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ALLOWABLE POWERPLANT WEIGHTS FOR TYPICAL NUCLEAR ROCKET APPLICATIONS

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INTRODUCTION

At present, assumptions and calculations of space-mission requirements and vehicle-component weights seem to be more reliable than those regarding nuclear-rocket-powerplant characteristics. Consequently, a study which presents allowable powerplant weight in terms of powerplant performance and pertinent mission and vehicle parameters has been conducted. The results are intended to be useful in the comparison of the many reactor and propulsion-system concepts which should be investigated during early phases of nuclear-rocket development.

Two basically-different nuclear rocket applications are of immediate interest: (1) orbital-launch vehicles, and (2) upper booster stages. Since great flexibility is permitted in design and operating conditions when the mission is begun from a satellite orbit, the study parameters have been varied over large ranges. Thrust, specific impulse, initial nuclear-vehicle weight and mission velocity requirement are the parameters upon which payload and allowable powerplant weight are shown to depend. Estimation of desired payload permits rapid determination of allowable powerplant weight, or vice versa.

When a nuclear rocket powerplant is used in an upper stage of a booster system, the permissible variation in thrust level is greatly reduced. In fact, an optimum thrust level can be computed as well as a lower limit. The increase in payload put into orbit resulting from the substitution of a nuclear stage for the original chemical stage in a given booster configuration is strongly affected by the division of stages. In consideration of this dependence and in an attempt to provide results of near-future usefulness, specific boosters have been utilized.

Atlas, Saturn I and Nova have been selected for use with the nuclear stages, and the flight conditions at commencement of nuclear rocket propulsion correspond to the staging of the chemical systems modified by an optimization of first-stage "kick angle." The initial weights in orbit for the orbital-launch calculations also correspond to the above-listed chemical boosters plus Saturn II after deduction of anticipated transition structure to support the nuclear vehicle.

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The mission for the booster applications is to place a payload in a 300-statute-mile circular satellite orbit, whereas ranges of missions are illustrated for the orbital-launch applications. The difficulty of the latter missions is graduated in such a way that the capability range corresponding to each initial weight is covered. The missions selected also provide a continuity from one booster system to the next, thereby revealing the growth in performance capability to be expected with time. Obviously, the number of missions which may be conceived is endless. The missions selected are meant to be sufficiently representative to serve as means of preliminary comparison, but in no way indicate the extent of nuclear rocket application now envisioned.

ORBITAL-LAUNCH APPLICATIONS

Methods and Assumptions

Values of powerplant-plus-payload weight have been estimated for all combinations resulting from the following ranges or values of parameters: (1) thrust levels which give thrust-to-initial-weight ratios between 0.01 and 1.0; (2) specific impulses of 450, 600, 800, and 1000 lb/(lb/sec); (3) initial nuclear-vehicle weights of 7600 lb. (Atlas-Centaur), 31,300 lb. (Saturn I), 77,000 lb. (Saturn II), and 226,100 lb. (Nova); and (4) mission velocity requirements as shown in the following tables:

CASE FILE COPY

	Mission	Hyperbolic Velocity mi/sec		Velocity Increment mi/sec
A.	Escape from Earth	0.00		1.96
B.	75-day Venus probe	2.80		2.55
C.	100-day Mars probe	4.91		3.60
D.	413-day Jupiter probe	7.42		5.27
E.	125 days to Mars orbit	4.90 ~~3.81~~	(Earth)	~~2.99~~ 3.58
		5.00 ~~5.67~~	(Mars)	~~4.39~~ 3.80
			(Total)	7.38
F.	100 days to Mars orbit	6.09 ~~4.91~~	(Earth)	~~3.59~~ 4.33
		6.65 ~~7.76~~	(Mars)	~~6.35~~ 5.30
			(Total)	~~9.94~~ 9.63

Initial Weight lb.	Missions
7,600	A,B,C
31,300	B,C,D
77,000	C,D,E
226,100	D,E,F

All flights start from a 300-statute-mile circular orbit about Earth, and those flights going into orbit about Mars (missions E and F) enter a 1000-statute-mile circular orbit at destination. All probe missions have propulsion at Earth only. The hyperbolic velocities for Mars and Venus missions correspond to optimum non-ecliptic trajectories, whereas the Jupiter values are based on a path which leaves tangent to Earth's orbit and assumes circular, co-planar planetary orbits.

Estimation of powerplant-plus-payload weight requires knowledge of two quantities: mass ratio and tank-plus-structure weight. Mass ratios, or gross-to-empty-weight ratios (W_G/W_E), for the propulsion periods involved in the specified missions are read from charts such as those presented in figure 1. The mass-ratio charts cover ranges of thrust-to-initial-weight ratio (F/W_G) from 0.001 to 1.0, hyperbolic velocity (v_h) from 0 or 1 to 12 miles/sec, and specific impulse (I) from 450 to 1000 lb/(lb/sec) for both leaving Earth and entering Mars orbits. The charts are the result of IBM-704 calculations using a Runge-Kutta numerical-integration technique. The thrust vector is assumed to be parallel to the velocity

vector.

Tank and structure weights are so dependent upon nuclear-vehicle and booster configuration that generalization is not possible with much assurance of accuracy. Of primary importance when using booster vehicles of predetermined dimensions is the problem of compatibility between the nuclear vehicle and the booster top stage. If the hydrogen tank has a diameter much larger than the booster stage the transition-structure weight becomes excessive, whereas if the diameter is reduced the tank encounters increased bending stresses because of its length. The compromise chosen for this study, based on a current NASA design study of a Saturn-boosted nuclear vehicle, is that the diameter of the hydrogen tank be 1.175 times the diameter of the top booster stage.

The tanks are assumed to consist of cylinders with hemispherical ends, made of aluminum of 175 lb/cu ft density and 59,500 psi design stress, and having uniform wall thickness throughout. The thickness is determined by the pressure required to keep the tank in tension during a 6g boost acceleration, a value of 23 psi having been used for all sizes although this may be conservative for the Atlas-Centaur- and Saturn-I-boosted vehicles. The resulting tank weights are shown in figure 2 as functions of propellant weight for nuclear-vehicle diameters corresponding to Atlas-Centaur (11.8 ft), Saturn (15.7 ft), and Nova (23.5 ft). A top-stage diameter of 160 inches was assumed for Saturn on the basis of reports that bending-moment problems would make 10-foot stages unsatisfactory when boosting a geometrically-large payload such as a nuclear vehicle. Insulation and ablation-material weights were not included explicitly in the tank weights because of the present uncertainty regarding the choice of materials and the resulting weight penalty. Should this weight be appreciable, it must be included in the powerplant weight.

Another tank problem, that of meteoroid damage, affects those applications which require propulsion after a prolonged coast period. Data on meteoroid distribution and composition are inadequate to permit reliable estimation of tank thicknesses required to provide desired probabilities of success. Consequently, the tank weights of figure 2 have been used with the understanding that they may be as much as 30 percent low. It should be noted that the choice of aluminum for the tank material was made, in part, because of the meteoroid protection afforded by the relatively large wall thicknesses which result.

Structure weights are also considered to be functions of tank diameter. The powerplant and payload of the nuclear vehicle are assumed to be supported by minimum-weight structures, the weights of which are proportional to the square of the tank diameter because the diameter controls both circumference and length of the structure. Accordingly, the following structure weights have been used for one-tank configurations:

Tank Diameter ft.	Structure Weight lb.
11.8	750
15.7	1000
23.5	1500

The value of 1000 lb has been obtained from the NASA design study. For two-tank configurations, such as those which go into orbit at Mars, the structure weight is assumed to increase by 50 percent.

The transition structure between booster and nuclear vehicle is assumed to be jettisoned with the empty booster stage, but its weight must be subtracted from the booster payload usually quoted. The initial weights for the nuclear vehicles are based on a 5 percent reduction of booster payload to account for the transition

structure, the specific percentage having been obtained from the NASA design study.

Allowable-Powerplant-Weight Charts

Charts of powerplant-plus-payload weight as a function of nuclear-propulsion-system thrust and specific impulse are presented in figure 3. Each chart represents the combination of an initial weight and a mission. The combinations are arranged in the same order as shown in the preceding table of missions.

An example can be utilized to indicate the magnitudes of powerplant weight which are likely to be required. Figures 3(a), (b), and (c) present powerplant-plus-payload weights for Atlas-Centaur-boosted nuclear vehicles. If a payload of 1000 pounds is deemed useful for the missions concerned, and a powerplant developing 1000 pounds thrust at a specific impulse of 880 lb/(lb/sec) is to be evaluated, the allowable powerplant weight varies from 43 to 20 percent of initial gross weight over the velocity-increment range from 1.96 to 3.6 miles/second. In more tangible terms, the powerplant weight must be between 1500 and 3250 pounds. Not much improvement could be expected by increasing the thrust; the allowable-powerplant-weight range has an upper limit of 2000 to 3500 pounds for the mission spread assumed. Such powerplant weights appear feasible with low-power reactors containing metallic or ceramic fuel elements.

Figure 3 may also be used to obtain general information regarding the effects of changes in specific impulse on either allowable powerplant weight or required thrust. For example, a useful relationship to have in mind would be the approximate change in powerplant (or payload) weight for a specified percentage change in specific impulse, assuming constant thrust-to-initial-weight ratio. For the combinations of initial weights and missions covered in figure 3 a rough

generalization can be noted: In the neighborhood of I = 800 lb/(lb/sec) each percent change in I will produce a change in allowable powerplant weight equal to about one-third of a percent of initial weight in orbit, or

$$\frac{\Delta W_{pp}/W_G}{\Delta I/I} = 0.33 \pm 0.05$$

The deviation of 15 percent covers almost all cases, the exceptions being principally extremes such as very low thrust-to-initial-weight ratios or mission F, for which $(\Delta W_{pp}/W_G)/(\Delta I/I) = 0.26$. The relation is not sensitive to median specific impulse.

Since reactor power is a parameter frequently discussed in connection with nuclear-powerplant performance, figures 4 and 5 have been included to relate power, thrust and specific impulse for typical combinations of reactor-exit temperature and pressure. In figure 4 the ratio of power to thrust is plotted versus pressure for values of temperature between 2500 and 5000°F. The corresponding values of specific impulse are given in figure 5. The previous example, with I = 880 lb/(lb/sec), could correspond to T=4500°F and P=100 psi, in which case the reactor power would be about 22 mw with F=1000 lb. Maximum allowable powerplant weight, obtained when F=7600 lb. in figure 3, corresponds to a reactor power of 168 mw. The assumptions upon which the values are based are listed on figures 4 and 5.

The effect of a change in specific impulse on required reactor power, while not reducing to a handy rule-of-thumb, can be qualitatively visualized with the use of the charts. For example, if powerplant and payload weights are assumed to remain constant, an increase in specific impulse is equivalent to a translation to the left at a constant weight on the charts of figure 3. Required thrust diminishes accordingly. Figures 4 and 5 indicate that power will be roughly proportional to

thrust. The shapes of the curves in figure 3 are such that, if the initial condition is at a relatively high thrust-to-weight ratio, the first percent increase in specific impulse results in a large (15 to 20%) reduction in reactor power. Further improvements in specific impulse have progressively lesser effects upon reactor power. An increase in I from 800 to 1000 lb/(lb/sec) may be shown to reduce Q_R by about 70 to 80 percent, so that the ratio of percent power reduction to percent impulse increase is only 3 to 1. This concept should be kept in mind when it appears possible to trade specific impulse for power or thrust, noting that net gains appear likely only when starting from relatively high power levels. In other words, reactor power can be expected to optimize near the value corresponding to a thrust-to-weight ratio of 0.2 to 0.3.

UPPER-STAGE APPLICATIONS

Methods and Assumptions

Values of powerplant-plus-payload weight have also been estimated for booster systems using nuclear upper stages with variations of thrust-to-initial-weight ratio from 1.0 down to near the minimum value. Nuclear rocket propulsion has been substituted for chemical in the final stage of Atlas-Centaur, Saturn I, and Nova. In addition, use of a nuclear stage to replace both second and third stages of Saturn I has been investigated. Only one value of specific impulse, 900 lb/(lb/sec), has been considered, and, in all cases, the mission is to put the payload into a 300-statute-mile circular orbit.

Empty weights in orbit have been calculated by means of a trajectory analysis which approximately optimizes the path from the end of the initial boost stage and also optimizes the "kick angle" of the first stage. Flight conditions at first-stage cut-off for appropriate values of "kick angle" were the input to a

trajectory program which employed an approximate closed-form solution of linear-tangent paths in a central-force field. "Kick angle" has been optimized at each thrust-to-weight ratio from 1.0 down to within 0.05 of the value at which the desired circular orbit could not be achieved, with the exception of the second-stage of Saturn I. In the latter case the values of first-stage cut-off conditions available were not adequate to allow approach to the lower limit.

Powerplant-plus-payload weights have been calculated from empty weights by subtraction of tank and structure weights. The tanks and structure are assumed to be of the same configurations as in the orbital-launch vehicles. In the booster application the tank pressures required to maintain tension during a 6g acceleration are increased for the larger vehicles, as listed below:

Booster	Tank Pressure psi
Atlas	23
Saturn I (3rd stage)	23
Saturn I (2nd stage)	52
Nova	59

The 23-psi values are nominal to correspond to the values used in the orbital-launch analysis. An allowance of 15 lb/sq ft of tank surface area has been added for insulation and ablation material. To the resultant tank weights have been added the same structure weights as used in the orbital-launch-vehicle analysis, again as a function of tank diameter. The tank-plus-structure weights thus computed are shown in figure 6 for appropriate ranges of propellant weight.

Allowable-Powerplant-Weight Curves

Curves of powerplant-plus-payload weight as a function of reactor power are presented in figure 7. Power is substituted for thrust on the basis of the assumption

that boost-stage reactors would operate at both high temperature and high pressure, where the ratio of power to thrust is quite insensitive to the temperature-pressure combination involved (figures 4 and 5). Using a pressure of 500 psi for Atlas and Saturn I (third stage) applications and 1000 psi for Saturn I (second stage) and Nova nuclear rocket powerplants, power-to-thrust ratios of 0.0231 and 0.0234 result, respectively.

The variation of powerplant-plus-payload weight with reactor power is shown to be slight. From maximum allowable powerplant weight to the lowest permissible thrust the reduction in powerplant-plus-payload weight is only 3 to 7 percent. Thus, the important criterion in the determination of minimum power is the lower limit of thrust-to-weight ratio rather than any consideration of performance deterioration. In fact, the anticipated variation of powerplant weight with power will cause the optimum-payload conditions to shift to lower powers than those yielding maximum powerplant-plus-payload weight.

As a rough indication of the payload increases resulting from the use of nuclear rocket propulsion in the booster upper stages, some typical powerplant weights have been used in an estimation of the payloads listed below:

Booster	All-Chem Payload lb.	Reactor Power mw	Powerplant + Payload Wt. lb.	Chem-Nu. Payload, lb.	Increase %
Atlas	8,000	250	16,000	13,000	62
Saturn I (N3)	33,000	400	42,100	39,000	18
Saturn I (N2)	33,000	5000	98,700	90,000	173
Nova	238,000	5000	370,000	361,000	52

The last column, which lists the percentage increase in payload due to the substitution of nuclear for chemical propulsion, shows the large effect of the selection

of staging technique. Replacement of the top stage of Saturn I results in only a small gain because the original chemical stage was small. Third-stage replacements on Atlas-Centaur and Nova result in larger gains because more energy is imparted by the top stages of these boosters. Replacement of both second and third stages of Saturn I results in a very large gain, nearly tripling the payload. Performance improvements such as these illustrate the potential which has directed interest toward the boost application of nuclear rockets in spite of the high powers and operating problems which are involved.

