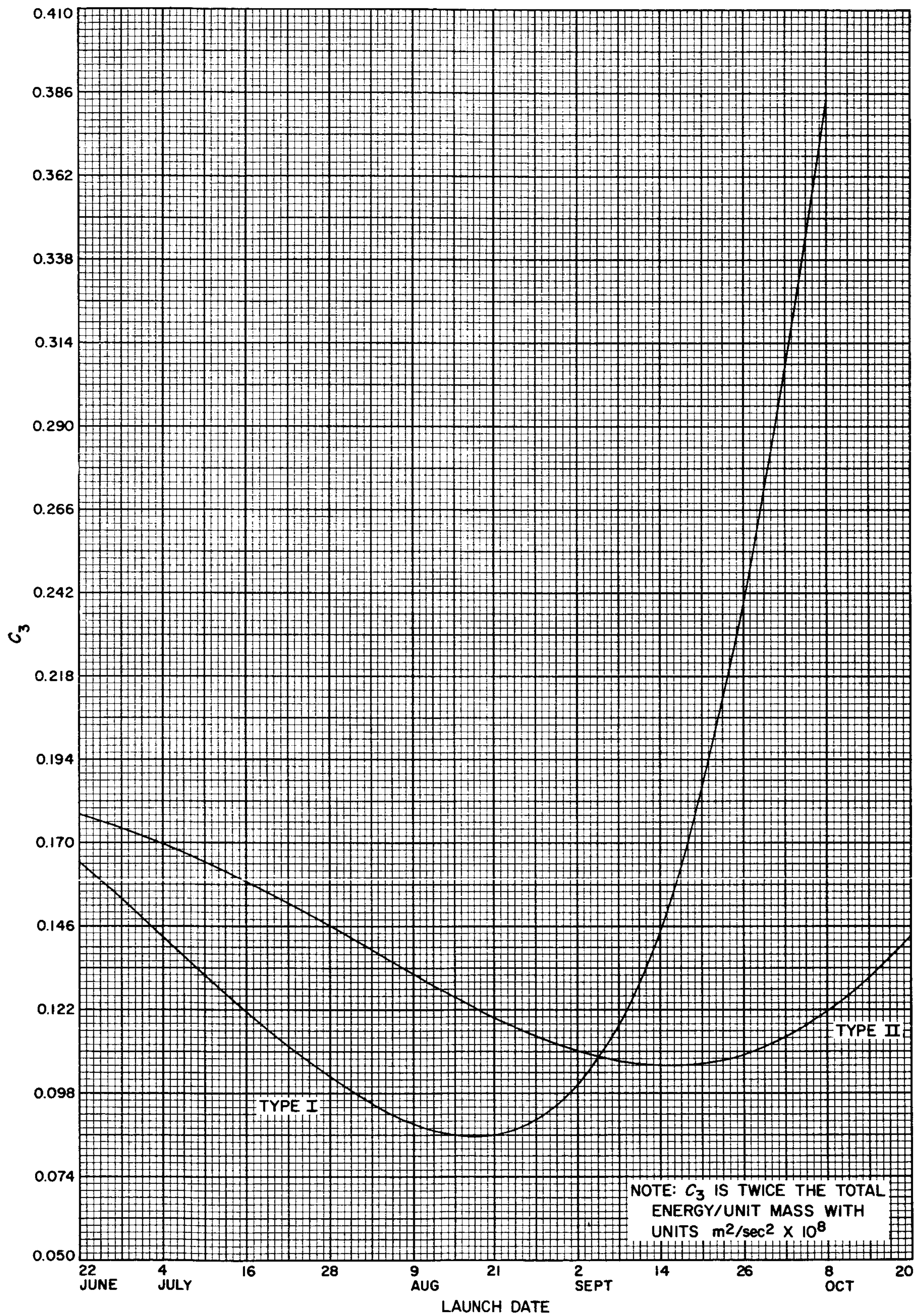

Fig. 8. Venus 1970: Minimum injection energy vs launch date

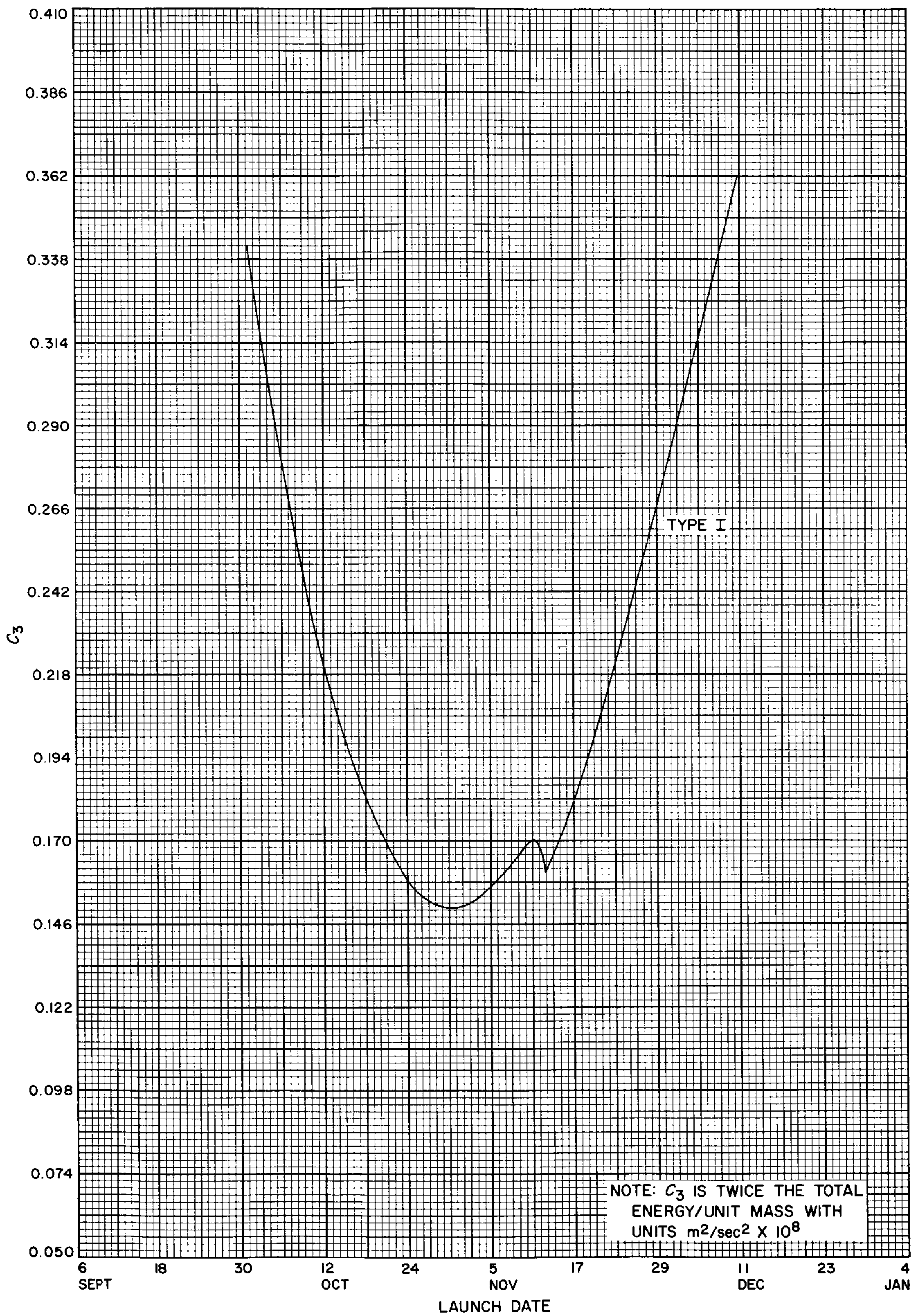

