John Boyd

ENERGY MANEUVERABILITY
MAXIMUM MANEUVER CONCEPT

6-4265

VARIABLES

VARIABLES	NAME	DIMENSION
E_S	SPECIFIC ENERGY	FT
h	ALTITUDE	FT
ν	VELOCITY	$\frac{FT}{SEC}$
P_S	SPECIFIC EXCESS POWER (ENERGY RATE)	$\frac{FT}{SEC}$
T	THRUST	LBF
D	DRAG	LBF
L	LIFT	LBF
η	LOAD FACTOR	– –
$\dot{\Theta}$	TURN RATE	$\frac{DEG}{SEC}$
r	TURN RADIUS	FT
Mn	MACH NUMBER	– –

TOTAL OF 11 VARIABLES

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ENERGY-MANEUVERABILITY EQUATIONS

EQUATION	DESCRIPTION
$E_S = h + \frac{\nu^2}{2g}$	ENERGY EQUATION
$\eta = \frac{L}{W}$	DEFINITION
$r = \frac{\nu}{\dot{\theta}}$	KINEMATIC EQUATION
$\dot{\theta} = \frac{g\sqrt{\eta^2 - 1}}{\nu}$	KINETIC EQUATION
$P_S = \left(\frac{T - D}{W}\right)\nu$	KINETIC EQUATION
$T = f_1\,(h, \nu)$	AERODYNAMIC RELATIONSHIP
$D = f_2\,(h, \nu, L)$	AERODYNAMIC RELATIONSHIP
$M_n = f_3\,(h, \nu)$	ATMOSPHERIC RELATIONSHIP

TOTAL OF 8 EQUATIONS

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DEFINITION

MANEUVER: THE ABILITY TO CHANGE ALTITUDE, AIRSPEED AND DIRECTION, IN ANY COMBINATION

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PARAMETERS TO MEASURE MANEUVER OBJECTIVES

MANEUVER OBJECTIVE	PARAMETER OF INTEREST
• CHANGE ALTITUDE	Ps
• CHANGE AIRSPEED	Ps
• CHANGE DIRECTION OF FLIGHT PATH, EMPHASIZING	
– POINTING AIRCRAFT NOSE	$\dot{\theta}$
– ACCELERATING PERPENDICULAR TO FLIGHT PATH	n
– TURNING IN CONFINED AIRSPACE	r

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DEFINITIONS

MANEUVER STATE: A SET OF FLIGHT PARAMETERS THAT DETERMINES THE AIRCRAFT'S MANEUVER POTENTIAL

MANEUVER STATE DESCRIPTOR: $[P_s, (\eta: \dot{\Theta}, r)]$

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DEFINITIONS

FRAME-OF-REFERENCE (FOR): THE CHOICE OF FLIGHT PARAMETERS WITHIN WHICH TO ILLUSTRATE OR COMPARE MANEUVER STATES

INDEPENDENT PARAMETER: A FLIGHT PARAMETER CHOSEN TO DEFINE THE MANEUVER STATE

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ILLUSTRATION

"TRADITIONAL" ENERGY MANEUVERABILITY
FRAME-OF-REFERENCE: (h, Mn)

<u>CASES</u>

1. INDEPENDENT PARAMETER: η
   MANEUVER STATE: $[P_s, (\eta: \dot{\Theta}, r)]$

2. INDEPENDENT PARAMETER: $P_s = 0$
   MANEUVER STATE: $[P_s = 0, (\dot{\Theta}_s: \eta_s, r_s)]$

3. INDEPENDENT PARAMETER: P_s
   MANEUVER STATE: $[P_s, (\dot{\Theta}_m: \eta_m, r_m)]$

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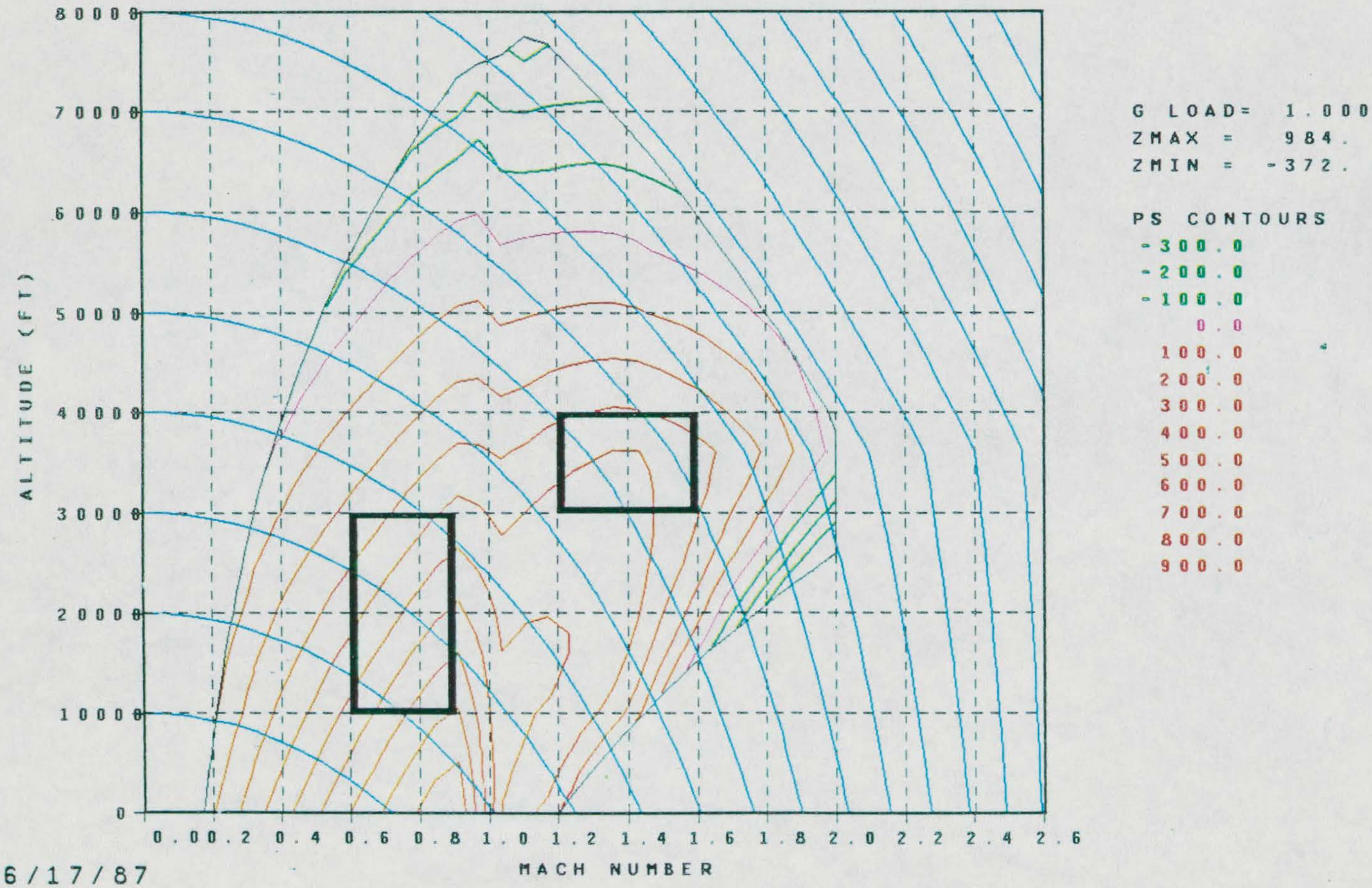
AIRCRAFT 1, 50% FUEL
SPECIFIC EXCESS POWER (FT/SEC)



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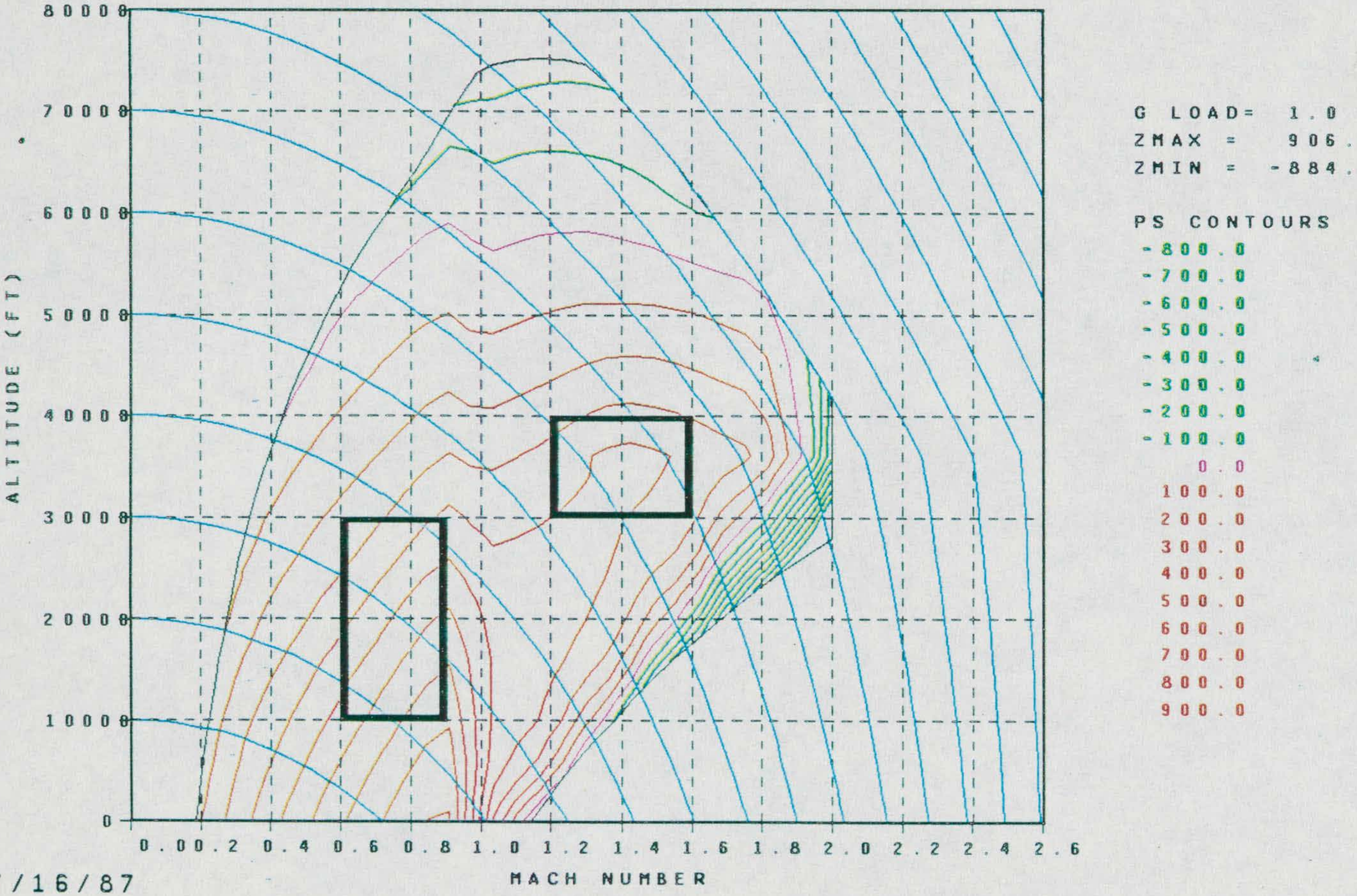
AIRCRAFT 2, 50% FUEL
SPECIFIC EXCESS POWER (FT/SEC)



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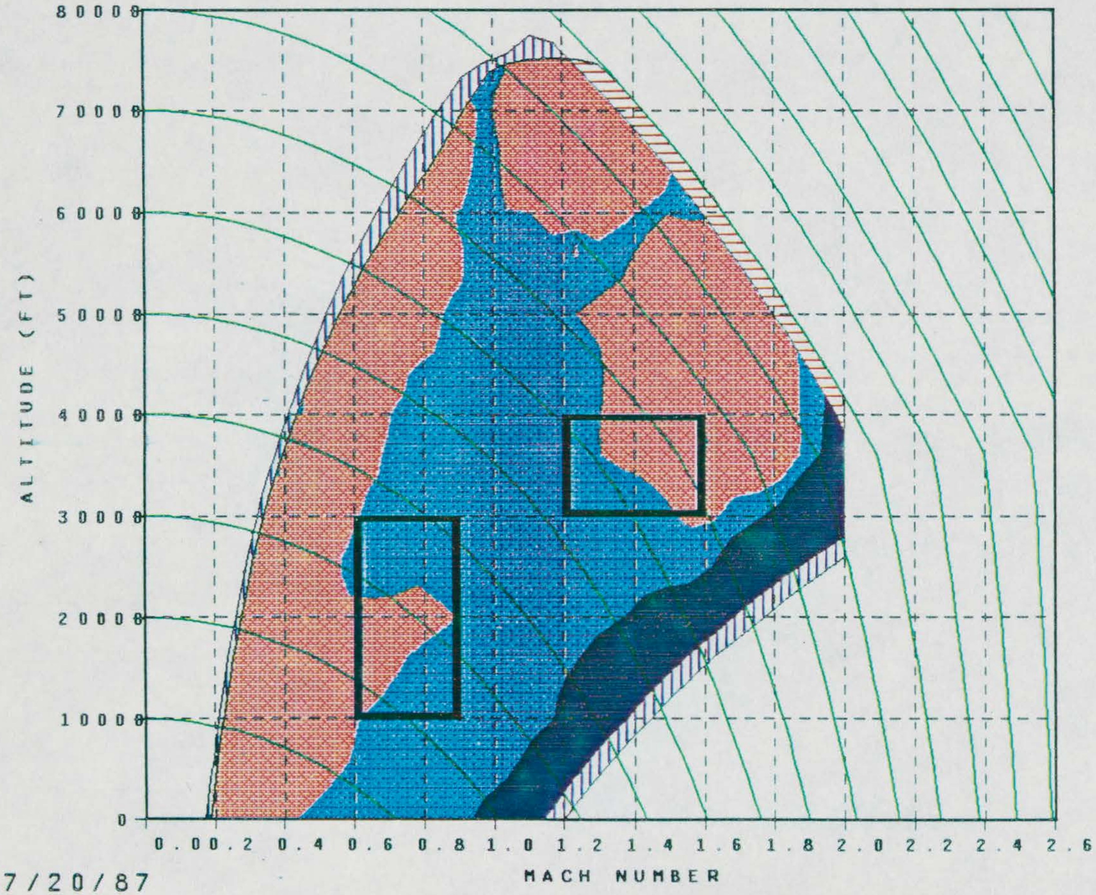
DELTA PLOT
AIRCRAFT 1, 50% FUEL
AIRCRAFT 2, 50% FUEL
SPECIFIC EXCESS POWER (FT/SEC)



G LOAD= 1.0
ZMAX = 626.
ZMIN = -91.

