Comparing the Effectiveness of Air-to-Air Fighters: F-86 to F-18

April 1982
Contract MDA903-81-C-0312

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INTRODUCTION

PURPOSE

The purpose of this study is a) to derive and document a method for comparing the effectiveness of air-to-air fighters, based on historical combat experience; b) apply this method to the important air-to-air fighters of the last 30 years; c) compare the analytical assessment of these fighters with the combat results they obtained over the last 30 years; and d) derive some insights that may be useful in the conceptual design of the next generation of air-to-air fighters.

SCOPE

The study addresses only air-to-air effectiveness; air-to-ground considerations are excluded. The fighters to be examined are the principal U. S. fighters from the F-86 to the F-18, plus a small number of particularly significant foreign fighters. The measures of effectiveness are to be based, wherever possible, on relatively simple, easy-to-obtain technical data.

CONTENTS

Chapter II describes the nature of air-to-air combat, in air wars from WWII to the 1973 Arab-Israeli War. It also introduces the fighters to be compared. Based on the nature of air combat, Chapter III derives measures of effectiveness for comparing air-to-air fighters. Chapter IV calculates estimates of these measures for the principal fighters of the last 30 years and draws overall comparisons. Chapter V tests these analytical comparisons against the combat results of the air wars of the last 30 years. Chapter VI derives insights concerning the desirable characteristics of the next generation of air-to-air fighters.

CHAPTER II

THE NATURE OF AIR-TO-AIR COMBAT

INTRODUCTION

This chapter describes some of the salient features of air-to-air combat, as it has taken place in WWII, Korea, Vietnam, the 1971 Indo-Pakistani War and the 1973 Arab-Israeli War. The purpose is to provide the background for Chapter III, which will derive, from the combat experience, the principal measures of effectiveness for comparing air-to-air fighters. The chapter also introduces the aircraft to be compared in Chapter IV.

No attempt is made to provide a comprehensive summary of the history of aerial combat. The description emphasizes day combat, since this has been and continues to be the dominant form of air-to-air engagement. However, the markedly different nature of night combat, as actually fought, is briefly discussed.

EARLY WWII COMBAT

Air Combat Before the Battle of Britian

The 1939 German blitzkrieg campaign against Poland saw little significant air-to-air combat because of the one-sided dominance of German pilots and German fighters, both in performance and numbers. Remarkably, however, a few Polish fighter pilots became aces in 225 mph open cockpit fighters against modern 375 mph Messerschmitt 109's --an early indication of relative importance of pilot skill versus aircraft performance.

The same one-sided dominance was seen again in the blitzkrieg invasion of France -- even though Allied air-to-air fighters outnumbered the

German fighters by to .[1] The French fighters offered little effective opposition, mostly due to the weak and demoralized senior leadership of the French forces. The heaviest aerial opposition the Germans faced were the British fighters over northern France, particularly those covering the evacuation at Dunkirk.

Despite the competitive speed and maneuvering performance of the Spitfires (and the nearly competitive performance of the Hurricane), the British did poorly in these engagements. Their exchange ratio was probably less than : . The reasons were simple: some of the German pilots had had combat experience in Spain and Poland and, perhaps even more important, the Germans used better tactics derived from much more realistic peacetime training.

The RAF tactics were based on peacetime one versus one dogfight training (and very little of that for most pilots) plus a rigid adherence to the three-ship "vic" formation--a formation well-suited to canned air show maneuvers but impossible to maintain in the chaos following a surprise bounce in combat.

The Luftwaffe, in contrast, trained with regular <u>squadron-on-squadron</u> engagements from the mid-thirties on. The realistic chaos of such large engagements led them, quite naturally, to evolve the much more flexible "fingers four" formation, composed of a relatively loose spread of two two-ship elements. This was then refined, using Spanish Civil War combat experience, by the brilliant Luftwaffe tactician, Werner Mölders.[2] The fingers-four formation was, of course, far easier to handle during both attack and defense. Under the pressure of hard maneuvers, instead of dissolving like the "vic" into vulnerable singles, the finger-four would break

1/ Ref.

2/ Interview with Adolf Galland and Stanford Tuck. See footnote , ref . During this interview, the British ace Stanford Tuck pointed out that many-on-many training engagements were unthinkable in the peacetime RAF because of the possible accidents. Galland replied that the Luftwaffe was convinced that squadron-on-squadron training was critical and simply accepted the possibility of losses.

into two pairs which could still maintain leader-wingman mutual support.[1]

The very intense combat and high losses over Dunkirk in , 1940 represented a turning point for RAF tactics. Here the superiority of the German finger four and its associated tactics became obvious to the younger RAF pilots. And, as the British ace Stanford Tuck observed, the new tactics made rapid headway because many of the older RAF flight leaders insisting on adherence to the three ship "vic" were lost at Dunkirk.[2]

The Battle of Britian

The Battle of Britian saw the first protracted, intense air-to-air combat of WWII as well as the first use of a radar air defense net to help fighters intercept enemy bomber raids.

The battle pitted German light bombers, with fighters to cover them, against defending British fighters. At the beginning of the battle, the British fighters were badly maldeployed with most arrayed in the east and southeast of England, facing Germany.[3] Incomprehensibly, this maldeployment lasted for the full months of the battle. Thus, almost the entire weight of the fight--and of the British losses--fell on the fighters of 11th Group in south central England facing France.

Early warning of the larger bomber raids was usually by radar and by communications intercept. Only the latter could distinguish diversions from main effort. The radar, then as now, gave unreliable height information and raid size. Surprisingly, all tracking once the bombers crossed the English coast was based on visual observer reports, not radar. A highly centralized system

1/ This mutual support was critical for two reasons: a) if an attacker got onto the tail of either ship, the other could maneuver to threaten the attacker; and b) even more important, both ships could visually scan each other's rear blind cone to prevent dangerous surprise bounces.

2/ Ibid.

3/ Dizzy Allen. There were more than enough airfields available to bed down at least double 11th Group's initial strength.

Typical engagements started as squadron-size scrambles.[1/] The main problem of the defending fighters was to take off soon enough to get high enough to permit surprise bounces at high speed against the incoming raid. Time to climb to 20,000 feet was minutes for Spitfires and an even longer minutes for the Hurricane. If they were spotted by the escorting German fighters while still climbing at a vulnerable mph, they were at a severe disadvantage in both surprise and energy level. The result was usually a mauling.

A further problem was to get accurate and timely enough height and position information on the raid so the fighters could get within visual detection distance for a successful intercept. Less than percent of scrambles actually intercepted, due to poor height information, excessive time delays in the overcentralized control system,[2/] and radio channels saturated by RAF headquarters' insistence on close control of fighters.[3/] The failure to intercept on percent of sorties was, in effect, a painful percent reduction in the already inadequate 11th Group force size.

The exchange ratio in fighter-to-fighter combat was at least :1 against the British, due to a combination of adverse factors. The British pilots had inferior tactics since they were still in the process of changing over to the finger four system. Many of the RAF pilots were woefully undertrained, with less than 200 hours in fighters, some with less than 20 hours in type. The grossly inadequate force size in 11th Group led to overfatigue of the few available pilots, aggravated by the demoralization caused by heavy attrition.

However, a few factors worked in favor of the RAF. Most important was the geographical advantage of defending over friendly territory: about 50 percent of RAF pilots shot down were recovered safely; nearly 100 percent of

1/ The British preference for grass fields rather than concrete runways, gave a significant advantage in scramble time, since 12 aircraft could take off abreast without any subsequent waste of time in formation join-up. Leigh-Mallory of 12th Group advocated multi-squadron formations called "balbos", but they wasted so much time in forming up that they rarely arrived in time to intercept--nor is it clear that their great size would not have sacrificed most chances for surprise.

2/ At best, track position information provided by fighter controllers was at least 4 minutes old, due to the rigidly hierarchical control system which feed radar reports first to

3/ Close control means direct vectoring of each fighter formation to the target by a separate ground controller and a separate radio channel. The decentralized alternative is broadcast control, where one controller simply broadcasts to all fighters in the area, using a single channel, a "running commentary" on the position, heading, height and speed of the target raid. The fighters then independently decide on the best intercept tactics. Broadcast control, the few times it was tried during the Battle of Britian, worked well. Today, U.S. (and even more so, Soviet) air defense control systems are all designed around the close control doctrine.

German pilots shot down in the Battle of Britian were either lost or taken prisoner. Another favorable factor was the astonishing German failure to use belly tanks--even though they were available[1] -- which limited Messerschmitt 109's to 20 minutes over England. This left most Luftwaffe bombers uncovered as they approached London. German fighter losses were also increased by the orders of their bomber general, Speule, to provide close escort to the bombers -- which greatly increased their vulnerability to surprise bounces due to lowered cruise speed and increased visual detectability. And, of course, as both sides discovered, the bombers themselves were all too vulnerable to fighters, no matter how much defensive armament they carried.

Due to the mistakes on both sides, the battle for air superiority was a see-saw. By , the Germans had gained clear air superiority over 11th Group and held it for several weeks.[2] But instead of focusing their bombing effort on the 11th Group bases and control system, they succumbed to the temptation of bombing London. This saved 11th Group, magnified the German bomber (and fighter) lossed since London stretched the Messerschmitts to the limits of their fuel reserves, and greatly hardened the British population's resolve and morale.

Eventually, through the attrition of German pilots (aircraft were being replaced at an adequate rate), the balance of the battle swung toward the British side. The German bombing efforts petered out towards the end of , 1940 and soon the Luftwaffe switched over to relatively ineffectual night harrassment raids with small formations of bombers, mostly sneaking into England at low altitude below the radar coverage.

1/ p. , _The First and the Last_, Adolf Galland. Galland implies that German fighter pilots initially were afraid of a possible fire hazard with belly tanks. Eventually, they overcame this, presumably after gaining familiarity with the hazards of too little fuel.

2/ Allen

AIR-TO-AIR COMBAT OVER GERMANY

Luftwaffe Fighter Defenses Against Daytime Bombing

From until the breakout from Normandy, there were continuing fighter engagements by Allied fighter sweeps over northern France, but most German fighter forces were soon redeployed to the defense of the Reich against the buildup of massive Allied bomber raids.

The strength of the Reich's fighter defenses, initially about 300 to 400 fighters in 1943, was sufficient to inflict over 20 percent losses on unescorted B-17 raids such as the two disastrous attacks on Schweinfurt. This made daytime bombing nearly impossible until the advent of long range fighters, the P-47 and the P-51. With drop tanks, these fighters had operational radii of and 800 miles, much longer than the Spitfire's 170 miles. By the end of 1943, American fighters were escorting bombers and conducting independent sweeps deep into Germany. By mid-1944, as many as 2,000 fighter sorties per day were attacking German fighters everywhere: taking off, landing or parked at operational bases; at training schools; and, of course, during the frequent German attempts to break up the big bomber formations.

American tactics, like the RAF before them, copied the German loose finger-four system --mainly because of its great advantages in maintaining effective lookout and mutual support against the surprise bounce.

The Advent of the American Long-Range Fighters

Up through the end of 1943, the 300 to 400 fighters defending the German homeland made deep, unescorted daylight bombing by B-17's prohibitively expensive -- as witness the 20 percent or more attrition inflicted on the two disastrous Schweinfurt raids.

In late 1943, the advent of the P-38, the P-47 and P-51, together with sufficient supplies of the essential long range drop tanks, made deep fighter escort possible. The P-47 had an operational radius of 600 miles; the P-51 had 800 miles; the P-38 had 900 miles combat radius. The big 500 to 1,000 bomber raids of 1944 had fighter escorts of at least 1 fighter for every 2 bombers, sometimes more.

The P-38 was the least successful of these escort fighters; due to high losses and a poor kill record, by spring of 1944 General Doolittle had decided to begin replacing them with P-51's. The 17,500 P-38, despite its excellent 360 mph cruise speed and 400 mph top speed, was too large and visible,[1/] too inferior in maximum g,[2/] and had both poor roll rate and poor dive acceleration. In addition, its two engines proved to be mostly a survivability handicap; if either one was hit over Germany, the aircraft was likely to be lost due to either fire or enemy fighters downing the straggler.

The 10,100 pound P-51D was the most successful of the long range fighters: it was not much larger than the Focke-Wulf 190A and the Messerschmitt 109G, had a much better 360 mph cruise and 437 mph top speed, had better dive acceleration, could equal or out-turn the German fighters, and could match their roll performance.

The 13,500 pound P-47 did nearly as well as the P-51. Although the P-47 was somewhat larger and slightly slower, it had unparalleled dive and roll performance and a more survivable engine (due to absence of a vulnerable liquid cooling system). The major advantage of the P-51 in the air war over Germany was its longer range and higher cruising speed.

1/ "Since the P-38s were easily recognized, even at great distances, the enemy simply attacked the bomber stream at other points". P. 116, P-38 Lightning at War, J.Christy and J.Ethell, Scribner's, 1979.

2/ Except at speeds below 140 mph, but turning at these slow speeds was rarely useful in combat.

Fighter Combat Over the Reich

Due to their limited fighter strength, the German defenders concentrated on attacking the U.S. bombers while minimizing engagements with the escorting fighters -- much as the British defenders did in the Battle of Britian. Like the British, they also experimented with "Big Wing" attacks on the large bomber raids.

These consisted of as many as 100 intercepting fighters; roughly two thirds of these "battle formations" were high performance light fighters for engaging the escorts and one third were less-agile bomber-destroyer fighters weighed down with heavy armament -- 30mm and 37mm cannon, rockets, etc -- for attacking the heavily armored heavy bombers. These unwieldy formations scored occassional successes when they managed to avoid or penetrate the American fighter escort surrounding the bomber stream. Mostly, however, the bomber-destroyer fighters [1/] were sitting ducks for the faster and more agile P-47s and P-51s.

From their first arrival in the European theater, the American fighters adopted the loose finger-four system, usually flying in three flights of four under a squadron leader. The most successful American pilots emphasized high speed surprise bounces, heavy use of the diving and rolling superiority of the P-47 and P-51 (in abrupt transient maneuvers such as the Split-S, the rolling attack, and the zoom plus turn reversal), and avoidance of steady turning engagements -- particularly against the better turning FW-190.

The endless debate about close escort versus loose escort for bombers broke out again, as it had for the German escort fighters in the Battle of Britian. The 8th Fighter Command solution was to usually assign a few squadrons as close escort with the rest flying loose top cover and

1/ These included the large twin-engine Messerschmitt 110 and 410 plus heavily cannon-armed destroyer versions of the single engine Focke-Wulf 190 and the Messerschmitt 109 fighters.

flank sweeps for the big bomber formations. The close escort squadrons usually suffered more surprise bounces and achieved less surprise kills due to slower speed and higher visibility; they also had difficulty in breaking up German fighter formations before their attacks on the bombers.

But by the end of 1943, the Allied fighters were achieving increasingly favorable exchange ratios in fighter versus fighter combat, both in escort and in independent sweeps over Germany. This, of course, was due to the continuous attrition of the better and more experienced German pilots. The best units, such as the P-47-equipped 56th Group, were exceeding 6:1 exchange ratios. This, combined with a spring 1944 buildup to nearly 2,000 fighter sorties on days of heavy action, led to such heavy pilot losses among the outnumbered Germans that they rarely managed to put up more than 400 sorties against the heaviest bomber raids.

For the Luftwaffe the bottleneck was clearly pilot production, not aircraft production. By September 1944 the Luftwaffe was receiving 3,000 new fighters per month but only 1,000 pilots per month[1/] --and the pilots they received were grossly undertrained. The poor pilot quality, in turn, led to a further increase in pilot losses and even less ability to protect aviation fuel production from bomber raids or to keep American fighter sweeps from disrupting the Luftwaffe flying training.

The Introduction of Jets to Combat[2/]

Fifteen Me262's forming a combat test unit, Erprobungskommands 262, began air-to-air operations at the end of July 1944[3/] flying from a base deep in Bavaria. In August, the unit claimed 5 kills, mostly reconnaisance aircraft. A deployment to forward airfields in western Germany during October had mixed results: claims of 19 kills including four B-24's, but at a

1/ The First and the Last, A.Galland, Henry Holt and Co., 1954

2/ This section is based on The German Jets in Combat, J.Ethell and A.Price, Jane's Publishing, London, 1979

3/ Much higher priority was given to an Me262 bomber unit, KG51, which began combat operations in France on July 20,1944. This unit was still flying more than half the total Me262 sorties up until March 1945. Its bombing operations had negligible effects on the Allies, but it suffered heavy losses. This unit's losses are excluded from the present discussion.

cost of six Me262's shot down and seven destroyed in accidents. The main reasons were green, undertrained pilots and unreliable engines. In early November, the unit was withdrawn back to Bavaria to receive pilots with more "thorough" conversion training. The training consisted of 25 hours in propellor fighters plus 10 hours in the Me262. By date February, the retrained unit was back in combat and able to fly about 25 sorties on days of heavy bomber action.

During March, American pilots were adapting to the jets. Standing fighter patrols were mounted near the known jet bases to catch them at takeoff or landing speeds. At higher altitudes, the Americans found that diving attacks at 450 to 500 mph could sometimes succeed in catching the Me262's, particularly if the jet pilots were inexperienced enough to turn hard or if they could be caught at their climb speed of 340 mph. Nevertheless, well-flown Me-262's could penetrate the escort fighter screens with ease and were extremely lethal against bombers, achieving the excellent record of about one heavy bomber kill for each 5 intercept sorties.[1/] At the same time, because the jet cruised about 100 mph faster than the P-51 and P-47, surprise bounces were a constant threat to American fighter pilots near the jet airfields.

The tactics made possible by superior cruise speed are well summarized by William Green:

"Operating at normal altitudes for fighter combat, a formation of Me262's could, upon sighting Allied fighters, accept or refuse combat as the formation leader chose owing to the jet fighter's superior speed. He could climb to gain altitude and simultaneously overhaul any Allied formation. When attacked by Me262's from above, Allied fighter pilots invariab-

1/ Me262 operations were aimed almost exclusively at shooting down bombers. Less than one fighter was shot down for each three bombers destroyed by Me262's.

ly turned into the attacking jets, but some always straggled and were shot down, and the Me262 was usually able to pull up and repeat the attack. If the Allied fighters were circling defensively it was considered practical to dive and fire while going through one-third or half a turn with them and then climb away. Longer turning engagements always placed the Me262 at a disadvantage." 1/

Pilot quality in most of the Me262 units kept on declining: one notably unsuccessful unit consisted of rapidly converted bomber pilots; most units had sizable numbers of pilots with only 100 to 200 hours total flying time. By March, jet conversion training was down to as little as two sorties. One exception was JV 44, composed mostly of highly experienced fighter aces who volunteered in January 1945 to serve under the recently relieved Inspector General of Fighters, Adolf Galland. But JV 44 was actually operational for only the last four weeks of the war, scoring about 50 claimed kills.

By March 1945, over 950 Me262's had been delivered. Despite this, only 30 to 45 sorties per day were flown against the large daytime bomber raids. There was no shortage of airframes but the shortages of combat-capable pilots, spares and fuel were crippling. By end-April, nearly 1,400 Me262's had been delivered, but the largest number flown in a single day against an Allied bomber force was only 55. This was at a time when 1,000 Allied fighters would escort a major raid and perhaps another 1,000 fighters would be sweeping and strafing all over Germany.

By April, it was a matter of luck to take off and land a flight of Me262's without being bounced by a squadron of Allied fighters patrolling over the field; actually firing at a bomber formation practically guaranteed attacks from one or more squadrons of escort fighters. In the end, 1/ The Warplanes of the Third Reich, W.Green, Doubleday and Company, 1970 the Me262 day fighter probably shot down no more than 150 Allied aircraft. In exchange, about 100 of the jets were destroyed in aerial combat with perhaps 75 of them downed by fighters.

Even though the Me262's performance rendered obsolete all earlier fighters, in the end it had a negligible effect on the air war. It had been crushed by the numerical superiority of the Allied fighter force and the Germans' inability to produce enough first-rate fighter pilots.

Air-to-Air Armament in WWII

WWII opened with the British Hurricanes and Spitfires using eight Browning .303 caliber machine guns firing a total of 180 rounds in one second at a velocity of 2440 feet per second. The lethality of these rifle rounds against fighters was marginal; against the quite lightly armored German twin engine bombers this armament proved to be inadequate.[1/]

The Messerschmitt 109E that faced the Hurricanes and Spitfires was only slightly better armed: it had two Oerlikon MG FF 20mm cannons firing a heavy 4.7 ounce HE shell, but the velocity was only 1950 feet per second and total rate was only 12 in one second. It also carried two 7.9mm rifle caliber machineguns. This armament was adequate against fighters but later proved quite inadequate against the heavily armored U.S. heavy bombers.

By spring of 1941, four Hispano-Sinza 20mm cannons had been adapted for wing mounting on Hurricane Mark IIC fighters. These four fired 47 rounds/sec at a velocity of 2820 feet per second; their HE shell weighed 4.4 ounces. Reliability of the feed installation was poor but lethality--as demonstrated in combat over France, North Africa and Malta--was much more satisfactory than the eight Brownings. Later Spitfire models were up-gunned to two 20mm Hispanos and four Brownings.