Fig. 9. Mars 1962: Minimum injection energy vs launch date

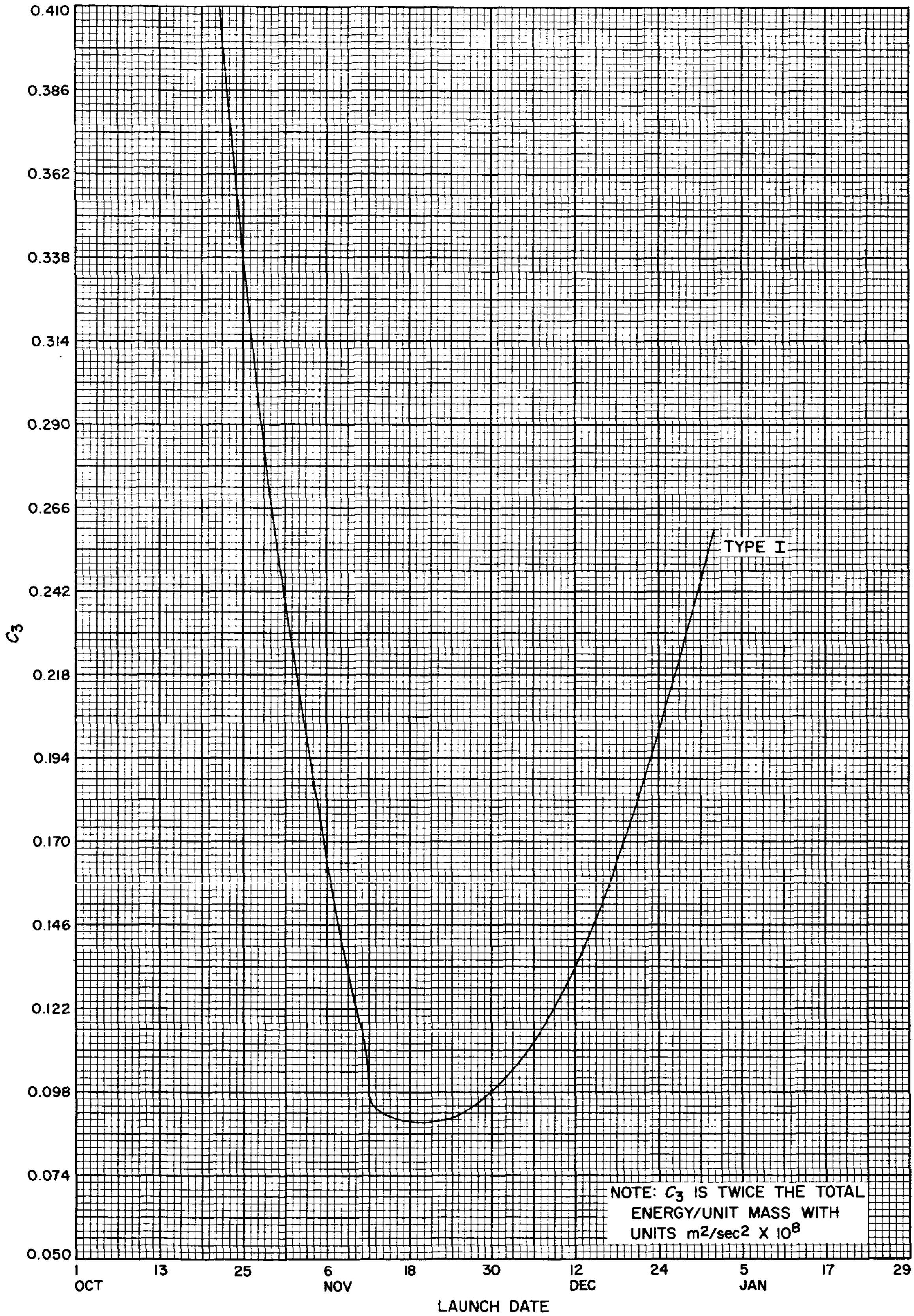

Fig. 10. Mars 1964: Minimum injection energy vs launch date

