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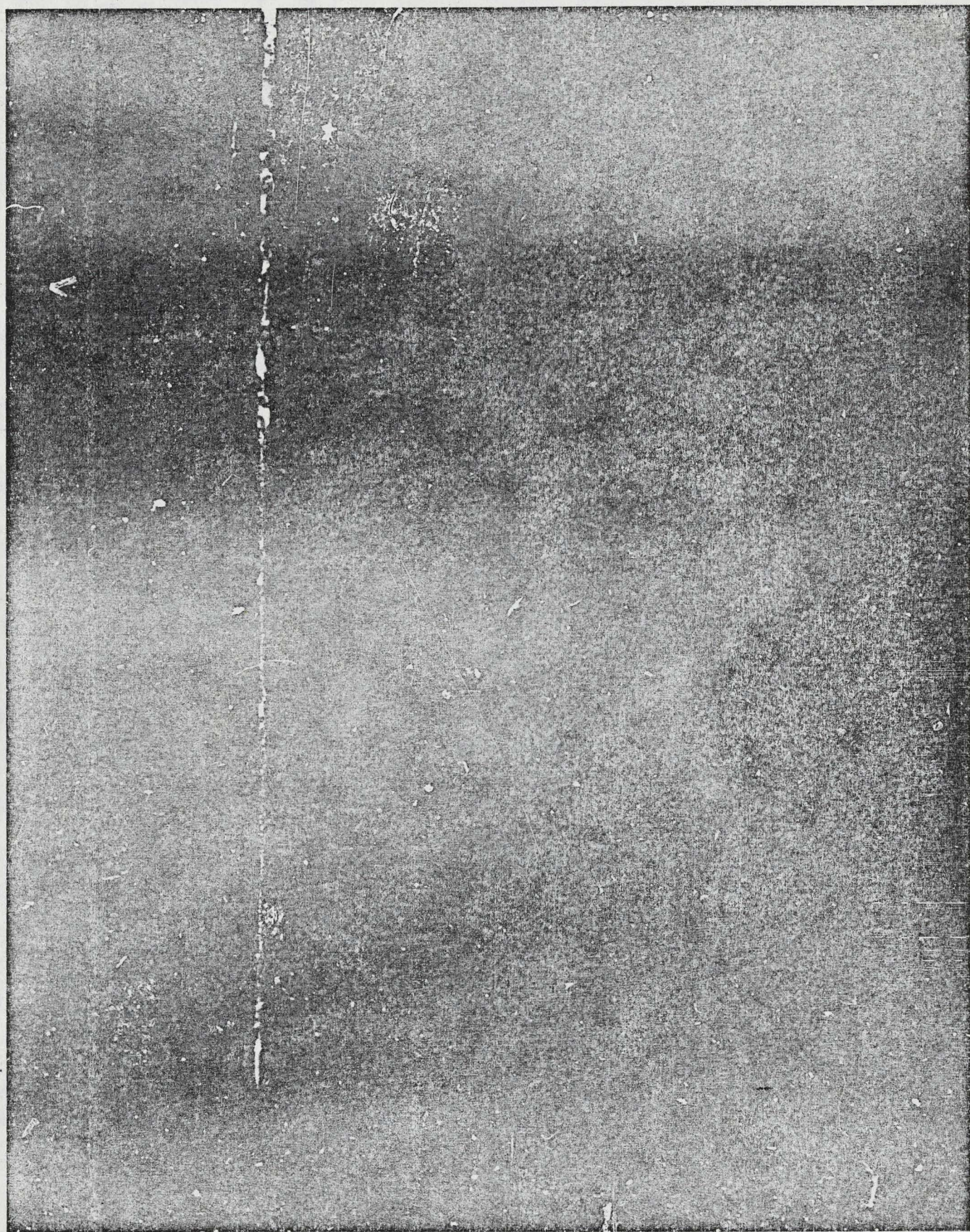
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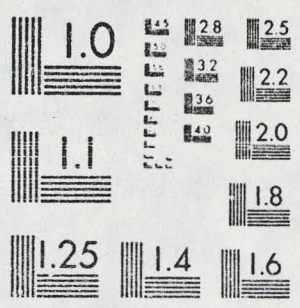
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AFATL-TR-72-116

AD 522272

MAXIMUM MANEUVER CONCEPT (U)

PROJECTILE, INCENDIARY, AND SELECTED SYSTEMS ANALYSIS
BRANCH
WEAPON SYSTEMS ANALYSIS DIVISION

TECHNICAL REPORT AFATL-TR-72-116

JUNE 1972

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Maximum Maneuver Concept (U)

John R. Boyd, Col, USAF

Thomas P. Christie

Robert E. Drabant, Capt, USAF

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FOREWORD

(U) This report presents the investigations conducted by the Air Force Armament Laboratory, Analysis Division (DLYD), in conjunction with Colonel John R. Boyd, Headquarters AFSC, in regard to the effect of advanced energy maneuverability concepts as they apply to tactics and design. This effort constitutes a portion of an overall investigation of aircraft performance which relates directly to air-to-air gun and missile methodology.

(U) This technical report has been reviewed and approved.

Thomas P. Christie
THOMAS P. CHRISTIE

Director, Analysis Division

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ABSTRACT

(U) The ideas developed in this report expand the energy maneuverability concept to provide a capability to describe aircraft performance in general and maneuverability in particular. Specifically, the report identifies the best region in which to change altitude, airspeed, and direction. Using these results, the concepts are applied tactically to develop a general maneuver strategy, show where the air battle should take place, and perform a comparative analysis. Finally, the concepts are related to the design of aircraft and how they can be used for configuration and performance selection.

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SECTION I

PURPOSE

(U) The purpose of this report is to show how the maximum maneuver concept can be used to devise a general maneuver strategy, define air battle arenas, perform comparative analyses, and develop new designs.

(U) In the air-to-air role, maneuverability is needed with superior weapons and electro-optical countermeasures to enable fighter aircraft to negate the threat posed by enemy aircraft as well as to gain a superior position to destroy that threat. Maneuverability can be defined as the ability to perform a change, or combination of changes, in altitude, airspeed, and direction. The key point relevant to this definition is that maneuverability is more than just the ability to change direction. The correctness and impact of this definition will become evident as it is applied and used for logical guidance in this report.

(U) In this report, the outline of the discussion is as follows. First, a theory is developed using a building block approach that builds simple and seemingly unrelated ideas into a conceptual structure with connecting threads of logic between these ideas. Next, the theory is applied tactically to: (1) devise a general maneuver strategy for out-maneuvering an air-to-air adversary; (2) define a combat relevant air battle arena; and (3) devise an orderly concise scheme for performing relevant comparative analyses. Finally, the theory is applied design-wise to show how superior configurations and performance can be developed for new fighters.

(U) Additional information pertaining to aircraft maneuverability can be found in References 1 to 3.

SECTION II

THEORY

A. CHANGING ALTITUDE AND AIRSPEED

(U) The building block approach will be used in discussing maneuverability as it relates to changing altitude and airspeed. The steady state envelope (Figure 1) of a contemporary fighter (F-4E) with four AIM-7 missiles can be used to show how slow, how high, or how fast the aircraft can go. The specific energy (E_s) contours curving downward from left to right show how altitude can be traded-off for airspeed (or vice versa) or how much energy must be added (lost) to increase (decrease) altitude, airspeed, or both.

(U) The ability to gain altitude and/or airspeed can be represented by embedding energy rate (P_s) contours within the flight envelope. As shown in Figure 2, these contours depict how quickly energy can be gained, or stated another way, how rapidly the F-4E can climb or accelerate or do both anywhere in the flight envelope. For example, at constant airspeed at Mach 0.9 and 10,000 feet, the F-4E can climb at 600 ft/sec. At this same point, the F-4E can perform a constant altitude acceleration by gaining specific energy at 600 ft/sec or by gaining airspeed at approximately 20 ft/sec².

$$a = P_s \frac{g}{v} = \frac{600 \text{ ft/sec} \times 32.2 \text{ ft/sec}^2}{970 \text{ ft/sec}} = 20 \text{ ft/sec}^2$$

(U) In addition, the approximate location of a best path for gaining energy in minimum time can be identified by finding the maximum energy rate at each specific energy level. The maximum energy rates are located at the points of tangency between the E_s and the P_s contours (Figure 3).

(U) One of the principal points to be derived from the energy climb charts is determining the energy rate available to change altitude and airspeed (energy) anywhere in the flight envelope. These charts can also be used to identify the optimum paths, or corridors, for changing altitude and airspeed in the least time.

B. CHANGING DIRECTION

(U) In addition to the changes in altitude and airspeed, a similar look at changing direction may show where turns should also be accomplished. Experience suggests the importance of maximum rate or minimum radius turns in order to change direction as quickly as possible. From an aerodynamic standpoint, the quickest or tightest turn, for any given altitude/airspeed combination, is performed at maximum useable lift. Maximum turn rates or minimum turn radii, at this lift, can be represented over the altitude/airspeed spectrum for any aircraft at any attitude.

STEADY STATE ENVELOPE - 1G

F-4E (U)
4 AIM-7 MISSILES

MAXIMUM THRUST

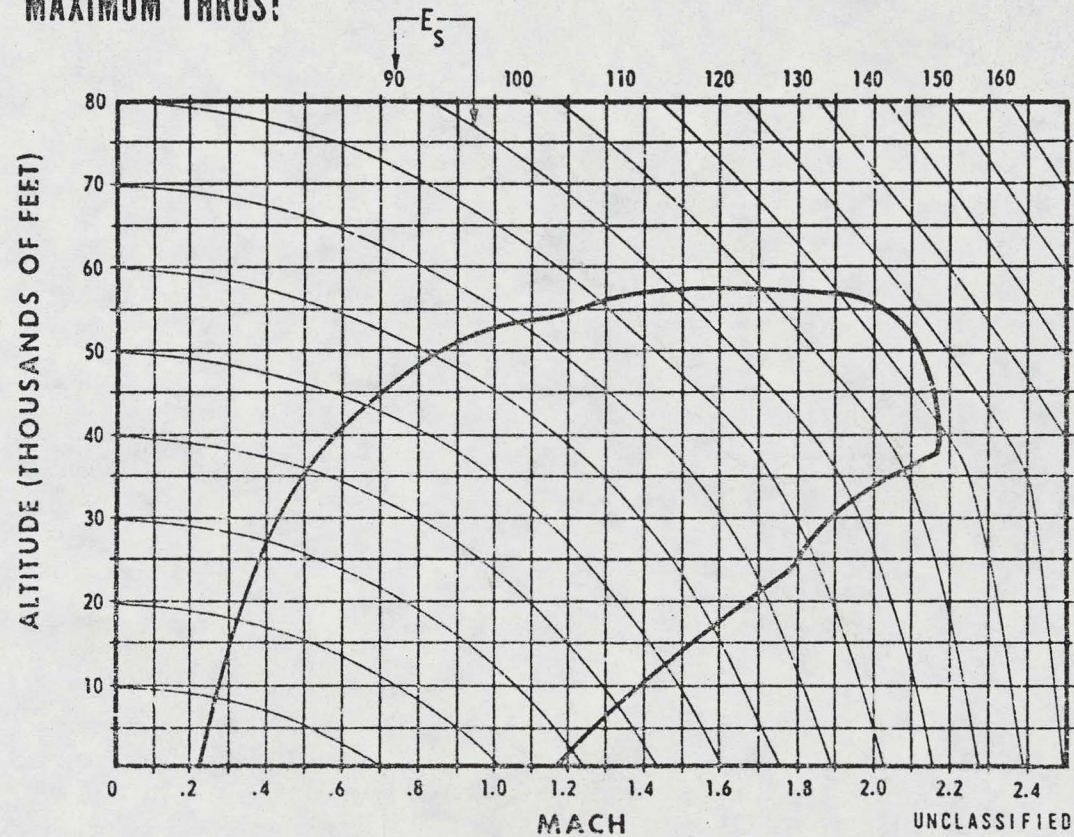


Figure 1. F-4E Steady State Envelope

ENERGY CLIMB - 1G

F-4E (U)
4 AIM-7 MISSILES

MAXIMUM THRUST E_s

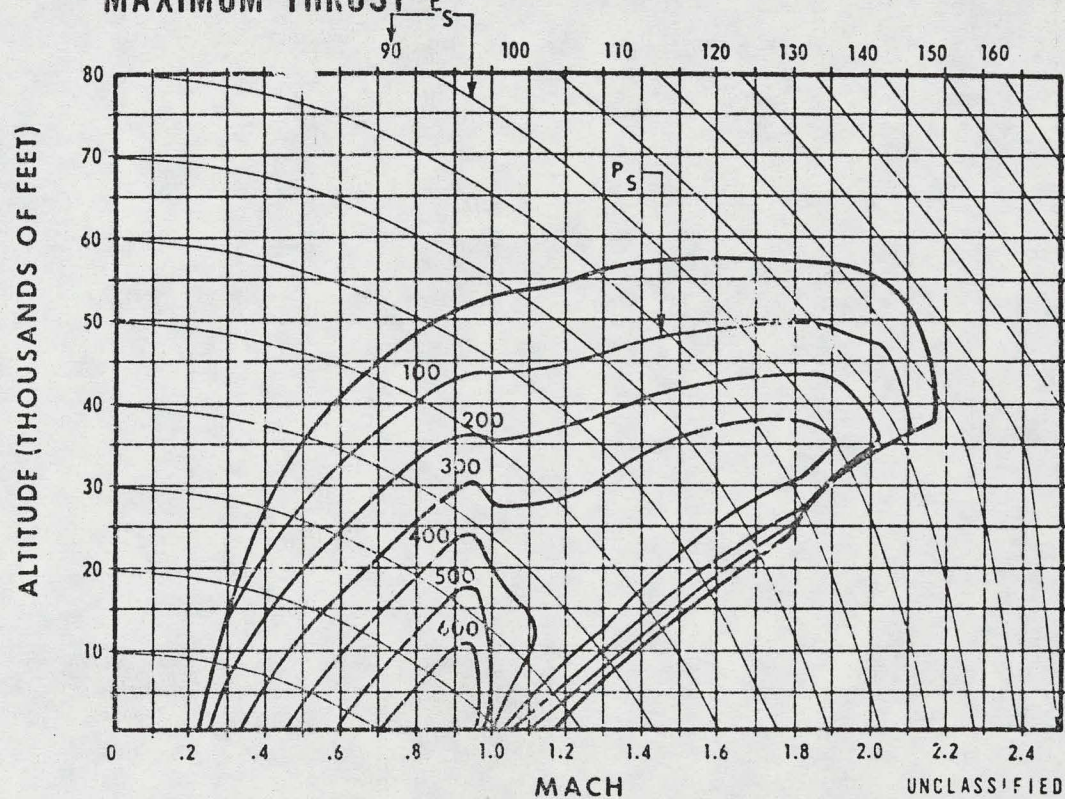


Figure 2. F-4E Energy Climb Diagram

ENERGY CLIMB - 1G

F-4E (U)