1/ For instance, during the Battle of Britian six Spitfires fired a total of 7,000 rounds at a DO-17 bomber with no result (p.107, Fighter, L.Deighton, Jonathan Cape Ltd, 1977). Similarly, in 1940 a German bomber with 220 caliber .303 holes in it returned to base safely (Duel of Eagles, P.Townsend, Wiedenfeld and Nicolson, 1970).

The main American fighters quickly standardized on the .50 caliber M2 Browning machine gun, using eight in the P-47 and six in the P-51D. The P-47 installation fired 113 rounds per second at a good muzzle velocity of 2900 feet per second;[1/] each bullet was four times as heavy as the rifle caliber .303 bullet. This proved to be quite adequate against both fighters and light bombers. Gen. J.C.Meyer, a high-scoring P-51 pilot, has stated that, against fighters, kills per pass were between .4 and .5, a remarkably high lethality. How the .50 caliber would have fared against an armored four engine bomber is open to question.

To address the heavy bomber threat, by spring 1942 the Luftwaffe had mounted on the FW-190 two Mauser 20mm cannons (each firing 3.5 oz shells at 2500 feet per second and 13 rounds per second) and, peculiarly, two of the much slower Oerlikon MG FF cannons firing the heavier, slower 20mm round for a total of 38 cannon rounds in one second.

The 20mm systems proved to be marginally lethal against heavy bombers: Luftwaffe gun camera film analysis showed that an average of 20 hits to kill a heavy bomber with 20mm shells --and only 2% hits were being achieved by average pilots.[2/] Assuming a 2 second average burst length and the FW-190 cannons' rate of fire, this translates into 13 passes per kill. Or, put another way, the average FW-190 pilot was getting only about .08 kills per pass against heavy bombers.

The poor effects of the 20mm led the Luftwaffe to experiment with a variety of heavier bomber-killing ordnance including 30mm through 50mm cannons and rockets ranging from 55mm to 210mm.[3/] The 30mm cannon was widely used[4/] and each 11 oz HE projectile proved to be about 6 times as lethal in combat as one 20mm shell. Only 3 to 4 hits were required, on average, to down a heavy bomber. However, the 30mm had only 1750 feet per second

1/ Also available were special high velocity caliber .50 rounds for aircraft work with 3200 feet per second.

2/ Keep in mind that the vast majority of bombers were shot down by pilots much better than average, getting results perhaps as good as 2 or 3 passes per kill.

3/ The 55mm, with 12 mounted under each wing of an Me262, was fairly successful from ranges of 600 yards against non-maneuvering heavy bomber formations. The relatively low burnout velocity of 1740 feet per second precluded its having much chance of hitting maneuvering targets.

4/ Four 30mm cannons were installed on the Me262. By late 1943, bomber destroyer versions of the FW-190 and Bf-110 carried two; the destroyer Bf-109 carried three, including one firing through the propeller hub.

velocity and only 11 rounds per second rate of fire. The 30 percent lower velocity meant the 30mm had to be fired about 30% closer than the Mauser 20mm to get equivalent hit percentages. In Fact, Luftwaffe experience showed that 400 yards was the typical open fire range for an effective 20mm pass; 300 yards was typical for 30mm cannons.

Night Air-to-Air Combat in WWII

The switch to night bombing by both the RAF and the Luftwaffe during and after the Battle of Britain sparked the rapid development and rise of night fighter forces on both sides. By summer 1940, German Ju-88 twin engine bombers were already flying night intruder patrols over RAF bomber bases to shoot down British bombers during the takeoff and landing phases of major raids; for the next year, they shot down twice as many bombers over England as were lost to German homeland night fighters.[1/]

Both sides pressed into night fighter service twin engine fighters (or light bombers) that had failed as dayfighters: for the Germans, mainly the Messerschmitt 110 and destroyer models of the Ju-88; for the British, the Blenheim, the Beaufighter and later the excellent Mosquito light bomber. Since night fighting was entirely a matter of stalking level-flying enemy bombers in order to obtain an unseen approach, the main airframe characteristics desired were good endurance and better sustainable speed than the target.

The British had installed their first airborne radars on Blenheim and Beaufighter night fighters by the fall of 1940. By the spring of 1941, the six or so squadrons of RAF night fighters were inflicting consistent, though far from decisive, losses on the frequent small raids being mounted by the Germans.[2/] These German raids soon declined to twenty or thirty

1/ The German intruders were controlled by a special radio intercept intelligence unit that listened in on RAF bomber radio channels (Fighter Tactics and Strategy, 1914-1970, E.H.Sims, Aero Publishers, Inc., 1980).

2/ The last big raid on London was a 500 bomber attack on May 10, 1941. British flak and night fighters together only inflicted a 1.4% loss rate.

single raiders on a typical night, due to the demands of the Eastern Front. Despite the difficulty of intercepting these fast and wary single raiders, particularly at the very low altitudes they preferred, the high scoring 604 Squadron was able to claim 200 kills in the three years between January 1941 and January 1943.

Starting in the summer of 1943, first one and then several British night fighter squadrons took on intruder raids over Germany,[1/] mainly to stalk German night fighters intercepting the big RAF bomber raids or to catch the Germans in their landing pattern. The high-scoring intruder pilot, Wing Commander Robert Braham, claimed 29 kills.

The Luftwaffe organized its first specialized night fighter squadron in July, 1940 and by the end of the year had one understrength wing (perhaps 50 Messerschmitt 110s) in place. This had increased to six wings and about 350 night fighters by early 1943.[2/] None of these fighters had onboard radar. To get within night visual range, they relied on radar vectors provided by ground tracking radars or on ground searchlight "cones" pinpointing the target bomber.

Despite the lack of onboard radar, German night fighters and flak were exacting 3% to 5% losses from the largest night bombing raids --such as the Cologne and Hamburg attacks --in the spring and summer of 1943. By March 1943, German night fighter claims reached 2000 kills, 80% of them heavy bombers.[3/]

The first operational quantities of airborne radars in the Luftwaffe were installed on Messerschmitt 110's and then on Ju-88's in the late summer of 1943. The 350 specialized night fighters were augmented by several more wings of converted single seat day fighters, now permitted to roam freely searching for British bombers by the light of air-dropped parachute flares, 1/ Only night fighters with obsolete radars were allowed on the intruder missions, to avoid compromising the British three year lead in airborne radar.

2/ Galland, ibid.

3/ Galland, ibid.

artillery illumination, and burning bombers.[1/]

By fall of 1943, the Germans had abandoned the easily-saturated close control vectoring of night fighters by ground radar controllers. Instead, broadcast control was introduced, this allowed the night fighters to select their own tactics for entering the bomber stream, based on a single "running commentary" broadcast of the position and progress of the main bomber force. Due to the combination of broadcast control, the gradual installation of airborne radars, increased flak and the add-on "Wild Boar" single seaters, RAF night bomber losses increased to beyond 6% during the winter of 1943-44. During the February 1944 "Big Week" of round-the-clock raids on German aircraft factories, British night bomber losses were 6.6%, actually higher than the American daytime losses of 6%. The peak of night fighter effectiveness was reached in March 1944: the British bomber loss rate during the disastrous raid on Nuremberg was 12%.

As in the case of German day fighters, the night fighter force's effectiveness over the last year of the war deteriorated --despite a surplus of airframes --mainly due to shortages of adequately trained pilots.

Over the entire course of the war, several thousand aircraft were shot down in night combat. There were three salient features of this type of combat, painfully learned by the participants of both sides:

- First, the primacy of surprise or, put another way, the great difficulty (and danger) of shooting down an alerted opponent, that is, an opponent maneuvering violently and returning fire.
- Second, the absolute necessity for visually distinguishing friend from foe (in order not to shoot down friendly fighters or bombers), even though this might require, on occasion, an

1/ These were the effective "Wild Boar" tactics developed to counter the temporary blinding of German ground radars by the chaff dropped for the first time in the Hamburg raids.

approach as close as 200 feet.

- Third, the necessity to use single mission, night fighting pilots and the futility of multipurpose use of day-trained fighter pilots for this highly specialized mission.

Curiously, in the five most important air wars since WWII, there has been no significant air-to-air combat at night --despite the sizable progress in airborne radar over the last 35 years. And further, no air force since WWII has trained and established a night fighter force for tactical air warfare.

KOREA: THE FIRST JET WAR

The First Encounters with the MiG-15

Within the first two weeks of the Korean War, USAF F-80's had cleared the skies of the few slow, poorly-piloted propeller-driven Yaks of the North Korean Air Force. The first real challenge to U.N. control of the skies over all of Korea appeared in November, 1950. A flight of four F-80's encountered and pursued a formation of seven Russian-piloted MiG-15's near the Yalu; the MiG-15's retreated across the river, then returned with a high speed "bounce" out of the sun.[1/] Neither side scored, but in ensuing days it became clear that the MiG-15 enjoyed much the same advantage over the F-80 that the Me262 had over the P-51: about 100 mph higher cruise and dive speed, better climb and acceleration but somewhat poorer maximum turn capabilities. The slower-cruising F-80's were at a severe disadvantage in achieving a surprise first bounce, though like the P-51 they could defeat a MiG-15 bounce with a hard break, if they saw in time. The advantages of the MiG-15 accelerated the introduction of the F-86 to the theater; the first F-86's began operating from Kimpo in December.

1/ *Full Circle*, J.E. Johnson, 1964, Ballantine Books.

Within two weeks, eight MiG-15's had been shot down with only one F-86 lost, an exchange ratio not far from the roughly 10 to 1 that prevailed for the rest of the war.

The Air War in MiG Alley

A pattern of air combat soon emerged that lasted for the remaining one and a half years of the war. F-86's using tanks to extend endurance to 80 to 100 minutes would be launched at regular intervals to patrol MiG Alley, the 140 by 60 mile zone along the Yalu. Given the 180 mile distance from Kimpo airbase they could spend about 45-50 minutes patrolling at about 30,000 to 45,000 feet in MiG Alley. Two wings of F-86's were assigned to this air-to-air duty; they mounted up to 150 sorties a day, with perhaps two-thirds flying to MiG Alley.

The MiGs' main base was at Antung, only 40 miles from MiG Alley. Since the Yalu River border was routinely violated by the F-86's,[1] MiG's were actually in jeopardy from takeoff to landing. The MiG opposition, which included both first line Russian squadrons and Chinese units in various states of training, eventually built up to about 1,000 fighters. These fighters only flew 3 sorties per day on average. However, a peak day's activity might see more than 300 sorties since the Communist forces tended to fly sporadically, putting up large formations on days when they intended to engage. The quality of Communist pilots varied widely, with only a few pilots --presumably the best Russian instructors[2] or the most experienced Chinese pilots -- showing aggressiveness and competence. Since the opposing fighters almost always entered MiG Alley at very high altitude (30,000 to 45,000 feet), both sides enjoyed excellent ground radar coverage[3] of the battle area -- much better than in the Vietnam War where

1/ The saying among U.S. fighter pilots in Korea at the time was, "There are no aces made south of the Yalu".

2/ Soviet defectors report that at least one Soviet pilot made ace in Korea.

3/ U.S. coverage was much helped by the radar station on Ch'o Do Island, not much over 100 miles from MiG Alley.

the low altitude gap below 3,000 to 5,000 feet plagued both defenders and attackers. Ground radar position reports were often used to get F-86's into the general vicinity of enemy fighters, but close control was not attempted and all F-86 acquisitions were visual. The MiG's appeared to be under close control at the opening stages of most fights.

When U.S. radar or monitoring of MiG radio channels showed heavy enemy activity, relatively large F-86 missions would be scheduled, sometimes amounting to as many as 8 or 10 flights of four. These flights of four usually entered the MiG Alley combat arena independently and several minutes apart.[1/] So the actual dogfights, even against formations of 60 to 80 MiG-15's, quickly broke up into attacks by pairs or fours.

Comparison of the MiG-15 and F-86

The pound MiG-15 and the pound F-86 were surprisingly closely matched. The MiG-15 had slightly superior rate of climb, acceleration and level flight speed above 30,000 feet, but this was offset by the F-86's better speed in a dive. The MiG-15 also had an edge in maximum instantaneous turn, although its poor handling and tendency to spin at high angles of attack limited the extent to which average MiG-15 pilots could make use of this turning advantage. Moreover, the MiG-15 had substantially slower roll and pitch rates due to lack of hydraulically powered controls; thus, it was considerably slower in transitioning from one maneuver to another than the very "snappy" F-86. The F-86 also had substantially better cockpit visibility than the MiG-15, particularly in the all-important rear quadrant.

These differences very quickly led the F-86 pilots to devise specific maneuvers to exploit the F-86's largest advantage; the ability to transition much more quickly between maneuvers than the MiG-15. This was the reason why the horizontal scissors maneuver became so popular in Korea. It allower the F-86, at each successive turn reversal, to turn in more quickly toward the opponent's tail ahd thereby gain more favorable tail position. Starting from a position of equal advantage (i.e., abeam and on parallel courses), two or three turn reversals against the MiG-15 were frequently enough to gain a successful tail firing position.

Armament in the Korean War

The F-86 fought the entire war with the same armament as the WWII P-51, six caliber .50 machineguns. This proved to be adequate, with an overall average of .34 kills per firing pass when the lead computing gunsight wasn't used and .30 when the sight was used.[1/] One-quarter of the pilots with multiple engagements had better than .49 kills per pass.[2/] Altitude appeared to have a strong effect on kills: for firings near 20,000 feet, kills per pass were .51; at 39,000 feet, kills per pass dropped to .27 on average.

Interestingly enough, an in-combat evaluation of the .50 caliber versus the 20mm was conducted from January,1953 to the end of the war. The Gun-Val test introduced into combat one squadron of F-86's with four M-39 20mm cannons installed in the nose. Based on confirmed kills, the six .50 caliber machinegun installation scored 1.43 times as many kills per pass as the four 20mm cannons.[3/]

The MiG-15's armament consisted of two low velocity 23mm cannons and one low velocity, low rate 37mm. The overall combat lethality of this armament proved to be remarkably low --about .025 F-86 kills per pass[4/] --due, in part, to the low skill levels of most of the Communist pilots.

1/ F-86 versus MiG-15, Institute for Air Weapons Research, University of Chicago, 19 May 1954 (declassified). These kill statistics were based on detailed examination of all the available F-86 gun camera film for the Korean War plus confirmed kill records.

2/ Fighter Pilot Performance in Korea, D.Strawbridge and N.Kahn, Institute for Air Weapons Research, University of Chicago, 15 November 1955.

3/ See footnote 1. The four 20mm cannon installation carried 500 rounds and fired at a combined actual rate of about 80 shots per second. The 300 pound lighter cal .50 installation carried   rounds and fired at a combined actual rate of 110 shots per second.

4/ Newsletter Number 11 (Table 2), Institute for Air Weapons Research, University of Chicago, July 1953.

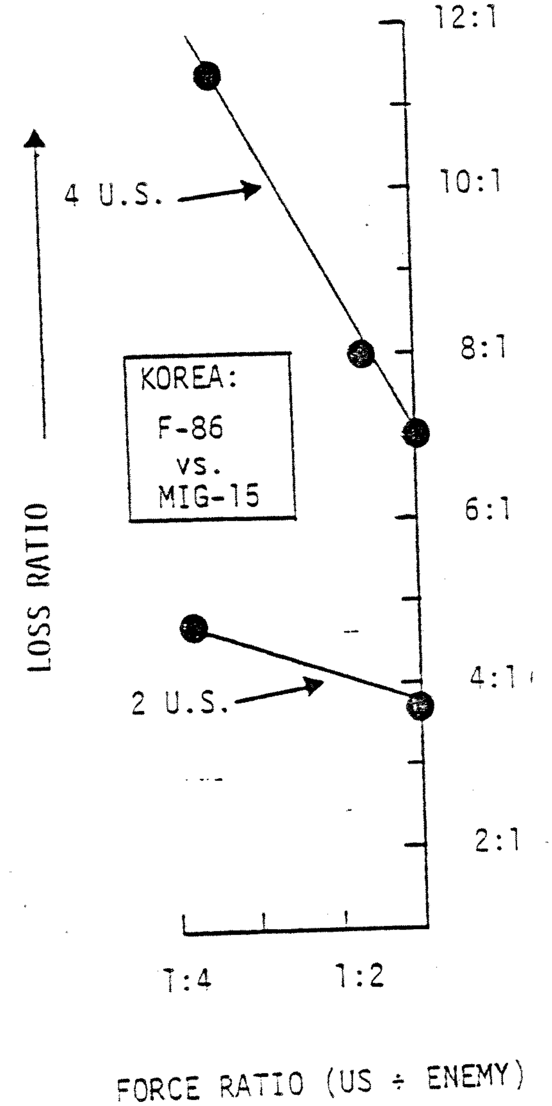
Air-to-Air Combat Outcomes

Over the entire course of the war, the F-86's of the 4th Fighter Interceptor Wing claimed 484 enemy aircraft destroyed and lost 48 F-86's to enemy fighters, a 10:1 loss ratio.[1/] The 51st Fighter Interceptor Wing had similar results. Of all 800 F-86 pilots who flew more than 25 counter-air missions in Korea, about 4.8% accounted for 48.2% of the kills,[2/] a number typical of most air-to-air wars.

Of considerable interest is the question of how combat outcomes varied with both the number of airplanes in the fight and with their relative force ratios. This is important both for insight into a) the tactical effect of increasing complexity and chaos within the dogfight; and b) the validity of Lanchester-type models for predicting loss ratios and combat outcomes. Since the Daily Intelligence Summaries for the Korean War[3/] provide F-86 and MiG-15 strengths for each encounter, as well as losses on both sides, it becomes a simple matter to categorize engagements and calculate exchange ratios. Figure 1 displays the exchange ratio as a function of force ratio for all engagements involving two F-86's and similarly for engagements involving four F-86's.[4/]

The results of the Figure 1 analysis are:

- o The more the F-86's were outnumbered, the more favorable their loss ratio --a clearly anti-Lanchesterian outcome.
- o Flights of four F-86's did at least twice as well as pairs.
- o When outnumbered about three and a half to one, four F-86's achieved, on average, loss ratios as good as eleven and a half to one.
- o At equal force size, four F-86's achieved a 7 to 1 favorable



12:1
10:1
8:1
6:1
4:1
2:1
4 U.S.
2 U.S.
KOREA:
F-86
vs.
MIG-15
LOSS RATIO
1:4
1:2
FORCE RATIO (US ÷ ENEMY)

Figure II-1

1/ Fighter Pilot Performance in Korea, D.Strawbridge and N.Kahn, Institute for Air Weapons Research, University of Chicago, 15 November 1955.

2/ Factors in Fighter-Interceptor Pilot Combat Effectiveness, E.P.Torrance et alia, Air Force Personel and Training Research Center, TR-57-11, November 1957.

3/ Quality-Quantity Tradeoffs: A Historical Analysis of Air Combat, C.T. Kelley, Jr. et alia, RAND R-1976-AF, April 1977 (C).

4/ Results for four F-86's include several engagements where five F-86's entered the fight.

loss ratio; pairs achieved only three and three quarters to one.

- The Communists would have substantially decreased their losses by flying in pairs or fours.

Many of the MiG Alley engagements involved U.S. forces much larger than pairs or fours, with nine engagements reported as involving 50 or more F-86's. These can also be analyzed, though it should be noted that the reporting of how many U.S fighters were involved in any one fight is inherently imprecise --particularly so since the F-86's tended to enter the fight as independent flights of four. Figure 2 displays the loss ratio outcomes as a function of U.S. strength for several fixed force ratios.

For engagements where the U.S. fighters faced equal or larger forces, the U.S. did best fighting in fours or eights; here loss ratios peaked at around 12 to 1. When larger U.S. gaggles entered the fray, loss ratios became less favorable: with 32 fighters engaged, loss ratios fell to 6 to 1. Furthermore, in these very large engagements, loss ratio was not improved by being outnumbered (as was clearly the case for pairs and fours).

For engagements where the U.S. outnumbered the Communists by about 2 to 1, there was no clear advantage for fours or eights. In general, loss ratios were much less favorable to the U.S. forces when they outnumbered the enemy than when they were outnumbered. The one exception is for very large fights involving 32 or so U.S. fighters, where an excellent 9.8 to 1 exchange ratio was achieved. This may be an anomalous point.

It should be noted that in the vast majority of engagements, U.S. forces were equal to or outnumbered by the MiG's. This, of course, helped greatly in keeping the overall U.S. loss ratio at such a high and favorable level as 10 to 1.

