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- A Method of Evaluating Air Combat Performance Effectiveness

Aerodynamics and Performance Branch
Flight Technology Division

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ABSTRACT

An Improved Method for Combat Performance Analysis

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Existing airplane performance analysis methods provide insight to the design, analysis and operation of aircraft used in air-to-air combat by describing the ability to turn, climb and accelerate and by locating optimum regions of such in the flight envelope.

Better definition is needed, however, of the relative value and interrelationship between typical EM parameters such as excess power, turn rate and combat time available as they influence air battle engagement results.

A simple mathematical model is developed that accounts for the combat relationship of all airplane performance parameters relative to those of a potential adversary. This innovative concept eliminates the need to subjectively weigh each aspect of the relative performance individually and, for the first time, indicates in definite and practical terms the amount of advantage or disadvantage that exists in a combat situation. The result is a better tool with which to conduct design trade studies and plan tactics. Application is made to current and future fighter aircraft designs.

TABLE OF CONTENTS

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FOREWORD

This paper has been prepared in an effort to provide a more enlightened point of view from which to judge and evaluate aircraft performance in an air-to-air role. Very valuable and expert consultation was provided by Mr. William Imfeld, ENFTA, Aeronautical Systems Division, and expert and patient typing excellence provided by Mrs. Rebecca M. Pfeiffenberger.

ABBREVIATIONS AND SYMBOLS

CPA	Combat Performance Advantage
E_s	Specific energy, $\frac{\text{ft-lb}}{\text{lb}}$, or ft
N_z	Normal load factor, g's
P_s	Time derivative of E_s, ft/sec
P'_{sA}	P_s of Airplane A at total turn rate of B ($\dot{\theta}_{T_B}$), ft/sec
t_a	Time available for combat of Airplane #1 given return fuel required, sec
t_c	Sum of t_E and t_θ; total time to advantage, sec
t_E	Time needed by A after angular conversion to reach opponent's (B) E_s, at opponent's total turn rate, sec
t_θ	Time needed to convert difference in heading angle to zero, sec
$\dot{W}_{fuel}$	Fuel flow rate of Airplane 1 at combat power setting, lb/sec
θ	Direction of velocity vector, i.e., heading angle, deg
$\dot{\theta}$	Time derivative of θ, deg/sec
$\dot{\theta}'_{I_A}$	Maximum instantaneous turn rate such that $\dot{\theta}_{T_A} = \dot{\theta}_{T_B}$

SUBSCRIPTS

A	The airplane (either #1 or #2) with the greater average turn rate (instantaneous and sustained)
B	The airplane with lesser $\dot{\theta}_T$
A/B	A relative to B
f	Final value
I	Referring to maximum instantaneous capability
0	Initial value
S	Referring to maximum sustained (thrust = drag) capability except when used with P_s and E_s
T	Referring to the average of instantaneous and sustained
θ	Referring to heading angle or heading angle change

SUMMARY

Existing airplane performance analysis methods provide insight to the design, analysis and operation of aircraft used in air-to-air combat by describing the ability to turn, climb and accelerate and by locating optimum regions of such in the flight envelope.

Better definition is needed, however, of the relative value and interrelationship between typical Energy Maneuverability (EM) parameters such as excess power, turn rate and combat time available as they influence air battle engagement results.

A simple mathematical model ~~is~~ was developed ~~here~~ that accounts for the combat relationship of all airplane performance parameters relative to those of a potential adversary. An important outcome of this study is definition of an optimum load factor to be used for offensive tracking and pursuit to reduce time needed to achieve advantage, thereby increasing combat effectivity. The importance of not merely high-g capability, but sustained high-g capability, can be more objectively evaluated. This innovative concept eliminates the need to subjectively weigh each aspect of the relative performance individually and for the first time, indicates in definite and practical terms the advantages or disadvantages that exist in a combat situation between opposing aircraft.

A comparison is made with aerial combat simulation models used for operational analyses. The result is a better tool with which to plan tactics and conduct total system design trade studies as influenced by airplane performance. Application is made to current and future fighter aircraft designs.

SECTION I

INTRODUCTION

A well-balanced fighter aircraft design should uniquely combine systems performance, weapons performance and vehicle performance in a total package. Good characteristics of each offers the user greater versatility in applying tactics.

Systems performance dictates the ability to detect and track targets (radar, for example), the ability to evade being tracked by the opponent (electronic countermeasures, reduced observables) and determines the general operability of the entire aircraft weapon system.

Weapon performance determines the lethality of the missile, rocket and/or gun projectile that is intended to actually destroy the target.

Vehicle performance is necessary to carry the weapons to the point of battle, achieve some attack position and establish an optimum set of delivery criteria. The aircraft must also use its performance to reposition itself sufficiently for successive re-attacks and still have sufficient fuel left to return to base.

The absence of any of these qualities is unacceptable and they therefore form a design triangle whose sides have to be well balanced and offer some advantages over the corresponding characteristics of the air-to-air opponent.

There is, of course, a special relationship between the weapons performance and the vehicle performance: between the two, the ordnance must be brought to bear on the target. The two extremes are the simple gun that more or less shoots where it is pointed and the sophisticated, all aspect, launch and leave missile that does all the final maneuvering itself. But even with an ideal weapon, tactics are narrowly constrained without adequate vehicle performance, and reaching optimum weapon delivery criteria and maintaining a good defensive situation relative to an opponent may be impossible.

Recognizing the above hypothesis but noting that in the real world, tactics and numerical advantages can render relative vehicle capability academic, we nonetheless desire to focus attention here on only the vehicle performance side of the triangle in an attempt to define what constitutes a relative performance advantage in aerial combat. Thus, the main thrust is not toward the operations analysis or total systems studies, but toward the vehicle performance problem.

SECTION II

BACKGROUND OF AIR COMBAT PERFORMANCE

Without actual flight testing, air battle engagements of expensive, hopelessly complex operational analysis simulations, relating measurable engineering quantities and their interrelationships to actual combat outcomes has been an undefined and very subjective art.

Methods previously applied to the design, development and employment of tactical combat aircraft - such as the Energy Maneuverability (EM) concept - have added much insight to the performance parameters that are important in obtaining advantage in air combat. However, these tools fail in providing two important things:

a. EM does not address a probable battle outcome and thus the real meaning and significance of an advantage - e.g., P_s, given two aircraft that are equal in other respects, and no mention is made of the absolute minimum total performance necessary to engage an opponent.

b. The systematic interrelationship between all performance items (P_s, turn rate and persistence) is not accounted for. The advantage of extra fuel in a battle versus its weight penalty cannot be well determined.

