NA61-1029

AERO-ASTRONAUTICS REPORT NO. 248

LANGLEY
GRANT
IN-05-CR
329318
P94

OPTIMAL TRAJECTORIES FOR AN AEROSPACE PLANE, PART 2: DATA, TABLES, AND GRAPHS

by

A. MIELE, W. Y. LEE, AND G. D. WU

RICE UNIVERSITY

1990

AERO-ASTRONAUTICS REPORT NO. 248

OPTIMAL TRAJECTORIES FOR AN AEROSPACE PLANE, PART 2: DATA, TABLES, AND GRAPHS

by

A. MIELE, W. Y. LEE, AND G. D. WU

RICE UNIVERSITY

1990

Optimal Trajectories for an Aerospace Plane, Part 2: Data, Tables, and Graphs[1,2]

by

A. Miele[3], W. Y. Lee[4], and G. D. Wu[5]

[1]Portions of this material were presented by the senior author at the 1990 American Control Conference, San Diego, California, May 23-25, 1990.

[2]This research was supported by NASA Langley Research Center Grant No. NAG-1-1029 and by Texas Advanced Technology Program Grant No. TATP-003604020.

[3]Foyt Family Professor of Aerospace Sciences and Mathematical Sciences, Aero-Astronautics Group, Rice University, Houston, Texas.

[4]Post-Doctoral Fellow, Aero-Astronautics Group, Rice University, Houston, Texas.

[5]Graduate Student, Aero-Astronautics Group, Rice University, Houston, Texas.

Abstract. This report is a follow-up to Ref. 1 and presents data, tables, and graphs relative to the optimal trajectories for an aerospace plane. A single-stage-to-orbit (SSTO) configuration is considered, and the transition from low supersonic speeds to orbital speeds is studied for a single aerodynamic model (GHAME) and three engine models.

Four optimization problems are solved using the sequential gradient-restoration algorithm for optimal control problems: (P1) minimization of the weight of fuel consumed; (P2) minimization of the peak dynamic pressure; (P3) minimization of the peak heating rate; and (P4) minimization of the peak tangential acceleration. The above optimization studies are carried out for different combinations of constraints, specifically: initial path inclination either free or given; dynamic pressure either free or bounded; tangential acceleration either free or bounded.

Key Words. Flight mechanics, hypervelocity flight, atmospheric flight, optimal trajectories, aerospace plane, sequential gradient-restoration algorithm.

1. Introduction

This report is a follow-up to Ref. 1 and presents data, tables, and graphs relative to the optimal trajectories for an aerospace plane. A single-stage-to-orbit (SSTO) configuration is considered, and the transition from low supersonic speeds to orbital speeds is studied.

The aerodynamic configuration is the general hypersonic aerodynamics model example (GHAME). For the engine model, three options are considered: (EM1) this is a ramjet/scramjet combination in which the scramjet specific impulse tends to a nearly-constant value at large Mach numbers; (EM2) this is a ramjet/scramjet combination in which the scramjet specific impulse decreases monotonically at large Mach numbers; (EM3) this is a ramjet/scramjet/rocket combination in which, owing to stagnation temperature limitations, the scramjet operates only at $M \leq M_*$; at higher Mach numbers, the scramjet is shut off and the aerospace plane is driven only by the rocket engines. Here, $M_* = 15$ is a threshold Mach number.

With the above understanding, we study four basic optimization problems: (P1) minimization of the weight of fuel consumed; (P2) minimization of the peak dynamic pressure; (P3) minimization of the peak heating rate; and (P4) minimization of the peak tangential acceleration. These optimization problems are solved for different combinations of constraints imposed on the initial path inclination γ_0, the dynamic pressure q, and the tangential acceleration a_T. Specifically, γ_0 can either be free or given ($\gamma_0 = 0$); q can either be free or bounded ($q \leq 1500$ lbf/ft^2);and a_T can either be free or bounded ($a_T \leq 3g_e$). A bound on the heating rate Q (for example, $Q \leq 150$ BTU/ft^{2}sec) is not imposed because it can be satisfied or nearly satisfied indirectly if the dynamic pressure bound is satisfied.

The notations used in this report are identical to those of Ref. 1. Therefore, a list of symbols is omitted.

2. Data

The following data are used in the numerical experiments on optimal trajectories.

2.1. Spaceplane. For the aerospace plane, the initial weight (weight at the end of the turbojet phase) is W_0 = 290000 lbf; the reference surface area (wing area) is S = 6000 ft^2; the lower bound on the angle of attack is $\alpha_\ell = -2.0$ deg; the upper bound on the angle of attack is $\alpha_u = 12.0$ deg.

The aerodynamic configuration is the general hypersonic aerodynamics model example (GHAME). For this configuration, Fig. 1 shows the drag coefficient C_D, the lift coefficient C_L, and the lift-to-drag ratio $E = C_L/C_D$ versus the Mach number M and the angle of attack α.

2.2. Engines. For all engine models, the inclination of the thrust with respect to the aircraft reference line is $\delta = 0.0$ deg; the lower bound for the power setting is $\beta_\ell = 0$; the upper bound for the power setting is $\beta_u = 1$.

Engine model EM1 is a ramjet/scramjet combination with combustor cross-sectional area S_e = 400 ft^2. For $\beta = 1$ and for engine model EM1, Fig. 2 (ramjet) and Fig. 3 (scramjet) show the thrust T, the specific impulse I_{sp}, and the fuel rate T/I_{sp} (weight of fuel consumed per unit time) versus the Mach number M and the altitude h.

Engine model EM2 is a ramjet/scramjet combination with combustor cross-sectional area S_e = 400 ft^2. For $\beta = 1$ and for engine model EM2, Fig. 2 (ramjet) and Fig. 4 (scramjet) show the thrust T, the specific impulse I_{sp}, and the fuel rate T/I_{sp} versus the Mach number M and the altitude h.

Engine model EM3 is a ramjet/scramjet/rocket combination with ramjet/scramjet combustor cross-sectional area $S_e = 400\ ft^2$ and maximum rocket thrust $T_* = 189200$ lbf. For $\beta = 1$ and for engine model EM3, Fig. 2 (ramjet), Fig. 5 (scramjet), and Fig. 6 (rocket) show the thrust T, the specific impulse I_{sp}, and the fuel rate T/I_{sp} versus the Mach number M and the altitude h.

Note that engine model EM2 differs from engine model EM1 as follows: in EM1, the specific impulse tends to a nearly constant value at large Mach numbers; in EM2, the specific impulse decreases monotonically at large Mach numbers.

Also note that engine model EM3 differs from engine model EM2 as follows: in EM2, the scramjet operates up to orbital speeds; in EM3, the scramjet operates only at $M \leq 15$; at higher Mach numbers, the scramjet is shut off and the aerospace plane is driven only by the rocket engines.

2.3. Physical Constants. The radius of the Earth is assumed to be r_e = 0.2093E+08 ft = 6378 km. The Earth's gravitational constant is μ = 0.1409E+17 ft^3/sec^2. The sea-level acceleration of gravity is $g_e = 32.20\ ft/sec^2$.

2.4. Atmospheric Model. The atmospheric model used is the US Standard Atmosphere, 1976 (Ref. 2). In this model, the values of the density are tabulated at discrete altitudes. For intermediate altitudes, the density is computed by assuming an exponential fit for the function $\rho(h)$. This is equivalent to assuming that the atmosphere behaves isothermally between any two contiguous altitudes tabulated in Ref. 2.

2.5. Initial Conditions. The initial time is the end of the turbojet phase and the beginning of the ramjet phase. At $t = t_0$, we assume that

$$x_0 = 0 \text{ ft}, \tag{1a}$$

$$h_0 = 42004 \text{ ft} = 12.8 \text{ km}, \tag{1b}$$

$$V_0 = 1936 \text{ ft/sec}, \tag{1c}$$

$$\gamma_0 = \text{free or } \gamma_0 = 0.0 \text{ deg}, \tag{1d}$$

$$W_0 = 290000 \text{ lbf}. \tag{1e}$$

2.6. Final Conditions. For engine models EM1 and EM2, the final time is the end of the scramjet phase; for engine model EM3, the final time is the end of the rocket phase. At $t = t_f$, we assume that

$$x_f = \text{free}, \tag{2a}$$

$$h_f = 262467 \text{ ft} = 80.0 \text{ km}, \tag{2b}$$

$$V_f = 25792 \text{ ft/sec}, \tag{2c}$$

$$\gamma_f = 0.0 \text{ deg}, \tag{2d}$$

$$W_f = \text{free}. \tag{2e}$$

These conditions correspond to orbital speed.

3. Problems

We study four basic optimization problems: (P1) minimum fuel weight; (P2) minimum peak dynamic pressure; (P3) minimum peak heating rate; (P4) minimum peak tangential acceleration.

In addition to the initial conditions (1) and the final conditions (2), we consider the following supplementary constraints:

$$\text{(A)} \quad \gamma_0 = \text{free}, \qquad q = \text{free}, \qquad a_T = \text{free}; \tag{3a}$$

$$\text{(B)} \quad \gamma_0 = \text{free}, \qquad q \leq 1500 \text{ lbf/ft}^2, \qquad a_T \leq 3.0\ g_e; \tag{3b}$$

$$\text{(C)} \quad \gamma_0 = 0.0 \text{ deg}, \qquad q = \text{free}, \qquad a_T = \text{free}; \tag{3c}$$

$$\text{(D)} \quad \gamma_0 = 0.0 \text{ deg}, \qquad q \leq 1500 \text{ lbf/ft}^2, \qquad a_T \leq 3.0\ g_e. \tag{3d}$$

Concerning the heating rate Q, we do not consider a bound of the form $Q \leq 150 \text{BTU/ft}^2\text{sec}$ because it can be satisfied or nearly satisfied indirectly if the dynamic pressure bound is satisfied.

The following terminology is self-explanatory: Problem (P1A) is Problem (P1) subject to conditions (A); Problem (P1C) is Problem (P1) subject to conditions (C); Problem (P3A) is Problem (P3) subject to conditions (A); and so on.

4. Results

Numerical solutions for the optimization problems of Section 3 were obtained by means of the sequential gradient-restoration algorithm (SGRA, Refs. 3-4) employed in primal form. We note that there are four basic performance indexes [(P1), (P2), (P3), (P4)], four combinations of supplementary constraints [(A), (B), (C), (D)], and three engine models [EM1, EM2, EM3]. This leads to a total of 48 optimization problems to be solved. A cross section of the solutions obtained is shown in Tables 1-12 and Figs. 7-9 of this report.

Tables 1-3 present summary results for groups of problems and list the following quantities: the weight of fuel consumed; the peak dynamic pressure; the peak heating rate; the peak tangential acceleration; the initial path inclination; the time duration of each segment of the trajectory; and the final time.

Tables 4-12 present detailed results for particular problems and list the following quantities: the weight of fuel consumed during the ramjet phase, the scramjet phase, and the rocket phase as well as the total weight of fuel consumed; the flight time of the ramjet phase, the scramjet phase, and the rocket phase as well as the total flight time; the peak heating rate and the peak dynamic pressure; the peak tangential acceleration, the peak normal acceleration, and the peak total acceleration; the values of the state variables at the beginning and at the end of each segment of the trajectory.

Figures 7-9 present detailed results for particular problems and show the following quantities as functions of the time: the altitude, the velocity, the path inclination, and the weight; the angle of attack and the power setting; the heating rate, the dynamic pressure, the tangential acceleration, and the total aerodynamic load; the Mach number, the specific impulse, and the thrust.

Regardless of how a particular optimal solution is generated, the judgment of its engineering usefulness depends on whether the following conditions are satisfied or nearly satisfied:

(i) γ_0 relatively small; (4a)

(ii) $q \leq 1500 \text{ lbf/ft}^2$; (4b)

(iii) $Q \leq 150 \text{ BTU/ft}^2\text{sec}$; (4c)

(iv) $a_T \leq 3g_e$. (4d)

To arrive at this judgment, it is appropriate to subdivide the solutions of the problems studied into three groups.

Group G1 includes the solutions of Problems (P1A), (P2A), (P3A), (P4A). These are solutions of the four basic optimization problems obtained for engine model EM1 and for constraints of Type (A). Hence, γ_0 is free, the dynamic pressure q is unconstrained, and the tangential acceleration a_T is unconstrained; the heating rate Q is also unconstrained. Inspection of Table 1 and Tables 4-7 shows that none of the solutions of Group G1 satisfies the requirements (4).

Group G2 includes the solutions of Problems (P1A), (P1B), (P1C), (P1D). These are solutions of the minimum fuel weight problem obtained for engine model EM1 and for constraints of Type (A), (B), (C), (D), respectively. Inspection of Table 2, Table 4, and Tables 8-10 shows that only one of the solutions of Group G2 nearly satisfies the requirements (4). This is the solution (P1D).

Group G3 includes the solutions of Problem (P1D) for engine models EM1, EM2, EM3, respectively. Inspection of Table 3, Tables 10-12, and Figs. 7-9 shows that all of the solutions of Group G3 satisfy or nearly satisfy the requirements (4). In percentage of the initial weight W_0 (weight at the end of the turbojet phase), the minimum fuel weight is 34.3% for engine model EM1, 44.3% for engine model EM2, and 60.7% for engine model EM3.

Assume now that the weight of fuel consumed during the turbojet phase is 5% of the take-off weight. One concludes that, in percentage of the take-off weight W_{T0}, the minimum fuel weight is 37.6% for engine model EM1, 47.1% for engine model EM2, and 62.7% for engine model EM3.

To sum up, if engine model EM2 is the one closer to reality, the SSTO mission appears to be feasible; obviously, its ability to deliver payloads into orbit can be improved via progress in the areas of aerodynamic properties and specific impulse properties. On the other hand, if engine model EM3 is the one closer to reality, the SSTO mission appears to be marginal, unless substantial progress is achieved in the areas of aerodynamic properties and specific impulse properties. Under the latter scenario, alternative consideration should be given to studying the feasibility of a two-stage-to-orbit (TSTO) mission.

References

1. MIELE, A., LEE, W. Y., and WU, G. D., Optimal Trajectories for an Aerospace Plane, Part 1: Formulation, Results, and Analysis, Rice University, Aero-Astronautics Report No. 247, 1990.

2. NOAA, NASA, and USAF, US Standard Atmosphere, 1976, US Government Printing Office, Washington, DC, 1976.

3. MIELE, A., and WANG, T., Primal-Dual Properties of Sequential Gradient-Restoration Algorithms for Optimal Control Problems, Part 1, Basic Problem, Integral Methods in Science and Engineering, Edited by F. R. Payne et al, Hemisphere Publishing Corporation, Washington, DC, pp. 577-607, 1986.

4. MIELE, A., and WANG, T., Primal-Dual Properties of Sequential Gradient-Restoration Algorithms for Optimal Control Problems, Part 2, General Problem, Journal of Mathematical Analysis and Applications, Vol. 119, Nos. 1-2, pp. 21-54, 1986.

Table 1. Unconstrained solutions, engine model EM1, various performance indexes, constraints of Type (A).

Quantity	Problem				Units
	(P1A)	(P2A)	(P3A)	(P4A)	
$(W_0-W_f)/W_0$	0.337	0.347	0.357	0.550	-
max(q)	1540	999	1157	3751	lbf/ft^2
max(Q)	165	161	98	495	BTU/ft^2sec
$max(a_T)/g_e$	9.1	5.2	4.0	1.1	-
γ_0	42.0	50.0	40.4	38.3	deg
τ_1	34	54	48	144	sec
τ_2	409	475	731	704	sec
θ_f	443	529	779	848	sec

$W_f = W_2$ and $\theta_f = \theta_2$ for engine model EM1.

Table 2. Constrained solutions, engine model EM1, minimum fuel weight, various constraint combinations.

Quantity	Problem				Units
	(P1A)	(P1B)	(P1C)	(P1D)	
$(W_0-W_f)/W_0$	0.337	0.340	0.339	0.343	-
max(q)	1540	1112	1765	1500	lbf/ft^2
max(Q)	165	148	200	153	BTU/ft^2sec
$max(a_T)/g_e$	9.1	3.0	13.7	3.0	-
γ_0	42.0	39.4	0.0	0.0	deg
τ_1	34	55	34	55	sec
τ_2	409	498	335	487	sec
θ_f	443	553	369	542	sec

$W_f = W_2$ and $\theta_f = \theta_2$ for engine model EM1.

Table 3. Effect of the engine model, Problem (P1D), minimum fuel weight, constraints of Type (D).

Quantity	Engine model			Units
	EM1	EM2	EM3	
$(W_0-W_f)/W_0$	0.343	0.443	0.607	-
max(q)	1500	1425	1500	lbf/ft^2
max(Q)	153	157	110	$BTU/ft^2 sec$
$\max(a_T)/g_e$	3.0	3.0	3.0	-
γ_0	0.0	0.0	0.0	deg
τ_1	55	44	57	sec
τ_2	487	472	97	sec
τ_3	-	-	277	sec
θ_f	542	517	431	sec

$W_f = W_2$ and $\theta_f = \theta_2$ for engine models EM1, EM2.

$W_f = W_3$ and $\theta_f = \theta_3$ for engine model EM3.

Table 4A. Results for Problem (P1A), engine model EM1, minimum weight of fuel consumed, γ_0=free, q=free, a_T=free.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet fuel consumption	0.3687E−01	0.2900E+06	0.1069E+05	lbf
Scramjet fuel consumption	0.2999E+00	0.2900E+06	0.8697E+05	lbf
Total fuel consumption	0.3368E+00	0.2900E+06	0.9767E+05	lbf
Ramjet flight time	0.6573E−02	0.5161E+04	0.3393E+02	sec
Scramjet flight time	0.7920E−01	0.5161E+04	0.4088E+03	sec
Total flight time	0.8577E−01	0.5161E+04	0.4427E+03	sec
Peak heating rate (θ = 125.9 sec)	0.1099E+01	0.1500E+03	0.1648E+03	Btu ft^{-2} sec^{-1}
Peak dynamic pressure (θ = 23.4 sec)	0.1027E+01	0.1500E+04	0.1540E+04	lbf ft^{-2}
Peak tangential acceleration (θ = 20.7 sec)	0.9053E+01	0.3220E+02	0.2915E+03	ft sec^{-2}
Peak normal acceleration (θ = 62.5 sec)	0.9298E+00	0.3220E+02	0.2994E+02	ft sec^{-2}
Peak total acceleration (θ = 20.7 sec)	0.9384E+01	0.3220E+02	0.3022E+03	ft sec^{-2}

Table 4B. Results for Problem (P1A), engine model EM1, minimum weight of fuel consumed, γ_0=free, q=free, a_T=free.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet initial altitude	0.1600E+00	0.2625E+06	0.4200E+05	ft
Ramjet initial velocity	0.7506E−01	0.2579E+05	0.1936E+04	ft sec^{-1}
Ramjet initial path inclination	0.7328E+00	0.5730E+02	0.4199E+02	deg
Ramjet initial weight	0.1000E+01	0.2900E+06	0.2900E+06	lbf
Scramjet initial altitude	0.3629E+00	0.2625E+06	0.9525E+05	ft
Scramjet initial velocity	0.2625E+00	0.2579E+05	0.6771E+04	ft sec^{-1}
Scramjet initial path inclination	0.2157E+00	0.5730E+02	0.1236E+02	deg
Scramjet initial weight	0.9631E+00	0.2900E+06	0.2793E+06	lbf
Scramjet final altitude	0.1000E+01	0.2625E+06	0.2625E+06	ft
Scramjet final velocity	0.1000E+01	0.2579E+05	0.2579E+05	ft sec^{-1}
Scramjet final path inclination	0.0000E+00	0.5730E+02	0.0000E+00	deg
Scramjet final weight	0.6632E+00	0.2900E+06	0.1923E+06	lbf

Table 5A. Results for Problem (P2A), engine model EM1, minimum peak dynamic pressure, γ_0=free, q=free, a_T=free.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet fuel consumption	0.3726E−01	0.2900E+06	0.1080E+05	lbf
Scramjet fuel consumption	0.3095E+00	0.2900E+06	0.8975E+05	lbf
Total fuel consumption	0.3467E+00	0.2900E+06	0.1006E+06	lbf
Ramjet flight time	0.1047E−01	0.5161E+04	0.5404E+02	sec
Scramjet flight time	0.9204E−01	0.5161E+04	0.4751E+03	sec
Total flight time	0.1025E+00	0.5161E+04	0.5291E+03	sec
Peak heating rate (θ = 196.6 sec)	0.1073E+01	0.1500E+03	0.1609E+03	Btu ft^{-2} sec^{-1}
Peak dynamic pressure (θ = 0.0 sec)	0.6661E+00	0.1500E+04	0.9991E+03	lbf ft^{-2}
Peak tangential acceleration (θ = 39.5 sec)	0.5227E+01	0.3220E+02	0.1683E+03	ft sec^{-2}
Peak normal acceleration (θ = 0.0 sec)	0.5379E+01	0.3220E+02	0.1732E+03	ft sec^{-2}
Peak total acceleration (θ = 0.0 sec)	0.5462E+01	0.3220E+02	0.1759E+03	ft sec^{-2}

Table 5B. Results for Problem (P2A), engine model EM1, minimum peak dynamic pressure, γ_0=free, q=free, a_T=free.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet initial altitude	0.1600E+00	0.2625E+06	0.4200E+05	ft
Ramjet initial velocity	0.7506E−01	0.2579E+05	0.1936E+04	ft sec^{-1}
Ramjet initial path inclination	0.8735E+00	0.5730E+02	0.5005E+02	deg
Ramjet initial weight	0.1000E+01	0.2900E+06	0.2900E+06	lbf
Scramjet initial altitude	0.3726E+00	0.2625E+06	0.9780E+05	ft
Scramjet initial velocity	0.2581E+00	0.2579E+05	0.6657E+04	ft sec^{-1}
Scramjet initial path inclination	0.1603E+00	0.5730E+02	0.9184E+01	deg
Scramjet initial weight	0.9627E+00	0.2900E+06	0.2792E+06	lbf
Scramjet final altitude	0.1000E+01	0.2625E+06	0.2625E+06	ft
Scramjet final velocity	0.1000E+01	0.2579E+05	0.2579E+05	ft sec^{-1}
Scramjet final path inclination	0.0000E+00	0.5730E+02	0.0000E+00	deg
Scramjet final weight	0.6533E+00	0.2900E+06	0.1894E+06	lbf

Table 6A. Results for Problem (P3A), engine model EM1, minimum peak heating rate, γ_0=free, q=free, a_T=free.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet fuel consumption	0.3556E−01	0.2900E+06	0.1031E+05	lbf
Scramjet fuel consumption	0.3215E+00	0.2900E+06	0.9323E+05	lbf
Total fuel consumption	0.3570E+00	0.2900E+06	0.1035E+06	lbf
Ramjet flight time	0.9369E−02	0.5161E+04	0.4836E+02	sec
Scramjet flight time	0.1416E+00	0.5161E+04	0.7307E+03	sec
Total flight time	0.1509E+00	0.5161E+04	0.7791E+03	sec
Peak heating rate (θ = 380.8 sec)	0.6549E+00	0.1500E+03	0.9823E+02	Btu ft^{-2} sec^{-1}
Peak dynamic pressure (θ = 12.1 sec)	0.7711E+00	0.1500E+04	0.1157E+04	lbf ft^{-2}
Peak tangential acceleration (θ = 33.9 sec)	0.3968E+01	0.3220E+02	0.1278E+03	ft sec^{-2}
Peak normal acceleration (θ = 136.0 sec)	0.6961E+00	0.3220E+02	0.2242E+02	ft sec^{-2}
Peak total acceleration (θ = 9.2 sec)	0.3994E+01	0.3220E+02	0.1286E+03	ft sec^{-2}

Table 6B. Results for Problem (P3A), engine model EM1, minimum peak heating rate, γ_0=free, q=free, a_T=free.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet initial altitude	0.1600E+00	0.2625E+06	0.4200E+05	ft
Ramjet initial velocity	0.7506E−01	0.2579E+05	0.1936E+04	ft sec^{-1}
Ramjet initial path inclination	0.7054E+00	0.5730E+02	0.4042E+02	deg
Ramjet initial weight	0.1000E+01	0.2900E+06	0.2900E+06	lbf
Scramjet initial altitude	0.3658E+00	0.2625E+06	0.9600E+05	ft
Scramjet initial velocity	0.2519E+00	0.2579E+05	0.6498E+04	ft sec^{-1}
Scramjet initial path inclination	0.1694E+00	0.5730E+02	0.9704E+01	deg
Scramjet initial weight	0.9644E+00	0.2900E+06	0.2797E+06	lbf
Scramjet final altitude	0.1000E+01	0.2625E+06	0.2625E+06	ft
Scramjet final velocity	0.1000E+01	0.2579E+05	0.2579E+05	ft sec^{-1}
Scramjet final path inclination	0.0000E+00	0.5730E+02	0.0000E+00	deg
Scramjet final weight	0.6430E+00	0.2900E+06	0.1865E+06	lbf

Table 7A. Results for Problem (P4A), engine model EM1, minimum peak tangential acceleration, γ_0=free, q=free, a_T=free.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet fuel consumption	0.4512E−01	0.2900E+06	0.1309E+05	lbf
Scramjet fuel consumption	0.5051E+00	0.2900E+06	0.1465E+06	lbf
Total fuel consumption	0.5502E+00	0.2900E+06	0.1596E+06	lbf
Ramjet flight time	0.2788E−01	0.5161E+04	0.1439E+03	sec
Scramjet flight time	0.1363E+00	0.5161E+04	0.7036E+03	sec
Total flight time	0.1642E+00	0.5161E+04	0.8475E+03	sec
Peak heating rate (θ = 467.6 sec)	0.3302E+01	0.1500E+03	0.4953E+03	Btu ft^{-2} sec^{-1}
Peak dynamic pressure (θ = 464.1 sec)	0.2501E+01	0.1500E+04	0.3751E+04	lbf ft^{-2}
Peak tangential acceleration (θ = 478.1 sec)	0.1060E+01	0.3220E+02	0.3413E+02	ft sec^{-2}
Peak normal acceleration (θ = 126.6 sec)	0.2109E+01	0.3220E+02	0.6792E+02	ft sec^{-2}
Peak total acceleration (θ = 126.6 sec)	0.2361E+01	0.3220E+02	0.7601E+02	ft sec^{-2}

Table 7B. Results for Problem (P4A), engine model EM1, minimum peak tangential acceleration, γ_0=free, q=free, a_T=free.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet initial altitude	0.1600E+00	0.2625E+06	0.4200E+05	ft
Ramjet initial velocity	0.7506E−01	0.2579E+05	0.1936E+04	ft sec^{-1}
Ramjet initial path inclination	0.6690E+00	0.5730E+02	0.3833E+02	deg
Ramjet initial weight	0.1000E+01	0.2900E+06	0.2900E+06	lbf
Scramjet initial altitude	0.3678E+00	0.2625E+06	0.9655E+05	ft
Scramjet initial velocity	0.2578E+00	0.2579E+05	0.6651E+04	ft sec^{-1}
Scramjet initial path inclination	0.1701E+00	0.5730E+02	0.9745E+01	deg
Scramjet initial weight	0.9549E+00	0.2900E+06	0.2769E+06	lbf
Scramjet final altitude	0.1000E+01	0.2625E+06	0.2625E+06	ft
Scramjet final velocity	0.1000E+01	0.2579E+05	0.2579E+05	ft sec^{-1}
Scramjet final path inclination	0.0000E+00	0.5730E+02	0.0000E+00	deg
Scramjet final weight	0.4498E+00	0.2900E+06	0.1304E+06	lbf

Table 8A. Results for Problem (P1B), engine model EM1, minimum weight of fuel consumed, γ_0=free, $q \leq 1500$ psf, $a_T \leq 3.0\ g_e$.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet fuel consumption	0.3944E−01	0.2900E+06	0.1144E+05	lbf
Scramjet fuel consumption	0.3005E+00	0.2900E+06	0.8713E+05	lbf
Total fuel consumption	0.3399E+00	0.2900E+06	0.9857E+05	lbf
Ramjet flight time	0.1076E−01	0.5161E+04	0.5554E+02	sec
Scramjet flight time	0.9640E−01	0.5161E+04	0.4976E+03	sec
Total flight time	0.1072E+00	0.5161E+04	0.5531E+03	sec
Peak heating rate (θ = 224.7 sec)	0.9879E+00	0.1500E+03	0.1482E+03	Btu ft^{-2} sec^{-1}
Peak dynamic pressure (θ = 11.7 sec)	0.7410E+00	0.1500E+04	0.1112E+04	lbf ft^{-2}
Peak tangential acceleration (θ = 122.7 sec)	0.3000E+01	0.3220E+02	0.9660E+02	ft sec^{-2}
Peak normal acceleration (θ = 48.3 sec)	0.1642E+01	0.3220E+02	0.5287E+02	ft sec^{-2}
Peak total acceleration (θ = 15.0 sec)	0.3724E+01	0.3220E+02	0.1199E+03	ft sec^{-2}

Table 8B. Results for Problem (P1B), engine model EM1, minimum weight of fuel consumed, γ_0=free, $q \leq 1500$ psf, $a_T \leq 3.0\ g_e$.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet initial altitude	0.1600E+00	0.2625E+06	0.4200E+05	ft
Ramjet initial velocity	0.7506E−01	0.2579E+05	0.1936E+04	ft sec^{-1}
Ramjet initial path inclination	0.6886E+00	0.5730E+02	0.3945E+02	deg
Ramjet initial weight	0.1000E+01	0.2900E+06	0.2900E+06	lbf
Scramjet initial altitude	0.3775E+00	0.2625E+06	0.9908E+05	ft
Scramjet initial velocity	0.2621E+00	0.2579E+05	0.6759E+04	ft sec^{-1}
Scramjet initial path inclination	0.1665E+00	0.5730E+02	0.9538E+01	deg
Scramjet initial weight	0.9606E+00	0.2900E+06	0.2786E+06	lbf
Scramjet final altitude	0.1000E+01	0.2625E+06	0.2625E+06	ft
Scramjet final velocity	0.1000E+01	0.2579E+05	0.2579E+05	ft sec^{-1}
Scramjet final path inclination	0.0000E+00	0.5730E+02	0.0000E+00	deg
Scramjet final weight	0.6601E+00	0.2900E+06	0.1914E+06	lbf

Table 9A. Results for Problem (P1C), engine model EM1, minimum weight of fuel consumed, $\gamma_0=0.0$ deg, q=free, a_T=free.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet fuel consumption	0.3859E−01	0.2900E+06	0.1119E+05	lbf
Scramjet fuel consumption	0.3005E+00	0.2900E+06	0.8716E+05	lbf
Total fuel consumption	0.3391E+00	0.2900E+06	0.9835E+05	lbf
Ramjet flight time	0.6615E−02	0.5161E+04	0.3414E+02	sec
Scramjet flight time	0.6490E−01	0.5161E+04	0.3350E+03	sec
Total flight time	0.7152E−01	0.5161E+04	0.3691E+03	sec
Peak heating rate (θ = 84.4 sec)	0.1333E+01	0.1500E+03	0.1999E+03	Btu ft^{-2} sec^{-1}
Peak dynamic pressure (θ = 25.6 sec)	0.1177E+01	0.1500E+04	0.1765E+04	lbf ft^{-2}
Peak tangential acceleration (θ = 60.9 sec)	0.1373E+02	0.3220E+02	0.4420E+03	ft sec^{-2}
Peak normal acceleration (θ = 2.0 sec)	0.5376E+01	0.3220E+02	0.1731E+03	ft sec^{-2}
Peak total acceleration (θ = 60.9 sec)	0.1373E+02	0.3220E+02	0.4422E+03	ft sec^{-2}

Table 9B. Results for Problem (P1C), engine model EM1, minimum weight of fuel consumed, $\gamma_0 = 0.0$ deg, q=free, a_T=free.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet initial altitude	0.1600E+00	0.2625E+06	0.4200E+05	ft
Ramjet initial velocity	0.7506E−01	0.2579E+05	0.1936E+04	ft sec^{-1}
Ramjet initial path inclination	0.0000E+00	0.5730E+02	0.0000E+00	deg
Ramjet initial weight	0.1000E+01	0.2900E+06	0.2900E+06	lbf
Scramjet initial altitude	0.3466E+00	0.2625E+06	0.9097E+05	ft
Scramjet initial velocity	0.2626E+00	0.2579E+05	0.6773E+04	ft sec^{-1}
Scramjet initial path inclination	0.2367E+00	0.5730E+02	0.1356E+02	deg
Scramjet initial weight	0.9614E+00	0.2900E+06	0.2788E+06	lbf
Scramjet final altitude	0.1000E+01	0.2625E+06	0.2625E+06	ft
Scramjet final velocity	0.1000E+01	0.2579E+05	0.2579E+05	ft sec^{-1}
Scramjet final path inclination	0.0000E+00	0.5730E+02	0.0000E+00	deg
Scramjet final weight	0.6609E+00	0.2900E+06	0.1917E+06	lbf

