

**THE FORTY-FOURTH
HARMON MEMORIAL LECTURE
IN MILITARY HISTORY**



**The Aircraft that Decided World War II:
Aeronautical Engineering and Grand Strategy,
1933-1945,
The American Dimension**

John F. Guilmartin, Jr.

United States Air Force Academy
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The oldest and most prestigious lecture series at the Air Force Academy, the Harmon Memorial Lectures in Military History originated with Lieutenant General Hubert R. Harmon, the Academy's first superintendent (1954-1956) and a serious student of military history. General Harmon believed that history should play a vital role in the new Air Force Academy curriculum. Meeting with the History Department on one occasion, he described General George S. Patton, Jr.'s visit to the West Point library before departing for the North African campaign. In a flurry of activity Patton and the librarians combed the West Point holdings for historical works that might be useful to him in the coming months. Impressed by Patton's regard for history and personally convinced of history's great value, General Harmon believed that cadets should study the subject during each of their four years at the Academy.

General Harmon fell ill with cancer soon after launching the Air Force Academy at Lowry Air Force Base in Denver in 1954. He died in February 1957. He had completed a monumental task over the preceding decade as the chief planner for the new service academy and as its first superintendent. Because of his leadership and the tensions of the cold war, Congress strongly supported the development of a first-rate school and allotted generous appropriations to build and staff the institution.

The Academy's leadership felt greatly indebted to General Harmon and sought to honor his accomplishments in some way. The Department of History considered launching a lecture series to commemorate his efforts, and in 1959 the Harmon Memorial Lecture Series in Military History was born.

The Harmon Lecture series supports two goals: to encourage the interest in contemporary military history and to stimulate in cadets a lifelong interest in the study of the history of the military profession. The lectures are published and distributed to interested individuals and organizations throughout the world and many are used in courses at the Academy. In this way, we continue to honor the memory of General Harmon, who during his lifetime developed a keen interest in military history and greatly contributed to establishing the United States Air Force Academy.

LIEUTENANT GENERAL HUBERT REILLY HARMON

Lieutenant General Hubert R. Harmon was one of several distinguished Army officers to come from the Harmon family. His father graduated from the United States Military Academy in 1880 and later served as Commandant of Cadets at the Pennsylvania Military Academy. Two older brothers, Kenneth and Millard, were members of the West Point class of 1910 and 1912, respectively. The former served as Chief of the San Francisco Ordnance District during World War II; the latter reached flag rank and was lost over the Pacific during World War II while serving as Commander of the Pacific Area Army Air Forces. Hubert Harmon, born on April 3, 1882, in Chester, Pennsylvania, followed in their footsteps and graduated from the United States Military Academy in 1915. Dwight D. Eisenhower also graduated in this class, and nearly forty years later the two worked together to create the new United States Air Force Academy.

Harmon left West Point with a commission in the Coast Artillery Corps, but he was able to enter the new Army air branch the following year. He won his pilot's wings in 1917 at the Army flying school in San Diego. After several training assignments, he went to France in September 1918 as a pursuit pilot. Between World Wars I and II, Harmon, who was a Major during most of this time, was among that small group of Army air officers who urged Americans to develop a modern, strong air arm.

At the outbreak of World War II, Brigadier General Hubert Harmon was commanding the Gulf Coast Training Center at Randolph Field, Texas. In late 1942 he became a Major General and head of the 6th Air Force in the Caribbean. The following year General Harmon was appointed Deputy Commander for Air in the South Pacific under General Douglas MacArthur, and in January 1944 he assumed command of the 13th Air Force fighting in that theater. After the war General Harmon held several top positions with the Air Force and was promoted to Lieutenant General in 1948.

In December 1949 the Air Force established the Office of Special Assistant for Air Force Academy Matters and appointed General Harmon its head. For more than four years Harmon directed all efforts at securing legislative approval for a U.S. Air Force Academy, planned its building and operation, and served on two commissions that finally selected Colorado Springs, Colorado, as the site for the new institution. On August 14, 1954, he was appointed first Superintendent of the Air Force Academy.