The objective, then is to develop an analysis and design tool that considers the total relative performance of two adversary aircraft and that will define and quantify any resulting advantage. Once this is determined, the value of other desired combat features (avionics, ECM, fire/flight control, survivability, etc.) can be evaluated from a more advantageous, although still subjective, viewpoint.

SECTION III

DEVELOPMENT OF COMBAT PARAMETER

The fundamental objective of an air-to-air battle is to reach an opportunity to fire a weapon at an opponent. With an ultimate weapon that required no aiming or consideration of position or relative motion, and with complete reliability, the need for superior airplane maneuvering performance would be minimized. But even with all-aspect air-to-air missile capability, the attacker must satisfy some firing envelope criteria by maneuvering his airplane relative to the opponent. The greater success in reaching an optimum firing envelope, the greater the probability of kill of any weapon. The less capable a weapon delivery system is, the more valued the relative performance becomes since the airplane must be used to put the weapon in a position to be fired. Repositioning and maintaining altitude and airspeed for subsequent attacks, the ability to keep vulnerable areas away from the opponent, and defensive disengagement all require some minimum level of persistence, agility and acceleration.

Being directly behind an opponent at zero relative motion is the <u>best</u> situation to accomplish the <u>dual</u> objective of making the opponent most defenseless while simultaneously making the attacker least vulnerable. Of course, this is not necessarily required for a successful attack as evidenced by many actual air-to-air combat encounters. This criteria, however, is judged to be the most demanding for evaluating the aircraft performance dimension of air-to-air combat, and should therefore be the basis for a combat parameter aimed at that facet of the overall air-to-air superiority picture.

Starting from the neutral initial conditions of a head-on encounter at the same altitude and airspeed, it is obvious that a turning engagement is necessary to reach the desired firing opportunity. We first wish to determine which airplane will have the advantage in such an engagement and how long it takes to obtain the advantage.

An ideal fighter aircraft should not only be able to turn faster in order to gain an angular advantage, but should be capable of doing so without an undesired loss of altitude and airspeed relative to his opponent in the process. For aircraft capable of large flight envelopes in which the extremes of the energy states can vary widely - such as high speed jet fighter aircraft - the result of losing energy from the high extreme to the low in a hard turn can mean widely varying translational distances between opponents. An airplane with a very high maximum turn rate may be able to achieve an angular advantage, but if it ends up 300 knots slower and 10,000 feet lower than its opponent - and thus still perhaps unable to fire weapons - a true advantage does not exist.

The relationship, then, between the ability to turn and the associated rate of energy change is and should be one of the fundamental design concerns of tactical aircraft. As a result, it would be desirable to quantify this relationship in a manner consistent with the above stated initial conditions and objectives. This can be done by considering the necessary time needed to complete each combat task in an attempt to gain a conversion or advantage.

As stated above, turning maneuvers in an engagement result from an offensive player desiring to narrow the difference in velocity vectors with his opponent or, as a corollary, the defensive player wishing to enlarge this difference. If we assume both players are initially offensive, desirous of advantage, but start from even conditions of non-advantage, the time, t_θ, necessary for narrowing the difference in the direction of the velocity vectors to zero is simply the angular difference of the vectors divided by the average rate of closure.

Any penalties associated with maintaining a superior turn capability during the time t_θ can be expressed in terms of the time, t_E, necessary to regain any lost energy - relative to the opponent - while just maintaining the angular advantage gained (i.e., equal turn rates for both aircraft while regaining energy).

The total time needed for transformation of conditions of neutrality to complete advantage is the sum of the above items,

$$t_C = t_\theta + t_E. \qquad \text{eq 1}$$

The time to accomplish the angular conversion, t_θ, may be reduced if an increase in the maneuvering load factor can be obtained. This, of course, is paid for with increased induced drag and a more unfavorable energy rate relative to the opponent, thereby forcing t_E larger:

$$t_E = f[{}^1/t_\theta] \qquad \text{eq 2}$$

The definite relationship between t_θ and t_E suggests that the minimum convergence time, t_c, does not necessarily occur when t_θ is minimum, but perhaps at a larger value to obtain a lower t_E such that the sum of the two, t_c, is minimum.

If we know the minimum time necessary for a superior airplane to obtain an advantage and thus an optimum firing opportunity, the next step is to determine if this time is available as constrained by fuel requirements. The fuel and thus the time available for combat - the persistence - depends on the requirements of the other mission legs, including how far from the operating base the combat takes place. The efficiency at which this fuel is burned at the combat power setting depends on the engine characteristics and the Mach/altitude condition.

In the analysis being developed here, the goal is to determine the performance capability of the subject airplane design (noted as Airplane #1) against a fixed, known threat (noted as Airplane #2). With this in mind and in order to do meaningful trade studies of variable mission range, engine characteristics, etc., the time available for combat will be determined solely from the Airplane #1 characteristics and its mission scenario.

The combat fuel available at the start of a combat engagement is the fuel on board minus that needed to return to base with sufficient reserves. It is therefore a function of cruise efficiency, loiter fuel flow, the distance from the home base, and as discussed later, fuel required to accelerate or climb if the combat Mach and altitude are at a higher energy state than the outbound cruise or pre-engagement loiter condition. The time available over the engagement energy spectrum is:

$$t_a = \frac{\text{Fuel Quantity for Combat}}{\text{Average Fuel Flow at Combat}} \qquad \text{eq 3}$$

Having identified the time required for accomplishing an advantage or a conversion, t_c, and the time available, t_a, all aspects of the performance of the two-airplane system are considered. Through a comparison of t_a to t_c an important relationship surfaces that weighs all the variables together in a logical manner. The ratio of t_a to t_c implies a degree of effectiveness of our subject airplane in terms of its performance advantage (or disadvantage). This will be defined as the Combat Performance Advantage, CPA.

$$\text{CPA} = \frac{\text{Combat time available}}{\text{Conversion time required}} = \frac{t_a}{t_c} \qquad \text{eq 4}$$

1. DETAILED EVALUATION

In an actual air battle engagement, the airspeed and altitude of each opponent is continuously and perhaps independently changing, reflecting not only the performance characteristics of the airplanes, but the human decision logic and tactics of the pilots. In order to evaluate the terms of eq 4 which are certainly dependent on the Mach/altitude trajectories, a complex flight path integration scheme involving differential tactics would be necessary and many assumptions would be required. This would be evaluated between the initial and final energy states. Although several air battle schemes and computer routines have been developed to model actual engagements - and supposedly with some success and usefulness - they are perhaps too broad in scope, complicated and assumption dependent to reach the objective stated here.