Table 10A. Results for Problem (P1D), engine model EM1, minimum weight of fuel consumed, $\gamma_0 = 0.0$ deg, $q \leq 1500$ psf, $a_T \leq 3.0\ g_e$.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet fuel consumption	0.4079E−01	0.2900E+06	0.1183E+05	lbf
Scramjet fuel consumption	0.3022E+00	0.2900E+06	0.8764E+05	lbf
Total fuel consumption	0.3430E+00	0.2900E+06	0.9947E+05	lbf
Ramjet flight time	0.1057E−01	0.5161E+04	0.5457E+02	sec
Scramjet flight time	0.9437E−01	0.5161E+04	0.4871E+03	sec
Total flight time	0.1049E+00	0.5161E+04	0.5417E+03	sec
Peak heating rate (θ = 210.4 sec)	0.1018E+01	0.1500E+03	0.1528E+03	Btu ft^{-2} sec^{-1}
Peak dynamic pressure (θ = 13.1 sec)	0.1000E+01	0.1500E+04	0.1500E+04	lbf ft^{-2}
Peak tangential acceleration (θ = 186.1 sec)	0.3000E+01	0.3220E+02	0.9660E+02	ft sec^{-2}
Peak normal acceleration (θ = 1.1 sec)	0.4994E+01	0.3220E+02	0.1608E+03	ft sec^{-2}
Peak total acceleration (θ = 2.7 sec)	0.5532E+01	0.3220E+02	0.1781E+03	ft sec^{-2}

Table 10B. Results for Problem (P1D), engine model EM1, minimum weight of fuel consumed, $\gamma_0 = 0.0$ deg, $q \leq 1500$ psf, $a_T \leq 3.0$ g_e.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet initial altitude	0.1600E+00	0.2625E+06	0.4200E+05	ft
Ramjet initial velocity	0.7506E−01	0.2579E+05	0.1936E+04	ft sec^{-1}
Ramjet initial path inclination	0.0000E+00	0.5730E+02	0.0000E+00	deg
Ramjet initial weight	0.1000E+01	0.2900E+06	0.2900E+06	lbf
Scramjet initial altitude	0.3729E+00	0.2625E+06	0.9786E+05	ft
Scramjet initial velocity	0.2618E+00	0.2579E+05	0.6752E+04	ft sec^{-1}
Scramjet initial path inclination	0.1717E+00	0.5730E+02	0.9837E+01	deg
Scramjet initial weight	0.9592E+00	0.2900E+06	0.2782E+06	lbf
Scramjet final altitude	0.1000E+01	0.2625E+06	0.2625E+06	ft
Scramjet final velocity	0.1000E+01	0.2579E+05	0.2579E+05	ft sec^{-1}
Scramjet final path inclination	0.0000E+00	0.5730E+02	0.0000E+00	deg
Scramjet final weight	0.6570E+00	0.2900E+06	0.1905E+06	lbf

Table 11A. Results for Problem (P1D), engine model EM2, minimum weight of fuel consumed, $\gamma_0 = 0.0$ deg, $q \leq 1500$ psf, $a_T \leq 3.0\ g_e$.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet fuel consumption	0.3624E−01	0.2900E+06	0.1051E+05	lbf
Scramjet fuel consumption	0.4073E+00	0.2900E+06	0.1181E+06	lbf
Total fuel consumption	0.4435E+00	0.2900E+06	0.1286E+06	lbf
Ramjet flight time	0.8617E−02	0.5161E+04	0.4447E+02	sec
Scramjet flight time	0.9150E−01	0.5161E+04	0.4723E+03	sec
Total flight time	0.1001E+00	0.5161E+04	0.5167E+03	sec
Peak heating rate (θ = 226.3 sec)	0.1050E+01	0.1500E+03	0.1575E+03	Btu ft^{-2} sec^{-1}
Peak dynamic pressure (θ = 10.2 sec)	0.9500E+00	0.1500E+04	0.1425E+04	lbf ft^{-2}
Peak tangential acceleration (θ = 205.0 sec)	0.3000E+01	0.3220E+02	0.9660E+02	ft sec^{-2}
Peak normal acceleration (θ = 2.7 sec)	0.5449E+01	0.3220E+02	0.1755E+03	ft sec^{-2}
Peak total acceleration (θ = 2.7 sec)	0.5909E+01	0.3220E+02	0.1903E+03	ft sec^{-2}

Table 11B. Results for Problem (P1D), engine model EM2, minimum weight of fuel consumed, $\gamma_0 = 0.0$ deg, $q \leq 1500$ psf, $a_T \leq 3.0\ g_e$.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet initial altitude	0.1600E+00	0.2625E+06	0.4200E+05	ft
Ramjet initial velocity	0.7506E−01	0.2579E+05	0.1936E+04	ft sec^{-1}
Ramjet initial path inclination	0.0000E+00	0.5730E+02	0.0000E+00	deg
Ramjet initial weight	0.1000E+01	0.2900E+06	0.2900E+06	lbf
Scramjet initial altitude	0.3415E+00	0.2625E+06	0.8964E+05	ft
Scramjet initial velocity	0.2371E+00	0.2579E+05	0.6115E+04	ft sec^{-1}
Scramjet initial path inclination	0.9738E−01	0.5730E+02	0.5580E+01	deg
Scramjet initial weight	0.9638E+00	0.2900E+06	0.2795E+06	lbf
Scramjet final altitude	0.1000E+01	0.2625E+06	0.2625E+06	ft
Scramjet final velocity	0.1000E+01	0.2579E+05	0.2579E+05	ft sec^{-1}
Scramjet final path inclination	0.0000E+00	0.5730E+02	0.0000E+00	deg
Scramjet final weight	0.5565E+00	0.2900E+06	0.1614E+06	lbf

Table 12A. Results for Problem (P1D), engine model EM3, minimum weight of fuel consumed, $\gamma_0 = 0.0$ deg, $q \leq 1500$ psf, $a_T \leq 3.0\ g_e$.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet fuel consumption	0.4407E−01	0.2900E+06	0.1278E+05	lbf
Scramjet fuel consumption	0.1562E+00	0.2900E+06	0.4531E+05	lbf
Rocket fuel consumption	0.4070E+00	0.2900E+06	0.1180E+06	lbf
Total fuel consumption	0.6073E+00	0.2900E+06	0.1761E+06	lbf
Ramjet flight time	0.1098E−01	0.5161E+04	0.5667E+02	sec
Scramjet flight time	0.1886E−01	0.5161E+04	0.9735E+02	sec
Rocket flight time	0.5367E−01	0.5161E+04	0.2770E+03	sec
Total flight time	0.8351E−01	0.5161E+04	0.4310E+03	sec
Peak heating rate (θ = 139.4 sec)	0.7333E+00	0.1500E+03	0.1100E+03	Btu ft^{-2} sec^{-1}
Peak dynamic pressure (θ = 43.1 sec)	0.9998E+00	0.1500E+04	0.1500E+04	lbf ft^{-2}
Peak tangential acceleration (θ = 148.2 sec)	0.3000E+01	0.3220E+02	0.9660E+02	ft sec^{-2}
Peak normal acceleration (θ = 2.3 sec)	0.5171E+01	0.3220E+02	0.1665E+03	ft sec^{-2}
Peak total acceleration (θ = 2.3 sec)	0.5643E+01	0.3220E+02	0.1817E+03	ft sec^{-2}

Table 12B. Results for Problem (P1D), engine model EM3, minimum weight of fuel consumed, $\gamma_0 = 0.0$ deg, $q \leq 1500$ psf, $a_T \leq 3.0$ g_e.

Quantity	Dimensionless value	Reference value	Dimensional value	Units
Ramjet initial altitude	0.1600E+00	0.2625E+06	0.4200E+05	ft
Ramjet initial velocity	0.7506E−01	0.2579E+05	0.1936E+04	ft sec^{-1}
Ramjet initial path inclination	0.0000E+00	0.5730E+02	0.0000E+00	deg
Ramjet initial weight	0.1000E+01	0.2900E+06	0.2900E+06	lbf
Scramjet initial altitude	0.3507E+00	0.2625E+06	0.9205E+05	ft
Scramjet initial velocity	0.2656E+00	0.2579E+05	0.6849E+04	ft sec^{-1}
Scramjet initial path inclination	0.1480E+00	0.5730E+02	0.8479E+01	deg
Scramjet initial weight	0.9559E+00	0.2900E+06	0.2772E+06	lbf
Rocket initial altitude	0.6295E+00	0.2625E+06	0.1652E+06	ft
Rocket initial velocity	0.6289E+00	0.2579E+05	0.1622E+05	ft sec^{-1}
Rocket initial path inclination	0.7083E−01	0.5730E+02	0.4058E+01	deg
Rocket initial weight	0.7997E+00	0.2900E+06	0.2319E+06	lbf
Rocket final altitude	0.1000E+01	0.2625E+06	0.2625E+06	ft
Rocket final velocity	0.1000E+01	0.2579E+05	0.2579E+05	ft sec^{-1}
Rocket final path inclination	0.0000E+00	0.5730E+02	0.0000E+00	deg
Rocket final weight	0.3927E+00	0.2900E+06	0.1139E+06	lbf

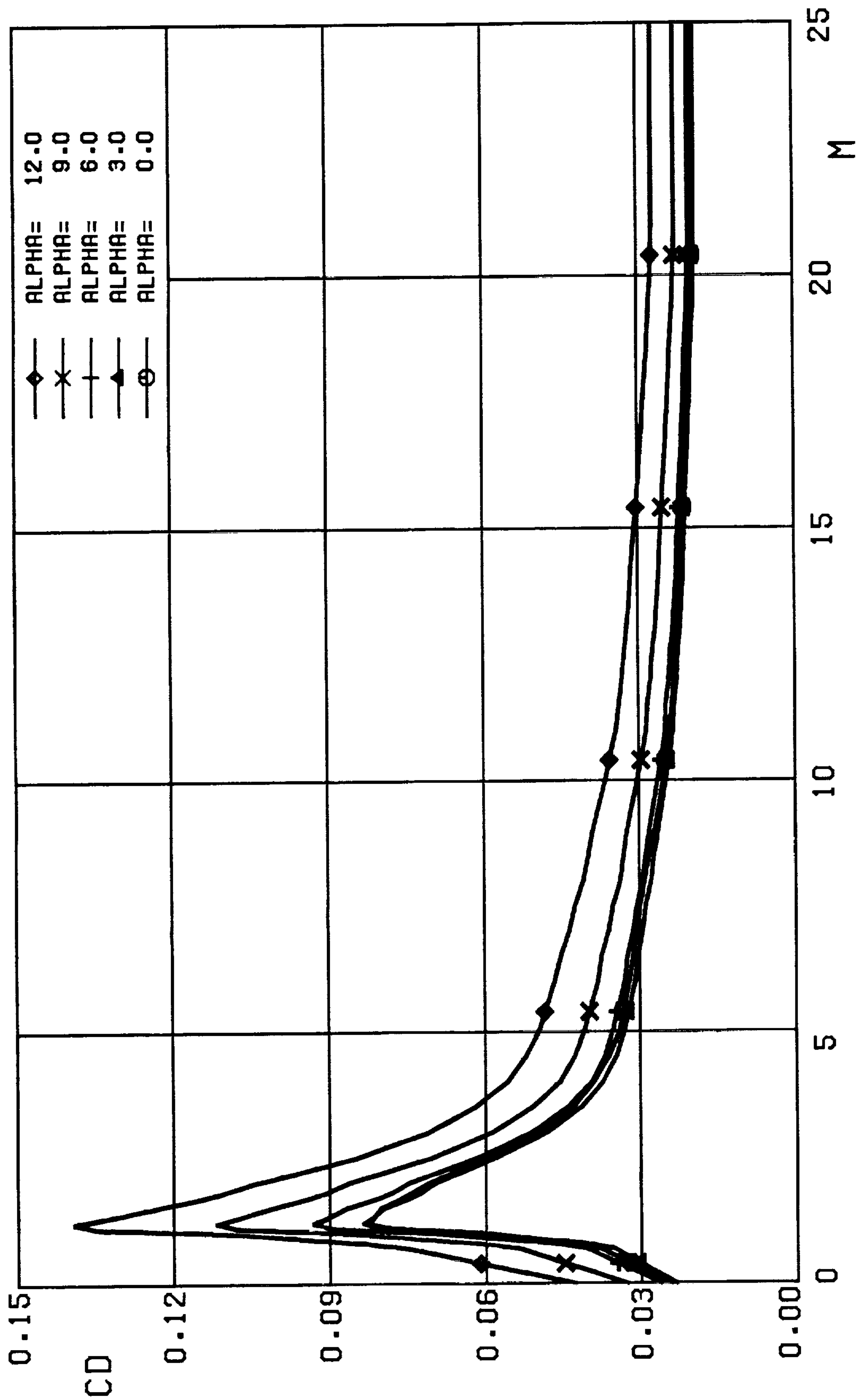

FIG. 1A. DRAG COEFFICIENT,
GHAME CONFIGURATION.

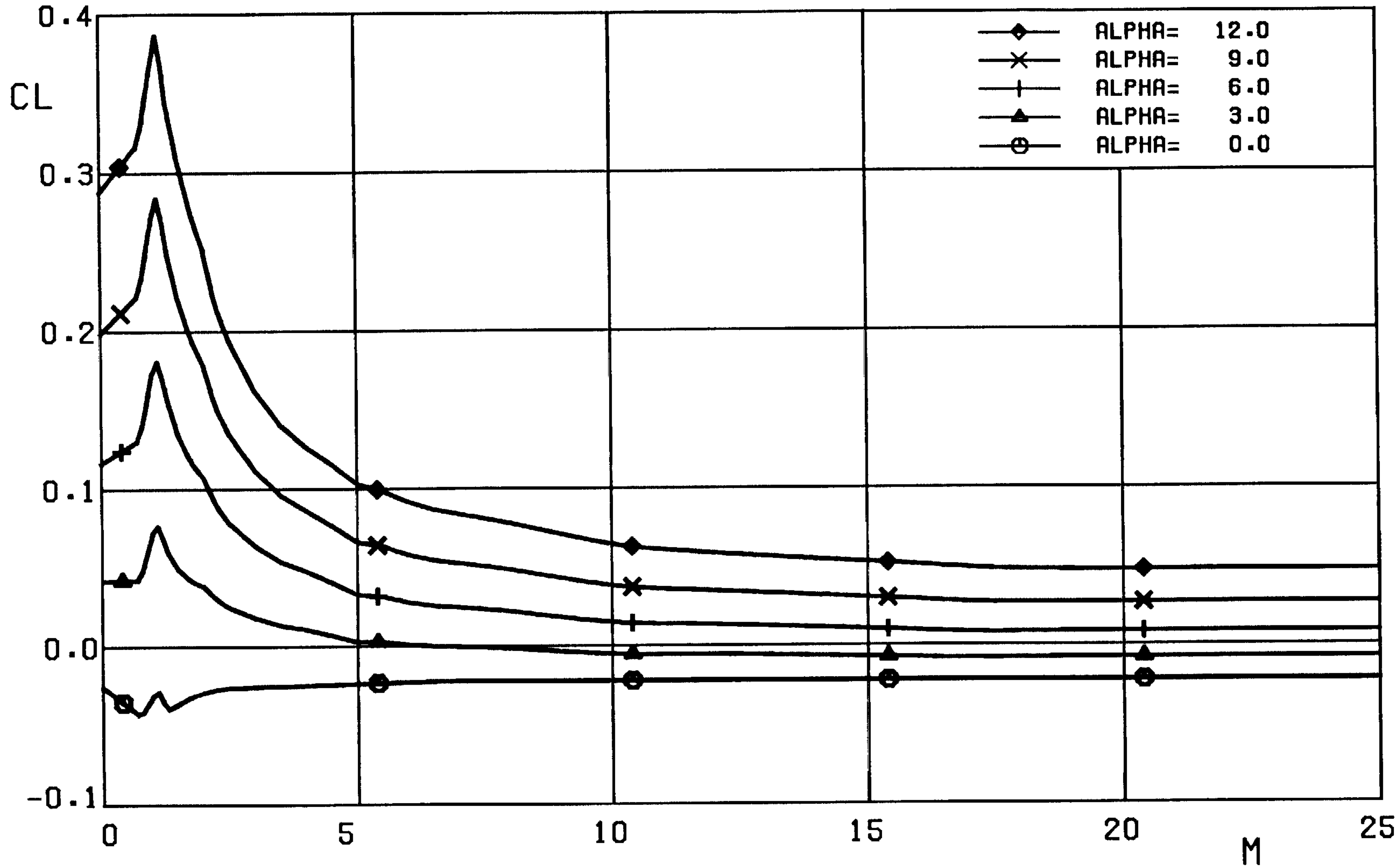

FIG. 1B. LIFT COEFFICIENT,
GHAME CONFIGURATION.

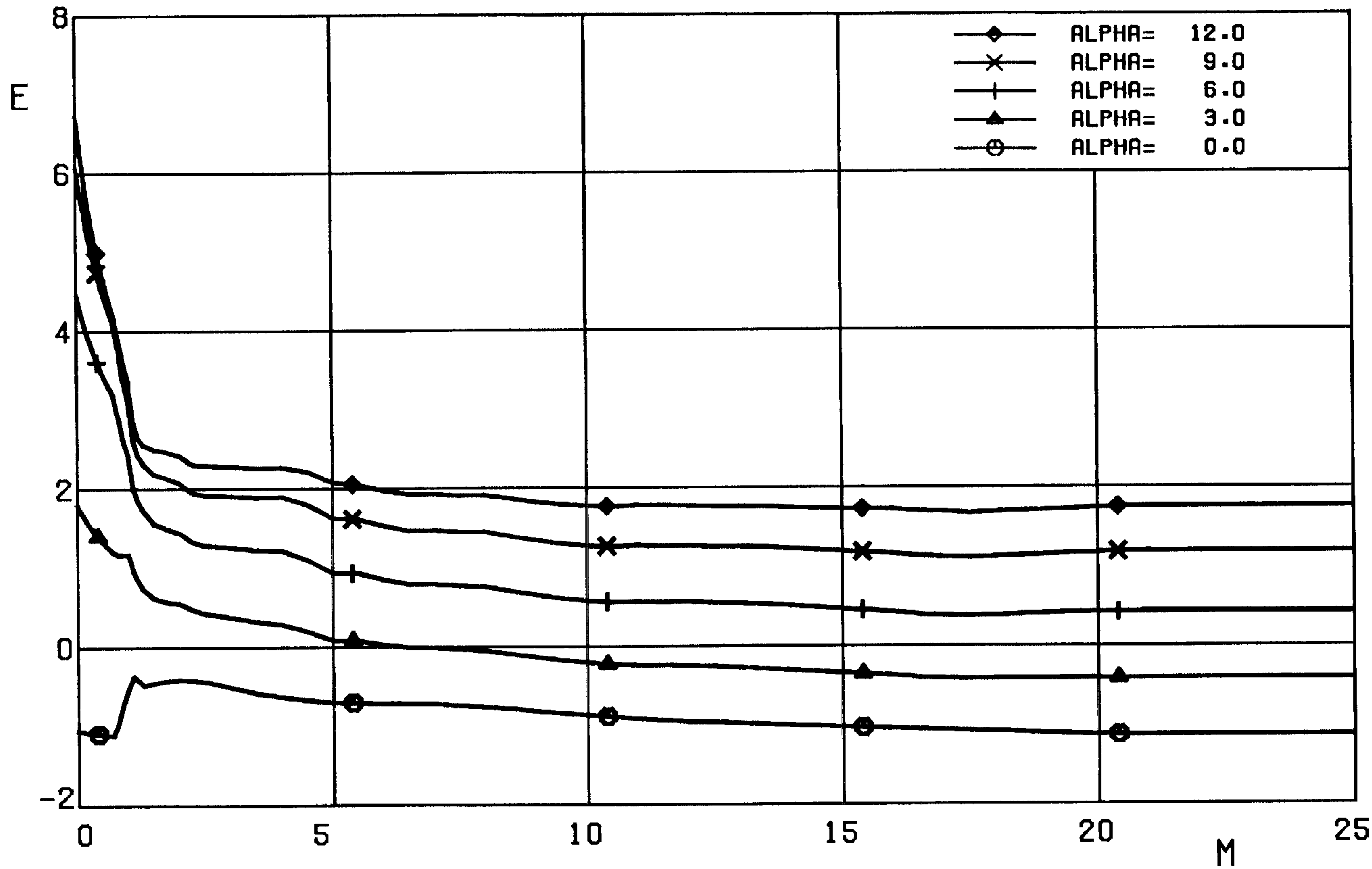

FIG. 1C. LIFT-TO-DRAG RATIO,
GHAME CONFIGURATION.

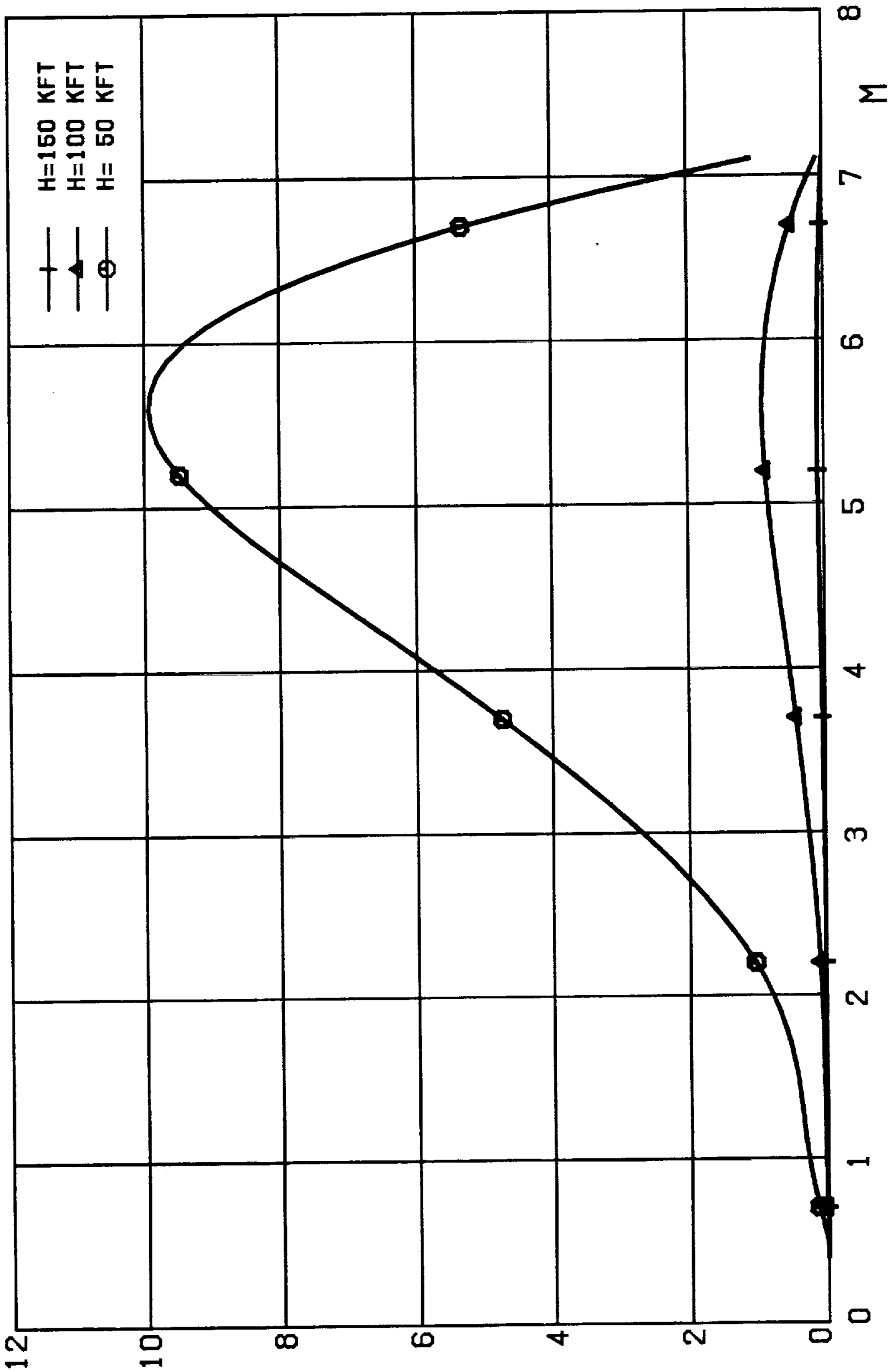

FIG. 2A. THRUST (MLBF), BETA=1, RAMJET ENGINE,
ENGINE MODELS EM1, EM2, EM3.

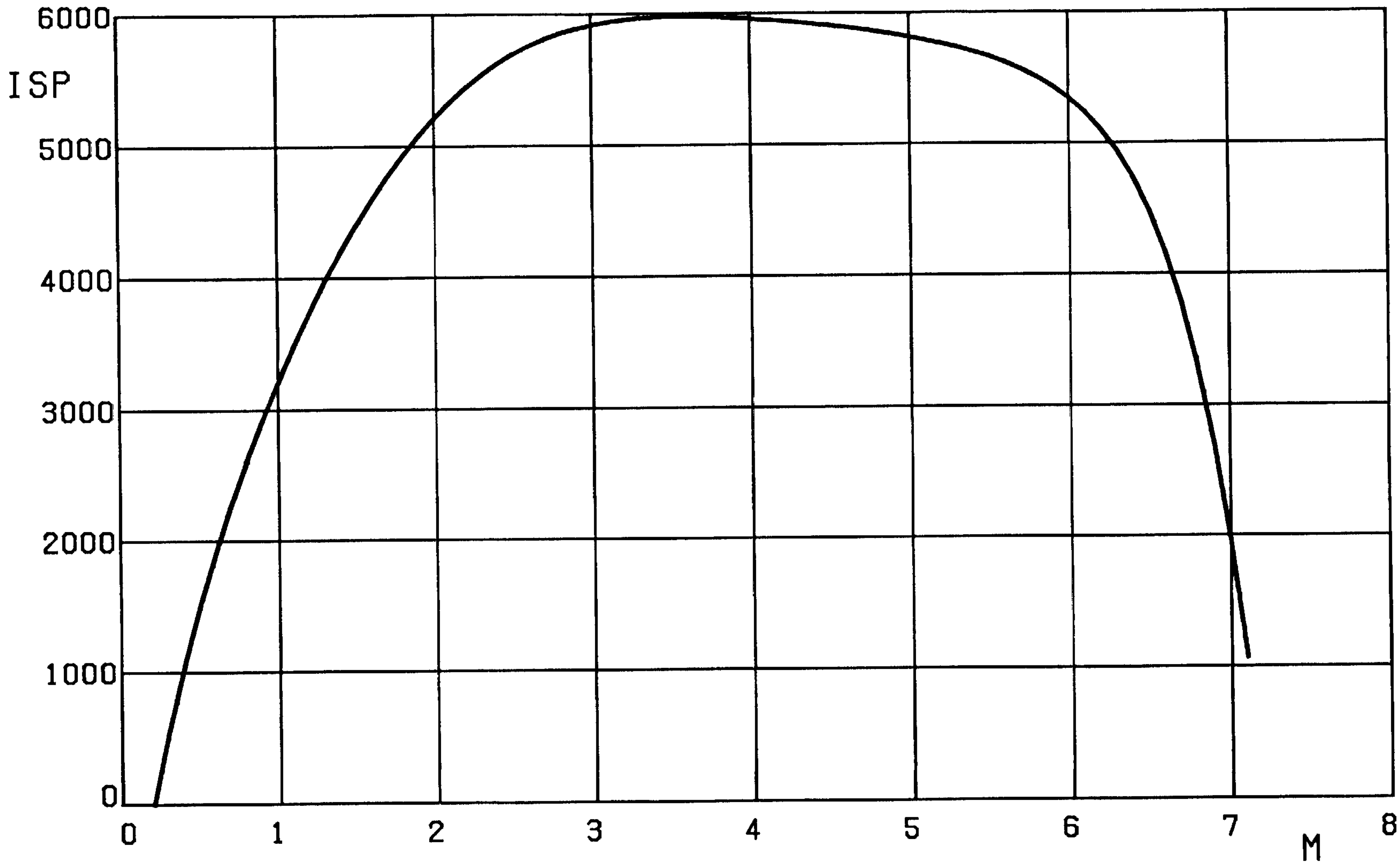

FIG. 2B. SPECIFIC IMPULSE (SEC), BETA=1, RAMJET ENGINE, ENGINE MODELS EM1, EM2, EM3.

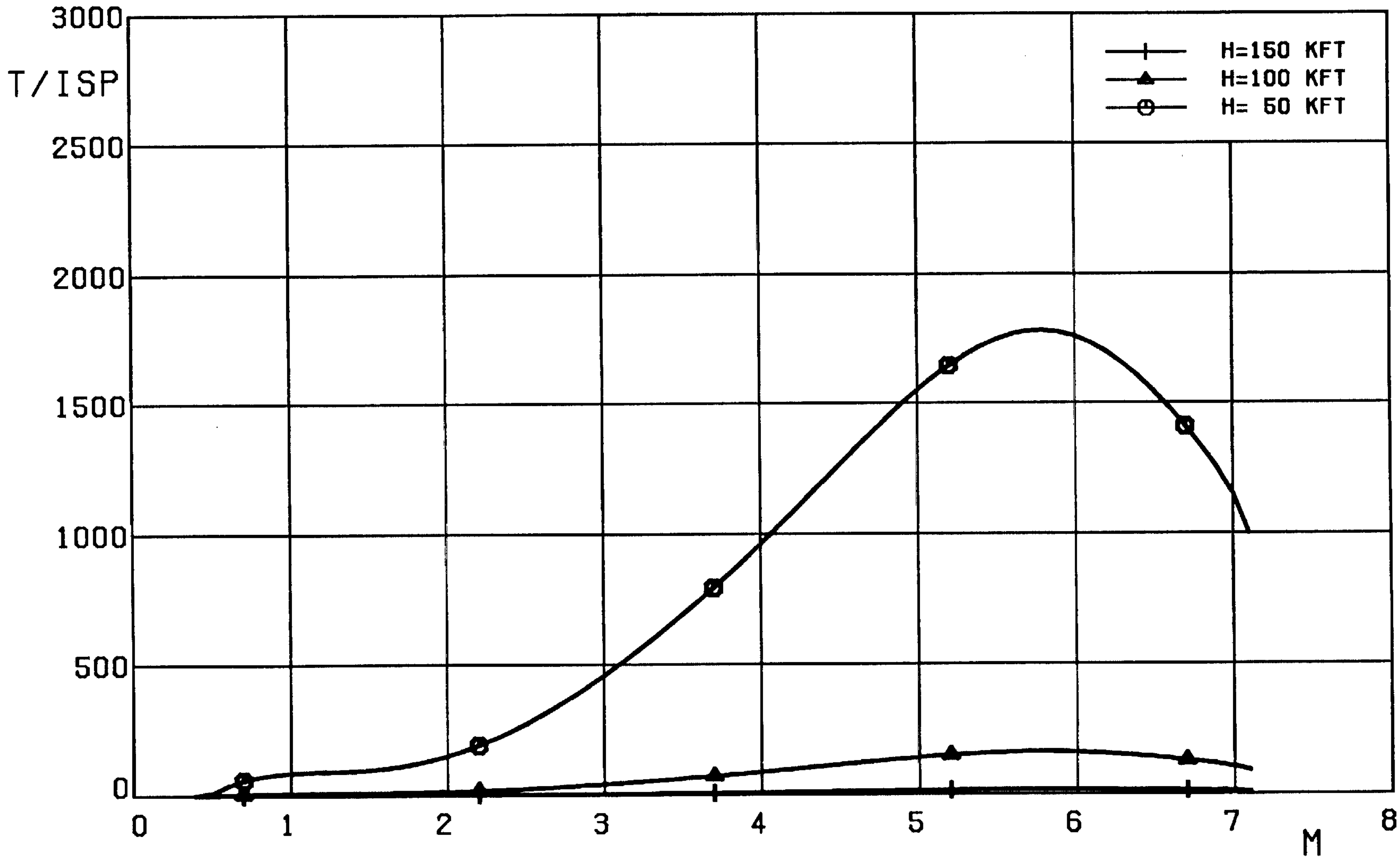

FIG. 2C. FUEL RATE (LBF/SEC), BETA=1, RAMJET ENGINE,
ENGINE MODELS EM1, EM2, EM3.