EFFECT OF INCREASING NUMBER
OF U.S. AIRCRAFT IN THE FIGHT:
F-86 vs MiG-15 IN KOREA

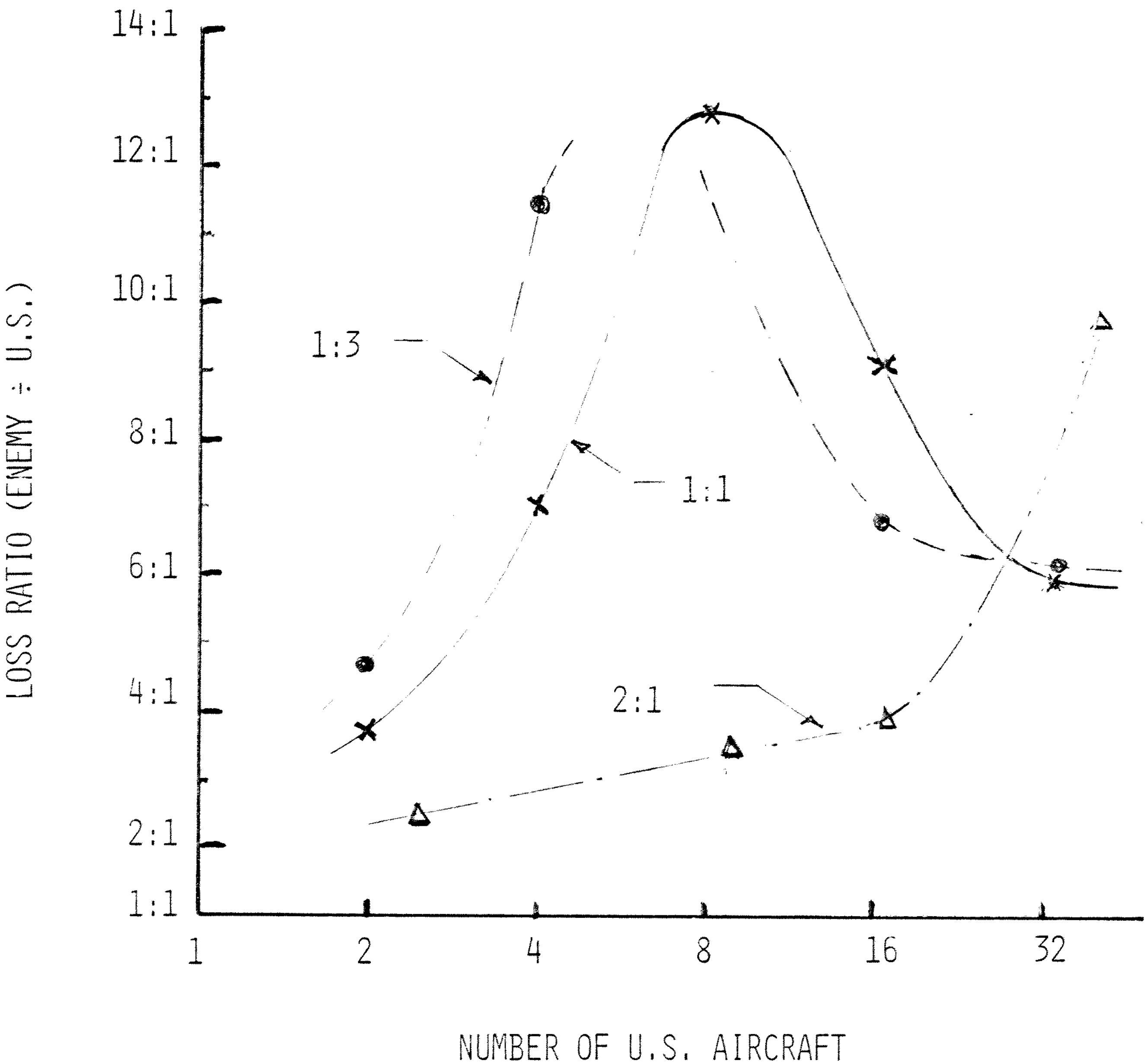


Figure II-2

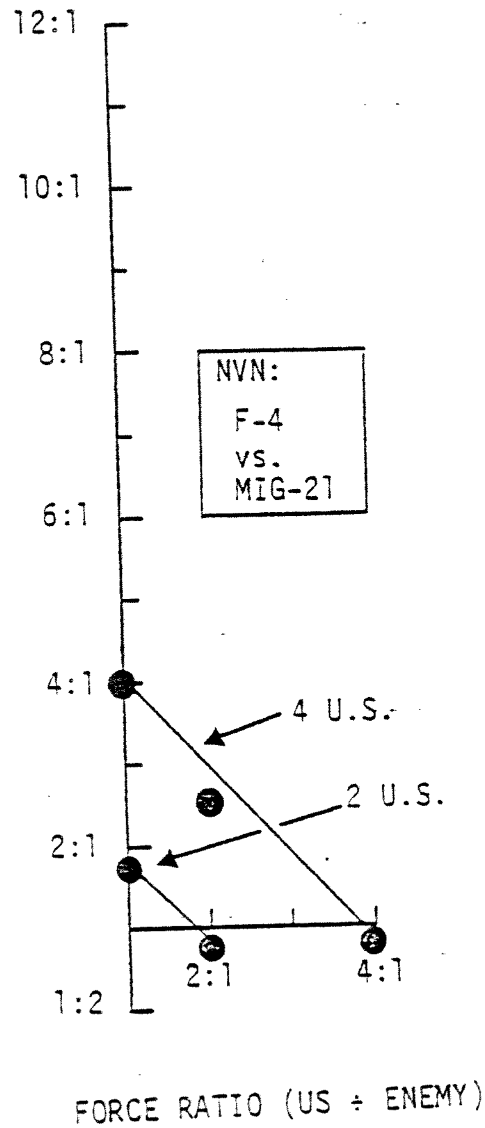

12:1
10:1
8:1
6:1
4:1
2:1
1:2
NVN:
F-4
vs.
MIG-21
4 U.S.
2 U.S.
2:1
4:1
FORCE RATIO (US ÷ ENEMY)

Figure II-3

CHAPTER III

MEASURES OF EFFECTIVENESS

INTRODUCTION

This chapter derives from the nature of air combat as described in Chapter II measures of effectiveness for comparing air-to-air fighters. First, the force characteristics needed to win air battles are divided into four major areas. Then, specific measures are defined within each major area, together with a procedure for calculating each measure.

FORCE CHARACTERISTICS NEEDED TO WIN AIR BATTLES

Table I presents, in approximate order of priority, the four major force characteristics that appear to be central to victory in air combat. The historical basis for each of these four is discussed below:

I. Achieve surprise bounces without being surprised. As shown in the last chapter, the dominant fact of air combat is that roughly 80% of all fighter victims in war are shot down unaware of their attacker -- and this appears to be at least as true of combat with radar-equipped Mach 2 fighters as with 90 knot biplanes. Stated another way, 80% of fighters shot down had no opportunity to use their maneuvering performance, their fire control or their weapons, no matter how superb these may have been technically.

However, this observation does not imply that achieving surprise is a random event independent of pilot ability, tactics and aircraft design. The way to gain surprise more often is to

- o Detect and identify hostile aircraft more quickly, accurately and consistently than the enemy;

COMBAT-DERIVED
EFFECTIVENESS CRITERIA
IN PRIORITY ORDER

I	ACHIEVE SURPRISE BOUNCES WITHOUT BEING SURPRISED	• FROM WWI TO VIETNAM, 65% TO 85% OF ALL AIR-TO-AIR LOSSES WERE SHOT DOWN UNAWARE
II	OUTNUMBER THE ENEMY <u>IN THE AIR</u>	• 70 VASTLY SUPERIOR ME-262s WERE GROUND DOWN BY 2000 INFERIOR P-47s AND P-51s
III	OUTMANEUVER THE ENEMY TO GAIN FIRING POSITION	• ALWAYS DOMINATED BY PILOT ABILITY/TRAINING • ENERGY MANEUVERABILITY PLUS TRANSIENT PERFORMANCE
IV	ACHIEVE RELIABLE KILLS DURING ANY SPLIT-SECOND OPPORTUNITY	• AIR COMBAT HAS ALWAYS REQUIRED VISUAL ID • THE MORE AIRCRAFT ENGAGED, THE MORE FLEETING THE FIRING OPPORTUNITIES

TABLE I

- o Be harder to detect and identify than the enemy; and
- o Approch the enemy from the rear, his zone of poorest detection.

Specific measures quantifying the above aspects of surprise are provided later in the chapter.

II. Outnumber the enemy in the air: although smaller air forces have often won major air battles where they have better pilots (and better surprise), there is little question that having two or three times more fighters in the air is a significant advantage. [1] For example, the growing U.S. superiority in numbers destroyed the initial Japanese domination of the air war in the Pacific. More dramatically, the greatly superior Me 262 jet was unable to affect the air war over Germany; the Luftwaffe could only put up about 70 jet sorties per day [2] (out of an inventory of 500 jets) to face about 2000 P-47s and P-51s. The overwhelming numbers of inferior prop fighters crushed the handful of jet fighters in the air. Needless to say, this is not an argument for procuring inferior fighters.

How does an air force achieve larger numbers in the air? By selecting fighters whose design is

- o inexpensive enough to let larger numbers be bought within the allotted budget;
- o sufficiently simple and maintainable to permit flying many combat sorties per day per aircraft;
- o low enough in peacetime operating costs to allow training adequate numbers of pilots to the 30 to 45 sortie per month level required to reach peak proficiency. [3]

1/ This does not imply that entering a dogfight with a formation larger than the enemy's is an advantage. Combat outcomes from Korea and Vietnam show that exchange ratio decreases markedly as force ratio in the dogfight increases.

2/ W. Green, Warplanes of the Third Reich, Doubleday, 1970.

3/ Note that attaining superiority in pilot skills may well dominate effectiveness in three of the four areas defined here: achieving surprise, outmaneuvering the enemy, and weapons lethality.

III. Outmaneuver the enemy: in those 20% or so of engagements where the opponent is not shot down unawares, it will be necessary to outmaneuver the enemy to gain firing position and/or to deny him a firing opportunity. In air wars to date, pilot skill has almost always dominated performance differences in determining who wins a maneuvering engagement. Even though aircraft maneuvering performance is probably secondary to pilot skill, it is important to define and assess this performance comprehensively. Three areas are involved:

- o outaccelerating, outdecelerating, outclimbing and outturning the enemy;
- o transitioning from one maneuver to another faster than the enemy;
- o outlasting the enemy, in terms of fuel, while outmaneuvering him.

IV. Obtain reliable kills during any firing opportunity: firing opportunities are defined as much by the nature of combat as by the specific weapons envelope. Maximum usable firing range is normally limited by the range at which positive identification can be acheived, usually visually.[1/] Aspect during the firing opportunity is determined by the kinematics of engagement, which somewhat favor rear hemisphere aspects because of the very short time available for positive identification during head-on passes.[2/] And, perhaps most important of all, the time duration of most firing opportunaties is measured in seconds, particularly in the chaos of many on many engagements.

Thus, weapons lethality needs to be assessed under the unfavorable circumstances of combat: extreme time pressure, possibly unfavorable aspect angle and/or range, multiple targets and background clutter to distract sensors, and an enemy strongly motivated to use intelligent counter-maneuvers and/or countermeasures.

1/ Positive visual identification is not to be thought of as an archaic relic of past wars, but as an inherent aspect of nearly all combat, air or ground. Because of the unpredictable, relatively random intermingling of friendly fighters and friendly attack aircraft as well as enemy fighters and attack aircraft, it is rarely possible to use radar (or IFF) to sort friend from foe. Thus, even in WWII night combat using radar GCI and radar-equipped fighters, positive visual identification was a prerequisite for firing. The only adequately secure electronic means of identification proposed to date is by using the opponent's distinctive radar signature--if he is rigid enough to leave it on continuously.

2/ As evidenced by the fact that SPARROW firing attempts in NVN were three times as numerous from the rear quadrant as the nose quadrant, even though pilots were taught that the missile is more effective in head-on firings.

There remains the question of why weapons lethality is last on the list of factors needed to win air battles. Taking the long view of air combat history, fighters in good position to shoot -- whether by surprise or by out-manuvering the enemy -- have normally acheived kills one-third to one-half the time, no matter what weapons were carried. Thus, weapons traditionally have not been the bottleneck in getting aerial kills. Finding enemy fighters and gaining favorable position has, in most wars, been the most critical constant. However, in the Vietnam air war, given the remarkably low combat Pk's shown by current radar missile armament, weapons may in fact have become abottleneck in winning air battles (see page). Whether or not this is a temporary aberration in the course of air warfare depends on whether our next generation of missiles corrects the serious missile effectiveness deficiencies revealed over North Vietnam.

SPECIFIC MEASURES OF EFFECTIVENESS

ACHIEVING SURPRISE WITHOUT BEING SURPRISED

Table II presents a summary of the measures used to assess effectiveness in achieving surprise. Pilot visual acuity and alertness, of course, is more important than any of the technical characteristics that bear on surprise. It is enhanced by rigorous peacetime training of a type that few air forces are willing to risk.[1/] The pilot's alertness can also be assisted by off-aircraft warning, whether from early warning radars or from communications intelligence.

INVISIBILITY

Aircraft characteristics that contribute to surprise start with relative visual and electronic invisibility, which is best assessed by means of direct side-by-side detection trials. Since such tests are almost never conducted, the

COMBAT-DERIVED
EFFECTIVENESS CRITERIA: I

DESIRED EFFECT	NECESSARY EFFECTIVENESS CHARACTERISTICS	MEASURE
ACHIEVE SURPRISE BOUNCES AND DON'T GET BOUNCED	• INVISIBILITY	• PRESENTED AREA • SMOKE OR NO SMOKE • ELECTRONIC EMISSION OR NO EMISSION
	• SUSTAINED SPEED ADVANTAGE IN COMBAT AREA	• ΔV_{CRUISE}
	• REARWARD VISIBILITY	• ANGLE OBSCURED

TABLE II

1/ The Israelis train for alertness by giving formal reprimands to any fighter pilot whose tail number is photographed on any peacetime sortie by another's gun camera. Even maintenance test flights are not exempted. Even more useful are regular squadron-on-squadon engagements, as practiced by the Luftwaffe throughout the 1930s. Both air forces accepted the inherent risk of accidents involved in such realistic training.

following three measures are used instead for the comparisons in this study:

- o visible engine smoke (yes or no)
- o physical size (top, side and front presented area in square feet)
- o electronic detectability (radar on or radar off; presence or absence of detectable lock-on).

Of these, the most important is engine smoke, since this can increase the visual detection range of a fighter by up to a factor of 3 to 5, depending on how badly the engine smokes. For instance, when the F-4 is not smoking (i.e., in afterburner), it can be seen at about 5 miles. This increases to 15 to 25 miles when the engine smokes, which it does in most cruise conditions.[1/] Thus, smoke increases air-to-air combat losses in two ways:

- o The volume of sky within which hostile aircraft can detect first is increased by a factor of as much as 9 to 25.[2/] The number of surprise bounces against the smoking fighter are likely to increase more or less proportionately to detection volume.
- o The smoke solves the enemy's IFF problem, at least if friendly aircraft are the only smokers in the theater. This allows the enemy to fire an IR missile from maximum range without having to close for identification and with the best possible chance of an unaware target.

If the fighter engine is smoke-free, then the plane's physical size, shape and camouflage govern the visual detection distance. Camouflage effects can be large,[3/] but for comparison purposes are assumed equal across fighters. Size is easily measured by obtaining top, side and front presented areas. Shape certainly affects the visibility of two fighters of equal size, but no flight experiments have been conducted to shed any light on this important subject.

1/ There is a $30,000 J-79 engine modification currently available which eliminates smoke. It was developed only several years after the Vietnam War and has been installed on a few squadrons of USN F-4s.

2/ The square, not the cube, of the detection range increase is used since the possible vertical detection range is constrained by the ground and the cruise altitude limits of the hostile aircraft.

3/ See Lt. Cdr. C. Heatley, .

Figure I shows the rough relationship between head-on size and head-on detection distance for various current fighters; the deviations from a smooth curve give some idea of the effect of shape. Unfortunately, the numbers are based on verbal reports from USN and USAF tactics instructors, due to the dearth of controlled flight tests available.

Electronic invisibility is dominated by the question of whether the target's radar is on or off. If it is on, then any competently-designed passive radar warning receiver and antenna will detect the radar's emission long before the target's radar can detect an opposing fighter.[1/] Not only will the radar warning receiver detect, it can also provide positive identification since Soviet radar signals are easily distinguished from U.S. ones by frequency, pulse rate and waveform. Finally, the radar warning receiver can detect when the enemy has locked on, which provides two vital pieces of information:

- o First, lock-on means the enemy is blind, can see no other airplanes on radar, and is immediately vulnerable to surprise attack by other friendlies.
- o Second, lock-on means a missile launch is imminent, thus making it possible to see the missile and outmaneuver or jam it.

Other signatures of the fighter, such as radar reflectivity and infrared emissions, are not assessed in this study since they make little difference in combat detections of fighters. Use of infrared for initial detection (as opposed to missile homing) has proven ineffective due to high false alarm rates and very short detection ranges.[2/] Differences in radar reflectivity between small and large cross section fighters may change ground or airborne radar detection distance by about 50%,[3/] but only for head-on detection against pulse-type, short

1/ This is because radar range varies as the fourth root of power transmitted due to the need for the signal to travel out and back; on the other hand, radar warning receiver range varies as the square root of power since the signal need travel only a one-way path.

2/ As shown in numerous engineering tests and operational evaluations ot the F-106 and the initial F-14 infrared search detectors, as well as the F-111 infrared tail warning set.

3/ For instance, the F-5E has an X-band radar cross section of about 2 m^2 as compared to 10 m^2 for the F-4. Taking the fourth root of (10÷2) yields 1.5, or a 50% difference in range. Note that physical size has little relation to cross-section, as evidenced by the small MiG-21 which appears to have about a 10 m^2 cross section. Only cross-section measurements taken on real aircraft in the air are useful. Ground range or model measurements are almost never confirmed by the airborne, real aircraft measurements.

wavelength radars. From side aspects, all fighters have huge cross-sections and show no useful differences. Against VHF early-warning radars (such as the numerous Soviet Tall King radars), we have no published tests of whether fighters differ significantly. In any case, radar cross section suppression techniques have negligible effects against such long wave lengths. Against doppler radars, particularly medium PRF types, the scant detection data available indicates little difference in detection range between small and large fighters [1/] -- and some evidence to indicate that radar cross section suppression can actually increase doppler detection range.

ACHIEVING REAR QUADRANT APPROACHES

Surprise is enhanced if approaches can be made consistently from the rear quadrant, the enemy's zone of relative "blindness". This is difficult to achieve with an aircraft that cruises slower than the enemy; conversely, it is easily achieved by cruising faster than the enemy. The classical example is the Messerschmitt 262, which cruised about 100 to 150 mph faster than the 360 mph of the P-51 and P-47, thus enabling it to "bounce" the slower prop fighters at will. The The P-51s and P-47s achieved few surprise "bounces" against the Me262, except when it was slowed by maneuvering or by a landing approach.

Cruise speed, as used here, is simply the actual speed of the fighter as it traverses the zone of potential engagements. In other words, it is the maximum speed that the fighter can sustain for the 20 to 30 minutes (or more) that he wishes to spend in hostile airspace.

The relevant measure is clear: it is the difference between the cruise speeds of the friendly and the enemy fighter. Maximum speed advantages are quite

1/ Conventional radar cross-section tests, using pulse radars, measure the total power reflected by the target, ignoring any frequency shifts. But doppler radars respond only to the power within a narrow frequency band. If the target scatters the transmitted signal across many frequencies, as happens with jet engine modulation, then the doppler radar receives one weakened true target and many false targets at other frequencies. Thus, strong jet engine modulation can act as a jammer and can actually make a large fighter harder to detect than a small target with little engine return.

irrelevant here, since maximum speed cannot be usefully sustained in the combat zone for more than a few minutes.

DETECTING ATTEMPTED "BOUNCES"

The principal means of detecting an attempted surprise attack, particularly if the enemy is clever enough to attack with his radar off, is visual detection. The aircraft characteristic that helps visual detection of "bounces" is rearward visibility. This can be quantitatively assessed with a cockpit visibility map covering the entire sphere around a pilot's head. However, qualitative comparisons based on examining drawings is relatively adequate here.

For those cases where the enemy is unwise enough to attempt achieving surprise with his radar on, it is easy to detect the attack with a radar warning receiver. The relevant measure here is simply the presence or absence of a radar warning receiver capable of sorting the opponent's fighter radar from all competing land and airborne signals. Detection range of the receiver should also be checked, but in an adequate design range will naturally be much greater than the range of the opposing radar.

FORCE EFFECTIVENESS: ABILITY TO OUTNUMBER THE ENEMY

The second most important effectiveness area, after ability to surprise, is ability to outnumber the enemy. This dimension of effectiveness is also an inherent characteristic of the design of a fighter, since the design determines the procurement cost, the operating cost and the sorties per day.

Table III summarizes the measures useful for comparing effectiveness in this area.