To conveniently avoid this and to develop a tool that is a logical extension of the Energy Maneuverability concept, CPA will be evaluated at fixed values of Mach and altitude. This altitude and Mach number will be treated as independent variables throughout the common flight envelope with CPA plotted as constant-valued contours.

This approach allows the time available in eq 4 to be determined from simply dividing the combat fuel available at the given range by the fuel flow rate at the subject flight conditions:

$$t_a = \frac{\text{fuel (range)}}{\dot{W}_f \text{ (Mn, altitude)}} \qquad \text{eq 5}$$

The maneuvering capability of aircraft is generally characterized by that turn performance limited by the lesser of the load factor resulting from the maximum aerodynamic lifting ability and the maximum structural load factor allowable. The airplane drag associated with maneuvering at this turn rate, $\dot{\theta}_I$, is generally greater than the thrust available, and energy losses - airspeed and/or altitude - must occur at the rate, $P_{s_{\dot{\theta}_I}}$.

By adjusting the maneuvering load factor such that the resulting drag equals the thrust available no losses need occur. This defines the sustained turn rate, $\dot{\theta}_S$.

Actual maneuvering is done in three dimensions and can be performed at any combination of the above rates. To arrive at a parameter that measures the relative quality of turning of opponent airplanes, the average of each airplane's maximum instantaneous and maximum sustained level altitude turn rates will be defined as the total effective turn capability, $\dot{\theta}_T$.

$$\therefore \quad \dot{\theta}_T = \frac{\dot{\theta}_s + \dot{\theta}_I}{2} \qquad \text{eq 6}$$

The time, t_θ, necessary to perform an angular conversion from the initial angle-off to that desired is

$$t_\theta = \frac{\Delta\theta}{(\dot{\theta}_{T_1} - \dot{\theta}_{T_2})} = \frac{\Delta\theta}{\left[\frac{(\dot{\theta}_s + \dot{\theta}_I)_1}{2} - \frac{(\dot{\theta}_s + \theta_I)_2}{2}\right]} \qquad \text{eq 7}$$

Thus for each airplane, half the time t_θ will be at maximum instantaneous turn rate and half at maximum sustained.

To evaluate t_E which is a result of the $\dot{\theta}_I$ component, the energy rate,

$P_{s_{\dot{\theta}_I}}$, must be known at the maximum instantaneous load factor for each aircraft. The relative energy loss is

$$\Delta E_{s_{\text{loss } A/B}} = (\text{time at } \dot{\theta}_I) \times (P_{s_{\dot{\theta}_{I_B}}} - P_{s_{\dot{\theta}_{I_A}}}) \qquad \text{eq 8}$$

where Aircraft "A" and "B" are determined by the sign of t_θ ((+): A = #1, B = #2; (-): B = #1, A = #2). The time at $\dot{\theta}_I$ is one-half t_θ since the average of sustained and maximum was used for t_θ computation.

If the opponent with the higher average turn rate, "A," is to meet the total conversion and criteria of enclosing the angular difference which takes the time t_θ, and also being at the same final energy state, $\Delta E_{s_{\text{loss}_{A/B}}}$ must be regained while "A" is turning at the same average rate as "B." This will maintain the advantage gained during the time, t_θ, while also equalizing the energy states. The time rate at which the relative loss can be regained is

$$\frac{d}{dt}\left(\Delta E_{s_{\text{loss } A/B}}\right) = \frac{P'_{s_A} - P_{s_{\dot{\theta}_{I_B}}}}{2} \qquad \text{eq 9}$$

where P'_{s_A} is the energy rate associated with the value of maximum instantaneous turn rate, $\dot{\theta}'_{I_A}$, necessary to maintain the same <u>average</u> rate as B.

$$\text{i.e., } \frac{\dot{\theta}'_{I_A} + \dot{\theta}_{s_A}}{2} = \frac{\dot{\theta}_{I_B} + \dot{\theta}_{s_B}}{2} \qquad \text{eq 10}$$

The energy rate values in eq 9 are divided by 2 since $\dot{\theta}'_I$ and $\dot{\theta}_{I_B}$ (and, therefore, P'_{s_A} and $P_{s_{\dot{\theta}_{I_B}}}$) occur only half as often as $\dot{\theta}'_{T_A}$ and $\dot{\theta}_{T_B}$.

Therefore,

$$t_E = \frac{\Delta E_{s_{\text{loss } A/B}}}{\frac{d}{dt}\left(\Delta E_{s_{\text{loss } A/B}}\right)} = \pm \frac{\frac{t_\theta}{2}\left[P_{s_{\dot{\theta}_{I_B}}} - P_{s_{\dot{\theta}_{I_A}}}\right]}{\left[\dfrac{P'_{s_A} - P_{s_{\dot{\theta}_{I_B}}}}{2}\right]}$$

from which eq 11

$$= \frac{t_\theta\left[P_{s_{\dot{\theta}_{I_B}}} - P_{s_{\dot{\theta}_{I_A}}}\right]}{\left[P'_{s_A} - P_{s_{\dot{\theta}_{I_B}}}\right]}$$

Certain conditions apply to the evaluation of this equation. They are:

(1) This term, t_E, is set to zero if, instead of losing energy during t_θ, "A" actually gains energy relative to "B" ($P_{s_{\dot{\theta}_{I_A}}} > P_{s_{\dot{\theta}_{I_B}}}$). Thus, no attempt is made to quantify the additional advantage of gaining energy relative to an opponent while also out-turning him.

(2) If P'_{s_A} is algebraically less than $P_{s_{\dot{\theta}_{I_B}}}$, the lost energy cannot be regained and t_E is set to infinity.

(3) The sign of the term, t_E, takes on that of t_θ as the result of (1) and (2) above.

Only if Airplane "A" can accomplish both tasks defined by t_θ and t_E does it have an edge and only if the sum of those times is less than t_a does a true and complete performance advantage exist.

As mentioned before, t_c can be minimized by reducing the maximum turning load factor in certain situations, thereby decreasing the energy loss which in turn decreases t_E. Investigation has shown that the Airplane "A" maximum turning load factor optimizes at less than the maximum allowable only when there are large differences in the performance of the two opponents. This process assesses both the benefit and penalty of using high load factor turning and identifies the optimum.

In a similar manner, the CPA can be further increased by optimizing the combat power setting for the subject aircraft. Provided that a positive, finite value of t_c can be maintained as thrust is reduced, the variation in CPA can be studied for the maximum value resulting from the reduced fuel flow and, thus, the increased time available, t_a.