PS DIFFERENCE

	Z <	-100.0
-100.0	< Z <	0.0
0.0	< Z <	100.0
100.0	< Z	

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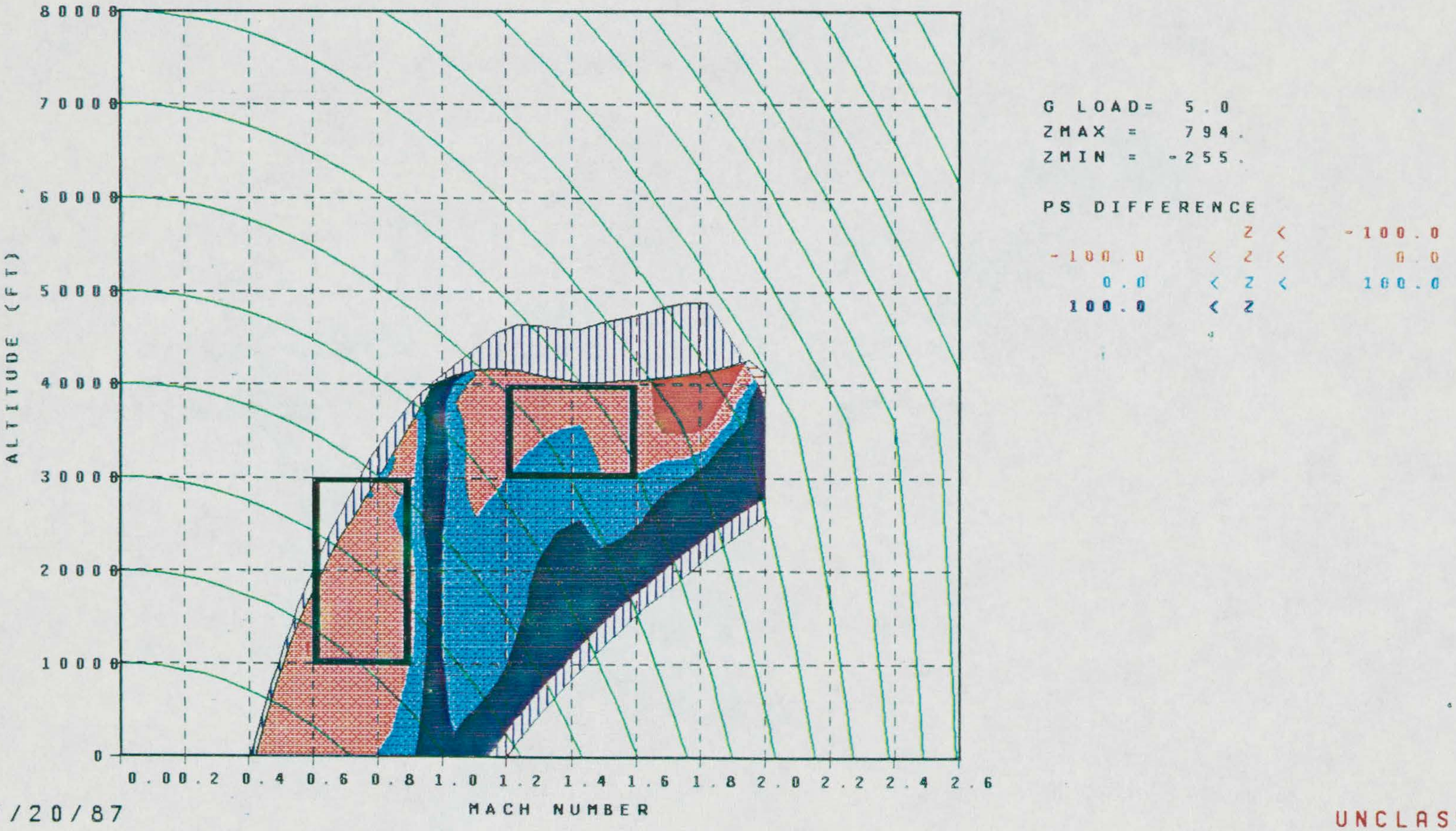
DELTA PLOT
AIRCRAFT 1, 50% FUEL
AIRCRAFT 2, 50% FUEL
SPECIFIC EXCESS POWER (FT/SEC)



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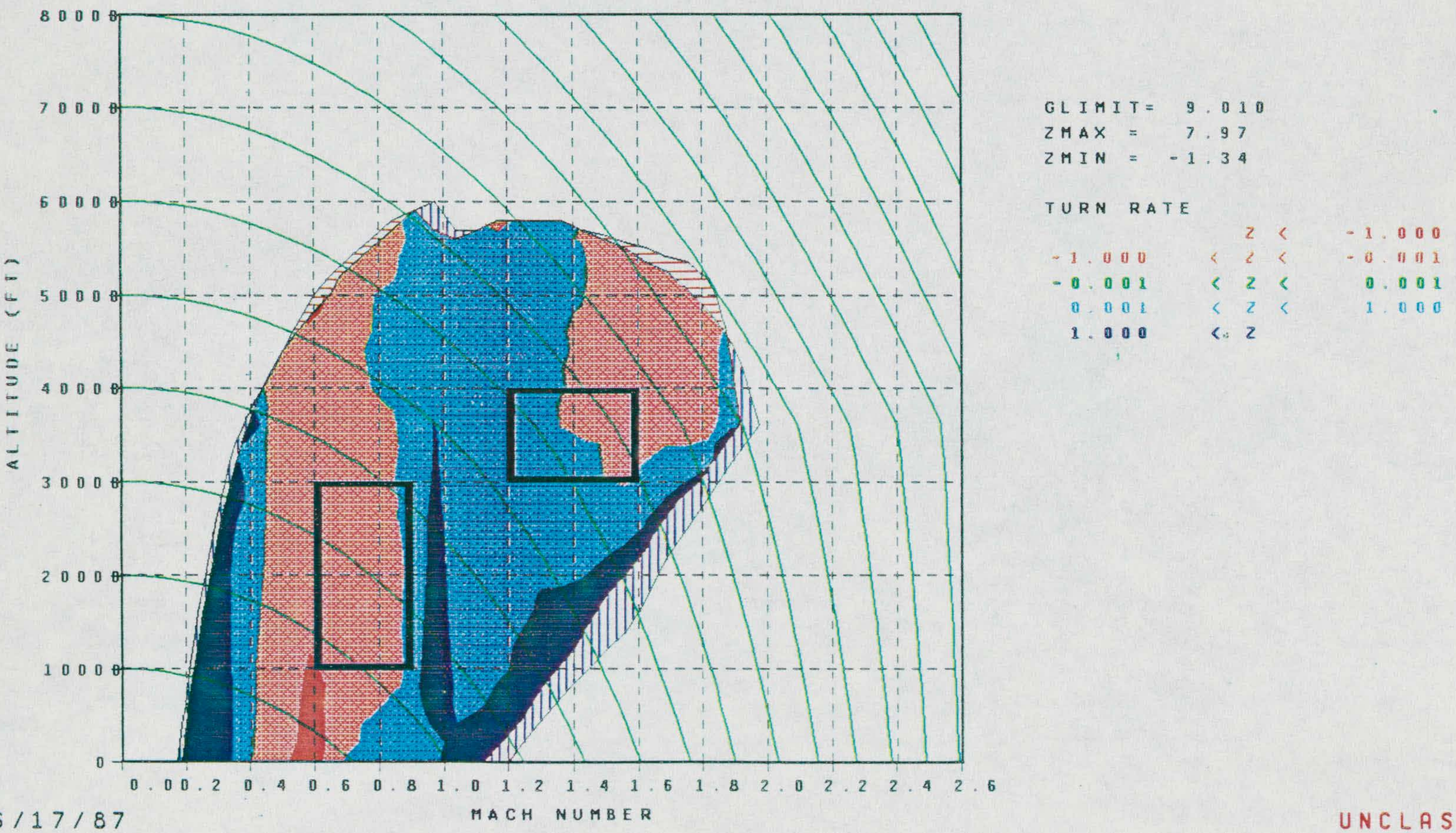
DELTA PLOT
AIRCRAFT 1, 50% FUEL
AIRCRAFT 2, 50% FUEL
STEADY STATE TURN RATE (DEG/SEC)



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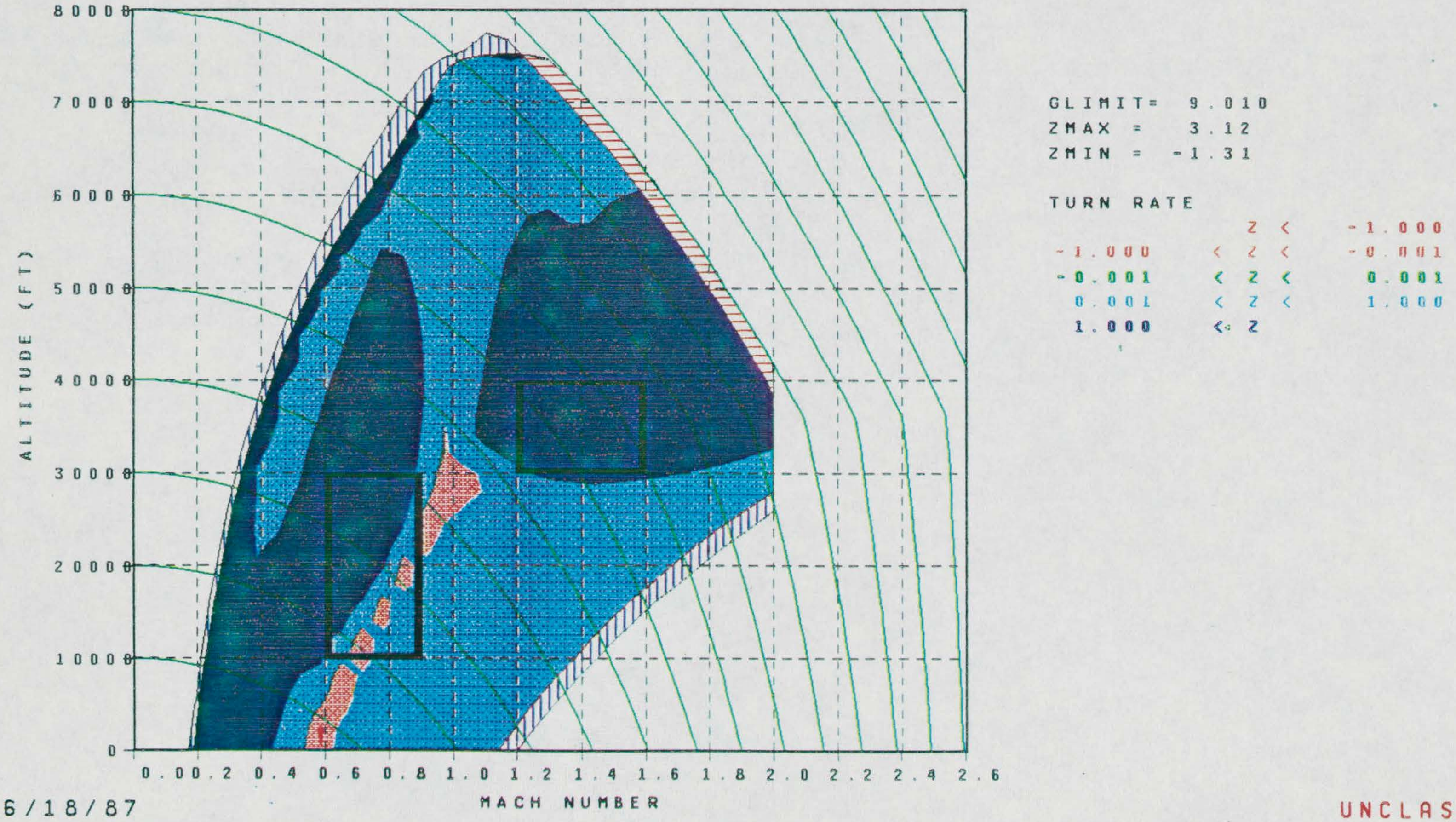
DELTA PLOT
AIRCRAFT 1, 50% FUEL
AIRCRAFT 2, 50% FUEL
INSTANTANEOUS TURN RATE (DEG/SEC)



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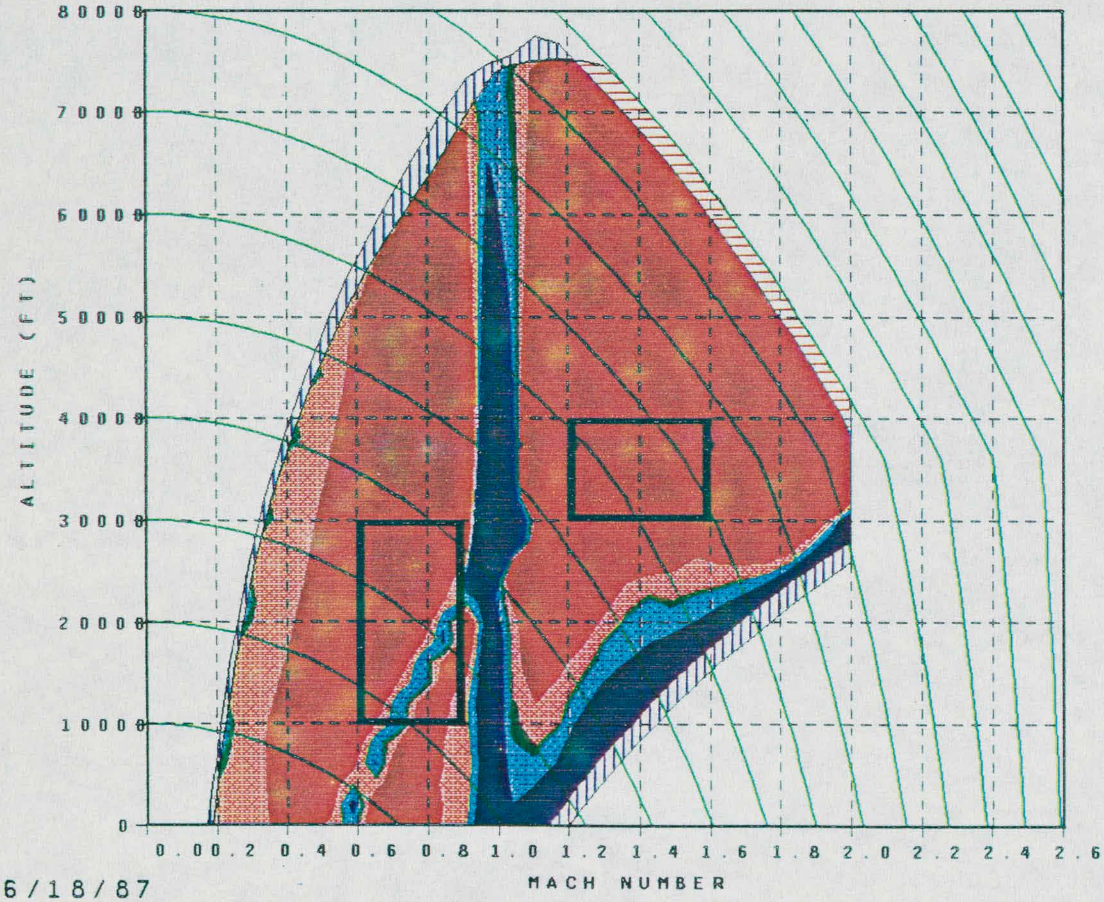
DELTA PLOT
AIRCRAFT 1, 50% FUEL
AIRCRAFT 2, 50% FUEL
PS AT MAX INSTANTANEOUS TURN RATE



G LOAD= 1.163
ZMAX = 1065.
ZMIN = -2305.