To measure the ability to outnumber the enemy is relatively simple. Ideally, we would like to calculate the <u>wartime</u> sorties per day capability that can be bought for a fixed 10 year cost, considering total acquisition cost plus the cost of enough peacetime flying over ten years to train pilots at the minimum 30 sortie per month level required for superior skills. This can be calculated as follows:

$$\text{Force sorties/day} = \frac{(\text{Total }\$)}{(\text{Unit }\$) + 3600\ (\$/\text{Sortie})} \times (\text{sorties/day/plane})$$

To further simplify the calculation, we note that operating cost per sortie is approximately linearly proportional to unit acquisition cost [1/] and that the steady-state wartime sortie per day capability of an aircraft is approximately inversely proportional to maintenance manhours per sortie. [2/]

These two approximations allow us to drop the operating cost term from the above expression and to substitute a constant divided by maintenance man hours per sortie for the sorties per day per plane term. The resulting calculation becomes:

$$\text{Force sorties per/day per billion \$ of acquisition} = \frac{1{,}000{,}000{,}000}{\text{Unit acquisition }\$} \times \frac{35}{\text{MMH per sortie}}$$

To provide fair comparisions of this force effectiveness measure among fighter types it is important to use:

- o constant dollar costs;
- o costs adjusted to a single size of production run (say 750 aircraft); and

1/ See Appendix I, Figure I for a graph demonstrating this proportionality based on actual acquisition costs and officially estimated operating costs. Note that the USAF and USN hourly cost factors for each aircraft are based on arbitrary allocations of overhead costs among the various aircraft types, with considerable incentive to allocate cost away from complex aircraft toward the simpler types. Thus, "true" operating costs might rise faster than linearly with acquisition cost.

2/ See Appendix I, Figure 2 for a graph demonstrating this relationship, using data from several maximum sortie rate tests conducted in combat during the Vietnam War.

COMBAT-DERIVED
EFFECTIVENESS CRITERIA: II

DESIRED EFFECT	NECESSARY EFFECTIVENESS CHARACTERISTICS	MEASURE
OUTNUMBER THE ENEMY IN THE AIR	• LARGE FORCE SIZE (IN A/C AND SKILLED PILOTS) WITHIN AVAILABLE BUDGET • HIGH SORTIE RATE	• SORTIES/DAY PER PROCUREMENT $

TABLE III

o maintenance manhours of a fully mature airframe in operational use (as opposed to MMH measured during test)

OUTMANEUVERING THE ENEMY

Table IV summarizes the measures useful in comparing the ability of fighters to gain firing position (and to deny the enemy a firing position) in those 20% or so of engagements where surprise does not decide the issue.

Classical Maneuverability

Classical maneuverability -- that is, accelerating, decelerating, climbing and turning performance -- is best described in terms of energy maneuverability theory.[1/] This theory compares aircraft by comparing their specific energy rates[2/] at each point throughout the full flight envelope of altitude, airspeed and g. For purposes of initial comparisons of fighters, it is possible to represent the results of a full energy-maneuverability analysis by means of two points that represent the two extremes of maneuvering combat: maximum acceleration and maximum turn or, equivalently, maximum energy gain and maximum energy loss. HOWEVER, FOCUSING ON JUST TWO POINTS IN THE ENVELOPE IS NOT ADEQUATE FOR DESIGN PURPOSES.

The reason for using the two extremes of maximum acceleration and maximum turn is that flight in many-on-many combat tends to alternate abruptly between these extremes, with little or no time spent in between at sustained turn conditions.[3/] In many-on-many combat, the pilot tends to "blow through", keeping up speed and energy, by unloaded acceleration, interspersed by occasional high g "breaks" to remain unpredictable to the all-important unseen attacker. Of course, when an attacker is detected, high g breaks or rolls are used to get out of his firing envelope, defeat his missile homing or gun-

1/ See J. Boyd and T. Christie "Energy-Maneuverability Theory", Eglin AFB, 1962 (S).

2/ Specific energy rate = (thrust-drag) ÷ weight at any given point in the flight envelope. It represents the rate at which the aircraft can gain or lose kinetic and/or potential energy at that point in the flight envelope, normalized by weight. Conceptually, it can be thought of as the rate at which the airplane would climb (or dive) at that point in flight envelope, if it chose to hold airspeed and g constant.

3/ A sustained turn is a turn just hard enough so that airspeed and altitude remain constant. Energy rate is zero at this condition.

COMBAT-DERIVED EFFECTIVENESS CRITERIA: III

DESIRED EFFECT	NECESSARY EFFECTIVENESS CHARACTERISTICS	MEASURE
OUTMANEUVER ENEMY TO: • GAIN FIRING POSITION • DENY/DEFEAT HIS FIRING	• QUICK ACCELERATION OR CLIMB	• 1G P_S (SUBSONIC, TRANSONIC)
	• QUICK DECELERATION AND HIGH INSTANTANEOUS G (OR TURN RATE)	• $C_{L_{MAX}} \left(\frac{S}{W}\right)$
	• QUICK TRANSIENTS	• TIME TO ROLL 180° AND BACK AT MAX G • TIME TO PITCH FROM 1G TO MAX G AND BACK TO 1G
OUTLAST THE ENEMY <u>WHILE OUTMANEUVERING HIM</u>	• ADEQUATE FUEL TO COMPLETE MORE COMBAT TASKS (MANEUVERS) IN EQUAL OR LESS TIME THAN ENEMY	• NUMBER OF ACCELS/DECELS AVAILABLE (AT VARYING H, V AND R) • FOR ROUGH COMPARISONS, USE FUEL FRACTION

TABLE IV

tracking solution, and possibly drive him out front.[1/] As opposed to peace-time one-on-one dogfighting, in wartime many-on-many combat, there is little time or opportunity for moderate g sustained turning.

The actual measures to represent maximum energy rate/acceleration and maximum turning/energy loss capabilities are simple. They are:

- <u>Maximum rate of climb</u>, as published in Jane's, Standard Aircraft Characteristics Charts, or other sources: Maximum rate of climb for jet fighters is always achieved close to Mach .9 at sea level. Expressed in feet per second, it is the same as maximum 1g energy rate.
- Maximum g, as calculated by the following standard formula:

$$\text{Max } g = \frac{\text{density (speed)}^2 \text{ (max lift coefficient) (wing area)}}{\text{weight}}$$

This needs to be calculated at a speed slow enough so that g is lift-limited, not structurally limited. For the present study, Mach .5 and 30,000 feet was chosen,[2/] but the results are not sensitive to speed and altitude.

Care in insuring that these two numbers represent actual capabilities of fighters in operational configuration, not optimistic "brochure" or engineering estimates, is crucial. Where direct flight measurements for operational aircraft are not available, Figure 3, Appendix I permits estimating maximum rate of climb when only thrust-to-weight ratio and engine type are known.

For maximum turn, the crucial input is the maximum lift coefficient. This needs to represent the maximum in-flight <u>controllable</u> lift of the fighter, not a maximum wind tunnel result. Figure 4, Appendix I provides a chart for approximating this input when only sweepback, aspect ratio and type of high lift device are available.

1/ Note that high rates of energy loss or, equivalently, high deceleration, are most desirable in these hard turns intended to defeat missiles and guns or to force opponents into an overshoot.

2/ The relative max g among fighters will not change much at other subsonic speeds (below the structural limit) because $C_{L\,max}$ varies slowing between Mach .5 and Mach .9 except for swing-wing fighters, which tend to be favored by a Mach .5 comparsion.

Transient Performance

Chapter II established that transient performance, the ability to transition rapidly from one maneuver to another, is so important that pilots in combat have actually chosen to sacrifice their fighters' classical maneuvering performance in order to alleviate deficiencies in transient performance.[1/] Unfortunately, no standard measures for transient performance exist and consequently, no fighter has ever been designed to meet a transient performance requirement.

Transient performance is, in fact, easy to define and measure since aircraft can transition from one maneuver to another only by rolling and/or pitching.[2/] Thus, combat-relevant measures of transient performance need only reflect the time to roll and the time to pitch (or the equivalent roll and pitch rates) at high g[3/] during maneuver transitions typical of combat.

This study proposes, as standard specifications for comparing or designing fighters, two measures of transient performance:[4/]

- Time to roll 180° in one direction and then 180° in the opposite direction while pulling a constant percentage of maximum controllable g (somewhere between 80% and 100% of maximum g), to be measured at several subsonic and low supersonic speed-altitude points within the combat maneuvering envelope. This maneuver can be thought of as half a barrel roll over the top in one direction followed by half a barrel roll underneath in the opposite direction. For display and comparison purposes, the time to roll should probably be converted to an average roll rate over the entire roll reversal maneuver, expressed in degrees per second.
- Time to pitch up to maximum g (or 80% of maximum g) and back down to

1/ See p_____, Chapter II

2/ Fighters can also use yaw (that is, sideslip) to enhance violent maneuver transitions, as in the snap roll, an effective decelerating maneuver for simultaneously destroying the enemy's tracking solution while driving him out front. However this maneuver has not been used in fighter tactics since the F-86, and even that aircraft's vertical tail was prone to breaking under the sideloads induced by particularly enthusiastic snap rolls.

3/ Roll rates (and pitch rates) in straight and level flight are more representative of airshow maneuvers than combat tactics. Unfortunately, almost all available standardized flight test maximum roll rate measurements are at 1 G. The F-18 is designed to a 1 G roll rate requirement which in no way ensures adequacy of roll performance at the g actually used in combat maneuvers.

4/ These measures are the outcome of continuing discussions with Col. John R. Boyd, USAF (ret'd) on fighter handling qualities and transient performance, discussions that first began in 1970 on the subject of evaluating handling qualities differences among the International Fighter Aircraft candidates: the F-4, the F-8 and the F-5.

1 G, or alternatively, time to pitch up to a predetermined body axis angle such as 45° or 60° and back to level flight. The result, as in the case of roll, is probably best displayed as an average g rate or pitch rate over the full pitch reversal maneuver.

Naturally, the feasibility and utility of these measures need to be explored in flight tests of several markedly different fighters before they can be adopted as standards for fighter design. Suggested specific flight test profiles for such an investigation are provided in Appendix II. The appendix proposes that an integral part of the flight measurement be a requirement to hit the roll or pitch reversal points and the end points accurately, say within $\pm$ $^{1}/_{2}$ g. This would automatically incorporate aircraft controllability and control precision into the transient performance measures.

Conceptually, it is useful to understand the difference between this approach to transient performance and the closely related classical aerodynamic definitions of handling qualities. Obviously, aircraft with poor or dangerous handling qualities will not be able to achieve very quick high g roll reversals or pitch reversals, so good handling qualities are required to achieve high transient performance. However, the objective of the classical handling qualities approach is smooth and controllable roll and/or pitch transitions; if necessary, quickness of transition can and is sacrificied in modern control system design to achieve smoothness and safety. The key advance in the proposed transient performance definition is that the desired result is not smoothness but maximum abruptness and unpredictability of maneuver while retaining precise control and safety. Violence and unpredictability of maneuver are critical to gaining position advantage and preventing the enemy from selecting effective counter-moves.

Since there exist essentially no standard condition flight test results that permit comparing high g transient performance among fighters, the present study is forced to use subjective rankings by pilots. Subjective comparisons as to quickness in pitch and roll between each pair of fighters are based on the rankings of at least two fighter pilots who have flown both aircraft. Although this approach is much less desirable than one based on flight test data, it is striking that there were no conflicting rankings among the pilots interviewed. Final results are presented as a three point rating -- excellent, fair, and poor -- for the roll performance of each fighter and a similar rating for the pitch performance.

Outlasting the Enemy While Outmaneuvering Him

Clearly, a 2:1 advantage in maneuvering performance is of little use if it only lasts for 15 seconds. Therefore, a fighter's ability to persist[1/] in combat needs to be evaluated along with its maneuvering performance. The classical approach to combat persistence has been to define an "adequate" amount of combat fuel as the fuel needed for a fixed time at maximum power, say 3 minutes or 5 minutes. This is the approach used in the NATO rules and the DIA rules for calculating mission radius of existing fighters, or the Navy mission fuel requirements for fighter design studies such as the original VFX and F-14 studies.

The weakness of the fixed time approach is that it does not take into account that high performance fighters can throttle back and extend persistence while still outmaneuvering lower performance fighters. Thus, the high performance or high thrust-to-weight fighter is severely penalized, whether in comparisons of existing fighters or in design tradeoffs. The solution is to use fixed combat tasks, rather than fixed time, to define the combat phase of a mission. The first such combat task rule was divised by Col. John R. Boyd during the FX tradeoff studies that led to the F-15. His defined task was to gain 144,000 feet of energy, 1/ The term persistence, as used here, is due to Col. Everett Riccioni, USAF (ret'd).

based on the 1 g specific energy rate available at Mach .9 and 10,000 feet. Thus, a fighter capable of 1000 feet per second energy rate would use 144 seconds of maximum power fuel, one with only 500 feet per second would require 288 seconds of fuel. This 144,000 foot task can be thought of as a series of brief 1 g accelerations or climbs summing to a total energy gain of 144,000 feet.[1/]

A further advance in combat task definitions was introduced in the Light Weight Fighter design requirements that led to the F-16. Here, the combat task was defined as one acceleration from Mach .9 to Mach 1.6 at 30,000 feet, two Mach 1.2 sustained turns at 30,000 feet and four Mach .9 sustained turns at 30,000 feet. This incorporated more emphasis on transonic conditions and on the turning component of the flight.

In light of what we now know about the nature of many-on-many combat and its relative absence of sustained turning conditions, design tradeoff studies for a new fighter might refine the F-16 task rules to a definition based on some mix of maneuvers such as the following:

- o Acceleration from Mach .9 to 1.2 at 10,000 feet (starting at cruise power)
- o Acceleration from Mach .8 to 1.5 at 30,000 feet (starting at cruise power)
- o Maximum g decelerating level turn from Mach 1.5 to Mach .8 at 30,000 feet (at maximum power)

This task definition adds emphasis on low altitude transonic acceleration and substitutes maximum g turns for sustained turns.

In any case, exact adherence to the F-16 combat task or improved versions would require lengthy computations, probably requiring computer assistance, to establish the fuel consumed in combat for persistence comparisons.

1/ A useful aspect of this particular task definition is that the total fuel consumed (but not the time required) is relatively constant for altitudes between sea level and 35,000 feet.

In order to permit fighter persistence comparsions requiring only simple calculations, this study falls back on a simpler index of persistence: fuel fraction, defined as total internal fuel divided by clean takeoff weight. Given a fixed combat task and resulting combat fuel allocation, it can be shown (by use of Breguet's range equation) that the "go-home" range[1/] of a fighter is extremely sensitive to fuel fraction. To demonstrate this, Appendix III provides a simple method for calculating combat fuel and go-home range of a fighter, given only its fuel fraction, aspect ratio, wetted area and engine type.[2/] The appendix also establishes the remarkable insensitivity of fighter range to changes in engine technology.

Although fuel fraction gives a useful basis for fighter persistence comparisons, it must be remembered that there is a more fundamental and empirical basis for comparing persistence: whether or not one fighter type outlasts another in actual, many-on-many dogfights. This is not entirely a matter that can be settled by paper fuel calculations. For instance, a fighter with an afterburner lightoff problem will frequently choose to stay in low afterburner rather than risk no light or even a flameout. This considerably reduces persistence below the levels predicted by fuel calculations. In fact, this was one of the reasons that F-5s frequently ran F-15s out of fuel in the 1977 AIMVAL/ACEVAL tests.

OBTAINING RELIABLE KILLS

Table V summarizes the specific measures used to assess the ability to obtain reliable kills during the firing opportunities actually presented in combat. This means the ability to obtain kills a) at all ranges from near miss to the maximum range at which positive visual (or RHAW) identification can be achieved; and b) within the very short time "window" that combat normally per-

1/ The "go-home" range is the range of a clean fighter that starts combat at full fuel, uses its combat fuel, and then cruises home on the remaining fuel, excluding the required landing reserves. This assumes the fight starts at or before the emptying of the external fuel tanks, which are of course dropped immediately at the opening of the fight. This is the way air-to-air missions at maximum range were flown in WWII, Korea, and Vietnam. The F-16 range requirement was based on such a go-home range.

2/ Using the Appendix III computational approach will be necessary when comparing fighter persistence in geographically assymmetrical situations, i.e. when one fighter has to travel 100 miles to the fight while the opponent has to go 300.

COMBAT-DERIVED
EFFECTIVENESS CRITERIA: IV

DESIRED EFFECT	NECESSARY EFFECTIVENESS CHARACTERISTICS	MEASURE
OBTAIN A RELIABLE KILL DURING ANY SPLIT-SECOND FIRING OPPORTUNITY FROM 100 FEET TO MAX VISUAL ID RANGE	• HIGH P_K VS. CLOSE-IN MANEUVERING TARGETS	• KILLS/TRIGGER SQUEEZE (IN COMBAT)
	• ADEQUATE AMMO FOR MULTIPLE ENGAGEMENTS	• NUMBER OF ON-BOARD KILLS
	• MIN TIME FROM OPPORTUNITY RECOGNITION TO BREAKAWAY (TO ATTACK NEW TARGET OR TO AVOID ATTACK	• TIME FROM OPPORTUNITY TO BREAKAWAY
	• MINIMUM VULNERABILITY TO HARDWARE ECM OR TACTICAL COUNTERMEASURES	• WEIGHT/COST OF ENEMY ECM • PENALTY OF TACTICAL COUNTERS

TABLE V

mits. This does not imply that one weapon must cover the entire spectrum of range, aspect and time.

Probability of kill

First and generally most emphasized is probability of kill. It would be most desirable to be able to predict probability of kill by means of engineering calculations or computer simulations based on the technical characteristics of existing or proposed weapons and fire control. Unfortunately, all available experience with air-to-air weapons lethality models indicates that none have been confirmed by combat results. In the case of missiles, some have been optimistic by a factor of 10. For instance, pre-Vietnam predictions of the lethality of the AIM-4 FALCON were generally above .9; combat results of the FALCON were .07 or below. Since there exists no usable analytical method for predicting of probability of kill, only combat results -- confirmed kills per firing attempt[1/] -- can be used for comparing fighter effectiveness. Unfortunately, this means only weapons already tested in combat can be assessed. Indirectly, this also implies that new fighters should never be designed to rely <u>only</u> on new weapons; the chances of being let down by new air-to-air weapons untried in combat are substantial.

A useful adjunct to probability of kill is a plot of the relative frequency of kills and the probability of kill versus aspect and distance to the target. This defines the combat-based envelope of the weapon, as opposed to the relatively artificial engineering envelope. However, size of envelope by itself is not a usable measure of effectiveness, since it would need to be related to the "envelope" of firing opportunities to be meaningful. This has never been done and, in fact, may not be possible since combat firing opportunity data -- as opposed to firing attempt data -- cannot be collected. Nevertheless, the combat-based envelope is

1/ All firing attempts are included in this definition, whether wild shots, duds, or accidental or intentional "out-of-envelope" firings. Attempts to segregate out these causes of misses, particularly "out-of-envelope" firings, leave to much room for bias. Further, accidental "out-of-envelope" firings represent an inherent limitation of the weapon, that is, the relative difficulty of knowing the envelope and remaining within it.

useful in defining the complementarity of different weapons, particularly insofar as it estimates the usable outer <u>and</u> inner boundaries for each weapon.

Adequacy of On-Board Ammunition

Once probability of kill is known, adequacy of on-board ammunition for each weapon is easily calculated by multiplying the probability of kill times the number of firing attempts possible within the on-board weapons load. Since combat persistence requirements are intended to provide fuel adequate for several engagements, the weapons load should be adequate for several kills. Dividing this up among different weapon types is somewhat arbitrary, but providing gun ammunition adequate for two or three kills and missile loads adequate for one kill, on average, would be consistent with typical loads actually carried in recent wars.

Vulnerability Interval During Weapon Firing

The time that a pilot is occupied in launching and guiding a weapon presents the unseen enemy with a golden opportunity for surprise. Times much beyond 3 to 5 seconds become exponentially more lethal to the pilot. Therefore, time from the decision to capitalize on a firing opportunity to the time at which the pilot is free to break away is the relevant measure of weapon-induced vulnerability.

Vulnerability of Weapon to Countermeasures or Counter-moves

Once a weapon begins to prove effective against the enemy, it must be assumed that he will expend extraordinary technical and/or tactical ingenuity in trying to reduce its probability of kill to zero. Two recent examples are:

- Early in the Vietnam War, MiG-17s discovered that the AIM-7 and the AIM-9 had no lookdown capability. Consequently, when not surprised, MiGs would quickly dive to prevent a look-up shot -- a most effective counter until the F-4s were finally permitted by 7th Air Force

HQ to carry gun pods. This also demonstrates the importance of complementarity of weapons capabilities.

- In the 1973 Arab-Israeli War, Israeli A-4s quickly fitted 18 inch tailpipe extensions which quickly reduced the already low probability of kill of the contact-fuzed SA-7 to essentially zero. Overall SA-7 probability of kill was below .0006 (one to three kills for about 5000 firings).

Some of the counters that need to be assessed are:

- Hard turns or turn reversals in response to seeing a missile,[1/] in order to overload the missiles g capability or beat its time constant
- Formation spacing to induce centroid misses by radar missiles or track crossing weaves to defeat track-while-scan fire control.
- Maximum simplicity countermeasures such as flares against IR missiles (nearly 100% effective against all IR missiles up through the AIM-9L) and chaff against radar missiles (partially effective though not adequately tested).
- Lightweight, low power ECM such as fuze jammers for doppler fuzes (probably almost 100% effective for AIM-7 and AIM-9 up through the H model) and blinking repeater jammers (almost 100% effective for all radar missiles).