4 AIM-7 MISSILES

MAXIMUM THRUST

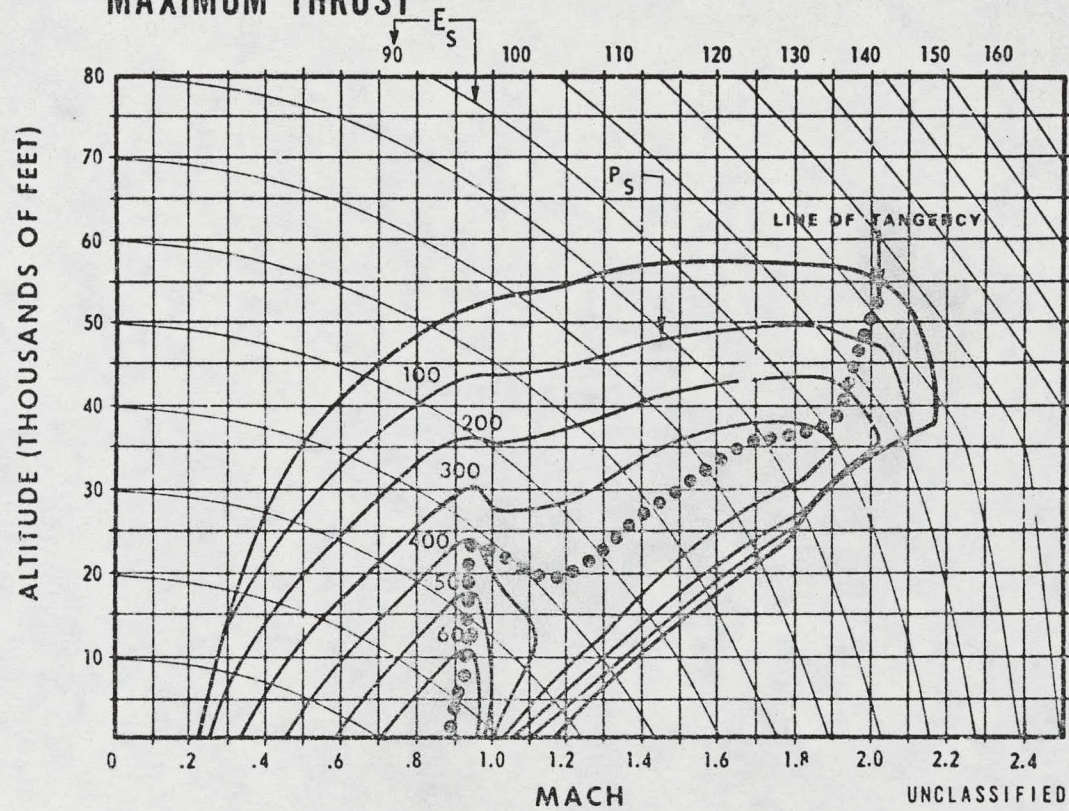


Figure 3. F-4E Energy Climb Diagram (Best Energy Climb Path)

(U) As shown in Figure 4, the maximum turn rate ($\dot{\theta}$) in degrees per second is represented over the entire flight envelope. Above and to the left of the maximum g boundary on this figure, maximum aerodynamic lift represents maximum useable lift. Below and to the right of this boundary, a structural g-limit of 7 represents maximum useable lift. At any specific energy level where altitude can be traded for airspeed (or vice versa), the global (or absolute) maximum turn rate occurs at the maximum g boundary - in this case 7g.

(U) If turn radius contours (R), with units in nautical miles, are embedded in the flight envelope (Figure 5), the global minimum turn radius occurs at the same limit load factor boundary where the global turn rate is maximum. Such results may seemingly imply that all turns should be performed along this boundary while all climbs and accelerations should be performed on the best energy climb path noted on the energy climb diagram. However, any confidence toward accepting this possibility is shaken by the high energy loss associated with such turns. In fact, at maximum turn rate (or minimum turn radius), energy loss is maximum (Figure 6). These results imply that maximum rate or minimum radius turns at the limit load factor boundary (locus of corner velocities) should not be employed as a dominant strategy in a maneuvering air-to-air duel since any contemporary adversary employing such a strategy will consistently perform the same maneuver option -- a descending spiral (or roll) that terminates upon impact with the ground. On the other hand, it should be understood that, for some cases, short duration maximum lift turns at limit load factor (with maximum energy loss) may be necessary defensively to secure an overshoot or offensively to gain a shooting position.

(U) For inverted flight, maximum rate turns occur at the limit load factor boundary while minimum radius turns at given energy levels (Figure 7) occur at higher altitude and lower airspeed where energy loss is less. Such results suggest that if minimum radius turns are necessary, they are best performed at high altitude and low airspeed while inverted in order to conserve energy needed for future maneuver/countermaneuver options.

(U) Aerodynamic considerations suggest that a turn with minimum energy loss due to drag can be accomplished if lift for turns is reduced until turning lift-over-drag is maximized for any attitude/altitude/airspeed combination. Maneuvers of this type can be defined as most aerodynamically efficient turns and can be represented over the entire flight envelope.

(U) As shown in Figure 8, turn rate is maximum and turn radius is minimum at the 7g boundary. The boundary on this diagram is lower than the 7g boundary on the quickest/tightest turn diagram (Figure 6). Other than this, little additional insight into the nature of maneuverability is provided. However, if energy rate contours are embedded in the most efficient turn diagram (Figure 9), the energy rate is negative in the

QUICKEST/TIGHTEST TURN
HORIZONTAL ATTITUDE
MAXIMUM THRUST

F-4E (U)
4 AIM-7 MISSILES

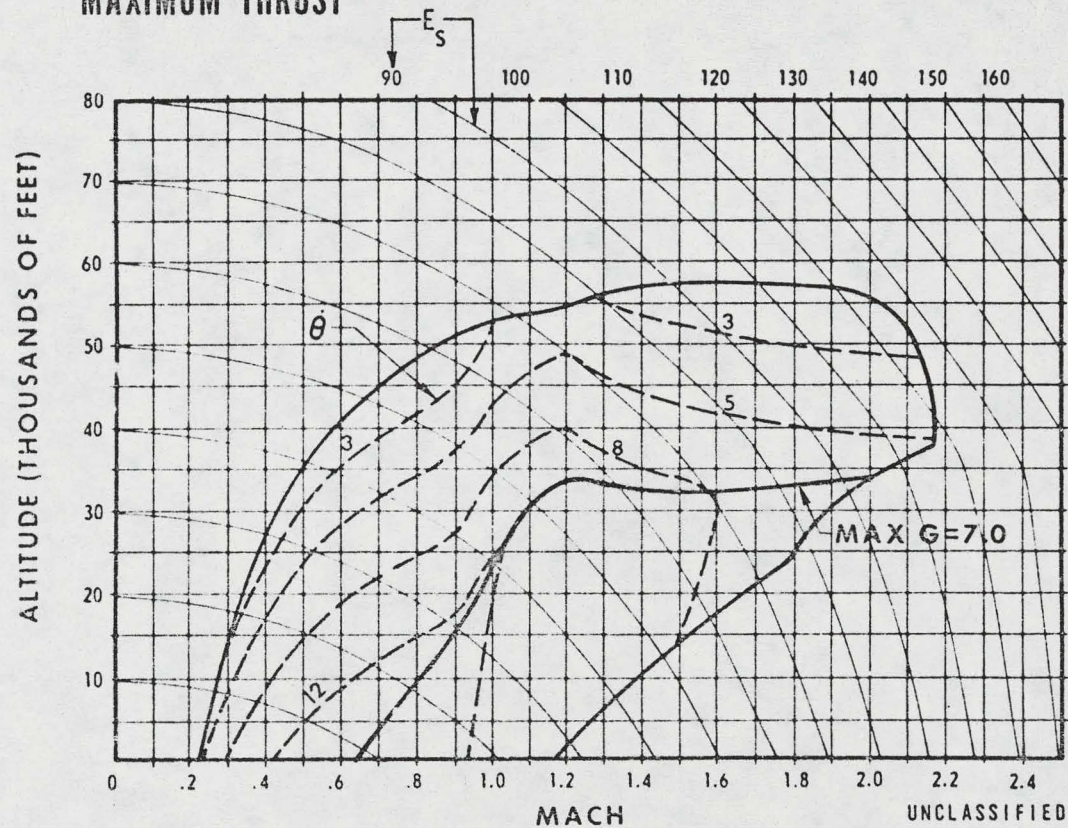


Figure 4. F-4E Quickest/Tightest Turn Diagram (Turn Rate Lines)

**QUICKEST/TIGHTEST TURN
HORIZONTAL ATTITUDE
MAXIMUM THRUST**

F-4E (U)
4 AIM-7 MISSILES

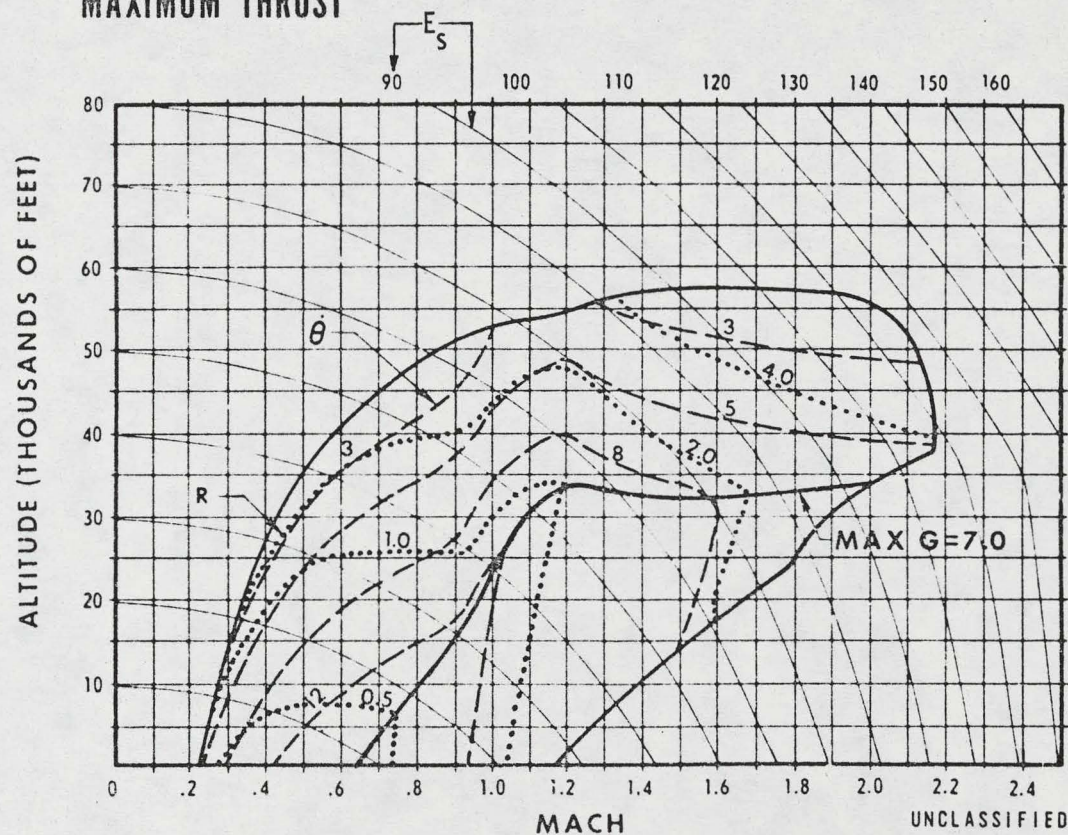


Figure 5. F-4E Quickest/Tightest Turn Diagram (Turn Rate and Turn Radius Lines)