CONCLUDING REMARKS

Although simplified calculations never result in information of permanent usefulness, they are often of great value during the formative period of a research and development program. The charts and curves herein presented are intended to serve such a purpose, giving ready-reference indications of allowable powerplant weights and payloads for typical applications of nuclear rockets and permitting rapid estimation of desirable power levels and operating conditions. As more data become available from design studies of nuclear rocket vehicles, estimates of tank, structure, and other weights will change, necessitating alteration of these preliminary results, but the trends shown are not expected to change significantly.

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FIGURE 1 - MASS RATIO CHARTS

(a) LEAVING EARTH

$I = 450$ lb/(lb/sec), $h_0 = 300$ st. mi, Tangential Thrust

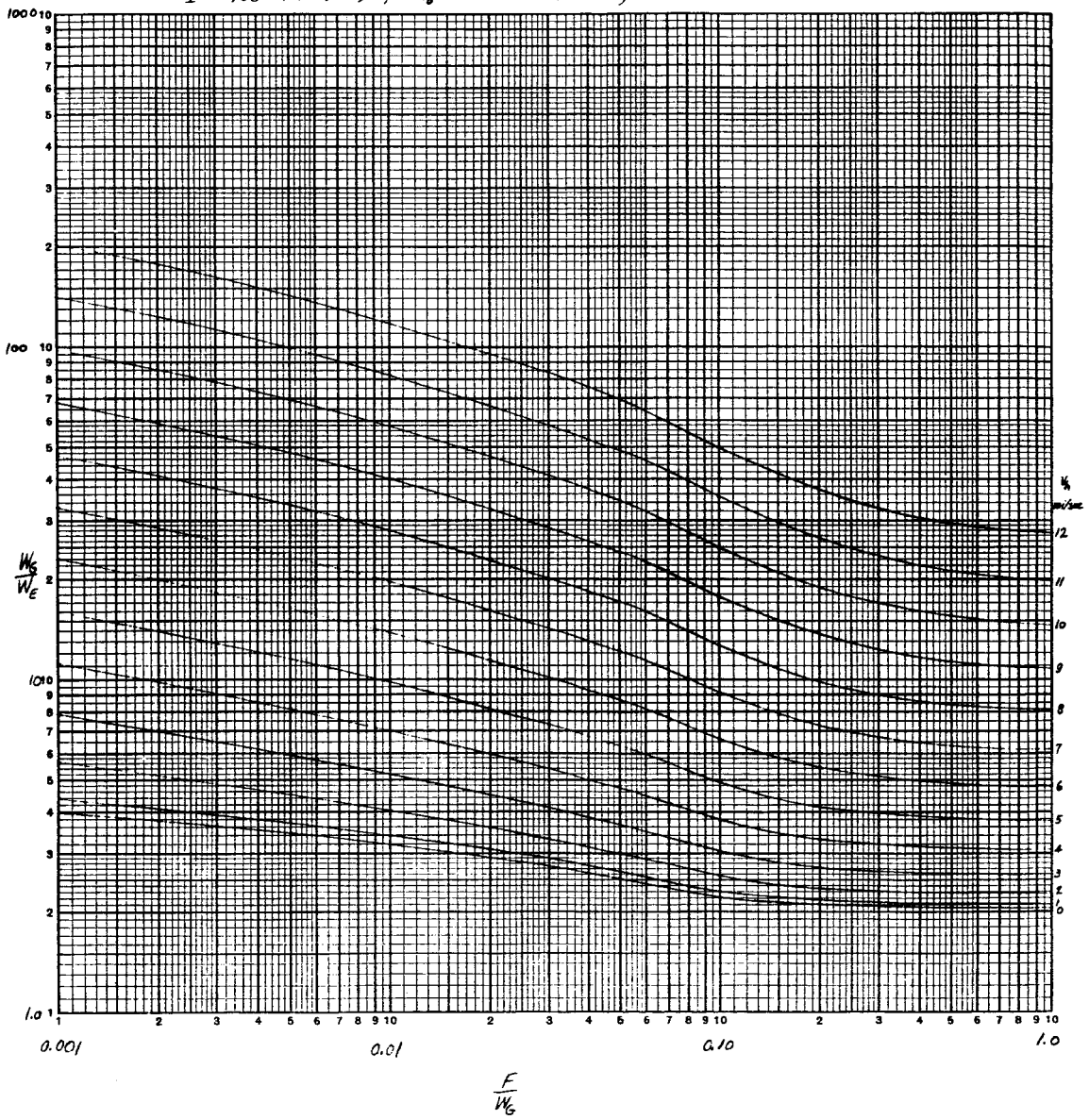


FIG. 1 - MASS RATIO CHARTS

(b) LEAVING EARTH. $I = 600$ LB/(LB/SEC), $h_0 = 300$ MI, TANGENTIAL THRUST

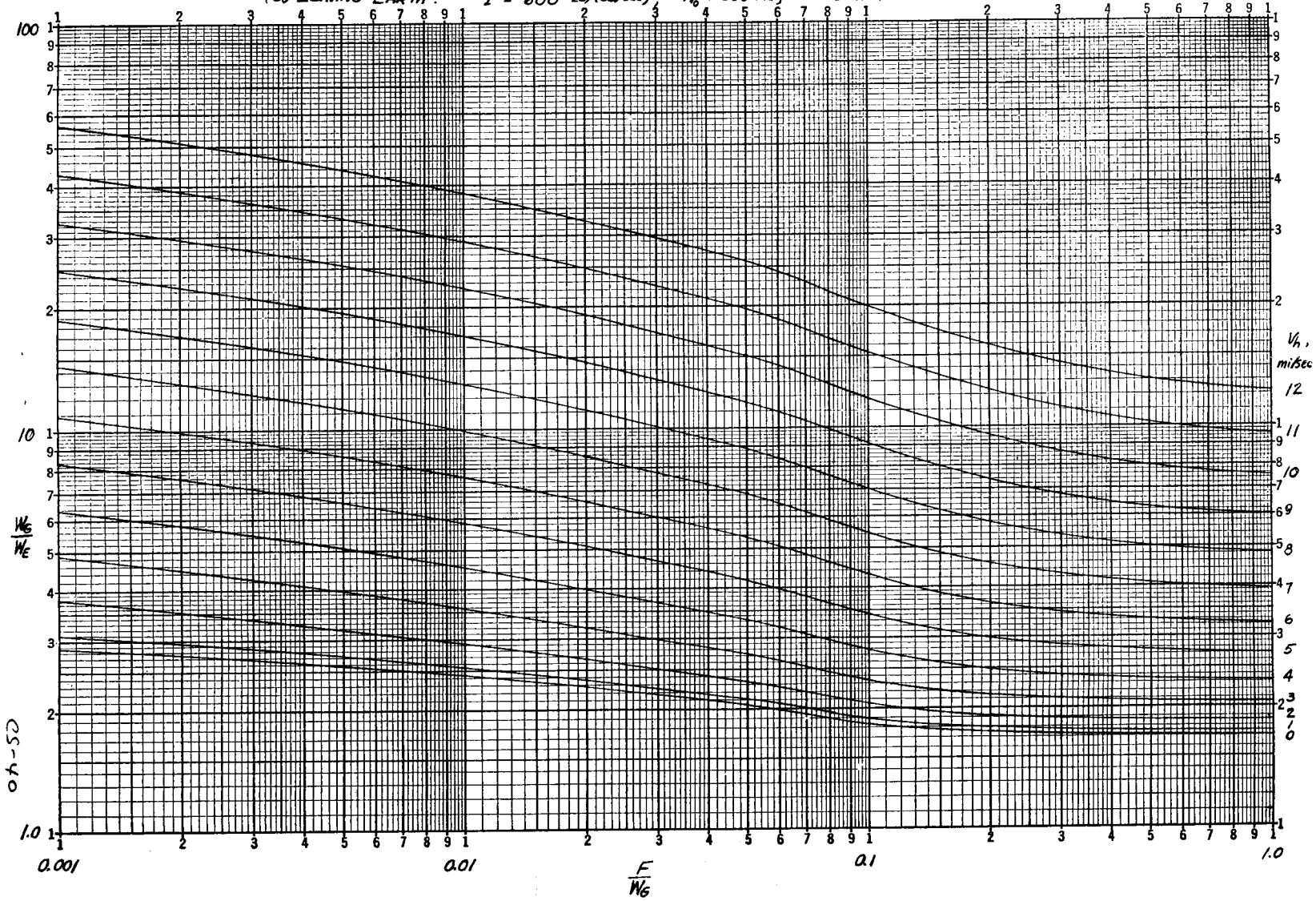


FIG. 1 - MASS RATIO CHARTS

(C) LEAVING EARTH. $I = 800$ LB/(LB/SEC), $h_0 = 300$ MI., TANGENTIAL THRUST

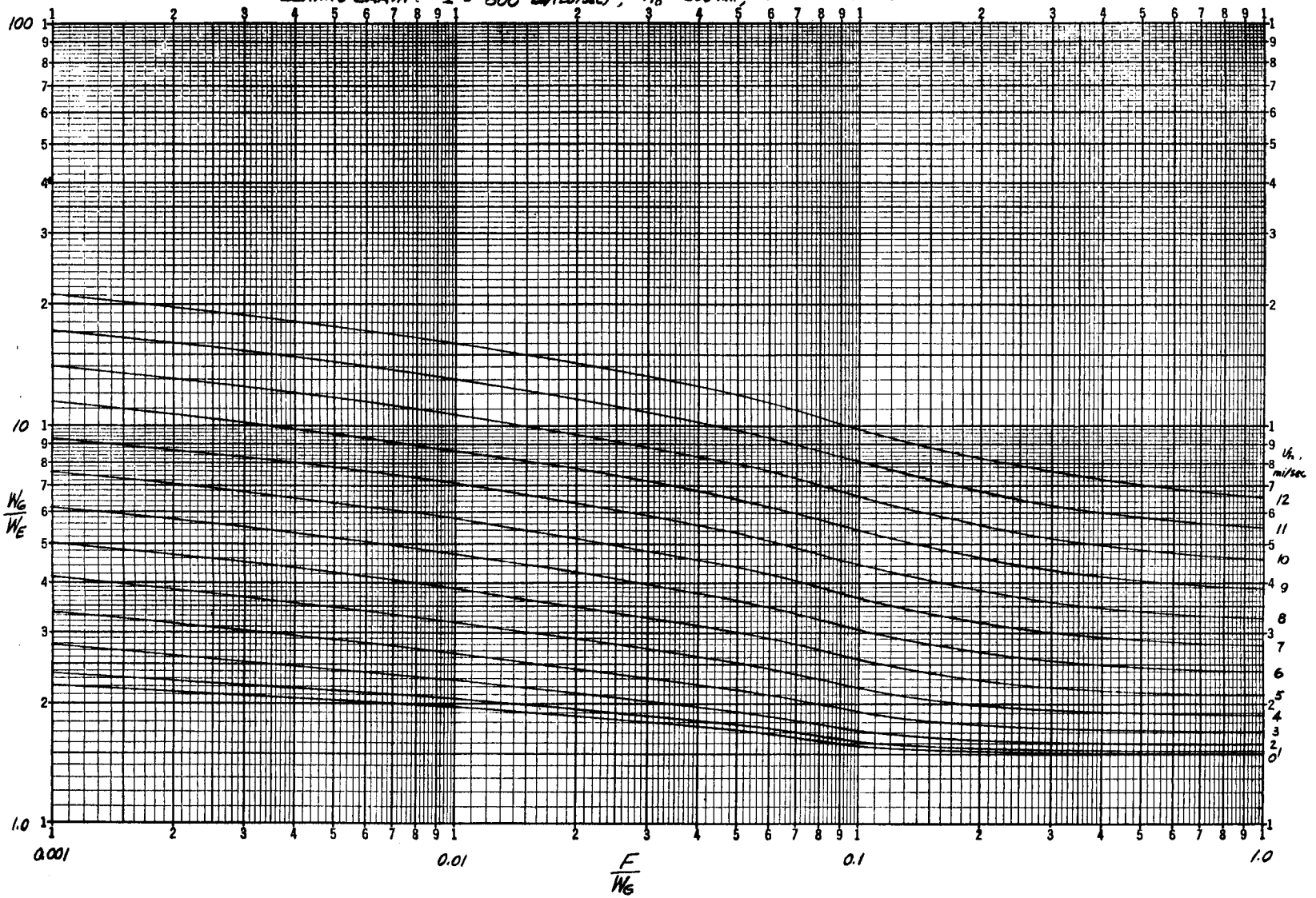
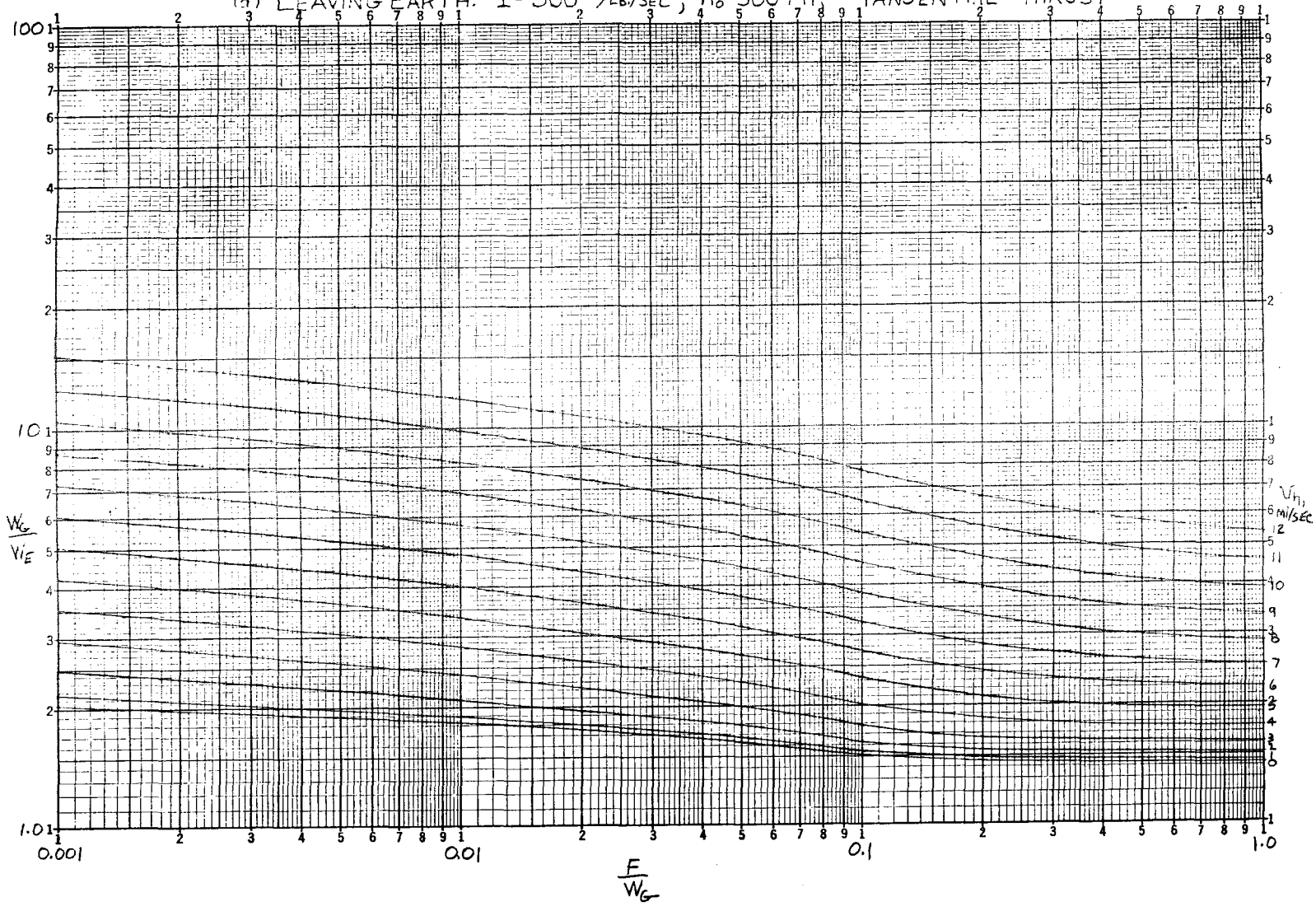