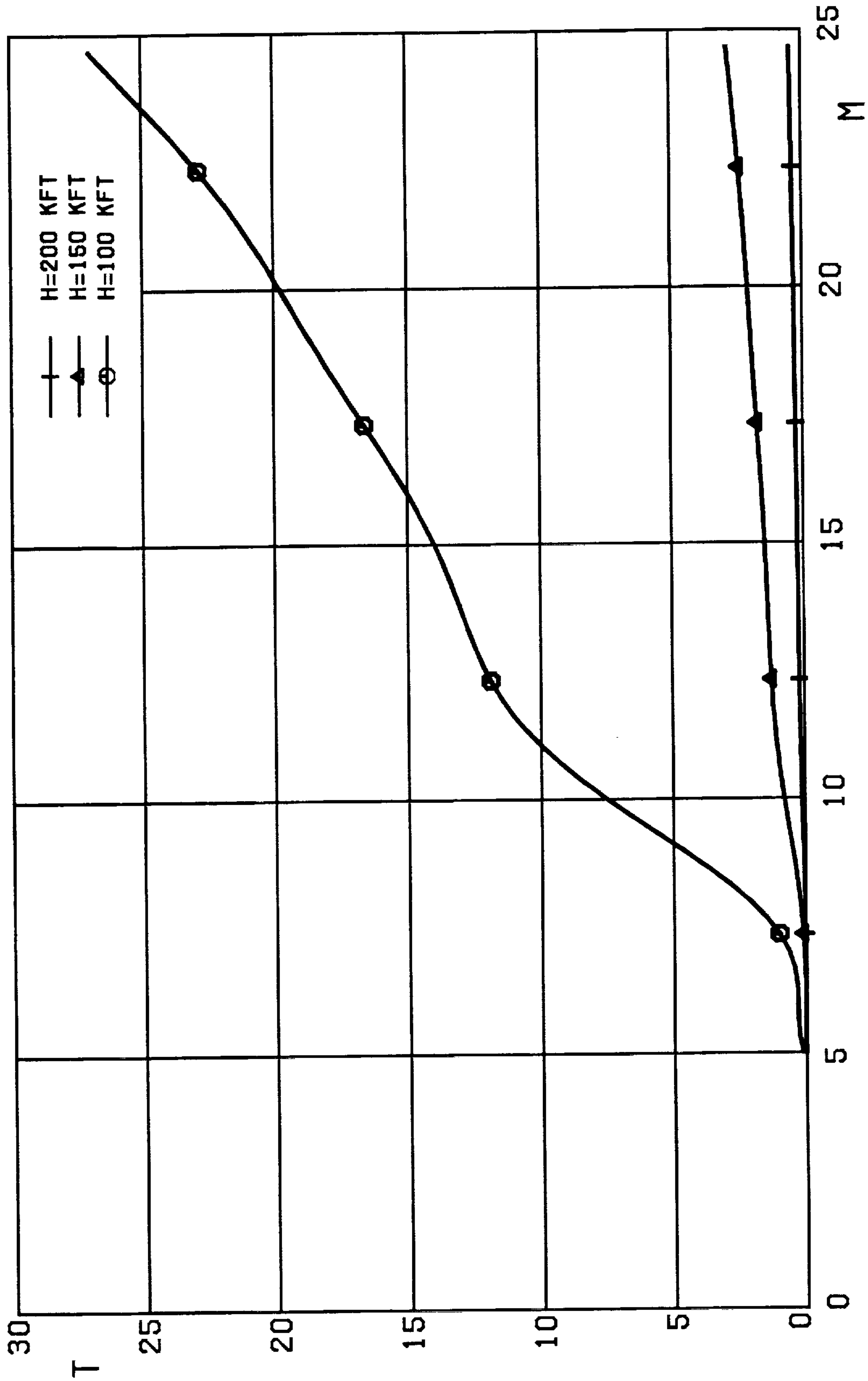

FIG. 3A. THRUST (MLBF), BETA=1, SCRAMJET ENGINE,
ENGINE MODEL EM1.

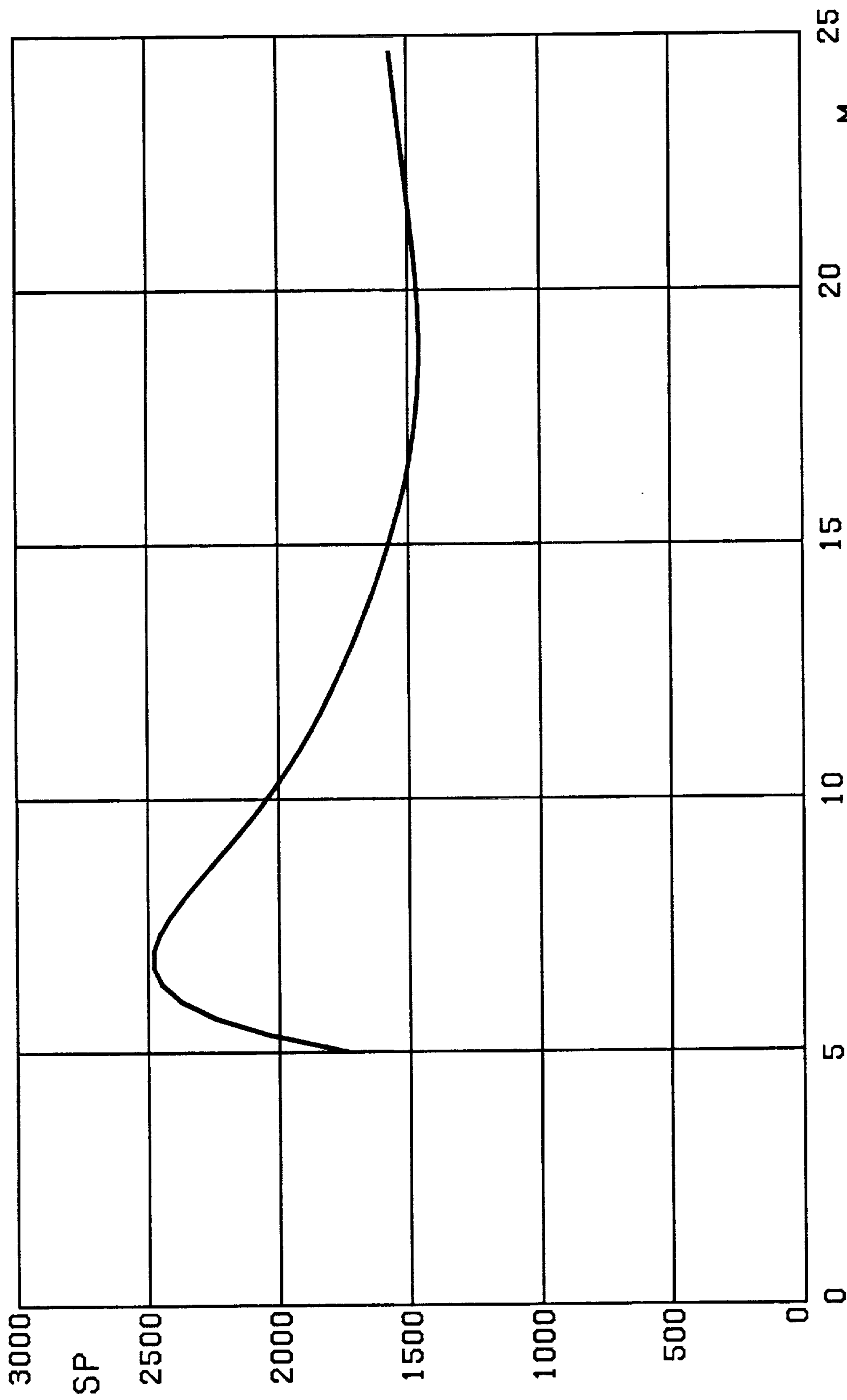

FIG. 3B. SPECIFIC IMPULSE (SEC), BETA=1, SCRAMJET ENGINE.
ENGINE MODEL EM1.

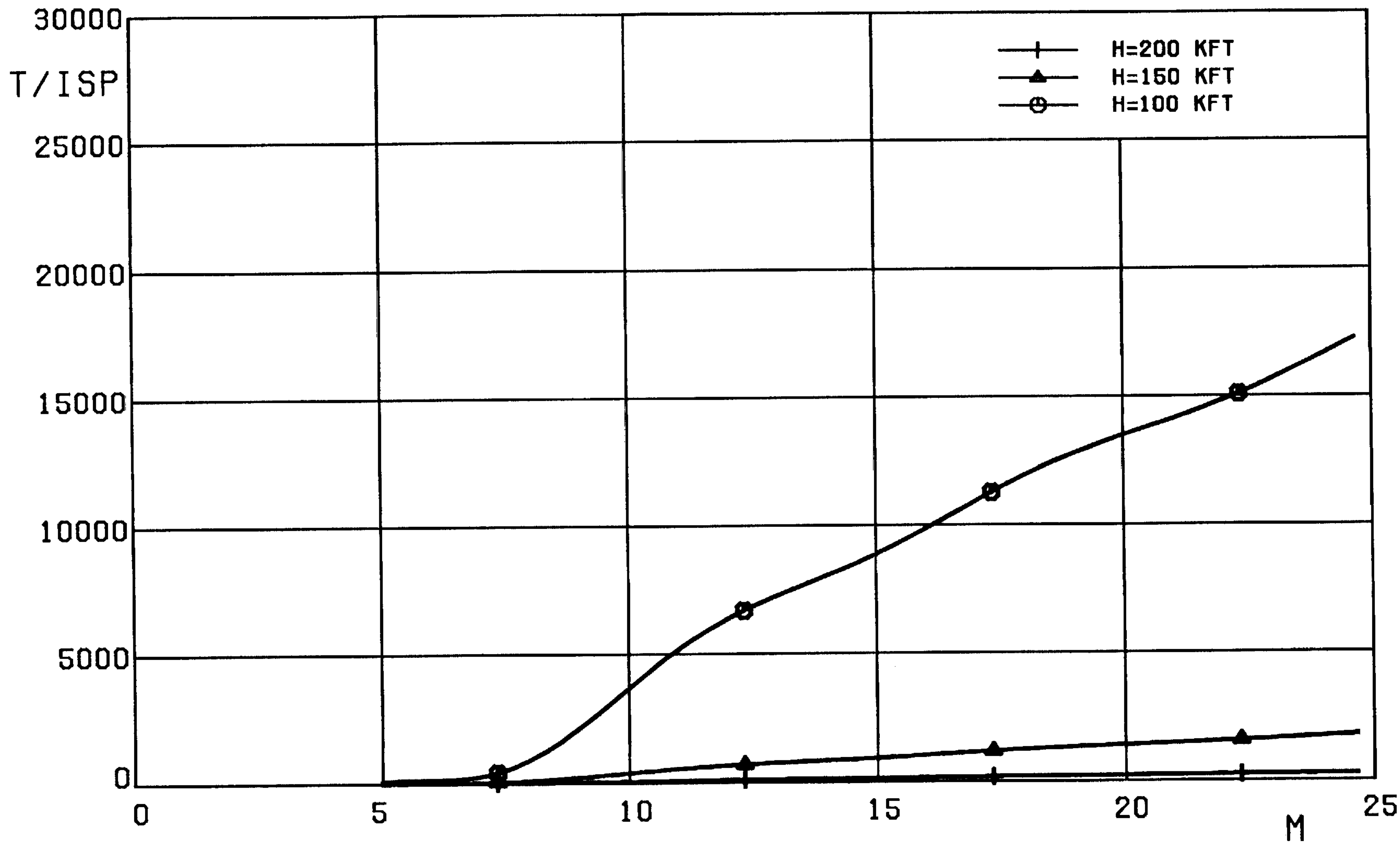

FIG. 3C. FUEL RATE (LBF/SEC), BETA=1, SCRAMJET ENGINE, ENGINE MODEL EM1.

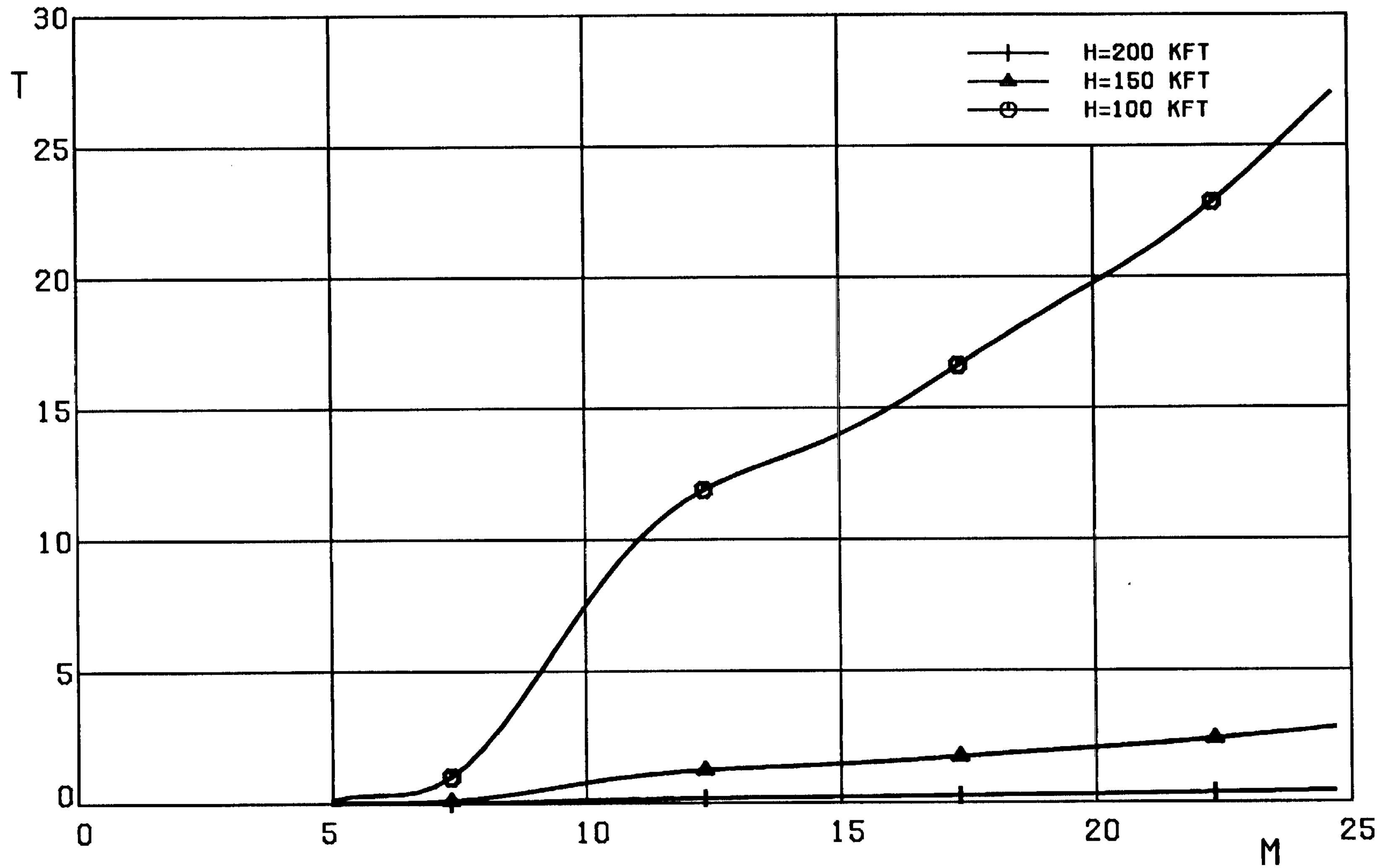

FIG. 4A. THRUST (MLBF), BETA=1, SCRAMJET ENGINE, ENGINE MODEL EM2.

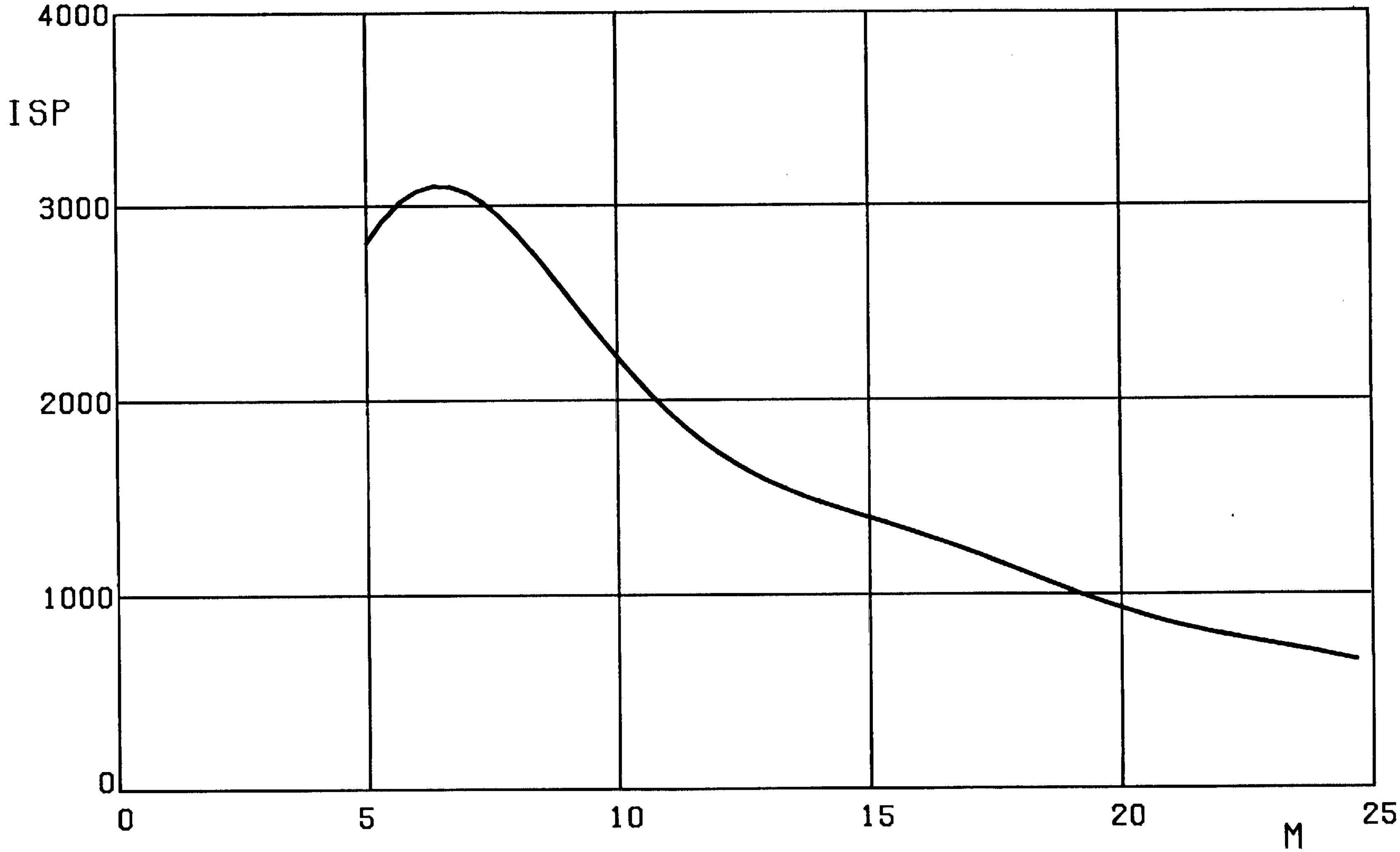

FIG. 4B. SPECIFIC IMPULSE (SEC), BETA=1, SCRAMJET ENGINE,
ENGINE MODEL EM2.

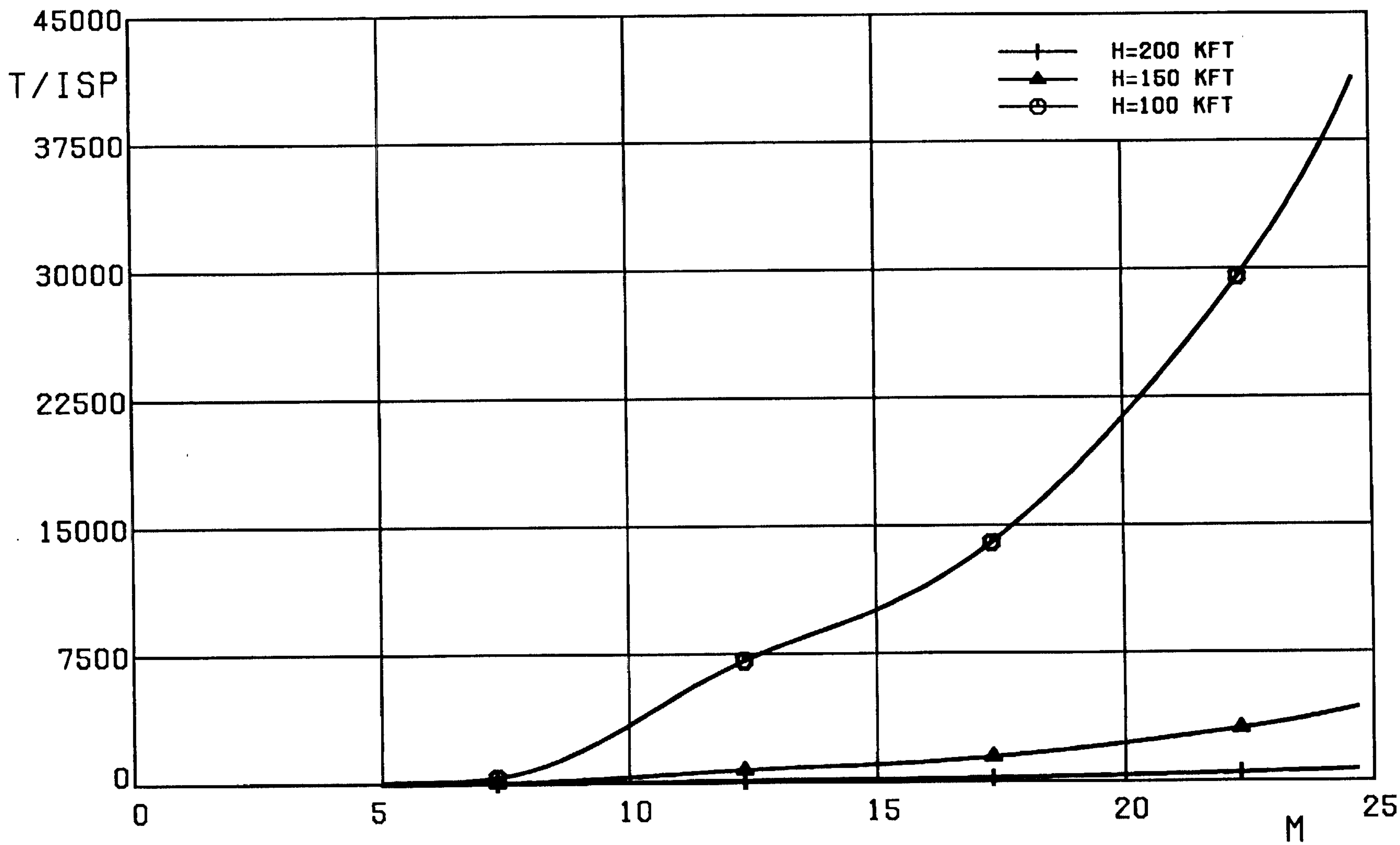

FIG. 4C. FUEL RATE (LBF/SEC), BETA=1, SCRAMJET ENGINE, ENGINE MODEL EM2.

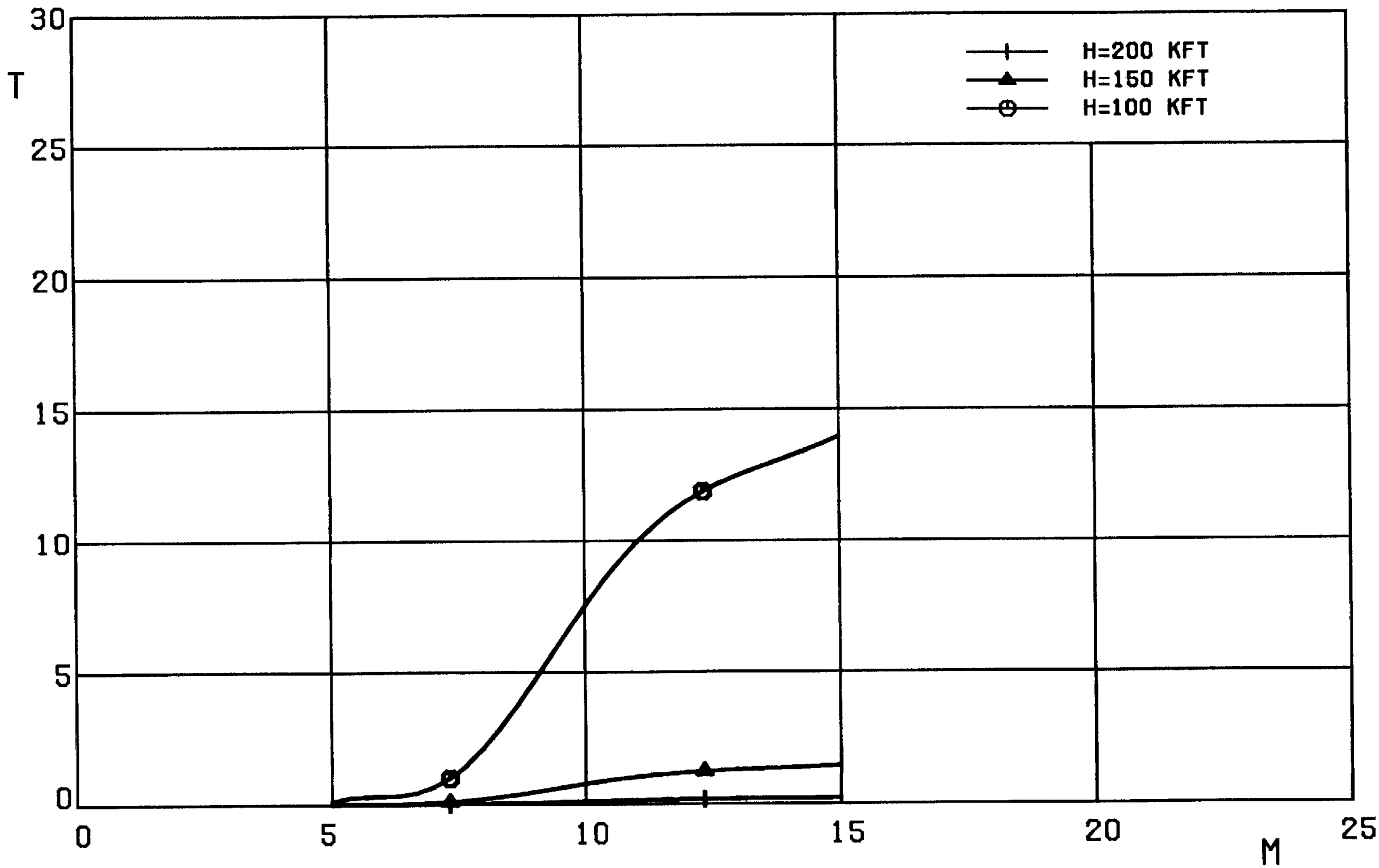

FIG. 5A. THRUST (MLBF), BETA=1, SCRAMJET ENGINE,
ENGINE MODEL EM3.

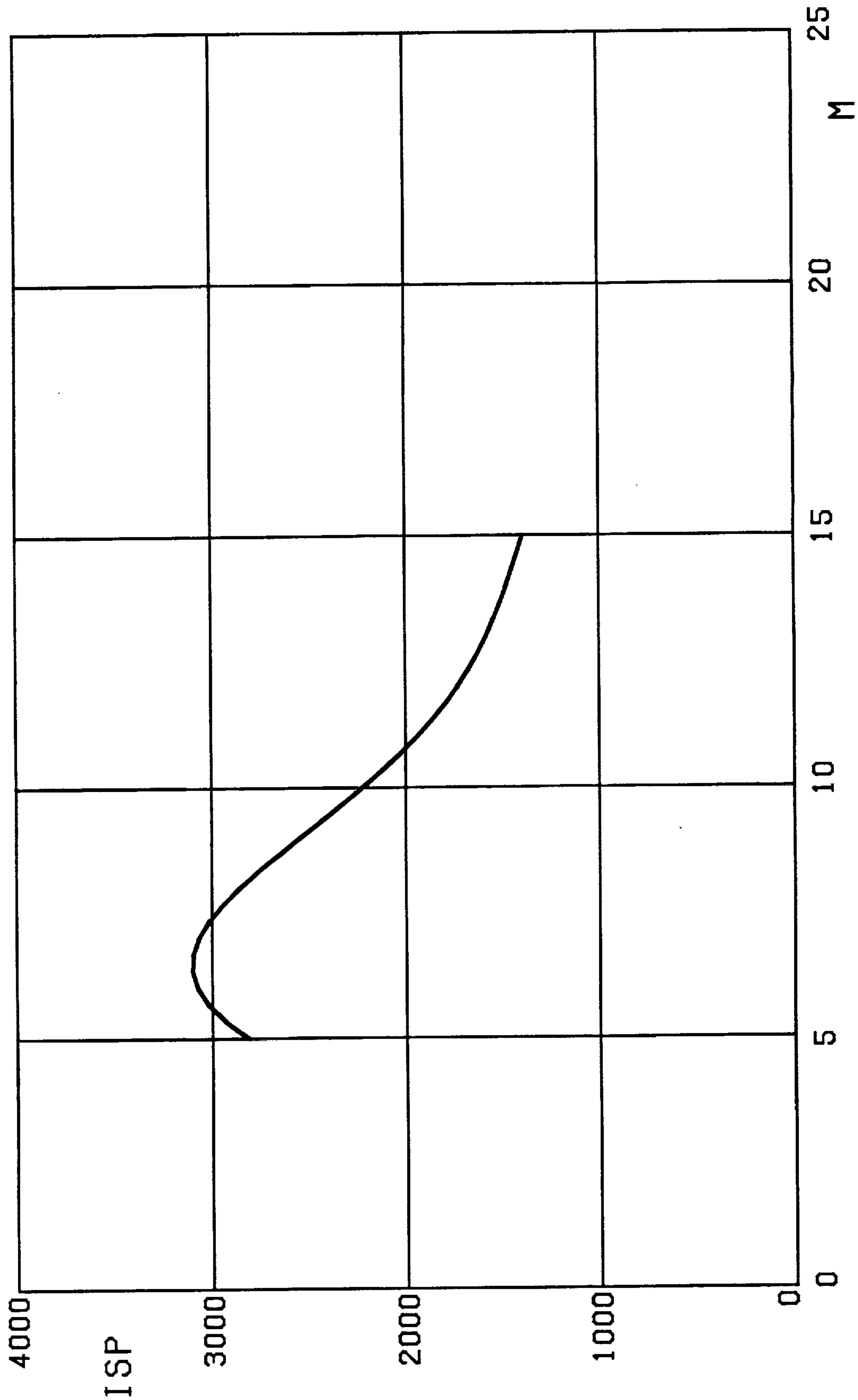

FIG. 5B. SPECIFIC IMPULSE (SEC), BETA=1, SCRAMJET ENGINE,
ENGINE MODEL EM3.

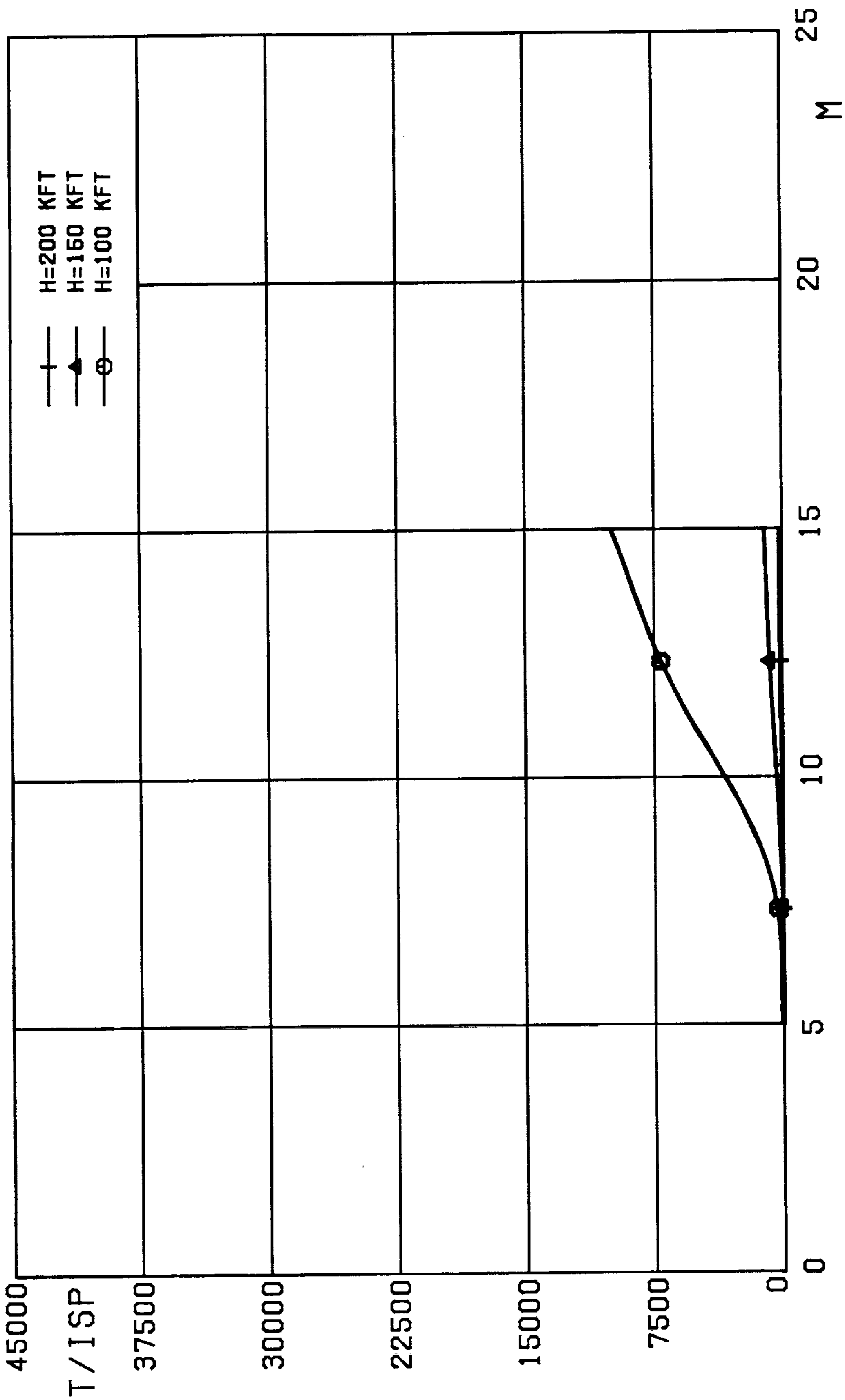

FIG. 5C. FUEL RATE (LBF/SEC), BETA=1, SCRAMJET ENGINE.
ENGINE MODEL EM3.