Upon General Harmon's retirement on July 31, 1956, the Secretary of the Air Force presented him with his third Distinguished Service Medal for his work in planning and launching the new service academy and setting its high standards. In a moving, informal talk to the cadets before leaving the Academy, General Harmon told the young airmen that the most important requirements for success in their military careers are integrity and loyalty to subordinates and superiors. "Take your duties seriously, but not yourself," he told the cadets.

General Harmon passed away on February 22, 1957, just a few months before his son Kendrick graduated from West Point. The general's ashes were interred at the Air Force Academy's cemetery on September 2, 1958. On May 31, 1959, the Academy's new administration building was named Harmon Hall in his memory.

JOHN F. GUILMARTIN, JR.

John F. Guilmartin, Jr., is professor of military history at Ohio State University, Columbus. He is also a Vietnam War veteran, having flown over 120 combat missions. He attended the United States Air Force Academy, earning a commission as a 2nd Lieutenant and graduating with a B.S. in 1962. He trained as a helicopter pilot at Stead AFB, Nevada, and went to Thailand in 1965 with the Aerospace Rescue and Recovery Service. He flew missions in Thailand, Laos and North Vietnam and was awarded two Silver Stars. In 1966 he returned to the United States and after a year as an instructor pilot at the Rescue Combat Crew Training School, received an AFTI assignment to Princeton University where he received his Master's and Doctorate degrees in 1969 and 1971, respectively. His first book, *Gunpowder and Galleys*, is derived from his dissertation. After receiving his Ph.D., Dr. Guilmartin returned to the Air Force Academy to teach history. In 1975 he volunteered for a second tour in Southeast Asia and participated in the evacuation of Saigon. His unit also flew in the operations involved in the *Mayaguez* incident; in 1995 he recorded their heroism in *A Very Short War*. Following the Vietnam War, Lt. Col. Guilmartin served in the Rescue Headquarters tactics shop from 1978-79. He then became the editor of the *Air University Review*, the professional journal of the U.S. Air Force, and retired from the service in 1983. He taught at Rice University and the Naval War College before coming to Ohio State.

Professor Guilmartin is an authority on military history, maritime history, and the history of technology. He is an early modern Europeanist whose research focuses primarily on the sixteenth and seventeenth centuries. He also is interested in aerospace history and has written about the Vietnam War and the Gulf War. He has also written *America in Vietnam: The Fifteen Year War* in 1991, and *Galleons and Galleys* in 2002.

The Aircraft that Decided World War II: Aeronautical Engineering and Grand Strategy, 1933-1945, The American Dimension

The purpose of this essay is to connect, from an American perspective, two propositions: that air power was critical to the conduct and outcome of the Second World War, and that aircraft design contributed the crucial role in the process. There is nothing controversial about the first proposition. Historians and theoreticians may debate the decisiveness of strategic bombing, but few would deny the decisiveness of air power in the generic sense, if for no other reason because control of the air invariably provided an essential ingredient of victory in the battles and campaigns comprising World War II and whose cumulative effects of airpower determined its flow and eventual outcome. Indeed, the war's only campaign of major strategic consequence won without benefit of air superiority was the US Navy's submarine campaign against Japanese shipping, a fact that is in part testimony to Japanese weakness in the air.¹

To underline air power's importance, consider the battles and campaigns principally responsible for shaping the course of the conflict: the Battle of France, the Battle of Britain, the early German victories on the Eastern Front; the Japanese Centrifugal Offensive; Midway; Guadalcanal; Stalingrad; El Alamein; the Tunisian campaign; the Battle of the Atlantic; D-Day; the Normandy campaign, breakout and pursuit; the Destruction of Army Group Center; the New Guinea campaign; the Central Pacific campaign culminating in the Battle of the Philippine Sea and the seizure of the Marianas; the Battle of Leyte Gulf; and the bombing of Japan. In every case, victory was secured from the air, was dependent upon its control, or both.²