To better measure the effects of combat at various energy levels within the flight envelope, the time available term for the turning engagement must be modified to account for the acceleration to higher speeds and altitudes than those at the end of the outbound cruise conditions.

$$\therefore \quad t_a = \frac{\text{(Combat fuel - Accel/Climb fuel)}}{\dot{W}_f} \qquad \text{eq 12}$$

This places a premium on the ability to rapidly and efficiently accelerate at 1g conditions.

2. MEANING AND SIGNIFICANCE

Although CPA is analytically derived from a math model inferring the number of conversions possible, it would be foolhardy to think of it in such absolute terms. In more practical terms, it is to indicate a comparison of the total performance characteristics. The relative ability to make a conversion, not necessarily the actual number of conversions, is the role intended for CPA. The actual number of conversions or the number of enemy aircraft defeated is too strong a function of mostly unquantifiable parameters such as tactics and the battle scenario, which are exactly the things from which we want to isolate the problem. Thus, the characteristics of the CPA model infers a "conversion efficiency," indicating the design balance of fuel, fuel flow, thrust and drag as they apply to the intended role - superiority over the threat.

If CPA is negative, of course the adversary definitely has the performance advantage. If CPA is between zero and one, either insufficient fuel is available for the existing turn advantage or much time must be spent regaining lost energy relative to the adversary. A value of unity implies the capability to make only one conversion within the time available; more realistically, this would serve as a boundary value below which a conversion is very unlikely. Of course, the greater the ideal number of conversions available, the higher the probability of successfully firing missiles or guns, or engaging additional opponents. The significance of CPA value is summarized in Table 1.

Attempts at correlating CPA results with complex air battle engagement effectiveness models have shown that, when differences in opponent vehicle performance were the items of concern, the same conclusions can be made. While typical operations analyses terms such as Exchange Ratio (ER) and Probability of Kill (P_k) and other various measures of merit such as Advantage Ratio (AR) do not usually consider the fuel or the persistence ability versus combat radii, they are somewhat sensitive to energy management and maneuverability (but *they are also sensitive to scenario* tactics, weapon characteristics, etc., which can only mask the results). Comparisons of CPA analyses to recently published results of a classified study of the same basic data yields the following interesting set of data:

	Exchange Ratio ER	Advantage Ratio AR	Combat Performance Advantage CPA
Case 1:	1.58	1.58	1.75
Case 2:	6.14	11.64	8.64

In Case 1, the engagements were between opponents whose only difference was performance, thus dampening effects of armament and tactics, etc. (considered by the Exchange Ratio analyses), and probably accounting for the very close agreement.

While the fundamental physical meaning and derivation of each of these measures of merit is completely different, the trends exhibited, the degrees of implied effectiveness, and the general sensitivities conveyed are very similar. The Exchange Ratio and Advantage Ratio are products of statistical trends, regression analyses, and empirical correlation to manned simulations, as opposed to CPA being a theoretical physical relationship bounded by the fuel constraints of the various mission legs and the threshhold level of required maneuverability.

SECTION IV

APPLICATION

No one can predict the exact outcome of an air battle between aircraft that have never before engaged just as no one can predict the weather with any accuracy without first having examined past trends and their correspondence to existing conditions. But by careful observation and astute consideration of the variables, useful conclusions can be drawn as to the conditions which will enhance a desired outcome. Likewise, the trends exhibited by the CPA parameter throughout the probable air battle arena can be a definite indicator - as far as vehicle performance is concerned - of a fighter's ability to successfully engage an opponent.

To illustrate the features of CPA, consider the following characteristics of two aircraft in terms of propulsion, aerodynamics, weight and their corresponding Energy Maneuverability parameters: At M = 1.2, altitude = 30,000 ft, standard day:

	A/C #1		A/C #2
Minimum drag coefficient	0.0410		0.0255
Efficiency factor	0.96		0.93
Aspect ratio	3.2		2.0
Max structural load factor (Nz)	7.5	g's	7.5
Ref wing area	310	ft^2	265
Net propulsive force	14500	lbs	9700
Specific fuel consumption	2.3	lb/lb/hr	N/A
Combat gross weight	21000	lbs	18000
Combat fuel (Wt_{fuel})	3000	lbs	N/A

By using theoretical drag due to lift relationships, the resulting performance parameters are:

Thrust/weight ratio	0.69		0.54
Wing loading	67	lbs/ft^2	68
P_s (1 g)	353	ft/sec	344
P_s (7.5 g)	-377	ft/sec	-572
$\dot{\theta}_s$	7.98	deg/sec	6.08
$\dot{\theta}_l$	11.49	deg/sec	11.49
Persistence (# 360° P_s = 0 turns)	6.6		-- --

Inspection of the turn rates, P_s, etc., shows that A/C #1 is somewhat better, but gives little insight to the combat effectiveness that could result. More importantly, it is not clear whether more thrust, greater fuel fraction, less weight, or other variations would more efficiently improve the design. The benefits of these must be weighed, also the penalty.

Using a convergence angle, $\Delta\theta$, of 180 degrees, CPA calculation gives

$$t_a = \frac{3000 \text{ lbs} \times 3600 \frac{\text{sec}}{\text{hr}}}{(14500 \text{ lbs})\ (2.5 \text{ lb/lb/hr})} = 298 \text{ sec.}$$

$$t_\theta = \frac{180°}{\frac{(11.49 + 7.98)}{2} - \frac{(11.49 + 6.08)}{2}} = 189 \text{ sec.}$$

$$t_E = 0 \qquad (P_{s_{\theta_{I_1}}} > P_{s_{\theta_{I_2}}})$$

$$\text{CPA} = \frac{298}{189} = 1.58,$$

indicating that an uncompromised and meaningful performance advantage exists and showing the relative balance of fuel, fuel flow, turn rate, etc.

If we wish to consider a design change to strengthen the advantage, CPA can be used as a sensitivity yardstick. If the $N_{z \max}$ can be increased to 9 g's in order to reduce the convergence time, CPA could possibly be increased. But there is the penalty paid in terms of the greater energy bled off at 9 g's. And, assuming the same average combat gross weight, the higher "g" would perhaps also require more supporting structural weight, dictating a lower fuel fraction, i.e., less combat fuel. A rule of thumb design estimate of this weight would be 500 lbs.