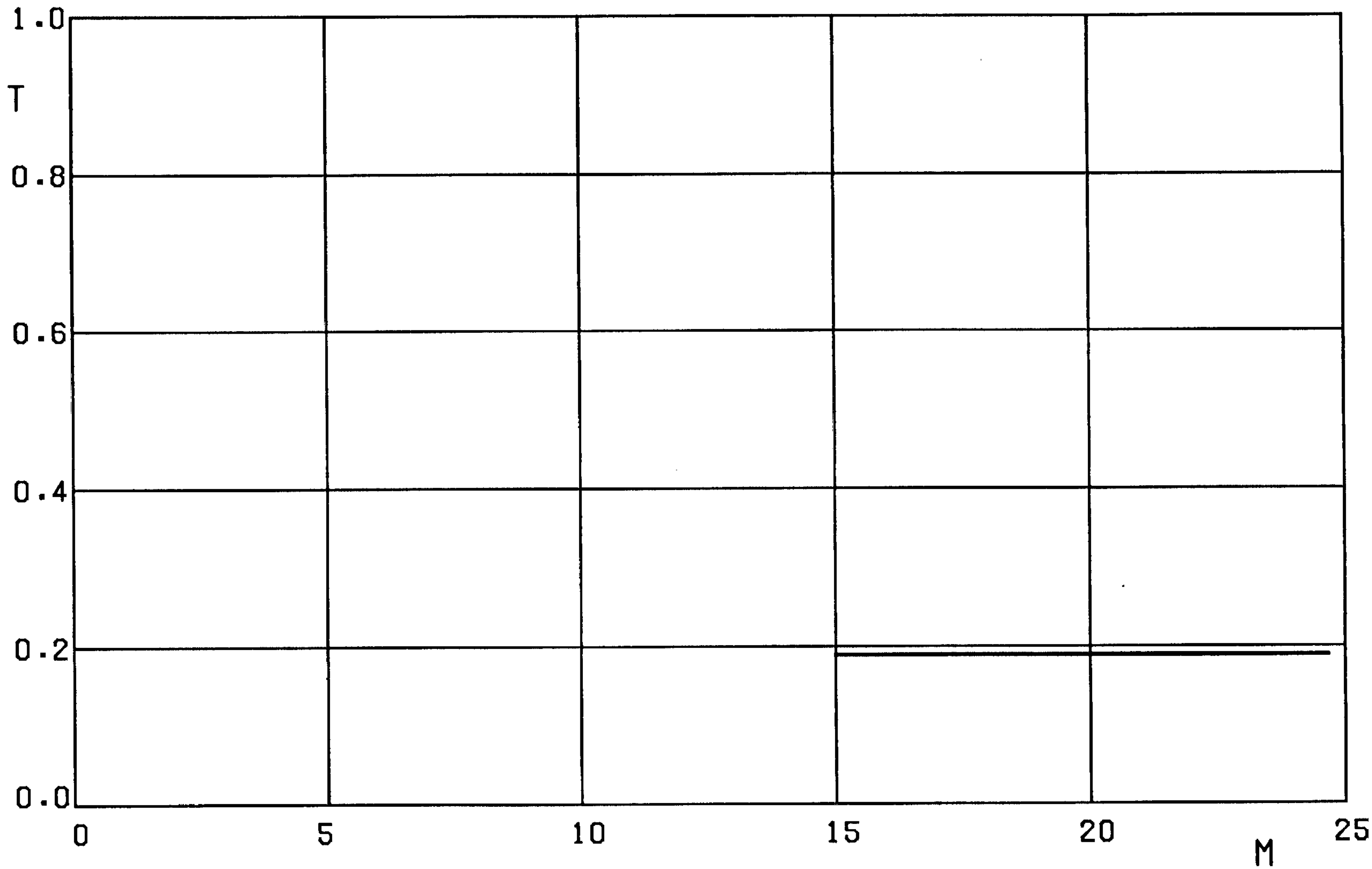

FIG. 6A. THRUST (MLBF), BETA=1, ROCKET ENGINE.
ENGINE MODEL EM3.

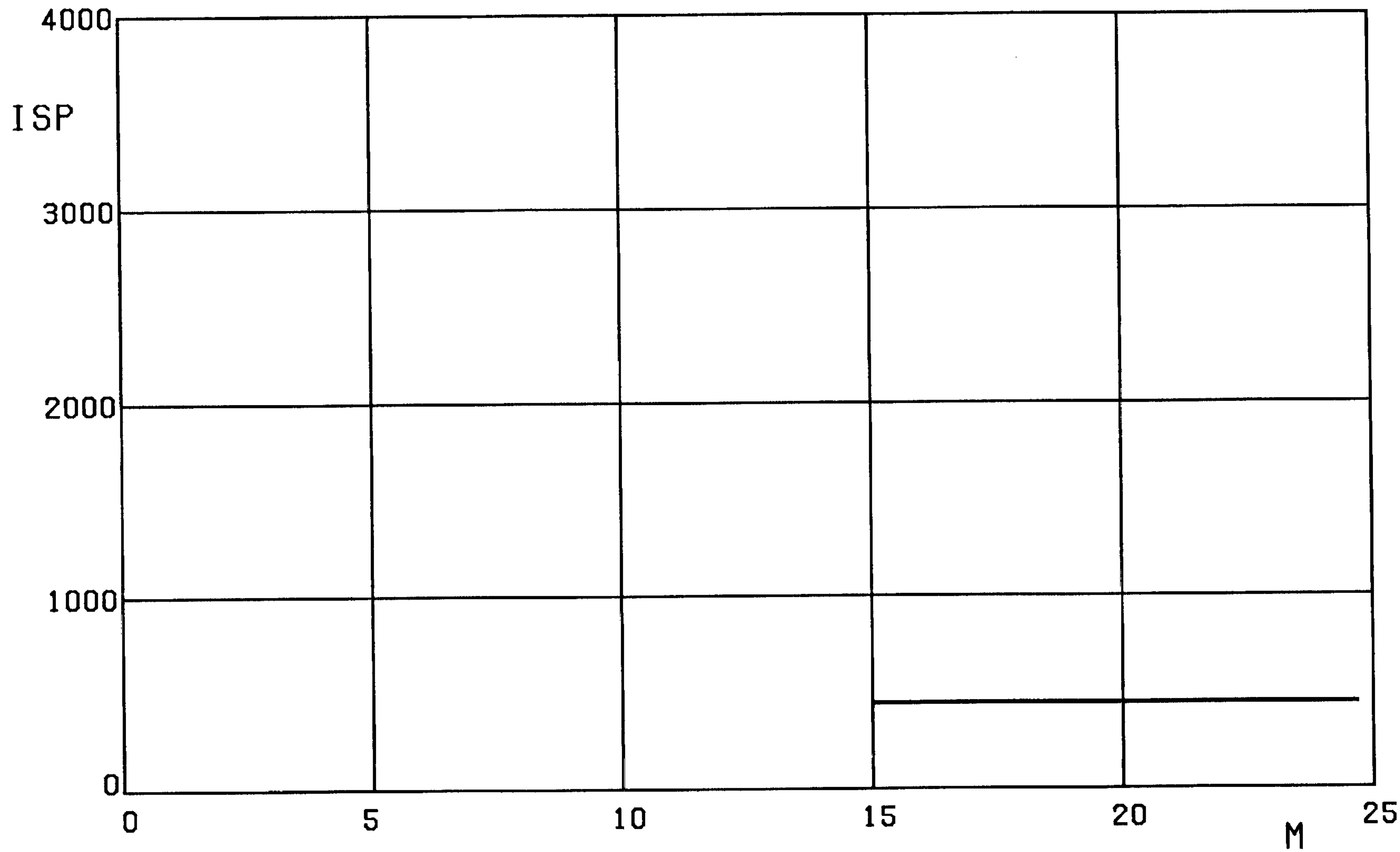

FIG. 6B. SPECIFIC IMPULSE (SEC), BETA=1, ROCKET ENGINE,
ENGINE MODEL EM3.

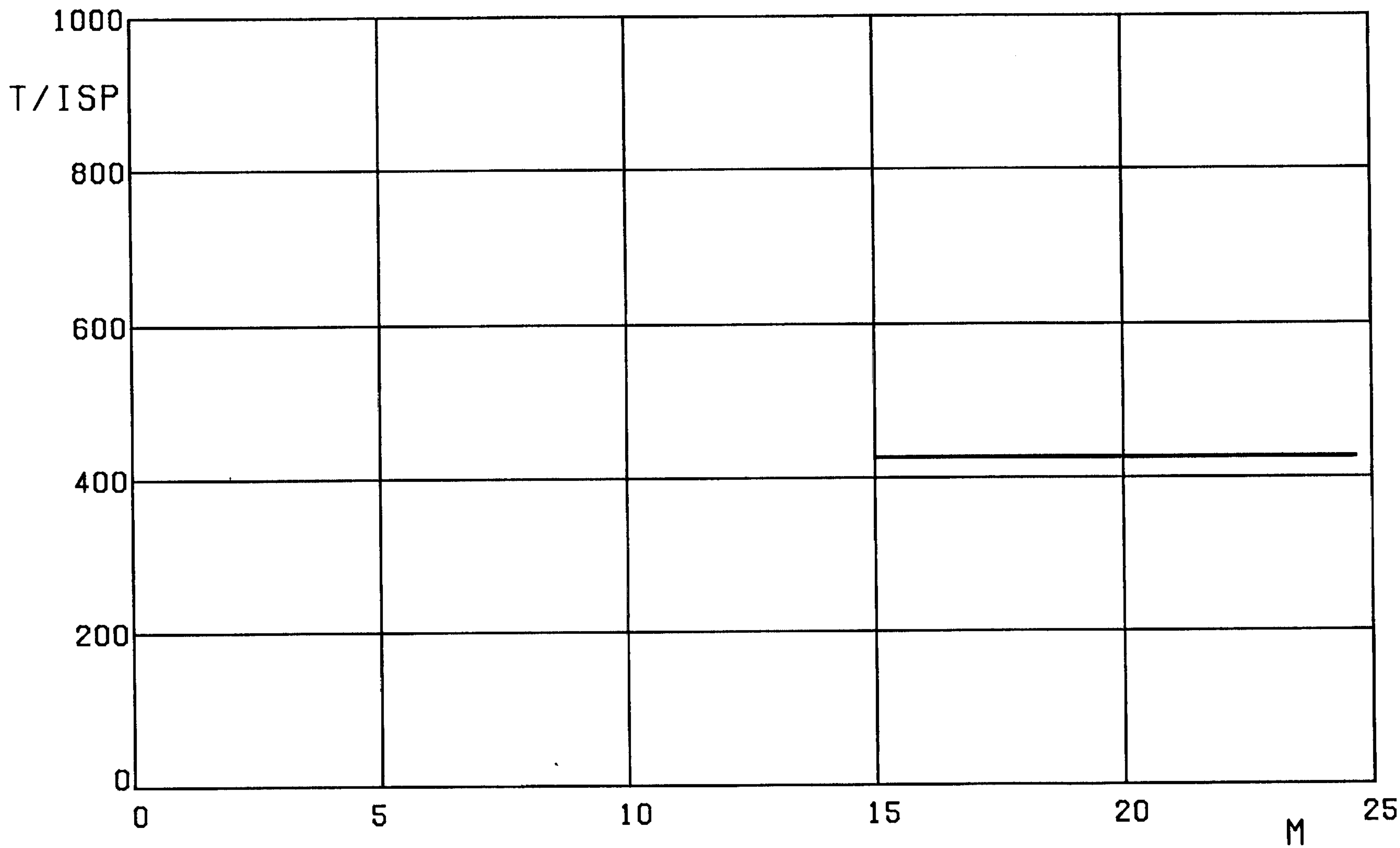

FIG. 6C. FUEL RATE (LBF/SEC), BETA=1, ROCKET ENGINE, ENGINE MODEL EM3.

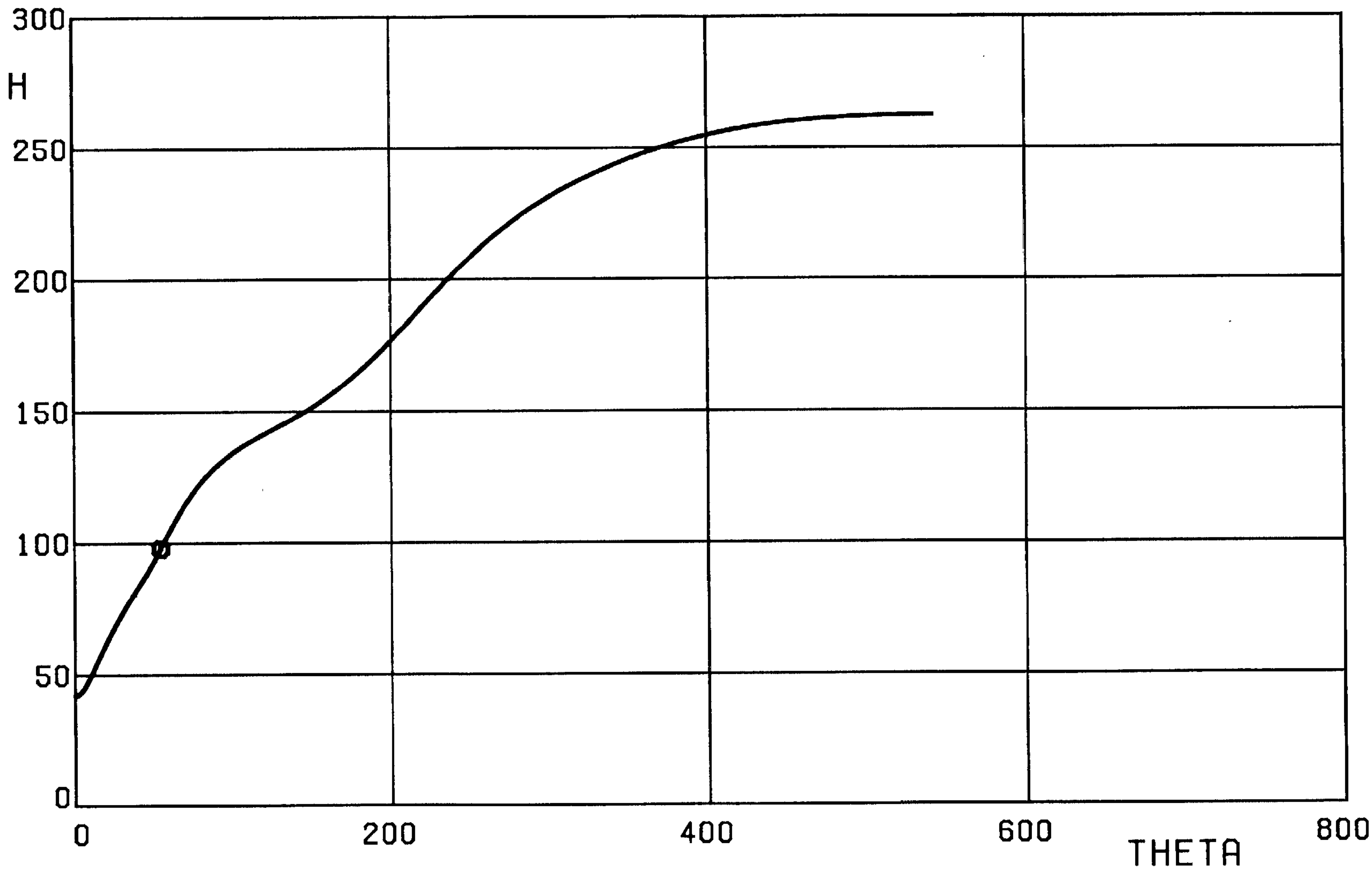

FIG. 7A. ALTITUDE(KFT) VS TIME(SEC), ENGINE MODEL EM1, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMAO=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

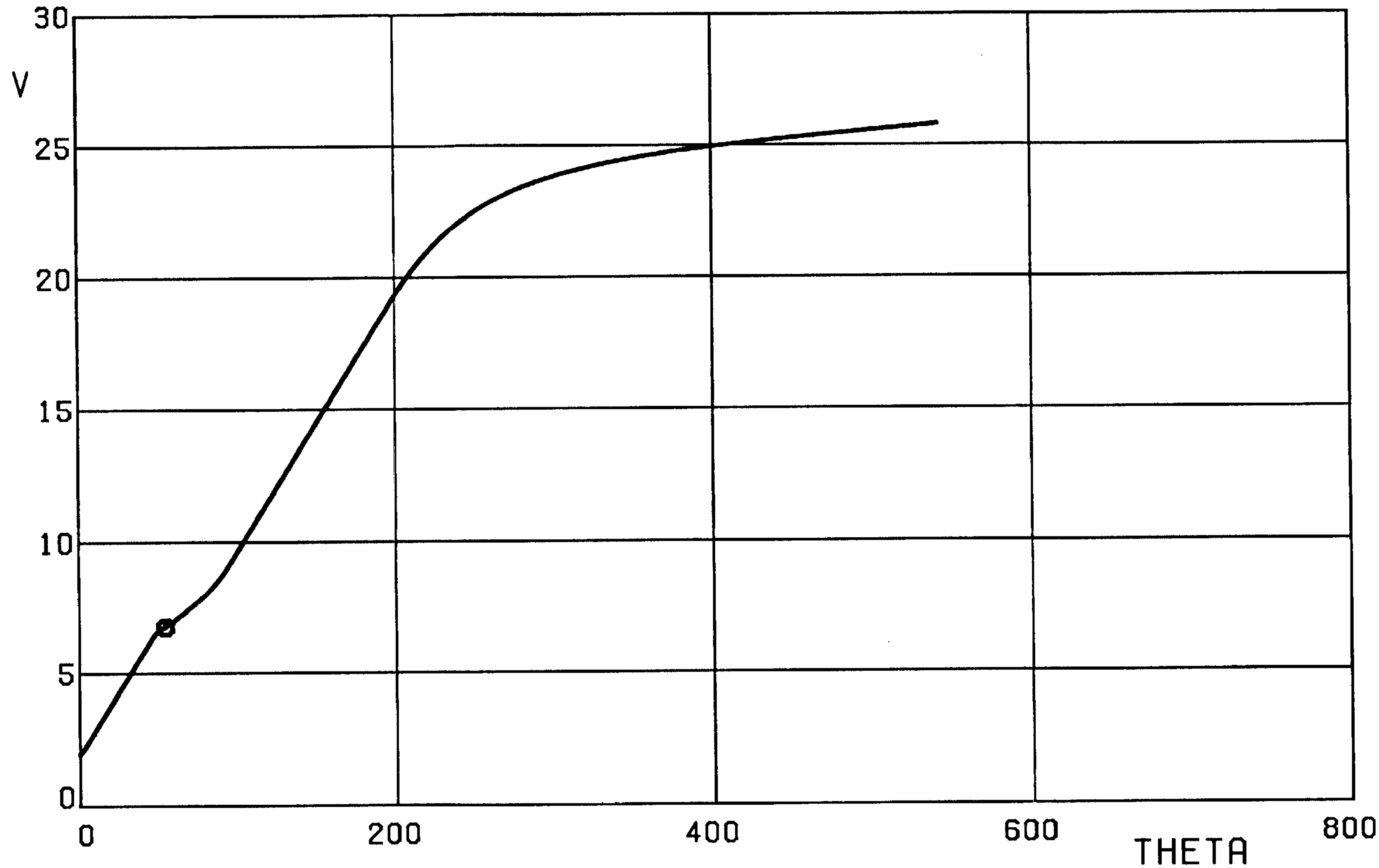

FIG. 7B. VELOCITY(KFT/SEC) VS TIME(SEC), ENGINE MODEL EM1, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

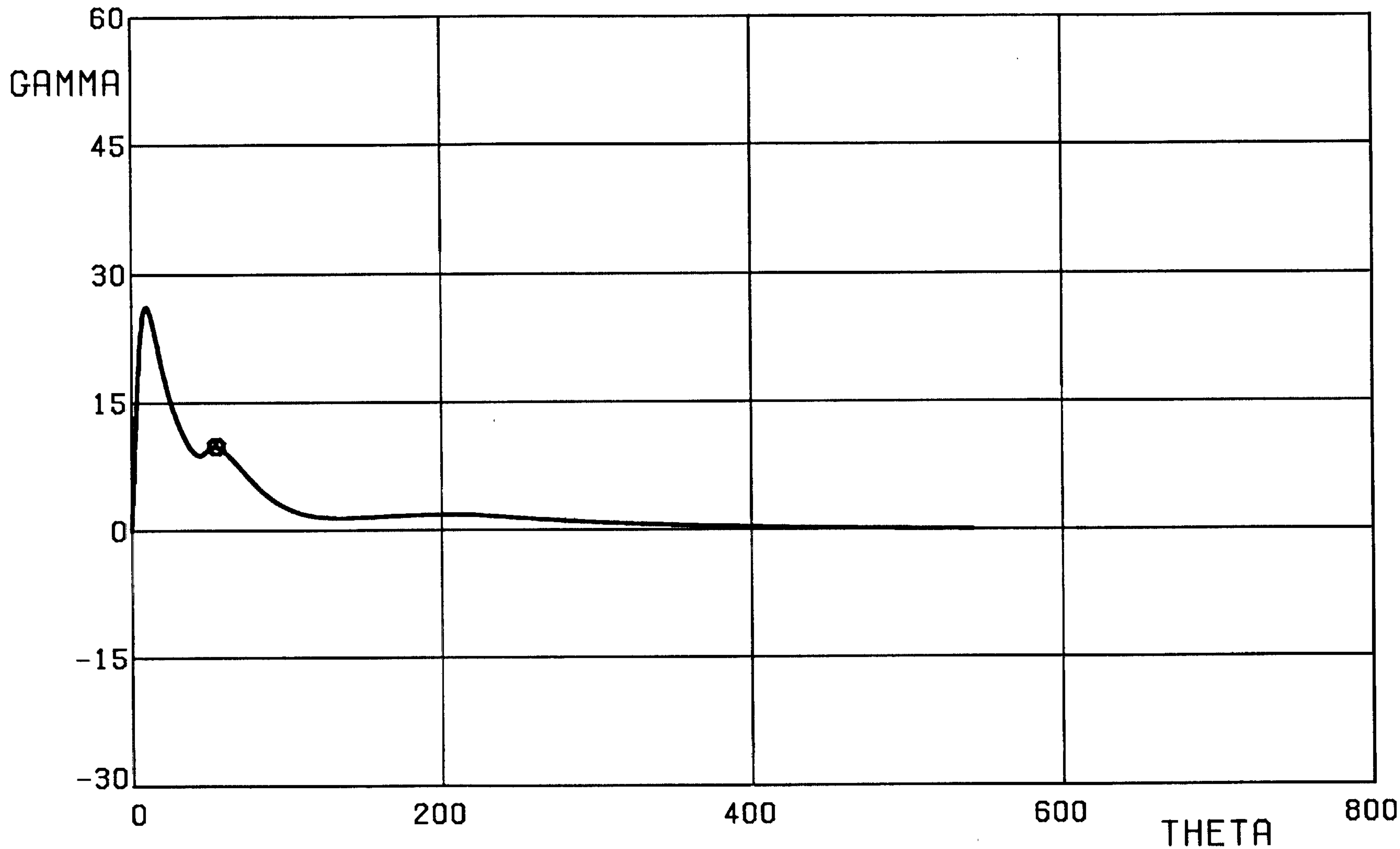

FIG. 7C. PATH INCLINATION(DEG) VS TIME(SEC), ENGINE MODEL EM1,
PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED,
GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

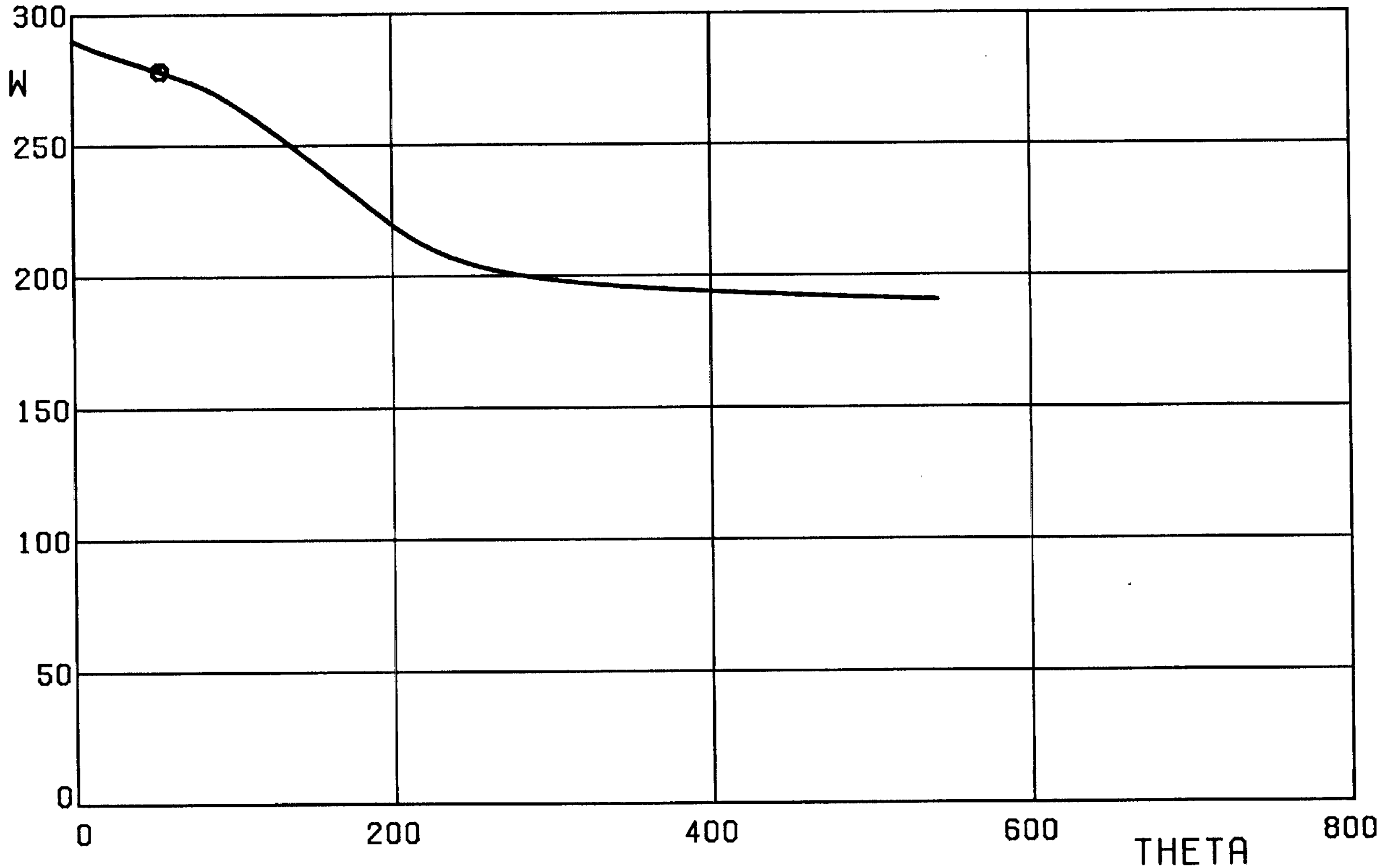

FIG. 7D. WEIGHT(KLBF) VS TIME(SEC), ENGINE MODEL EM1, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMAO=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

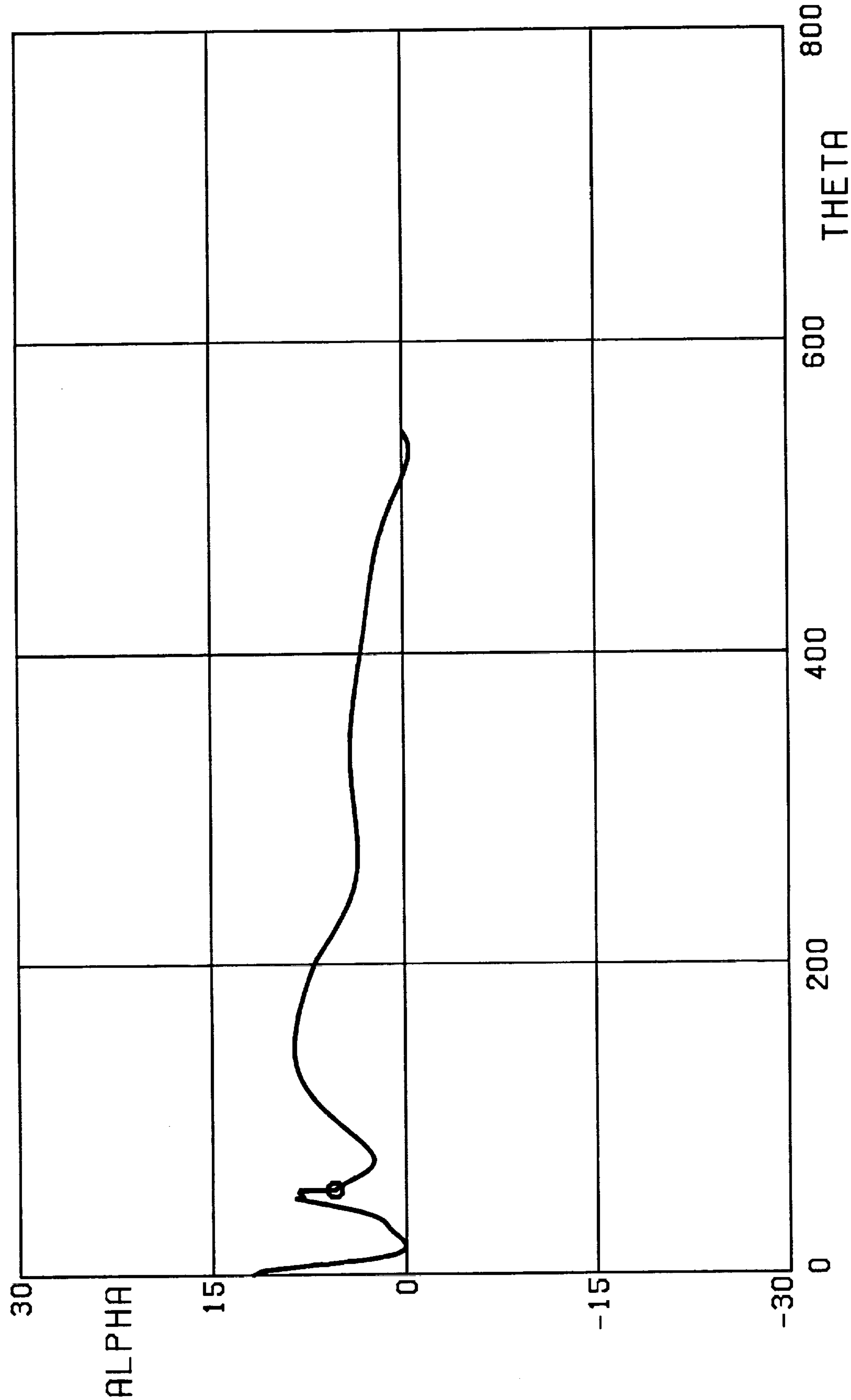

FIG. 7E. ANGLE OF ATTACK(DEG) VS TIME(SEC), ENGINE MODEL EM1, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED. GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