**QUICKEST/TIGHTEST TURN
HORIZONTAL ATTITUDE
MAXIMUM THRUST**

F-4E (U)
4 AIM-7 MISSILES

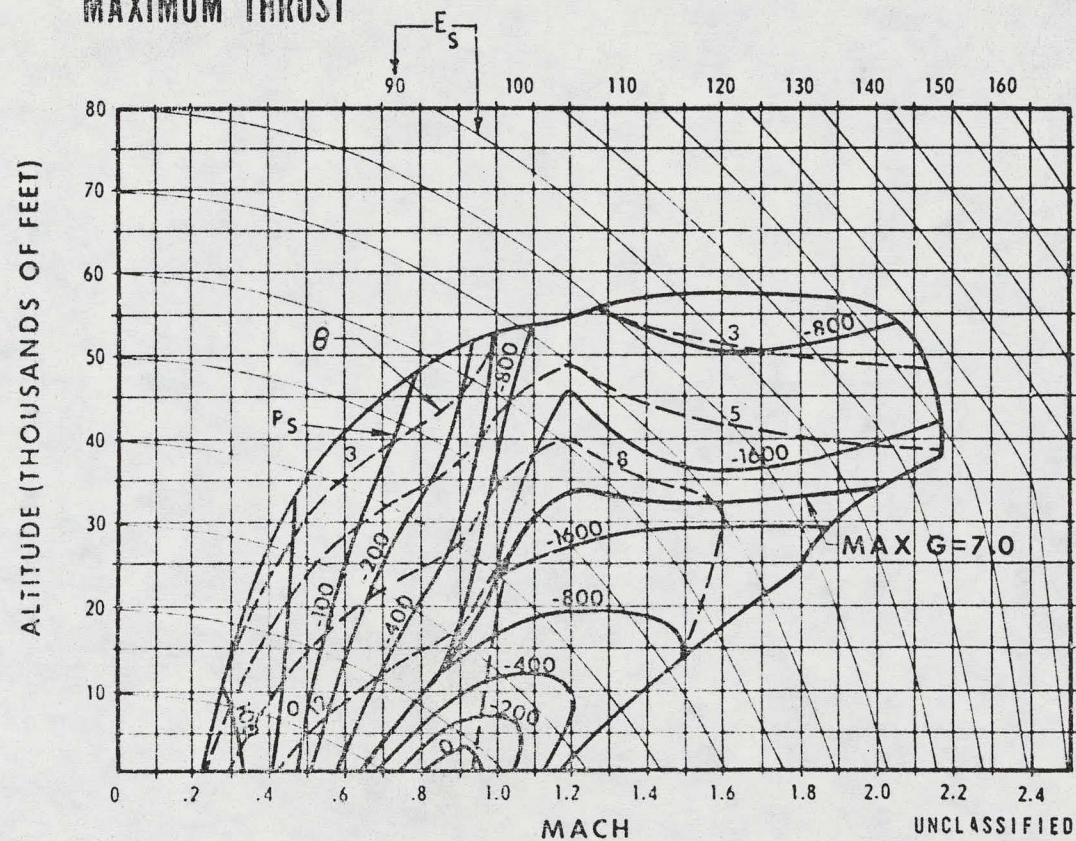
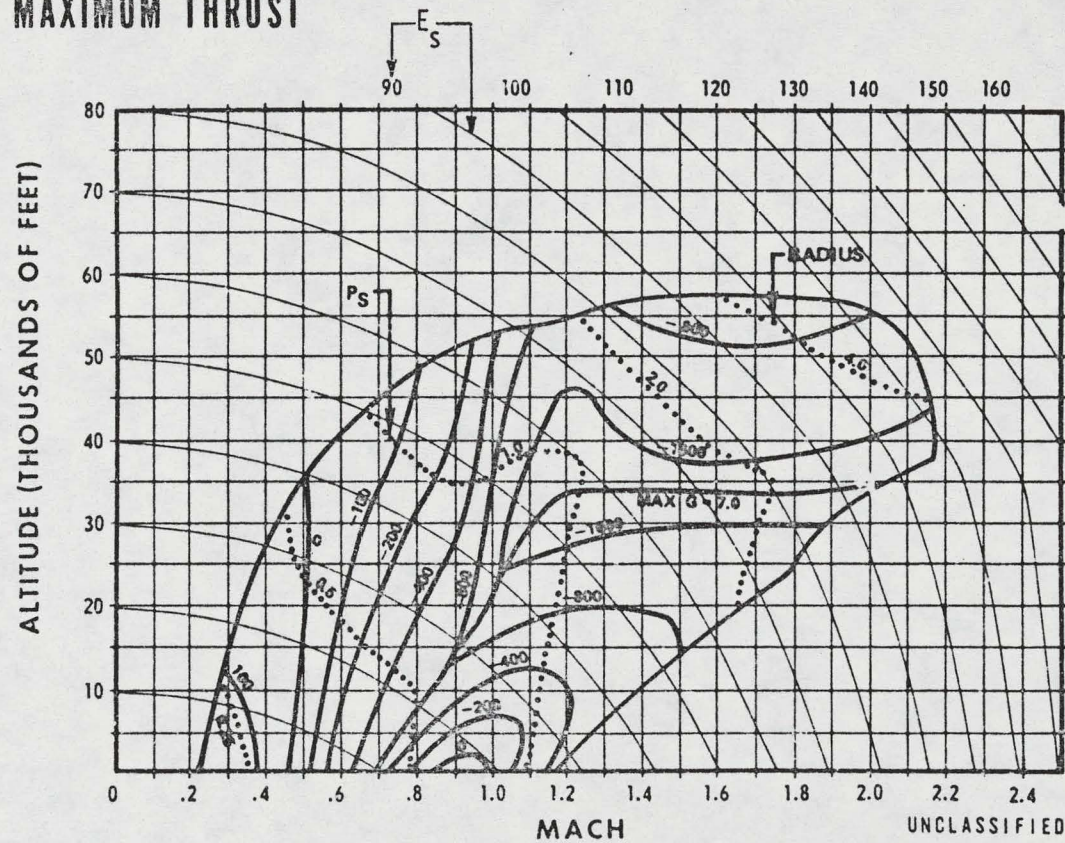


Figure 6. F-4E Quickest/Tightest Turn Diagram (Turn Rate and Energy Rate Lines)

QUICKEST/TIGHTEST TURN
PULL DOWN ATTITUDE
MAXIMUM THRUST

F-4E (u)
 4 AIM-7 MISSILES



**MOST EFFICIENT TURN
HORIZONTAL ATTITUDE
MAXIMUM THRUST**

F-4E (U)
4 AIM-7 MISSILES

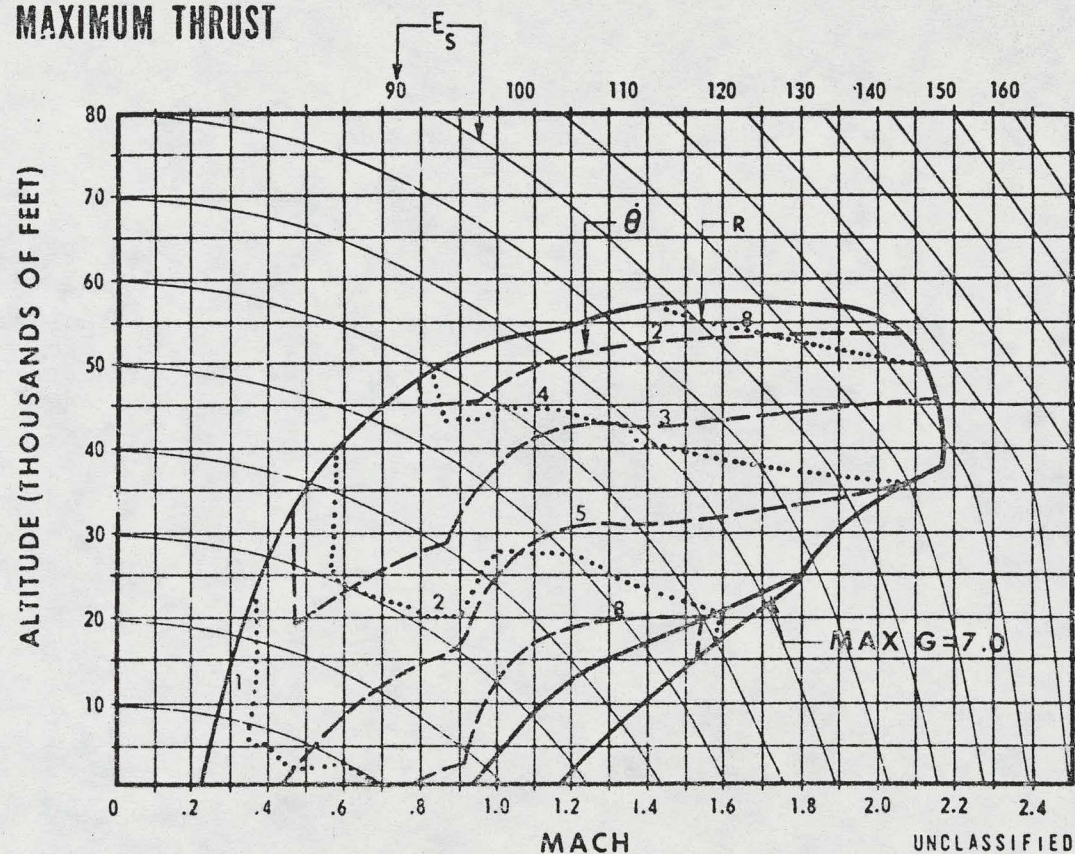


Figure 8. F-4E Most Efficient Turn Diagram (Turn Rate and Turn Radius Lines)

**MOST EFFICIENT TURN
HORIZONTAL ATTITUDE
MAXIMUM THRUST**

F-4E (U)
4 AIM-7 MISSILES

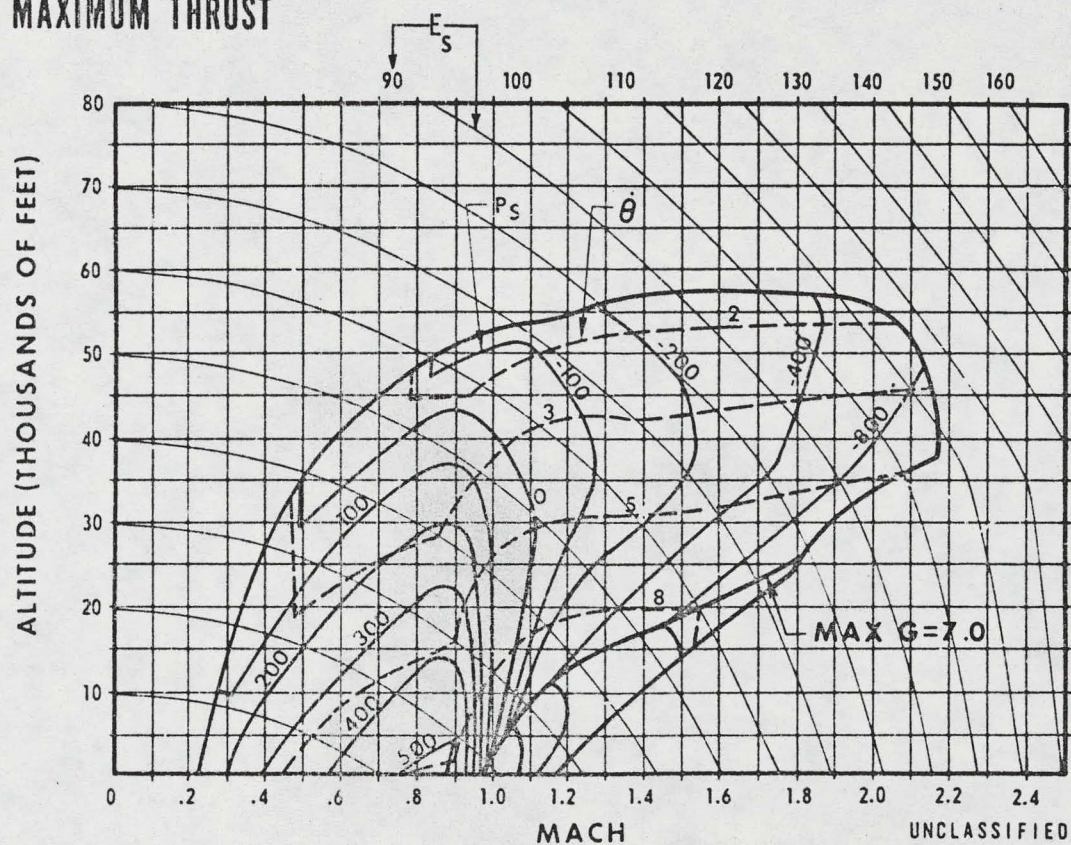


Figure 9. F-4E Most Efficient Turn Diagram (Turn Rate and Energy Rate Lines)

supersonic region. Only in the subsonic-transonic region is energy rate positive. Such results reveal that even though the F-4E is a supersonic aircraft, it is a subsonic-transonic maneuvering fighter since it cannot maintain altitude/airspeed while maneuvering most efficiently in the supersonic region. A similar evaluation of other existing U.S. fighter aircraft reveals this same key point to be true, since their energy rates are also negative in the supersonic region.

(U) In summary, the quickest, tightest, and most aerodynamically efficient turns have been identified, and some insight has been gained into the nature of where maneuvering combat can take place. However, the best combinations of energy rate, turn rate, and turn radius, and the optimum location for maneuvering combat have not been identified.

(U) Since it is known that an inverted pull-down turn or a maximum rate turn is a transient maneuver, and if a maximum lift turn at limit load factor is undesirable, then the type of turning maneuver to be performed must be determined. The resulting implication is that turns at less lift should be performed in an effort to retain energy for future maneuver/countermaneuver options.

C. CHANGING ALTITUDE, AIRSPEED, AND DIRECTION

(U) To account for changes in altitude and airspeed while changing direction implies that these changes should be evaluated simultaneously. Since energy rate is related to changing altitude and/or airspeed, while turn rate or turn radius can be used to measure changes in direction, if some consistent relationship between energy rate and turn rate (or turn radius) could be found, it might reveal the true nature of maneuverability and the impact on air-to-air combat.

(U) Considering a pilot must reduce the energy rate to improve the turn rate (or reduce the turn rate to improve the energy rate) and he must maneuver in the present sense as well as in the future, he would be expected to attempt to extract the highest turn rate for any energy rate (or the highest energy rate for any turn rate) in an effort to protect future maneuver/countermaneuver options. Since a pilot can trade turn rate for energy rate (or vice versa) and trade altitude for airspeed (or vice versa) at any energy level, as well as change energy levels, it follows that a maximum maneuver region could be determined by finding the highest turn rate for any energy rate (or conversely the highest energy rate for any turn rate) at any energy level across all energy levels in the flight envelope.

(U) A high speed computer can be used to search all energy levels in the flight envelope and identify those maximum energy rate/turn rate combinations between the zero turn rate associated with the best energy climb

and the turn rate where limit load factor is first encountered. A region identified as a result of this procedure can be projected upon the altitude/Mach plane as shown in Figure 10. This region is defined as the maximum maneuver corridor since maneuverability in terms of changing altitude, airspeed, and direction at maximum rate is indeed represented by the maximum energy rate/turn combinations contained therein.