FIG. 1 - MASS RATIO CHARTS

(1) LEAVING EARTH. $I = 900$ LB/LB/SEC, $h_0 = 300$ MI, TANGENTIAL THRUST



L

FIG. 1 - MASS RATIO CHARTS

(f) ENTERING MARS ORBIT. $I = 450$ LB/(LB/SEC), $h_0 = 1000$ MI, TANGENTIAL THRUST

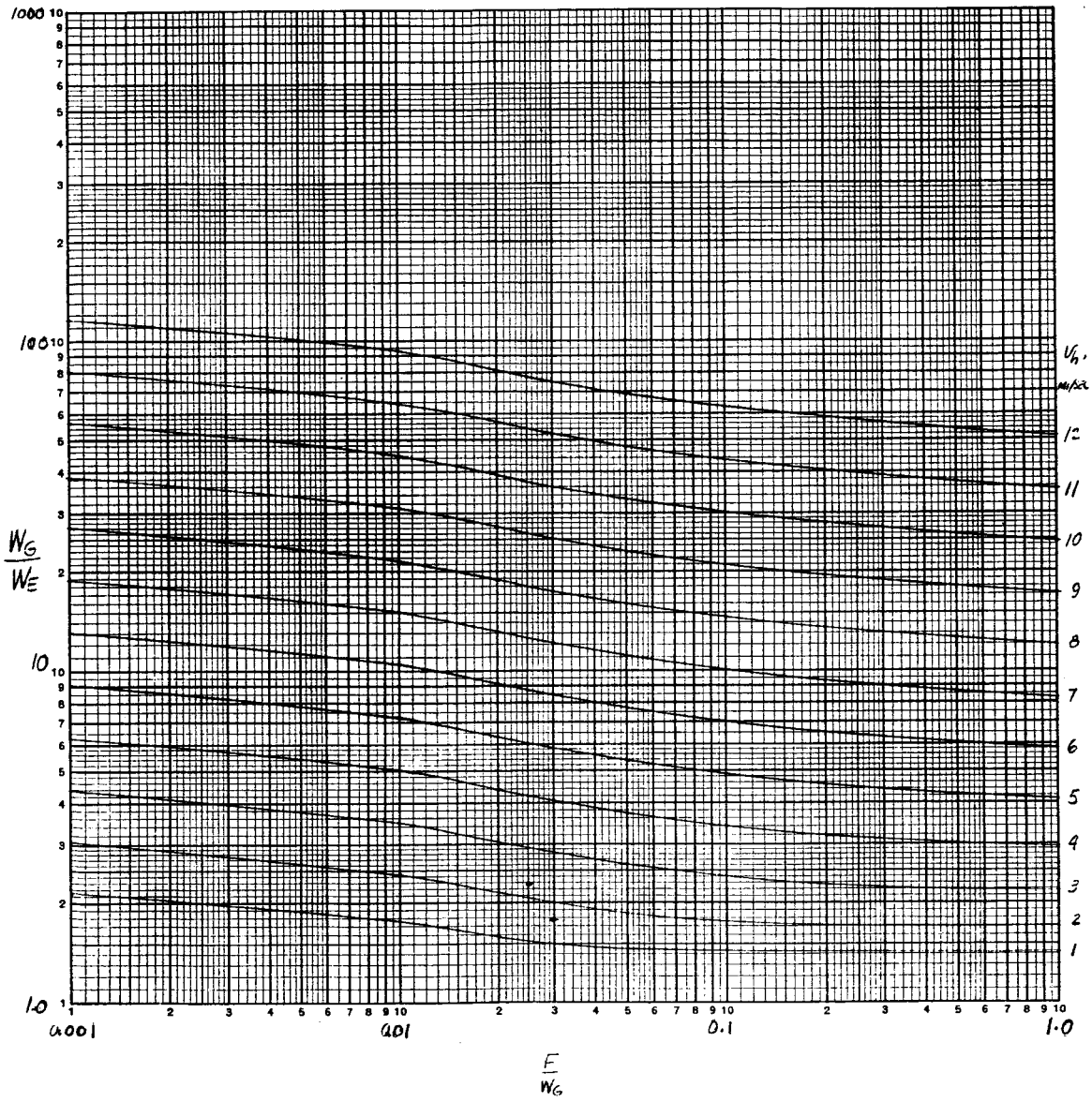


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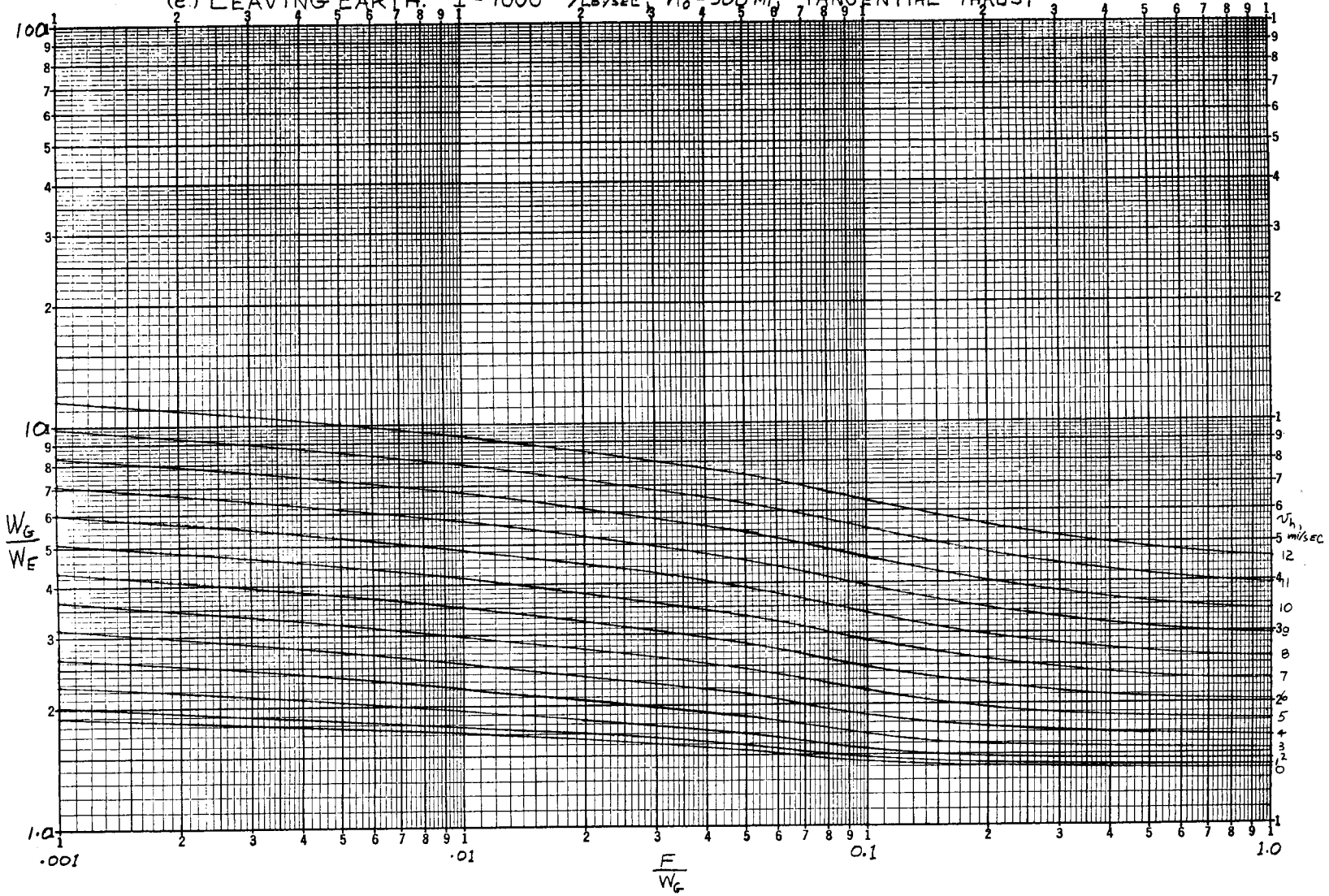
FIG. 1 - MASS RATIO CHARTS

(e.) LEAVING EARTH, $I = 1000$ LB/LB/SEC, $h_0 = 300$ MI, TANGENTIAL THRUST



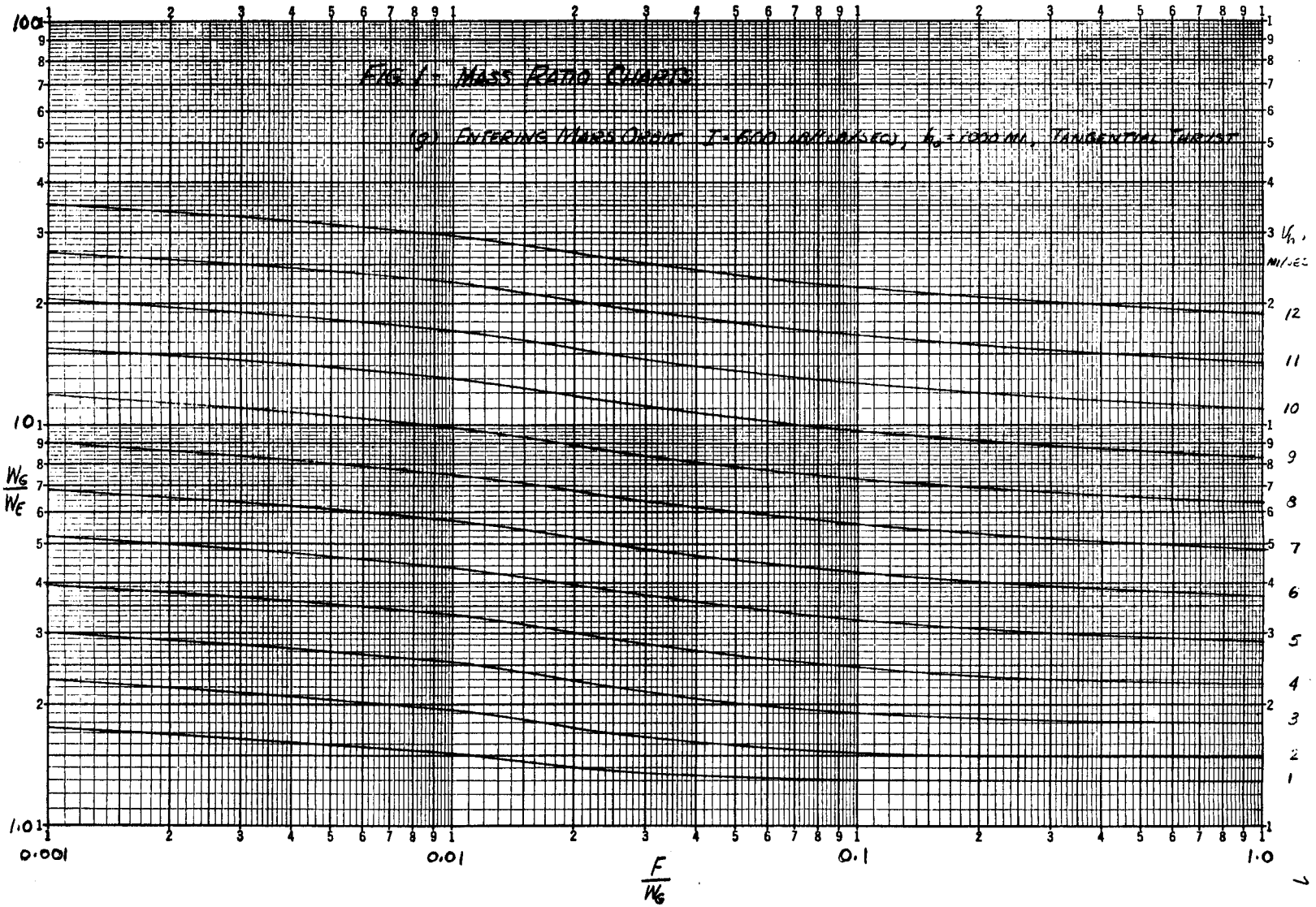


FIG 1 - MASS RATIO CHART
(a) ENTERING MASS ORBIT I = 600 LB/(LB/SEC), h_a = 1000 MI, TANGENTIAL THRUST
W_G/W_E
100
10
1.0
0.001
0.01
0.1
1.0
F/W_G
V_h, MI/SEC
12
11
10
9
8
7
6
5
4
3
2
1