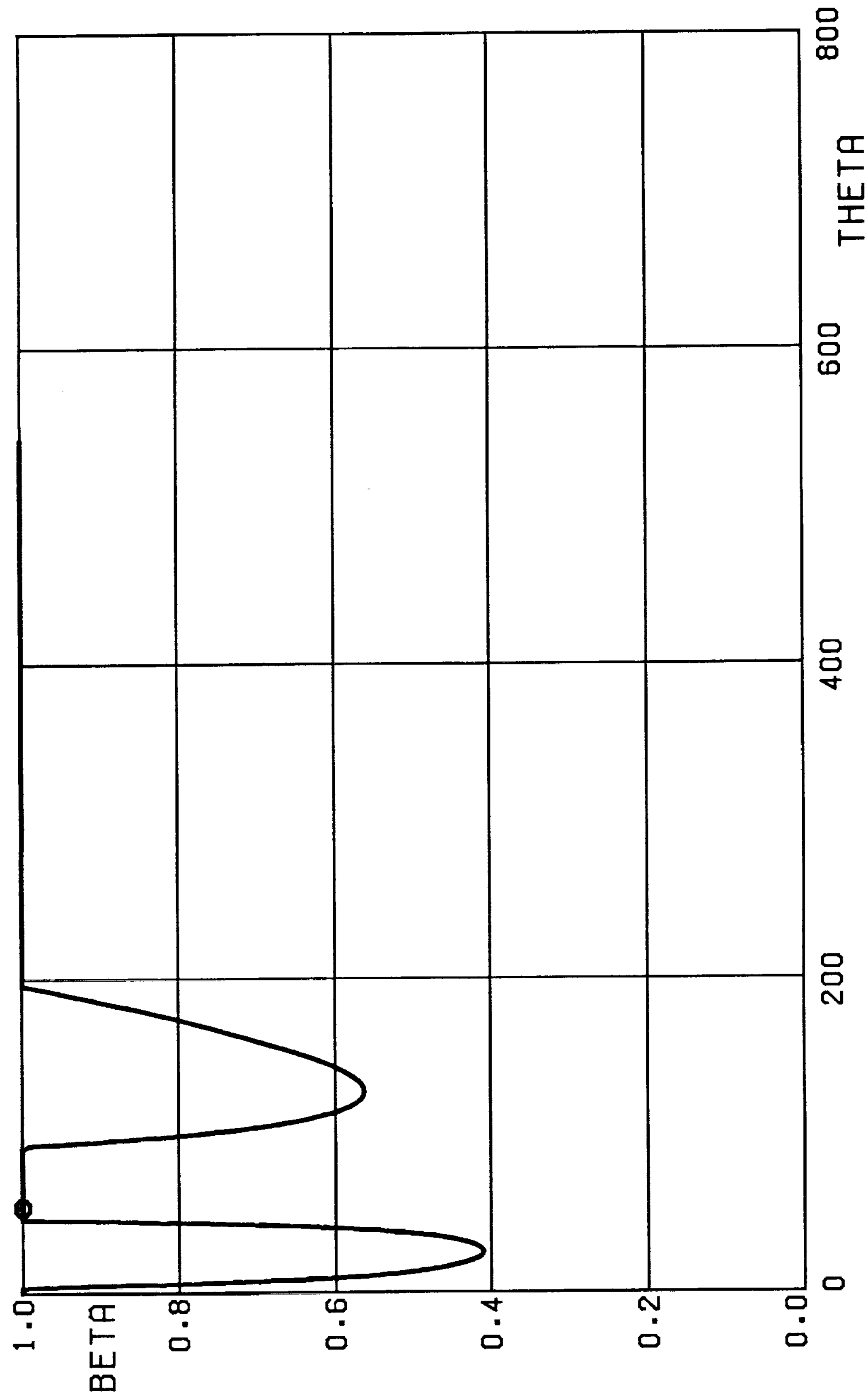

FIG. 7F. POWER SETTING VS TIME(SEC), ENGINE MODEL EM1, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

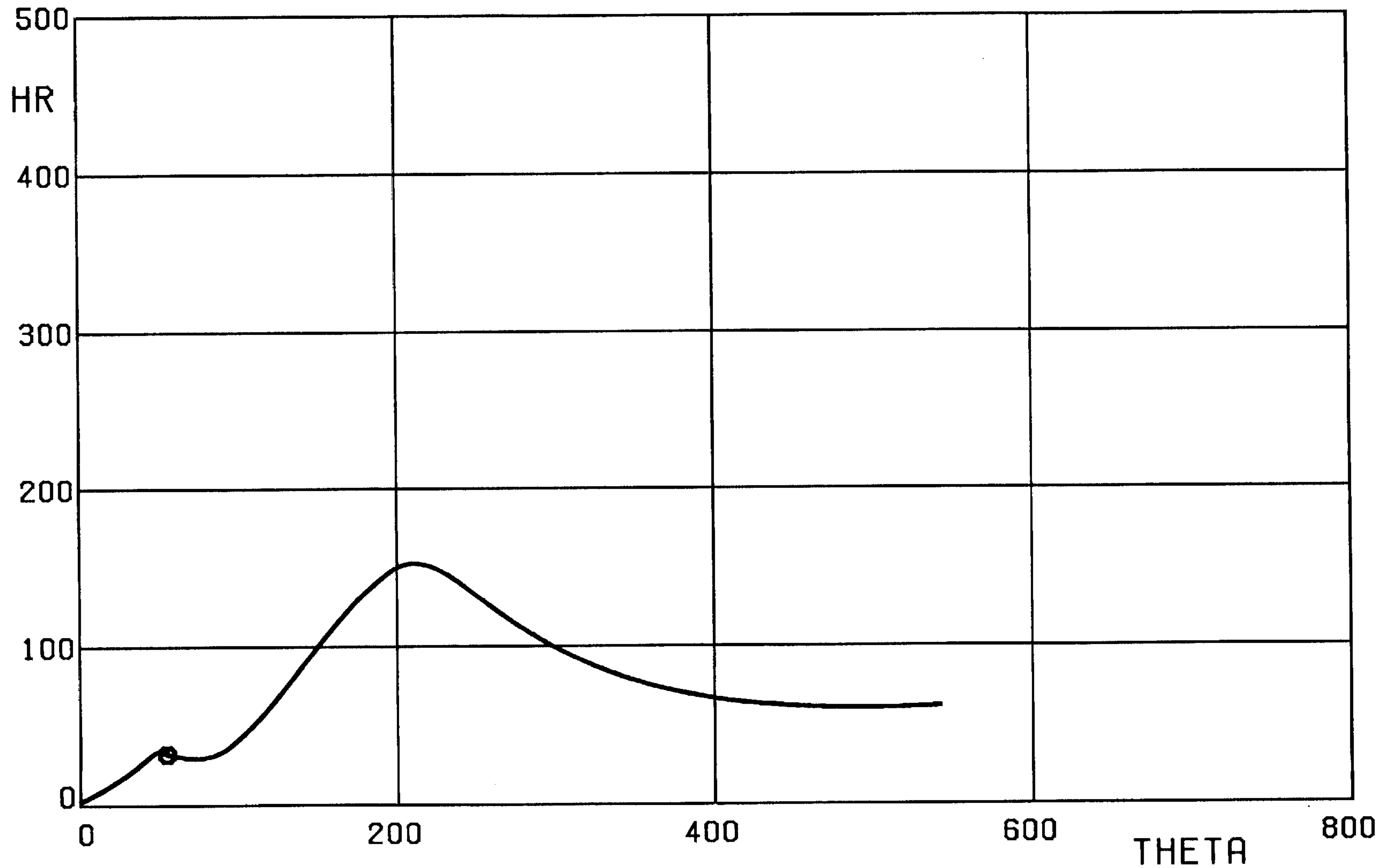

FIG. 7G. HEATING RATE(BTU/FT2 SEC) VS TIME(SEC), ENGINE MODEL EM1, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

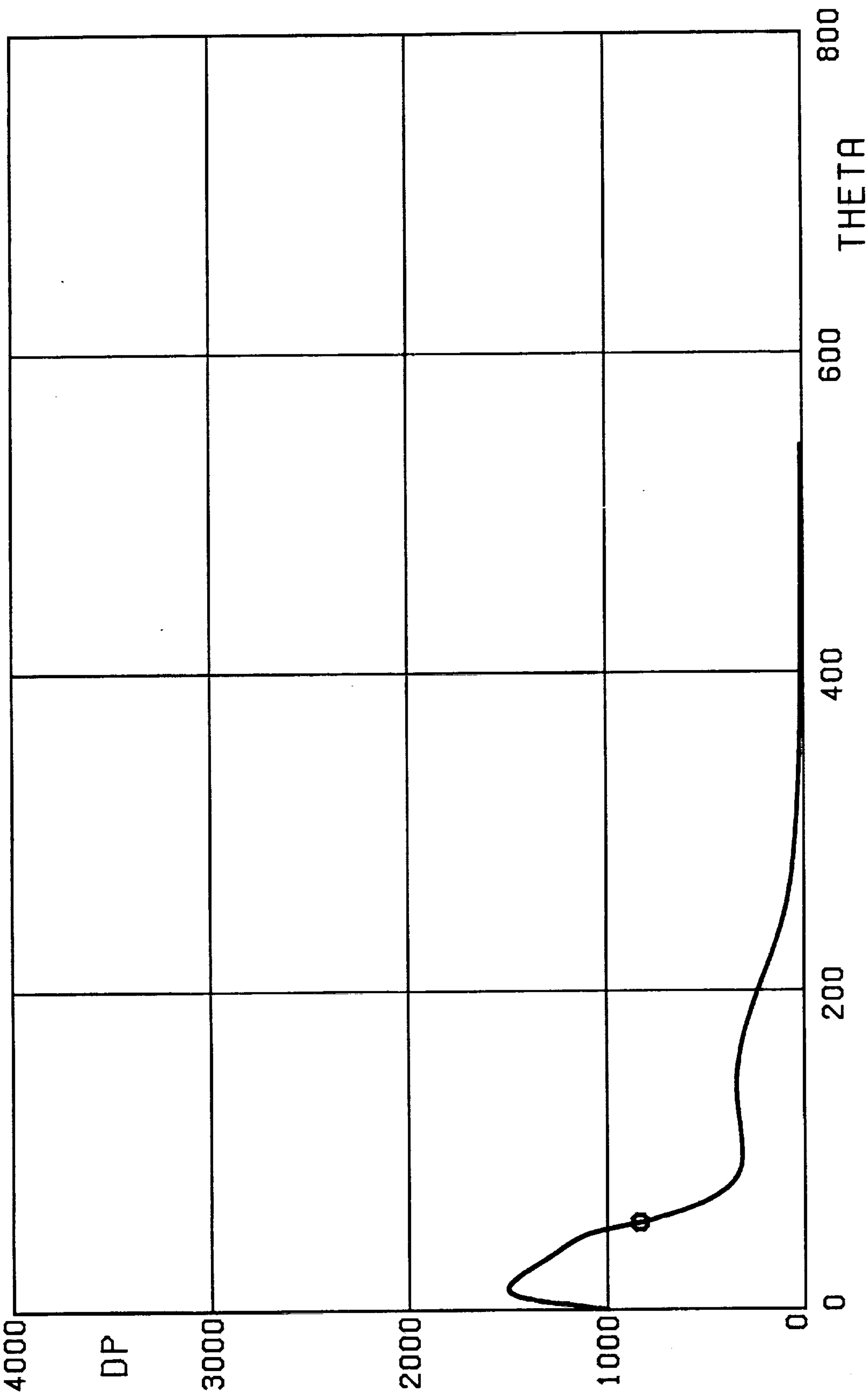

FIG. 7H. DYNAMIC PRESSURE(LB/FT2) VS TIME(SEC), ENGINE MODEL EM1, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

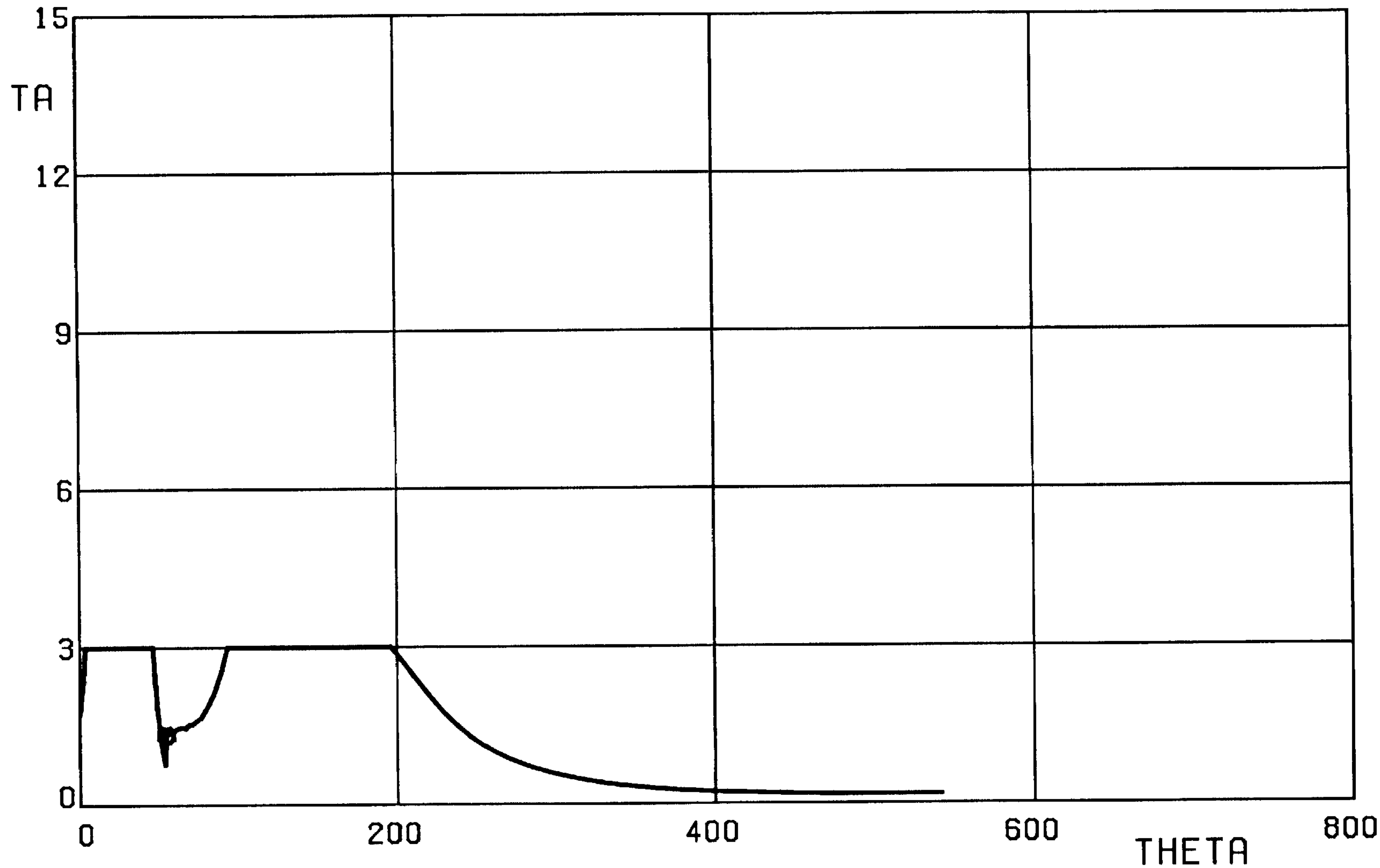

FIG. 7I. TANGENTIAL ACCELERATION(GE'S) VS TIME(SEC), ENGINE MODEL EM1, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMAO=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

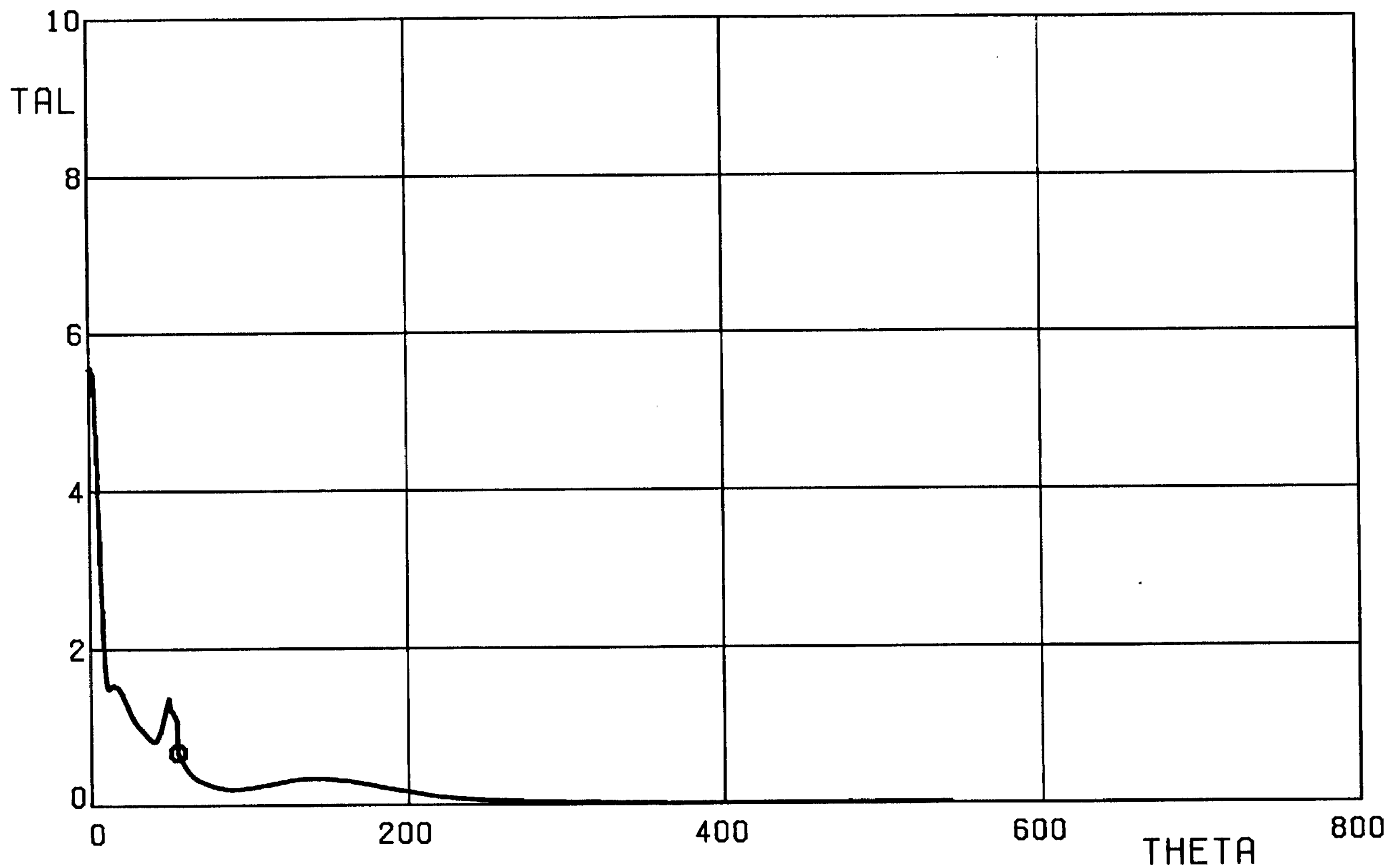

FIG. 7J. TOTAL AERODYNAMIC LOAD(GE'S) VS TIME(SEC), ENGINE MODEL EM1, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMAO=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

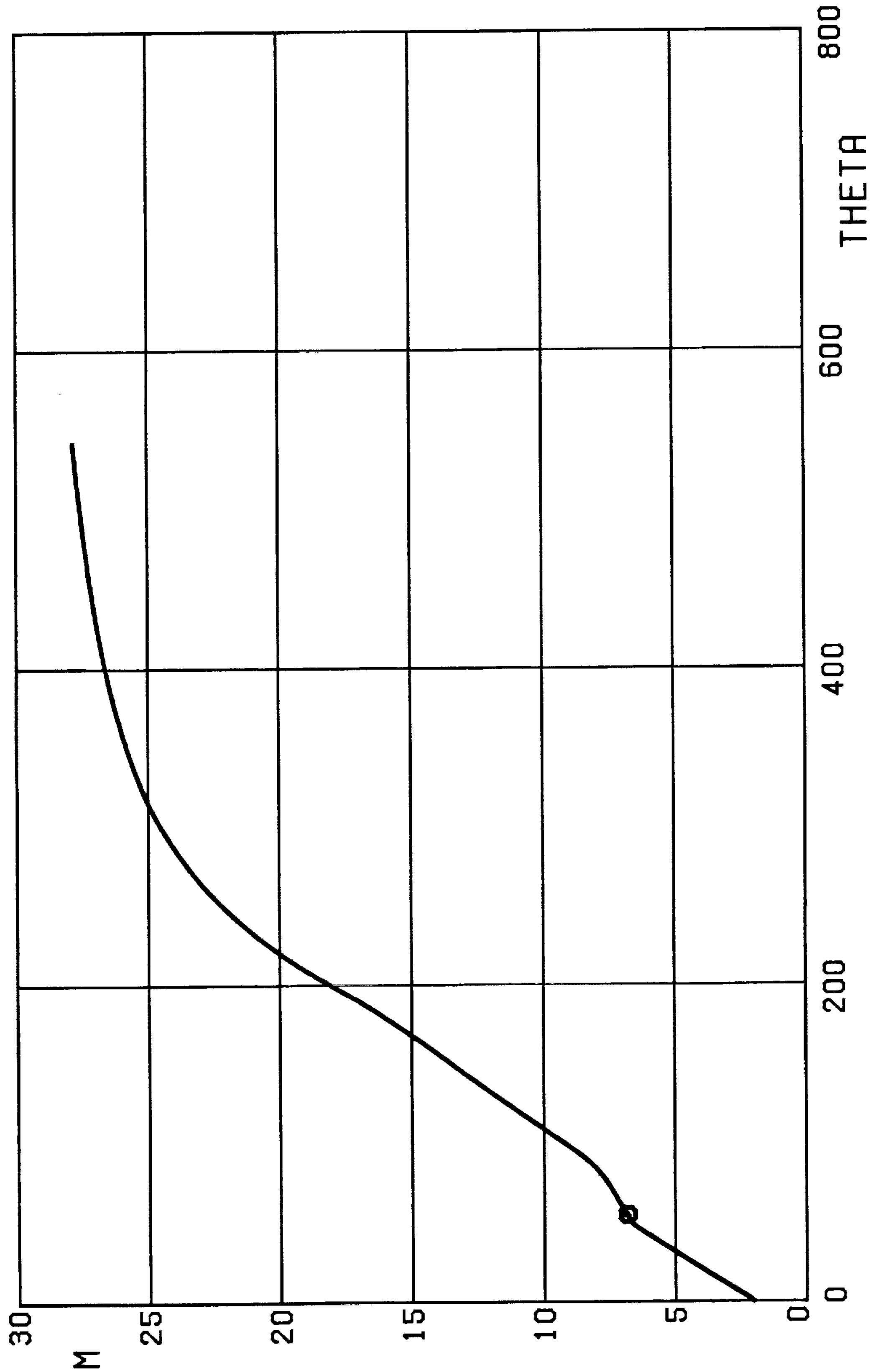

FIG. 7K. MACH NUMBER VS TIME(SEC), ENGINE MODEL EM1,
PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED,
GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

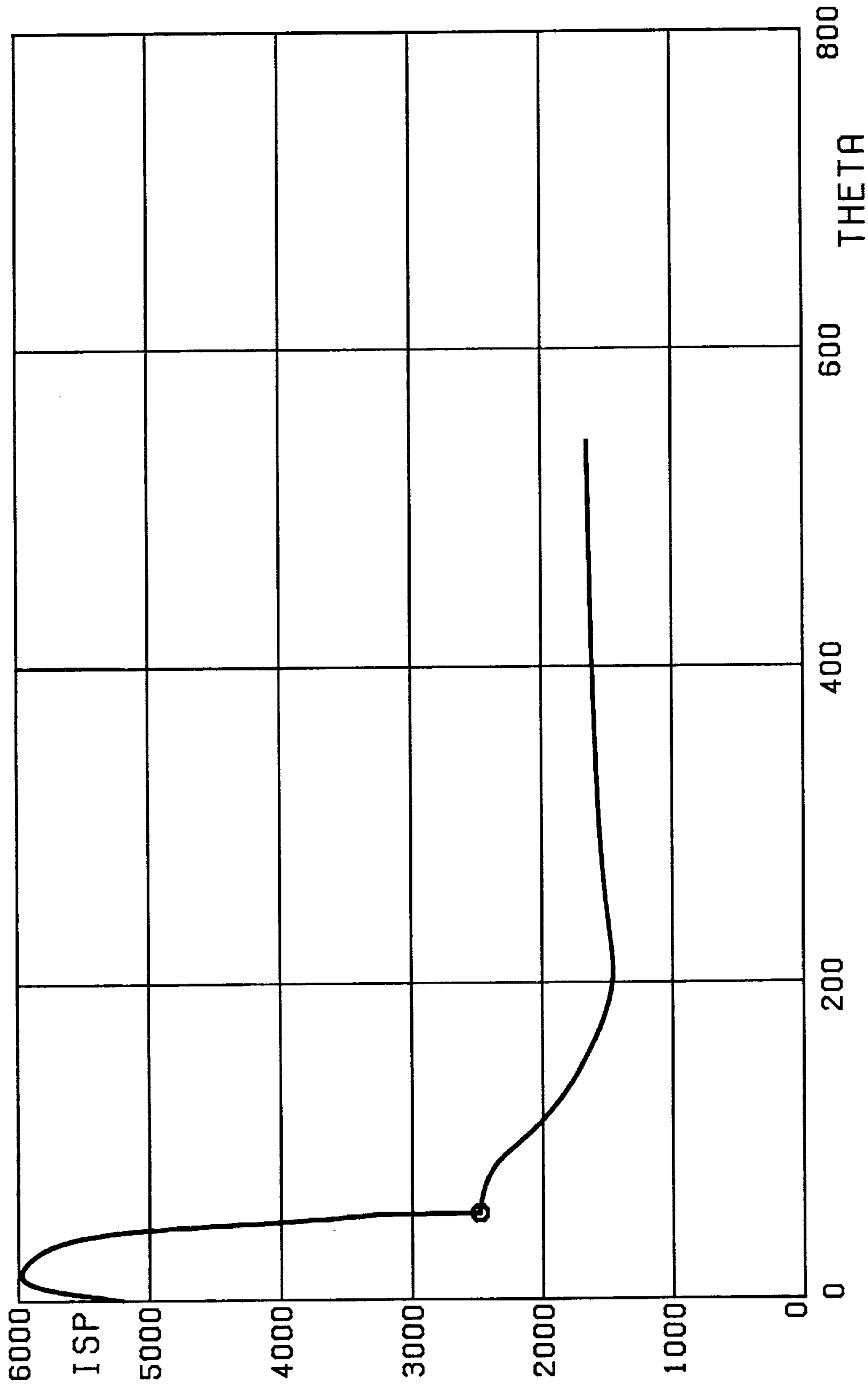

FIG. 7L. SPECIFIC IMPULSE(SEC) VS TIME(SEC), ENGINE MODEL EM1.
PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED.
GAMMAO=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

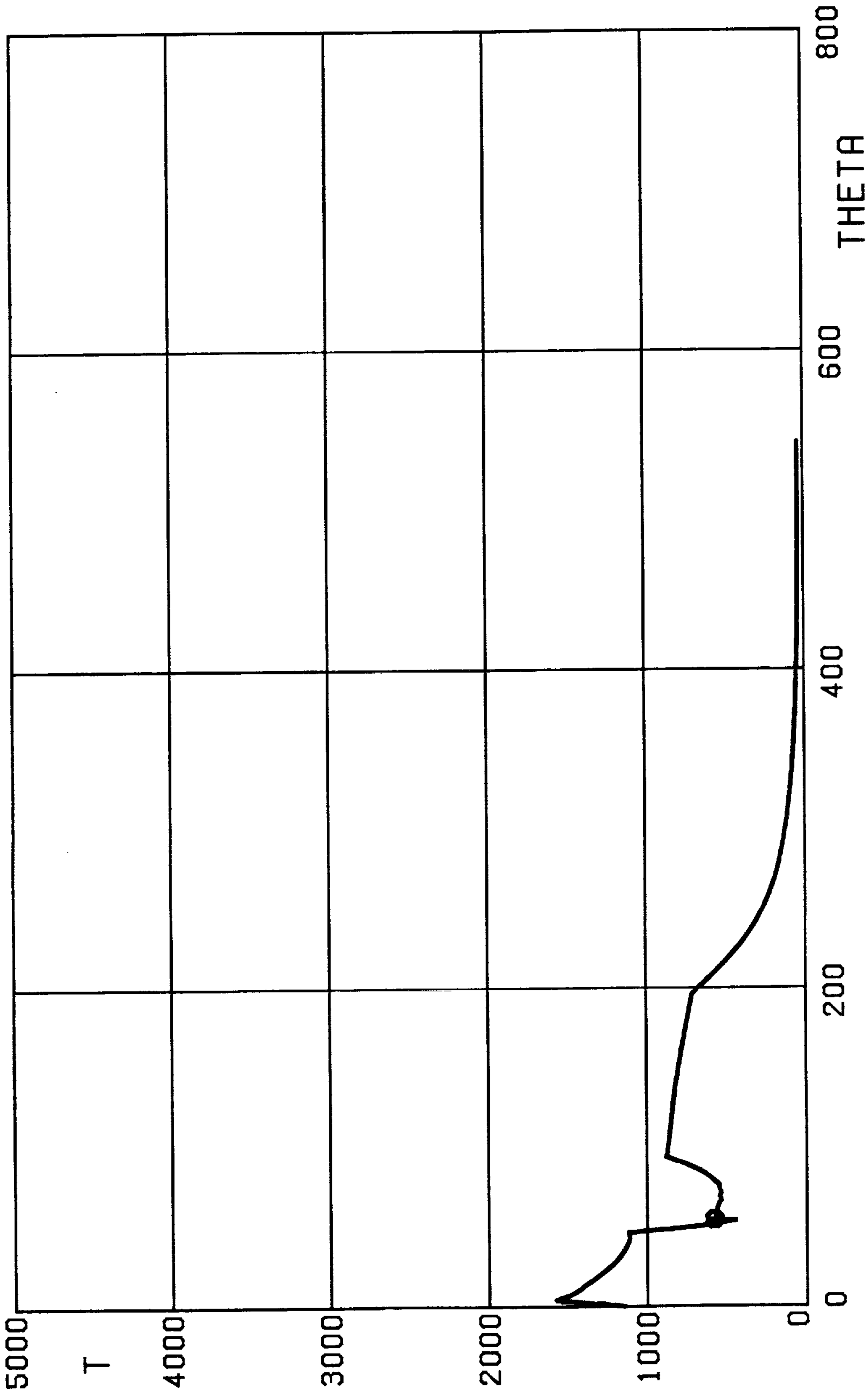

FIG. 7M. THRUST(KLBF) VS TIME(SEC), ENGINE MODEL EM1. PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED. GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