(U) However, all possible maximum combinations of energy rate and turn rate are not included in the maximum maneuver corridor. Specifically, all possible maximum turn rate/energy rate combinations between the place where limit load factor is first encountered and the global quickest/tightest turn boundary are not considered. To identify and locate these maximum combinations without exceeding maximum useable G, the computer search (or sweep out) must be continued until all remaining possibilities are extracted. A region identified as a result of this operation can be projected upon the altitude/Mach plane as shown in Figure 11. This is defined as the maximum maneuver region since these maximum energy rate/turn rate combinations (including those associated with the maximum maneuver corridor) represent the ability to maneuver at maximum rate.

(U) The P_s contours depicted in Figure 12 represent the maximum energy rate for any turn rate/energy level combination (or conversely the turn rate values depicted on the vertical axis represent the maximum turn rate available for any energy rate/energy level combination). Energy rates associated with the best energy climb are located along the longitudinal axis. The quickest/tightest turn boundary is at the top. The peak (or second order maximum) energy rate values at or near the 15,000 feet energy level represent a domain of maximum maneuver energy states within the maximum maneuver corridor. Correlation of these peak energy rate/energy level combinations with the maximum maneuver region diagram (Figure 11) reveals that this domain of maximum maneuver energy states is located at sea level between the quickest/tightest turn and Mach 0.9 where the maximum maneuver corridor begins to rise upward and to the right.

(U) Another way to present the maximum energy rate/turn rate combinations is shown in Figure 13. In this case, the maximum turn rate (θ) contours within the diagram and energy rate are along the vertical axis and the best energy climb values are now at the top. The quickest/tightest turn boundary is at the bottom. The domain of maximum maneuver energy states is located at the peak turn rates located near the 15,000 feet energy level. Except for the reversed locations, the maximum combinations contained in this diagram are the same as in Figure 12. The reason for presenting the data in a different format will appear when the maximum maneuver region and maximum maneuver diagrams are discussed.

MAXIMUM MANEUVER CORRIDOR
HORIZONTAL ATTITUDE
MAXIMUM THRUST

F-4E (U)
4 AIM-7 MISSILES

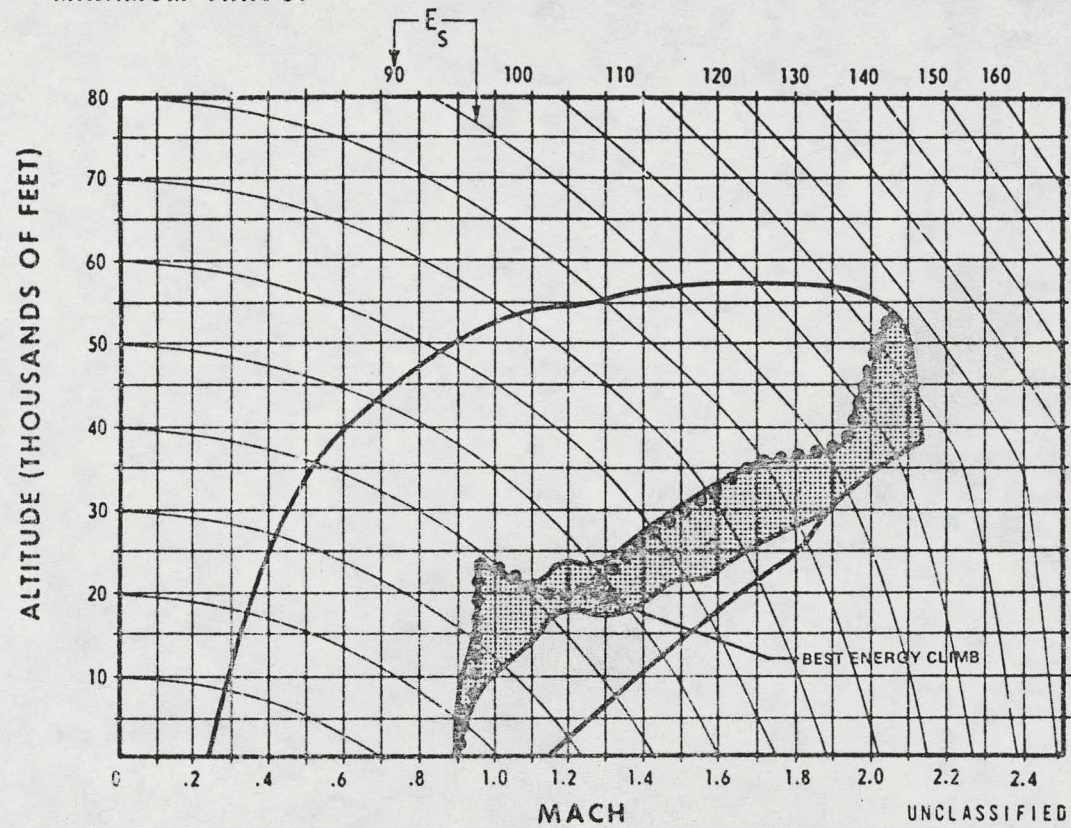


Figure 10. F-4E Maximum Maneuver Corridor

MAXIMUM MANEUVER REGION
HORIZONTAL ATTITUDE
MAXIMUM THRUST

F-4E (U)
4 AIM-7 MISSILES

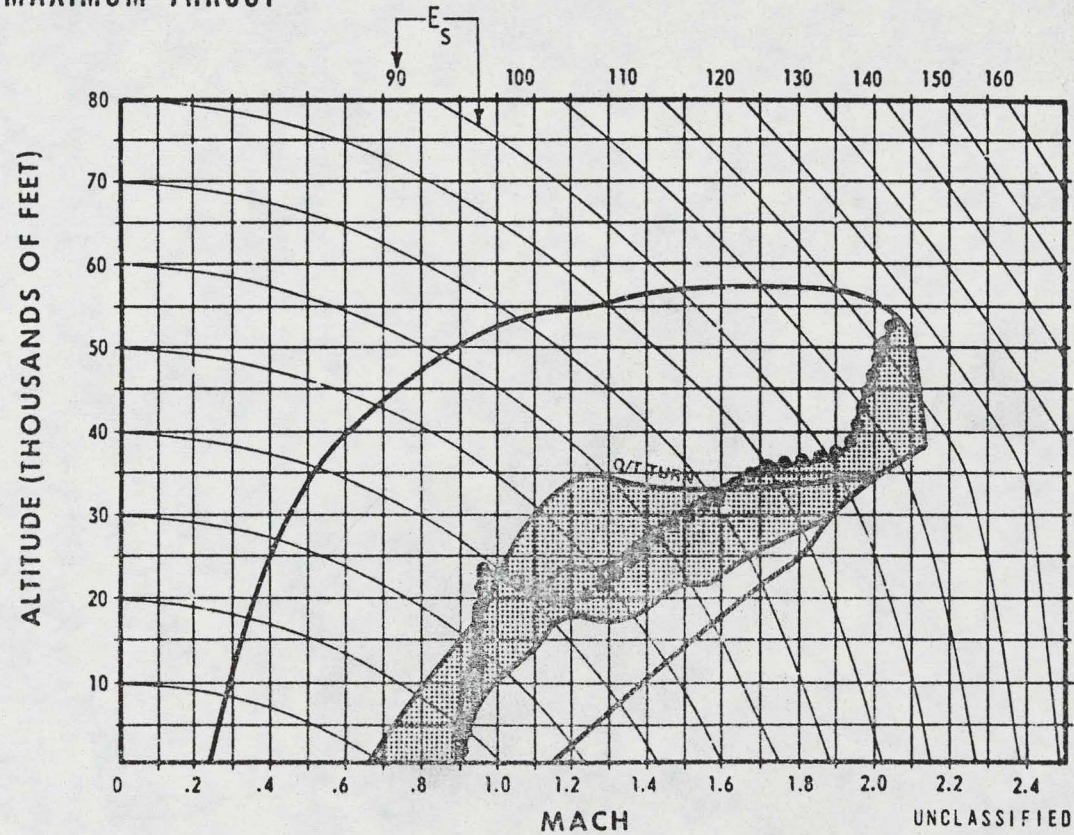


Figure 11. F-4E Maximum Maneuver Region

**MAXIMUM MANEUVER DIAGRAM
HORIZONTAL ATTITUDE
MAXIMUM THRUST**

F-4E (U)
4 AIM-7 MISSILES

17

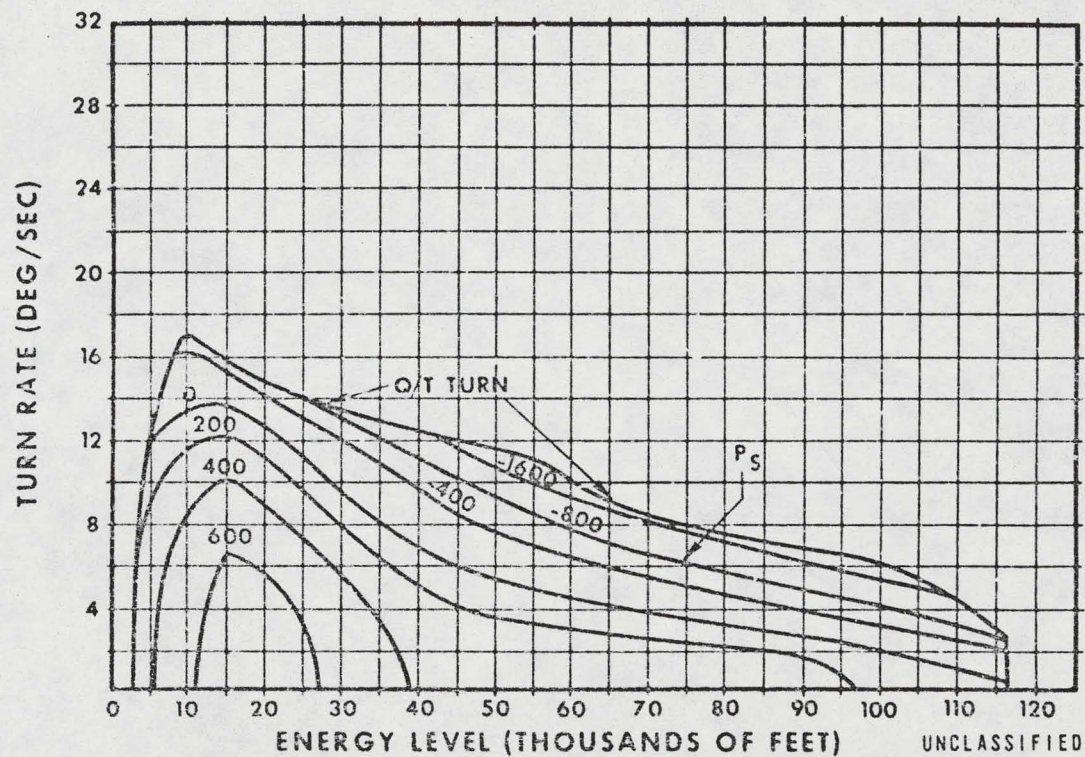


Figure 12. F-4E Maximum Maneuver Diagram (Turn Rate Versus Energy Level)

MAXIMUM MANEUVER DIAGRAM
HORIZONTAL ATTITUDE
MAXIMUM THRUST

F-4E (U)
4 AIM-7 MISSILES

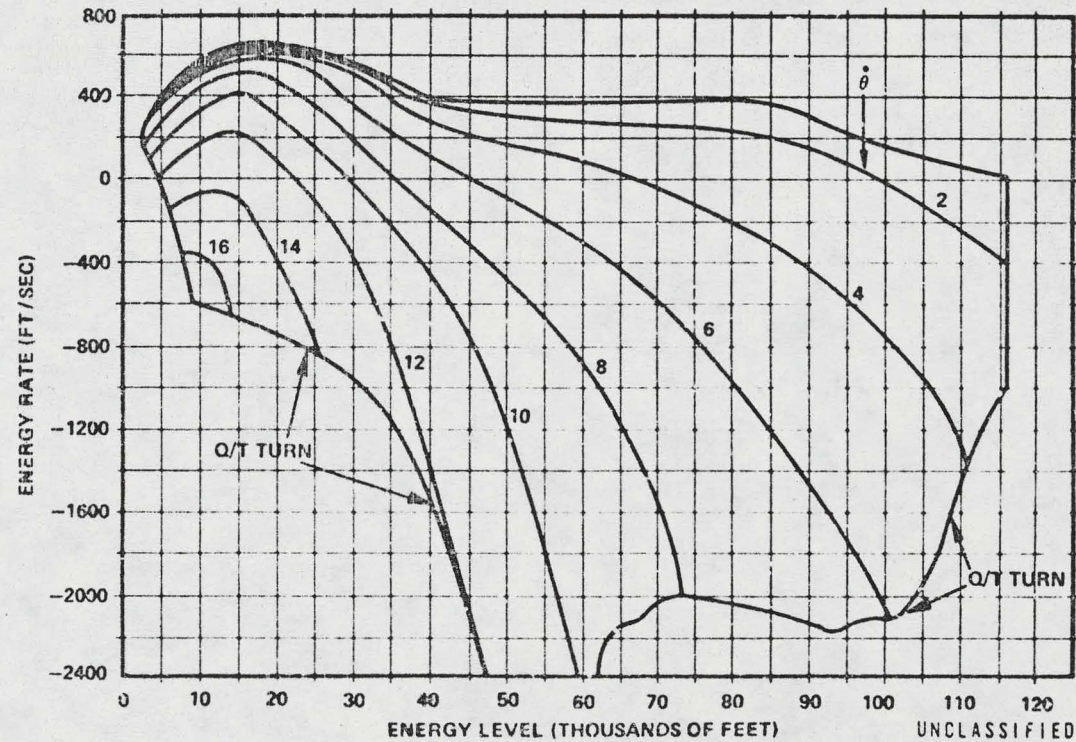


Figure 13. F-4E Maximum Maneuver Diagram (Energy Rate Versus Energy Level)

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D. SUMMARY

(U) The key ideas associated with the maximum maneuver concept, as developed thus far, are as follows:

(1) The maximum maneuver region is that domain of altitude/airspeed combinations across all energy states (within the flight envelope) where turn rate is maximum for any energy rate - or conversely where energy rate is maximum for any turn rate.