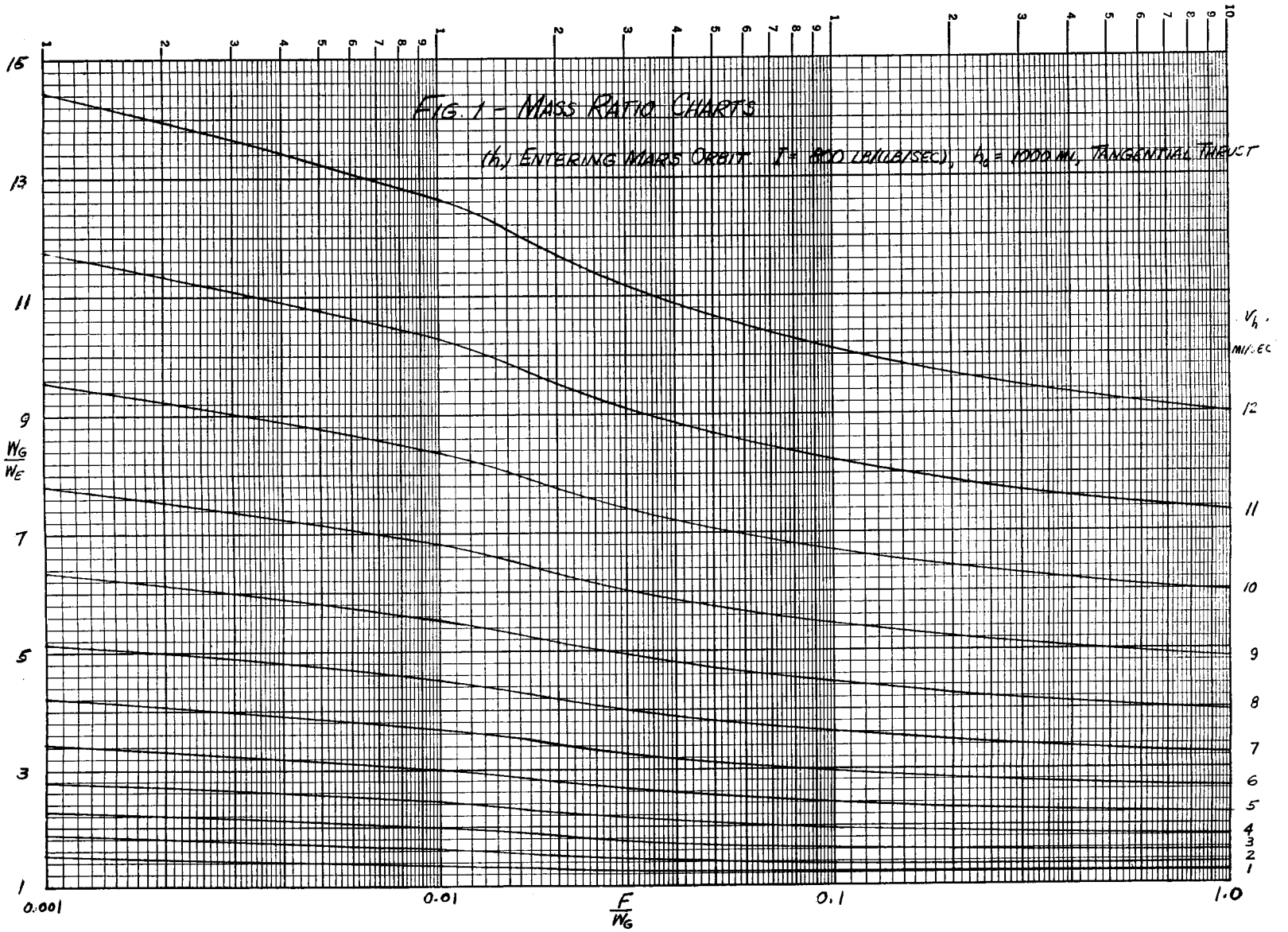


FIG. 1 - MASS RATIO CHARTS

(h_1) ENTERING MARS ORBIT. I = 800 LBF(LB/SEC), h_0 = 1000 MI, TANGENTIAL THRUST

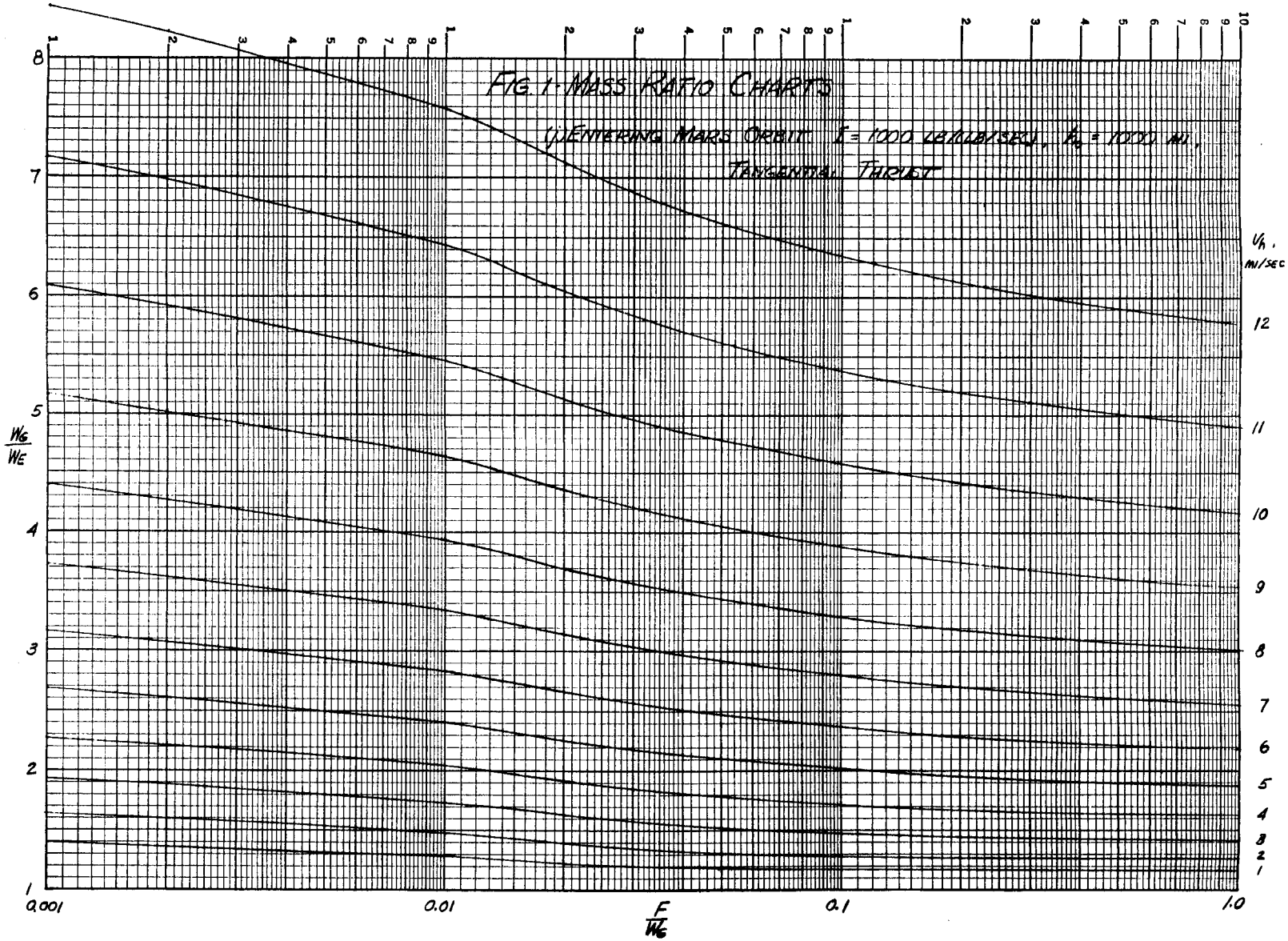


FIG. 1 - MASS RATIO CHARTS
(1) ENTERING MARS ORBIT, F = 1000 LB/(LB/SEC), h_p = 1000 MI.
TANGENTIAL THRUST
W_G / W_E
F / W_G
V_h, MI/SEC
0.001
0.01
0.1
1.0

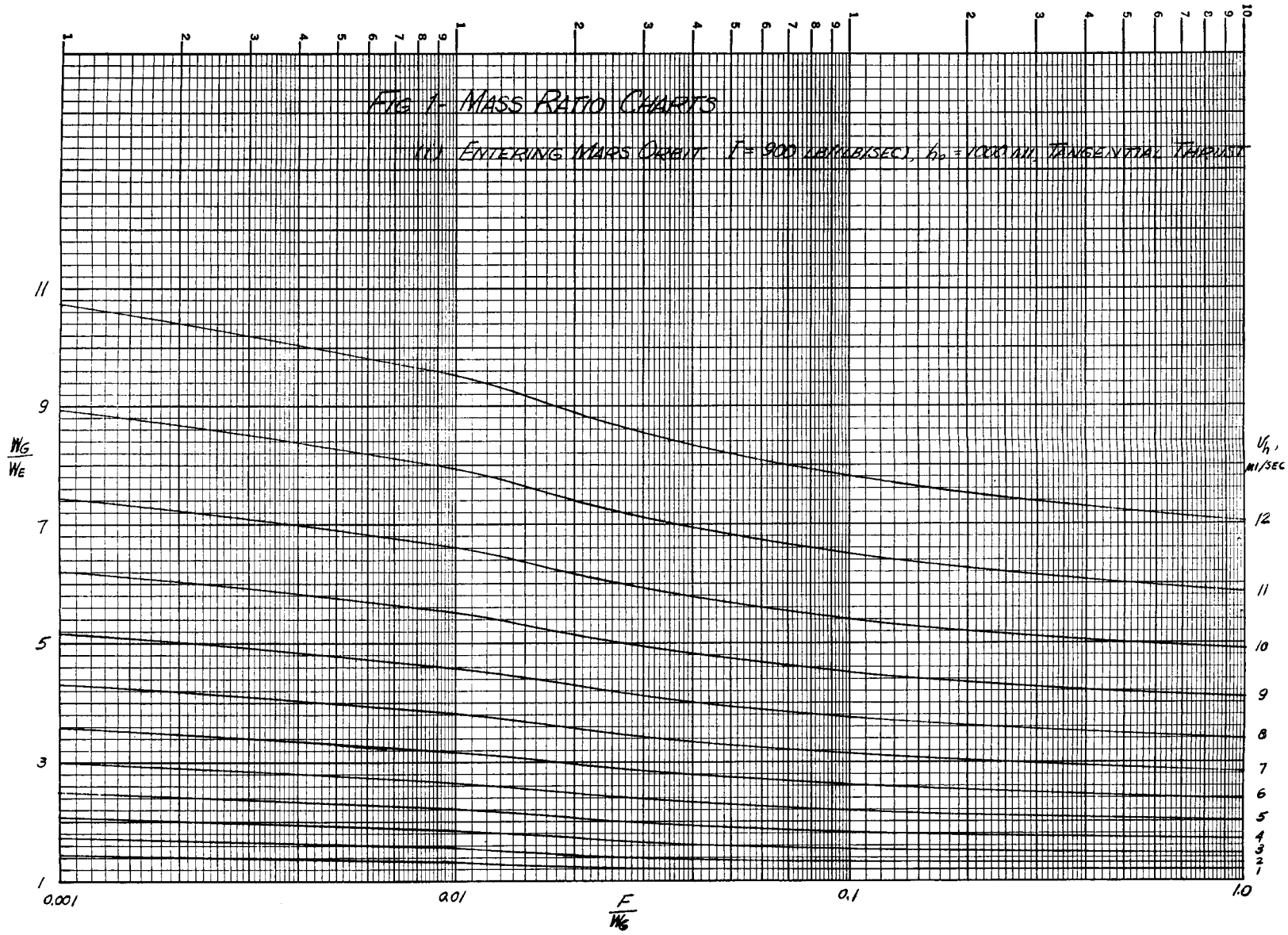


FIG 1- MASS RATIO CHARTS
(1) ENTERING MARS ORBIT F = 900 LBF(LBF/SEC), h₀ = 1000 MI, TANGENTIAL THRUST
W_G / W_E
11
9
7
5
3
1
0.001
0.01
0.1
1.0
F / W_G
V_h, MI/SEC
12
11
10
9
8
7
6
5
4
3
2
1

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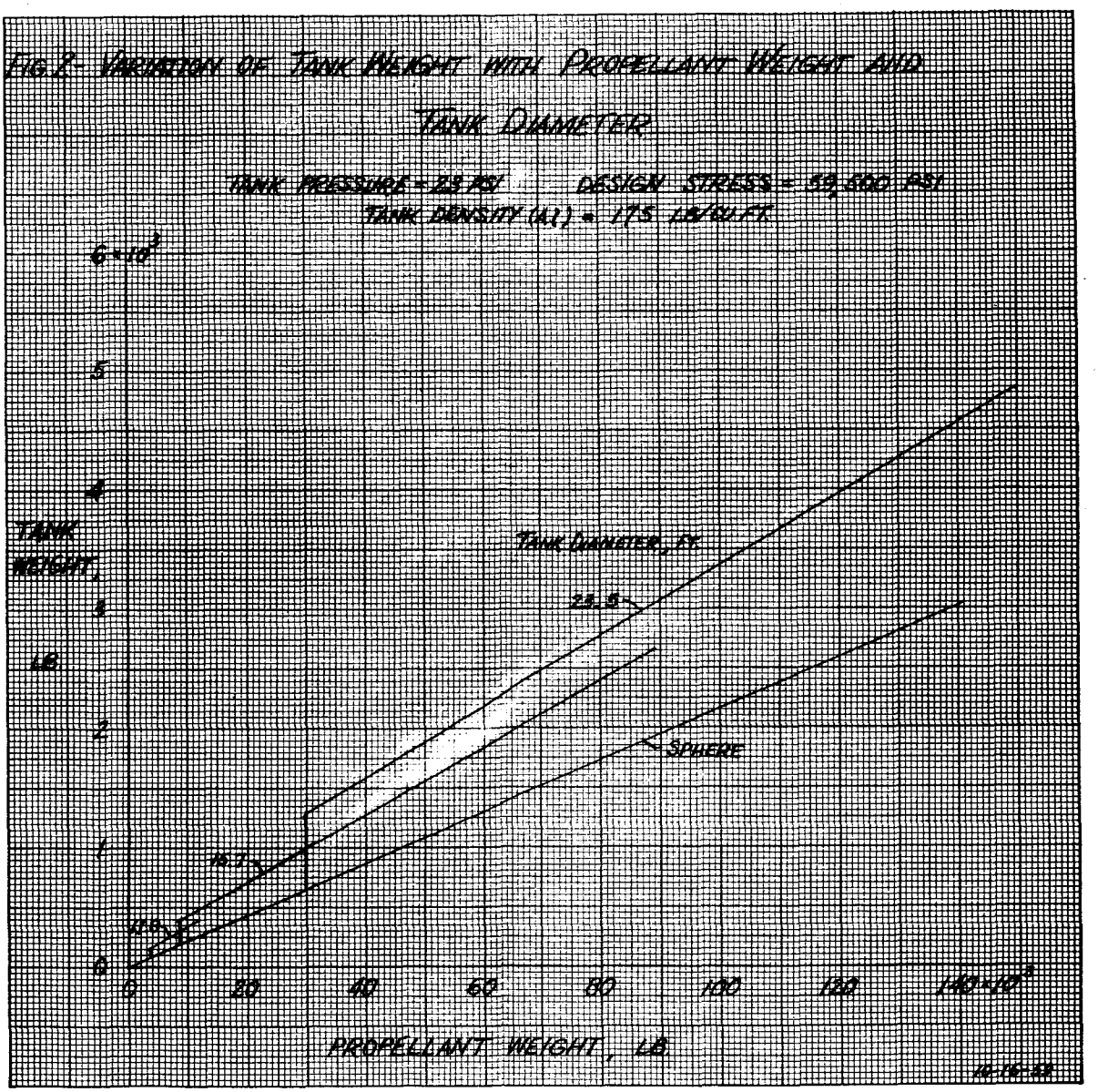


FIG. 2- VARIATION OF TANK WEIGHT WITH PROPELLANT WEIGHT AND TANK DIAMETER
TANK PRESSURE = 25 PSI
DESIGN STRESS = 59,500 PSI
TANK DENSITY (Al) = 175 LB/CU FT
TANK WEIGHT, LB
6×10³
5
4
3
2
1
0
TANK DIAMETER, FT
23.5
16.7
11.8
SPHERE
0
20
40
60
80
100
120
140×10³
PROPELLANT WEIGHT, LB

FIGURE 9 - ALLOWABLE POWERPLANT-WEIGHT CHARTS
(a) INITIAL WEIGHT IN ORBIT, 7600 LB (ATLAS-CENTAUR); MISSION, ESCAPE FROM EARTH (ΔV = 1.96 MPS)