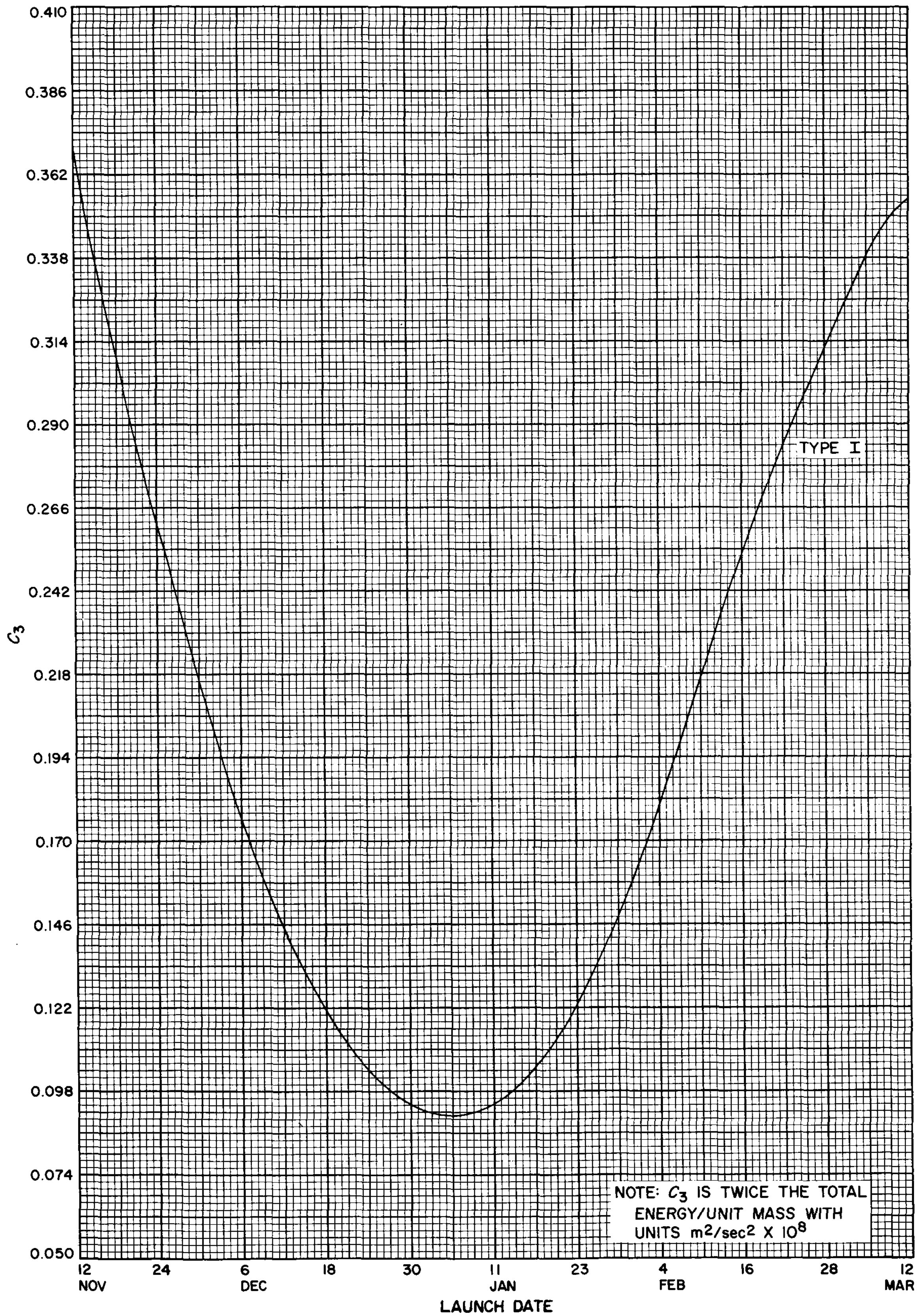

Fig. 11. Mars 1966–1967 : Minimum injection energy vs launch date

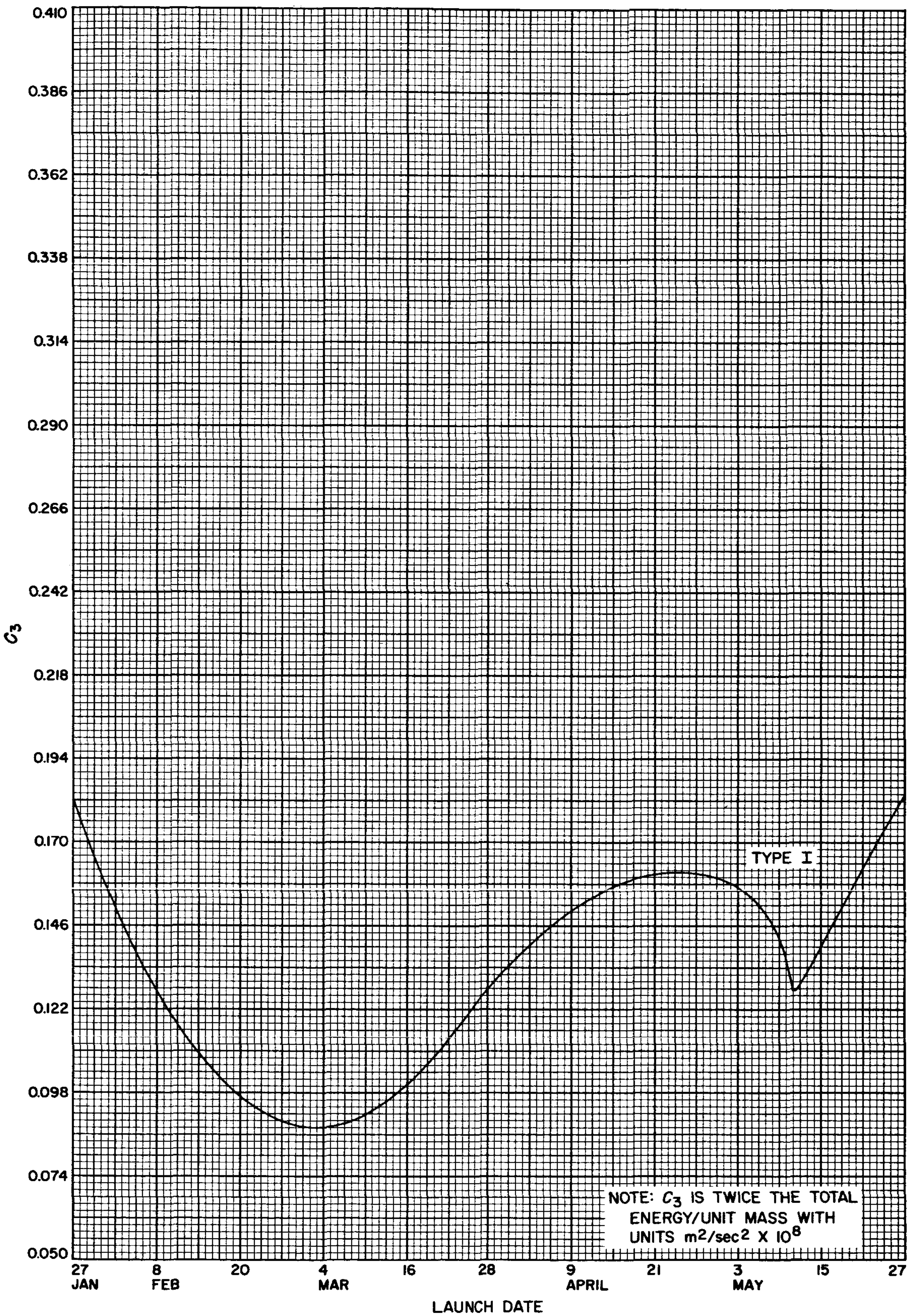

Fig. 12. Mars 1969: Minimum