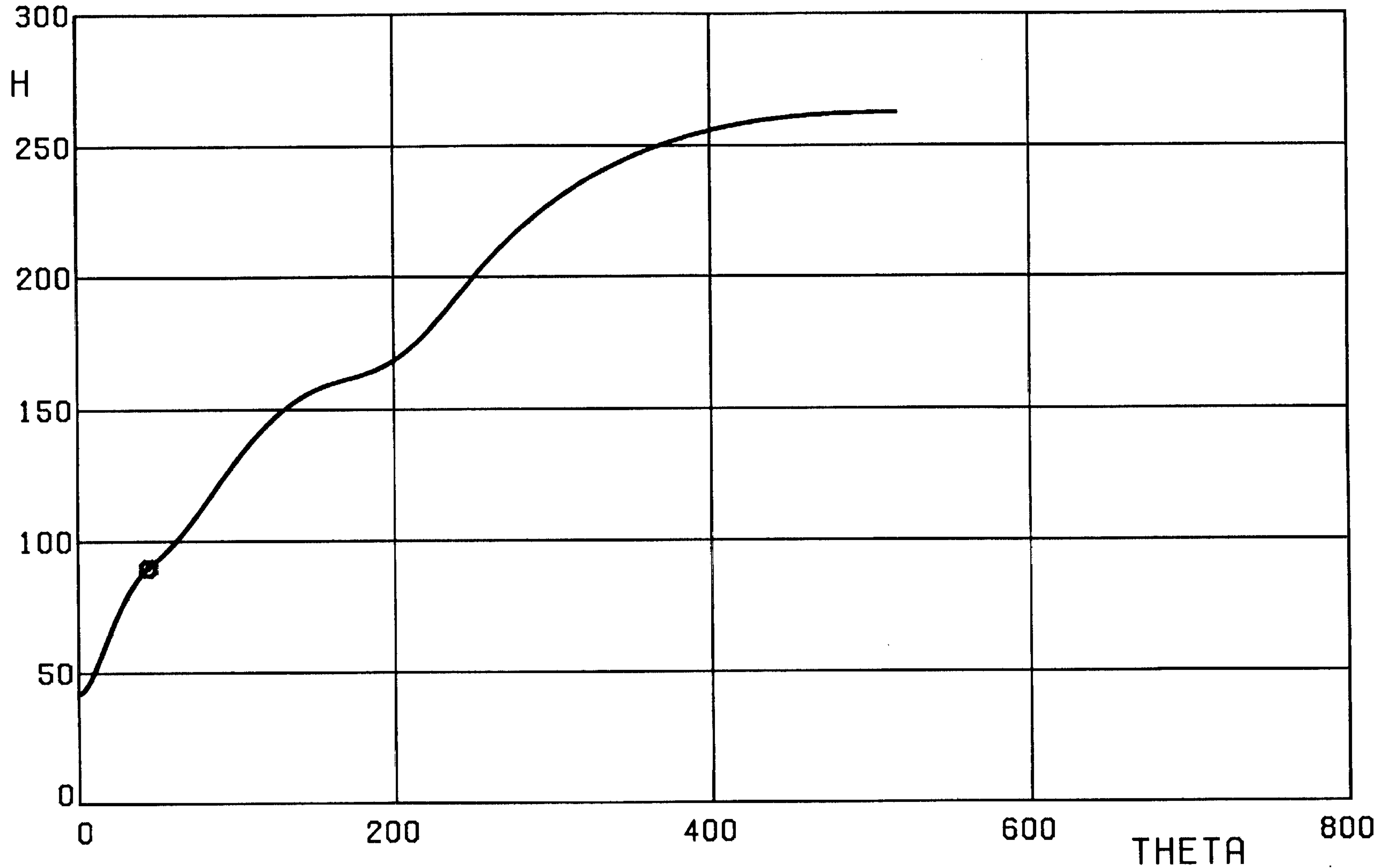

FIG. 8A. ALTITUDE(KFT) VS TIME(SEC), ENGINE MODEL EM2, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

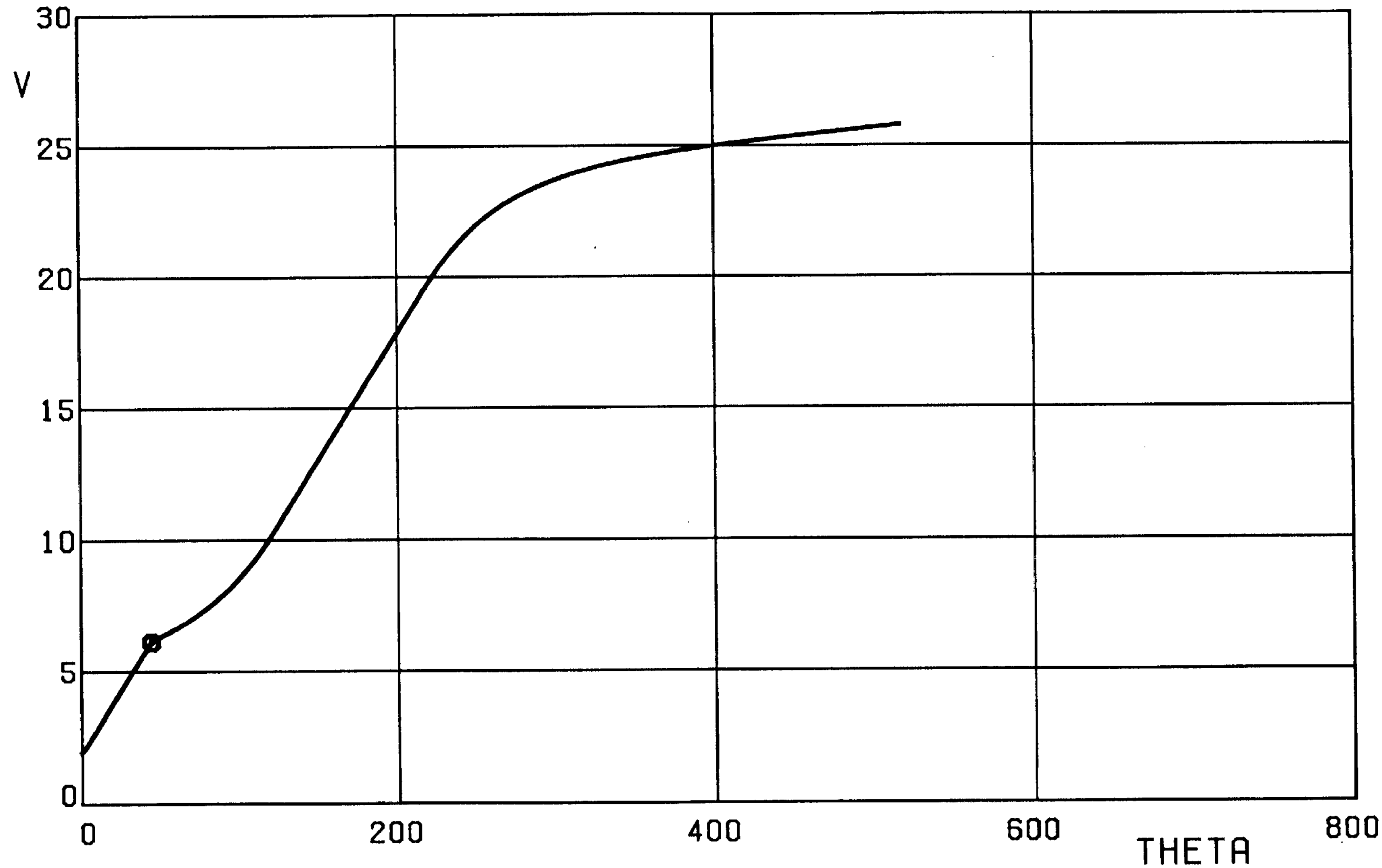

FIG. 8B. VELOCITY(KFT/SEC) VS TIME(SEC), ENGINE MODEL EM2, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

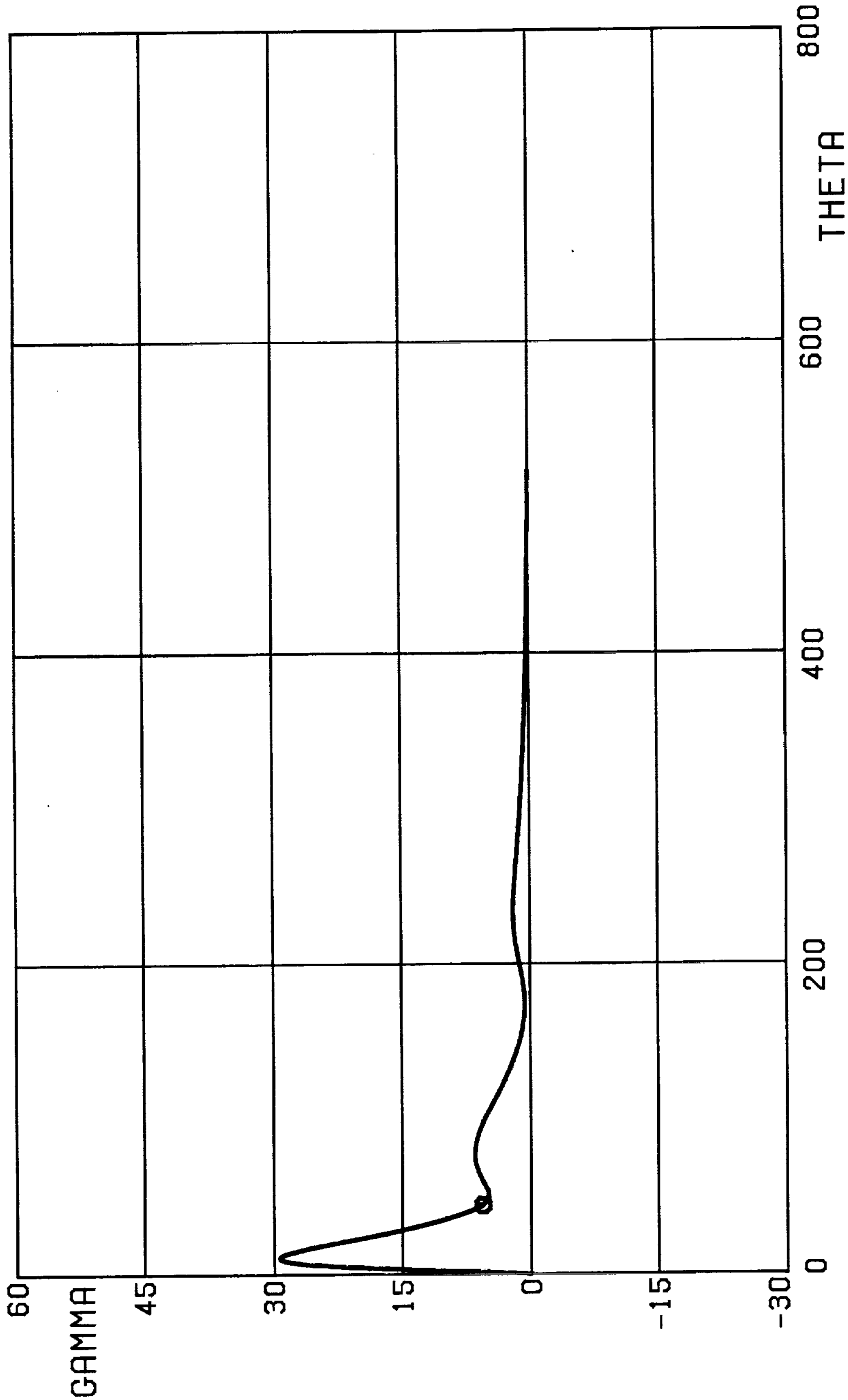

FIG. 8C. PATH INCLINATION(DEG) VS TIME(SEC), ENGINE MODEL EM2,
PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED,
GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

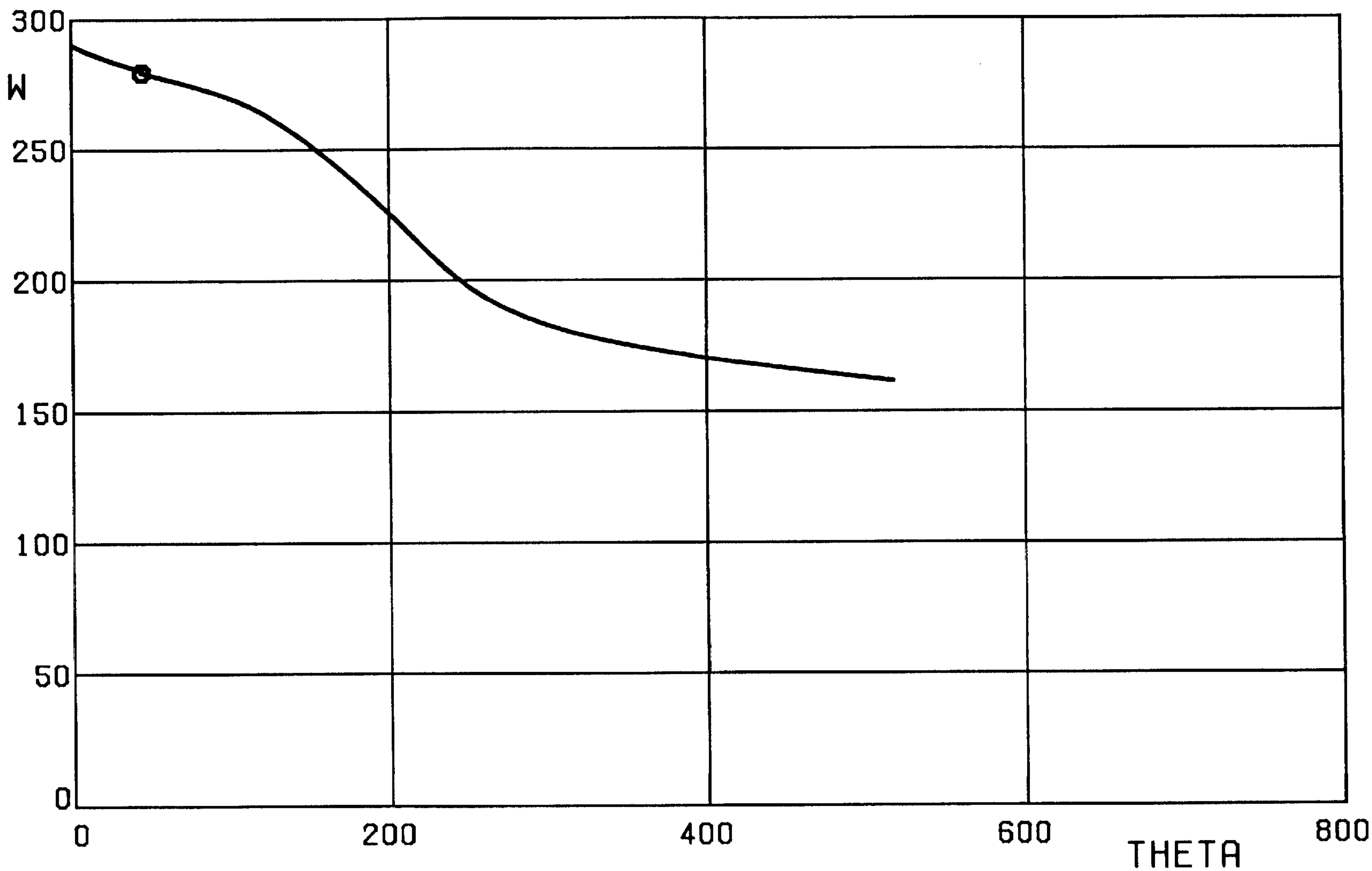

FIG. 8D. WEIGHT(KLBF) VS TIME(SEC), ENGINE MODEL EM2, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

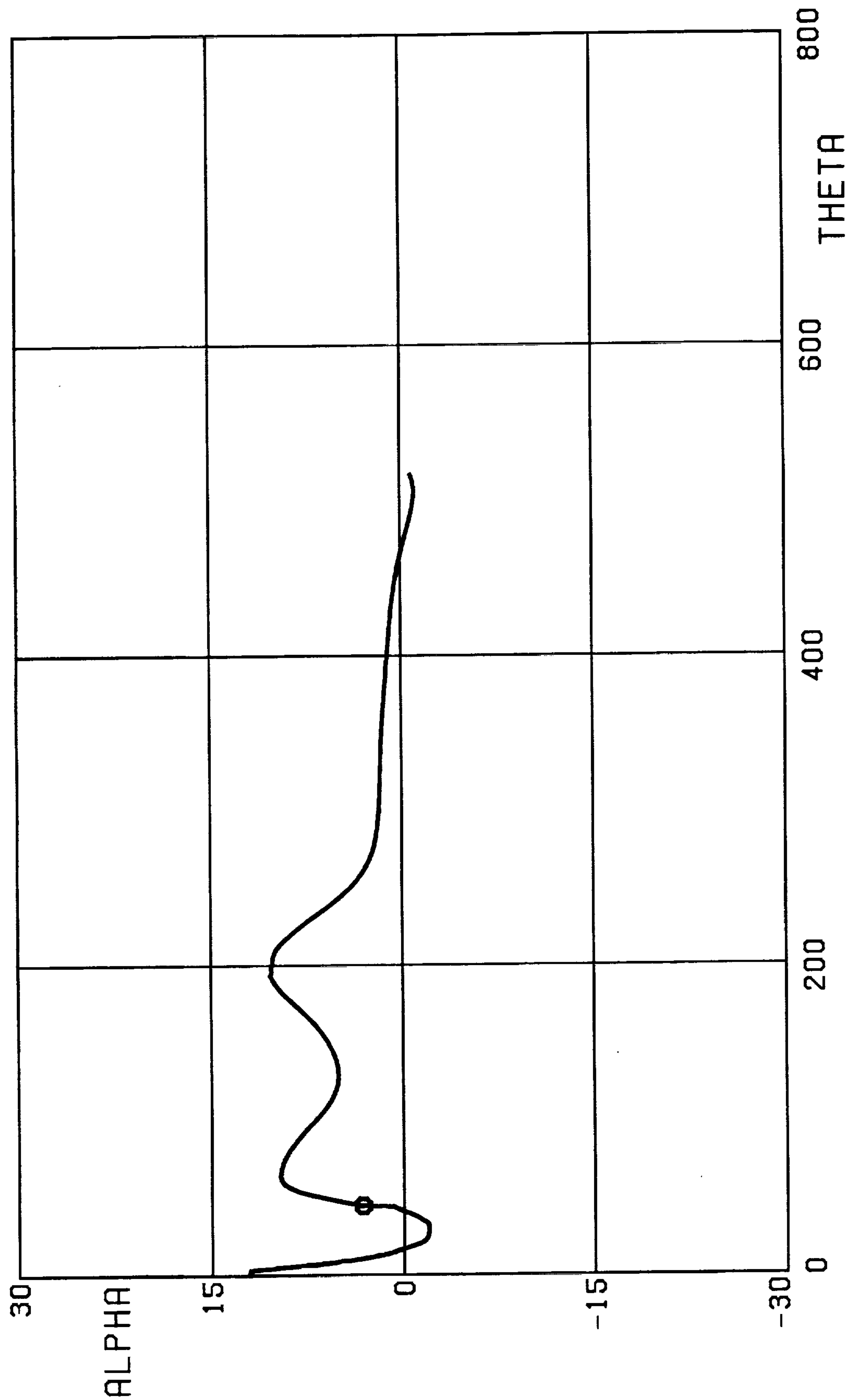

FIG. 8E. ANGLE OF ATTACK(DEG) VS TIME(SEC), ENGINE MODEL EM2.
PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED.
GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

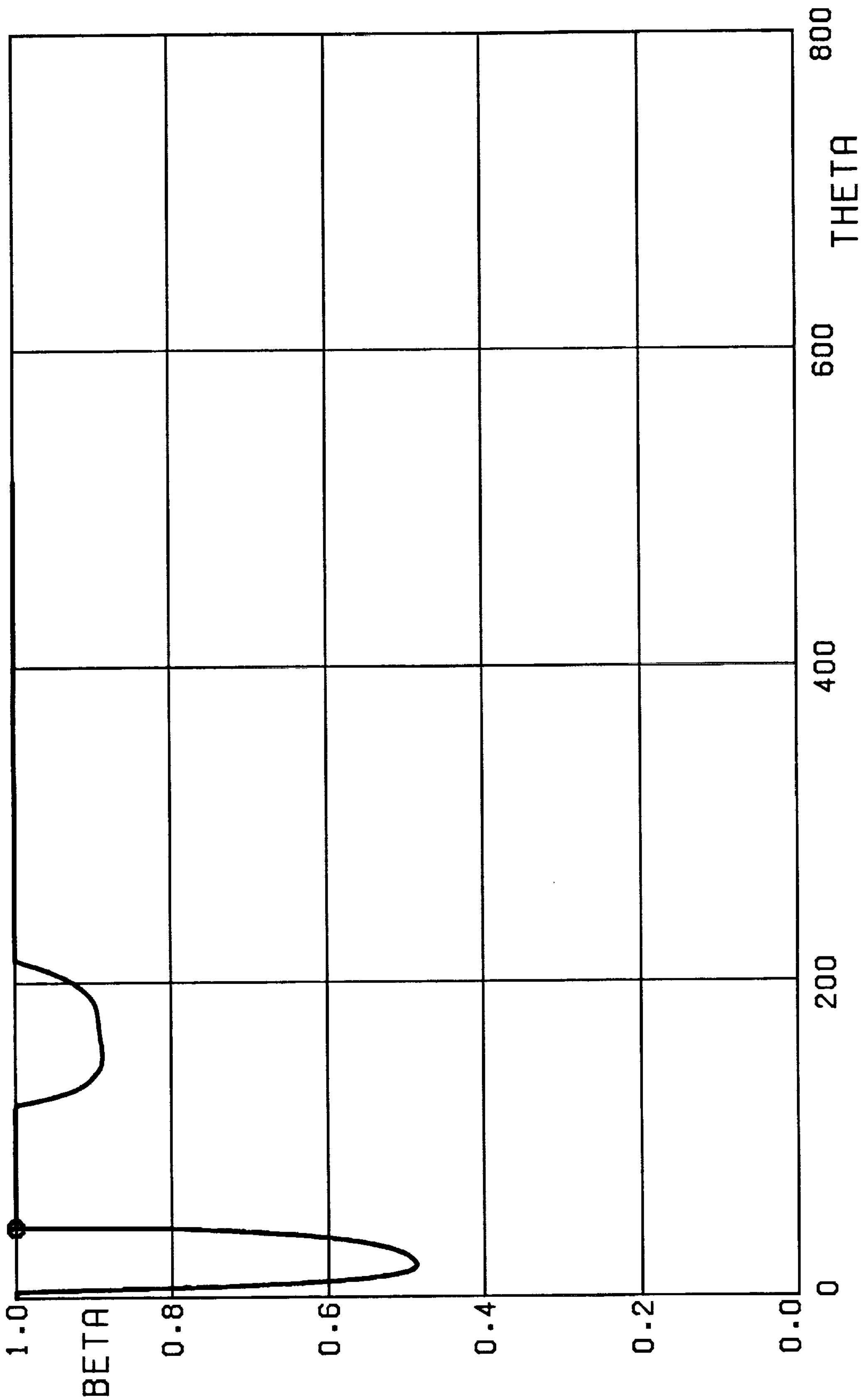

FIG. 8F. POWER SETTING VS TIME(SEC), ENGINE MODEL EM2, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

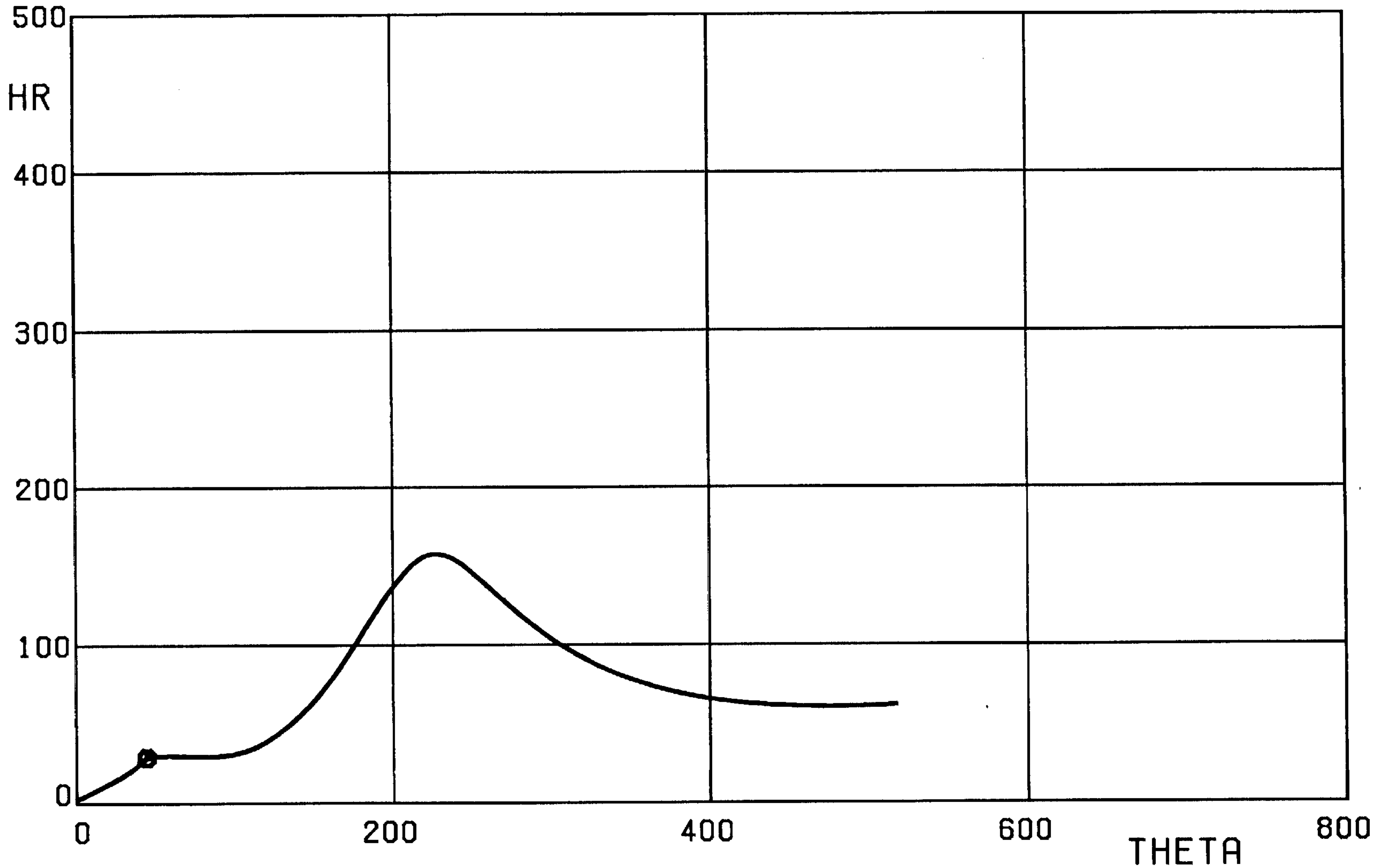

FIG. 8G. HEATING RATE(BTU/FT2 SEC) VS TIME(SEC), ENGINE MODEL EM2, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

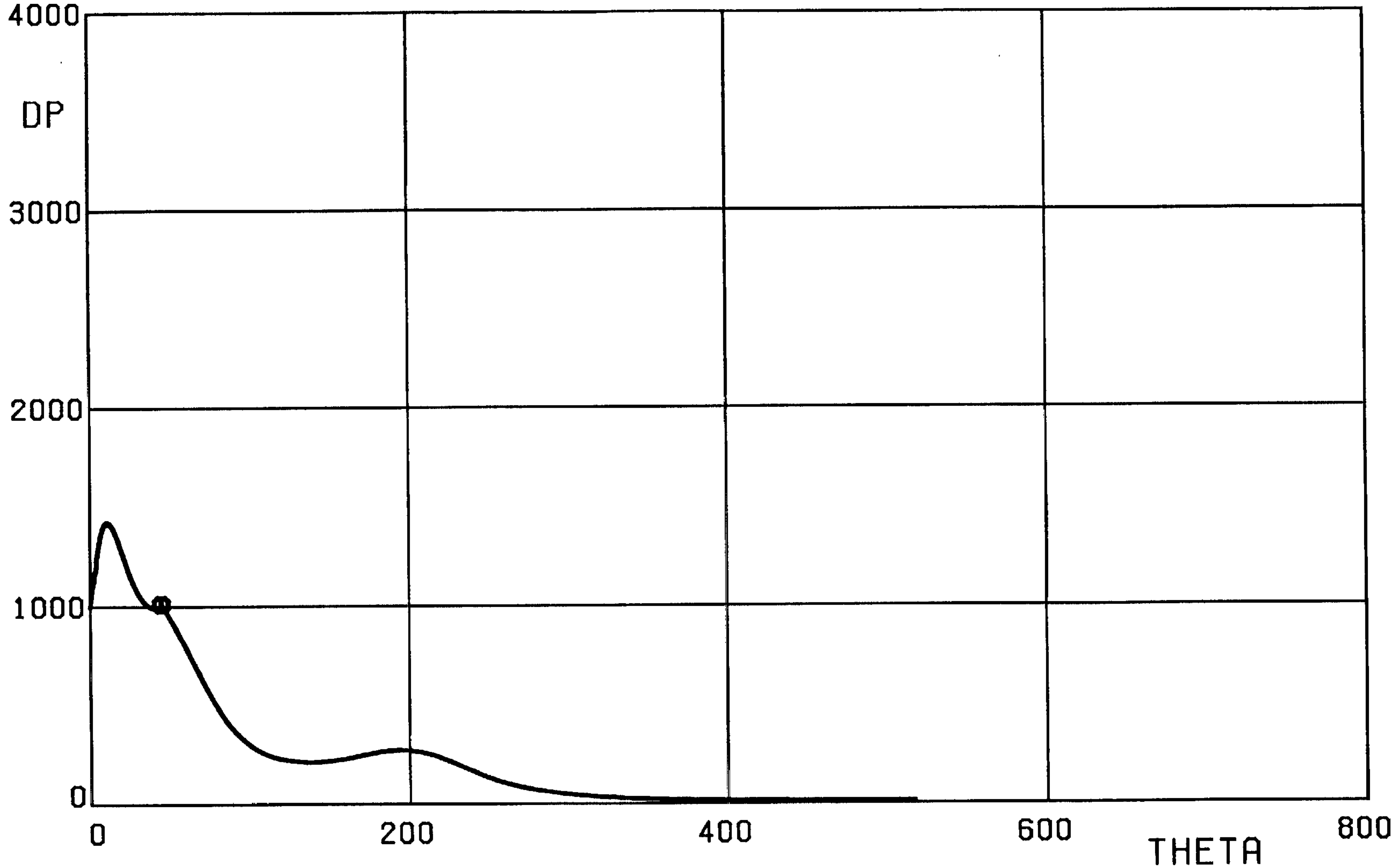

FIG. 8H. DYNAMIC PRESSURE(LB/FT2) VS TIME(SEC), ENGINE MODEL EM2, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMAO=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

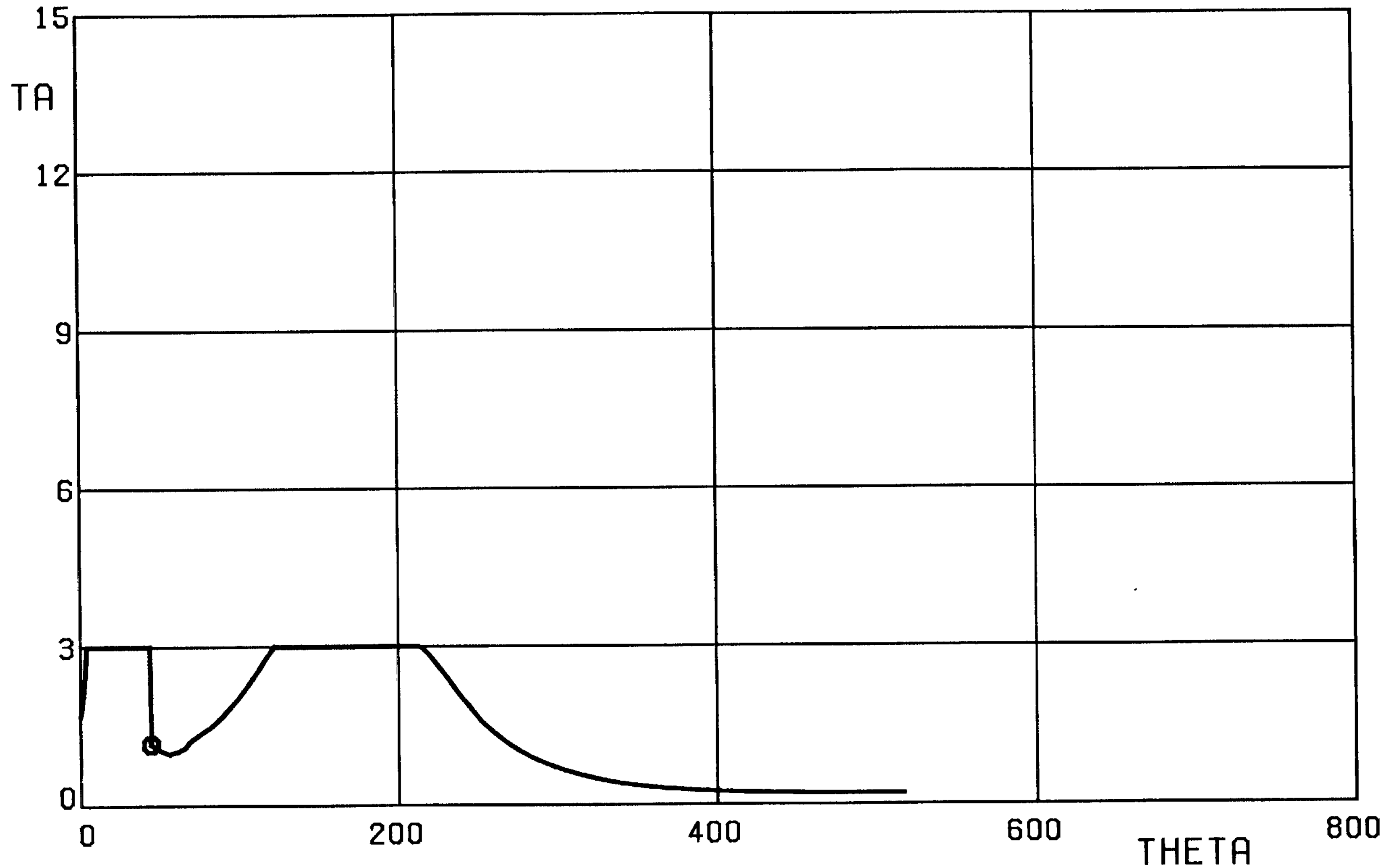

FIG. 8I. TANGENTIAL ACCELERATION(GE'S) VS TIME(SEC), ENGINE MODEL EM2, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