Extending our analysis to smaller engagements of strategic consequence yields a number of naval actions in which air power played a negligible role. Significantly, most were fought at night, testimony to the vulnerability of warships to daylight air attack even early in the war.³ Notable among them were a series of night surface engagements between Japanese and American forces during the Guadalcanal campaign.⁴ These engagements took place at night precisely because the Japanese Navy sought cover of darkness to negate US airpower. Note, too, that aerial reconnaissance (or the failure thereof) played a major role in most if not all of these engagements and that American superiority in the air was essential to Allied victory in the overall campaign.⁵ The other exceptions are partial and qualified. The Royal Navy was able to fight convoys through to Malta and Murmansk under heavy air assault and with little or no air cover, but at great cost. Indeed, Japanese successes in the Guadalcanal campaign aside, the only naval victory of consequence won by surface forces unaided by air and fought within range of enemy air fields was the 26 December 1943 Battle of North Cape in which the Royal Navy sunk the German battle cruiser *Scharnhorst*: confined to its Norwegian airfields by abominable weather, the *Luftwaffe* failed to intervene.⁶

We should also note that a number of the war's most important campaigns were fought entirely in the air, notably the Battle of Britain, the Combined Bomber Offensive, and the strategic bombing campaign of Japan. I would argue that all three were strategically decisive, an assertion that raises the question of strategic bombing's effectiveness in World

War II. I will address that question later, but first let me make a fundamental point: that war in the air is inherently different from other forms of warfare and that we do not truly understand it, even today, over a half century after VJ Day. A key problem is that we approach strategic bombing with the implicit assumption that air campaigns and battles can be judged using the vocabulary, criteria for success or failure, and analytical framework used to evaluate warfare on land and at sea. I contend that the appropriate criteria for judging strategic air campaigns, at least, are quite different and that in consequence the results of the debate so far are of dubious validity.

As evidence of our incomplete understanding of the nature of aerial warfare, consider the general lack of consensus—or even awareness—of what constitutes an air campaign. To illustrate the point, consider the last major Axis campaign victory of World War II. When asked to name the campaign in question, most draw a momentary blank and then think of the Battle of the Bulge before recalling that it ended in German defeat. It was, in fact, the Battle of Berlin, the effort by Royal Air Force Bomber Command between November 1943 and March 1944 to destroy Berlin repeating Hamburg's destruction the previous summer.⁷ In the process, the British inflicted considerable damage on Germany to be sure, but the result was unequivocally a German victory: Bomber Command called off its offensive after an accumulative loss of nearly eleven hundred aircraft, almost all of them four-engine bombers.⁸ Indeed, the final battle of the campaign, the 30 March Nuremberg raid, was one of the largest air battles of the war, if not *the* largest,⁹ and a signal German victory. There is no denying the strategic importance of the British defeat in terms of expenditure of resources and in lives lost, a cost made all the more painful by the fact that the lives in question were those of a highly-trained and strategically important elite aircrews, yet it was not a typical battle or campaign.

To expand on the point, consider the nature of the Combined Bomber Offensive. We ordinarily think of it as a campaign, but it was in fact something larger, for it contained within it operations that clearly qualify as campaigns in their own right: RAF Bomber Command's area bombing of German cities; the United States Army Air Forces' Unescorted Daylight Strategic Bombardment Campaign of 1943; the 1944 campaign against German sources of oil and fuel production; and Big Week, the USAAF effort in February 1944 that forced the *Luftwaffe* fighter force to accept battle and, ultimately, defeat. The lesson is evident. Not only does the terminology that we have inherited from land and naval warfare fit war in the air poorly, it carries with it analytical baggage that distorts analysis.

To further underline the inherent difference between war in the air and war on the surface, one can argue—and I do—that World War II in the air comprised a unitary global conflict in ways that the war on land and at sea did not. On land and at sea, the war can be usefully divided into theaters and fronts: the European Theater; the Eastern Front; and the Mediterranean, China-Burma-India, Southwest Pacific, and Central Pacific theaters, and so on. By and large, there was little movement of ground forces from one to another. With the partial exception of the Germans, who used interior lines to transfer their strategic reserves, once ground forces were committed to a theater or front they stayed there. The same general point applies to naval forces to an only slightly lesser degree. But what about air forces? Air forces *were* transferred from theater to theater with some frequency. The USAAF transferred much of its deployed force structure from Britain to North Africa in the autumn of 1942. The Germans shifted air units from front to front far more frequently than their ground reserves. The Japanese Army Air Force transferred much of its strength from the Home

Islands and Manchuria to the Southwest Pacific in 1942-43. The manner in which air reserves were deployed in certain critical instances leads me to the conclusion that at least senior Allied leaders implicitly understood that the air war was indivisible by theater. Let me make the point by example.