PS

	Z <	-100.0
-100.0	< Z <	-10.0
-10.0	< Z <	10.0
10.0	< Z <	100.0
100.0	< Z	

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ILLUSTRATION

"MAXIMUM MANEUVER" ENERGY MANEUVERABILITY

FRAME-OF-REFERENCE: (E_S, P_S)
INDEPENDENT PARAMETER: M_n

CASES

1. MANEUVER STATE: $[P_S = k, (\dot{\Theta}_{max}: \eta, r)]$
2. MANEUVER STATE: $[P_S = k, (\eta_{max}: \dot{\Theta}, r)]$
3. MANEUVER STATE: $[P_S = k, (r_{min}: \dot{\Theta}, \eta)]$

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CHOICE OF PARAMETERS FOR MAXIMUM MANEUVER FRAME-OF-REFERENCE (E_S, P_S)

- AN AIRCRAFT IN FLIGHT INHERENTLY POSSESSES ENERGY (E_S)

- THE PILOT MUST MANEUVER IN THE PRESENT WHILE ATTAINING SUFFICIENT ENERGY TO MANEUVER IN THE FUTURE

- HIS ABILITY TO ATTAIN AN ENERGY LEVEL FOR FUTURE MANEUVERING IS DETERMINED BY THE RATE AT WHICH THE AIRCRAFT'S ENERGY LEVEL IS CHANGING IN THE PRESENT (P_S)

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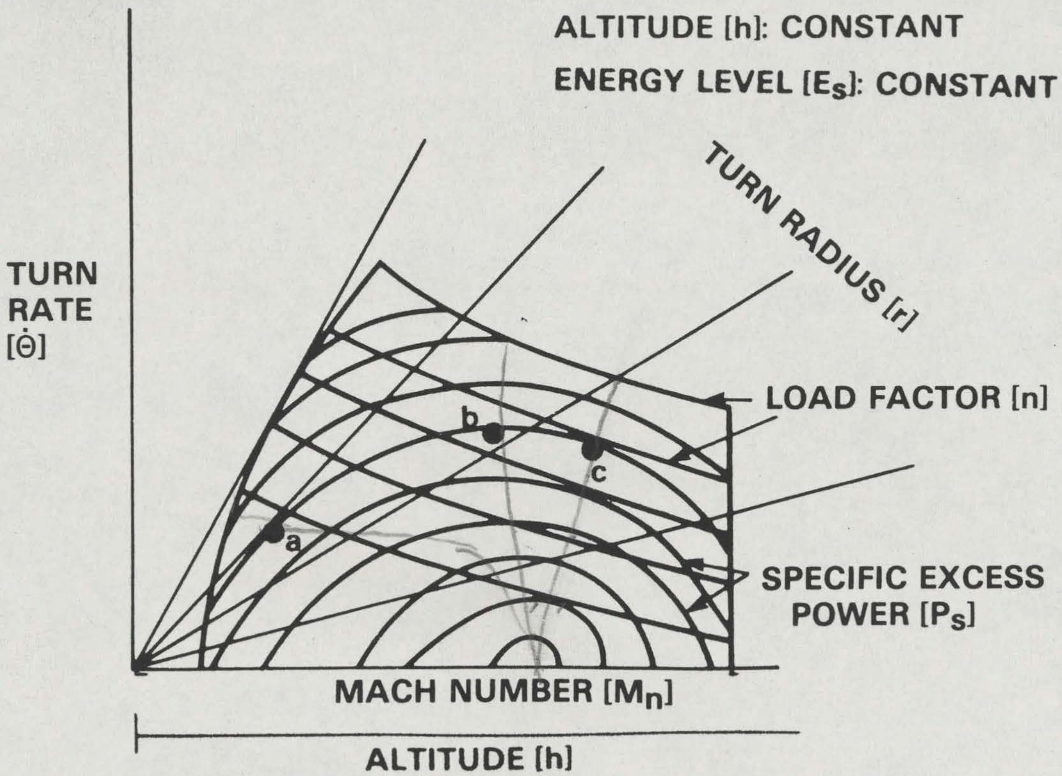
"DOG HOUSE" PLOT



a: $\dfrac{\delta r}{\delta M_n} = 0$ b: $\dfrac{\delta \dot{\Theta}}{\delta M_n} = 0$ c: $\dfrac{\delta \eta}{\delta M_n} = 0$

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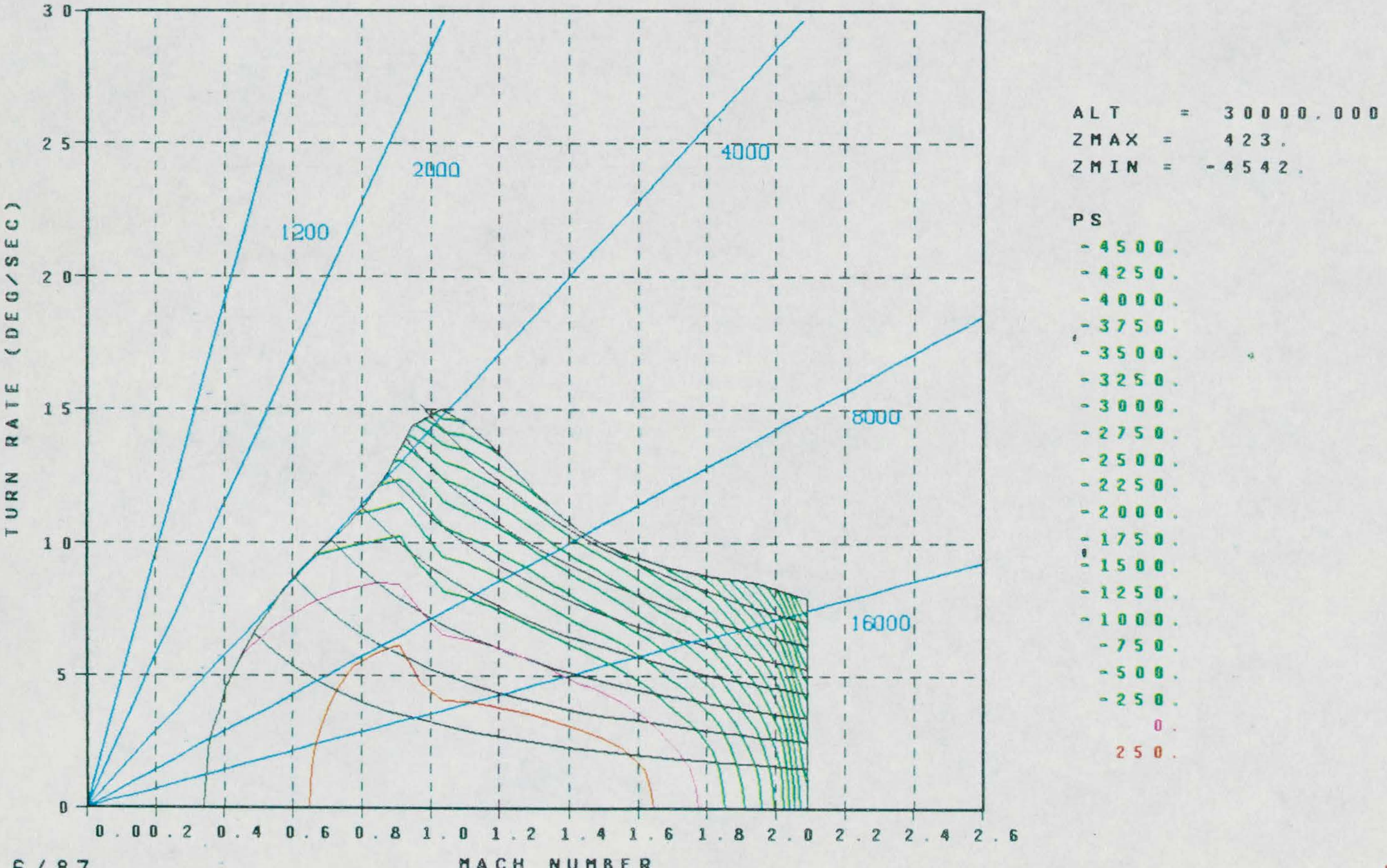
AIRCRAFT 2, 50% FUEL
PS ON TURN RATE VS MACH



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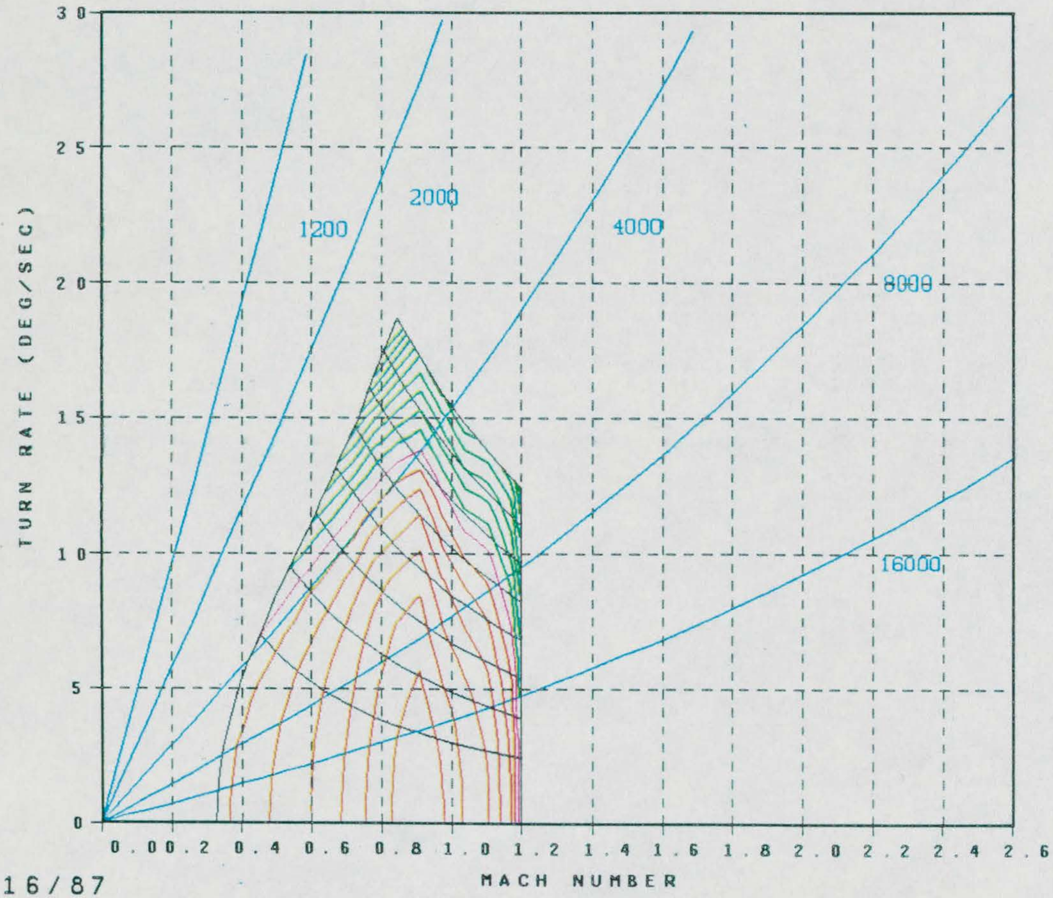
AIRCRAFT 2, 50% FUEL
PS ON TURN RATE VS MACH



ES = 30000.000
ZMAX = 695.
ZMIN = -905.

PS
-900.0
-800.0
-700.0
-600.0
-500.0
-400.0
-300.0
-200.0
-100.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0

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MAXIMUM MANEUVER EQUATIONS

TURN RATE

$$\left.\frac{\delta\dot{\Theta}}{\delta M_n}\right|_{P_S,\,E_S} = 0 \quad \forall\, P_S, E_S$$

$$\text{MAX } \dot{\Theta} = f\,(M_n \mid P_S, E_S) \quad \forall\, P_S, E_S$$

LOAD FACTOR

$$\left.\frac{\delta\eta}{\delta M_n}\right|_{P_S,\,E_S} = 0 \quad \forall\, P_S, E_S$$

$$\text{MAX } \eta = f(M_n \mid P_S, E_S) \quad \forall\, P_S, E_S$$

TURN RADIUS

$$\left.\frac{\delta r}{\delta M_n}\right|_{P_S,\,E_S} = 0 \quad \forall\, P_S, E_S$$

$$\text{MIN } \; r = f(M_n \mid P_S, E_S) \quad \forall\, P_S, E_S$$

CONSTRAINTS

$$\eta \leqslant \eta_{max}$$

$$C_\ell \leqslant C_{\ell_{max}}$$

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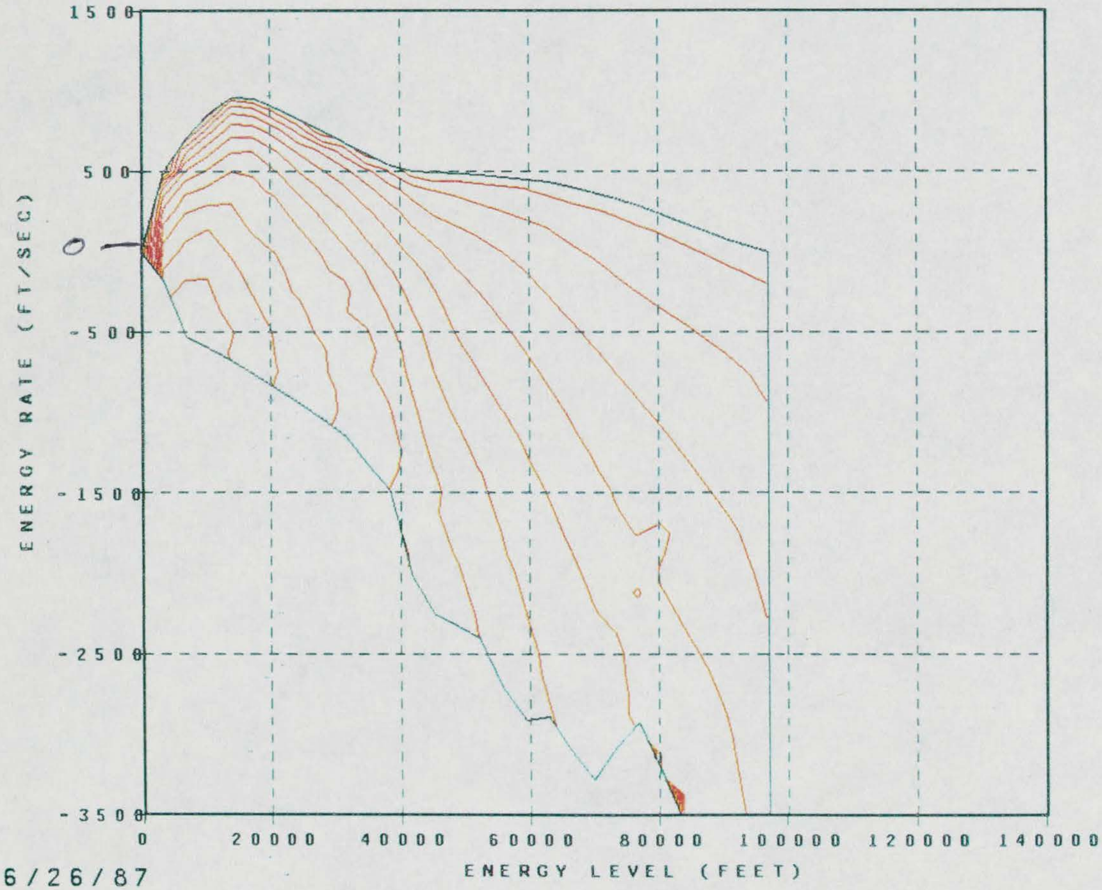
AIRCRAFT 1, 50% FUEL
MAX MANUEVER, TURN RATE