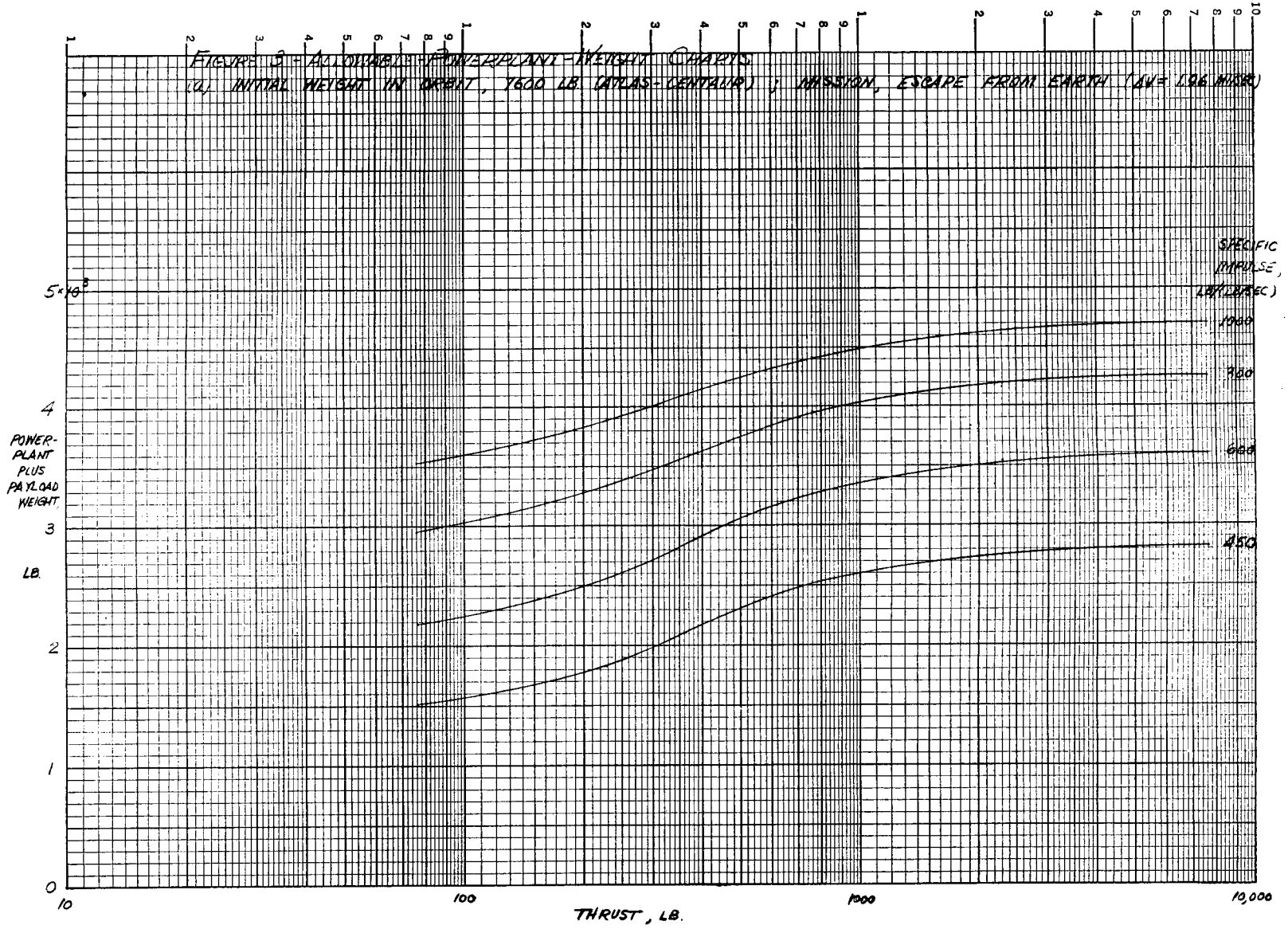
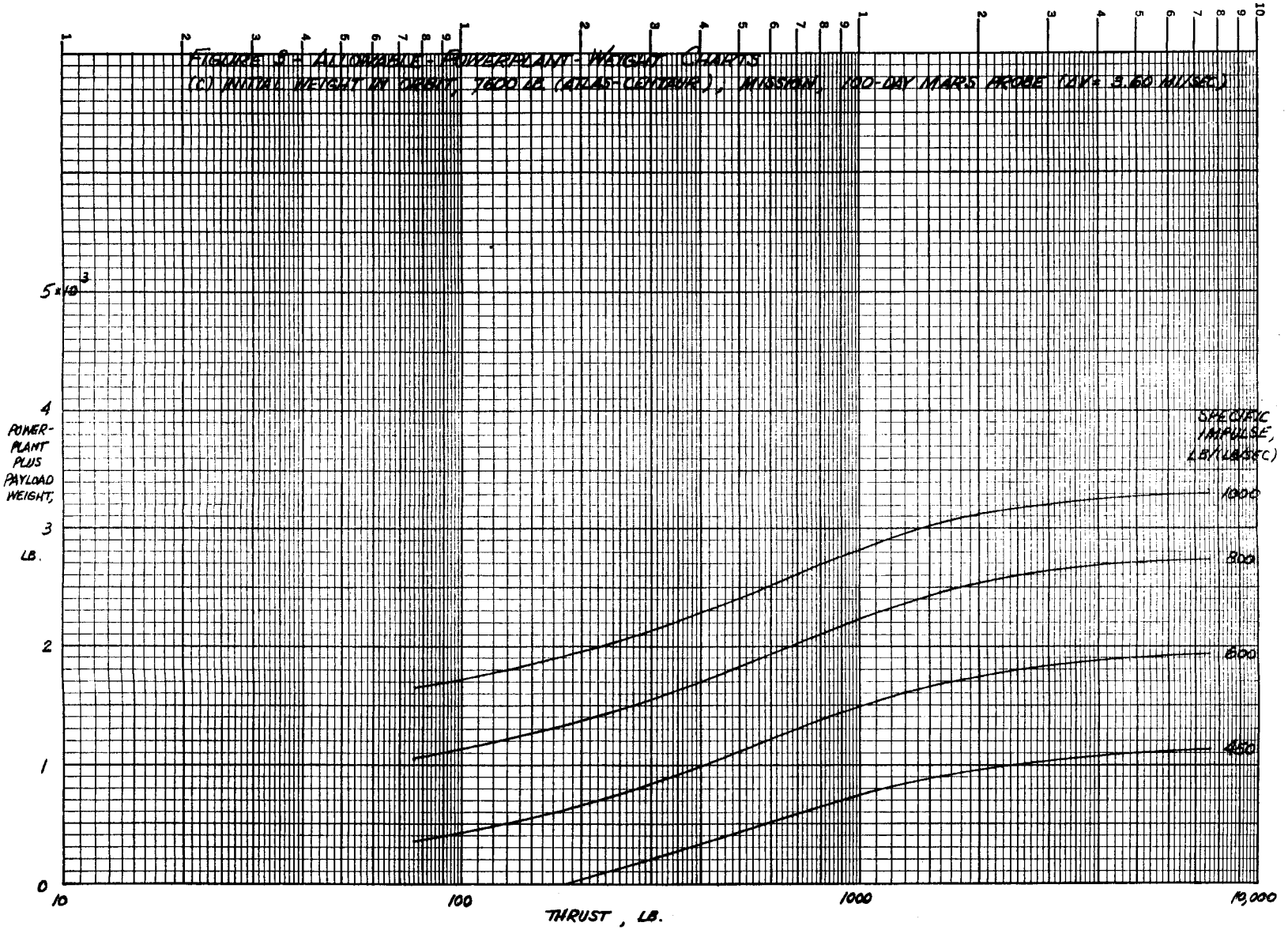


FIGURE 9 - ALLOWABLE POWERPLANT-WEIGHT CHARTS
(C) INITIAL WEIGHT IN ORBIT, 7600 LB. (ATLAS-CENTAUR), MISSION, 100-DAY MARS PROBE (ΔV = 3.60 MI/SEC)



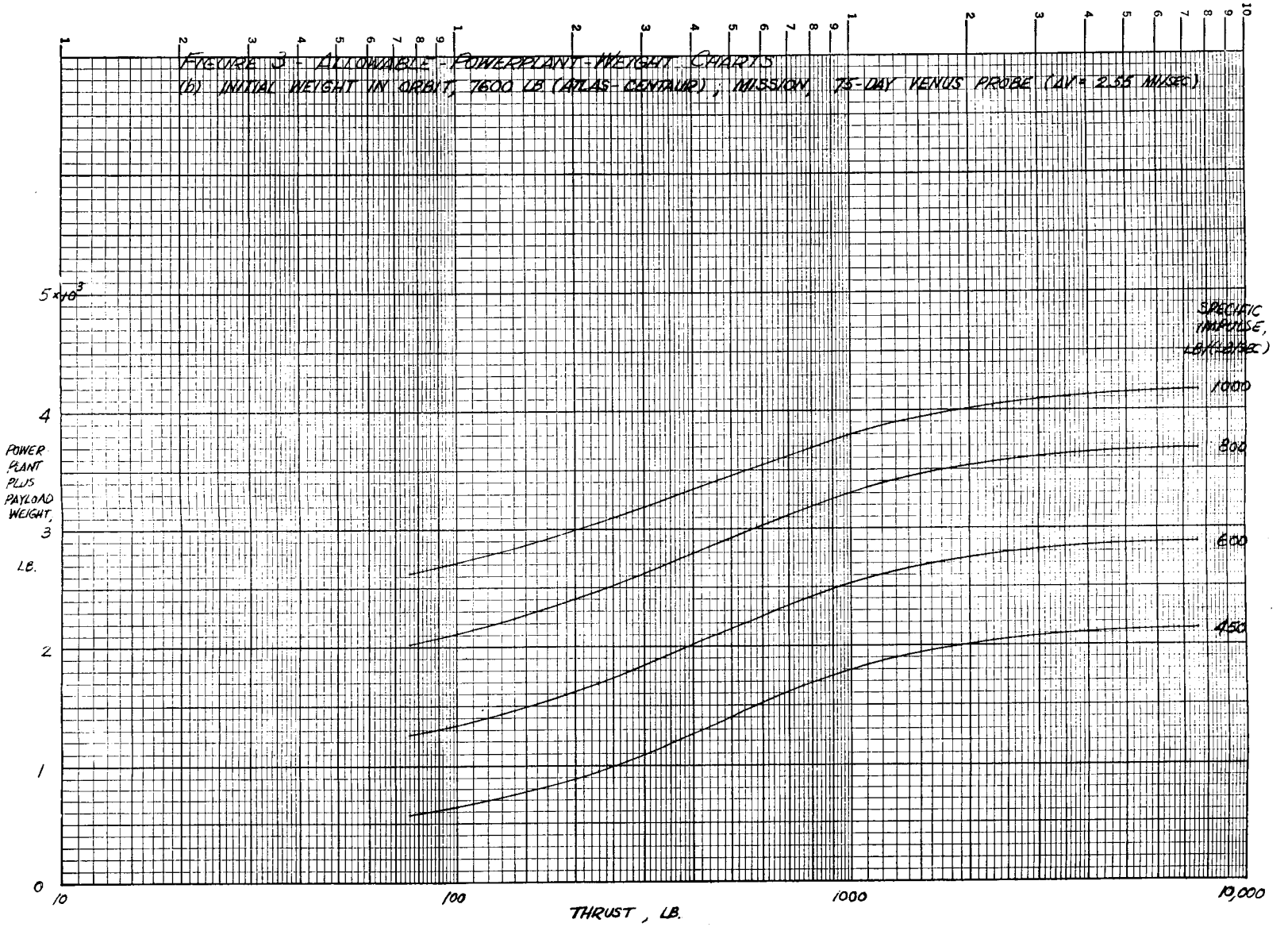
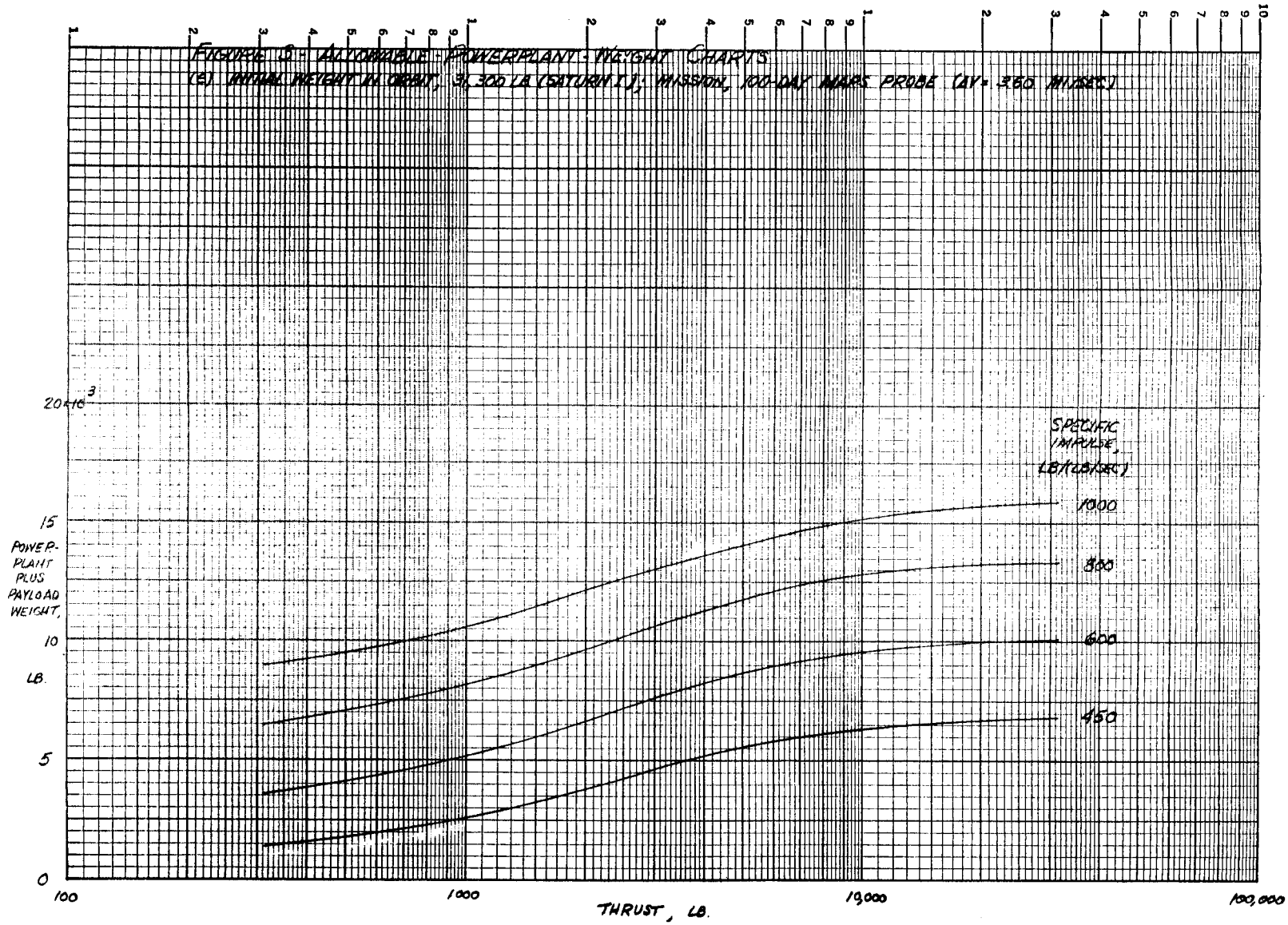


FIGURE 3 - ALLOWABLE - POWERPLANT - WEIGHT CHARTS
(b) INITIAL WEIGHT IN ORBIT, 7600 LB (ATLAS-CENTAUR), MISSION, 75-DAY VENUS PROBE (ΔV = 2.55 MI/SEC)
SPECIFIC IMPULSE, LB/(LB/SEC)
1000
800
600
450
POWER PLANT PLUS PAYLOAD WEIGHT, LB.
5 × 10^3
4
3
2
1
0
10
100
1000
10,000
THRUST, LB.