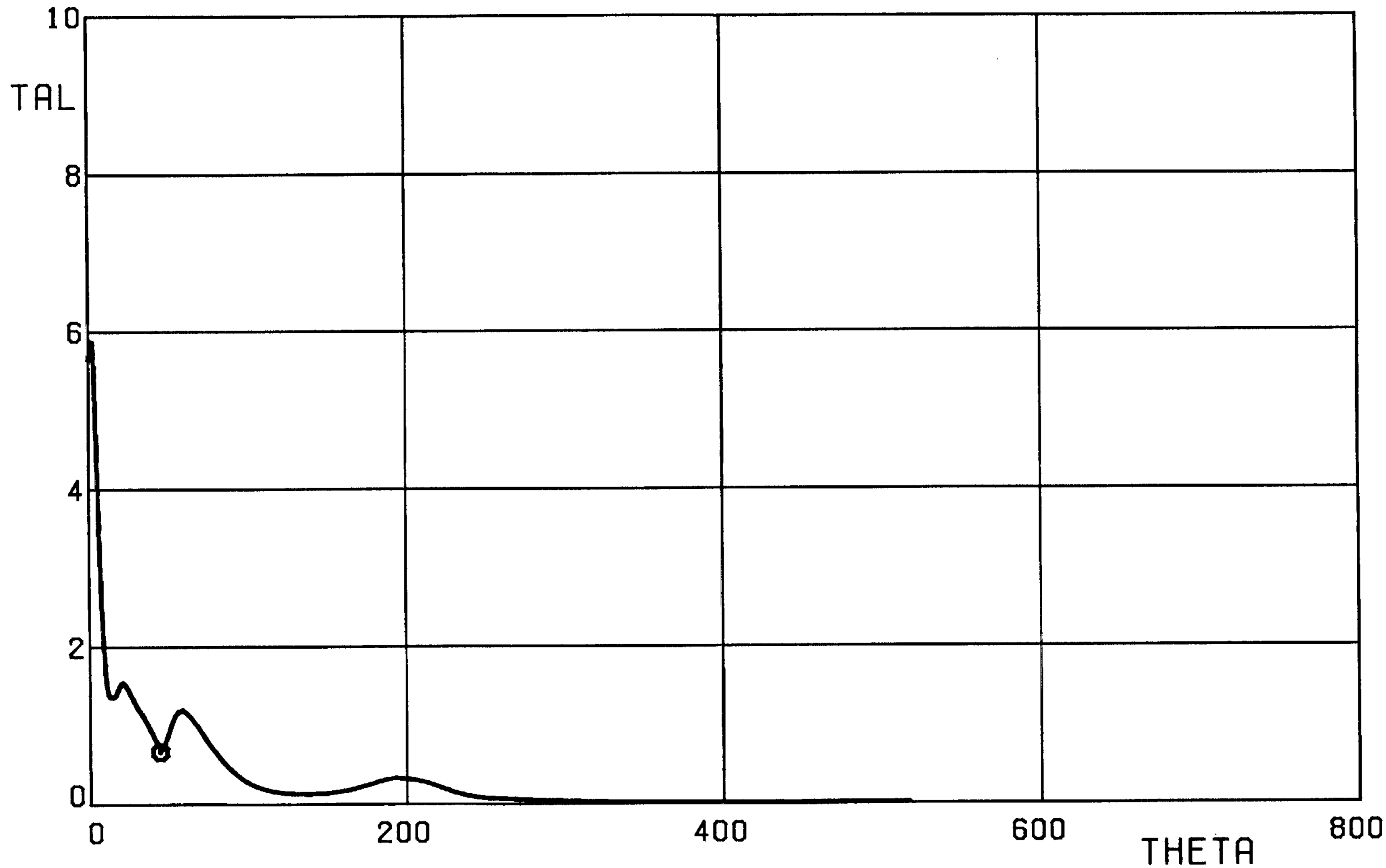

FIG. 8J. TOTAL AERODYNAMIC LOAD(GE'S) VS TIME(SEC), ENGINE MODEL EM2, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMAO=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

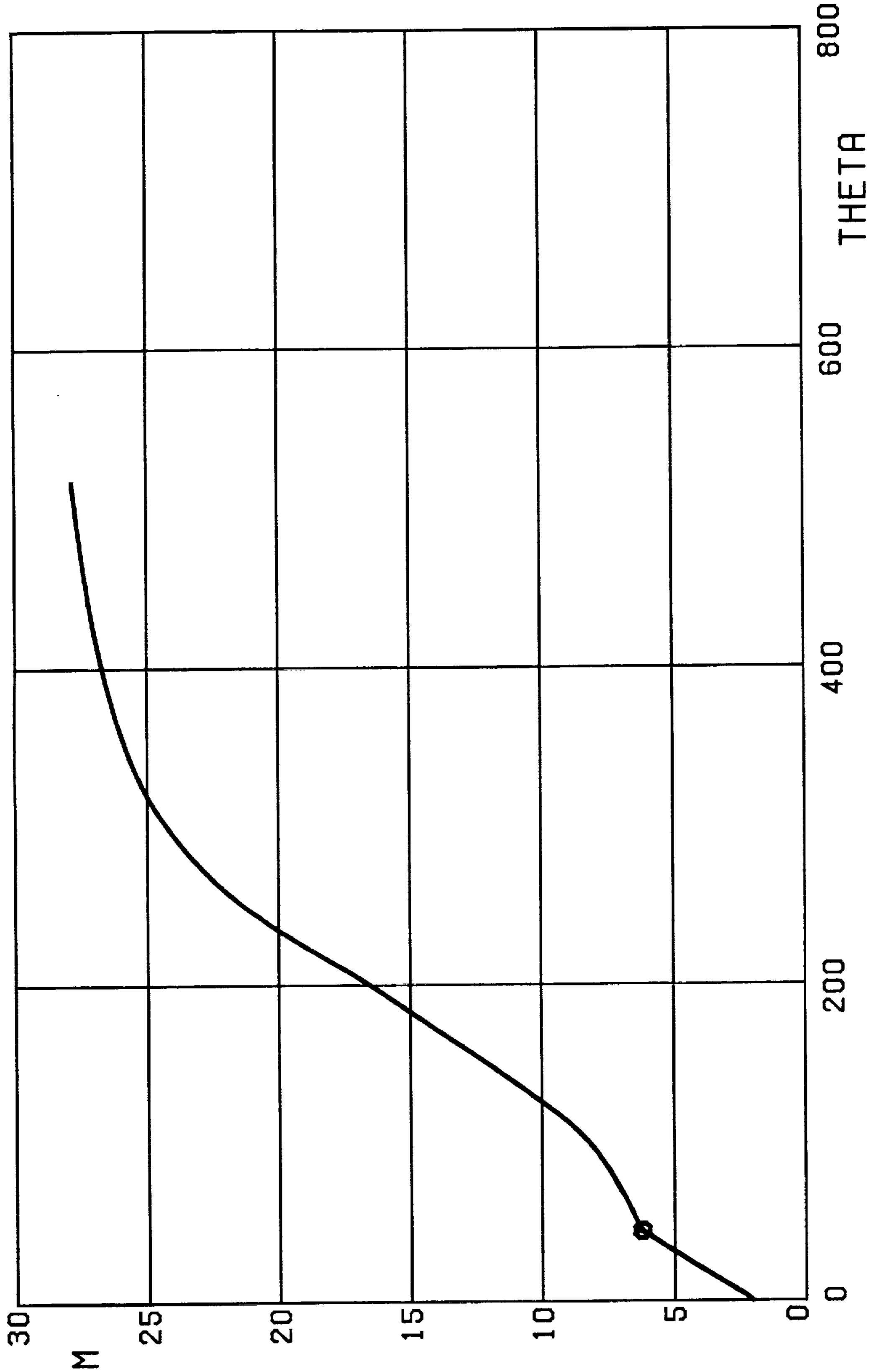

FIG. 8K. MACH NUMBER VS TIME(SEC). ENGINE MODEL EM2.
PROBLEM(P1D). MINIMUM WEIGHT OF FUEL CONSUMED.
GAMMA0=0.0 DEG. DPB=1500 PSF. TAB=3.0 GE.

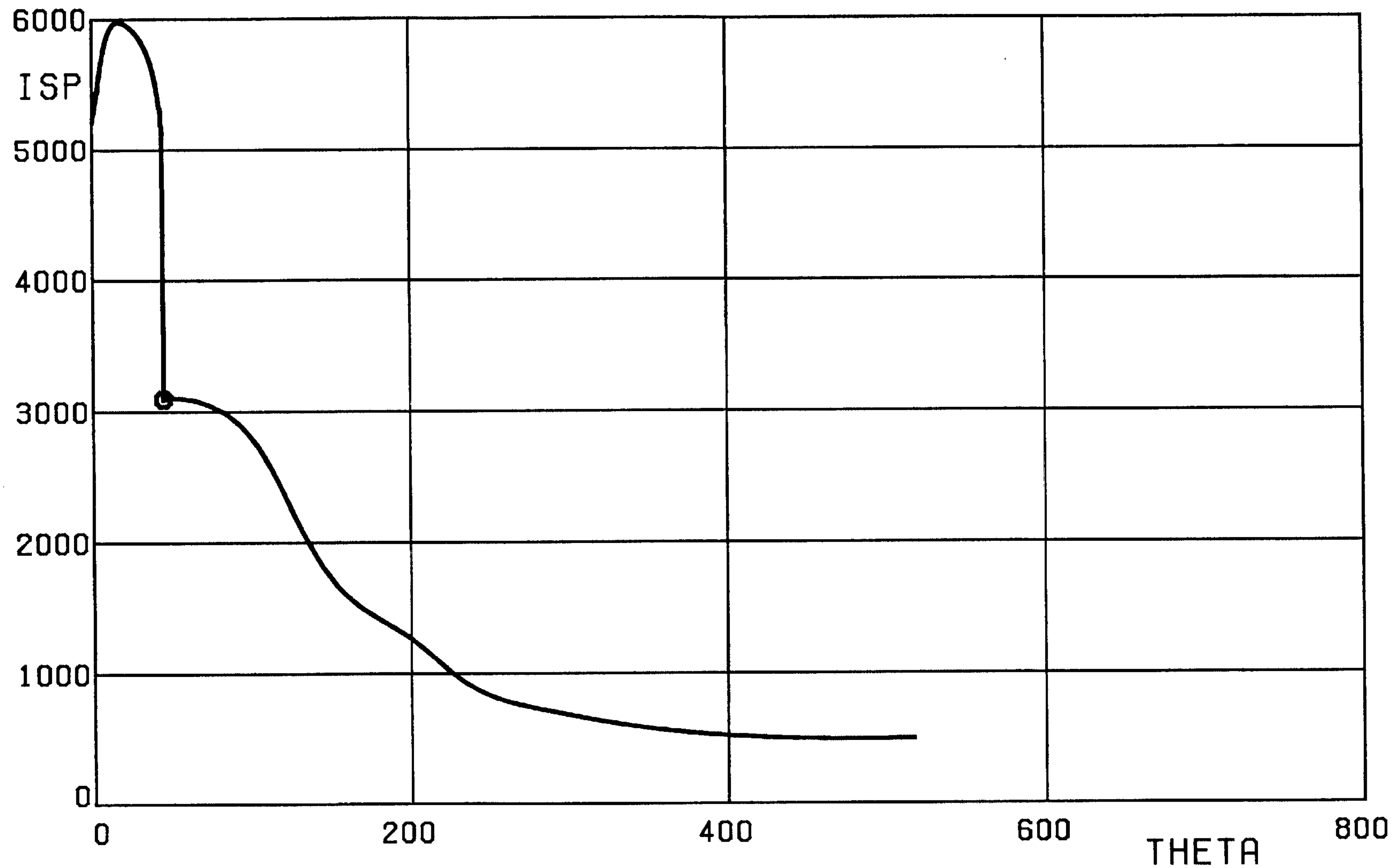

FIG. 8L. SPECIFIC IMPULSE(SEC) VS TIME(SEC), ENGINE MODEL EM2, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED. GAMMAO=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

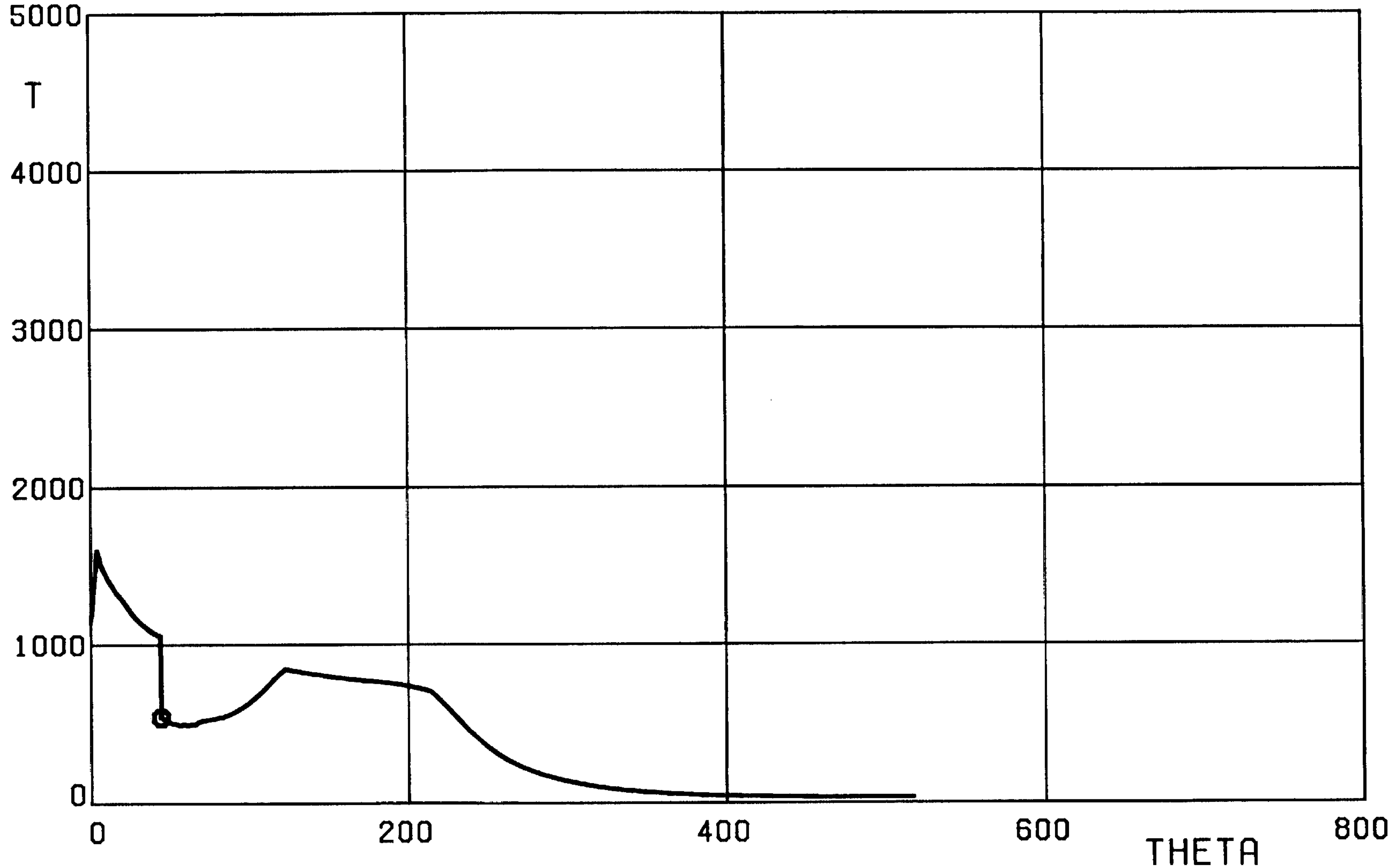

FIG. 8M. THRUST(KLBF) VS TIME(SEC), ENGINE MODEL EM2,
PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED,
GAMMAO=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

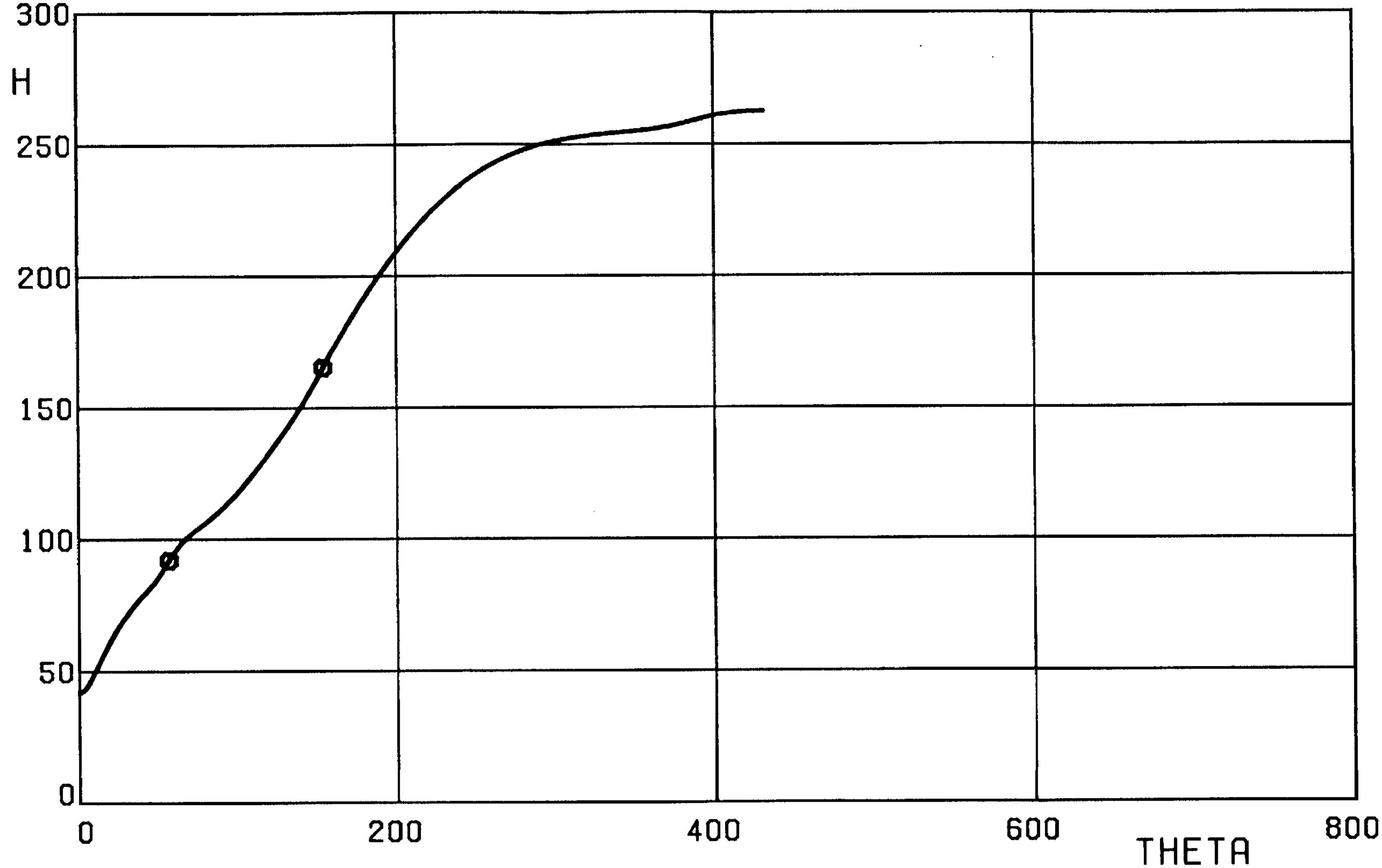

FIG. 9A. ALTITUDE(KFT) VS TIME(SEC), ENGINE MODEL EM3, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

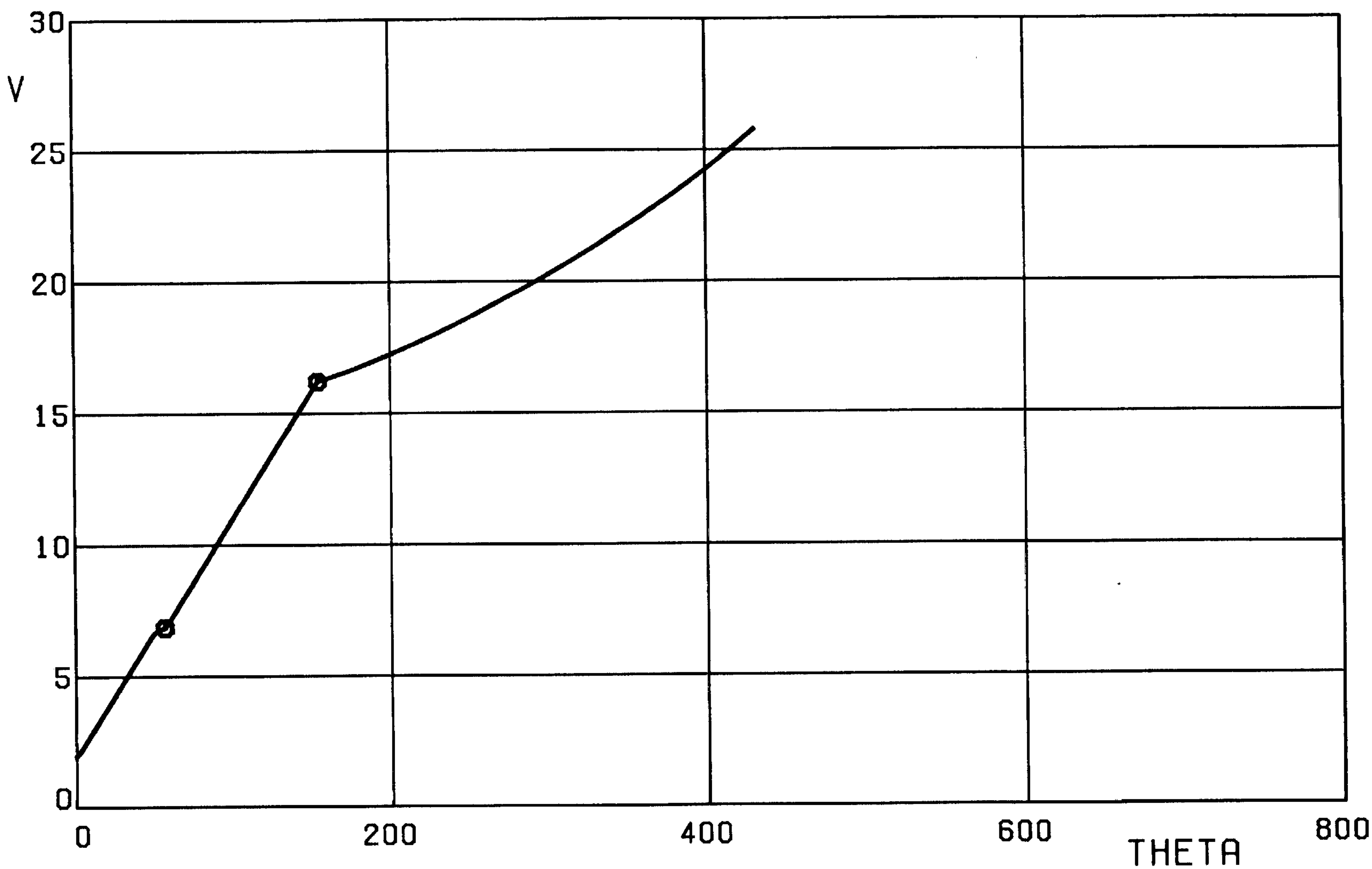

FIG. 9B. VELOCITY(KFT/SEC) VS TIME(SEC), ENGINE MODEL EM3, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMAO=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

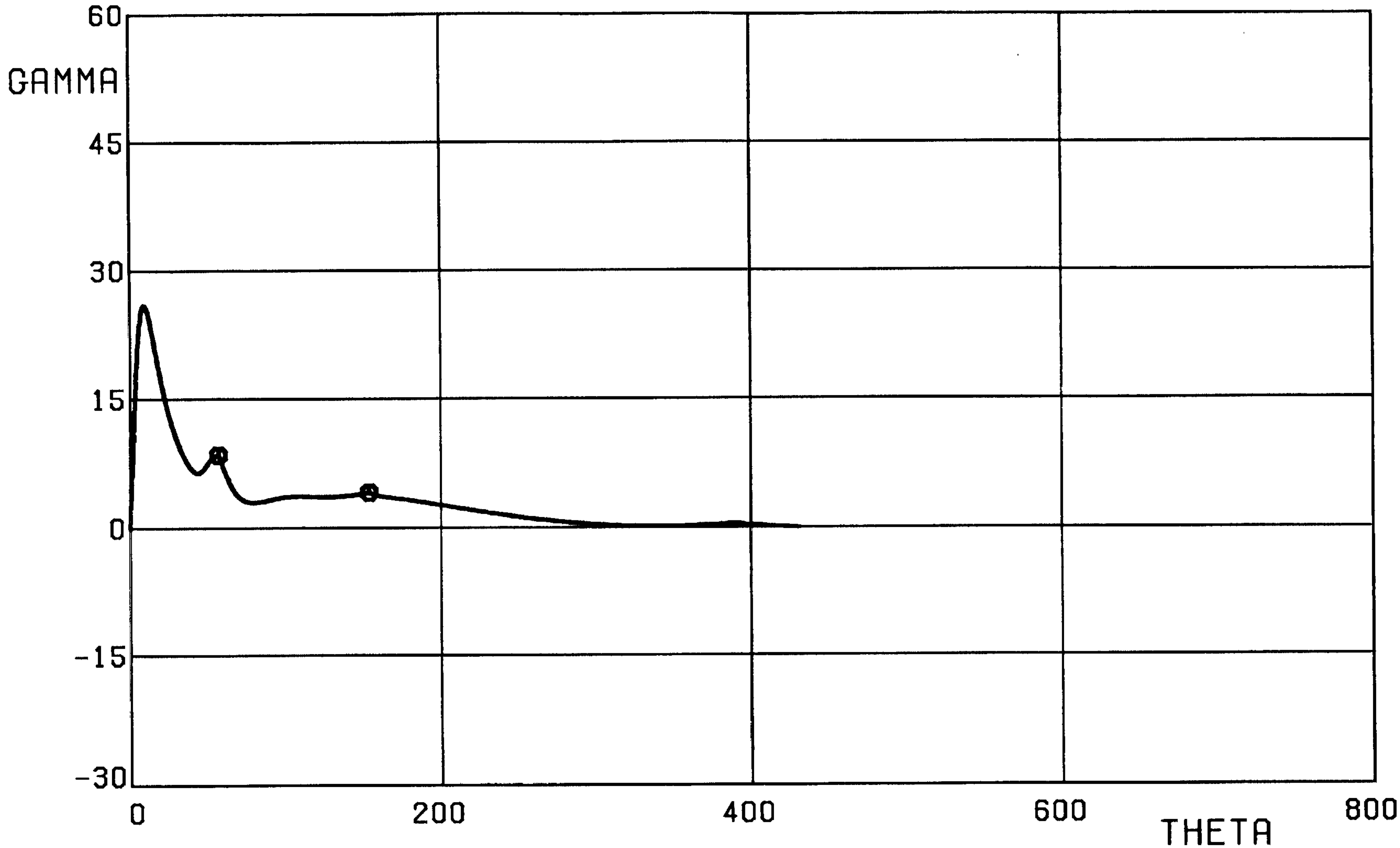

FIG. 9C. PATH INCLINATION(DEG) VS TIME(SEC), ENGINE MODEL EM3, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

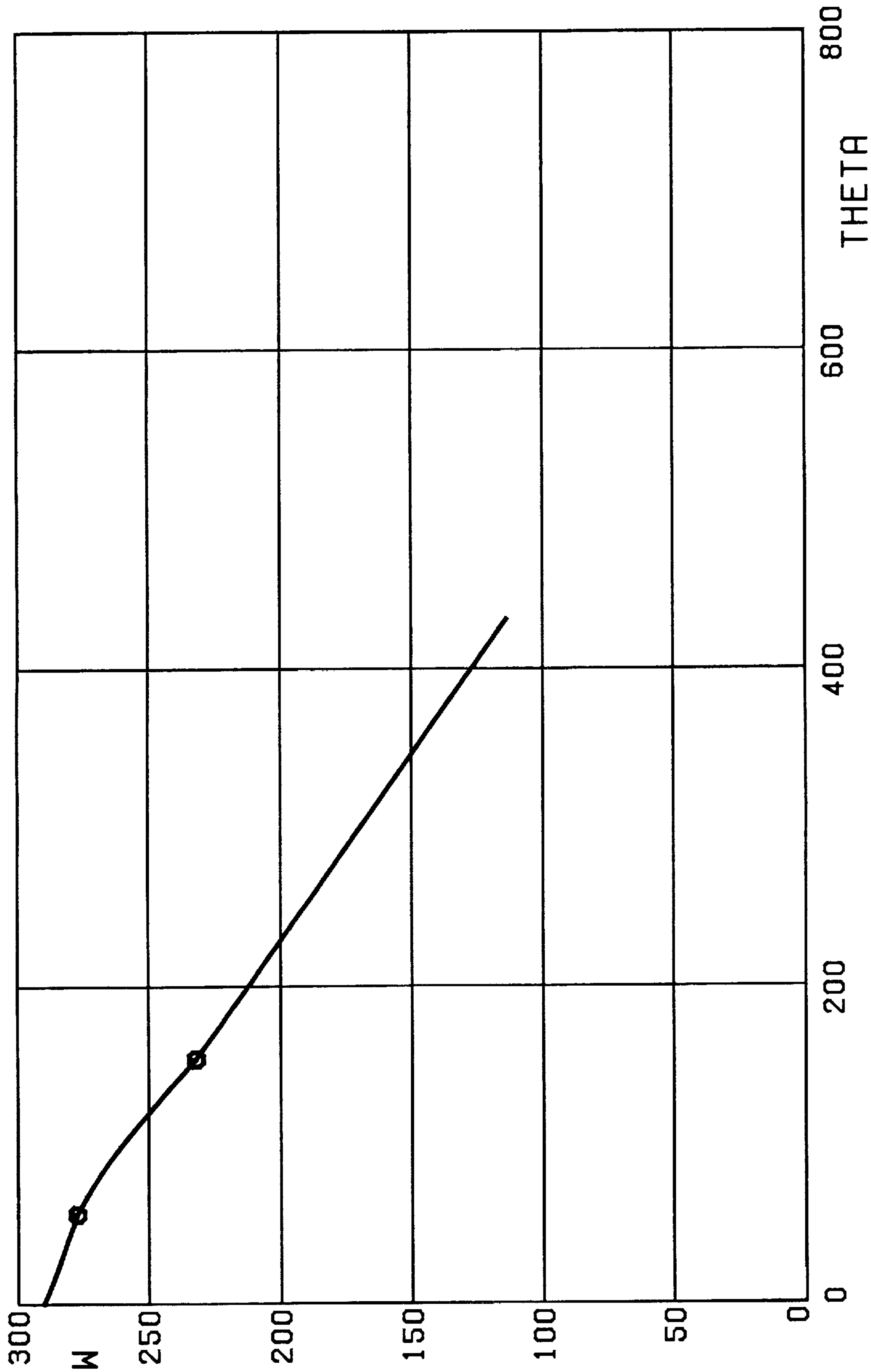

FIG. 9D. WEIGHT(KLBF) VS TIME(SEC), ENGINE MODEL EM3,
PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED,
GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