GLIMIT = 9.010
ZMAX = 23.9
ZMIN = 0.833

TURN RATE
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
22.0

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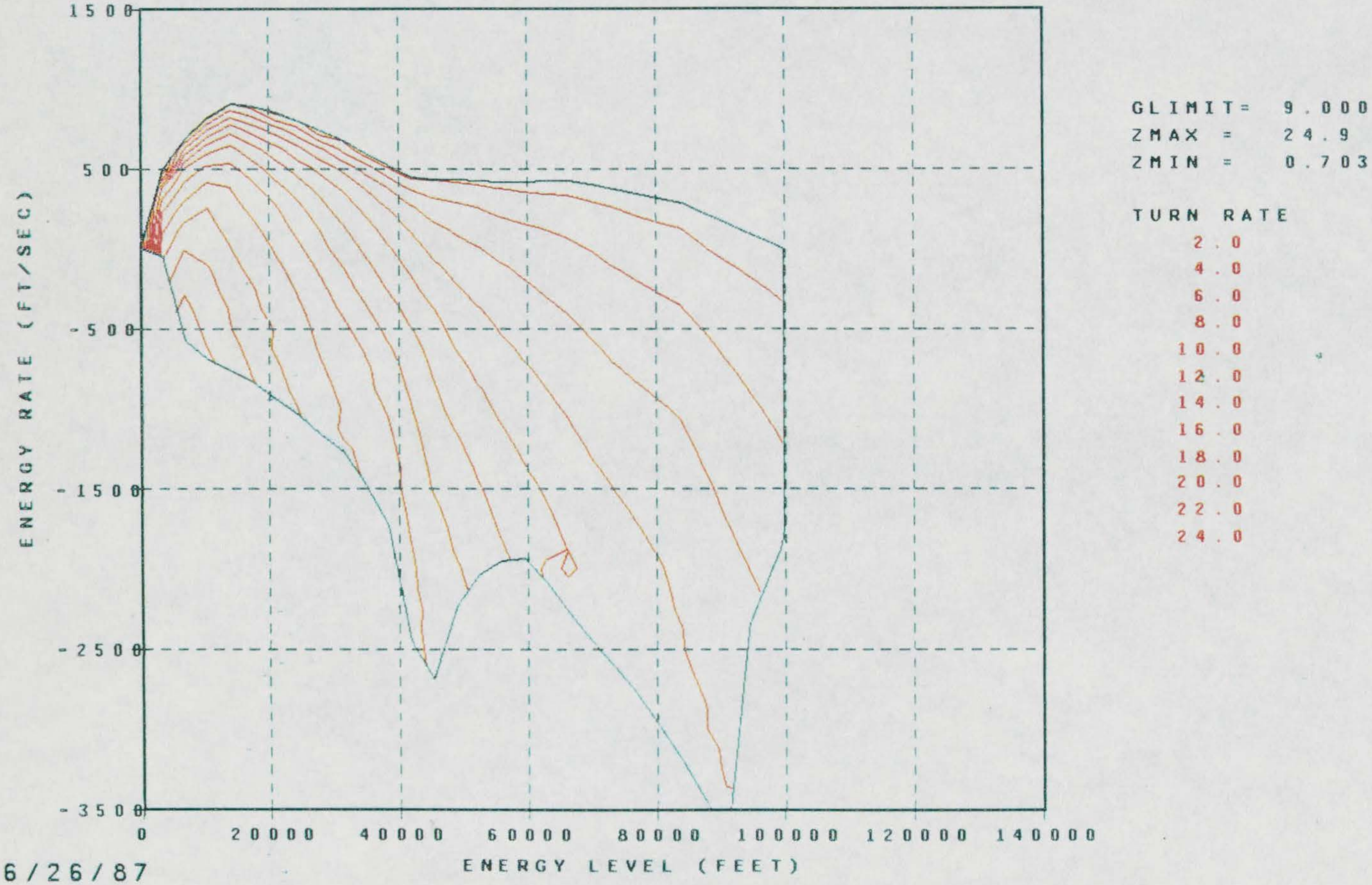
AIRCRAFT 2, 50% FUEL
MAX MANUEVER, TURN RATE



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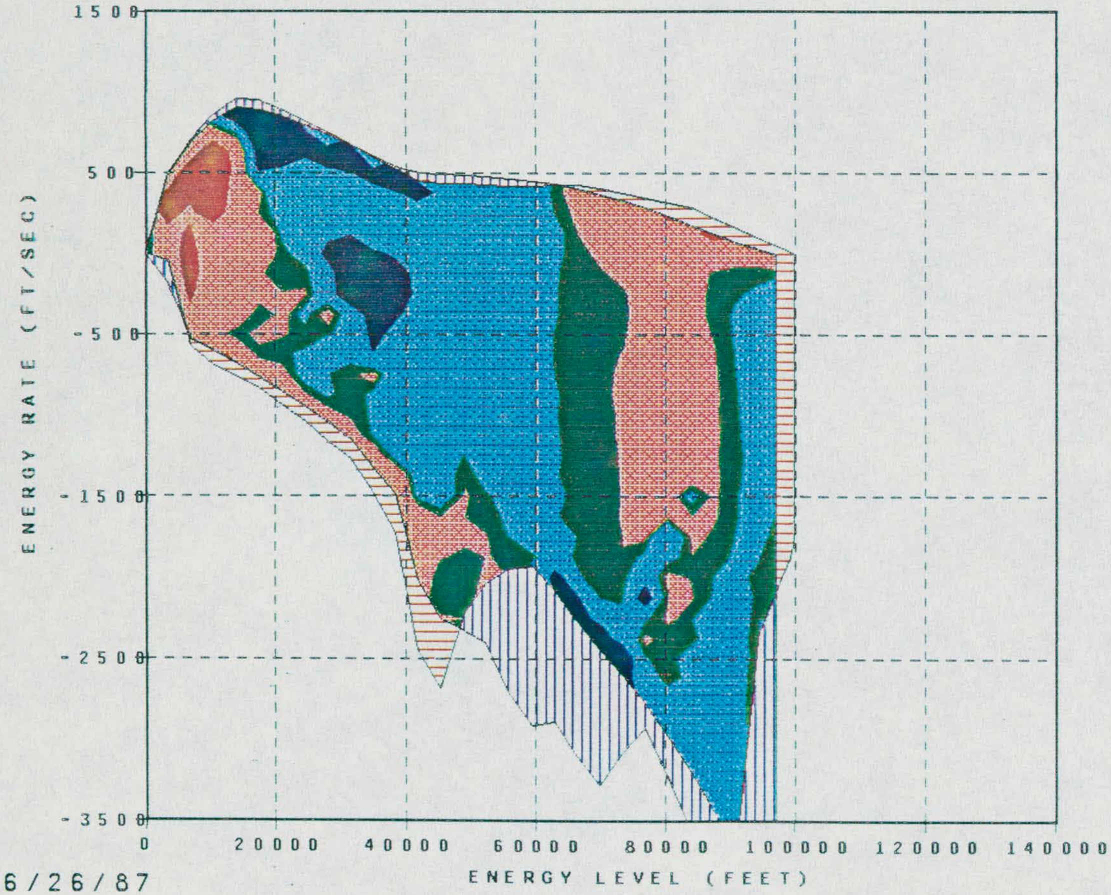
DELTA PLOT
AIRCRAFT 1, 50% FUEL
AIRCRAFT 2, 50% FUEL
MAX MANUEVER, TURN RATE



GLIMIT = 9.010
ZMAX = 2.81
ZMIN = -2.30

TURN RATE

	Z <	-1.0
-1.0	< Z <	-0.1
-0.1	< Z <	0.1
0.1	< Z <	1.0
1.0	< Z	

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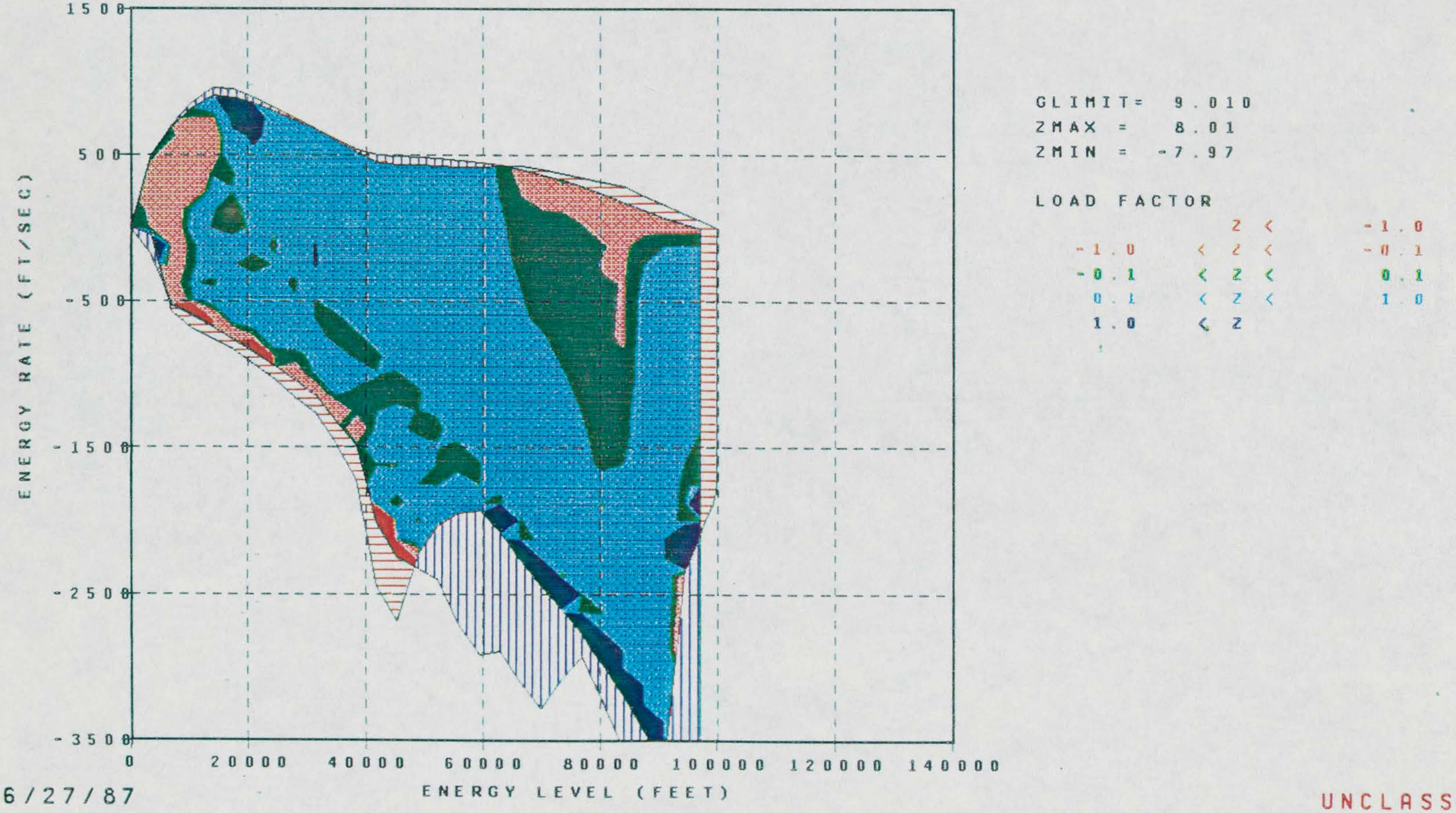
DELTA PLOT
AIRCRAFT 1, 50% FUEL
AIRCRAFT 2, 50% FUEL
MAX MANUEVER, LOAD FACTOR



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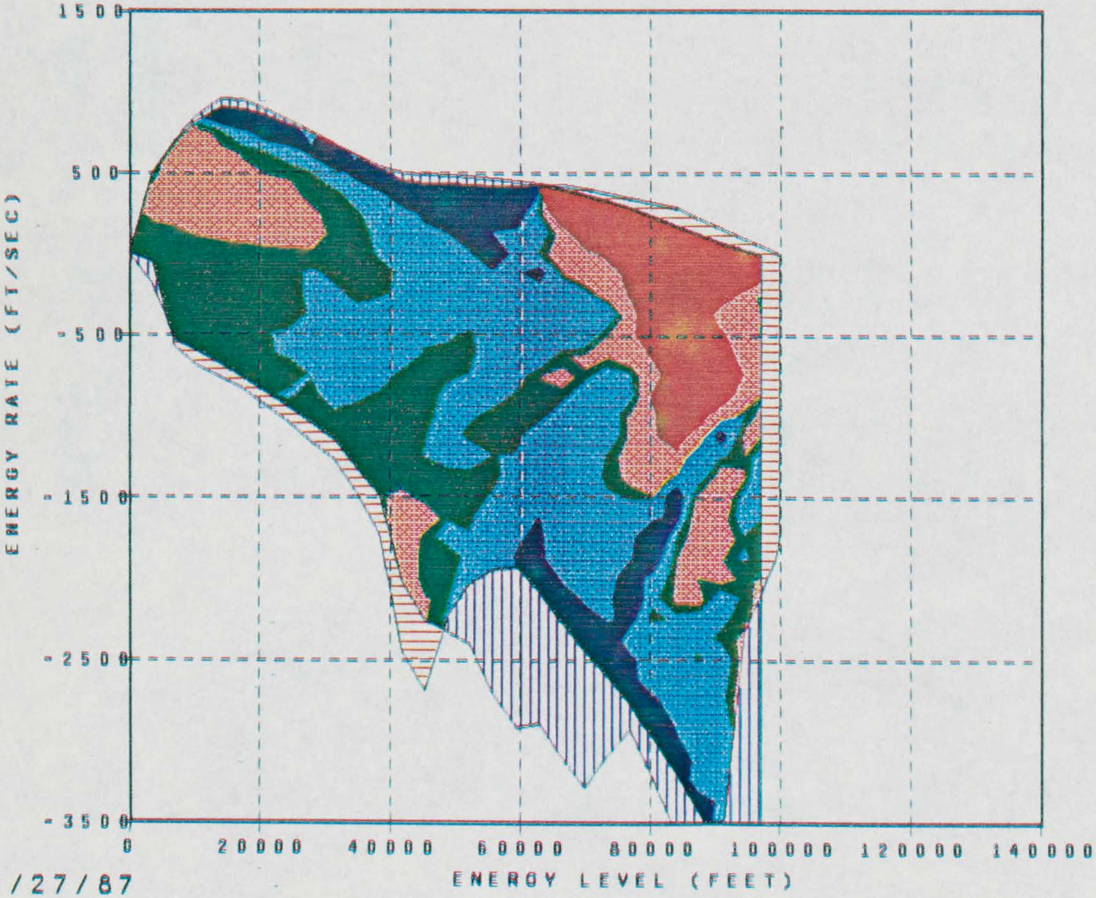
DELTA PLOT
AIRCRAFT 1, 50% FUEL
AIRCRAFT 2, 50% FUEL
MAX MANUEVER, TURN RADIUS



GLIMIT= 9.010
ZMAX = 10992.
ZMIN = -38530.