FIGURE 6 - AUTOMOBILE POWERPLANT WEIGHT CHARTS

(E) INITIAL WEIGHT IN ORBIT, 3,300 LB (SATURN I); MISSION, 100-DAY MARS PROBE (ΔV = 360 M/SEC)



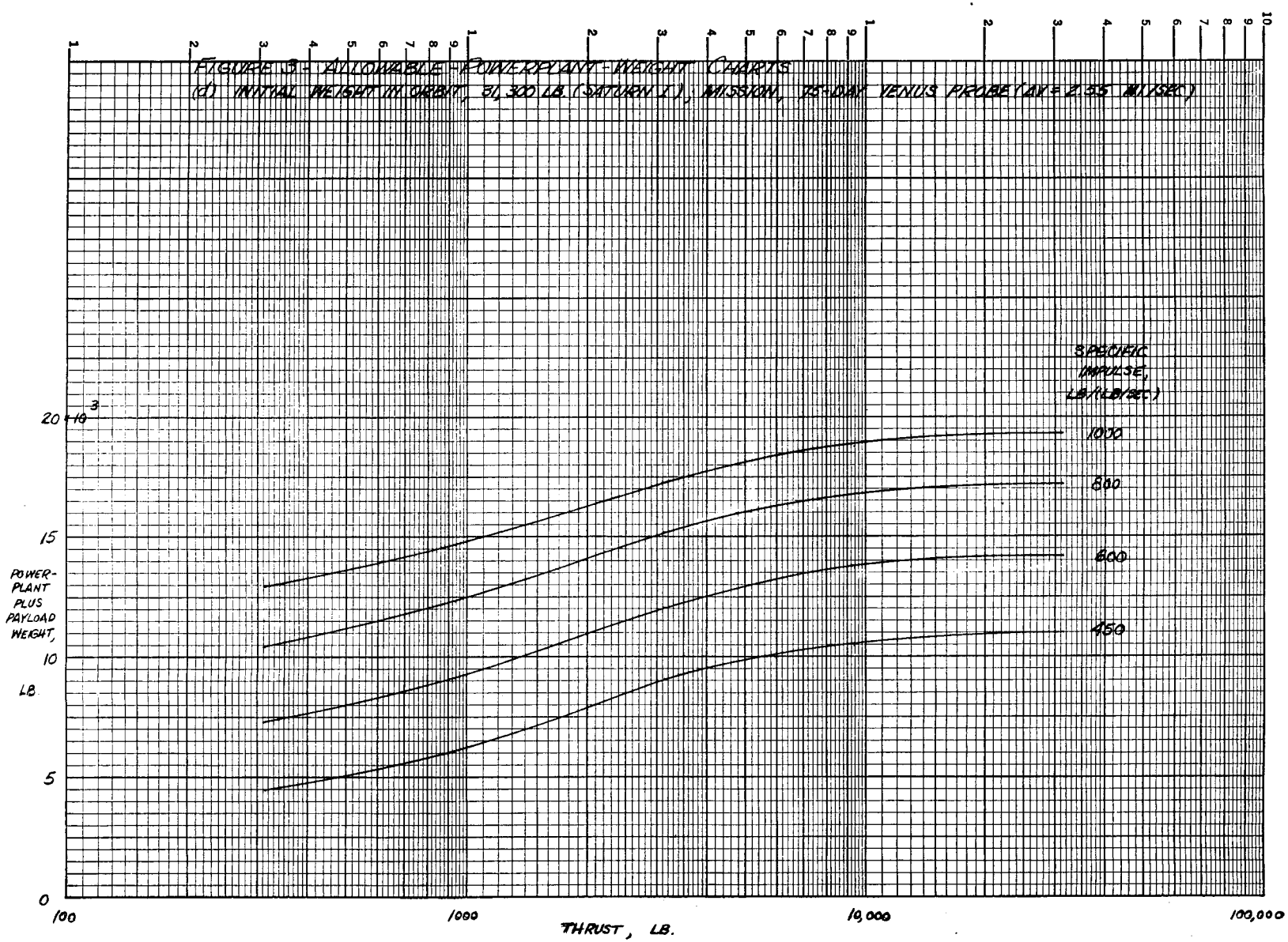
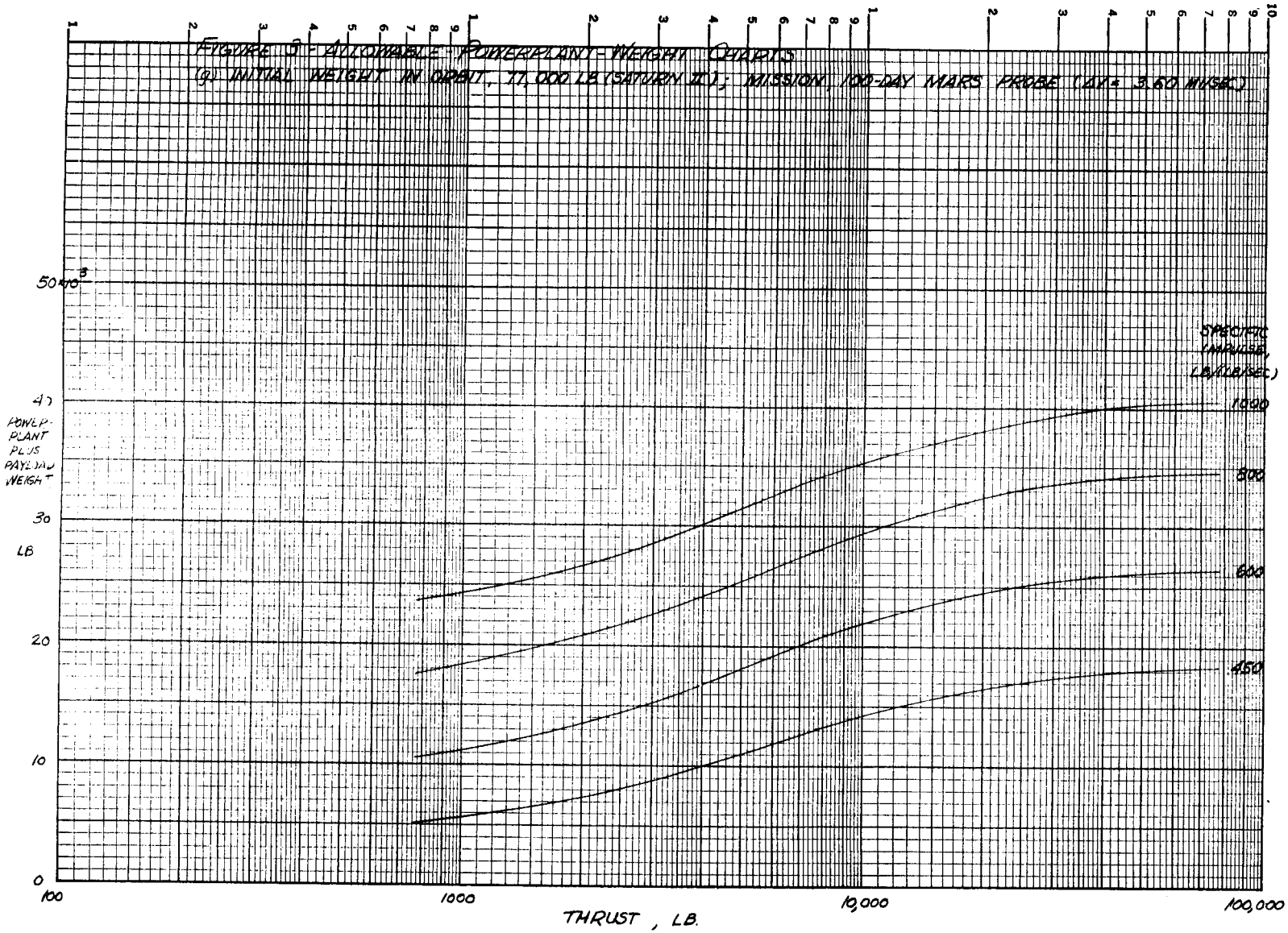


FIGURE 3 - ALLOWABLE-POWERPLANT-WEIGHT CHARTS

(d) INITIAL WEIGHT IN ORBIT, 31,300 LB. (SATURN I), MISSION, 75-DAY VENUS PROBE (ΔV = 2.55 MI/SEC)

FIGURE 5 - AVAILABLE POWERPLANT WEIGHT CURVES
(a) INITIAL WEIGHT IN ORBIT, 77,000 LB (SATURN IV); MISSION, 100-DAY MARS PROBE (ΔV = 3.60 MI/SEC)



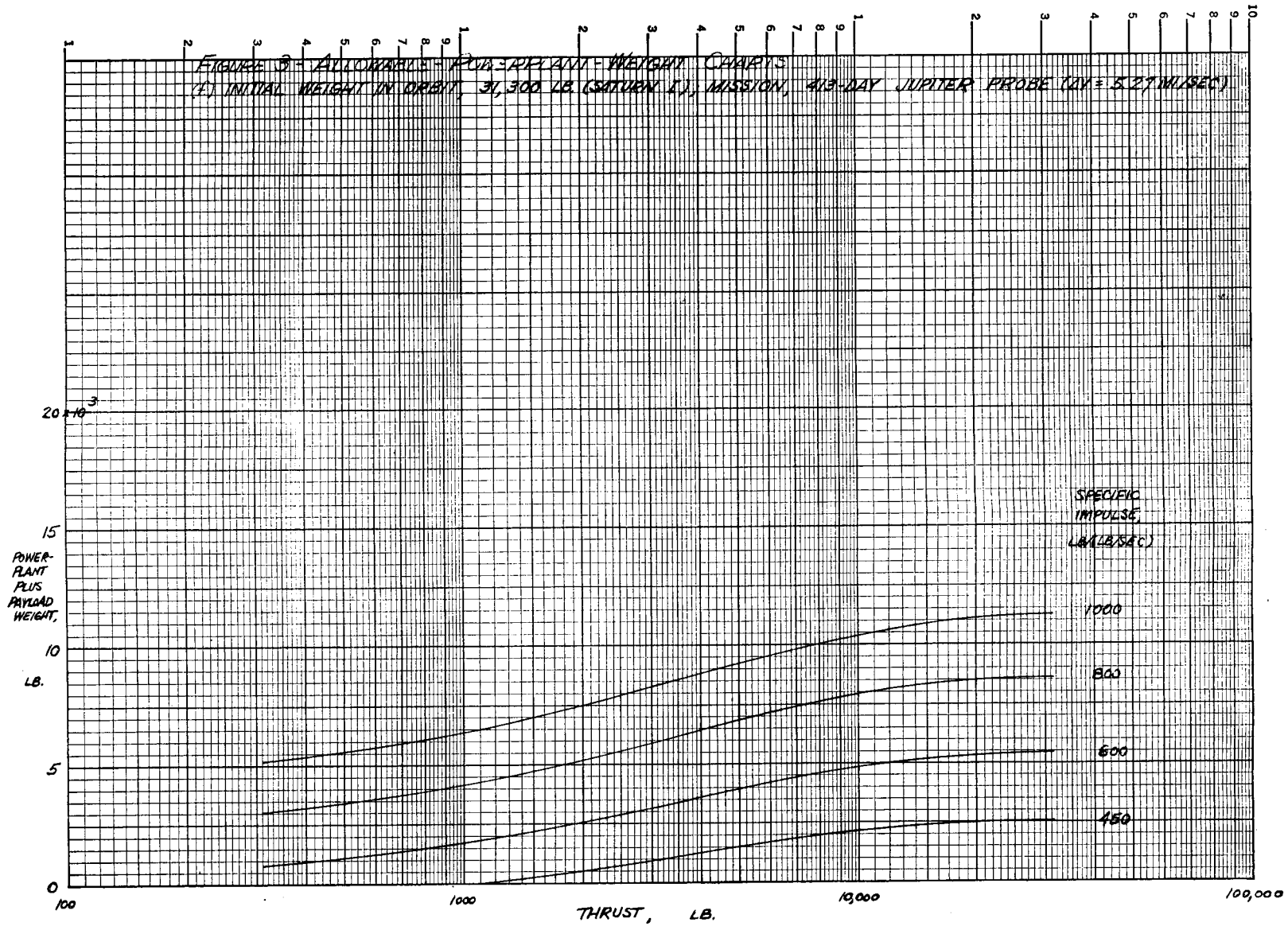


FIGURE 5 - AUTOMATIC - POWERPLANT - WEIGHT CHARTS
(7) INITIAL WEIGHT IN ORBIT, 31,300 LB. (SATURN I) MISSION, 413-DAY JUPITER PROBE (ΔV = 5.27 M/SEC)
20 x 10^3
15
10
5
0
POWER-PLANT PLUS PAYLOAD WEIGHT, LB.
100
1000
10,000
100,000
THRUST, LB.
SPECIFIC IMPULSE, LB(LB/SEC)
1000
800
600
450

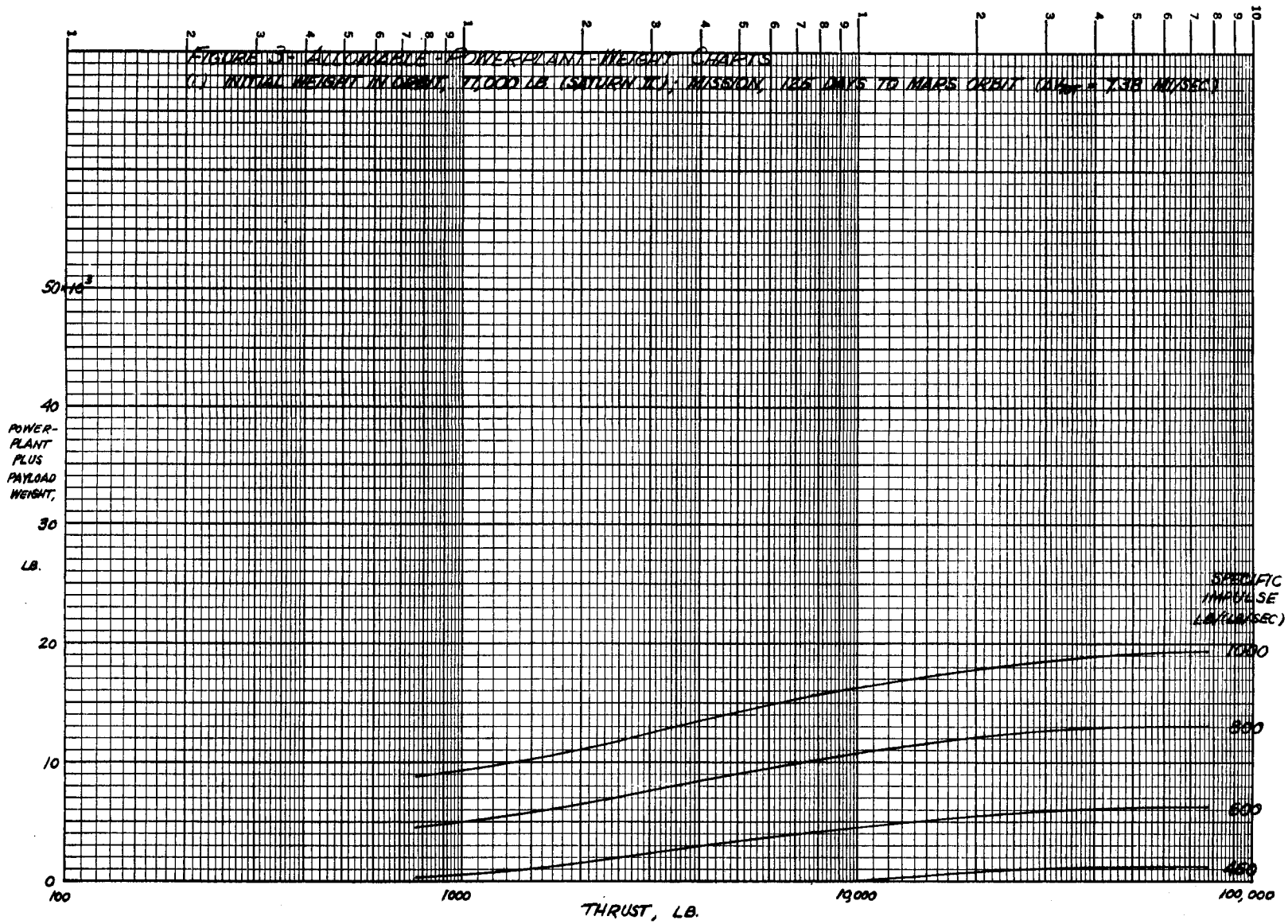


FIGURE 13. ALLOWABLE POWERPLANT-WEIGHT CHARTS
(1) INITIAL WEIGHT IN ORBIT, 77,000 LB (SATURN IC); MISSION, 125 DAYS TO MARS ORBIT (ΔV_{tot} = 7.38 KM/SEC)