injection energy vs launch date

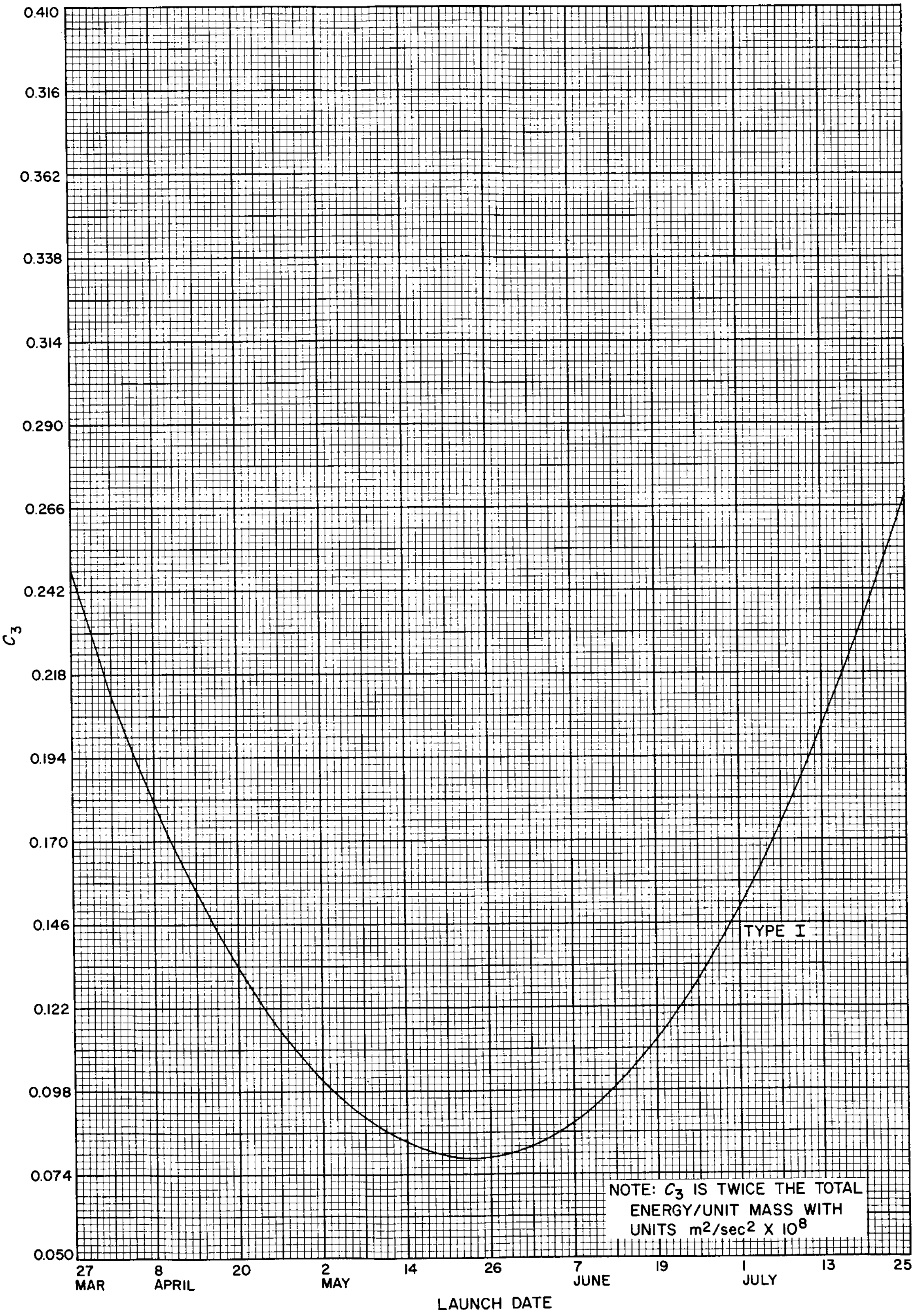

Fig. 13. Mars 1971: Minimum injection energy vs launch date

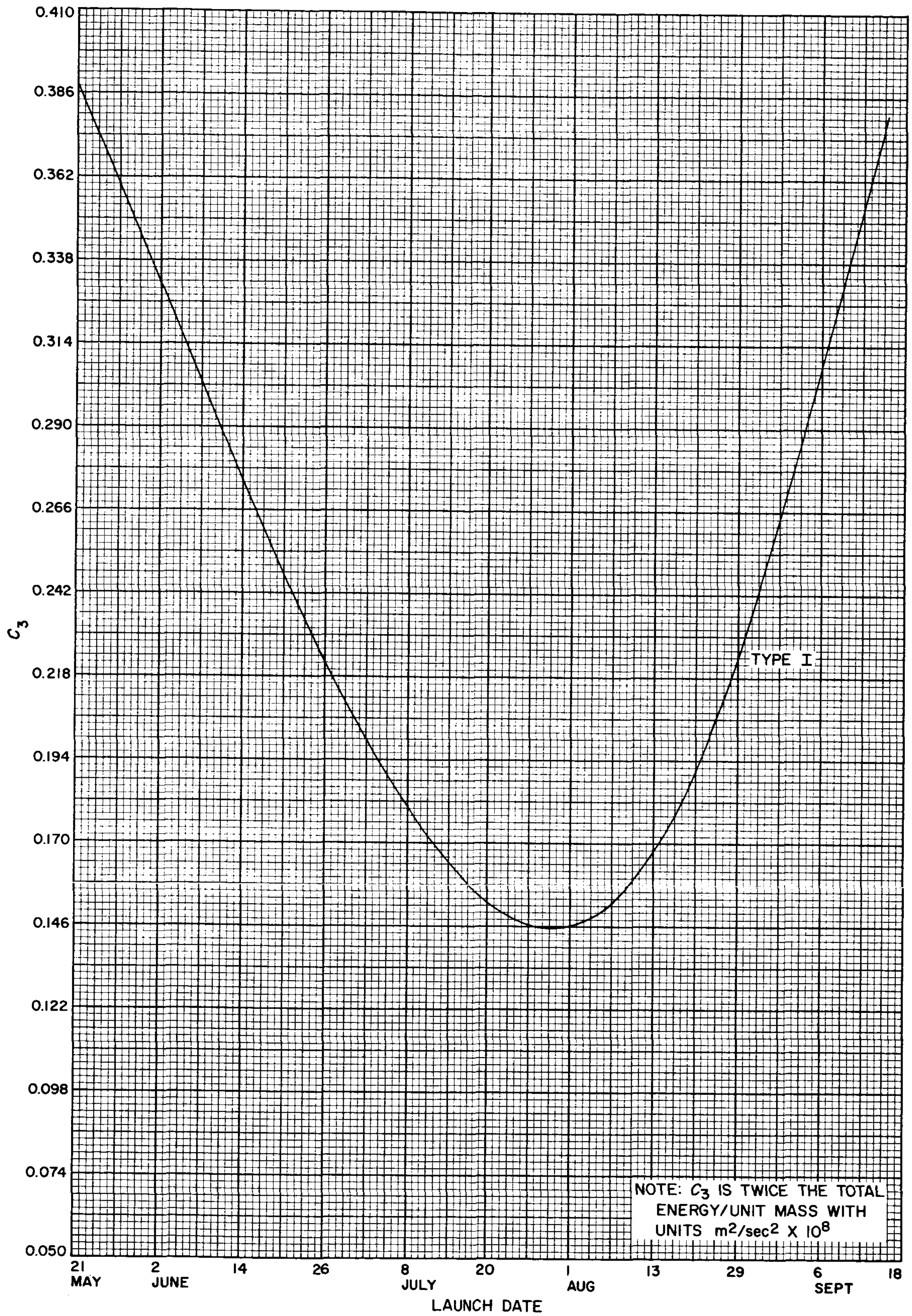