TURN RADIUS

	Z <	-1000.
-1000.	< Z <	-100.
-100.	< Z <	100.
100.	< Z <	1000.
1000.	< Z	

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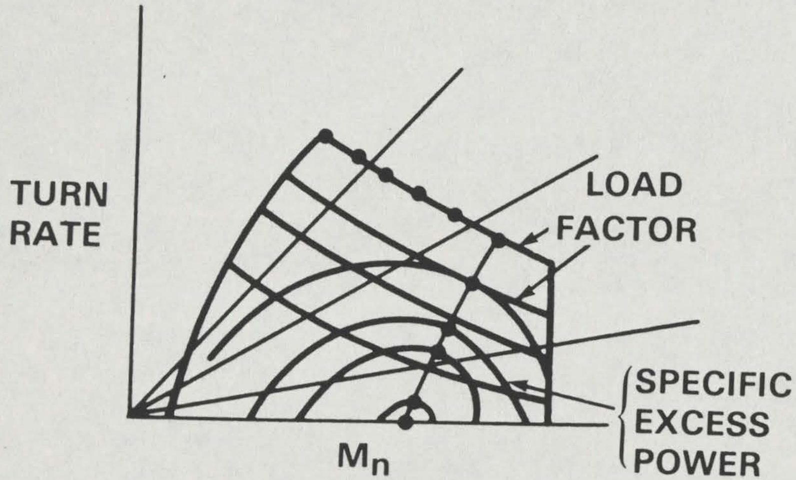
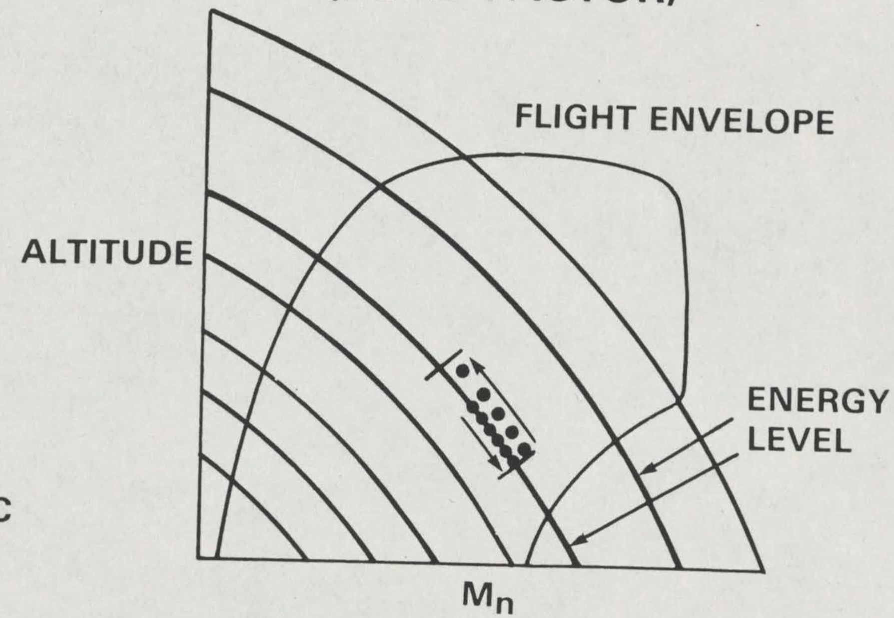
METHODOLOGY FOR CONSTRUCTING MAXIMUM MANEUVER CORRIDOR

"DOG HOUSE" PLOT

ENERGY LEVEL: CONSTANT



MAXIMUM MANEUVER
CORRIDOR
(LOAD FACTOR)



$$\left.\frac{\delta n}{\delta M_n}\right|_{P_s,\, E_s} = 0 \quad \forall \, P_s$$

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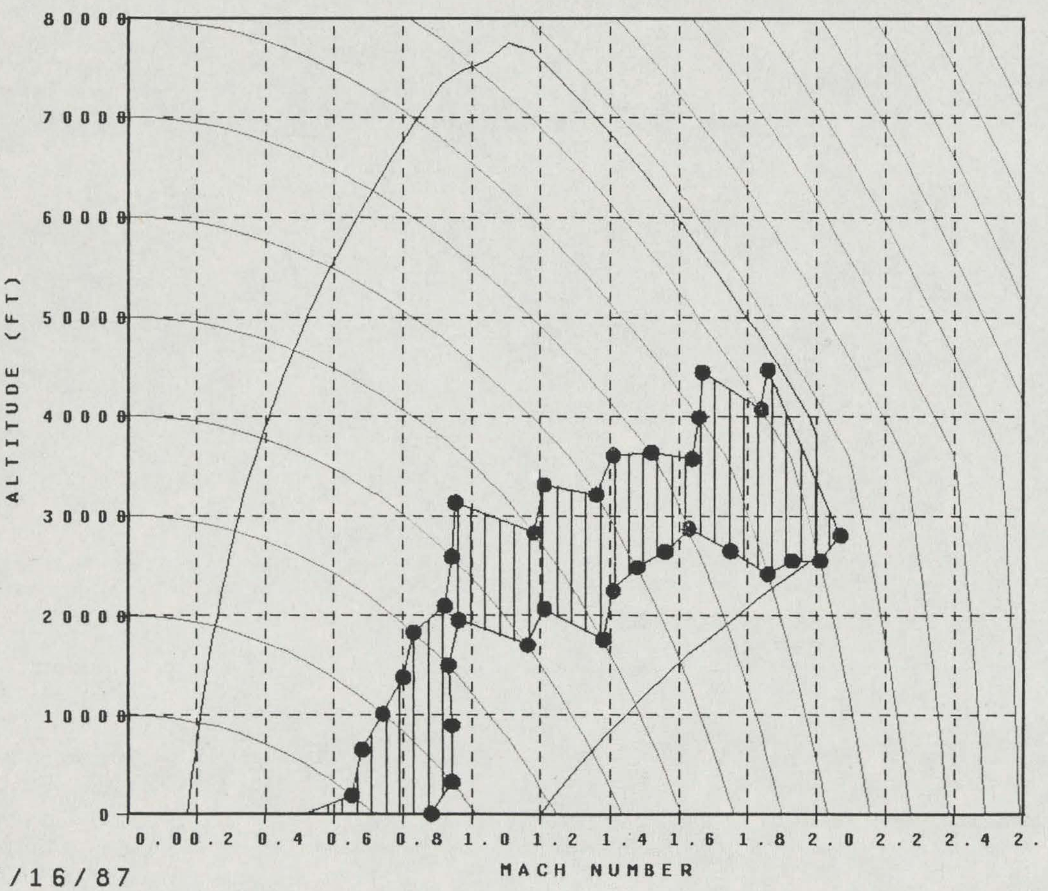
AIRCRAFT 1, 50% FUEL
MAX TURN RATE CORRIDOR



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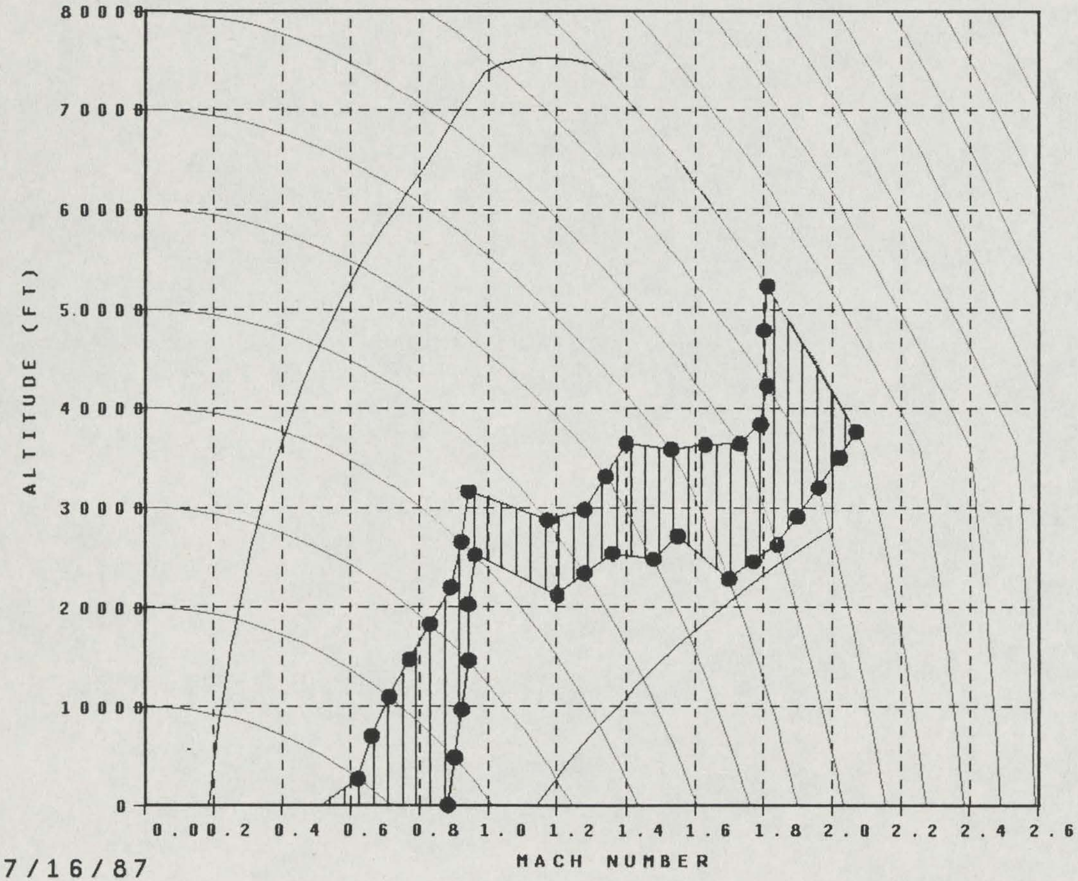
AIRCRAFT 2, 50% FUEL
MAX TURN RATE CORRIDOR



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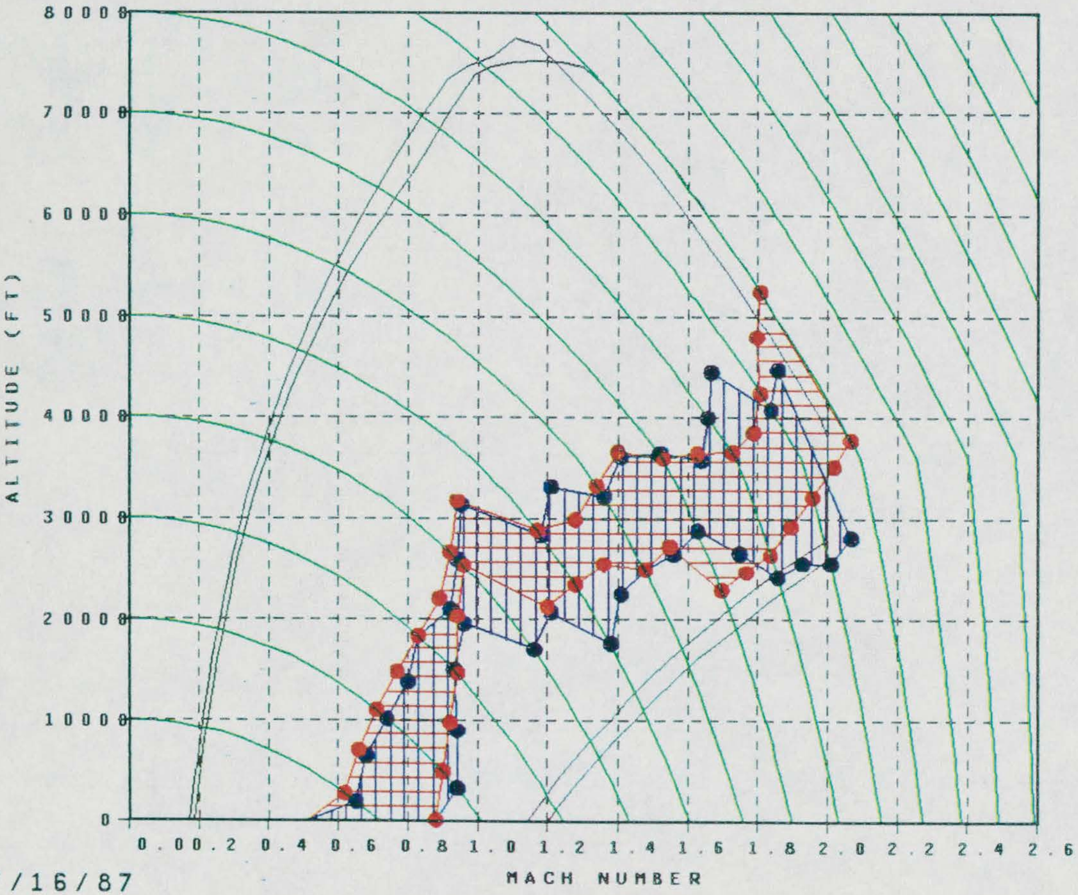
DELTA PLOT
AIRCRAFT 1, 50% FUEL
AIRCRAFT 2, 50% FUEL
MAX TURN RATE CORRIDOR