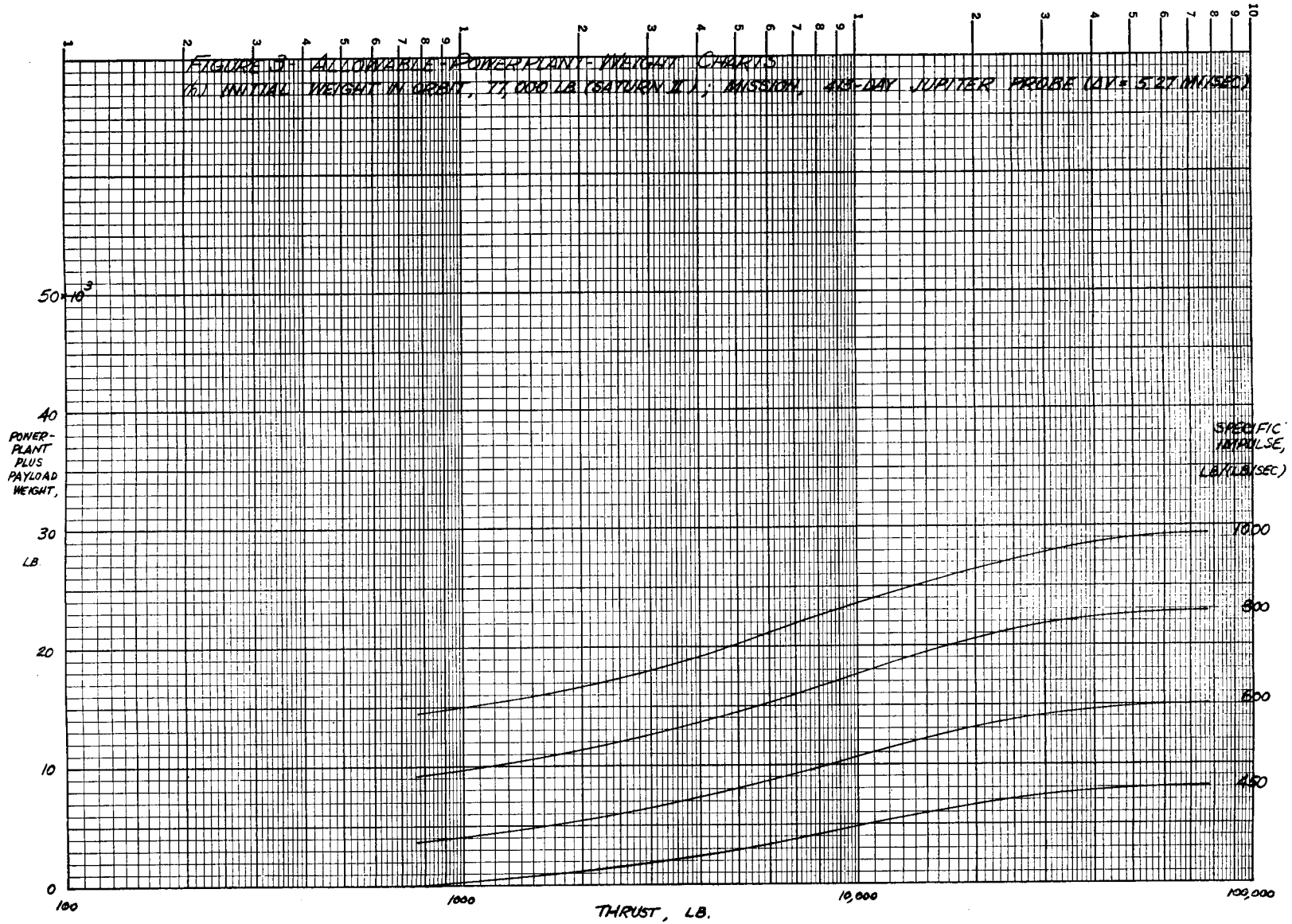
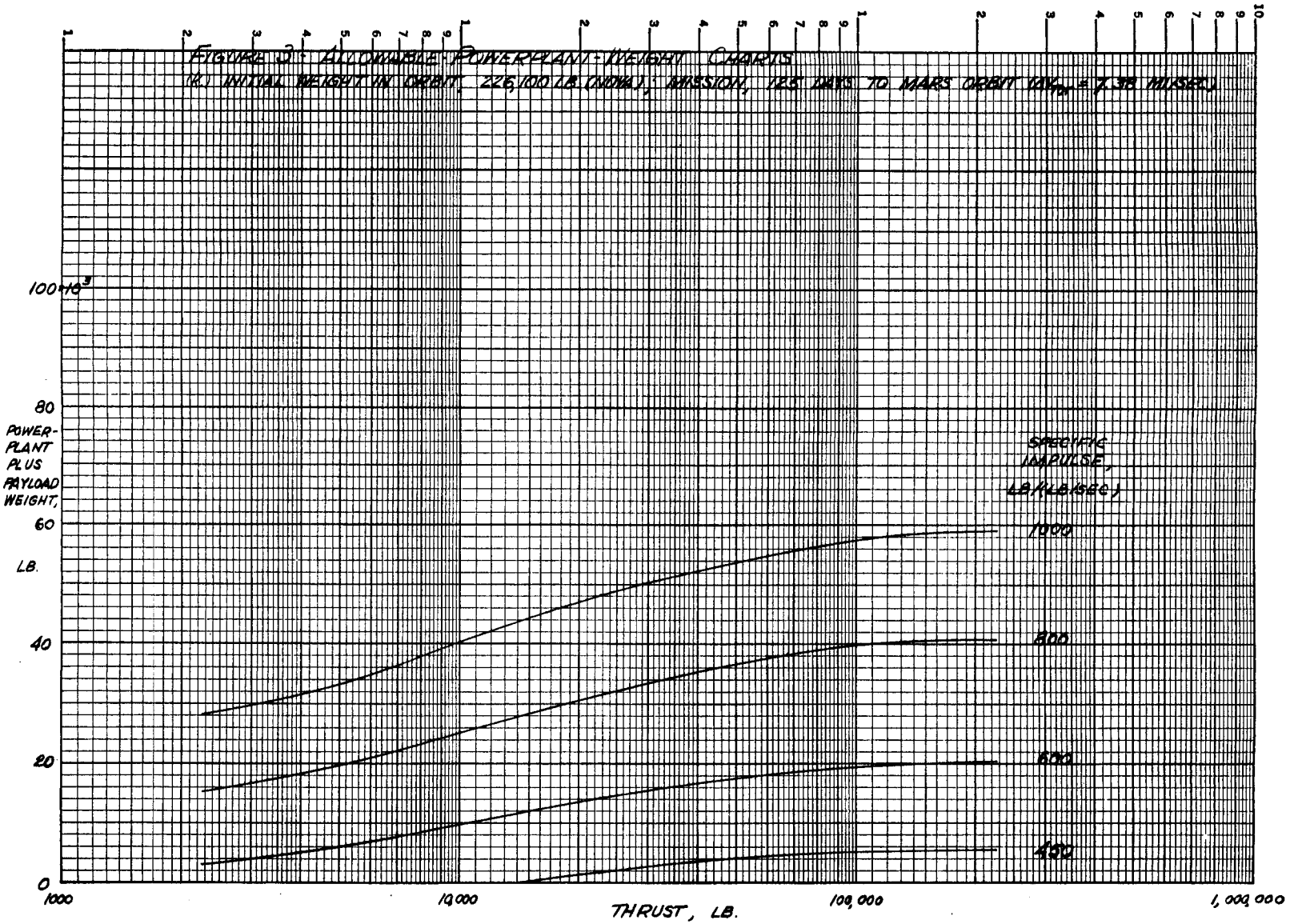


FIGURE 3.- ALLOWABLE POWERPLANT-WEIGHT CHARTS

(b) INITIAL WEIGHT IN ORBIT, 77,000 LB (SATURN V); MISSION, 423-DAY JUPITER PROBE (ΔV = 5.27 KM/SEC)

FIGURE 3: ALLOWABLE-POWERPLANT-WEIGHT CHARTS

(a) INITIAL WEIGHT IN ORBIT, 226,100 LB. (NOMA); MISSION, 165 DAYS TO MARS ORBIT (ΔV_{TOT} = 7.38 MI/SEC)



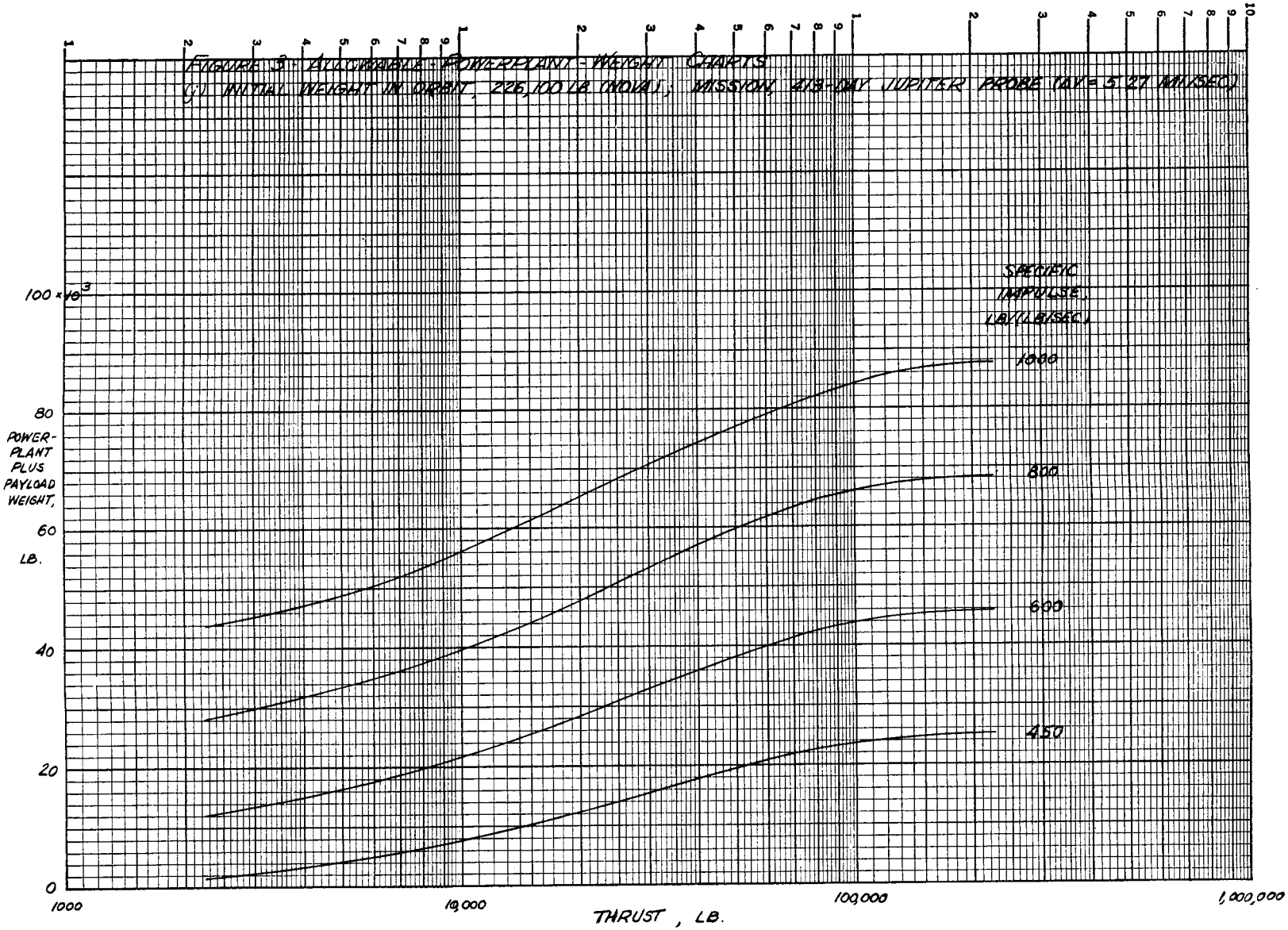


FIGURE 3. ALLOWABLE POWERPLANT WEIGHT CHARTS

(a) INITIAL WEIGHT IN ORBIT, 226,100 LB (NOVA); MISSION, 413-DAY JUPITER PROBE (ΔV = 5.27 MI/SEC)

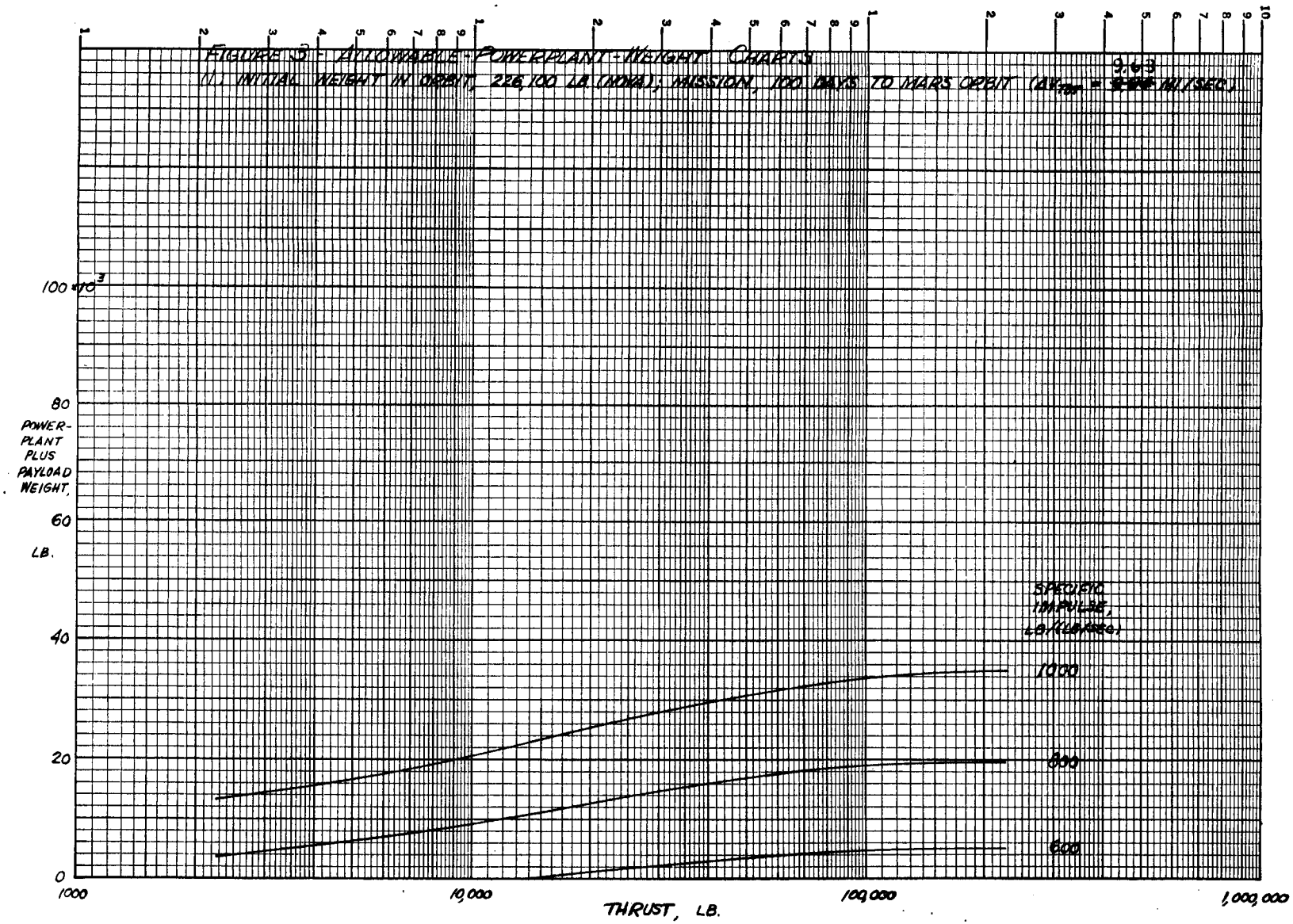


FIGURE 3 - ALLOWABLE POWERPLANT WEIGHT CHARTS

(1) INITIAL WEIGHT IN ORBIT, 226,100 LB (NOVA); MISSION, 100 DAYS TO MARS ORBIT (ΔV_{TOT} = 9.63 MI/SEC).