Therefore,

$$t_a = \frac{(2500 \text{ lbs})\ (3600 \frac{\text{sec}}{\text{hr}}}{(14500 \text{ lbs})\ (2.5 \text{ lb/lb/hr})} = 248 \text{ sec}$$

$$t_\theta = \frac{180°}{\frac{(13.83 + 7.98)}{2} - \frac{(11.49 + 6.08)}{2}} = 85 \text{ sec}$$

The energy rate associated with 9 g's is -707 ft/sec which is algebraically less than that for A/C #2 at 7.5 g's. Therefore, t_E will have a non-zero value.

$$t_E = t_\theta \quad \frac{P_{s_{\dot{\theta}_{I_2}}} - P_{s_{\dot{\theta}_{I_1}}}}{P_{s_A} - P_{s_{\dot{\theta}_{I_2}}}} = 85 \text{ sec} \ \frac{[-572-(-707)]}{[-228-(-572)]}$$

$$t_E = 33 \text{ sec}$$

from equation 12.

$$\therefore \quad CPA = \frac{248}{85 + 33} = \frac{248}{118} = 2.10$$

The increase in CPA due to the 9 g's, therefore, shows a net benefit for this design change.

The relationship, then, of 2.10 to 1.58 forms our sensitivity analysis and the performance measure of merit trade study.

There remains the problem of evaluation of CPA and the behavior of fighter aircraft designs as a function of the altitude, Mach number spectrum. With a computer, CPA is calculated and plotted as iso-contours throughout the common envelope of opposing aircraft as in Figures 1 through 6. In this way, a picture is available of the performance situation. With the computer, all aspects of the aircraft can be described as they vary with Mach number, altitude, etc., and the optimization features employed for load factor and power setting.

Figures 1 and 2 show the slatted F-4E against a hypothetical adversary. Figure 1 limits the F-4E to 7 g max load factor and 9 g's is allowed in Figure 2. Notice that while the CPA is increased in the 9 g case, the useful improvement occurs only below 20,000 ft and between 0.6 and 1.0. In other areas of the envelope the 9 g's cannot be reached due to insufficient wing maximum lift. The areas of CPA = 0.5 in the first diagram are due to the slightly greater sustained turning of the F-4E with slats. The hard wing F-4E would exhibit negative CPA values here due to its one to two degrees per second less sustained turn rate. And it could not take as much advantage of the 9 g capability due to its even more restrictive max lift capabilities.

If one is willing to make some assumptions of a more or less arbitrary nature, useful games can be played that could have meaning in operations analyses or systems effectiveness studies. If an area of engagement is defined in terms of Mach number and altitude and some relative distribution and weighting system is assumed, CPA can in effect be integrated over the energy spectrum. Figures 3 and 4 illustrate a possible set of assumptions applied to the previous F-4E examples. A simple average of the nine points that define the air battle arena results in a single CPA value of 0.61 for the 7 g F-4E and 1.40 for the 9 g version. In this case, more data points were taken at the lower altitudes in the air battle arena illustrating how the assumptions could be tailored to fit observed results of manned simulations or to drive desired areas of required performance.

Against the same opponent, and with the same air battle arena assumptions, Figures 5 and 6 show the comparison of a hypothetical fighter airplane with the general performance expected in advanced aircraft, bearing out the fact that actual achievement of this level of capability could be a vast improvement over the F-4E as evidenced by the increased CPA values. In this example, the effect of increasing combat weight is shown. With constant combat fuel and mission radius, the 14% increase in weight decreases the CPA in the air battle arena from 7.24 to 5.26 (38%). From this, the penalty incurred by the extra weight can be weighed against whatever benefit it is to the design or to the overall mission success.

SECTION V

CONCLUSIONS

The benefits derived from knowing the Combat Performance Advantage of either an operational aircraft or a conceptual design should be clear. A picture depicting areas of advantage and disadvantage related to mission range/radii should be of use to the tactics planner. Close consideration of CPA in the preliminary design phase of a fighter aircraft can prevent over-design or under-design for its intended purpose. Modification of the mathematical model to suit the mission could, like a design mission profile, be devised to properly size the airplane and perform enlightening trade studies.

While the absolute maneuvering load factor capability of present manned fighter aircraft is probably reaching the limits of human useful operating tolerance, it is available over only a portion of the normal operating envelope, hence dictating the conditions at which air battles may typically occur, restricting the pilot's options. Moreover, the region where this high-g maneuvering can be sustained, i.e., with airspeed or altitude loss, is even more restricted, again limiting the operational utility. The CPA concept proposed here uniquely addresses these facts in conjunction with the total energy management of the one-on-one scenario, and it should be a powerful tool in their evaluation.

TABLE I

COMBAT PERFORMANCE ADVANTAGE (CPA) - MEANING AND SIGNIFICANCE

$CPA < 0$: Disadvantage, inferior capability

$CPA = 0$: No conversion possible; outcome determined by non-performance factors

$0 < CPA < 1$: No conversion possible within time constraint; fuel-range-maneuver imbalance