The existence of highly effective, low cost, low weight counters do not automatically indicate a weapon should not be carried, provided

- the weapon still has utility in surprise attack firings (which excludes active weapons), or
- the counter-move (or countermeasure) induces vulnerability to a complementary weapon, such as a hard break against a missile creating an opening for a gun attack.

1/ This underscores the disadvantage of large visible missiles or of sustainer motors which leave a highly visible smoke trail, such as the sustainers incorporated in the Phoenix and the AIM-7F/M.

Unfortunately, there are no simple quantitative measures of a weapon's vulnerability to counter-moves and countermeasures. This effectiveness area can only be assessed qualitatively, though this does not diminish its importance.

CHAPTER IV

COMPARISONS OF EFFECTIVENESS: F-86 THROUGH F-18

INTRODUCTION

This chapter compares the selected fighters according to the specific measures of effectiveness derived in Chapter III. Each of the four major effectiveness areas -- surprise, numbers, outmaneuvering the enemy, and achieving kills -- is dealt with in turn. Wherever possible, numerical estimates are calculated. Overall comparisons and assessments of progress made in effectiveness are summarized in the final section.

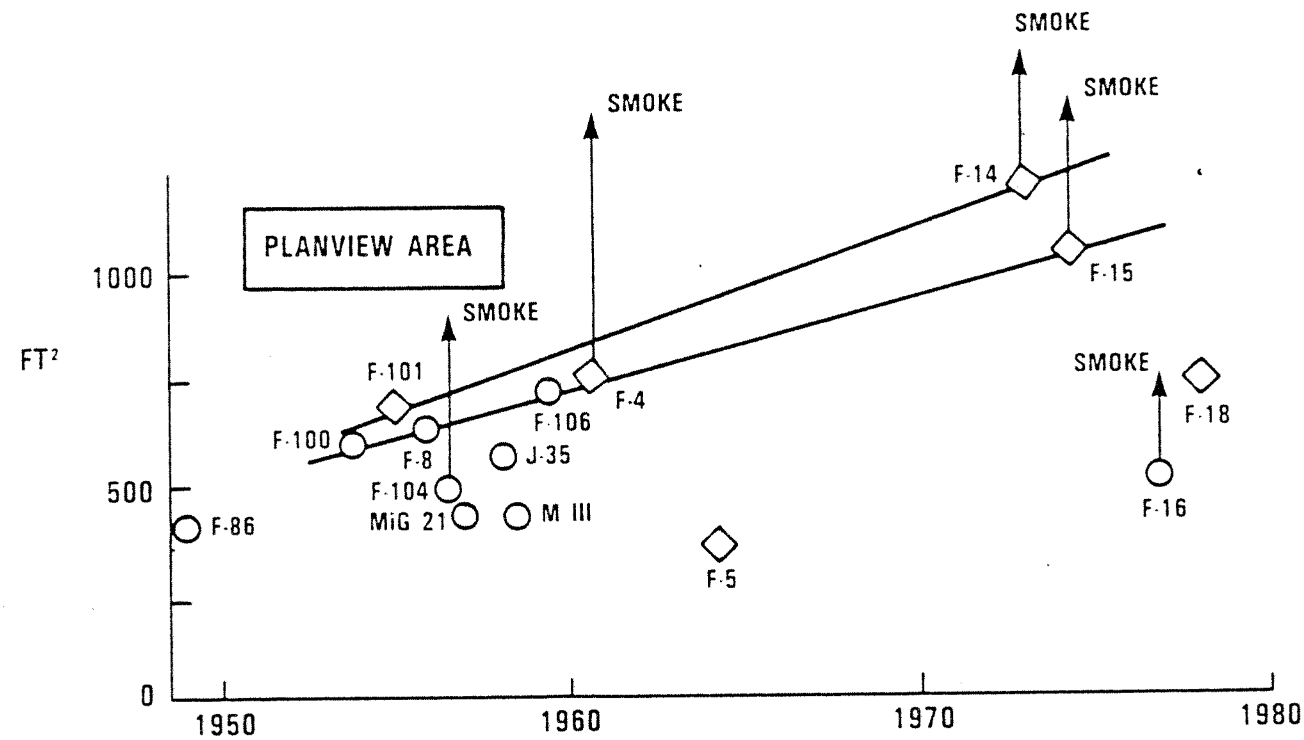
SURPRISE

The capability to achieve surprise and avoid being surprised depends on relative invisibility, sustained speed advantage, and visibility (particularly rearward) out of the cockpit, as outlined in Table III-2.

Invisibility

The relative invisibility of the selected fighters in the visual spectrum, which depends on physical size and visible smoke, is shown in Figure III-1. In 1950 the "first line" U.S. fighter, the F-86, had a commendably small size -- about 400 ft^2 in plan view. This was comparable to most of the good WWII fighters and somewhat larger than the 250 ft^2 of the Messerschmitt 109, which had the advantage of being the smallest major fighter of the war.

From the F-86 on, the standard "first line" air-to-air fighters of the U.S. climbed steadily in size up to the F-14 and F-15 at 1202 and 1055 ft^2, respectively.



SMOKE
SMOKE
SMOKE
SMOKE
SMOKE
PLANVIEW AREA
FT²
1000
500
0
1950
1960
1970
1980
F-14
F-15
F-101
F-100
F-8
F-106
F-4
J-35
F-104
MiG 21
M III
F-86
F-5
F-18
F-16

Figure IV-1

In contrast, the MiG-21 is much harder to see at only 445 ft^2, slightly larger than the F-86. The most interesting of the European fighters, the Mirage III and the Draken, are about the same size as the MiG.

Though the standard American fighters since the F-100 have been increasingly larger than the MiG-21, there have been several "austere" fighters that are about as hard to see as the MiG-21: the F-5 is about 20% smaller; the F-104 is about the same size and the F-16 is about 15% larger.

The size comparisons of Figure III-1 must be modified to account for visible smoke. Of the selected fighters, the worst smoker is the F-4, its smoke trail in cruise[1/] is sufficiently dense to increase visual detection distance out to 15 to 25 miles. Next come the F-14 and F-15, whose smoke trail density varies[2/] but is sometimes dense enough (particularly when viewed from near head-on or near tail-on) to increase detection distances to 10 to 15 miles. The F-104, with one instead of two J-79 engines, smokes somewhat less than half as much as an F-4. The F-16 smokes a little less than an F-104 and less than half as much as an F-15. Pilots engaging F-104's or F-16's report that their smoke is not quite dense enough to become a cueing factor in the majority of visual detections.

As to invisibility in the electronic spectrum, the selected fighters all have radars powerful enough to be detected at a hundred miles or more by a narrow band superheterodyne receiver. Therefore, there is no practical difference in their electronic invisibility -- that is, their ability to achieve surprise -- when the radar is on. When it is off, any of them equipped with a competent radar warning receiver can detect enemy fighter radars at well beyond the enemy's radar range;[3/] thus, surprise is on the side of the fighter with his radar off.

1/ F-4 pilots in air-to-air exercises sometimes elect to use low afterburner just to eliminate smoke and the attendant vulnerability to surprise bounces.

2/ The F-14 and F-15 engines were initially smoke-free, but, with subsequent modifications and reductions in temperature to ameliorate severe stall and engine life problems, have shown an increasing tendency to smoke.

3/ Radar: Shield or Target?, T.S.Amlie, Spectrum (IEEE), April 1982.

With respect to invisibility to ground early warning radars, there is little difference among the selected fighters since they can all be detected at beyond 150 n.m. by standard long range ground radars.[1/]

Sustained Speed Advantage

Figure III-2 shows the progress, or lack thereof, in sustained speed capabilities of fighters since 1950. The band covers the range between optimum cruise, which involves relatively low power settings, and the fastest sustainable cruise, typically at throttle settings near full military power (non-afterburning).

The differences in optimum cruise between fastest and slowest fighters is sizable: the swing-wings like the F-14 (or MiG-23 or F-111) have rather slow optimum cruise speeds around Mach .7;[2/] the tail-less deltas, the F-106, Mirage III and Draken, have optimum cruise speeds around Mach .92, a roughly 120 knot advantage. The conventional swept wing fighters are inbetween, with optimum cruise around .78 to .85. At the high cruise power settings more typical in the combat zone, (and with swing-wings in the swept-back position), the differences in speed are much smaller: all the selected fighters can sustain cruise for 20 minutes or more at Mach .9 to .95; the post-F-86 fighters can use Mach 1+ speeds but only in bursts, due to the high fuel consumption associated with the use of afterburners.

It appears that the practical differences in combat cruise speeds among the selected fighters are small. To the extent any of these fighters might have a small speed advantage, it would belong to the tail-less delta.

Rearward Visibility

Figure III-3 provides a rating of the rearward visibility of the

1/ Although the selected fighters vary considerably in radar cross-section, even the smallest cross-sections (i.e., the F-5E at 2 m^2) are large enough to permit reliable detection by large search radars at 150 to 200 n.m. The MiG-21 and F-4 are much larger at around 10 m^2; the F-15 and F-14 are approximately 20 m^2 head-on, based on the few airborne measurements available.

2/ Optimum cruise for variable sweep aircraft is always with the wings in the forward sweep position. But the resulting cruise speeds of Mach .7, though efficient, are unacceptably slow when enemy fighters might be present. Therefore, swing wing fighters such as the F-14 or MiG-23 will be unlikely to be able to use their efficient, wings-forward cruise in a combat zone. With wings swept back, their cruise is less efficient than fixed sweptwing fighters due to the weight and drag penalties of the wing pivot and glove installation.

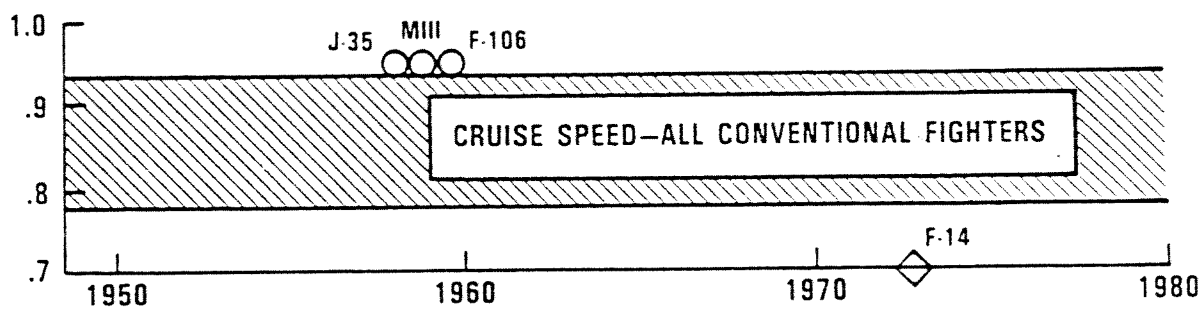

1.0
.9
.8
.7
J-35
MIII
F-106
CRUISE SPEED—ALL CONVENTIONAL FIGHTERS
F-14
1950
1960
1970
1980

Figure IV-2

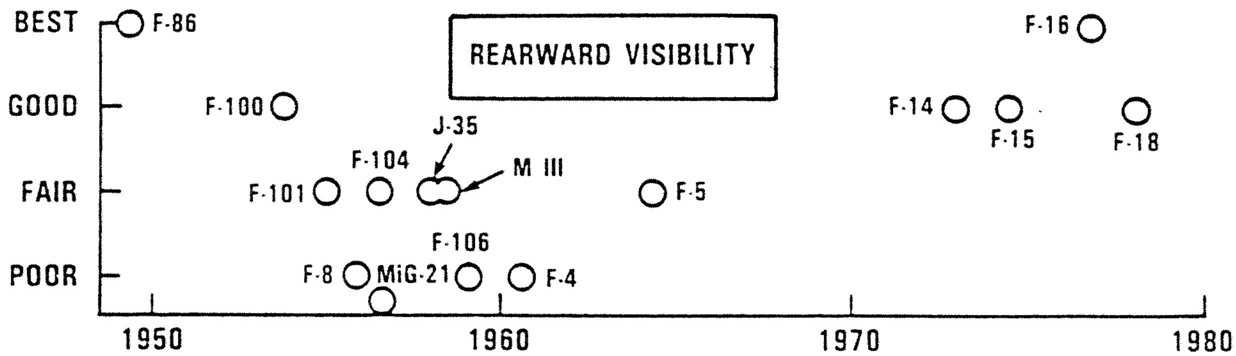

REARWARD VISIBILITY
BEST
GOOD
FAIR
POOR
F-86
F-100
F-101
F-104
J-35
M III
F-5
F-8
MiG-21
F-106
F-4
F-16
F-14
F-15
F-18
1950
1960
1970
1980

Figure IV-3

selected fighters, based on examining design three-views and on pilot comments.

Two of the fighters, the F-86 and the F-16, have excellent visibility -- the F-86 because of the influence of recent WWII combat experience, the F-16 because the Light Weight Fighter requirements specified visibility better than the F-86.

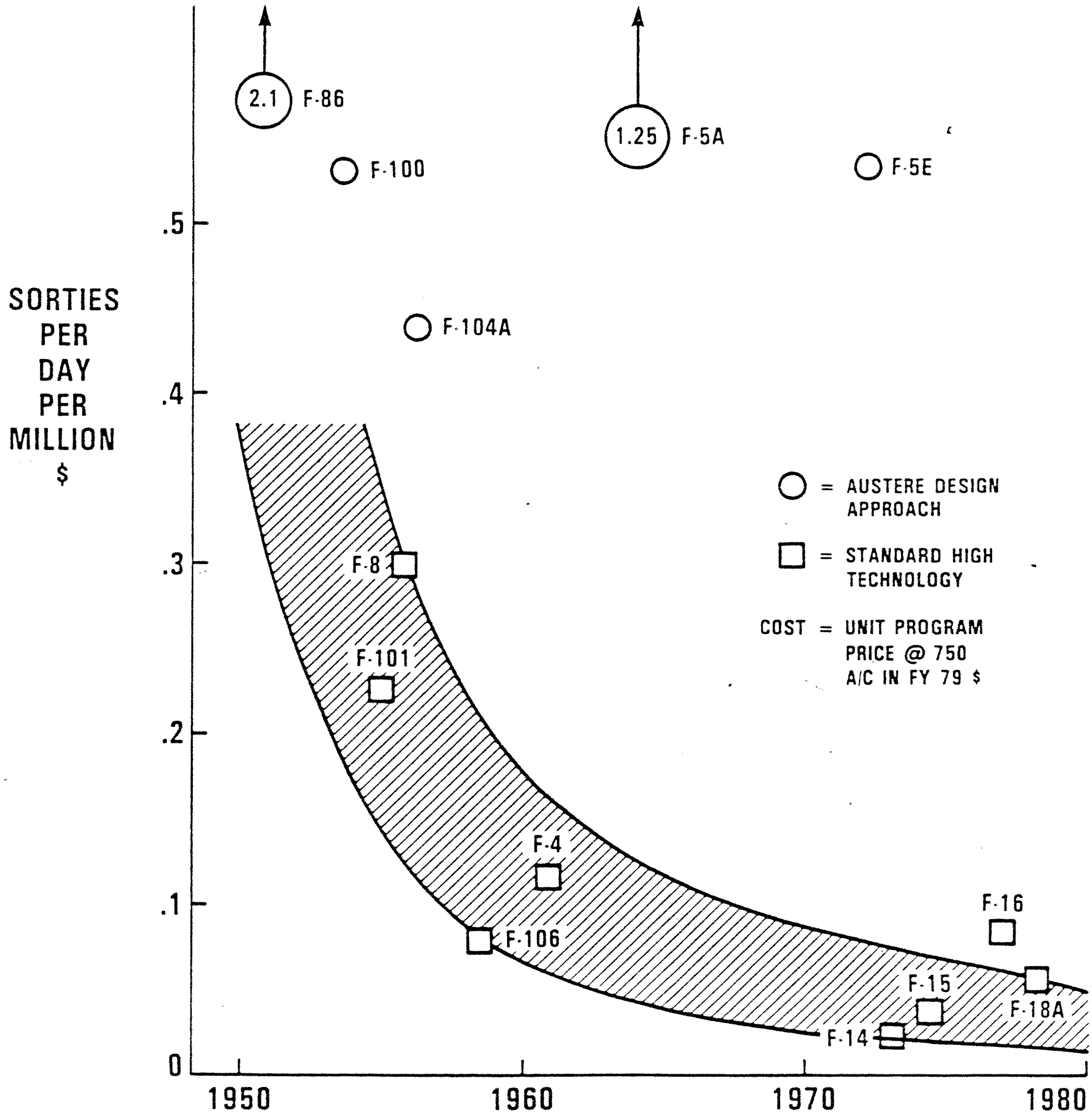
Not far behind in visibility are the F-14, F-15 and F-18, due to the beneficial effect of Vietnam experience.

Remarkably poor out of the cockpit visibility is shown by the F-8, the F-106, the F-4, the MiG-21 and the MiG-23: most of their rear hemisphere visibility is blocked out by behind-canopy fairings and/or high-backed ejection seats. All five were designed for supersonic air defense intercept in the belief that dogfights were a thing of the past.

NUMBERS IN THE AIR

The inherent ability of fighters to generate numbers in the air is compared in Figure III-4 which shows the relative sorties per day capability obtained for each billion dollars invested. Calculations as per p.II-17, are based on program unit costs in FY 82 dollars adjusted to a constant 750 aircraft program and on actual base-level maintenance manhours based on Service publications. Table III-1 gives the details of the calculation, allowing the reader to see what proportion of the difference between any two aircraft is due to unit cost as opposed to maintenance and sortie production capability.

The 30 year trend starts with 2,000 sorties per day per billion dollars for the F-86. By the early sixties, this had declined to 100 sorties



2.1
F-86
1.25
F-5A
F-100
F-5E
F-104A
SORTIES PER DAY PER MILLION $
.5
.4
.3
.2
.1
0
= AUSTERE DESIGN APPROACH
= STANDARD HIGH TECHNOLOGY
COST = UNIT PROGRAM PRICE @ 750 A/C IN FY 79 $
F-8
F-101
F-4
F-106
F-16
F-15
F-18A
F-14
1950
1960
1970
1980

Figure IV-4

per day with the F-4. Of the 1970's fighters, the F-14 shows the lowest sortie capability with about 25 sorties per day per billion dollars. The F-15 and F-18 are at about 35 sorties per day and the F-16 is at about 90 sorties per day.

Exceptions to the trend are the "austere" fighters. The F-104A, and the F-5E, produce between 400 and 500 sorties per day; the yet simpler F-5A produces over 1,000 sorties per day per billion dollars invested.

Accurate comparisons with foreign fighters are not possible due to lack of comparable program costs and maintenance man hours. A rough estimate, however, would place the Mirage IIIE at about the weight and cost of the F-104 but with slightly greater complexity and MMH/FH. Thus, sorties per day per billion dollars would be in the range of 300 to 400. The MiG-21C, if built in the U.S., should have about the same production cost as the F-5E, since it is slightly larger but simpler to manufacture than the F-5. On the other hand, the MiG-21's component reliability (particularly engine) is somewhat lower than the F-5's; therefore MMH/FH should be slightly higher. Overall, this would place the MiG-21C in the 400 to 500 sortie per day range -- if operated within a U.S.-equivalent logistics system.

OUTMANEUVERING THE ENEMY

The ability to gain firing position and/or to deny the enemy a firing position is compared in this section in terms of three major components: classical or "steady state" maneuvering performance, transient maneuvering performance, and outlasting the enemy.

Classical Maneuvering Performance

Acceleration/Climb

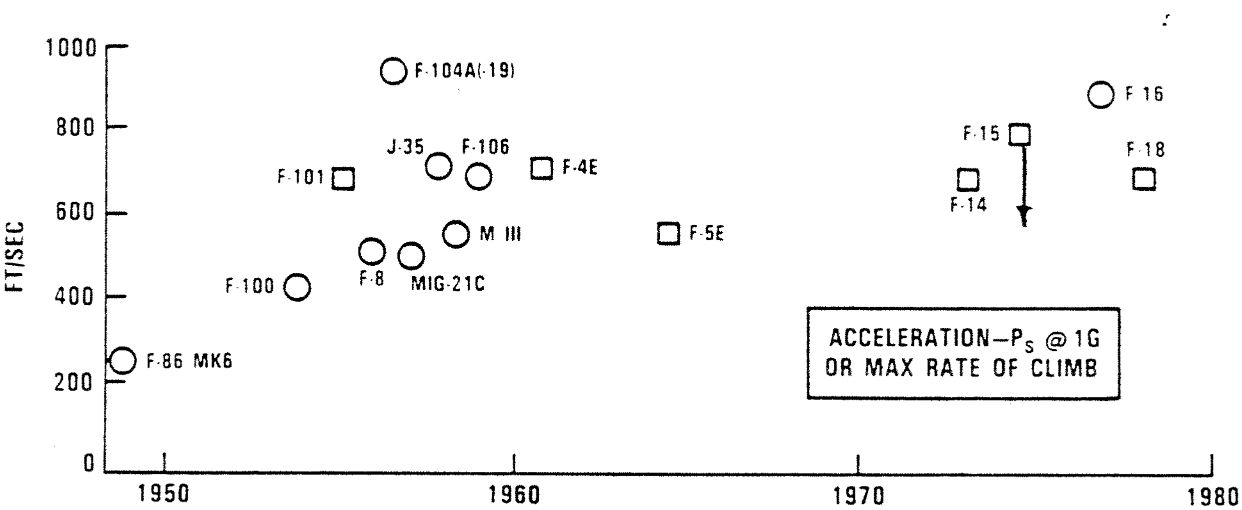
Figure III-5 compares the maximum rate of climb -- which is equivalent to the Mach .9, sea-level 1G specific energy rate and proportional to acceleration -- of the selected fighters. For each fighter, the model with the best performance is selected. For those fighters for which direct flight test data is not available, the rate of climb is calculated from thrust-to-weight ratio as per Figure 3 of Appendix I.