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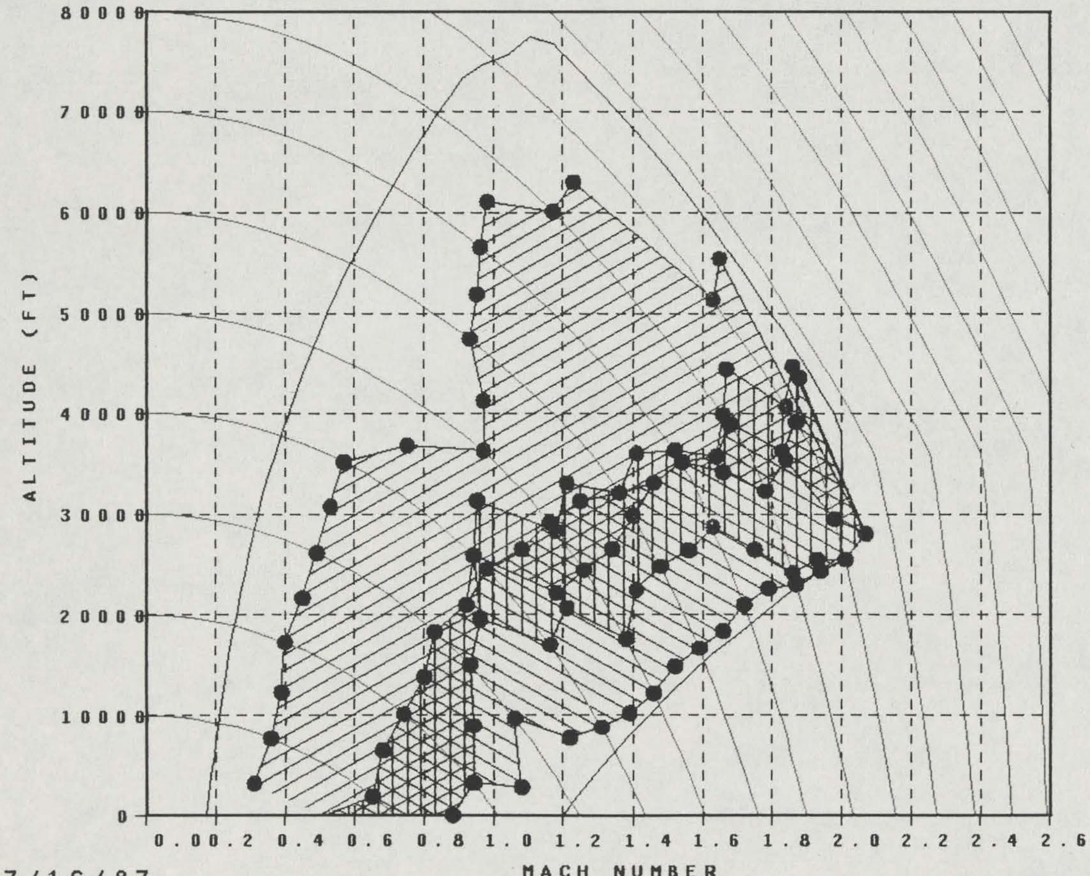
AIRCRAFT 1, 50% FUEL
MAXIMUM MANEUVER CORRIDORS



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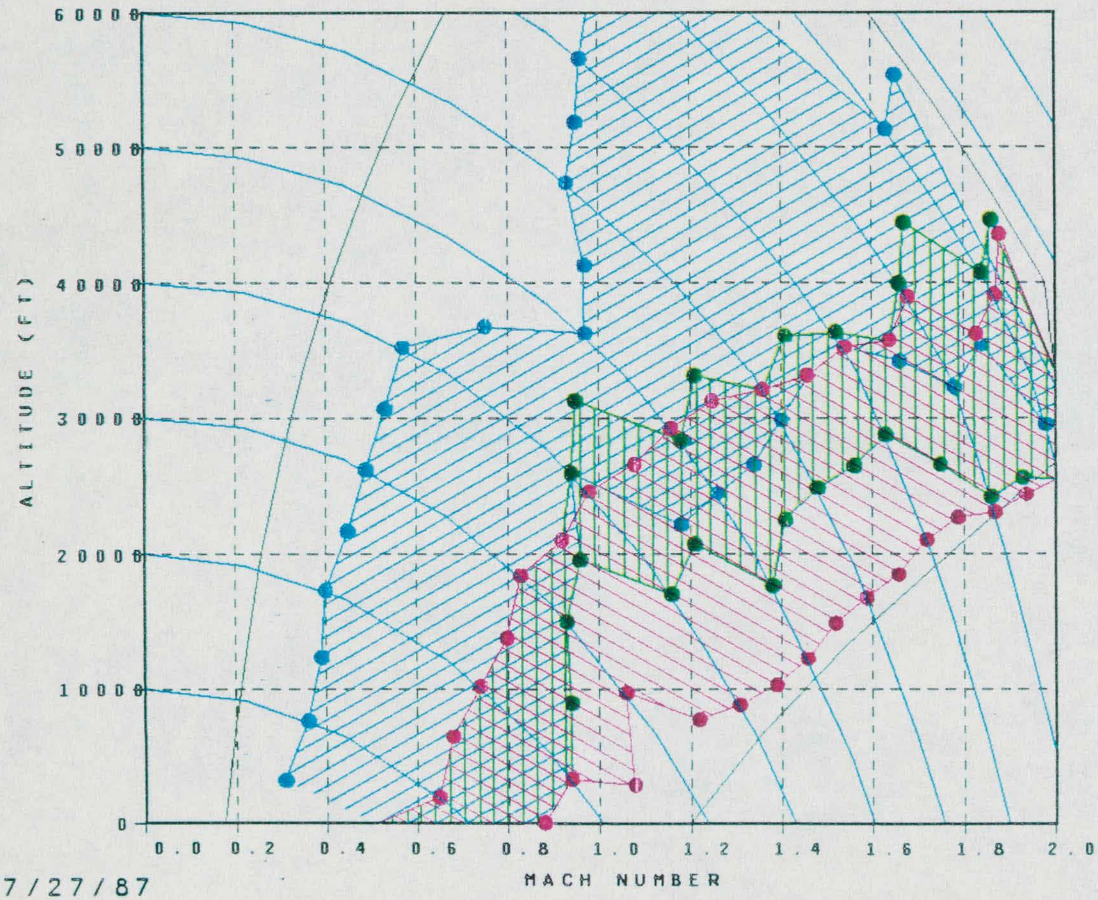
AIRCRAFT 1, 50% FUEL
MAXIMUM MANEUVER CORRIDORS



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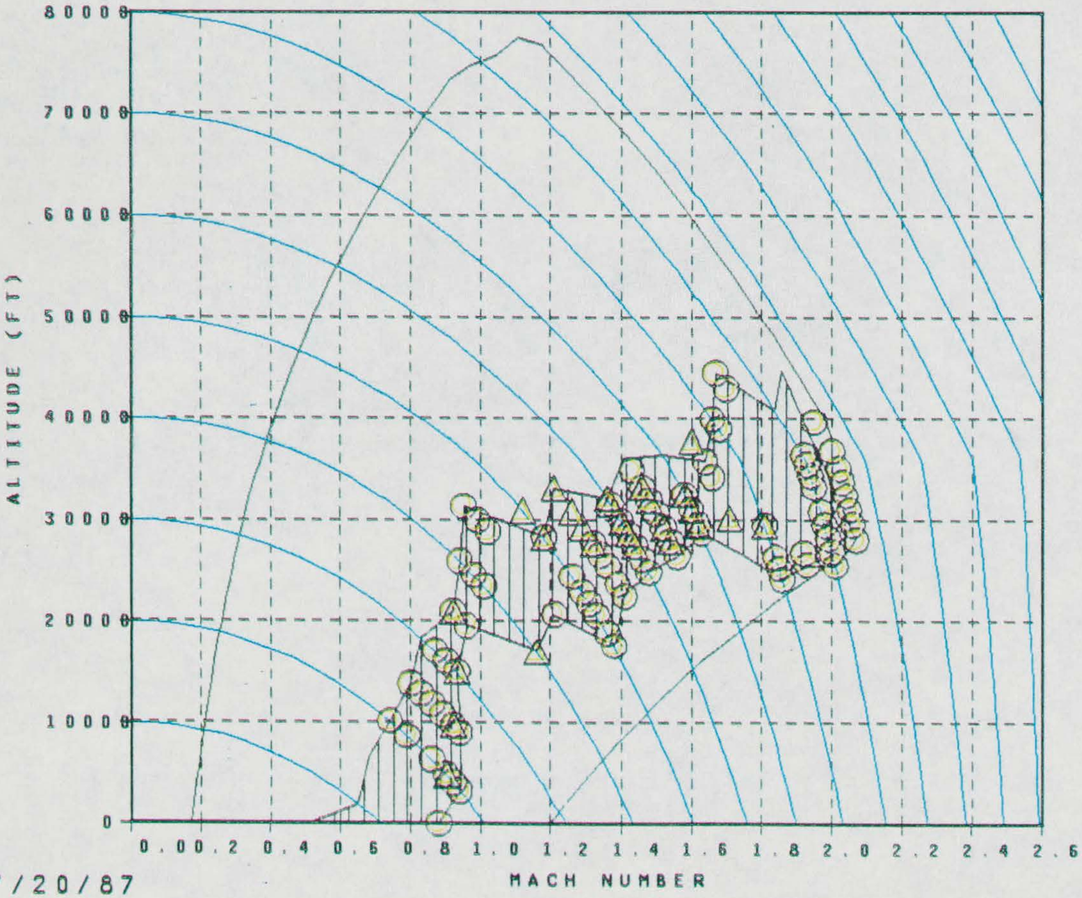
AIRCRAFT 1, 50% FUEL
MAX TURN RATE CORRIDOR



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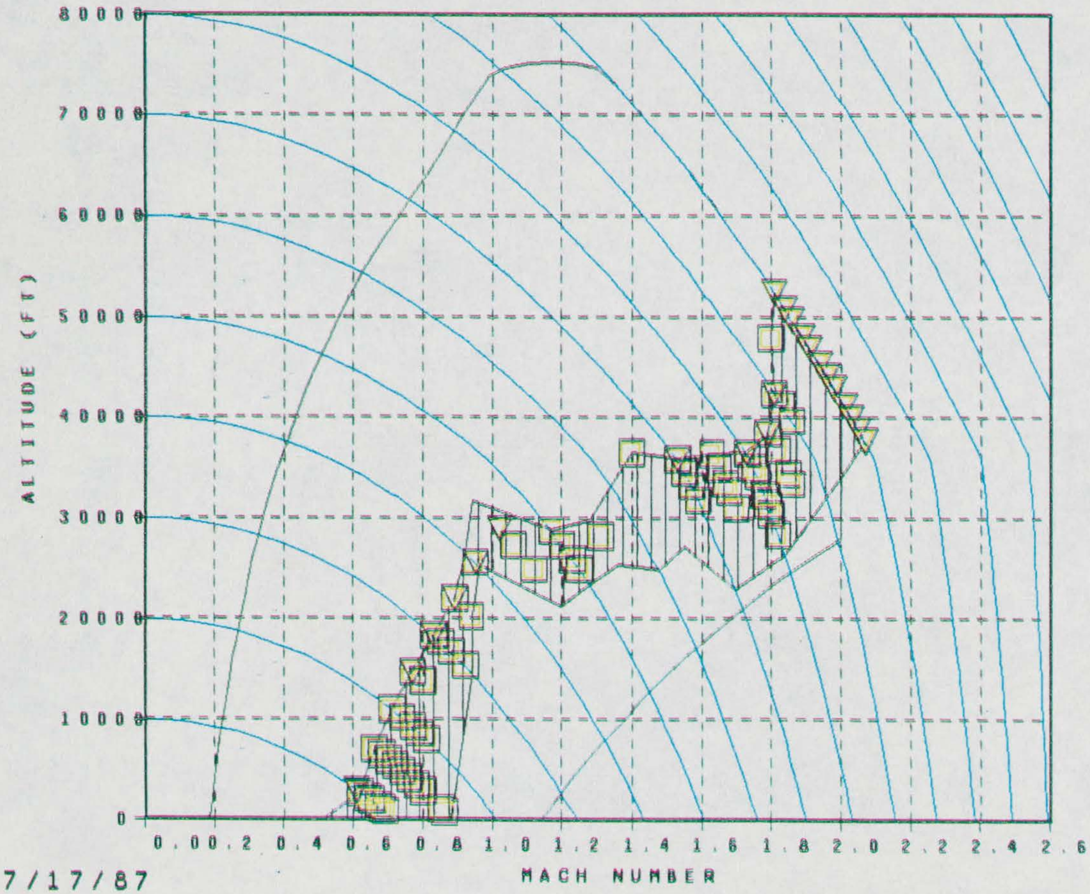
AIRCRAFT 2, 50% FUEL
MAX TURN RATE CORRIDOR



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RESEARCH QUESTIONS (EXAMPLES)

- IS (E_S, P_S) A SUPERIOR, EQUAL OR INFERIOR FRAME-OF-REFERENCE COMPARED TO (h, Mn)?
- DOES A SOUND RATIONALE EXIST FOR USING (h, P_S) AS A FRAME-OF-REFERENCE?
- CAN A MANEUVER STRATEGY BE DEVISED THAT INCORPORATES ALL ELEMENTS OF ENERGY MANEUVERABILITY/MAXIMUM MANEUVER CONCEPT?
- HOW CAN THE ENERGY MANEUVERABILITY/ MAXIMUM MANEUVER CONCEPT BE APPLIED TO AIRCRAFT DESIGN?