(2) The maximum maneuver corridors are the portions of the maximum maneuver region between the best energy climb (zero turn rate) and the first encounter with limit load factor.

(3) The maximum maneuver energy states are the domain of energy states where turn rate maximizes for energy rate - or where energy rate maximizes for turn rates.

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SECTION III

APPLICATION TO TACTICS

(U) In considering tactics, the maximum maneuver and related key ideas can be expanded and employed in order to devise a general maneuver strategy for outmaneuvering an air-to-air adversary, define a combat relevant air battle arena, and devise an orderly, concise scheme for performing relevant comparative analyses.

A. MANEUVER STRATEGY

(U) In developing a maneuver strategy, the interest is not in maneuvers that can be used in air-to-air combat, but rather in finding a common thread of logic that should be applied across all maneuvers in order to win in air-to-air combat. The information contained in the maximum maneuver region will now be used to attain this objective.

(C) The location of the maximum maneuver region and enclosed maximum maneuver corridor (Figure 14) implies that up to the first encounter with limit load factor, the turn rate increases for any energy rate as a specific energy contour is followed to approach the maximum maneuver corridor. Stated another way, a positive gradient (or component) of energy rate/turn rate combinations, along specific energy contours, is pointed directly toward the maximum maneuver corridor. The location of the domain of maximum maneuver energy states implies that another positive gradient (or component) of energy rate/turn rate combinations exists within the maximum maneuver corridor. It is pointed at the domain of maximum maneuver energy states. Taken together, these two gradient components suggest that a pilot, in order to maneuver in the present sense yet save energy for future maneuverability, can outmaneuver his adversary if he maneuvers more often between his adversary's energy state and his domain of maximum maneuver energy states and between his adversary and the maximum maneuver corridor.

(C) In applying this concept, a pilot may outmaneuver his adversary, but he will be unable to score unless he can get into position to employ his weapons. For example, against an adversary that remains high above the corridor, he will be unable to score unless he turns up and away from the corridor to achieve a firing position. If he does pull up, his adversary will very likely countermaneuver by pulling down into the attack. The result is that the adversary is given the opportunity to maneuver closer to both the maximum maneuver corridor and the domain of maximum maneuver energy states. Now, if he pulls down to go after his adversary, and his adversary pulls up to go after him, the cycle will continue with each adversary alternatively closer to the maximum energy rate/turn rate combinations that make up the maximum maneuver corridor and the domain of maximum maneuver energy states. Without further adjustment by either adversary,

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MAXIMUM MANEUVER REGION
HORIZONTAL ATTITUDE
MAXIMUM THRUST

F-4E (U)
4 AIM-7 MISSILES

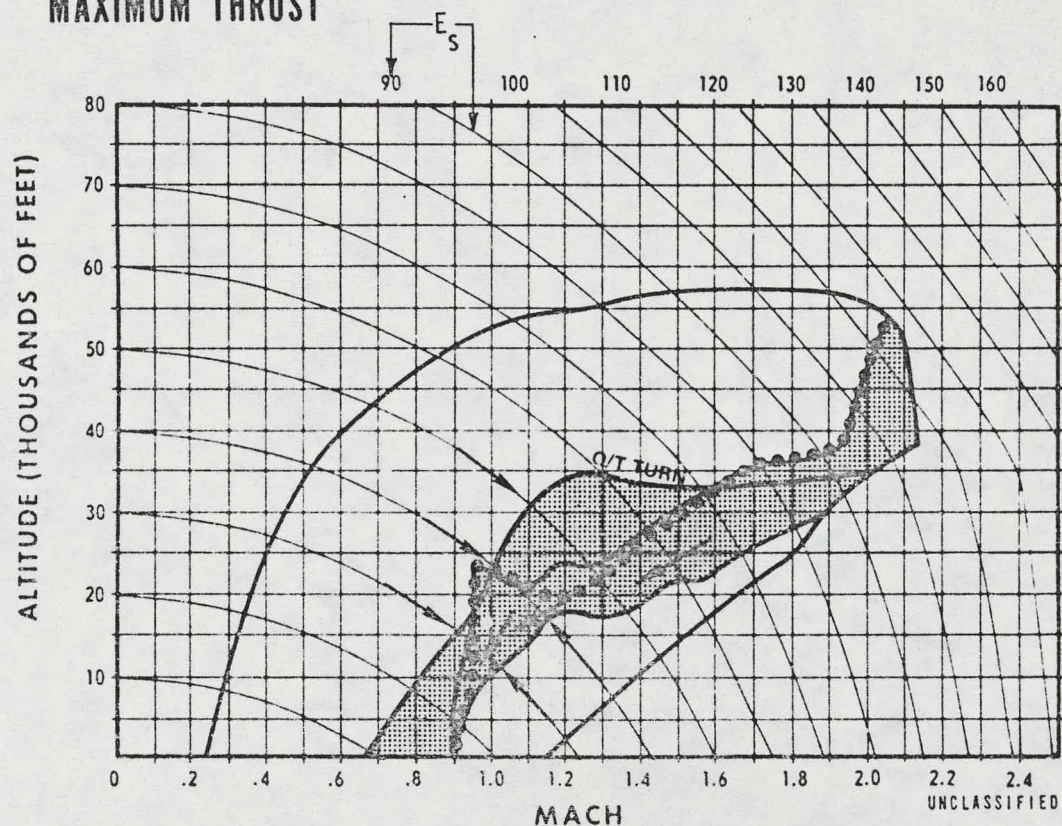


Figure 14. F-4E Maximum Maneuver Region (Gradient Lines)

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the result of such vertical maneuvering becomes an unsatisfying stalemate unless some better scheme can be defined. Knowledge of the gradient along the energy contours (to and from the corridor) suggests that hard (maximum lift) maneuvers should be executed over the top near or at the quickest/tightest turn boundary while soft (not maximum lift) energy conserving maneuvers should be executed at the bottom, near or at the maximum maneuver corridor. In other words, more time should be spent conserving energy and changing direction near the maximum maneuver corridor while less time should be spent in quickly changing direction and rapidly dissipating energy near the quickest/tightest turn boundary. The desired result would be a repeatable and faster overall turn designed to gain position advantage and win the fight. Clearly, it follows that such a maneuver scheme can be regarded formally as a general strategy for outmaneuvering an adversary in air-to-air combat. Naturally, if both adversaries maneuver in this fashion, a stalemate will most likely occur unless one adversary has a superior maneuvering vehicle.

(C) On the other hand, if a fighter could turn at maximum rate at the quickest/tightest turn boundary (locus of corner velocities) without losing energy, it follows that turns should be performed near or at the quickest/tightest turn boundary while climbs and/or accelerations should be performed near or at the best energy climb path in the maximum maneuver corridor in an effort to outmaneuver an air-to-air adversary. With such a fighter a general strategy for outmaneuvering an air-to-air adversary would be to deceive the adversary by turning near the quickest/tightest turn boundary and climb/accelerate near the best energy climb path in the maximum maneuver corridor. Such a strategy would conform to the ideas expressed in Reference 2.

P. AIR BATTLE ARENA

(U) After a general knowledge of how and where to maneuver (via the general maneuvering strategy) is obtained, the air battle arena can be defined. In performing this task, the interest is not in where the air battle actually takes place, but rather where it should take place in order to win.

(C) A fighter pilot would be interested in knowing not only how and where he should maneuver at maximum rate but also where he can or cannot sustain these maximum maneuvers. Thus, four mutually exclusive maneuver regions can be defined (Figure 15):

(1) The transient maneuver region is that portion of the flight envelope where turn rate is not maximum for any negative energy rate.

(2) The sustained maneuver region is that portion of the flight envelope, outside the maximum maneuver region, where turn rate is not

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AIR BATTLE ARENA HORIZONTAL ATTITUDE MAXIMUM THRUST

F-4E (U)
4 AIM-7 MISSILES

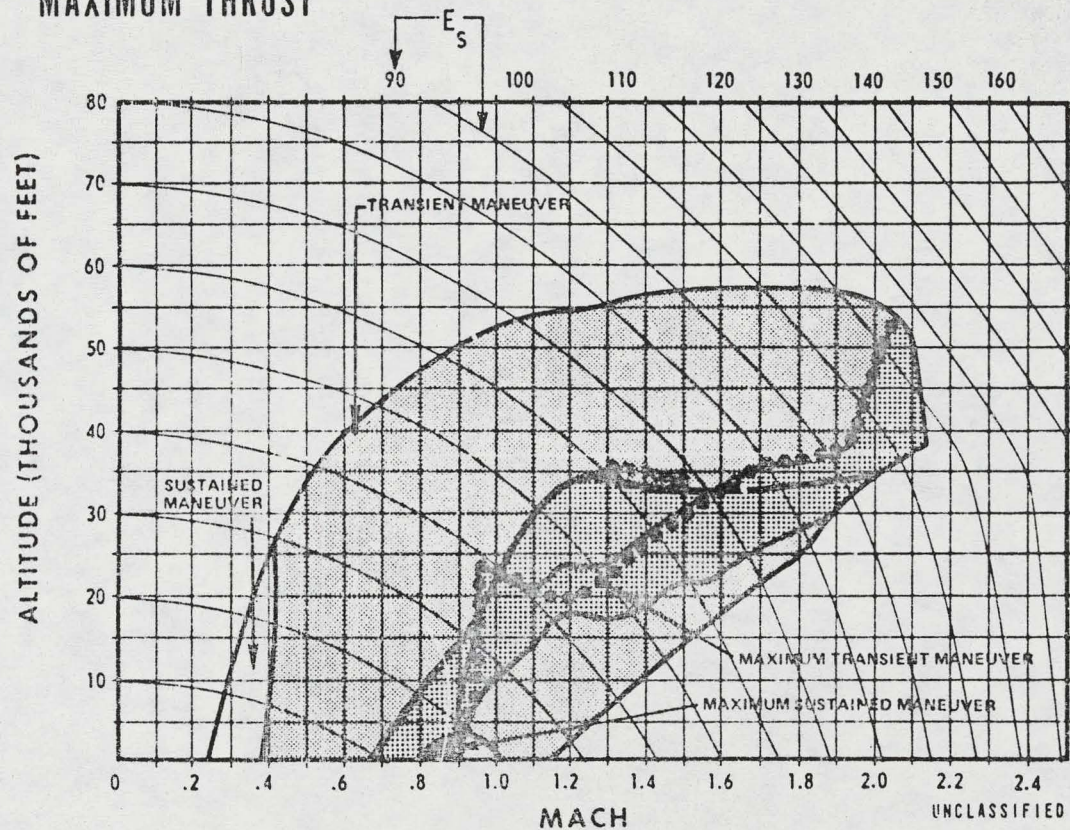


Figure 15. F-4E Air Battle Arena Diagram

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maximum for zero or any positive energy rate at maximum useable or any lower corresponding lift or load factor.

(3) The maximum transient maneuver region is that portion of the maximum maneuver region where turn rate is maximum for any negative energy rate.

(4) The maximum sustained maneuver region is that portion of the maximum maneuver region where turn rate is maximum for zero or any positive energy rate at maximum useable lift.

(C) Since the area of interest is in determining where the air battle should take place, it would seem that perhaps the maximum maneuver region should be constrained somewhere inside the steady state envelope. An examination of Figure 15 indicates that energy levels below those associated with the maximum sustained maneuver region should be avoided, since hard turning maneuvers here can easily drain away any existing energy that may be needed for future maneuverability.

(C) The existence of such a lower maneuver limit suggests that some upper practical limits also exist. Three limits come to mind: visibility, most efficient turn, and fuel. For visibility, if a turn radius of 2 nautical miles is used as a limit, the quickest/tightest turn diagram would show that maneuvering combat beyond 1.6 Mach is meaningless. On the other hand, if the rationale associated with the most efficient turn diagram is used, maneuvering combat beyond the most efficient sustained turn (maximum turning lift-over-drag at zero energy rate) appears unlikely except for hit and run attacks or other short duration encounters where turn is relatively unimportant. For the F-4E, this limit is at approximately Mach 1.1. Fuel limits have only recently been addressed, and the results and related rationale are not yet ready for proper discussion; therefore this limit, although recognized, will not be considered here. With only two limits to consider, the most efficient turn is more restrictive (for the F-4E), hence it is shown as the upper practical limit for the maneuvering air battle.

(C) In summary, the maximum sustained and maximum transient maneuver regions in Figure 16 between the lower and upper limits as discussed represent that portion of the air battle arena where the general maneuver strategy should be employed to win.