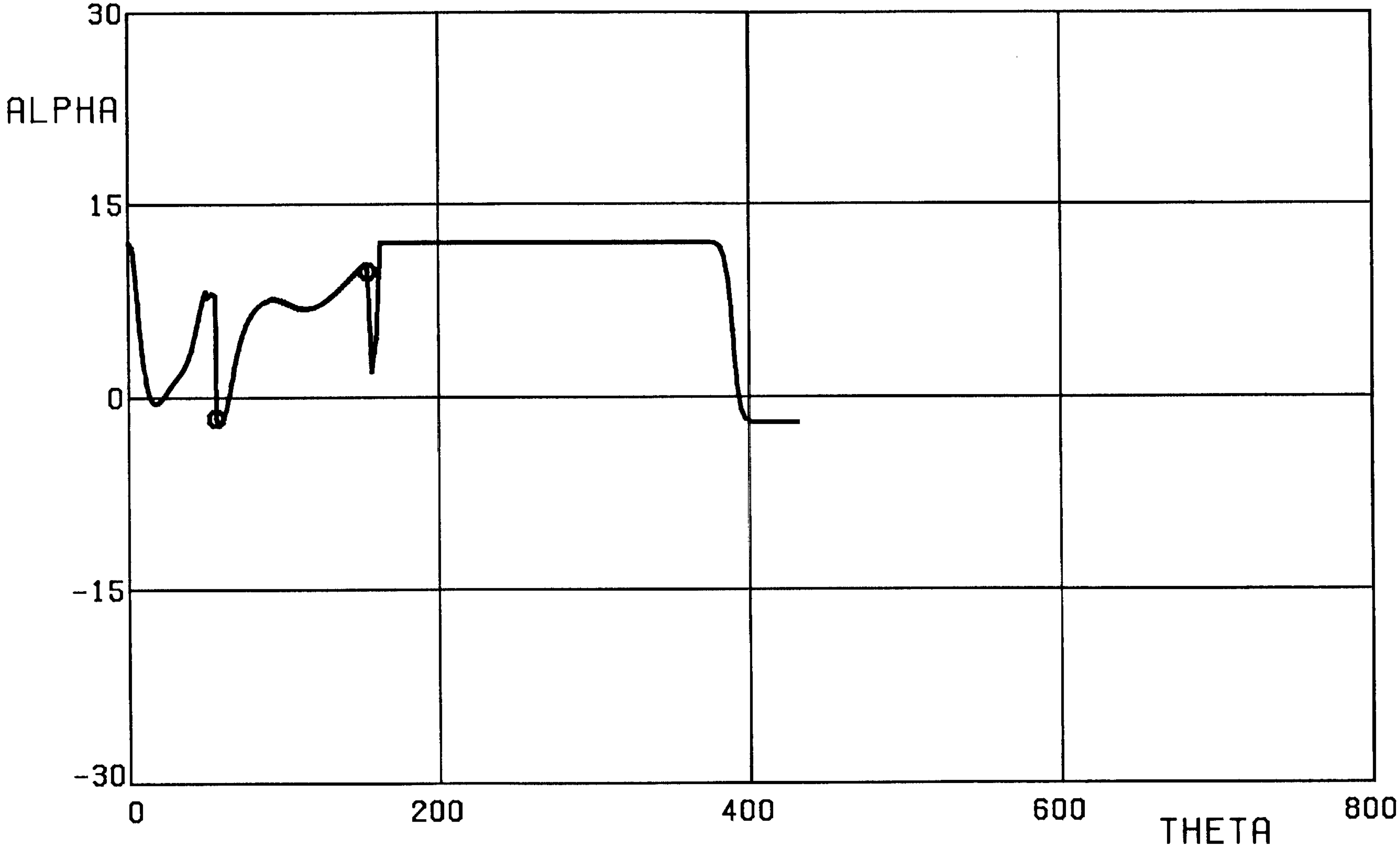

FIG. 9E. ANGLE OF ATTACK(DEG) VS TIME(SEC), ENGINE MODEL EM3, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

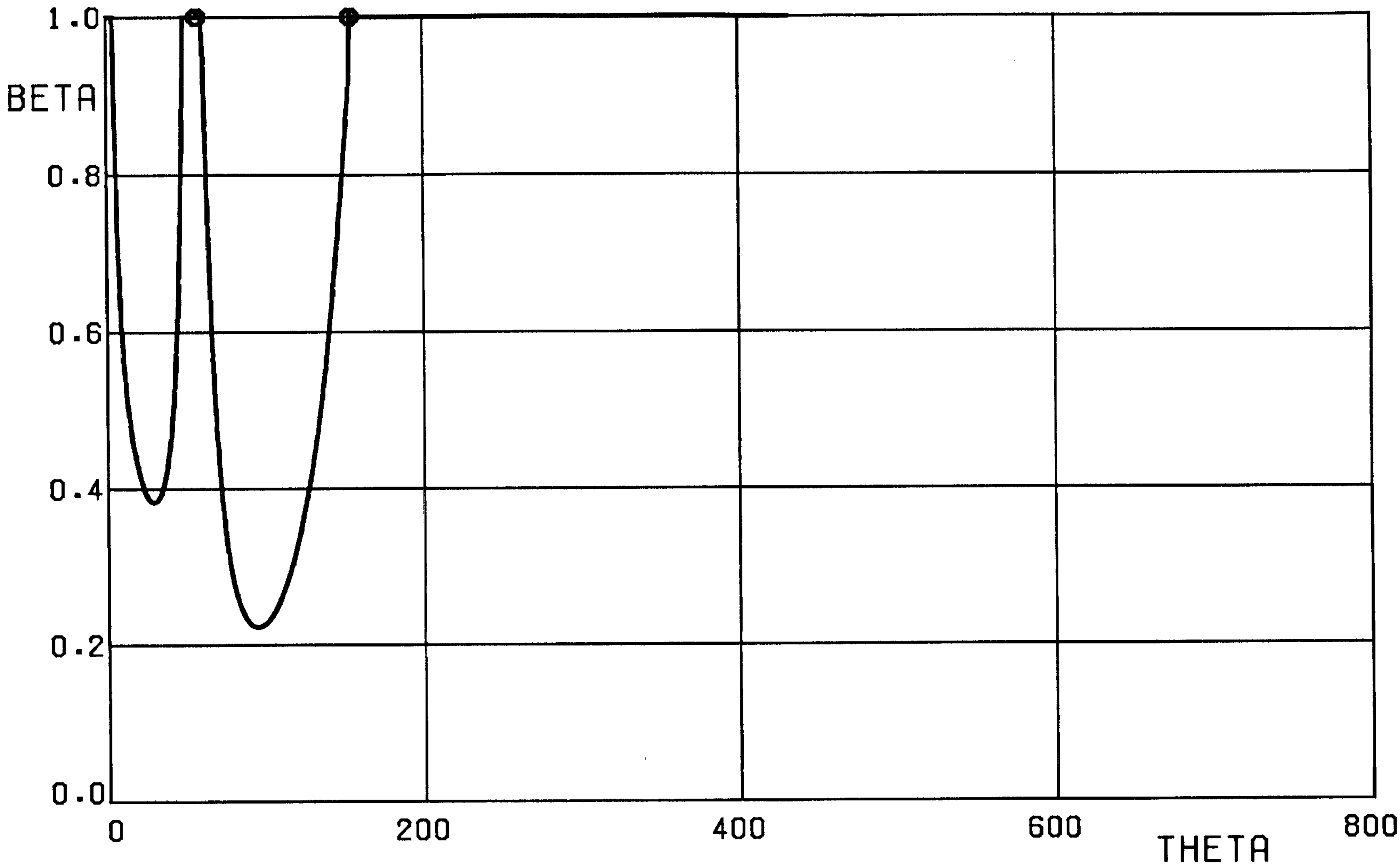

FIG. 9F. POWER SETTING VS TIME(SEC), ENGINE MODEL EM3, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMAO=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

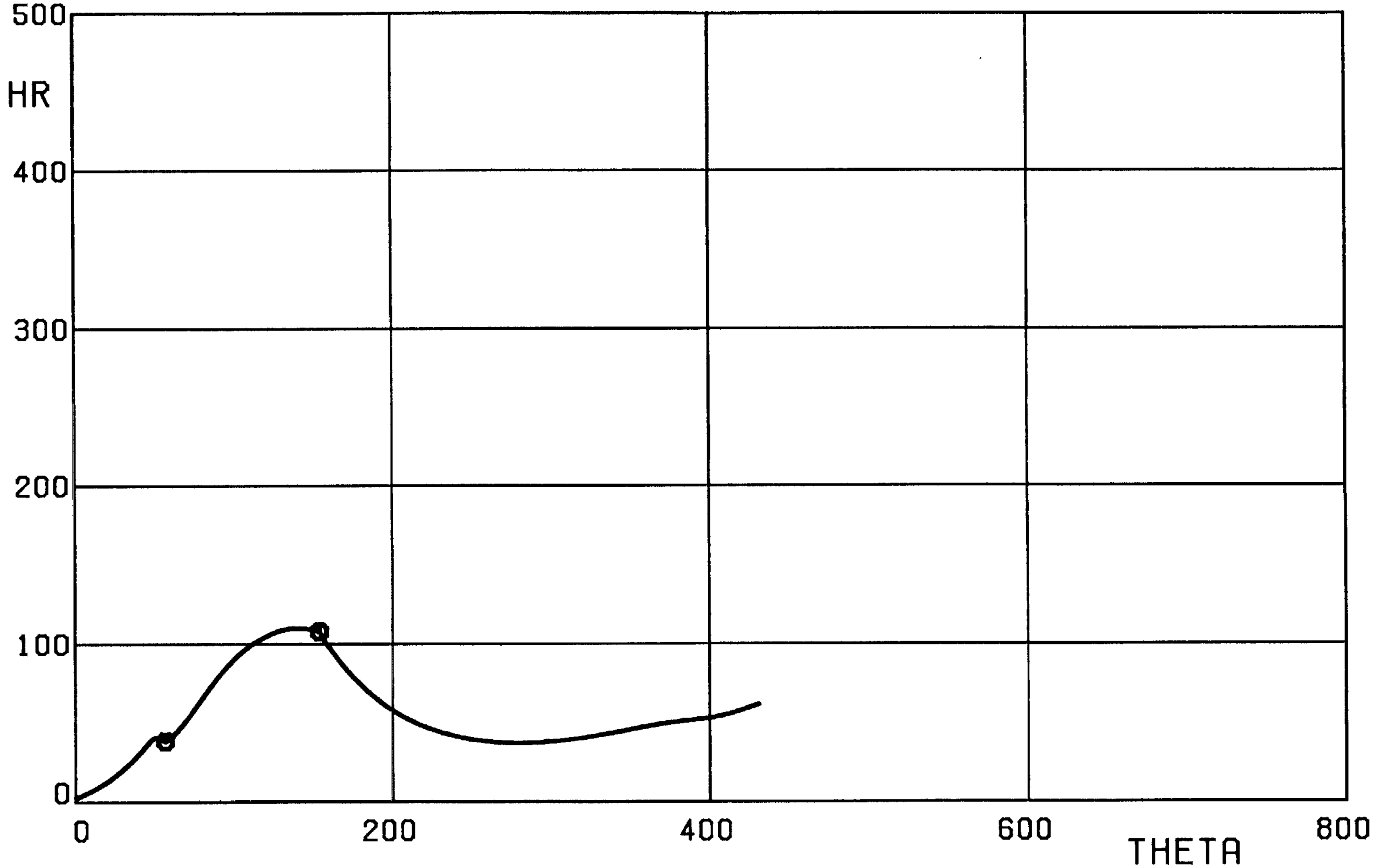

FIG. 9G. HEATING RATE(BTU/FT2 SEC) VS TIME(SEC), ENGINE MODEL EM3, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMAO=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

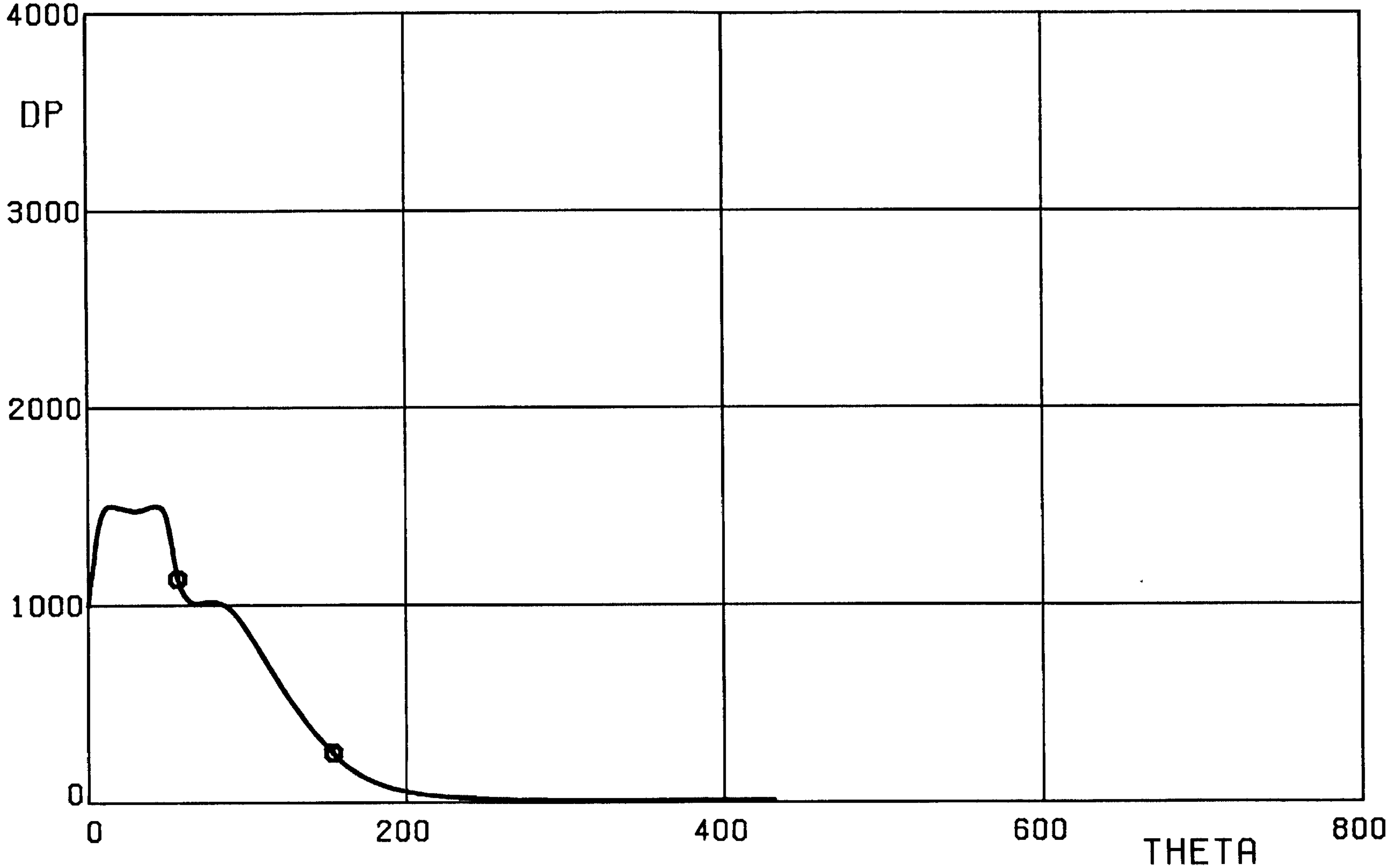

FIG. 9H. DYNAMIC PRESSURE(LB/FT2) VS TIME(SEC), ENGINE MODEL EM3, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

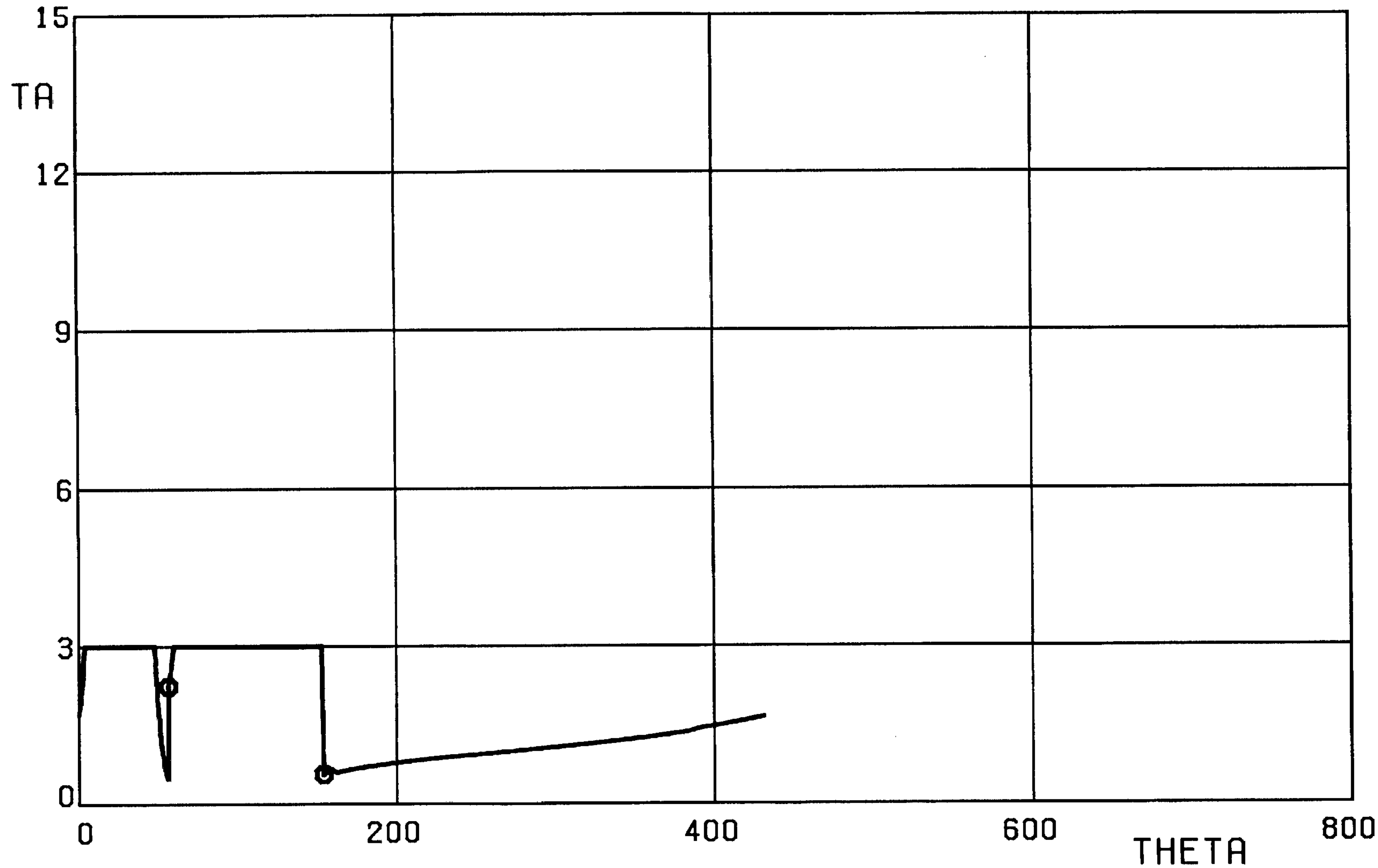

FIG. 9I. TANGENTIAL ACCELERATION(GE'S) VS TIME(SEC), ENGINE MODEL EM3, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMAO=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

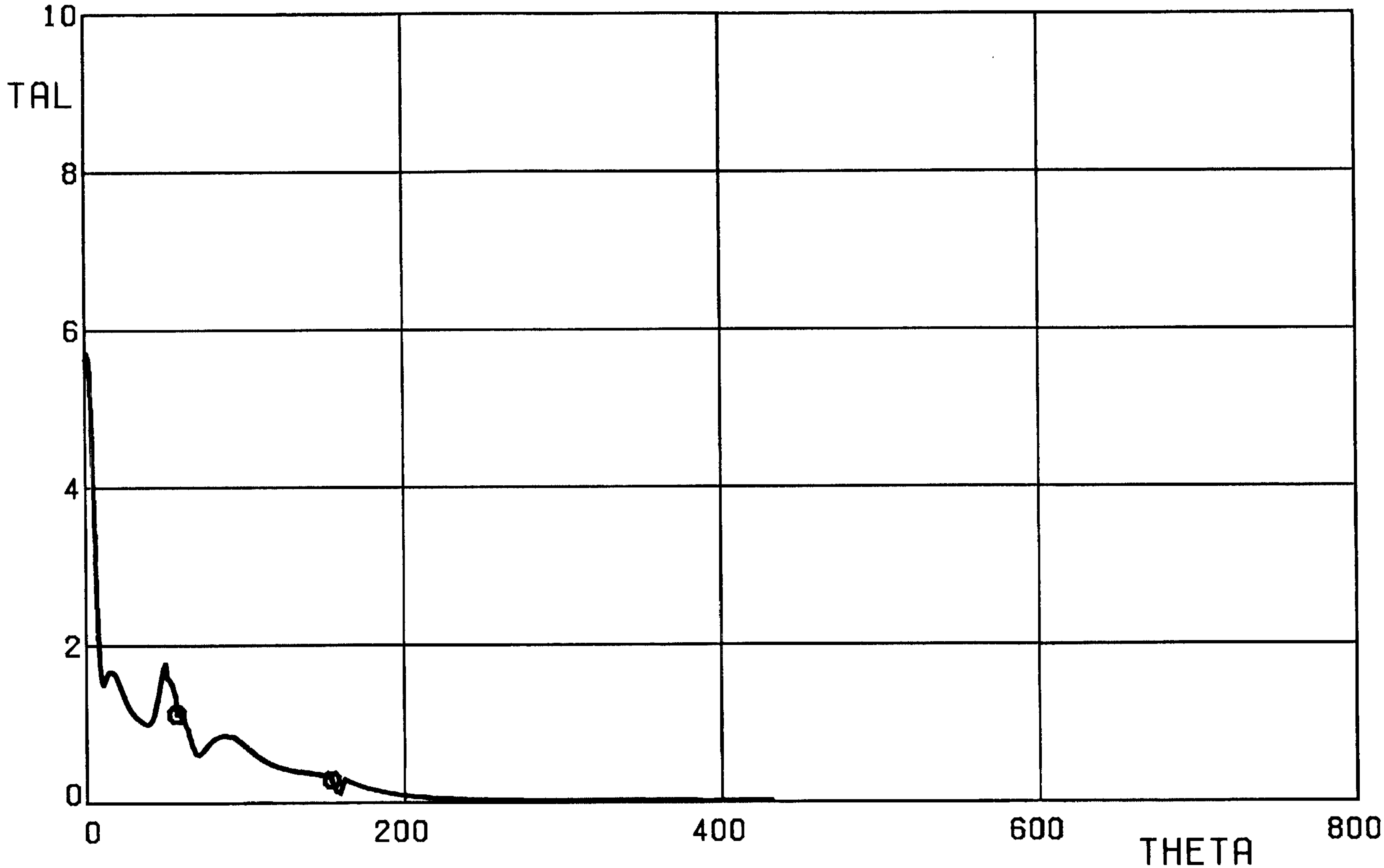

FIG. 9J. TOTAL AERODYNAMIC LOAD(GE'S) VS TIME(SEC), ENGINE MODEL EM3, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

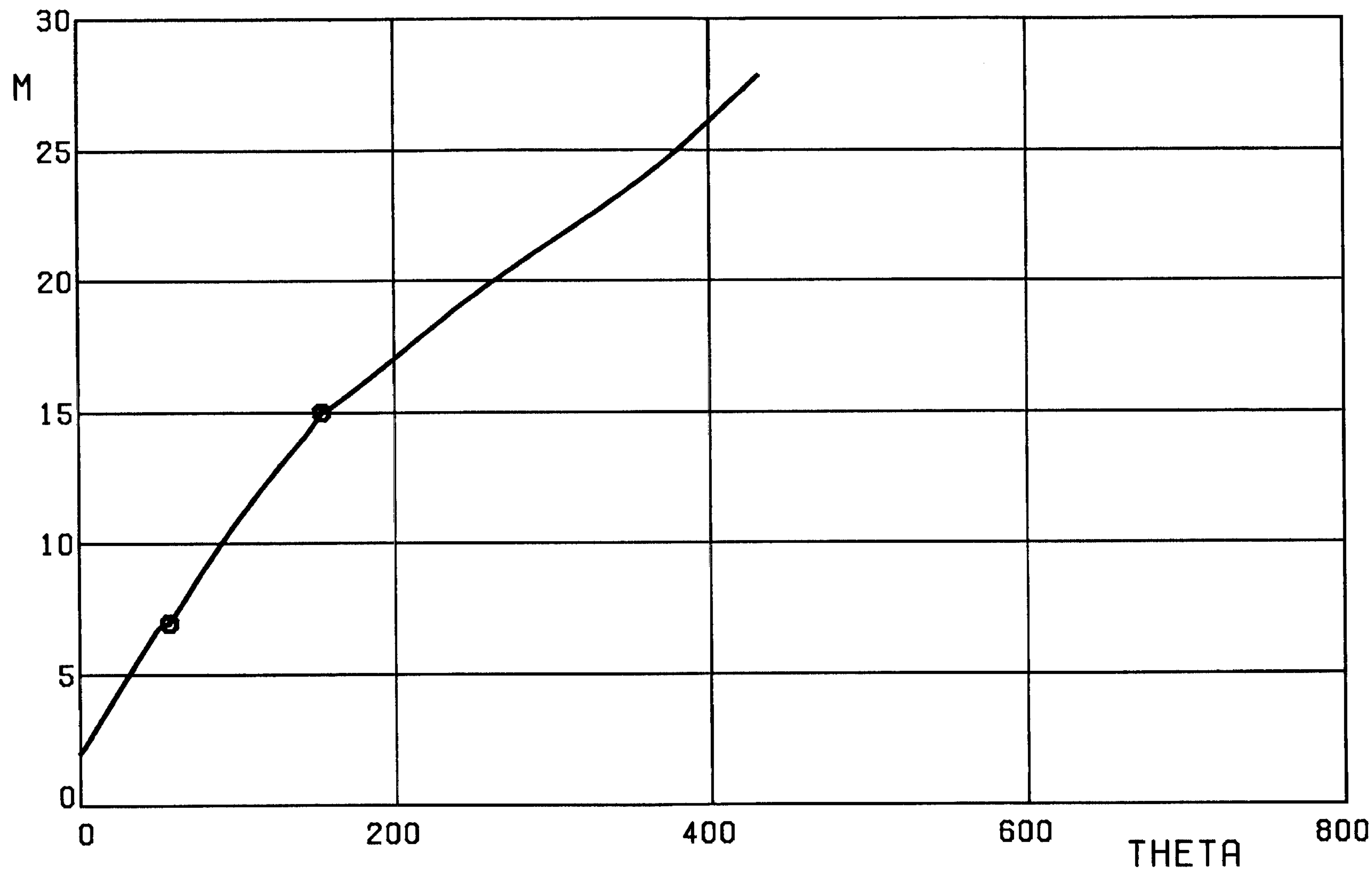

FIG. 9K. MACH NUMBER VS TIME(SEC), ENGINE MODEL EM3,
PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED,
GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.

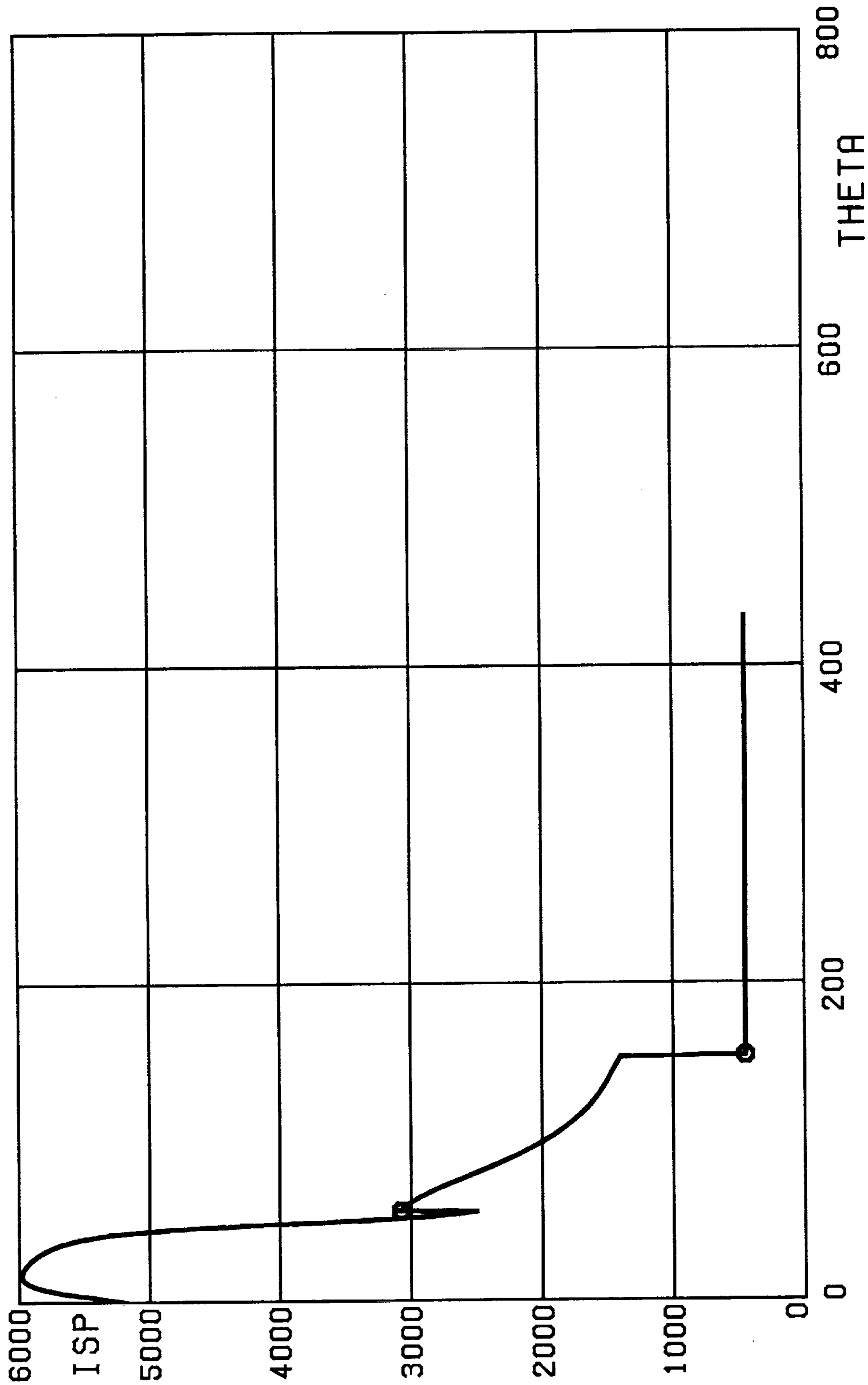

FIG. 9L. SPECIFIC IMPULSE(SEC) VS TIME(SEC). ENGINE MODEL EM3. PROBLEM(P1D). MINIMUM WEIGHT OF FUEL CONSUMED. GAMMA0=0.0 DEG. DPB=1500 PSF. TAB=3.0 GE.

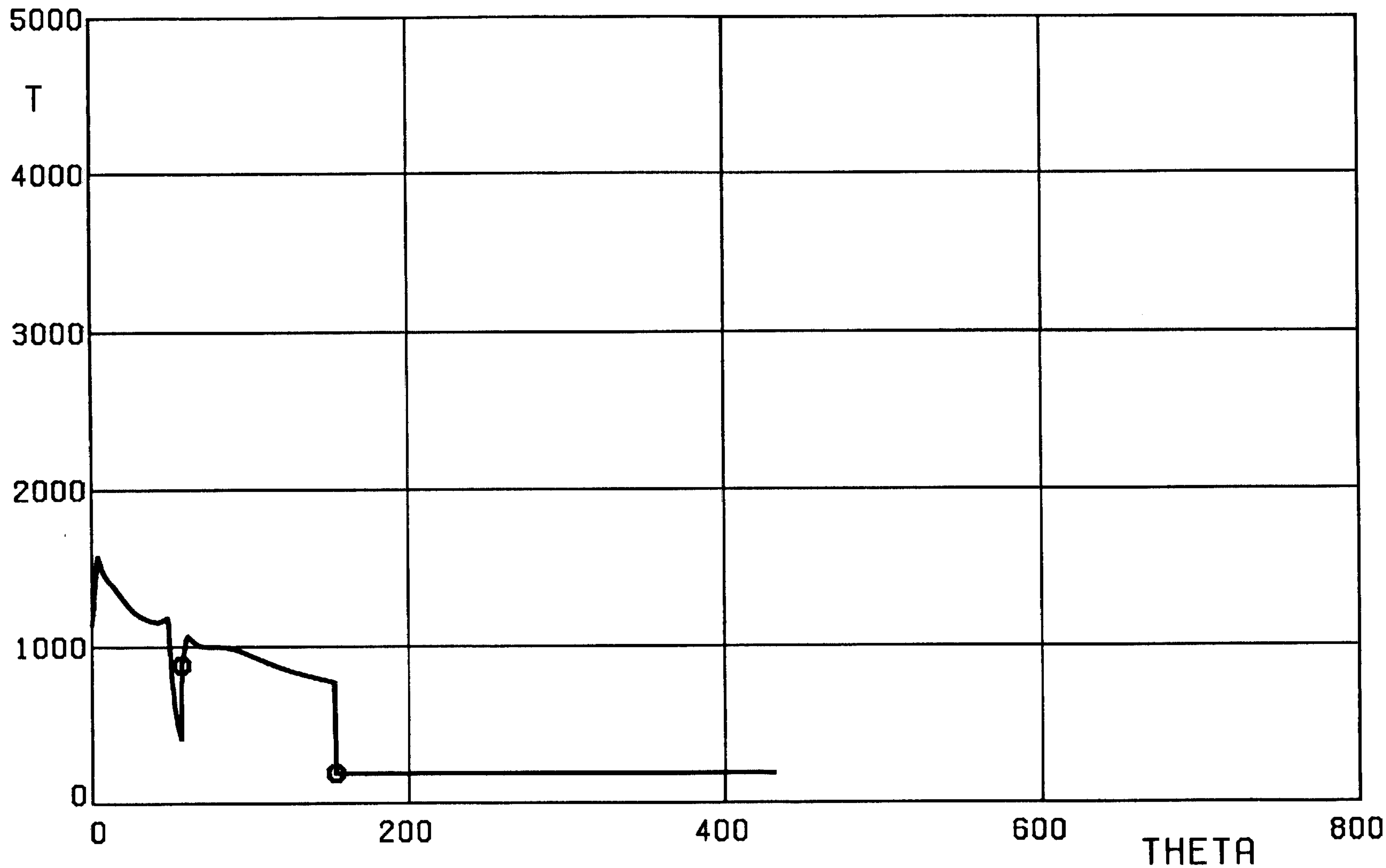

FIG. 9M. THRUST(KLBF) VS TIME(SEC), ENGINE MODEL EM3, PROBLEM(P1D), MINIMUM WEIGHT OF FUEL CONSUMED, GAMMA0=0.0 DEG, DPB=1500 PSF, TAB=3.0 GE.