$CPA = 1$: One ideal conversion possible; only one optimum fire opportunity

$CPA > 1$: Definite advantage; superiority

F4ES VS 332A

CPA

PLOT PREPARED BY ASD/ENFTA 06/16/78

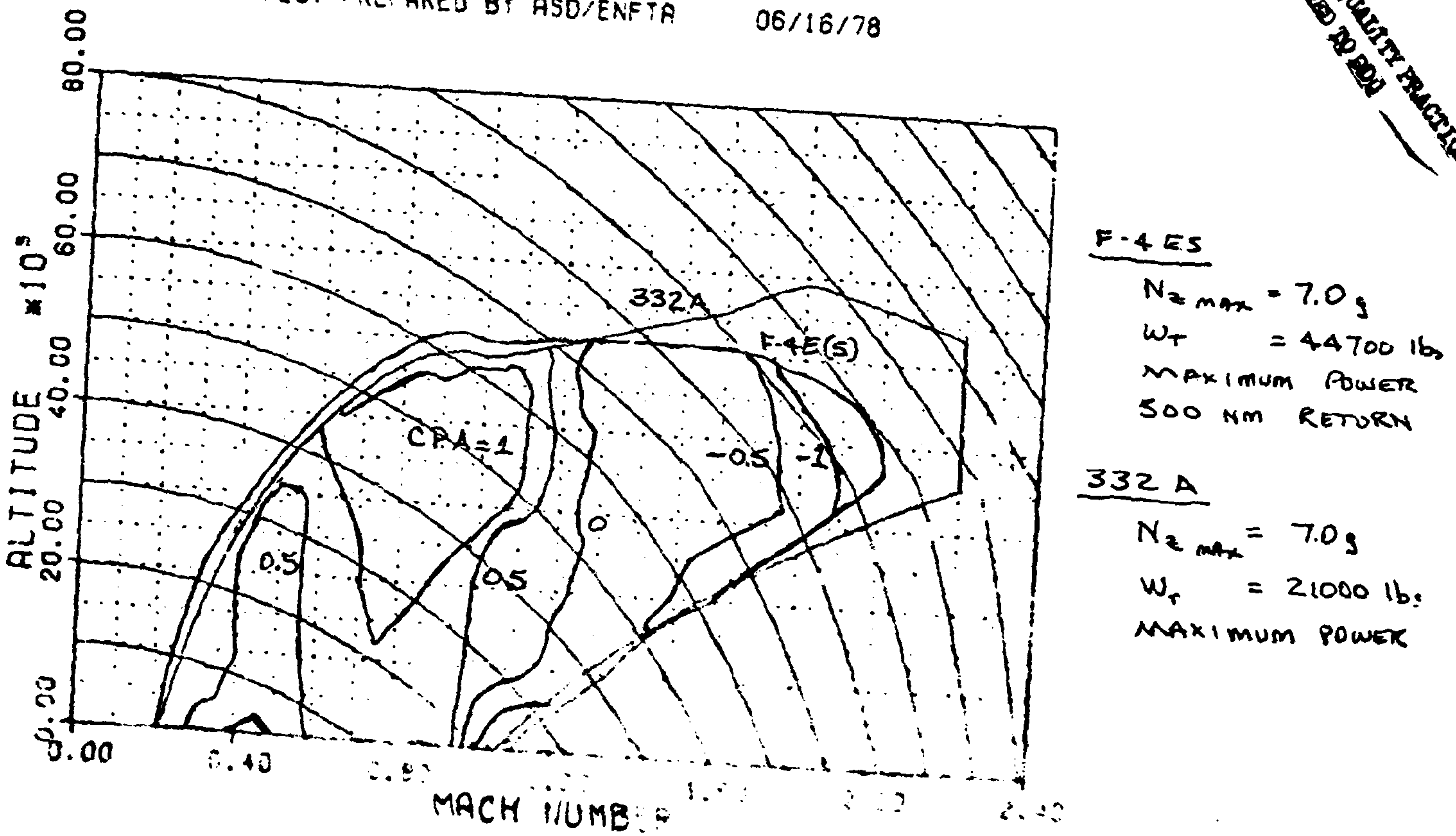
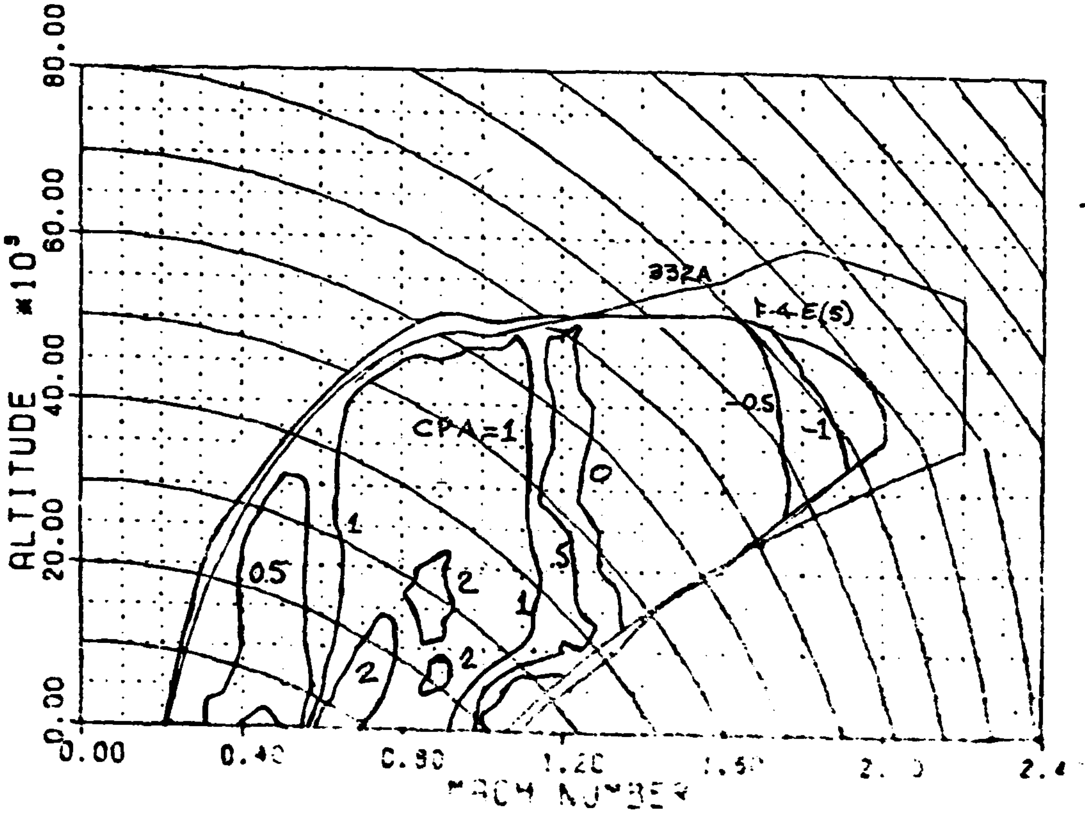