As can be seen from Figure III-5, the time trend in rate of climb starts with 250 feet per second for the F-86E/F. From this level, performance increased in three quick steps during the next eight years.

The first step upwards was the 450 to 550 feet per second class, which started in 1953 with the first afterburning engines and the first supersonic fighter, the F-100. This class, perhaps surprisingly, also includes the MiG-21C[1/] -- as well as the F-8, the Mirage III and the F-5E. Within the 450 to 550 class, the differences in accelerating performance are probably not large enough to significantly affect combat outcomes.

The next step upwards in acceleration and rate of climb, the 600 to 700 feet per second class, started less than two years later with the F-101 interceptor at toughly 650 feet per second. This class includes the J-35 Draken, the F-106, the F-4 and, surprisingly, two of the latest fighters: the F-14 and the F-18. Except for the latter two, the remaining aircraft in this class have fairly similar relative accelerating performance throughout the combat-relevant portion of their altitude-speed domain -- even though Figure III-5 compares them only at Mach .9, sea-level. The F-14's performance relative to the others will improve at transonic speeds and low altitudes (below 10,000 feet) because of a) the relatively higher ram effect of

1/ The MiG-21C is widely assessed as close to the F-4 in acceleration. This is clearly not the case as the rate of climb from Jane's (used here), as well as flight test experience, clearly shows. This common misassessment is reinforced by the apparently high thrust-to-weight of the MiG-21C, based on using the Soviet-rated thrust of 12,500 pounds. The Soviet thrust is not the sea-level static rating that is used for all Free World aircraft thrust-to-weights. Instead, it is a supersonic rating at a point where thrust is approximately 25% higher than sea-level static. Thus, the correct comparable static thrust for the MiG-21C is about 10,000 pounds. This same error in calculating thrust-to-weight is also frequently seen in assessments of newer Soviet fighters such as the MiG-23 and MiG-25.



1000
800
600
400
200
0
FT/SEC
1950
1960
1970
1980
F-104A(-19)
F 16
F-15
F-18
J-35
F-106
F-4E
F-101
F-14
M III
F-5E
F-100
F-8
MIG-21C
F-86 MK6
ACCELERATION—P_S @ 1G
OR MAX RATE OF CLIMB

Figure IV-5

its fan engine at higher speeds, compared to turbojets: and b) the transonic drag advantage of the variable sweep wing in its most swept position. At higher altitudes near 30,000 feet and subsonic speeds, the F-14 performance will decrease relative to the others because its fan engine loses thrust more rapidly with increasing altitude than the turbojets. The F-18, at subsonic speeds and higher altitudes will improve relative to the others because its engine has an artificially imposed thrust "limit"[1/] at low altitude, high speed. But at low altitudes and increasing transonic speeds, this thrust "limit" causes the F-18 performance to decrease relative to the conventional turbojets.

The final step up in acceleration, or rate of climb, is the 800 to 950 foot per second class, which started only a few years later with the F-104A (-19), an aircraft whose accelerating performance has yet to be surpassed by any newer Free World or Soviet fighter. The F-16A is a close second at around 900 feet per second and the F-15A is somewhat lower, depending on the individual F-15's state of engine "detuning". Some of the most sluggish F-15's have been accelerating nearly as slowly as F-5's, which means rate of climb for these examples was in the vicinity of 600 feet per second.

Maximum Turn

Figure III-6 compares the lift-limited maximum g capability of the selected fighters, calculated as per p.II-23.

The time trend in maximum g is fairly simple. The F-86 E/F started off with excellent maximum turn capability, that is, a relative lift index of .025. Most of the remaining fighters, including the MiG-21 and up through

1/ This is actually a turbine temperature limit at high q, intended to save cooling requirements and increase engine life.

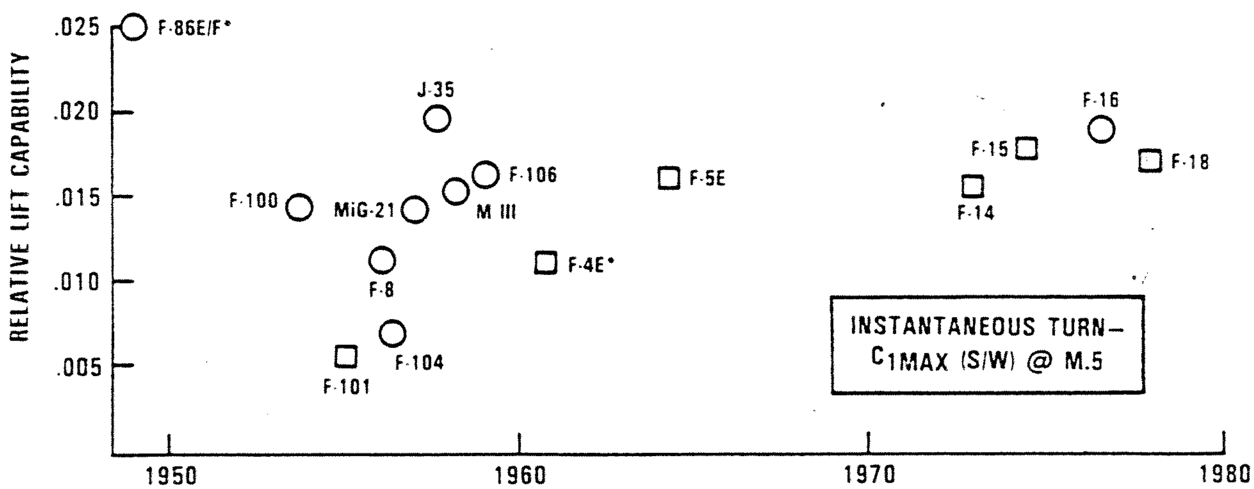

RELATIVE LIFT CAPABILITY
.025
.020
.015
.010
.005
1950
1960
1970
1980
F-86E/F*
J-35
F-100
MiG-21
M III
F-106
F-8
F-104
F-101
F-4E*
F-5E
F-15
F-14
F-16
F-18
INSTANTANEOUS TURN—
C1MAX (S/W) @ M.5

Figure IV-6

the F-14, are considerably lower and quite close to two-thirds of the maximum g of the F-86. Exceptions on the low side are the F-101 and F-104, which are crippled as fighters by a maximum turn capability less than one-quarter[1/] that of the F-86; the F-4E is better but has only half the maximum g of the F-86.

The airplane that most closely approaches the F-86 is the J-35 Draken[2/] with about four-fifths of the maximum g of the F-86. Slightly below the Draken but slightly better than the best turning of the sixties fighters such as the F-106 and F-5 are the F-15, the F-16 and the F-18.

The above ranking of fighters, although based on lift coefficients measured at Mach .5, remains generally valid for other speeds and altitudes (provided that the speed is slow enough and/or the altitude is high enough so that lift does not exceed the structural g limit), with one exception. The F-14's lift coefficient will decrease faster with speed than the fixed wing fighters because its wings will start to sweep aft at speeds beyond Mach .5; thus, its relative turn capability at higher speed will look poorer than it does in Figure III-6.

The improvement in turning performance of the latest U.S. fighters--- the F-15, F-16 and F-18 relative to the fighters of the sixties is a favorable development. There is, however, little pressure to improve much beyond this level since the latest Soviet fighters such as the MiG-23/27 and the MiG-25 have much worse turning performance than the MiG-21.

Transient Performance

In view of the nearly complete absence of flight test measurement of roll and pitch rates/accelerations at high g, subjective ratings are present-

1/ The poor turning performance of the F-101 and F-104 is due to both excessive wing loading (above 95 pounds per square foot) and low maximum lift coefficient (near .7) restricted by the violent pitch-up characteristics of the T-tail at high angles of attack.

2/ The Draken's good turn performance is due to a combination of light wing loading and the relatively good lift coefficient associated with the double-delta planform.

ed in Figure III-7 for pitch transient performance and roll transient performance under hard manuevering dogfight conditions. In each case, these ratings are based on the relative rankings of pairs of fighters both of which have been flown by at least two experienced pilots (with the exception of the J-35 and Mirage III, where only one pilot was available).

For roll transients, Figure III-7 shows that the F-86, F-104, J-35, Mirage III, F-106, F-5 and F-16 all have excellent roll performance.[1/] The F-100 and the MiG-21 can also achieve high roll performance, albeit at the risk of departure and/or spin, by using rudder and neutral ailerons to counteract their strong adverse yaw tendencies at high angles of attack. Notably sluggish roll performance is exhibited by the F-101, the F-4 and the F-14.

In pitch, the F-86, F-100, J-35, Mirage III, F-106, F-16 and F-18 all have excellent pitch performance at high angles of attack. Notably poor and dangerous are the F-101 and F-104, due to their violent pitchup tendency at high angles of attack.

Outlasting the Enemy

The combat persistence of the selected fighters is compared in Figure III-8 using fuel fraction as an approximate surrogate for actual ability to outlast the enemy while outmaneuvering him.

Based only on fuel fraction, the fighters that should have notably good combat persistence are the ones with at least 30% fuel fraction: the F-101, the F-8, the F-16 and the F-18. In fact, combat or ACM exercise experience confirms that these fighters (with the possible exception of the F-18 with its relatively inefficient cruise) are the ones with the best combat persistence and range. Of the rest, only the F-106 is known to have range and persistence competitive with the preceding four, presumably due to its some-

1/ Note that the fighters with the highest roll performance are, with the exception of the poor-handling MiG-21, the ones with the smallest wing-span, since this is the principal determinant of roll inertia. The F-18, with the latest modifications to increase roll control power, may have overcome its larger roll inertia. Unfortunately, reliable rankings are not yet available for the F-18 with these latest modifications.

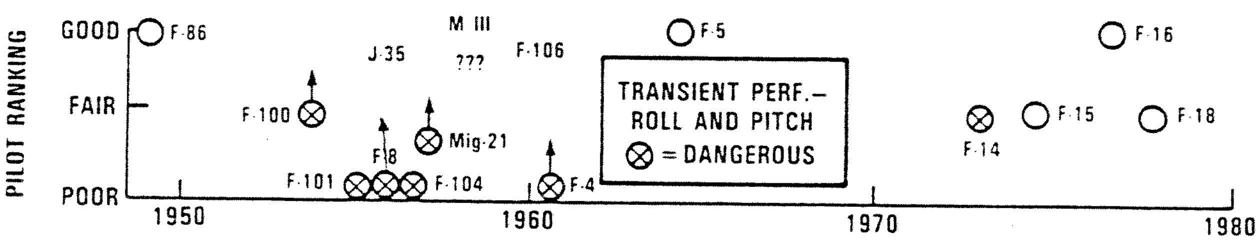
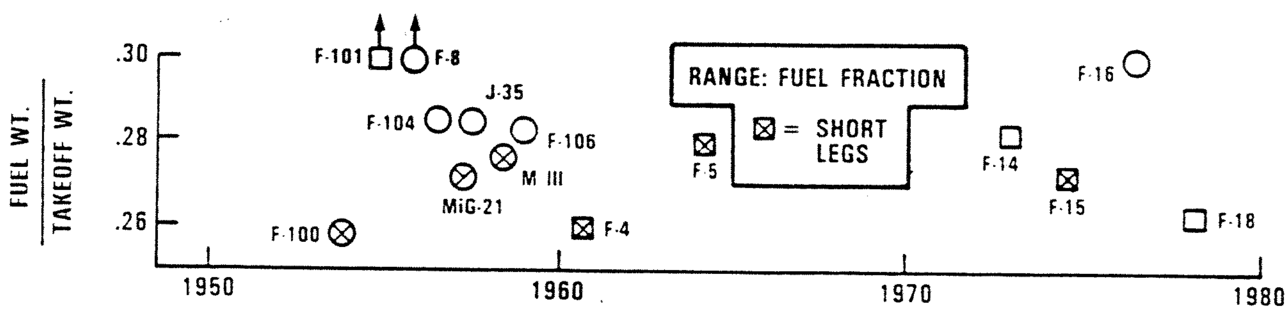

PILOT RANKING
GOOD
FAIR
POOR
F-86
F-100
J-35
M III
???
F-106
F-8
Mig-21
F-101
F-104
F-4
F-5
TRANSIENT PERF.–
ROLL AND PITCH
⊗ = DANGEROUS
F-14
F-15
F-16
F-18
1950
1960
1970
1980

Figure IV-7



FUEL WT.
TAKEOFF WT.
.30
.28
.26
F-101
F-8
J-35
F-104
F-106
M III
MiG-21
F-100
F-4
F-5
RANGE: FUEL FRACTION
= SHORT LEGS
F-16
F-14
F-15
F-18
1950
1960
1970
1980

Figure IV-8

what lower 28% fuel fraction being offset by its excellent cruise efficiency.

Of the remaining aircraft, the ones known to have combat persistence low enough to force frequent breaking off of combat (or of exercise dog-fights) are the F-100, MiG-21, F-4, F-5 and F-15. The F-100 and F-4 have inadequate fuel fractions of 26%. The MiG-21 has been notably short in range and persistence in combat [1/] -- despite its 27% fuel fraction -- mainly because of the very low efficiency of its engine compared to even the least efficient of U.S. engines. The F-5's 28% fuel fraction should be adequate but is offset by the inefficiency of its low pressure ratio J-85 engine.

The F-15A, in AIMVAL/ACEVAL and in Red Flag [2/] exercises, has shown combat persistence comparable to the F-5 and sometimes poorer. This is due to a combination of factors: a marginal fuel fraction of 27%; high cruise drag; and the pilots' tendency to remain in afterburner to avoid stall or relight problems. The F-15C has better persistence with its 30% fuel fraction, but its 3,000 pounds additional weight has reduced accelerating and turning performance relative to the F-15A.

It is noteworthy that the new technology engines of the F-14, F-15, F-16 and F-18 --despite their substantially higher temperatures, pressure ratios and by pass ratios compared to the fifties turbojets --have, in practice, provided no improvement over older fighters in actual cruise efficiency, as demonstrated in Appendix III. This appears to be due to three major factors: higher fuselage/inlet drag due to the increased frontal area of the fan engine [3/]; higher installation losses of the fans; and, excepting the F-16, higher boat-tail drag associated with twin engines. An additional sizable penalty to combat persistence is the significantly higher specific fuel consumption of fan engines in afterburner.

1/ In Vietnam, no MiG-21 engaged at much over 100 miles from base; many had to break off combat due to low fuel.

2/ The F-15 is typically the only fighter requiring aerial refueling in Red Flag exercises.

3/ Note that the engine frontal area accounts for a large proportion of total fighter cruise drag. This is not the case for transports, which is why fan engines have indeed improved cruise efficiencies of transports, despite larger engine frontal areas.

This explains why none of the new twin-engine fighters such as the F-14, F-15 and F-18 approach the range and combat persistence of the 1955 F-8. Only the single engine F-16 begins to compare in range with the F-8, though its cruise efficiency is still slightly lower (see Appendix III).

OBTAINING RELIABLE KILLS

The relative ability of fighters to achieve kills, given a firing opportunity achieved by either surprising or outmaneuvering the enemy, is compared on the basis of four effectiveness characteristics: kills per firing attempt, munber of on-board kills, time from opportunity to breakaway, and vulnerability to practical countermeasures.

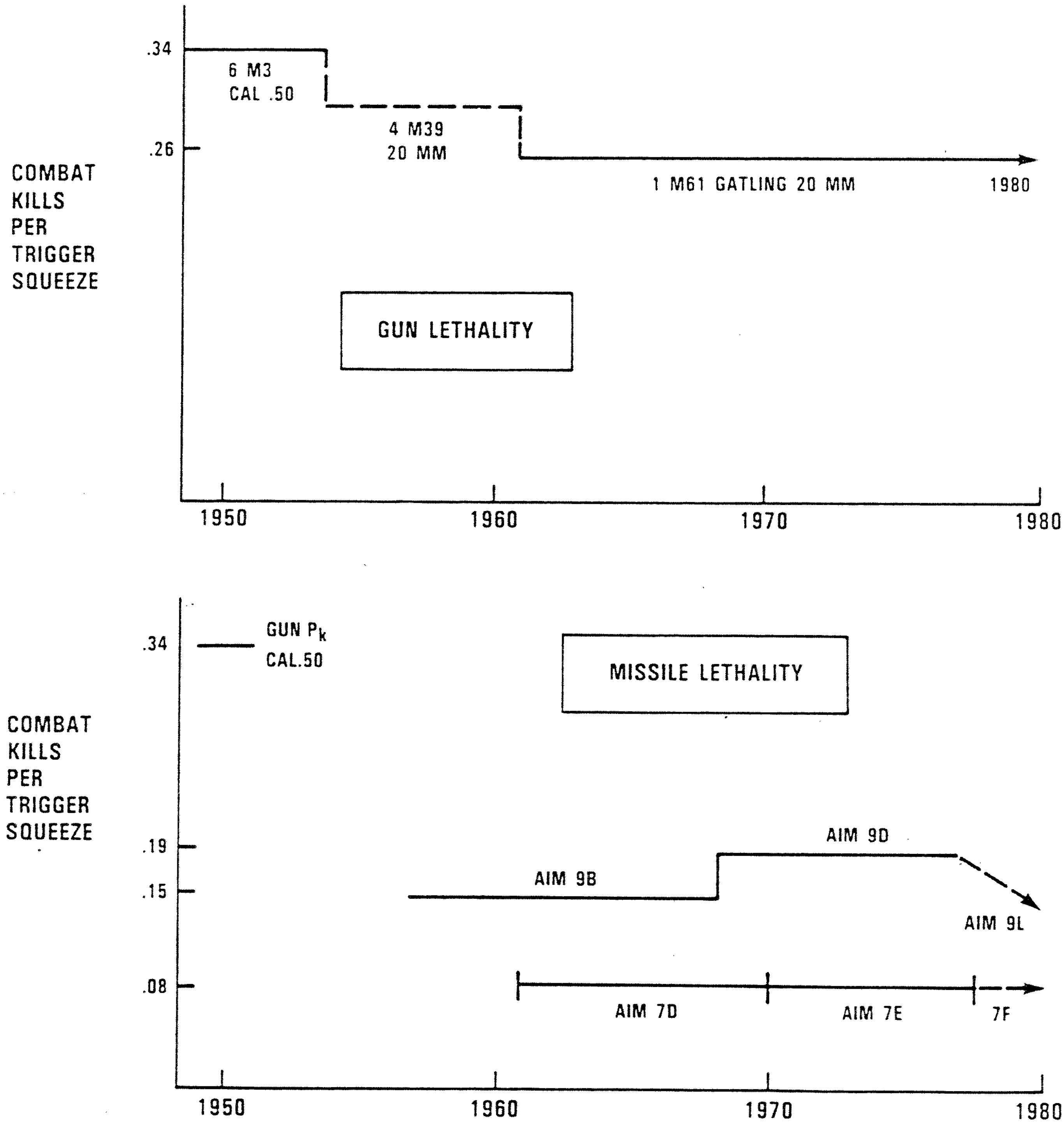
Kills Per Firing Attempt

Figure IV-9 shows the trends in combat kills per firing attempt for U.S. fighter armaments over the last 30 years.

Considering guns first, in Korea the six caliber .50 machineguns on the F-86 achieved .34 kills per firing pass against MiG-15s when the lead computing gunsight was not working and .31 when it was. In Vietnam combat fifteen years later, the M-61 20mm gatling cannon on F-105s and F-4s obtained only .26 kills per firing pass.[1/] There are many possible reasons contributing to the somewhat poorer performance of the 20mm gatling, including:

- o Time of flight beyond 1000 feet poorer than the .50 caliber (leading to fewer hits) due to the higher drag and lower density of the 20mm round.
- o Lack of fuze functioning at less than 15° graze angle.

1/ Note that this is remarkably close to the .24 kills per pass of the four M-39 20mm cannons used in the Gun-Val combat test during the Korean War (see p. II-).