Fig. 14. Mars 1973: Minimum injection energy vs launch date

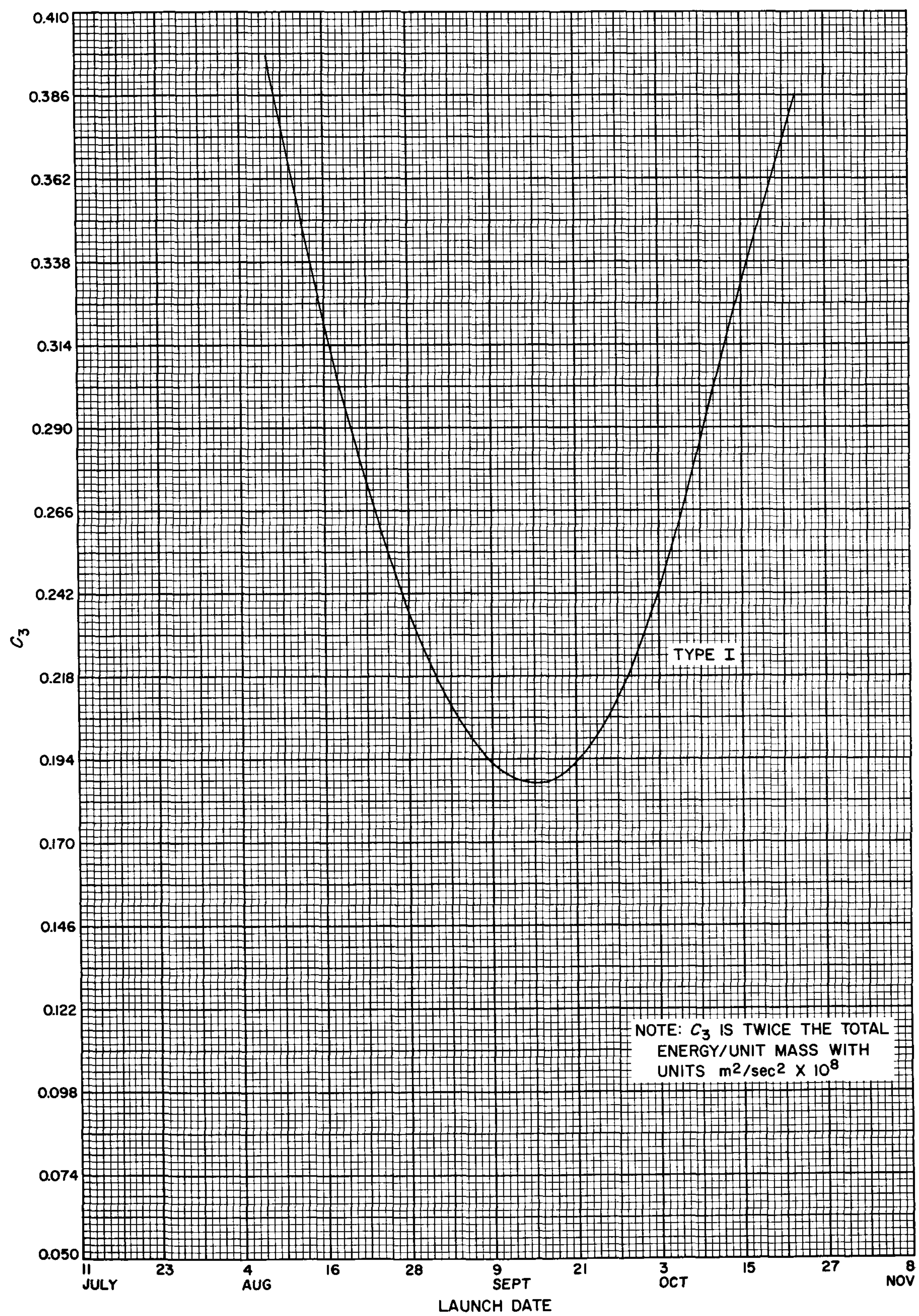

Fig. 15. Mars 1975: Minimum injection energy vs launch date