Figure 1

F4ES VS 332A

CPA

PLOT PREPARED BY ASD/ENFTA 06/16/78



F-4ES

$N_{z\,max}$ = 9.0 g

W_T = 44700 lbs

MAXIMUM POWER

500 NM RETURN

332A

$N_{z\,max}$ = 7.0 g

W_T = 21000 lbs

MAXIMUM POWER

Figure 2

F4ES VS 332A

CPA

PLOT PREPARED BY ASD/ENFTA 06/16/78

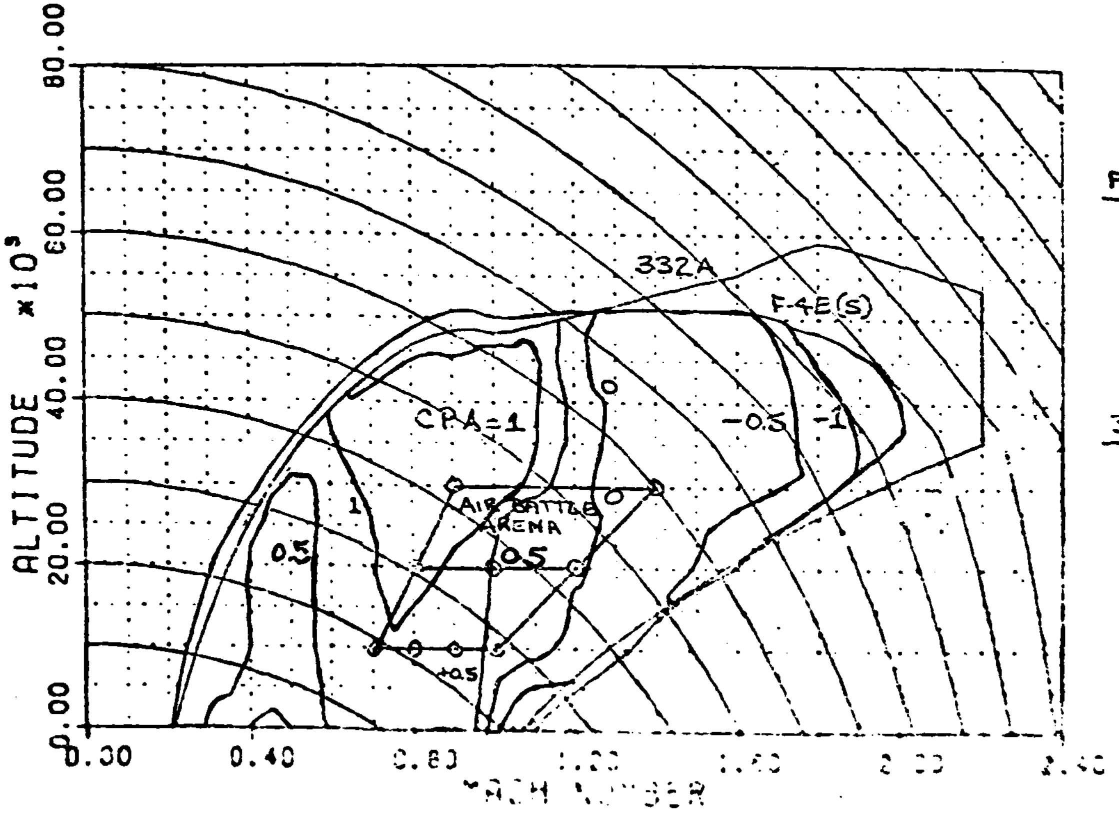


Figure 3

$\overline{CPA}_{\text{AIR BATTLE ARENA}} = +0.61$

F-4ES (+)