.34
6 M3
CAL .50
4 M39
20 MM
.26
COMBAT
KILLS
PER
TRIGGER
SQUEEZE
1 M61 GATLING 20 MM
1980
GUN LETHALITY
1950
1960
1970
1980
.34
GUN P_k
CAL.50
MISSILE LETHALITY
COMBAT
KILLS
PER
TRIGGER
SQUEEZE
AIM 9D
.19
AIM 9B
.15
AIM 9L
.08
AIM 7D
AIM 7E
7F
1950
1960
1970
1980

Figure IV-9

- Low lethality per round due to small HE load, weak incendiary effects, and lack of fuze delay in order to allow round to penetrate.
- Less pilot gunnery training for Vietnam F-105/F-4 pilots than for Korean F-86 pilots.
- F-4 and F-105 much less responsive as platforms for air-to-air gunnary than F-86.

Figure IV-9 shows no kill rate results for foreign fighters due to lack of well-documented combat samples. Israeli Mirages, using two DEFA 30mm cannons, are said to have achieved .4 to .5 kills per firing pass in the 1967 and 1973 wars. This lethality level appears credible considering the intensive, near-daily gunnery training of Israeli fighter pilots and the much higher per round HE load of the 30mm. However, the low 2400 feet per second muzzle velocity of the DEFA cannon makes it somewhat shorter in range than the U.S. 20mm with 3300 feet per second.

Missiles

Figure IV-9 shows the time trend in kills per firing attempt for the two major U.S. air-to-air missile "families", the AIM-7 Sparrow and the AIM-9 Sidewinder.

Kill rates in Vietnam proved to be consistently higher for the relatively simple and inexpensive infrared-seeking Sidewinders. The first model, the AIM-9B, achieved .15 kills per firing attempt.[1/] This increased to .19 for the first cooled models, the AIM-9D and J.[2/] The last model of Sidewinder, the USN AIM-9G (functionally equivalent to the AIM-9D) was introduced during the last year of the air war in Vietnam and, based on a small sample of firings, 1/ North Vietnamese kill rates with the Atoll missile, a Soviet copy of the AIM-9B, were about 20% lower.

2/ The USAF models of Sidewinder, the AIM-9E and the AIM-9J, scored approximately one third lower kill rates than their USN near-equivalents, the AIM-9B and AIM-9D, respectively. This was due to technical deficiencies in the USAF versions rather than differences in pilot training.

achieved about .4 kills per attempt. Whether this was a real improvement over the AIM-9D or a statistical fluctuation cannot be determined.

The Sparrow kill rates proved disappointing: the first model used in Vietnam, the AIM-7D, achieved only .08 kills per firing attempt.[1/] The next model, used in combat, the AIM-7E, was intended to correct the defects of the AIM-7D; it demonstrated .10 kills per attempt. A final model, the AIM-7E2, was introduced at the end of the Vietnam air war to correct the fuzing deficiencies of the AIM-7E; it showed a similar .08 kill rate.

The reasons for these disappointing Sparrow results are far from being fully understood, but appear to include the following:

- o Poor reliability, with 46% of attempts (i.e., half of the 92% non-kills) being failures to launch or to guide.[2/]
- o Out-of-envelope launches[3/] caused only 7% of the non-kills.
- o Early fuzing due to the AIM-7 fuze's high sensitivity to false doppler returns caused by jet engine modulation and/or ground clutter.
- o Poor clutter rejection in lookdown shots causing a lock onto ground clutter rather than the target.
- o Honing on the radar centroid of two or more targets flying less than about 5,000 feet apart.

It is noteworthy that about 3 times as many Sparrow firings were from the tail quadrant as from the nose quadrant, despite the fact that pilots were taught that the Sparrow was significantly more effective head-on. This reflects a) the difficulties of achieving positive visual identification early enough to shoot in a head-on pass; and b) the natural tendency of combat to provide more visual detection opportunities and more surprise oppor-

1/ In comparison, the infrared Falcon AIM-4D, achieved .07 kills per attempt. It was considered a failure and was cancelled and withdrawn from service.

2/ This compares with 30% and 37% failures to launch or guide for the AIM-9B and AIM-9D, respectively.

3/ These represent launches outside the "nominal" AIM-7 envelope. Actual AIM-7 envelopes are so complex and sensitive to target maneuvers as to be essentially unknowable. AIM-7 simulations (which do not provide accurate representations of clutter or fuzing problems) show large "swiss cheese" holes within the outer envelope boundaries for targets performing steady turns or S-turns above 3 g.

tunities during tail-on approaches to a potential target.

New Missiles

As mentioned in Chapter II, there is no valid analytical or simulation method for predicting the kill rates of missiles that have not been used in combat. Therefore, one can only speculate on the likely lethality of the new versions of the Sidewinder and the Sparrow, the AIM-9L and the AIM-7F.

The AIM-9L appears to have reduced two problems that plagued the AIM-9D: unreliability and inaccurate radio fuzing. The AIM-9L combination of optical fuzing and the less geometry-sensitive fragmentation warhead should significantly reduce non-lethal detonations. On the other hand, the high sensitivity of the AIM-9L infrared seeker (designed to permit locking onto the cool nose aspect of typical fighters) may increase the AIM-9D's already serious inability to discriminate the target from infrared-reflecting snow/clouds or from warm ground objects or from warm CO_2 bands at the horizon. Another problem stemming from the plume-seeking behavior of the more sensitive seeker may be an increased susceptibility to afterburner "puffs" and/or violent transient maneuvers intended to outgame the missiles time constant and its lead-bias.[1/]

The AIM-7F shows few significant improvements over its AIM-7E2 predecessor and at least one significant drawback. Unreliability continues to be a problem, though perhaps slightly less so than on older Sparrows. Early fuzing remains a problem. There is no solution to the multi-target centroid problem and single targets are not common in fighter combat. Telemetry-measured clutter rejection of the AIM-7F is no better than the earlier

1/ The excellent AIM-9L results in WSEP firings do not include firings against over-land lookdown targets, against afterburner "puffs", or against transient maneuvers that respond to the missile's behavior.

clutter-sensitive Sparrows, though possibly for different reasons.[1/] The new sustainer motor added to the AIM-7F, though it adds range and high altitude performance, may prove to be a serious drawback in combat. Unfortunately, the sustainer adds 10 seconds of highly visible smoke trail (over and above the normal 2 second initial boost) to the missile's signature. This visibility makes it much easier for the target pilot to initiate adaptive S-turn or split-S maneuvers that load up the Sparrow in one direction and then break hard in the other direction, playing against the missile's time delays to induce a wide miss. These adaptive tactics were almost invariably successful against the easily-seen SA-2 radar missiles in Vietnam. The AIM-7M now in development perpetuates the sustainer-induced problem.

Overall, it appears that there is little reason to expect that the new Sparrow models will show notably better kills per firing attempt than the .08 to .10 experienced in Vietnam. The AIM-9L is more of an open question: the breaklock problem due to clutter and high seeker sensitivity might reduce kill rates below the .19 of the AIM-9D/J; if this problem proves minor, then the AIM-9L could show kill rates even better than the .4 peak achieved by the AIM-9G.

Number of On-Board Kills

Guns

The F-86 --with .34 kills per pass, about 4 seconds firing time per pass,[2/] 267 rounds per gun and a per gun firing rate of 18 rounds per second--had enough on-board ammunition, on average, for about 3.7 passes or 1.3 kills.

1/ Both the AIM-7F and the AIM-7M may be suffering from plume modulation, that is, phase distortion induced by the rear reference antenna "looking" through the new sustainer motor rocket plume back at the fighter's illuminating radar. This phase distortion is indistinguishable from clutter within the missile's signal processing.

2/ Bi-variate Analysis of Korean Air-to-Air Combat Film, J.E.Hall, Institute for Air Weapons Research, University of Chicago, February 1954. This reference shows the average number of bursts per pass to be about 3.

Current fighters such as the F-15, F-16 and F-18 using the M-61 20mm gatling have about 940 rounds stowage and, using Vietnam results, about .26 kills per pass. Assuming 4 seconds firing time per pass as above, this equates to an average of 2.9 passes[1] or .76 kills for each full load of on-board ammunition.

This represents a considerable deterioration in sustainability of kills for guns over the last 30 years, most of the decrease being attributable to the decreased lethality per pass of the 20mm.

Missiles

The relatively standard load of 4 Sidewinders, used on most fighters since the F-4, add the same on-board kills (assuming the AIM-9D/J kill rate of .19) as the M-61 20mm cannon: .76 kills. Thus, the 20mm plus Sidewinders give a total of about 1.5 on-board kills, slightly more than the F-86's total on-board kills.

Four Sparrows adds little to this --about .32 to .4 kills, using the Vietnam results.

Time from Opportunity to Breakaway

In many-on-many fights, following a predictable trajectory -- as, for instance, during a weapons launch sequence -- for more than about 7 to 9 seconds is inviting a significant chance of being killed by surprise by an unseen enemy.[2]

Thus, the time from firing opportunity to breakaway becomes a critical measure of the risk inherent in firing a given weapon.

For air-to-air guns, this time is about 3 to 6 seconds, depending

1/ Based on an effective firing rate for the M-61 of 80 rounds per second. This assumes an average burst length of 1.25 seconds and .5 seconds to accelerate to full rate.

2/ This is why the USN Topgun School teaches that, in one-versus-many or many-versus-many fights, one must never pursue the same path or steady state maneuver for more than 7 seconds. These are the "look-shoot-break-look" tactics also favored by USAF Aggressor squadrons.

on the difficulty of stabilizing a gunsight firing solution and the length of the burst. For Sidewinder-type missiles, the time to obtain a lock-on, check firing parameters and launch is about 5 to 7 seconds -- a time approaching the danger limit.

For the Sparrow, the time to breakaway necessarily includes radar lock-on time (2 to 5 seconds, depending on target and false target multiplicity), fire control computer settling time (2 seconds), missile launch delay (2 seconds) and time of flight of missile[1/] (4 seconds at minimum range to about 15 seconds at maximum range). This amounts to a total duration of 12 to 26 seconds, a predictable flight path so long as to represent a major hazard to the Sparrow-launching fighter in the many versus many fight.

Susceptibility to Countermeasures

Guns

The principal counter to a gun attack is maneuver to defeat the firing solution.

Sidewinder

Early Sidewinders, the AIM-9B and AIM-9E (and Atoll), were frequently defeated in Vietnam combat by hard maneuvers. The possibility of engine transients, adaptive transient maneuvers, and lookdown as a counter to later models, the AIM-9D through the AIM-9L, has been previously mentioned but remains largely untested.

An active countermeasure that is nearly 100% effective against the radio-fuzed Sidewinder AIM-9D through AIM-9H is the doppler fuze jammer,--

1/ Since Sparrow requires the fighter radar to continuously illuminate the target until missile impact.

a simple, lightweight, low power device requiring no sophisticated electronics. Whether or not the Soviets have developed such a device for their fighters is unknown.

An even simpler active countermeasure that has demonstrated essentially 100% effectiveness against all models up through the AIM-9L [1/] is the infrared decoy flare dispenser, a device that has been developed by both the U.S. and the Soviets.

The inherent limitation on all these counters to the Sidewinder is that the target must first be aware that an infrared missile has been launched. Since the Sidewinder has the great advantage of being passive, it remains fully effective as a surprise weapon, even against an enemy carrying good countermeasures -- provided we avoid emission that could alert the enemy during our surprise attack.

Sparrows

The "centroid" formation and adaptive reversing maneuvers appear to be effective counters to the Sparrow, based on test and Vietnam experience.

A low power serrodyne repeater [2/] acting as fuze jammer would magnify the already-sizable fuzing problems of the AIM-9D/E/E2. A slightly different fuze jammer would work against the AIM-7F.

Blinking jammers [3/] alternating between a pair of fighters would be nearly 100% effective in countering Sparrow --and would free the pair from having to maintain the spacing for best "centroid" effect.

Since Sparrow is an active system with a distinctive lock-on signature prior to launch, it must be considered a weapon that destroys surprise--at least against any enemy with a moderately competent radar warning receiver

1/ This countermeasure may not work against the AIM-9M now in development since the new seeker is designed to discriminate against flare-type motion; however, the efficacy of this ECCM feature has not yet been subjected to operational test.

2/ This is simply a repeater that adds a false doppler shift to the incoming signal.

3/ There could be simple, low power CW signal repeaters (as used on target drones). They would be switched on and off at a frequency near the missile time constant; a quartz clock would be accurate enough to eliminate the need for timing signals to coordinate the two fighters' on-off cycles.

such as the MiG-21's Sirena receiver. This means that the enemy normally will be alerted in time to initiate countermeasures, be they maneuvers or active electronic devices.

SUMMARY OF EFFECTIVENESS TRENDS

This section briefly summarizes progress, or lack thereof, in air-to-air effectiveness over the last 30 years.

Achieving Surprise

Since the F-86, most Free World standard fighters have shown decreasing ability to achieve surprise -- primarily due to increasing physical size, smoke and the increasing reliance on continuously-emitting radars and radar missiles. The Soviets have shown a similar decline in capability to achieve surprise since the MiG-21.

Notable exceptions to the adverse trend in surprise are the F-5, the Mirage III/V, and the J-35 Draken and the F-16, though the latter is slightly handicapped by some engine smoke.

Outnumbering the Enemy

Increases in cost and complexity that were unnecessary to enhance air-to-air effectiveness have decreased today's effective force size per constant dollar by factors of 25 to 75, relative to the F-86's 2000 sorties/day per billion dollars.

The only large exception to this strikingly adverse trend is the F-5E, which manages to produce 500 sorties/day per billion dollars.

Soviet fighters have also deteriorated in effective force size capability since the MiG-15, but not as sharply as Free World fighters.

Outmaneuvering and Outlasting the Enemy

Acceleration and climb improved dramatically between the F-86 and F-104A, but current fighters do not quite match the F-104A.

Maximum turning g deteriorated sharply after the F-86, but the F-15, F-16 and F-18 have recently reversed this trend. They have significant maximum g advantages over the MiG-21 and much greater advantages over the MiG-23/27 and the MiG-25. Among supersonic fighters, their maximum turn capability is exceeded only by the J-35 Draken.

In ability to transition quickly between maneuvers, only the F-5 and the F-16 can match the excellent transient performance of the F-86. Progress is hampered by the continuing lack of standard measures (and standard flight tests) of transient performance at high g.

Combat persistence, the ability to outlast the enemy while outmaneuvering him, has generally deteriorated since the F-8 --mainly due to decreasing fuel fractions, the drag and weight penalties of twin engines, and the inefficiency of fan engines installed in fighters. Recently, only the F-16 comes close to the range and combat persistence of the F-8.

Achieving Reliable Kills

Gun lethality and range has probably deteriorated slightly since the caliber .50 of WWII and Korea, due to the poor ballistics and poor projectile of the U.S. 20mm round.

The infrared missile has added major tactical options for a) killing unalerted targets out to the limits of positive visual identification range; b) eliminating the non-maneuvering, accelerating escape used in WWII to defeat gun attacks; and c) forcing the enemy into a hard defensive break at long range, making him vulnerable to follow-up gun attacks. However, the kills per firing attempt of the best infrared missiles in Vietnam were only slightly better than half the kill rate of guns in Korea.

Radar missile lethality in Vietnam was less than half that of the best infrared missiles; head-on shots were used only about 1/3 as frequently as tail-on shots. Thus, the AIM-7D/E/E2 did not add much to fighter effectiveness over and above the capabilities of the AIM-9D.

The newest AIM-7F/M models are unlikely to correct the fundamental weaknesses demonstrated by the AIM-7s in Vietnam. The AIM-9L may or may not represent a significant increase in kills per attempt over the AIM-9D, depending on whether the high seeker sensitivity greatly increases lookdown and breaklock problems.

CHAPTER V

COMPARISON OF EFFECTIVENESS CALCULATIONS WITH COMBAT RESULTS

INTRODUCTION

This chapter compares the results of the Chapter IV effectiveness calculations with the outcomes of actual air-to-air combat over the last 30 years in order to assess the validity of the effectiveness analysis. Based on this, some overall evaluations of the most interesting fighters of the 30 year era are presented.

KOREA AND VIETNAM: F-86 VS F-4

In the Korean War, well-trained U.S. air forces with extensive WWII combat experience faced an inexperienced, developing country air force. The U.S. did extremely well with a 10 to 1 exchange ratio between F-86s and MiG-15s, even though the two fighters were surprisingly closely matched in performance. The major technical advantage of the F-86 was its considerably better transient performance.

In Vietnam, the U.S. faced an even more inexperienced, developing country air force. The two principal fighters, the F-4 and the MiG-21, were again well matched in performance, with some acceleration advantage for the F-4 --and a lop-sided superiority for the F-4 in radar range and radar missile capability. But this time the U.S. fighter only achieved a 2 to 1 exchange ratio, a much less satisfactory outcome than Korea.

What accounts for the difference? Examining the individual engagement descriptions in the Red Baron file quickly shows that the difference lies in the F-4s susceptibility to being surprised. When the F-4 achieved surprise, it was about as lethal as the F-86. But the F-86 was surprised only rarely; the F-4 was surprised frequently enough to ruin its exchange ratio.

The Chapter IV analysis shows clearly why the F-4 was much more vulnerable to surprise than the F-86: the F-4 smoked heavily and, secondarily, had very poor rearward visibility and was twice as large as the MiG-21. Even worse, the F-4 was the only fighter in the theater that smoked. Thus, MiGs could positively identify it at 15 to 25 miles and could launch an infrared missile at maximum range without having to close for normal visual ID.

Another important factor in the F-4s loss of surprise was that the F-4 flights normally outnumbered the MiG flights they engaged where as the reverse was true for the F-86 in Korea. A look at Figures II-1 and II-3 shows that, when fighting at 1 to 1 force ratios, the F-86 exchange ratio was only twice as good as the F-4s. Had the F-4s flown more often in pairs rather than fours, their exchange ratio would have improved.

ARAB-ISRAELI WARS: '67 AND '73

Because of the enormous disparity in pilot skill between Israeli and Arab --much larger than between American and North Vietnamese pilots -- not much can be concluded about the relative merits of the MiG-21 and the Mirage III from the over 20 to 1 exchange ratio of the Israelis. Nevertheless, some useful insights can be obtained.

First, the Israeli fighter pilots much preferred the Mirage III and often referred to the F-4 as the B-4. Their stated reasons for preferring the Mirage III were primarily small size and better agility (that is, better maximum turn and better transient performance); both advantages are clear in the Chapter IV analysis.

Secondly, the Israelis attributed about two-thirds of their air-to-air kills in both wars to guns or guns aided by an initial missile launch to force a hard break --a much higher proportion of gun kills than the U.S. experience in Vietnam, reflecting the much better gunnery training of the Israelis and the fact that the Mirage III was a substantially better gun platform than the F-4.[1/]

Thirdly, the Israelis attribute a negligible role to fighter radar and the Sparrow. General Hod stated to several American audiences that the Sparrow achieved either no kills or one kill in the 1973 war and that on-board radar was "essentially useless". This tends to support the Chapter IV emphasis on guns and infrared missiles as the principal components of achieving reliable kills.

INDO-PAKISTANI WAR: F-86 VS MiG-21

The backbone of the Pakistani air-to-air effort in the 1971 Indo-Pakistani war was a force of 96 Canadian Mark VI Sabres, the hottest model of the F-86 series.[2/] The Sabres, were equipped with Sidewinder missiles in addition to the usual six caliber .50 machineguns. The remaining 75 Pakistani fighters included Mirage III's, F-104s and Chinese MiG-19s. They faced 700 Indian fighters and attack aircraft. The main Pakistani advantage was better pilot training.

The Sabres did the lion's share of the killing, achieving an approximate 6 to 1 exchange ratio[3/] against the Indians' supersonic MiG-21s and

1/ Less than one-quarter of the F-4s that engaged MiGs in Vietnam were F-4Es, the only F-4 with an internal gun and a lead-computing gunsight.

2/ The Pakistanis had bought these 96 F-86s from the Luftwaffe a year earlier for a total of $10 million. This equates to 7500 sorties/day per billion dollars (FY 83), an extraordinary bargain.

3/ Based on the London Times observer team's account plus the engagement-by-engagement account in Shaheen, the Pakistani Air Force Journal. Wing Commander Alam, the leading Pakistani ace, stated in a 1981 Pentagon interview that the F-86 exchange ratio was 7 to 1.

Sn-7s and subsonic Hunters. Overall, the Pakistani Air Force achieved air superiority over its own territory in 7 days. The only Indian fighter in the war that killed several Sabres with no losses was the Gnat, currently the smallest fighter in the world at 7500 pounds. It is subsonic like the F-86, but has better acceleration.