For the US Navy, the series of actions in May and June of 1942 that culminated in the Battle of Midway were the most critical of the war, a fact of which senior commanders were keenly aware well before the fact. As they were also keenly aware, fleet carriers were *the* critical operational asset. At the beginning of May 1942, the US Navy had five fleet carriers capable of flight operations: *Lexington*, *Enterprise*, *Hornet*, *Yorktown* and *Wasp*.¹⁰ Of these, *Lexington* was sunk at the Coral Sea and *Enterprise*, *Hornet* and *Yorktown* fought at Midway. Where was *Wasp*? More precisely, why was *Wasp* not at Midway? Because she was delivering Spitfires to Malta! Those responsible for sending *Wasp* to the Mediterranean clearly understood the global nature of air power, and it is worth noting that American forces began to establish ascendancy in the air in the Pacific shortly thereafter, at the same time the British were taking the *Luftwaffe*'s measure in North Africa and the Mediterranean.

Returning to the definitional problem, the argument that strategic bombing failed in World War II is generally made by evaluating the results of individual campaigns in isolation. Most often cited are the USAAF efforts in the summer and autumn of 1943 to collapse the German war economy by unescorted daylight bombardment and RAF Bomber Command's night area bombing of German cities. While it is true that neither succeeded in achieving its stated objectives, both forced major reallocations of German resources that might have been more profitably used elsewhere. Of far greater importance to the subsequent course of the war, both campaigns, and in particular the American effort, depleted vital German resources that could not be replaced within available time constraints, most critically skilled fighter pilots. Thus while they may not have been victories within the analytical framework borrowed from warfare on land and at sea, both had long term consequences that contributed powerfully not only to allied victory in the air, but to the defeat of Nazi Germany.

So with an understanding that there is much that we do not understand about the nature of air warfare, let us turn to my second proposition, that aircraft design was a key variable in determining the strategic effect of airpower. This proposition, like my first one, is uncontroversial, although here the lack of controversy is mostly due to a lack of systematic examination of the problem. Almost by definition, well-designed aircraft have superior performance and should thus bestow to their possessors tactical, and therefore strategic, advantages, or so logic would dictate. But there is a danger in this assumption, for it is easy to conclude that strategic advantage obtained in the air must have flowed from superior design and that is not always the case.

In fact, the seemingly straightforward relationship between quality of design and tactical advantage on the one hand and strategic effect on the other turns out to be anything but. As a multitude of cases demonstrate superiority in numbers or employment tactics, acting together or independently, can do much to offset performance disadvantages. That part of the puzzle is generally understood. Not so well understood or systematically explored is the fact that design determines much more than performance in the narrow sense: speed, maneuverability, range, offensive capabilities, resistance to battle damage, and the other factors that influence tactical effectiveness. By predicting cost and ease of production, design sets limits on how many of a given design can be built with the fiscal and human

resources available. In controlling reliability and ease of maintenance, design has a major influence on in-commission rates. In establishing handling characteristics, in simple terms how easy or difficult an aircraft is to fly, design exercises a powerful influence on operational wastage. Finally, the design must be suited for the particular circumstances under which the aircraft is to be employed, and here a single performance parameter may be critical. To cite an obvious example, a bomber which is a superior design in every other respect, but which lacks the range to reach its targets is strategically useless.