(C) However, the validity of such a concept may be questionable since maneuverability by definition is dynamic. Yet, a static method - in this case an energy method - has been used to devise a general maneuver strategy and define the air battle arena. Obviously, since dynamic methods have not been used, there is some concern about the validity of such an undertaking. With this concern in mind, dynamic 3-D flight path optimization

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**AIR BATTLE ARENA
HORIZONTAL ATTITUDE
MAXIMUM THRUST**

F-4E (U)
4 AIM-7 MISSILES

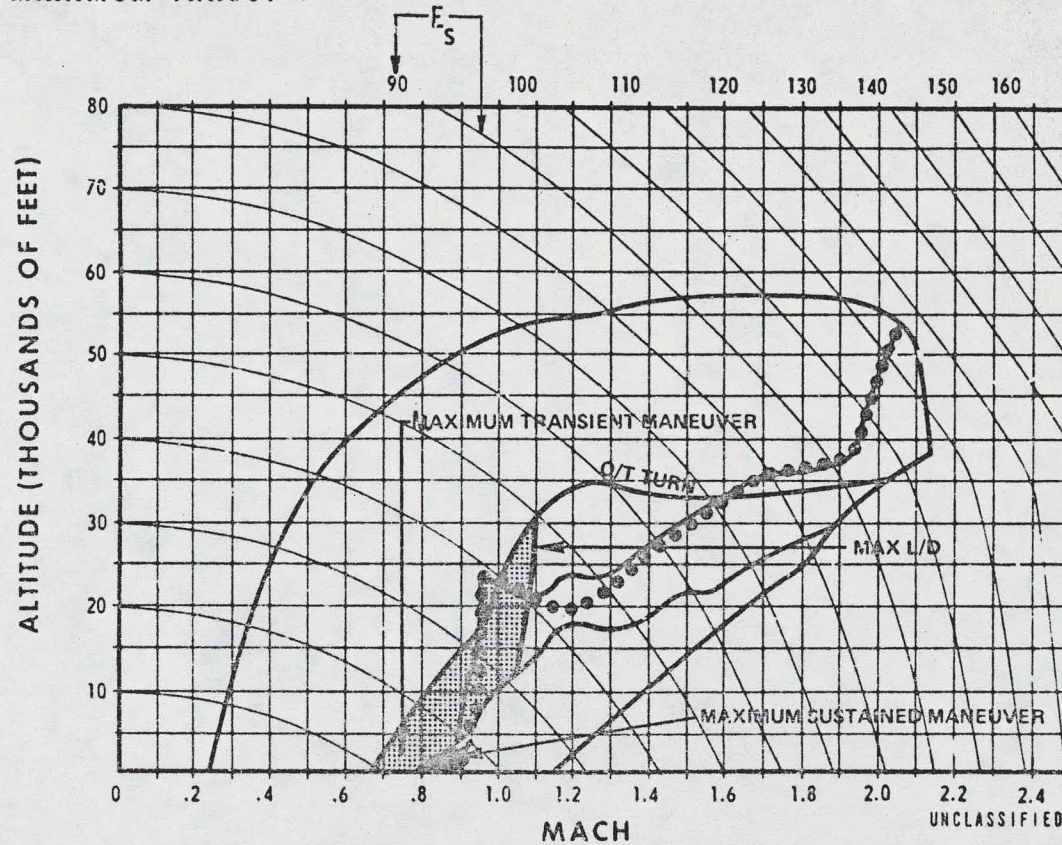


Figure 16. F-4E Air Battle Arena Diagram (Most Efficient Turn Constraint)

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techniques have been employed (Reference 3) in a broad parametric effort to verify or reject the ideas that makeup the maximum maneuver concept. Specifically, the effort attempted to verify or reject the following ideas: (1) optimum (minimum time or maximum rate) maneuvers are drawn toward the maximum maneuver corridor and the domain of maximum maneuver energy states, (2) optimum maneuvers do behave in accordance with the general maneuver strategy, and (3) optimum maneuvers are inhibited in proceeding beyond the quickest/tightest and the steady-state most efficient turn boundaries.

(C) Results obtained so far do not reject any of the preceding ideas. On the contrary, evidence obtained to date provides strong confirmation that optimum maneuvers are drawn toward the maximum maneuver corridor and the domain of maximum maneuver energy states, and that these maneuvers do tend to behave in accordance with the general maneuver strategy. On the other hand, insufficient evidence has been collected to date to support the contention that optimum maneuvers are inhibited in proceeding beyond the quickest/tightest and the steady-state most efficient turn boundaries. As a result, an additional effort is required to fully address this implication. Examples of the optimum maneuvers and how they tend to seek the maximum maneuver corridor are as shown in Figure 17.

C. COMPARATIVE ANALYSIS

(C) After determining how and where a fighter pilot should fight, it seems possible that the air battle arena and the maximum maneuver diagrams could be used to compare friendly versus threat fighters. The purpose of this comparison would be to identify margins of superiority (or inferiority) and to determine in more detail how and where in the air battle arena the maneuver strategy should be employed or modified to win.

(C) Before such a comparison is considered, however, energy state must be accepted as the desired frame of reference. Energy state, or energy level, must be demonstrated to be more sensitive and altitude/airspeed to be insensitive. The Northrop 3-D flight path optimization program (Reference 3) is being used to address these questions. The few results provided so far show that 360° minimum time turns started and terminated at the same energy level require approximately the same time to complete regardless of the altitude/airspeed point selected (at that energy level). These results also show that these same turns conducted at widely different energy levels require substantially more or less time depending upon the energy level selected. So far, such results support the idea that energy state is the superior frame of reference.

(C) On the other hand, it is expected that turns of fewer degrees will not require the same time to complete at the various altitude/airspeed combinations along an energy level. If this expectation is true, it follows that a concerned fighter pilot should place himself at those altitude/airspeed

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**AIR BATTLE ARENA
HORIZONTAL ATTITUDE
MAXIMUM THRUST**

F-4E (U)
4 AIM-7 MISSILES

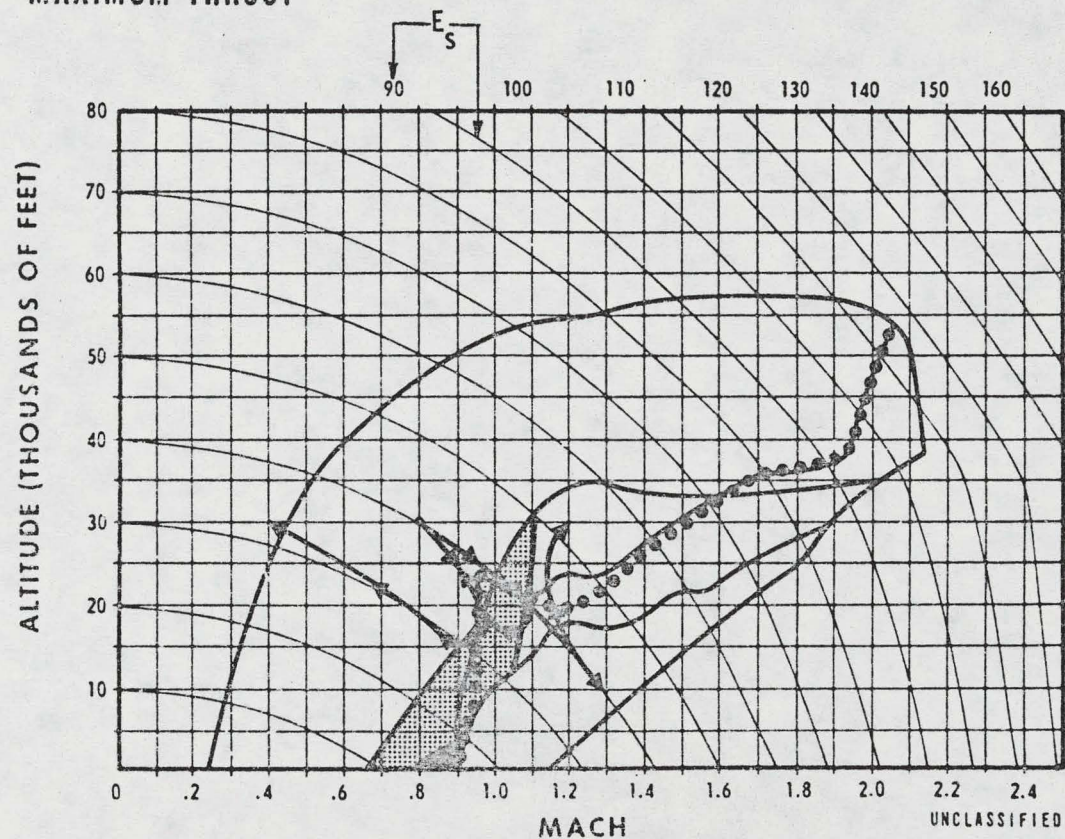


Figure 17. F-4E Air Battle Arena Diagram (Optimum Flight Paths)

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points where he has a turn rate/energy rate advantage over his adversary in order to guard against surprise attacks consisting of maneuvers of few degrees, or of short duration. Such rationale suggests that comparisons should be made using both energy level and altitude/airspeed as a frame of reference. In this way, the tactician and analyst will be presented with maneuvering margins of superiority (or inferiority) that can be used to minimize the impact of surprise attack as well as influence how and where the fighter pilot should maneuver during the air battle.

(C) In using this approach, a threat, the Fishbed F (MIG-21) described in Reference 4, will be compared with the F-4E (Reference 5).

(S) An examination of the air battle arenas (Figures 16 and 18) reveals that best maneuverability exists in approximately the same altitude/airspeed spectrum for each fighter. Since such maneuverability lies between the lowest specific energy level associated with the maximum sustained maneuver region and the energy level associated with the most efficient sustained turn boundary in the maximum maneuver corridor, it is advantageous for both the F-4E and Fishbed F to fight between about the 12,000 and 40,000 feet energy levels. Close examination reveals that the F-4E should fight at higher airspeeds since its best maneuver region is narrower and exists at higher Mach than that of the Fishbed F.

(S) Comparison of the F-4E and Fishbed F, via the turn rate/energy level maximum maneuver diagram, (Figure 19) reveals that, in general, the Fishbed F is superior to the F-4E. At the best maneuver energy levels, between about 12,000 and 40,000 feet, the Fishbed F with higher energy rates (ΔP_s) can outmaneuver the F-4E at the higher turn rates thereby suggesting that the Fishbed F would be superior in air-to-air combat. On the other hand, the F-4E might be superior between these energy levels if the F-4E fought at the lower turn rates where it is better. Because these conflicting views cannot be resolved by this approach, a resolution must be found elsewhere.

(S) First, the energy rate/energy level maximum maneuver diagram (Figure 20) will be used to compare the F-4E and Fishbed F. As shown, the Fishbed F appears to be better. On the other hand, at the best maneuver energy levels, between about 12,000 and 40,000 feet, the F-4E can outturn the Fishbed F at the higher energy rates. F-4E superiority here is equivalent to F-4E superiority in energy rate at the lower turn rates (Figure 19). Such results reinforce the idea that the F-4E should fight at the lower turn rates or, equivalently, at the higher energy rates in this region. However, closer observation reveals such a strategy is impossible since the energy rates are positive. As a result, an F-4E pilot must move to higher energy levels at positive energy rates and low turn rates or stay at lower energy levels by increasing turn rate and decreasing energy rate. Either way, the F-4E is forced to maneuver where