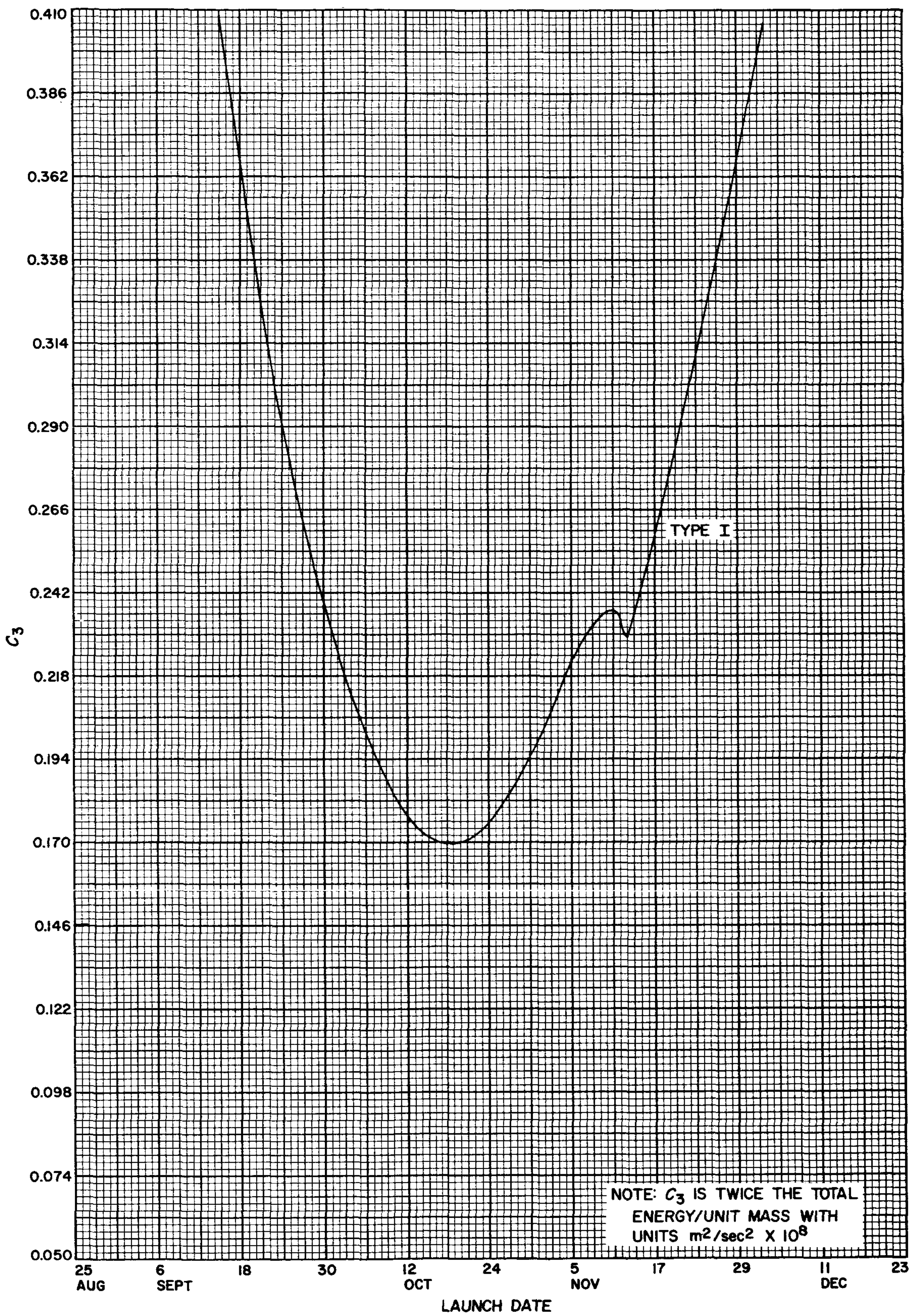

Fig. 16. Mars 1977: Minimum injection energy vs launch date

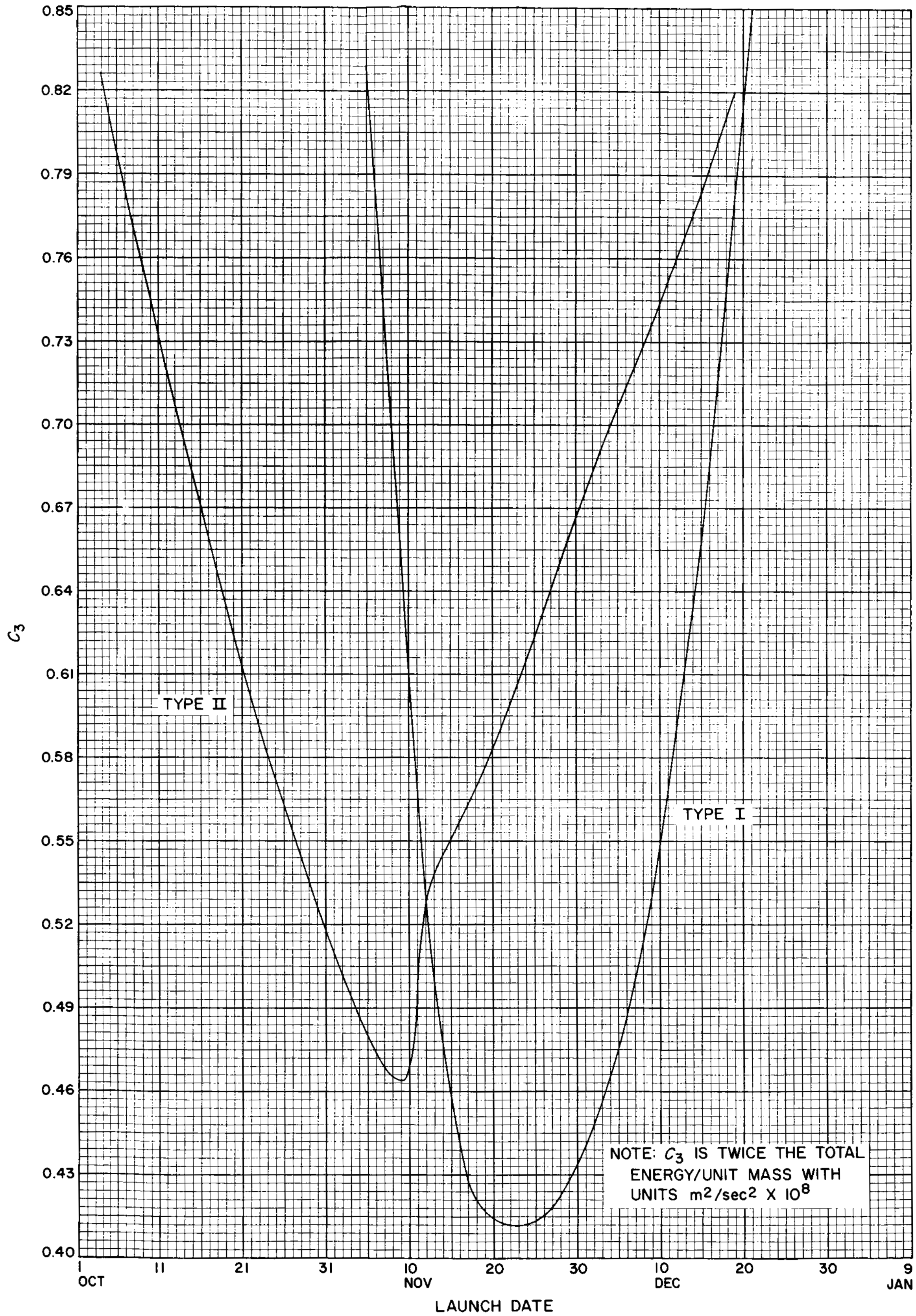