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ENERGY MANEUVERABILITY CHARACTERISTICS

- SIMPLE EQUATIONS
- SOUND THEORETICAL BASIS
- READILY EXPLAINED IN OPERATIONAL TERMS
- EASY TO UNDERSTAND WITH SIMPLE RULES
- USEFUL TO A WIDE VARIETY OF AUDIENCES
  - OPERATIONAL
  - ENGINEERING
  - ANALYSIS
  - MANAGERIAL

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REFERENCES

ENERGY MANEUVERABILITY

DDC #: AD372287

TECHNICAL REPORT: APGC-TR-66-4 VOL. 1
MARCH 1966 (CONFIDENTIAL)

MAXIMUM MANEUVER CONCEPT

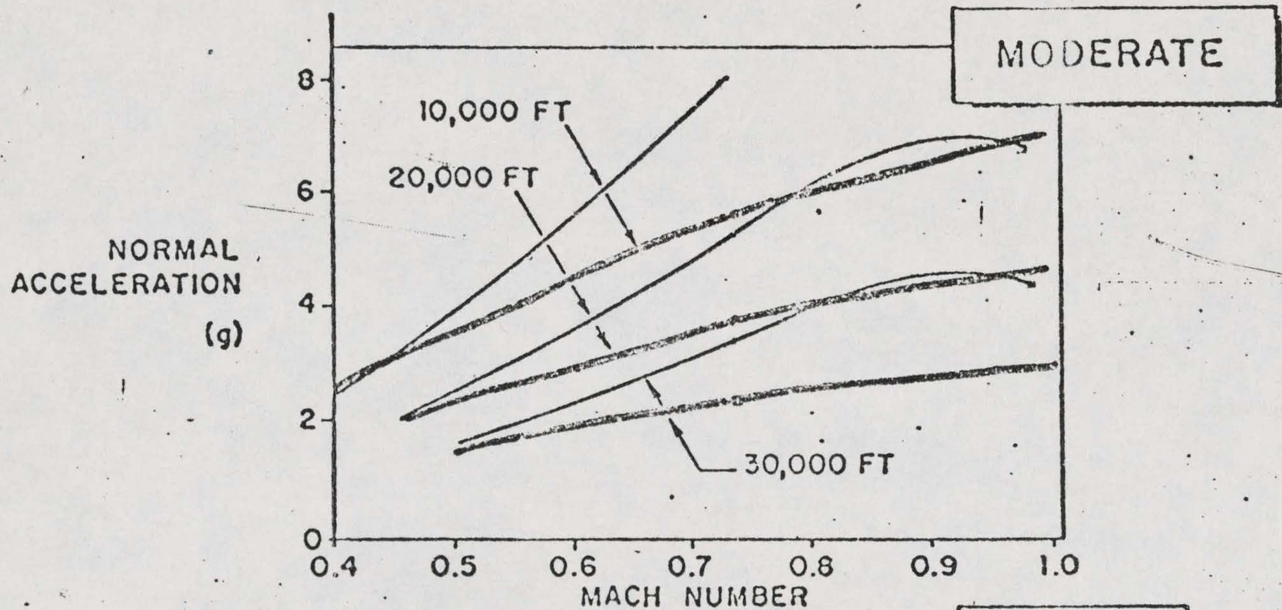
DDC #: AD522272

TECHNICAL REPORT: AF ATL-TR-72-116
JUNE 1972 (UNCLASSIFIED)

A REVIEW OF AIR COMBAT MANEUVERING PERFORMANCE PRESENTATIONS (UPDATE 1)

REPORT NUMBER: NADC - 84043-60
SEPTEMBER 1984 (UNCLASSIFIED)

BUFFET BOUNDARY



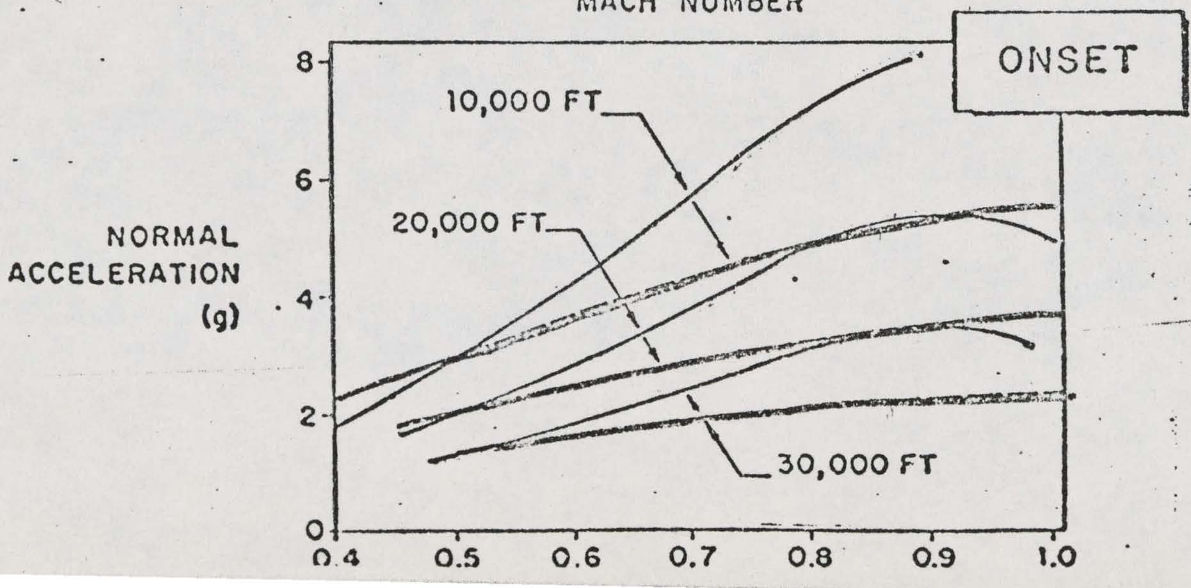
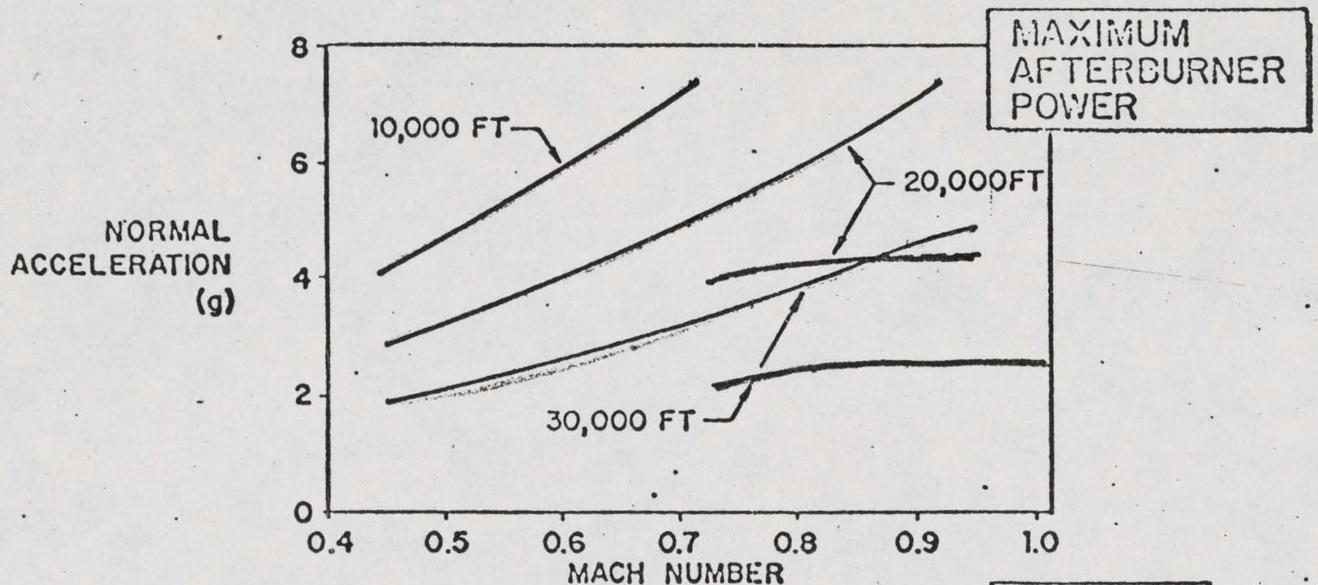


CHART NO. (4)

THRUST LIMITED TURNING PERFORMANCE



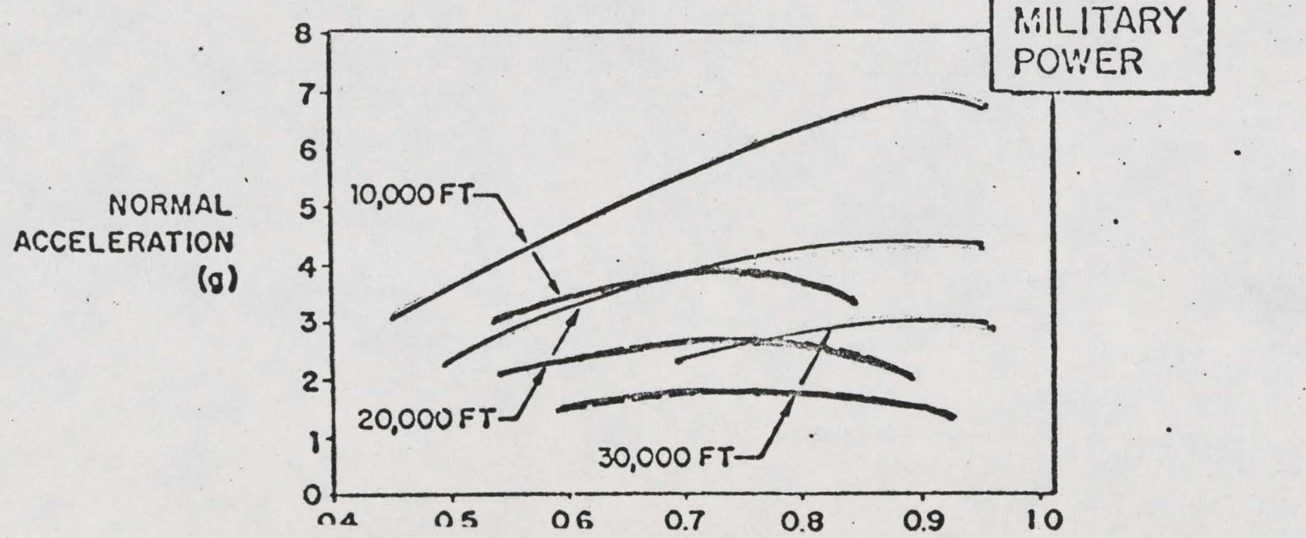
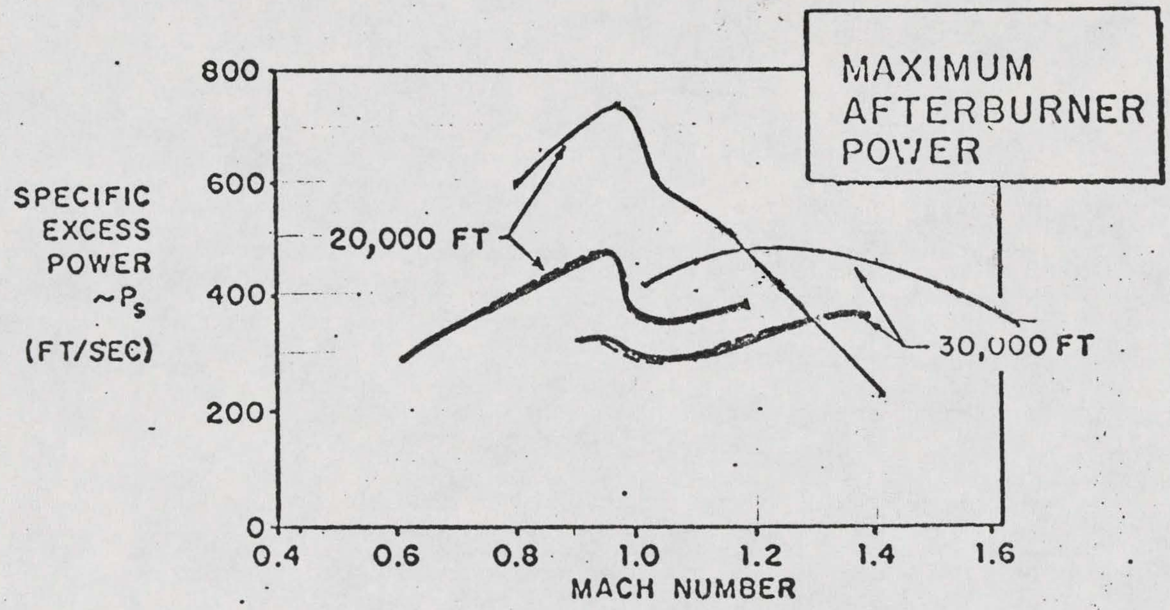


CHART NC. (5)

SPECIFIC EXCESS POWER



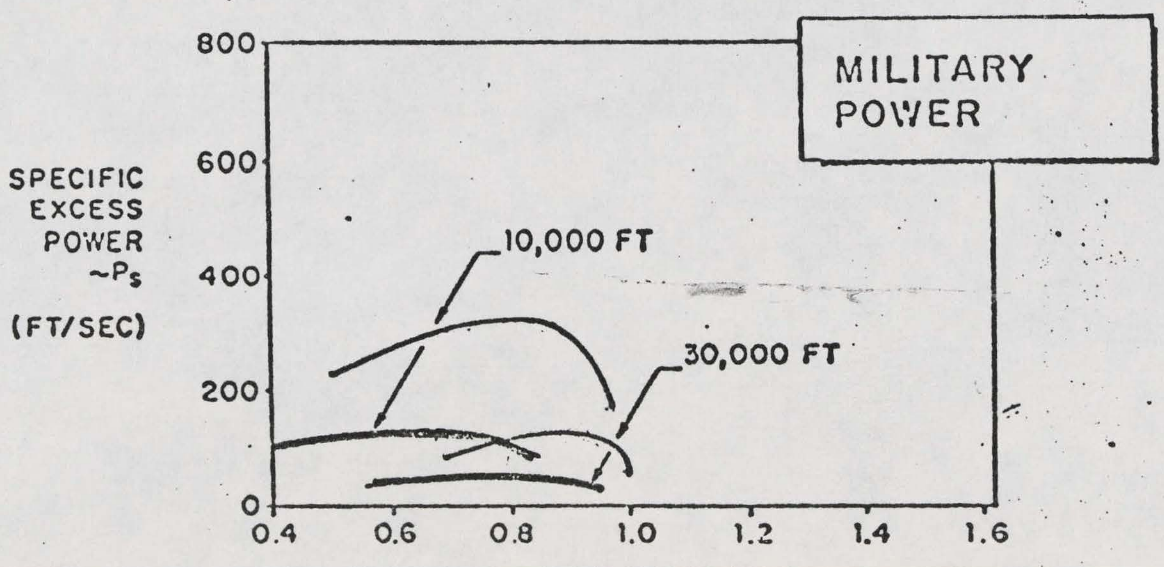
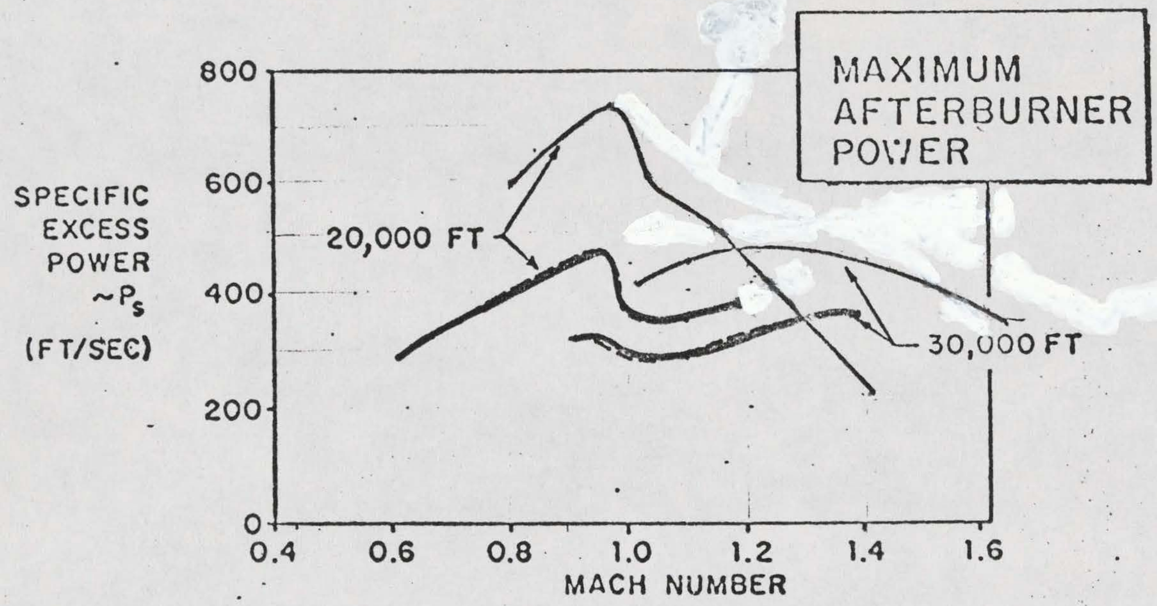
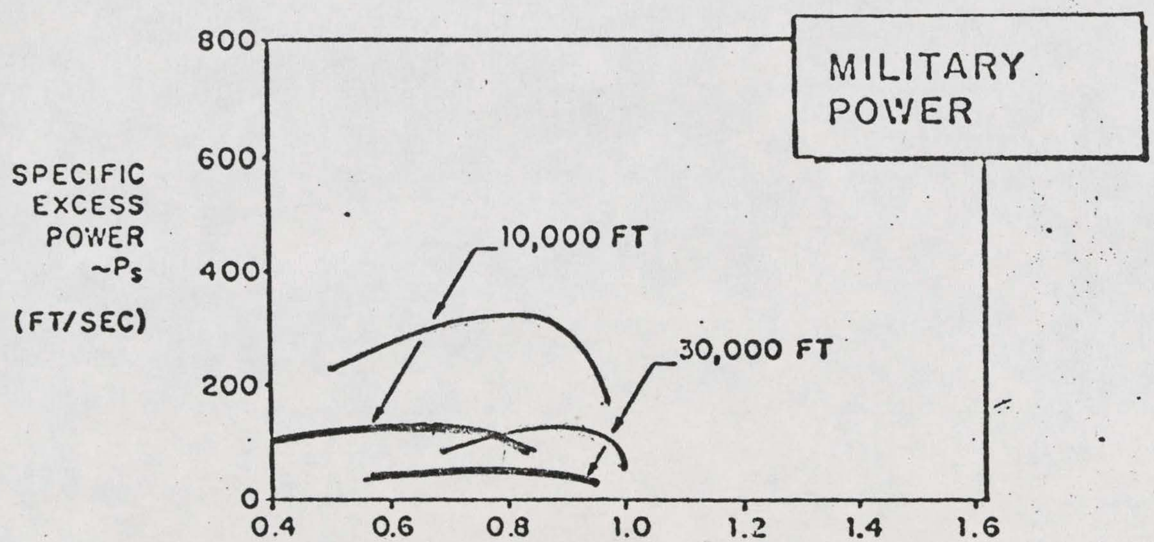