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AIR BATTLE ARENA

FISHBED F (s)
2 ATOLL MISSILES
MAXIMUM THRUST

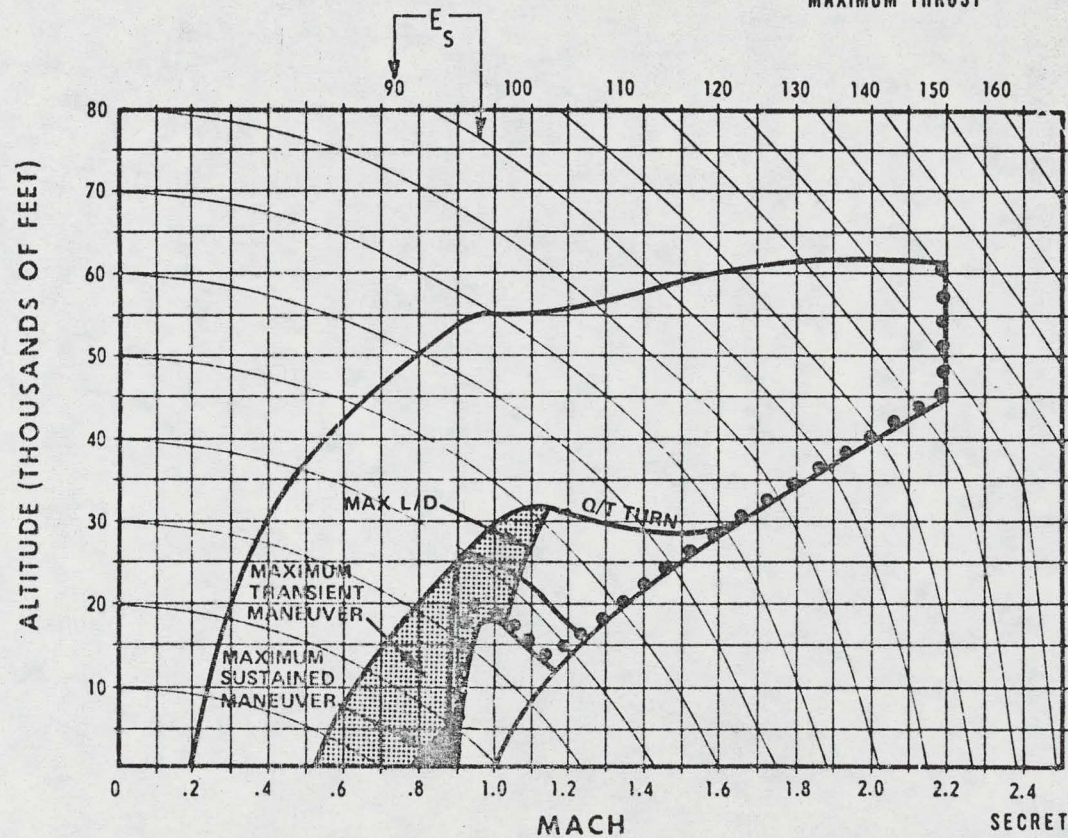


Figure 18. Fishbed F Air Battle Arena Diagram

MAXIMUM MANEUVER DIAGRAM HORIZONTAL ATTITUDE MAXIMUM THRUST

F-4E (U)
4 AIM-7 MISSILES
FISHBED F (S)
2AA-2 MISSILES

F-4E EXCLUSIVE
 FISHBED F EXCLUSIVE
 F-4E SUPERIOR
 FISHBED F SUPERIOR

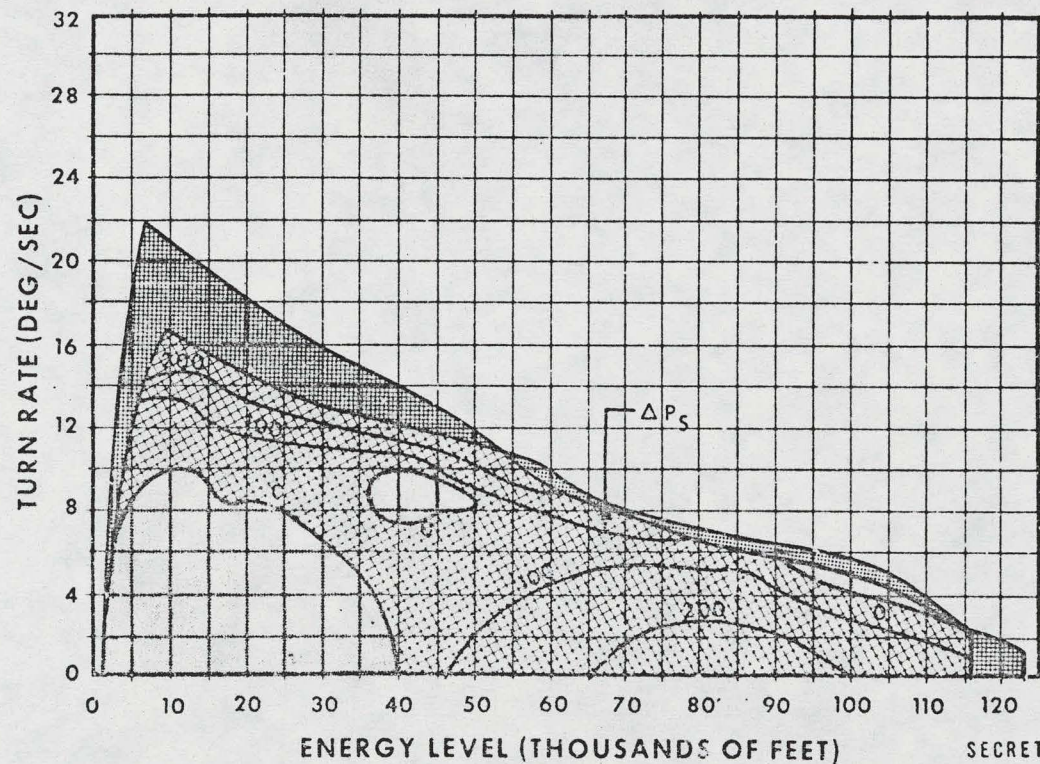


Figure 19. F-4E Versus Fishbed F Maximum Maneuver Difference Diagram (Turn Rate Versus Energy Level)

MAXIMUM MANEUVER DIAGRAM
HORIZONTAL ATTITUDE
MAXIMUM THRUST

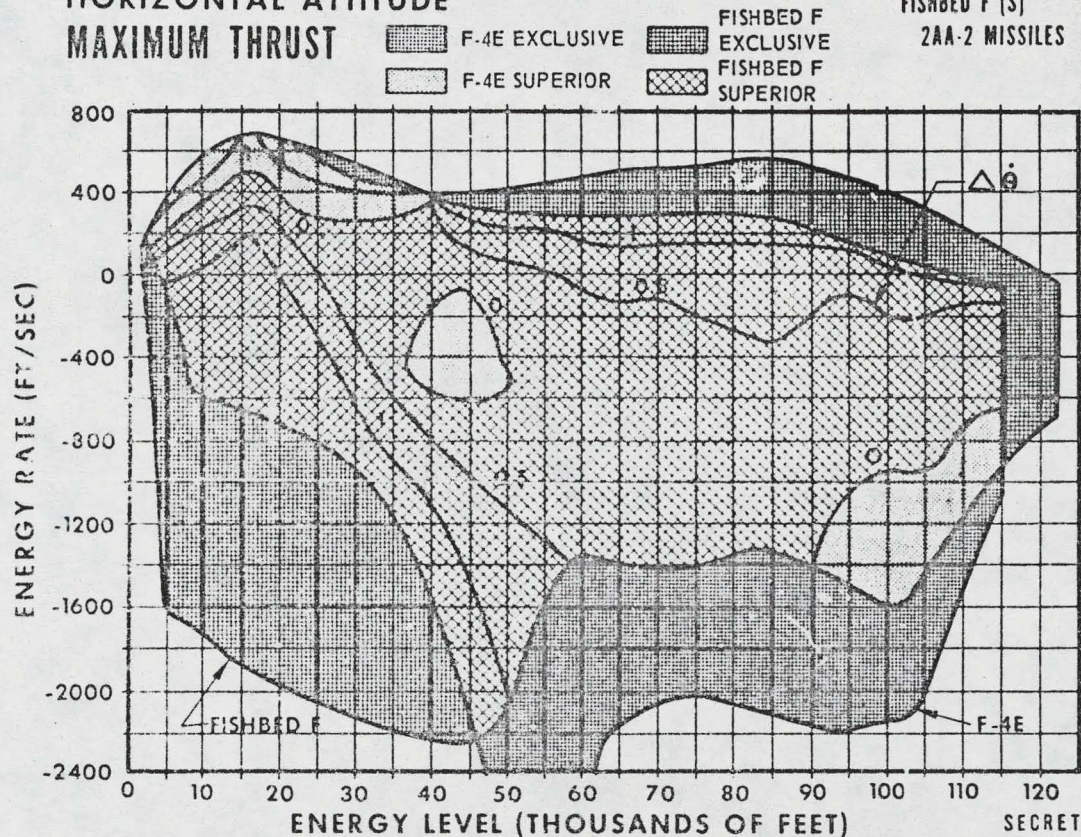


Figure 20. F-4E Versus Fishbed F Maximum Maneuver Difference Diagram (Energy Rate Versus Energy Level)

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the Fishbed F is superior. Clearly, this implies that the Fishbed F is the superior fighter and that the energy rate/energy level maximum maneuver diagram is superior for differential comparisons.

(S) On the other hand, before such an implication can be accepted, consideration must be given to the fact that if an F-4E pilot implements the general maneuver strategy, he has the opportunity to gain energy at low turn rates as well as to lose energy at high turn rates. Viewing maneuverability in this manner reveals the superior maneuver flexibility associated with the general strategy and the difficulty in precisely determining which of two quite different but closely matched maneuvering vehicles is superior. In an effort to prove that the Fishbed F is superior to the F-4E, the aircraft will be compared at the same altitude/airspeed combinations, as well as at the same energy levels. This comparison will use altitude/airspeed plots at constant 1g, 4g, and 7g--superimposed over the F-4E air battle arena. Examination of the 1g diagram (Figure 21) superimposed in this manner reveals that the F-4E can outclimb or out-accelerate the Fishbed F at the lower altitudes in the subsonic portion of the flight envelope--which includes the maximum maneuver corridor between the 12,000 and 40,000 feet energy levels. The F-4E also has a higher placard limit that allows it to reach higher airspeeds at a given altitude than the Fishbed F.

(S) On the other hand, examination of the 4g and 7g diagrams (Figures 22 and 23), superimposed over the F-4E air battle arena, show that the Fishbed F can outturn the F-4E at low airspeed where the F-4E cannot pull the same g force. Also, the Fishbed F can conserve energy better than the F-4E at every altitude/airspeed combination between the 12,000 and 40,000 feet energy levels as well as everywhere in the common portions of the maneuver envelopes. (At airspeeds beyond the common regions, the F-4E is obviously better.) Such comparisons reveal that the Fishbed F is better than the F-4E in defending against surprise attacks. These comparisons also reveal that the Fishbed F is better than the F-4E for employing the general maneuver strategy since the Fishbed F can outmaneuver the F-4E near the quickest/tightest turn boundary and near the maximum maneuver corridor. Only in low g, low turn rate maneuvers near the maximum maneuver corridor is the F-4E better. The conclusion is that the Fishbed F is the superior maneuvering fighter. This conclusion does not change if these two aircraft, in clean configuration, are compared against each other in the same manner.

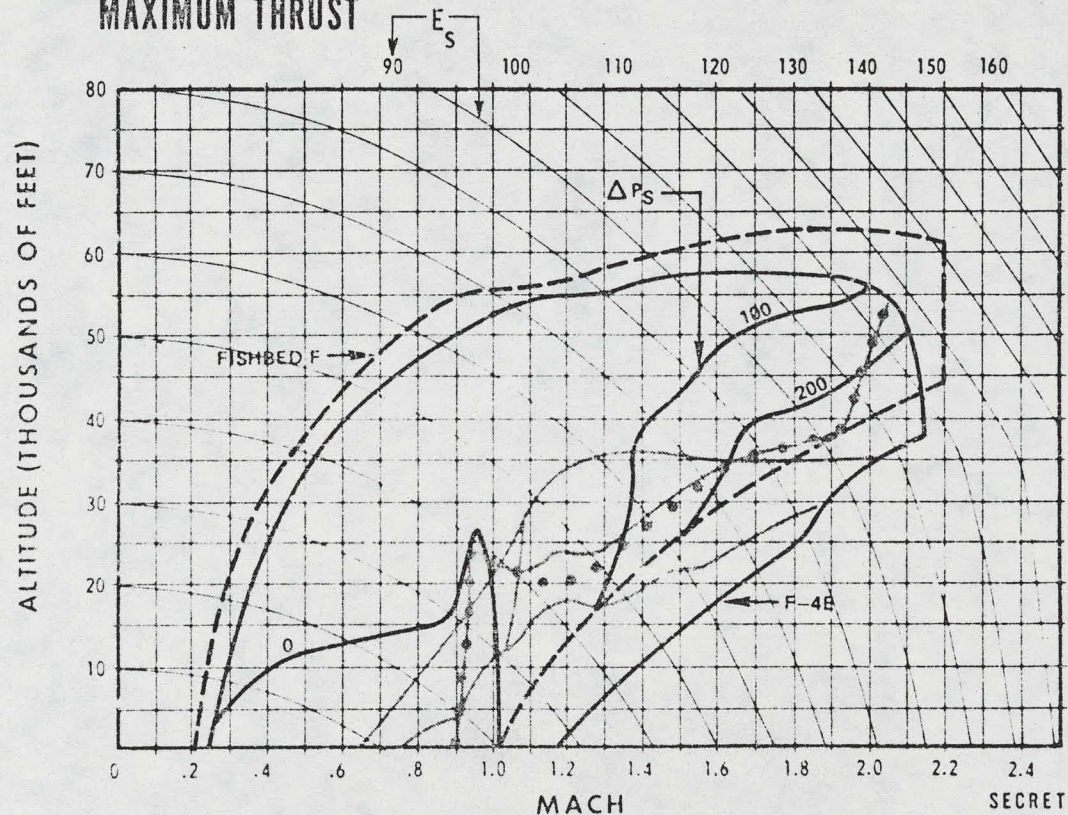
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AIR BATTLE ARENA
HORIZONTAL ATTITUDE
MAXIMUM THRUST

FISHBED F - F-4E (s)
1 G COMPARISON

F-4E (U)
4 AIM-7 MISSILES



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Figure 21. F-4E Versus Fishbed F 1g Overlay Diagram