Fig. 17. Mercury 1967: Minimum injection energy vs launch date

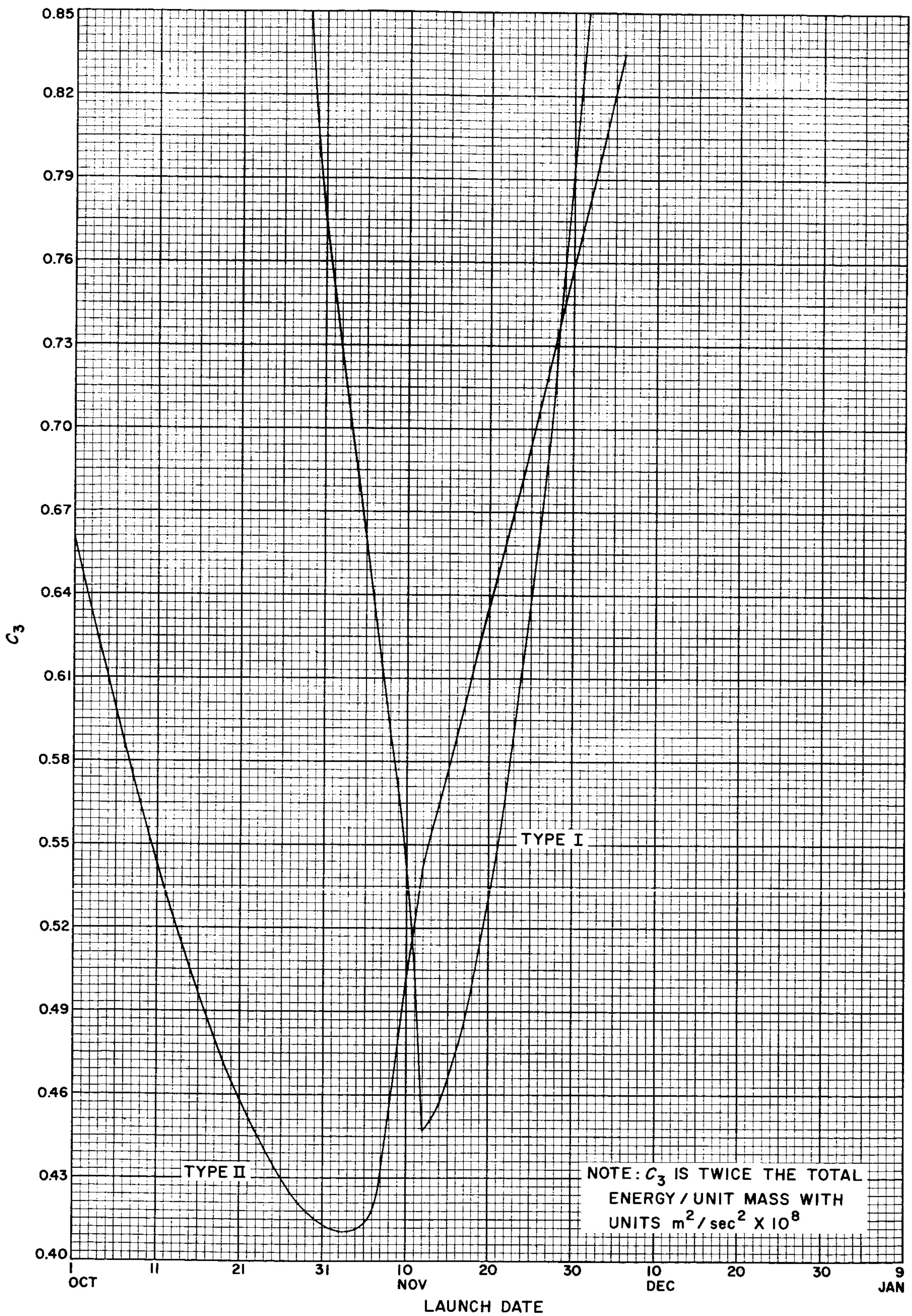

Fig. 18. Mercury 1968: Minimum injection energy vs launch date