$N_{z\,max} = 7.0\,g$

$W_T = 44700$ lbs

MAXIMUM POWER

500 NM RETURN

332 A (−)

$N_{z\,max} = 7.0\,g$

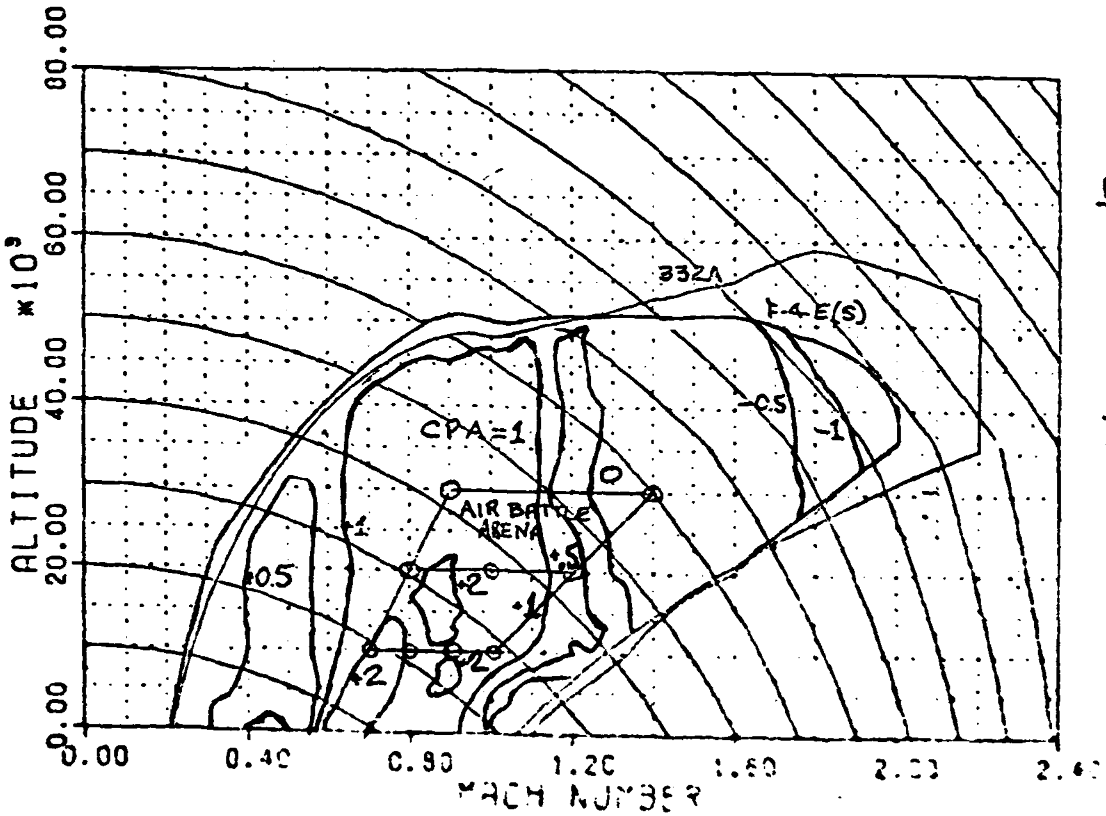
$W_T = 21000$ lbs

MAXIMUM POWER

F4ES VS 332A

CPA

PLOT PREPARED BY ASD/ENFTA 06/16/78



$\overline{CPA}_{\text{AIR BATTLE ARENA}} = +1.40$

F-4ES

$N_{z\,MAX} = 9.0$ g
W_T = 44700 lbs
MAXIMUM POWER
500 NM RETURN

332A

$N_{z\,MAX} = 7.0$ g
W_T = 21000 lbs
MAXIMUM POWER

Figure 4

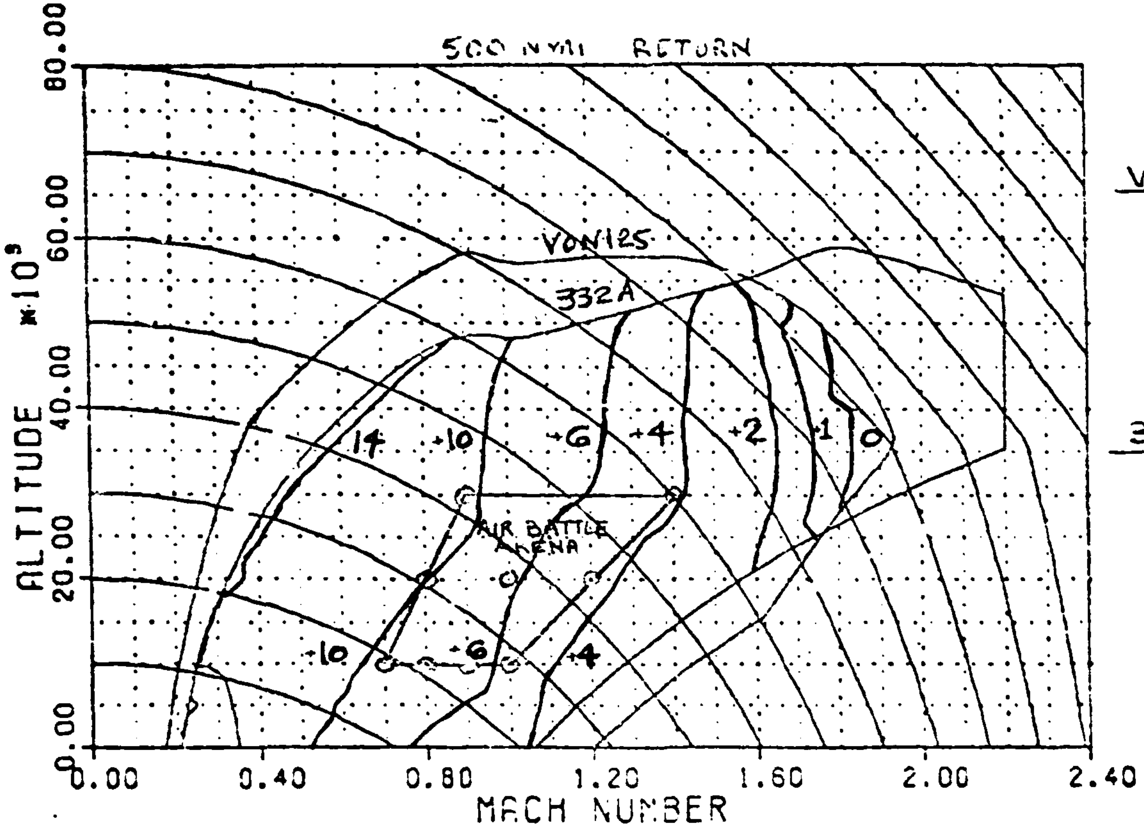
VON125 VS 332A

2-AIM 9 4-MISSILES

CPA-COMBAT PERFORMANCE ADVANTAGE

PLOT PREPARED BY ASD/ENFTA 04/26/78

$\overline{CPA}_{\text{AIR BATTLE ARENA}} = 7.24$



VON125 (+)

$N_{Z\,MAX}$ = 9.0g

W_T = 25000 lbs

MAXIMUM POWER

500 NMI RETURN

332A (−)

$N_{Z\,MAX}$ = 7.0g

W_T = 21000 lbs

MAXIMUM POWER

Figure 5

VON125 VS 332A

2-AIM9 4-MISSILES

CPA - COMBAT PERFORMANCE ADVANTAGE

PLOT PREPARED BY ASD/ENFTA 04/26/78

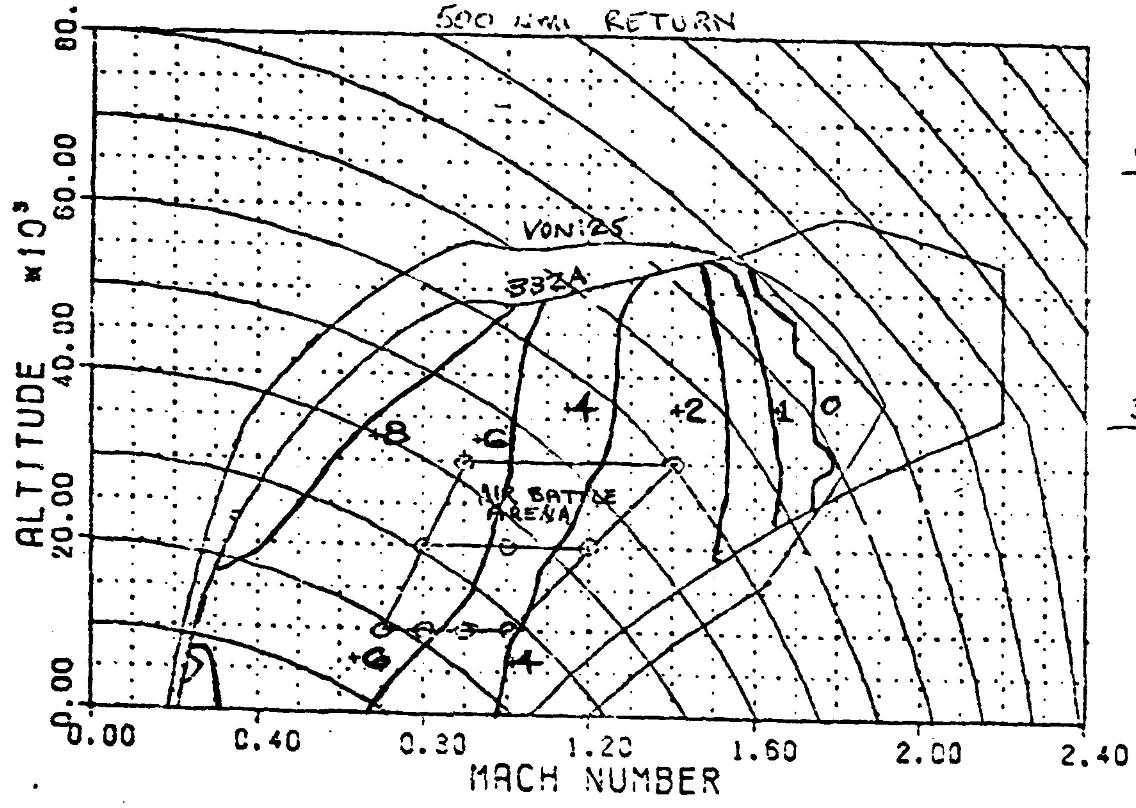


Figure 6

$\overline{CPA}_{\text{AIR BATTLE ARENA}} = 5.26$

VON125 (+)

$N_{Z_{MAX}} = 9.0g$

$W_T = 28500$ lbs

MAXIMUM POWER

500 NMI RETURN

332A (−)

$N_{Z_{MAX}} = 7.0g$

$W_T = 21000$ lbs

MAXIMUM POWER