Needless to say, the main reason for the Sabre's success was the superior skill of the Pakistani pilots. Nevertheless, the Sabre demonstrated that a hard-to-see, agile, subsonic fighter --equipped with guns plus infrared missiles and flown by superior pilots --can prevail against more modern Mach 2 fighters.[1/]

MANY-ON-MANY AIR-TO-AIR TESTS

In the last twenty years, the U.S. has conducted two major air-to-air tests involving engagements up to 4 on 4. The first, in 1965, was the USAF Featherduster test at Nellis. This test was intended to develop better tactics to counter the MiG-17 in North Vietnam. Air National Guard F-86Hs were used to simulate MiG-17s and pitted in offensive and defensive positions against F-100s, F-104s, F-105s, F-4s, and F-5s. For the first few weeks of the test, the F-86Hs achieved a lop-sided superiority over all the opposing fighters. Eventually, the Century series pilots adapted to the extreme maneuverability of the F-86 and developed better counter-tactics. Despite this, over the entire six month course of the test, only the F-5 came close to achieving a 1 to 1 exchange ratio against the F-86.[2/]

Twelve years later, a much more elaborately instrumented series of air-to-air tests was conducted in 1977 at Nellis, this time to provide evaluation and justification of a new generation of air-to-air missiles

1/ As usual, most of the Sabre kills were due to surprise, which was not difficult for the Sabre to achieve since it was small and cruised at the same speed as the MiG-21s and Su-7s.

2/ Next most successful was the F-104. According to the Featherduster final report, this was nearly as small and as hard to see as the F-5, though much less maneuverable.

and to test the effects of force size. The AIMVAL/ACEVAL ground rules[1/] and the restrictions imposed by the instrumentation led to more artificial conditions, with a far higher percentage of head-on engagements than had been experienced in Vietnam. The F-5 was used to simulate the MiG-21 against both F-14s and F-15s. Pilots on both sides were intensively trained and were far above average skills.

The outcome, despite the artificialities, was surprisingly similar to Featherduster. For the first three weeks, the F-14s and F-15s were hopelessly outclassed and demoralized. Eventually, they adapted with more suitable tactics. In the first test, AIMVAL, the pairs and fours of F-14s had an overall score of slightly less than 1 to 1 against the F-5s while the F-15s scored slightly above 1 to 1. In the second test, with further "tuning" of the rules, the F-14s did slightly better than breaking even with the F-5s in non-1 v 1 engagements; the F-15s got almost 2 to 1.

Despite the crippling artificialities of the tests, several insights were obtained which probably can be extended to real combat,[2/] including:

- o Even though the pilots were selected from among the best in the USAF and USN, differences in results among these hand-picked pilots were much larger than among the three airplane types.
- o Tactics had to be changed daily to remain unpredictable and to avoid devastating losses.
- o Pilots replaced during the test in the simple F-5 were up to full proficiency in two or three weeks; replacements in the F-15 were still learning after three months due to the system complexities.
- o The F-14s rear seat radar operator was a help in simple 1 v 1 situations; in complex 2 v 4 or 4 v 4 engagements he overloaded

1/ The ground rules heavily favored radar and long range shooting, allowed beyond visual range shooting after the first shot on each side, assigned artificial probabilities of kill to the missiles that were 3 to 8 times higher than Vietnam combat results, handicapped the use of guns and forbade the use of effective radar warning receivers by the F-5s.

2/ The most widely quoted results of AIMVAL/ACEVAL are the strong improvement in exchange ratio as force ratio advantage increases. This is flatly contradicted by the actual Korean and Vietnam air-to-air combat experience, as shown in Figures II-1 and II-3. Similarly, the AIMVAL/ACEVAL conclusion that exchange ratios approach 1:1 as the number of participants in a fight increase is also contradicted by real combat.

the pilot with inputs.

- Surprisingly, GCI assistance was more important to the highly automated F-14 and F-15 than to the F-5.
- Off-boresight features of advanced missiles improved results only slightly.

Perhaps the most important perception to be derived from the Featherduster and AIMVAL/ACEVAL tests, considering all their limitations, is relatively simple. In the 1965 tests, the F-5 could not dominate the F-86. In the 1977 tests, the F-14 and F-15 were not able to convincingly dominate the F-5 in air-to-air fights. Doesn't this raise serious doubts as to whether, despite our phenomenal technical advances over the last 30 years, we have made decisive progress in actual air-to-air effectiveness?

SUMMARY EVALUATION OF KEY AIR-TO-AIR FIGHTERS

Based on the preceding historical perspective and the Chapter IV effectiveness comparisons, it is possible to derive some useful insights by comparing several of the most interesting Free World fighters since the F-86. The interesting examples are the F-104A, the Mirage III, the F-5E, the J-35 Draken and the F-16.

F-104A

The F-104A's outstanding design achievement was to package a remarkably small fighter around a big engine, the J-79. The light weight of the first F-104 model[1/] coupled with the 19,000 pound thrust of the J-79-19 produced the best-accelerating fighter of the last 30 years. Unfortunately, due to the designers' focus on maximizing top speed (i.e., Mach 2 burst

1/ The F-104's weight jumped 2,000 pounds with the advent of the F-104G, the tactical nuclear bomber version that was exported to NATO.

speed rather than sustained speed), the F-104 proved to have so little wing area and turning performance as to be nearly unusable in a maneuvering fight. With 25% more wing area, a low tail and a transonically-optimized inlet --as was suggested while the F-104 was still in production -- the F-104 could easily have been the most effective, best performing, air-to-air fighter up through the late seventies.

Mirage III

The Mirage III design wrapped a fighter as small as the F-104 around an engine slightly bigger, but with poorer thrust, than the J-79. The resulting fighter, due to the large wing area made possible by the tail-less delta design, has excellent turn and transient performance. Even though it has less acceleration than the F-104 or the F-4, it strikes a more usable balance between turn and acceleration without sacrificing small size and invisibility --as demonstrated by the preference of Israeli fighter pilots for the Mirage III.

Had the Mirage III been designed around a better engine such as the J-79,[17] it would have been an even more effective fighter than a well-balanced version of the F-104. It would have been, in effect, a half-size F-106, sharing the F-106's excellent range and maneuvering performances but with better ability to achieve surprise.

F-5E

Though not widely conceded at the time, air-to-air tests and Aggressor squadron engagements have demonstrated that the F-5 was the most effective U.S. air-to-air fighter of the sixties and early seventies, up through

1/ The Israeli Kfir is basically a Mirage III retrofitted with the J-79 engine and with small canards added. Unfortunately, the retrofit compromises involved so much weight gain that the Kfir does not represent an advance in maneuvering performance.

and including the F-4E and F-14. Its main advantages are its very small size --particularly unusual for a twin[1] --and its high transient performance; even more important is the F-5's 500 sorties/day per billion dollars, about 5 to 6 times more sorties than either the F-4 or the F-16. The F-5's weaknesses are somewhat deficient acceleration, marginal rearward visibility and marginal combat persistence.[2]

The F-5E, with 15% less weight, would have corrected these deficiencies. As a result, its dominance in air-to-air over its contemporaries would have been considerably harder to ignore. Had the F-5E been developed as simply the J-85-21 up-engining of the 12,500 pound F-5A, then it could indeed have come in at about 13,000 pounds which would have resulted in a major performance improvement. Instead, design discipline was lost: each functional engineering group was left free to strengthen, expand or "upgrade" its subsystems and the F-5E grew 3,000 pounds to 15,500 pounds, thus cancelling out most of the benefit of the 25% growth in thrust[3] and maximum lift coefficient.

J-35 Draken

The J-35 Draken was the first high performance delta, preceding the F-100 and the Mirage III, it was also the first double delta. Its strenghts are:

- Small size, only slightly larger than the Mirage III.
- Good thrust-to-weight yielding acceleration better than the F-4 or F-100.
- Light wing loading and good lift coefficient, leading to the best maximum turn since the F-86.

1/ Historically, the F-5E is the first twin engine fighter to be among the best dogfighters of its time, an accomplishment mainly due to its being the first twin that was smaller than its contemporary single engine fighters.

2/ Based on AIMVAL/ACEVAL, F-5E combat persistence is about equal to the also-marginal F-15A.

3/ Note that this has been the case for almost every U.S. fighter model change since WWII. The last fighter that became lighter as the result of a model change was the P-51H, the finest P-51 of all.

o Good fuel fraction and the typical high cruise efficiency of single engine deltas, leading to good range and combat persistence.

The Draken appears to be a better dogfighter than any of the preceding three fighters --or any other of the Century series up to and including the F-14. It is significantly more effective in air-to-air than its replacement, the larger and relatively sluggish Viggen, as the Swedish Air Force is now discovering to its sorrow. In fact, Drakens have proved to be the most difficult dogfight opponents that F-16s have faced to date in Europe (including F-15s).

The major disadvantage of the Draken is its unnecessarily costly and ineffective Falcon fire control and missile system, which degrades both effective force size and the ability to achieve reliable kills.

F-16

The protopype YF-16, at 20,000 pounds fully armed,[1/] had a thrust-to-weight of 1.18 and a wing loading of 71 pounds per square foot. The resulting small size and unprecedented maneuvering performance --including acceleration even better than the F-104A(-19) --menat that, plane for plane, the YF-16 could dominate any other fighter in the world with ease. Due to prototype fabrication weight compromises, there was the further potential to lighten the production version by another 1500 pounds, had design discipline and focus on air-to-air effectiveness been exercised.

Instead, complexity and weight was added for multi-mission capabilities and "nice-to-have" features.[2/] Weight went up by 3,500 pounds (and is still increasing); thrust-to-weight decreased to 1.0 and wing loading rose to over 78 pounds per square foot. The major widening of the nose to accom-

1/ The YF-16 was armed with Sidewinders, two M-39 20mm cannons, bomb racks, a range-only radar and a computing gunsight for the missiles and guns.

2/ These included the air-to-air/air-to-ground radar which required larger generators and air conditioning, a complex air-to-ground stores management system, a multi-mission heads-up display, an on-board jet fuel engine starter, extra structure for 8,000 hours fatigue life and 9 g load factor, a large capacity digital computer, and nuclear stores wiring.

modate the large multi-function radar significantly degraded lateral stability at high angle of attack, which in turn reduced the maximum lift coefficient and the transient performance. Thus, maximum turning g deteriorated from the YF-16 to the F-16 by almost 25%. Cost went up by almost 60% and maintenance manhours increased by at least 25%. The result is a halving in sorties/day per billion dollars.

Despite this, the F-16 has won the substantial majority of air-to-air engagements in training exercises against all the fighters it has faced, including F-15s fighting under beyond visual range rules.

The F-16's major effectiveness weakness is that it produces only one-sixth as many sorties per day per billion dollars as the F-5E. Although plane for plane it is clearly superior in air-to-air combat to the F-5, it is not clear that one F-16 is more effective than six F-5s in defeating large numbers of MiG-21s and MiG-23s. This question is unlikely to be settled by any means short of actual combat experience.

CHAPTER VI

SOME INSIGHTS

INTRODUCTION

Based on the preceding analysis, this chapter summarizes both negative and positive insights: first, some factors that have prevented us from making major advances in overall fighter effectiveness since the F-86; second, an outline of how the effectiveness framework of this paper can be used to shape a dramatically superior fighter, using currently available technology.

WHAT HAS PREVENTED REAL PROGRESS IN FIGHTER EFFECTIVENESS?

Despite remarkable U.S. progress over the last 30 years in all the components of fighters --engines, structures,aerodynamics, and microelectronics --we have not been able to convert these advances into a fighter that is radically more effective than its predecessors and its foreign competitors. Some of the reasons include:

- A lack of clear understanding and definition of the critical qualities for fighter combat effectiveness. This makes it impossible to integrate individual technical advances into superior designs.
- An inability to enforce design discipline upon the DOD/Service R&D bureaucracies and the industry's engineering bureaucracies. It is not possible to build fighters of unmatched effectiveness if they are forced to haul heavy and/or complex features that are not absolutely essential to the single objective of victory in air

combat. This includes such combat irrelevances as boarding ladders, self-starters, emergency arresting gear, 8000 hour airframes, variable geometry inlets, auxiliary power units, twin engines, etc.

- A continuing insistence since 1950 on incorporating multi-mission capabilities in each fighter, despite the crippling penalties. An excellent air-to-air fighter cannot be built around design requirements that include ground attack, night-fighting/interception, or night bombing. Each of these missions is important enough to warrant a dedicated, single-purpose airplane. None can be done well by an air-to-air fighter.
- A failure to improve engine thrust-to-weight since the J-85-21, due to unnecessary engine specifications and the technologists' preference for excessive pressure ratios, turbine temperatures and high bypass ratios -- despite their adverse effect on fighter performance, reliability and cost.
- A refusal to recognize the failure of radar missiles in Vietnam and Israel, for inherent reasons that massive investment of R&D funds cannot eliminate.
- A similar refusal to recognize that AI radars contributed little to target acquisition in Vietnam and Israel --and that, in the future, our continuous use of radars will provide the enemy with more information (and a better missile-homing reference) than it gives us.

CAN HISTORICAL AIR-TO-AIR EFFECTIVENESS CRITERIA LEAD TO A MAJOR FIGHTER ADVANCE?

Effectiveness Areas that Allow Dramatic Improvement

Of the four key effectiveness areas --surprise, numbers, outmaneuvering the enemy, and achieving reliable kills --the two with the largest potential for improvement are the two we have ignored the most in the recent past: surprise and numbers.

To greatly improve the capability to achieve surprise requires only a few simple steps:

- o Cruise several hundred knots faster than the enemy in order to achieve dominance in surprise bounces.
- o Place primary electronic emphasis on passive on-board sensors, only the briefest use of active sensors, and off-aircraft cueing to avoid losing surprise.
- o Design for the smallest possible physical size, the least visible shape and camouflage, and absolute absence of smoke.

To improve effective force size by a factor of perhaps 10 relative to the F-15 and F-14 (or 3 relative to the F-16) is feasible by:

- o Returning to all-aluminum airframes.
- o Keeping size below F-5E levels.
- o Relying primarily on passive avionics based on advanced, simple technology.
- o Using a single, simple, engine with six or less stages (as opposed to the 17 stages of the F-100) and moderate temperature.
- o Using competitive skunk works prototyping and then competitive two-source production.

Technical Description and Feasibility

Speed

The driving influence on the design is the need to cruise at least several hundred knots faster than the enemy's current cruise speed of about Mach .9 or so. This means the new fighter needs to cruise at slightly beyond the Mach 1 to Mach 1.2 drag rise. A fighter shaped for minimum wave drag at low supersonic cruise and with a thrust-to-weight ratio above 1 will inherently be able to cruise at speeds from Mach 1.2 to Mach 1.6 or beyond, without a) having to carry the penalty of a heavy and expensive variable geometry inlet; or b) having to use any material beyond aluminum. To achieve this minimum wave drag will restrict the design to a single engine configuration.

Range and Persistence

There is no particular difficulty in cruising supersonically except for the inherently high fuel consumption, which is about twice that of subsonic cruise. Since useful supersonic cruise entails at least 20 or 30 minutes at this speed in enemy territory, it is immediately clear that fuel fractions will need to be substantially higher than the 30% of today's best fighters.

Based on several industry tradeoff studies, it appears that fuel fraction of 40% will be adequate for 20 or 30 minutes of supersonic patrolling after a subsonic cruise leg of 200 to 300 miles to enemy territory. The mission rules need to include a combat persistence reserve based on at least one acceleration from Mach .8 to 1.6 at 30,000 feet and possibly two from Mach .8 to 1.2 at 10,000 feet.

To obtain a fuel fraction as good as 40% means that something like 10% of the total weight of today's fighters need to be eliminated, whether from structures, accessories, avionics or weapons. This obviously entails a level of design discipline well beyond anything we have exercised since the P-51H. Potential weight savings areas will be discussed later.

Engine Characteristics and Acceleration

Assuming that acceleration equal to or better than the F-16 is important, a dry engine proves to be unsuitable because it would be throttled back inefficiently for low supersonic cruise. On the other hand, an afterburning engine could be sized to cruise at, say, Mach 1.4 or 1.5, at or near its maximum continuous non-afterburning power setting. Adding an afterburner would then provide a thrust-to-weight ratio of 1.2 or beyond, thus assuring acceleration substantially better than the F-16. This acceleration would be in the range of 50 to 65 seconds from Mach .9 to Mach 1.6 at 30,000 feet, as opposed to the approximately 70 seconds of today's F-16.

Preliminary engine cycle tradeoff studies show that an optimum cycle for such a supersonic cruising engine would be a turbojet with a pressure ratio of about 10 to 12 and a turbine temperature of between 2000° and 2200°. [1/] Using already-tested compressor designs, this means 3 to 4 compressor stages and a single, moderately-cooled turbine stage. Such an engine would be inherently much less expensive (and much more reliable) than today's $2 million fighter engines. Cost would be in the range of $500,000 to $750,000. At the same time, the simplicity of this engine would permit a sizable increase in engine thrust-to-weight from the current 7.8 to 1 to better than 10 to 1. This weight saving would contribute to achieving the 40% fuel fraction.

1/ The low pressure ratio results from the high ram pressure available at speeds beyond Mach 1.2; the relatively low temperature then follows because high temperaures only pay off in high pressure ratio engines.

Turning and Transient Performance

Improvements in maximum turning g beyond the F-16 level are not needed, particularly in view of the deterioration of Soviet turning performance since the MiG-21. Furthermore, the extra wing drag and weight associated with such improvements would heavily penalize supersonic cruise endurance.

On the other hand, maximum g must be good enough to allow achieving and maintaining firing position on subsonic targets, even if they break hard when bounced. Also of considerable importance is the ability to bleed off airspeed very rapidly from a supersonic approach down to a subsonic firing pass. A maximum g approximately equal to that of the F-16 appears to be a reasonable goal.

To meet these needs, tail-less delta or double-delta configurations merit examination. They have inherently lower structual fractions and higher available fuel volume than tailed or canard configurations. Deltas also have better supersonic cruise drag, particularly if trim drag is mimimized with negative static margin control systems. And finally, they have higher induced drag and therefore higher decelerations at their maximum angles of attack.

Transient performance requirements should aim at an improvement over the F-16, a not-difficult task since the new fighter would be considerably smaller and lower in inertia. Minimum requirements would be better roll and pitch transients (as defined in Appendix II) then the best among the YF-16, F-5 and F-86.

Avionics

To preserve the surprise gained by small size and a cruise speed advantage, primary reliance on passive sensors is essential. Thus, the most important avionics would be a radar warning receiver system with much-improved capability to a) sort air-to-air radars from ground-to-air radars; b) count air-to-air radars on adjacent frequencies in the same angular sector; and c) detect lock-ons and/or missile launch signals. Ideally, the all-aspect radar warning would be tied in to a more precise passive angle-tracking system based on receiving through the fighter radar antenna. This precise angle-tracking would be used to focus on threats being considered for attack.

With the angle-tracking antenna locked onto a potential target, it becomes possible to use an ultra-short radar burst through the same antenna to occasionally check or update range --without giving away too much position or warning information to the enemy. Thus, a "short-squirt" radar becomes a natural adjunct to the primary passive system.

The requisite radar-warning, signal sorting and angle-tracking electronics are inherently compact and very light in weight. The "short-squirt" radar, since it operates at very low average power levels, would also be much lighter than a conventional radar --and would require far less weight in the fighter's power generating and cooling subsystems. Thus, the primarily-passive avionics concept contributes to the weight saving essential for the 40% fuel fraction.

Weapons

The supercruising fighter could be designed successfully around existing weapons, the 20mm gun and the AIM-9L or later model infrared missiles. However, it would be desirable to undertake the following three weapons improvements in conjunction with a new fighter:

- A much lighter, more lethal, longer range gun based on a 4000 foot per second round of about .50 caliber with a depleted uranium projectile (or one of even better incendiary performance).
- An air-to-air ARM, based on the AIM-9C airframe/antenna/autopilot with a Sparrow rocket motor to provide range considerably in excess of normal Sparrow range. This would provide a BRR (beyond radar range) capability with the enemy's radar signal providing the solution to the IFF problem.
- An improved version of the AIM-9H or AIM-9L with major increases in lookdown capability, a much faster "snap-shoot" lock-on mode and an ability to reject decoy flares.

Design Discipline, Size and Cost

Further weight savings would be achieved by starting with the elimination of all existing military specifications from the design and the subsystems. Starting from this clean slate, each new specification that is proposed would have to be spelled out in its entirety (i.e., no specification trees) with supporting evidence of the need for such a specification. "Nice to have" items such as those on p. VI- would be eliminated. Even such smaller items as power canopies or the present USAF requirement that guns retain their spent cartridges would be dropped.

These design discipline savings plus the lighter guns, avionics, generators, cooling systems, and the better thrust-to-weight engine should combine to make possible a supercruising fighter with 40% fuel fraction and a weight below that of the F-5A. A reasonable design goal would be 10,000 pounds.

Given a 10,000 pound, all-aluminum airframe, a $500,000 to $750,000 engine, and a primarily passive avionics system with no air-to-ground complexities costing under $750,000, an overall flyaway cost of $5 million (FY82) for a 1,000 aircraft buy is quite feasible --particularly using two-source competitive procurement.

Summary Assessment

The surprise advantages of a small, supercruising fighter using passive avionics would represent a much more dangerous threat to today's Soviet fighters than the Messerschmitt 262 jet posed to P-51 prop fighters in WWII. If, in addition, this supercruising fighter provided three times the effective force in the air of today's F-16s, then the entire Soviet fighter force would be obsolete until replaced with an equivalent supercruiser.