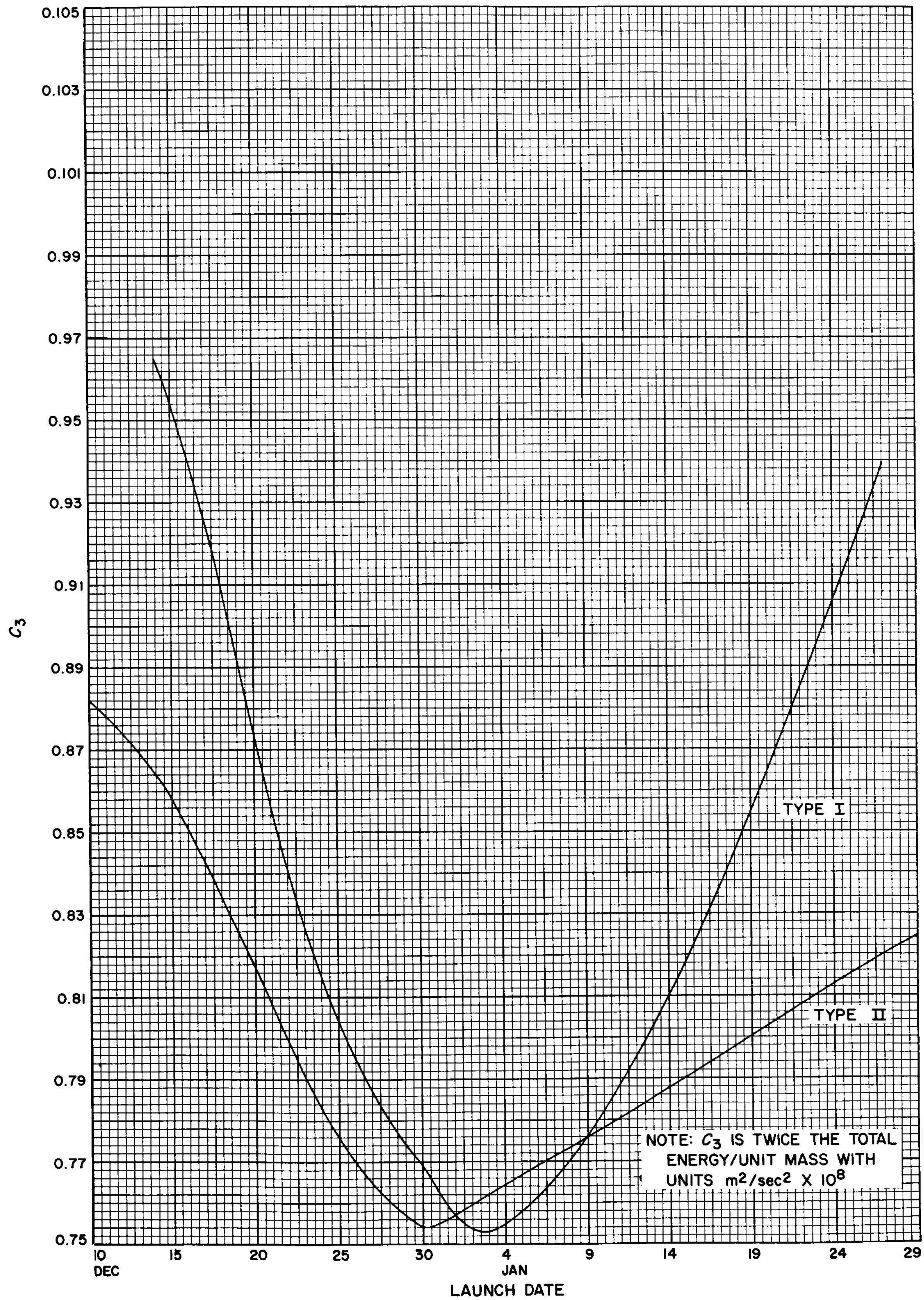

Fig. 19. Jupiter 1969: Minimum injection energy vs launch date

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