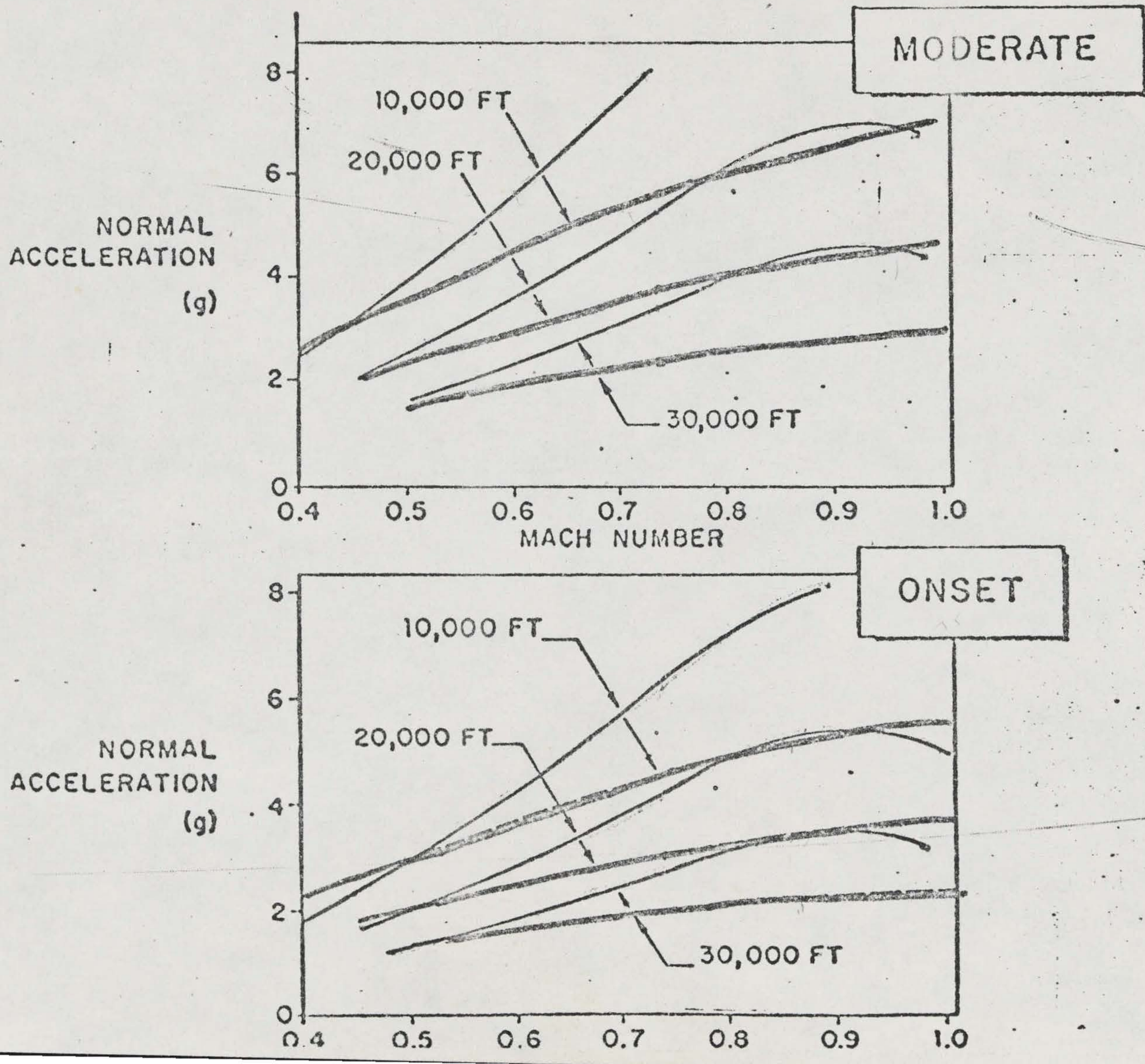
CHART NC. (5)

SPECIFIC EXCESS POWER

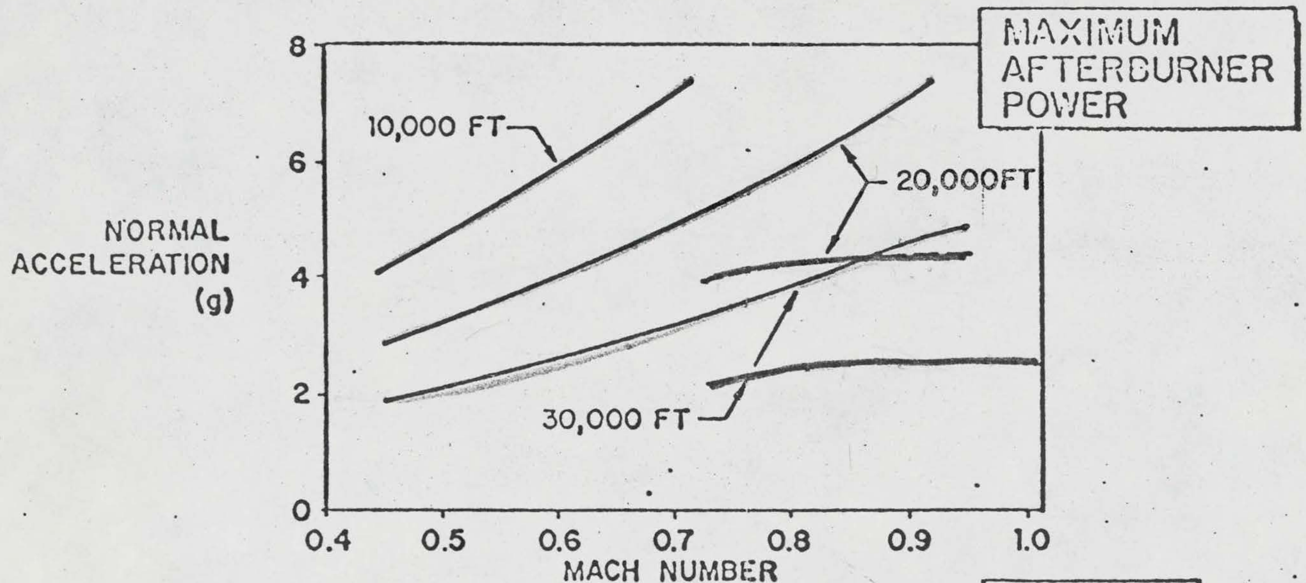


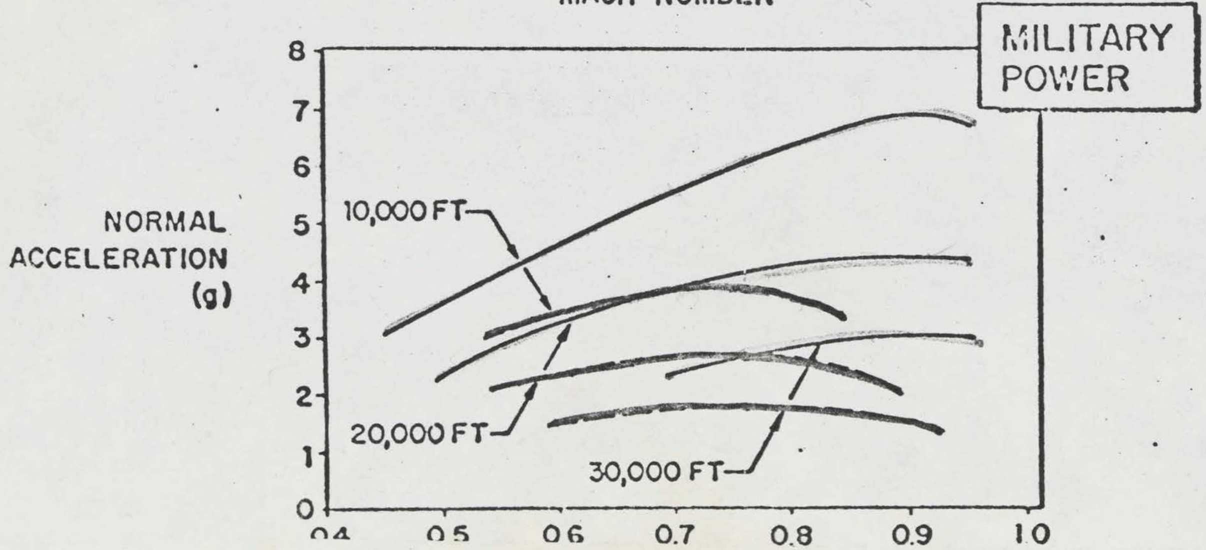


BUFFET BOUNDARY



THRUST LIMITED TURNING PERFORMANCE





SPECIFIC EXCESS POWER

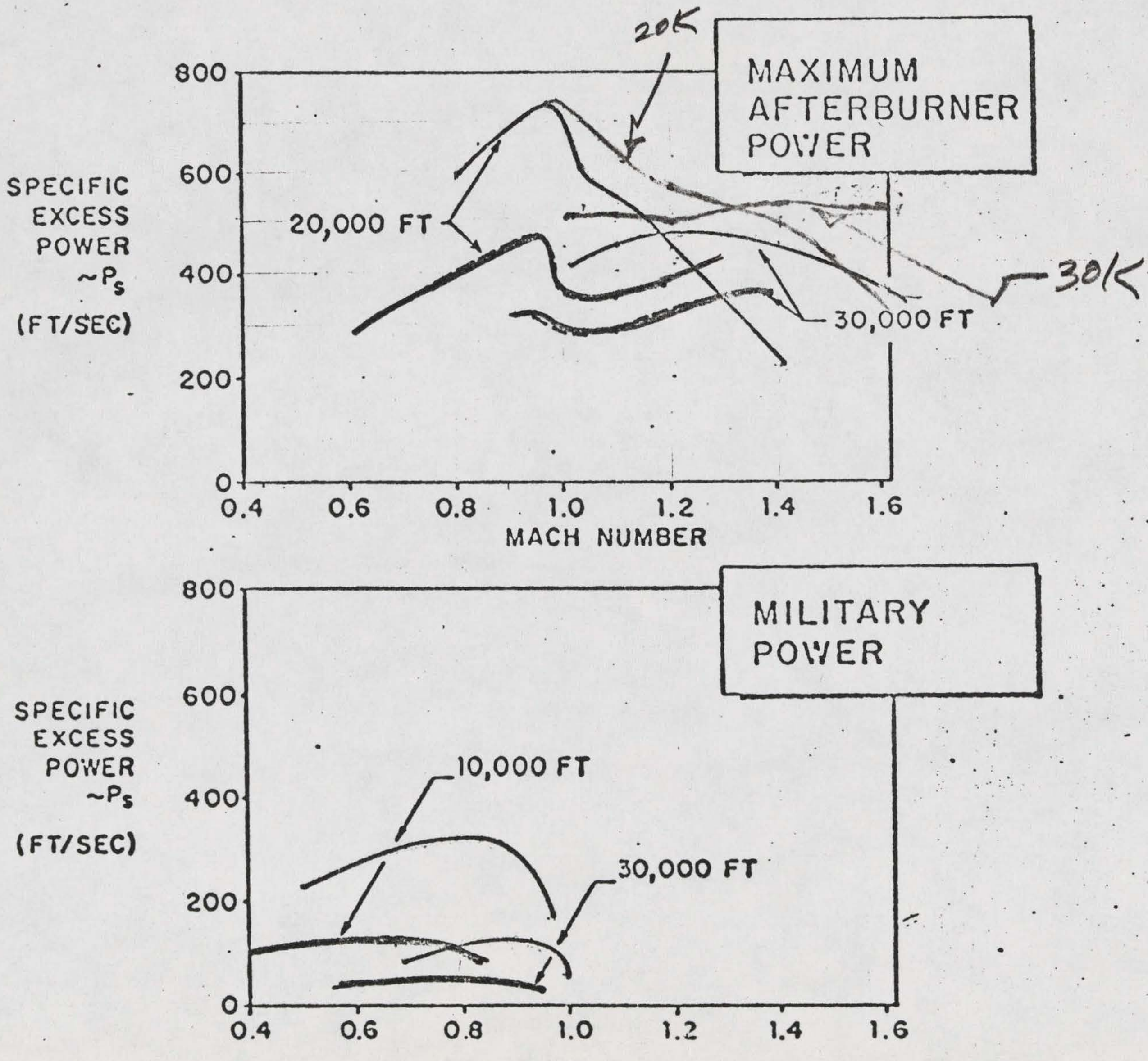


CHART NO. (5)

SPECIFIC EXCESS POWER