AIR BATTLE ARENA HORIZONTAL ATTITUDE MAXIMUM THRUST

FISHBED F - F-4E (s)
4 G COMPARISON

F-4E (U)
4 AIM-7 MISSILES

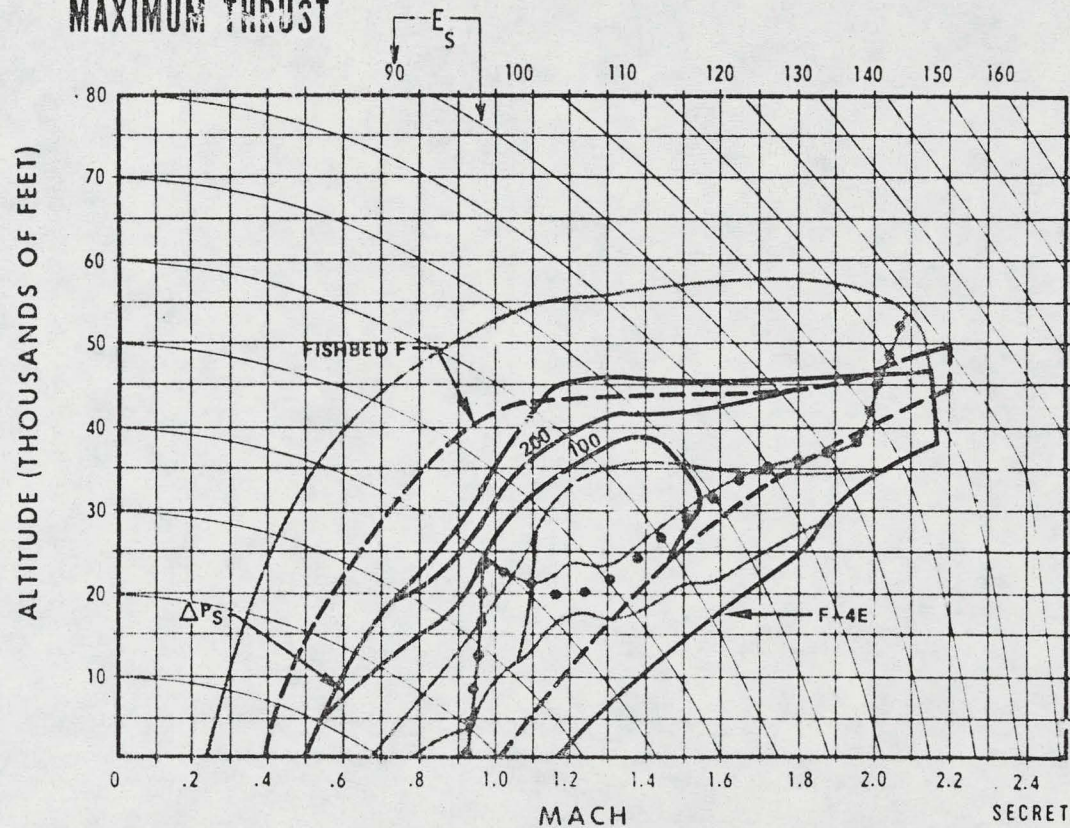


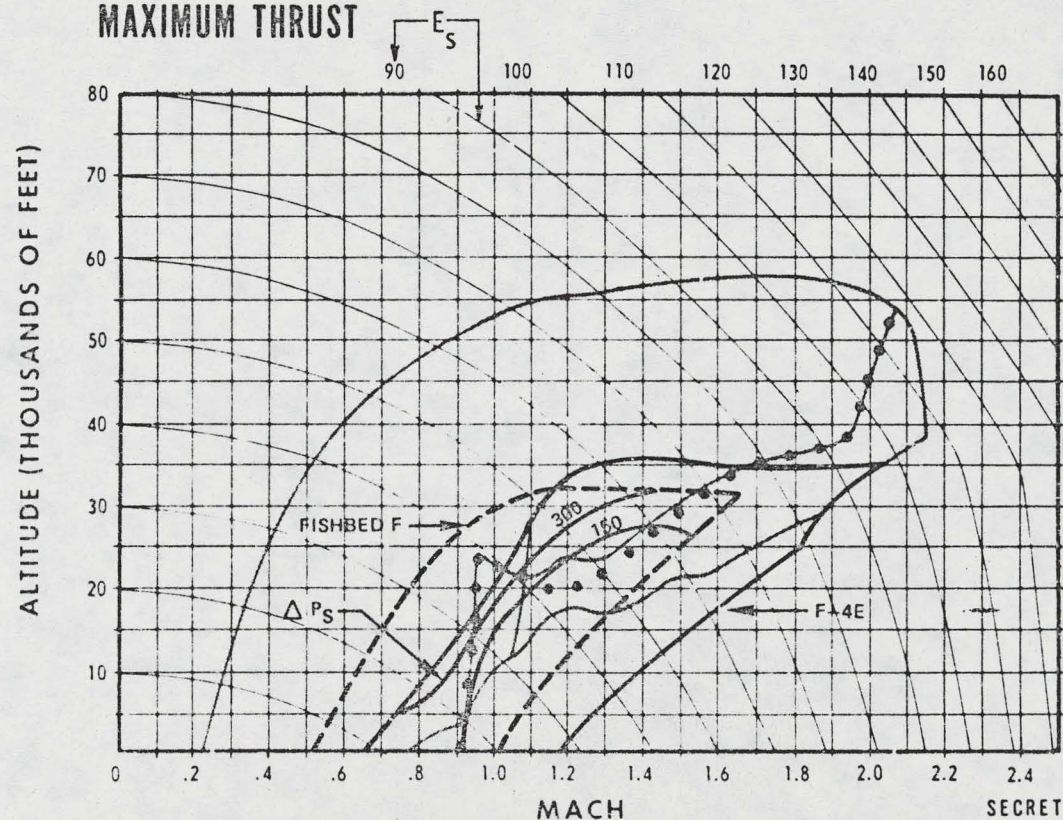
Figure 22. F-4E Versus Fishbed F 4g Overlay Diagram

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AIR BATTLE ARENA
HORIZONTAL ATTITUDE
MAXIMUM THRUST

FISHBED F - F-4E (s)
7 G COMPARISON

F-4E (U)
4 AIM-7 MISSILES



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Figure 23. F-4E Versus Fishbed F 7g Overlay Diagram

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SECTION IV

APPLICATION TO DESIGN

(U) Use of the maximum maneuver concept tactically to achieve superior results suggest that it can also be used during the design process to produce better performing fighters. Specifically, the energy methods associated with the maximum maneuver concept can be turned around to identify a criterion, or measure of merit, for selecting superior configurations. Also, the air battle arena and maximum maneuver diagrams can be used to produce performance superiority over the threat aircraft out of the configurations carried forward for that purpose.

A. CONFIGURATION SELECTION

(U) Configuration selection involves a match-up of those physical characteristics that produce superior airframe or configuration performance. In general, an examination of the key configuration characteristics, or parameters, shows that:

- Low sweep reduces drag due-to-lift while high sweep reduces supersonic wave drag.
- Low aspect ratio reduces profile or supersonic wave drag while high aspect ratio reduces drag due-to-lift.
- Low thickness-to-chord reduces profile or supersonic wave drag while high thickness-to-chord reduces structural weight.
- Low camber and twist reduce profile or supersonic drag while high camber and twist reduce drag due-to-lift at higher lift.
- Low maximum cross section and appropriate area distribution reduce supersonic wave drag while increased maximum cross section, and little attention to area distribution reduces costs but increases supersonic wave drag.

(U) Since the problem is to find how much sweep goes with how much aspect ratio, etc., some criterion, or measure of merit, must be identified in order to produce a configuration with the right combination of these conflicting characteristics that maximize maneuverability and/or range for a given cost.

(U) An examination of the maneuverability and range expressions reveals that thrust-to-weight (T/W) and specific fuel consumption (SFC) represent engine performance while drag-to-weight (D/W), radial g force (N') and drag (D) measure configuration performance. Using these expressions and manipulating those terms that are configuration dependent, shows that:

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Energy Rate (P_s) increases with a decrease in D/W .

$$P_s = \left(\frac{T}{W} - \frac{D}{W} \right) V = \left(\frac{T}{W} - \frac{D}{W} \right) V = \left(\frac{T}{W} - \frac{N}{L/D} \right) V$$

Turn rate ($\dot{\theta}$) increases while turn radius (R) decreases with an increase of N' .

$$\dot{\theta} = \frac{gN'}{V} R = \frac{V^2}{gN'}$$

Range (R_a) increases with a decrease in D or D/W at zero radial g and given weight.

$$R_a = V \frac{W_f}{\dot{W}} = V \frac{W_f}{(SFC)(D)}$$

Since an increase or decrease of N' produces an increase or decrease in load factor (N), then maneuverability and/or R_a can be maximized (for a given engine) if N is maximized for any D/W ratio or conversely if D/W is minimized for any N .

(U) Thus, N and D/W (the dissipative force in the P_s expression) can be used to represent configuration performance as follows:

$$N = \frac{C_L q}{W/S}$$

$$\frac{D}{W} = \frac{C_D q}{W/S}$$

where C_L is lift coefficient

C_D is drag coefficient

W/S is wingloading

q is dynamic pressure

Since q is configuration independent while $C_L/(W/S)$ and $C_D/(W/S)$ are configuration dependent, the configuration performance can be maximized if $C_L/(W/S)$ is maximized for any $C_D/(W/S)$ or conversely if $C_D/(W/S)$ is minimized for any $C_L/(W/S)$.

(U) Clearly, it follows that $C_L/(W/S)$ versus $C_D/(W/S)$ can be used to measure as well as to maximize configuration performance (Figure 24). When used in this manner $C_L/(W/S)$ can be regarded as load factor, or specific lift, independent of dynamic pressure while $C_D/(W/S)$ can be regarded as drag-to-weight, or specific drag, independent of dynamic

REPRESENTATIVE CONFIGURATION PERFORMANCE CURVES

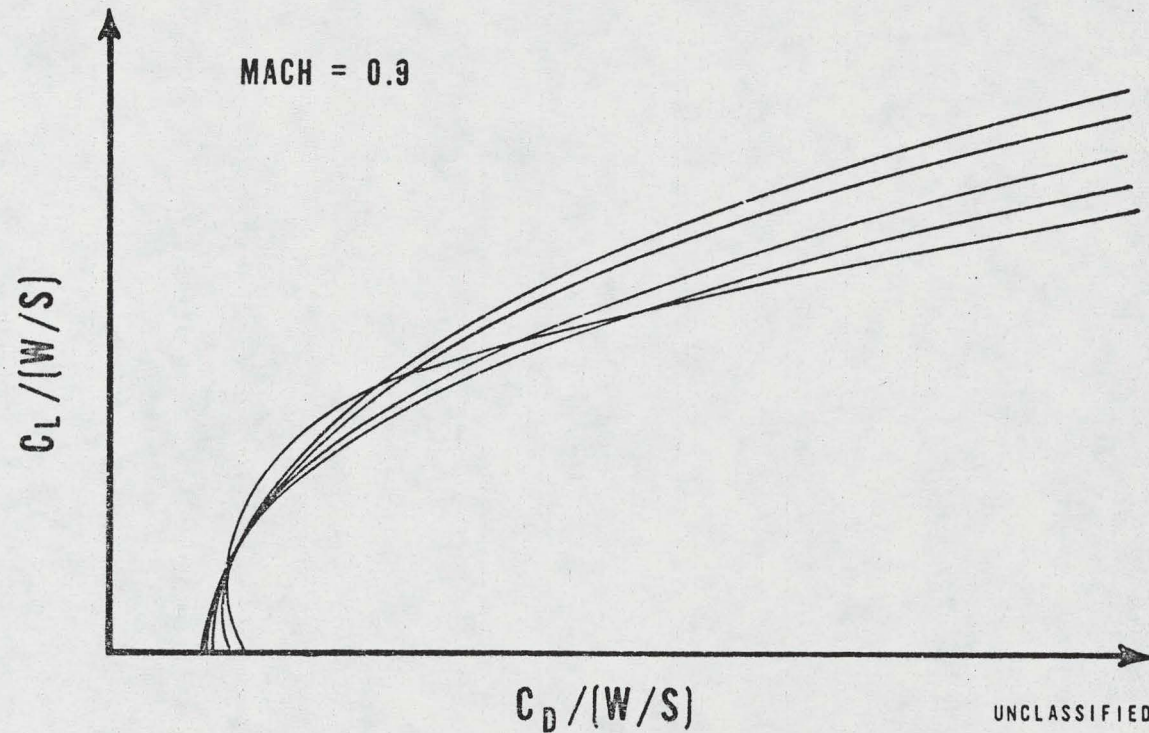


Figure 24. Representative Configuration Polars

pressure. Excellence is left and up. Using this criterion, existing configurations can be compared against one another. New configurations, possessing different combinations of sweep angle, aspect ratio, thickness/chord ratio, etc., can be compared against one another to surface those configuration options that produce maximum performance across a broad spectrum of altitude and airspeed for a given thrust, fuel, and gross weight (for performance realism, handling quality constraints - such as pitch-up, yaw, and roll reversal - must be imposed to insure that only useable $C_L/(W/S)$ and $C_D/(W/S)$ values are considered). Those options that exhibit superior configuration performance can then be carried forward to establish engine/airframe performance.

(U) In summary, the goal of configuration selections is to find that balance of configuration parameters that provides the highest N or $C_L/(W/S)$ for any D/W ratio or $C_D/(W/S)$ across a broad spectrum of altitude and airspeed. The configurations selected must satisfy this goal for a given gross weight, fuel fraction - fuel weight/weight (W_F/W), and T/W .

B. PERFORMANCE SELECTION

(U) Since a method has now been established for identifying superior configurations, a specific engine can be matched with an airframe. But first the performance level required to defeat a known or postulated threat must be identified.

(U) Key performance characteristics, or parameters, that must be considered are W/S , T/W , and W_F/W . In general, W/S determines how well a fighter can turn (low wingloading produces high turn rates and small turn radii); T/W determines how rapidly a fighter can climb and/or accelerate (high thrust/weight produces quick climbs and/or accelerations) and W_F/W determines how long a fighter can stay or persist in a fight, and/or how far he can go (high fuel fraction produces high persistence and/or long combat radius). Now, since low W/S , high T/W and high W_F/W improve combat maneuverability, combat persistence, and combat radius, the problem is to find which combinations produce superior maneuverability, persistence, and radius for a given cost.

(U) Stated another way, T/W , W/S , and W_F/W must be balanced to produce superior maneuverability, superior persistence, and sufficient combat radius to defeat a known or postulated threat. Fuel trade-offs related to persistence and combat radius have only recently been addressed, and the impact upon W_F/W is not yet ready for proper discussion, therefore, this factor will not be considered. With only T/W and W/S to vary, performance selection involves finding that balance of T/W and W/S needed to achieve maneuvering superiority across a broad spectrum of energy states, and then selecting T/W and W/S for a required combat persistence, combat radius, and given cost that provides the widest margin of maneuvering superiority.

(U) With maneuver superiority over the threat aircraft as the goal, the air battle arena and maximum maneuver diagrams can be used to maximize maneuver superiority margin for sufficient persistence, required combat radius, and given cost. To achieve such a result, T/W and W/S can be varied parametrically until the overall margin of energy rate/turn rate superiority over a known or postulated threat is maximized across the maximum transient and maximum sustained maneuver regions. Clearly, such a parametric variation should be accomplished on the best options provided during the configuration selection procedure. Equally clear, for these selected configurations, is the idea that the altitude/Mach location of the maximum maneuver corridor, maximum transient, and maximum sustained maneuver regions should be included in the configuration selection process then cycled forward through performance selection to be sure that configuration characteristics in terms of sweep angle, aspect ratio, thickness/chord, etc., are properly matched with performance characteristics in terms of T/W and W/S to maximize overall maneuver superiority.

SECTION V

CONCLUSION

(U) The analysis discussed in this report results in the conclusions that:

1. Superior air-to-air tactics and fighter designs can be developed by using the maximum maneuver concept.
2. The maximum maneuver concept (via air battle arena, maximum maneuver diagrams) and the results of attack geometry analysis with basic tactical maneuvers can be employed to devise superior maneuver/countermaneuver schemes and to determine the best flight regions for achieving tactical superiority over the threat.
3. Configuration performance curves $C_L/(W/S)$ versus $C_D/(W/S)$ can be employed to identify physical characteristics (AR, t/c , Ω , etc) necessary for superior airframe performance.
4. Air battle arenas and maximum maneuver diagrams can be employed to isolate the T/W and W/S domain necessary to achieve engine/airframe performance superiority over the threat aircraft.

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13. ABSTRACT The ideas developed in this report expand the energy maneuverability concept to provide a capability to describe aircraft performance in general and maneuverability in particular. Specifically, the report identifies the best region in which to change altitude, airspeed, and direction. Using these results, the concepts are applied tactically to develop a general maneuver strategy, show where the air battle should take place, and perform a comparative analysis. Finally, the concepts are related to the design of aircraft and how they can be used for configuration and performance selection.			

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