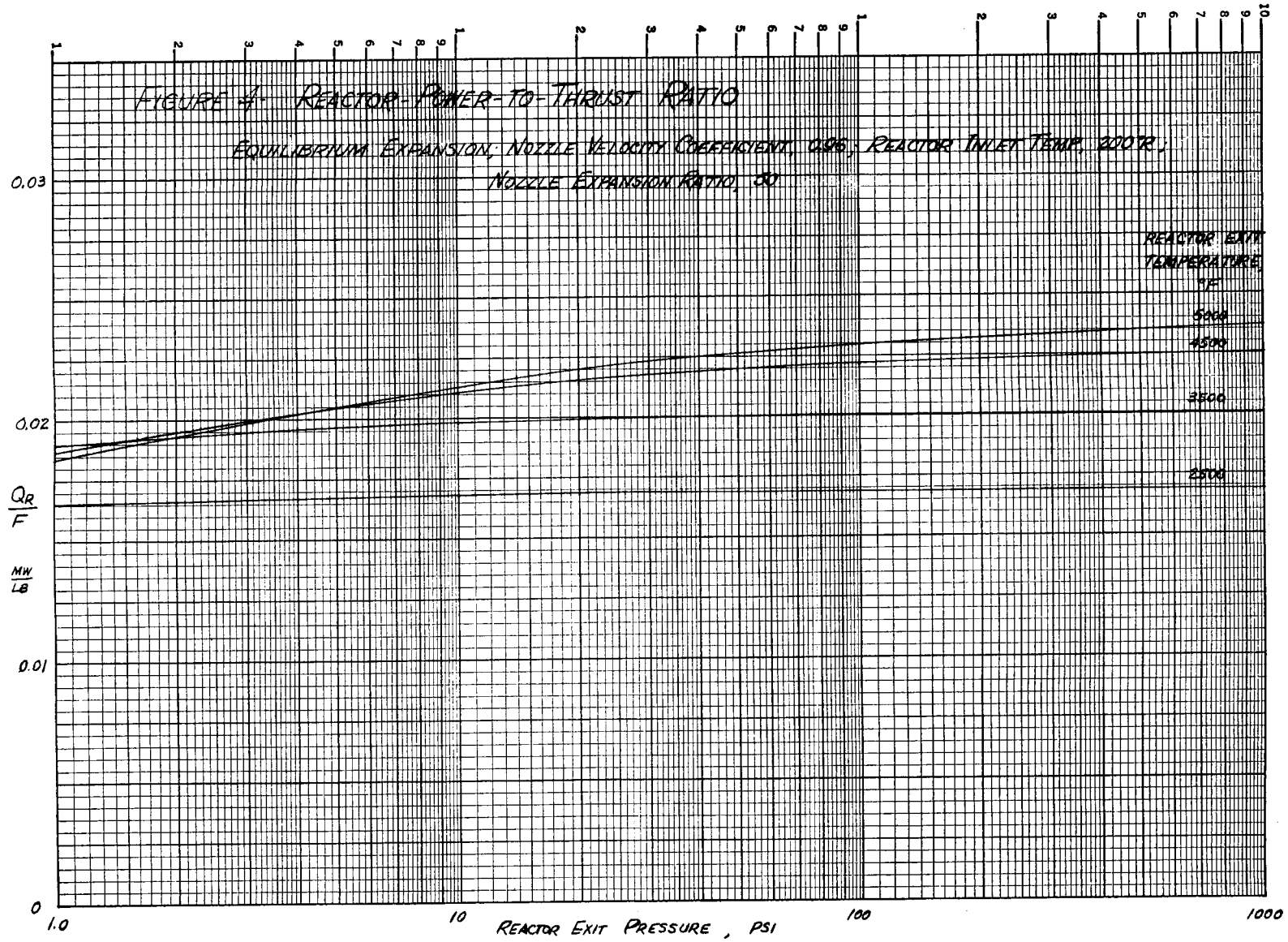


FIGURE 4 - REACTOR-POWER-TO-THRUST RATIO
EQUILIBRIUM EXPANSION; NOZZLE VELOCITY COEFFICIENT, 0.96; REACTOR INLET TEMP. 200°R;
NOZZLE EXPANSION RATIO, 30
REACTOR EXIT TEMPERATURE, °F
5000
4500
3500
2500
0.03
0.02
0.01
0
$\frac{Q_R}{F}$ $\frac{MW}{LB}$
1.0
10
100
1000
REACTOR EXIT PRESSURE, PSI

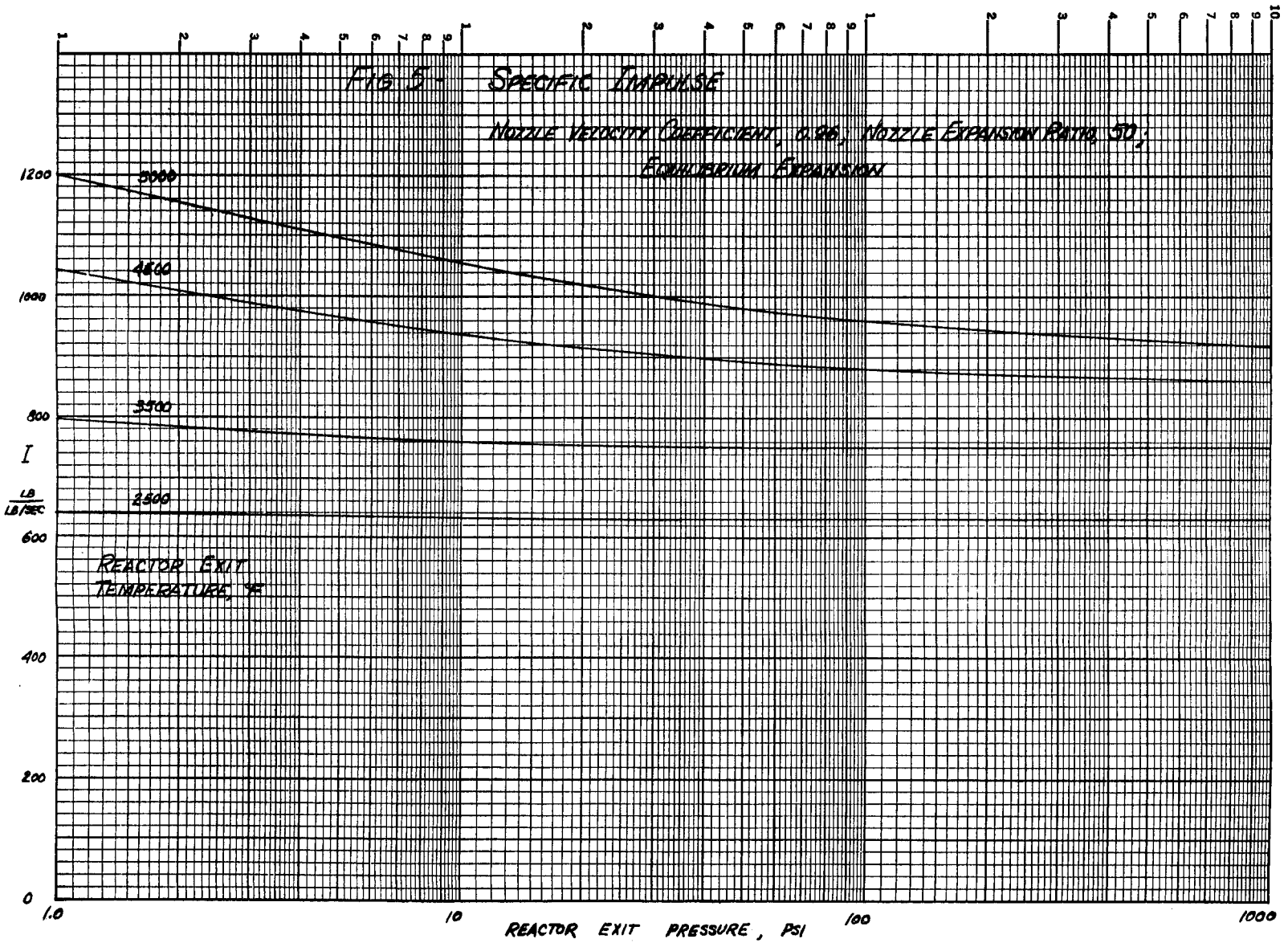


FIG 5 - SPECIFIC IMPULSE
NOZZLE VELOCITY COEFFICIENT, 0.96; NOZZLE EXPANSION RATIO, 50;
EQUILIBRIUM EXPANSION
5000
4500
3500
2500
REACTOR EXIT TEMPERATURE, °F
I
LB/LB/SEC
1200
1000
800
600
400
200
0
1.0
10
100
1000
REACTOR EXIT PRESSURE, PSI

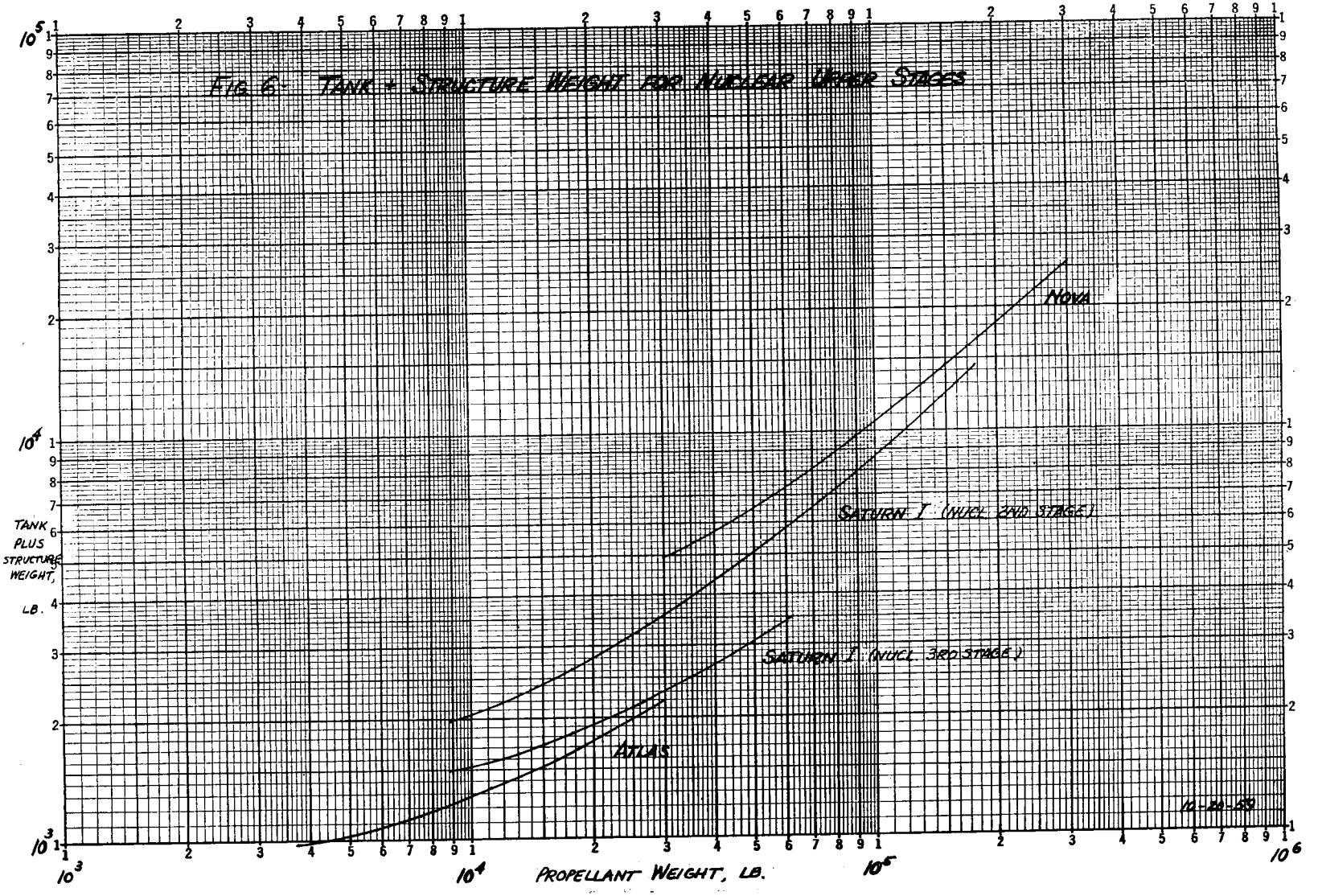


FIG. 6 - TANK + STRUCTURE WEIGHT FOR NUCLEAR UPPER STAGES

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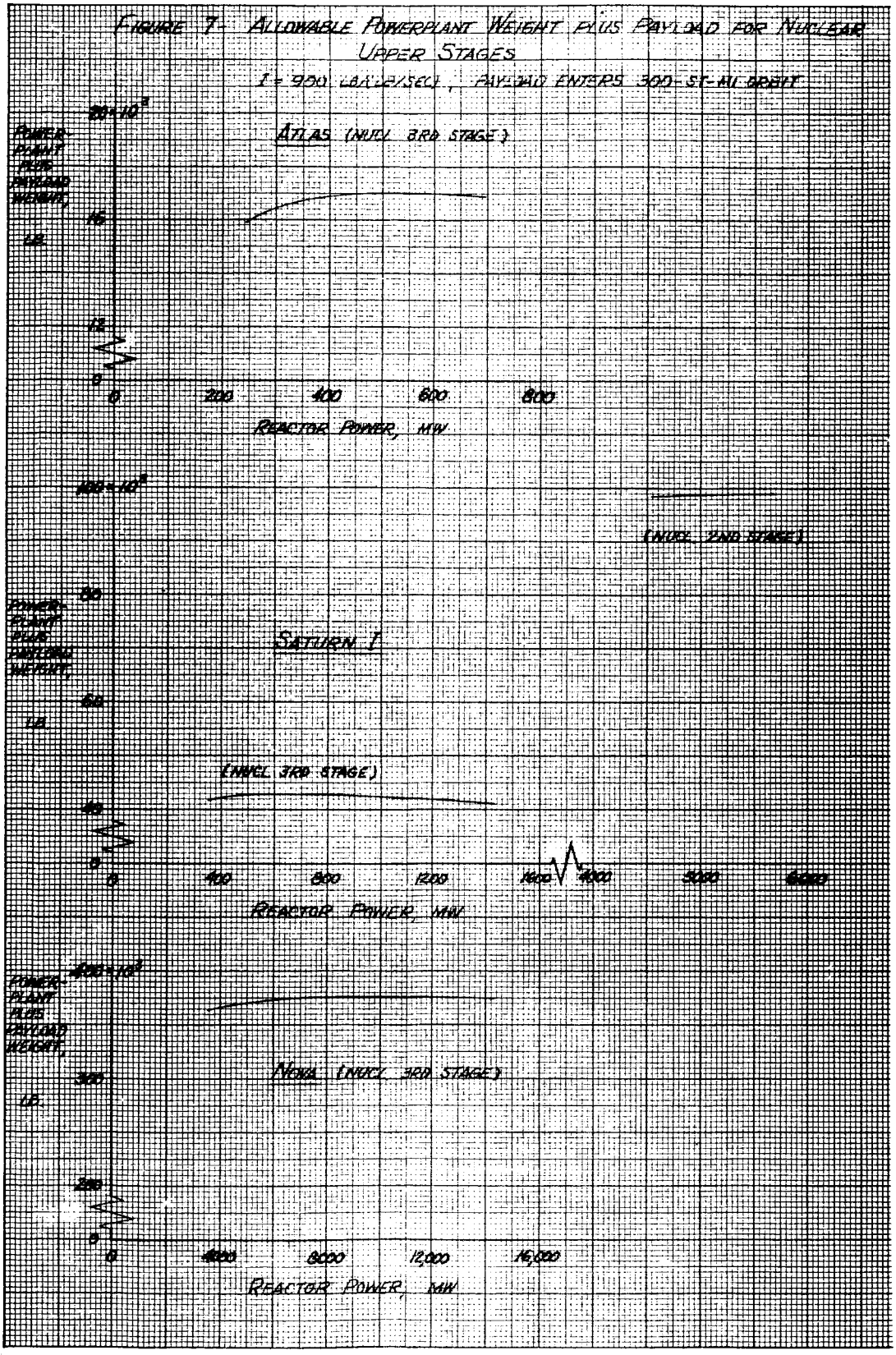
FIGURE 7- ALLOWABLE POWERPLANT WEIGHT PLUS PAYLOAD FOR NUCLEAR UPPER STAGES
I = 900 LBF-SEC/LB, PAYLOAD ENTERS 300-ST-MI ORBIT
ATLAS (INCL. 3RD STAGE)
POWER-PLANT PLUS PAYLOAD WEIGHT, LB.
REACTOR POWER, MW
(INCL. 2ND STAGE)
SATURN I
(INCL. 3RD STAGE)
NOVA (INCL. 3RD STAGE)