We are not helped much in our inquiry by the secondary literature, for little attention has been paid in detail to the connection between aeronautical design, tactical operation and strategic impact. A great deal has been written about the impact of airpower on World War II by theater, campaign, and battle, but few general accounts pay much attention to aircraft performance, let alone design. Similarly, much has been written about the aircraft with which the war was fought, their design histories, what they were like to fly, and how successful they were in combat, much of it for a buff audience. But while capturing an enormous amount of valuable information, this literature rarely addresses strategic issues. As a result of this divide in the literature, attempts to relate aircraft design to strategic effect are rare and generally limited to a single campaign or battle. The Battle of Britain is well served in this regard, but is very much the exception to the rule.¹¹

The intersection between aircraft design and strategic effect is an enormous topic, and in addressing it I confronted major problems. The key question was which aircraft to analyze, and it struck me that it might be useful to begin by ranking World War II aircraft according to their strategic importance. Such a rank-ordering would not only reduce the scope of the inquiry to manageable proportions, it would, or so I hoped, provide an analytical lens through which to selectively identify and evaluate those performance characteristics that were strategically most important. Having identified the critical performance parameters, I could then examine the design processes that produced them. In fact, this approach proved to be productive, yielding results that were often unexpected and counter-intuitive.

That approach is not without its difficulties. Comparing the strategic importance of aircraft that performed different missions in different theaters at different times poses obvious problems. The fact that aviation technology changed enormously during the period of our concern further complicates matters. In addition, we must consider counterfactuals if the inquiry is to make sense. My rankings are thus indicative rather than definitive. Still, I am satisfied that the rank ordering reflects strategic reality. I could easily justify moving many of the aircraft on the list up or down several places, but I am confident that the ranking is an accurate—albeit inexact—measure of relative strategic importance. To establish the ranking, I approached aircraft that played a major operational role in the Second World War with two questions:

- How did the aircraft in question strategically affect the conduct and outcome of the war?
- How would the conduct and outcome of the war have changed if the aircraft in question had not been developed and produced?

Neither question can be answered in any definitive sense. This is particularly true of the second question, which requires us to consider the responses of historical actors to events that did not, in fact, transpire. But while the answers may not be definitive, asking the

questions enhances our understanding of both the design process and the nature of World War II. You, the reader, must judge the value of the project.

To keep this work to a reasonable length, I truncated my analysis, focusing on the American experience. That proved to have value in its own right, highlighting the relationship of the American aviation industry to the armed forces and government of the United States and how that relationship differed from those prevailing among the European powers and in Japan.

Before presenting the list, a few points about the ranking process are in order. First, the rankings are heavily—though not exclusively—dependent on chronology. The circumstances of each successive campaign and battle were determined by those that went before, so aircraft whose strategic importance was manifested early in the war generally rank ahead of those that appeared later. German victory in the Battle of France determined that the war would be a long one if it did not end in outright Nazi victory, so the aircraft instrumental in the defeat of British and French forces in May and June of 1940, the Messerschmitt Bf 109 and the Junkers Ju 87, go to the top of the list. That those same aircraft were instrumental in the early German victories on the Eastern Front reinforces their position; so does the fact that the Bf 109 in its later versions played a preponderant role in defending the Reich against daylight attack. Victory in the Battle of Britain was an essential pre-condition for eventual allied victory, so the fighters responsible for turning back the *Luftwaffe* in the summer and autumn of 1940, the Hurricane and Spitfire, come next, and so on.

Next, to say that the course of the war would have differed significantly had a particular aircraft not been designed or produced implies that there was no available substitute. The Focke Wulf Fw 190 does not make the list for this reason, reinforced by the fact it did not enter service in significant numbers until early 1942. As good a fighter as it was, most of the strategic benefits it bestowed on the Reich could have been obtained by increasing Bf 109 production. Conversely, in the strategically decisive struggle for air supremacy over Germany from late 1943 on the Bf 109 *could* do one essential thing that the Fw 190 could not: survive in air-to-air combat against P-47s, P-38s and P-51s at altitudes of 25,000-30,000 feet. I applied the logic of this example throughout in determining which aircraft to include or exclude from my short list.

In a few cases, the strategic impact of a given aircraft was so great as to justify moving it higher than the timing of its operational debut would indicate. The B-17 is the salient example of both this point and the previous one. The rationale behind my decision to rank the B-17 as I did, fifth on the list, is thus worth examining in detail as an illustration of the process.

It is difficult to imagine the effective destruction of the *Luftwaffe* fighter arm prior to D-Day without the threat that high altitude daylight precision bombardment posed to the German war economy. The German high command could concede control of the air on the Eastern Front, albeit selectively, and did so following the failed July 1943 Kursk offensive.¹² It could concede control of the air in the Mediterranean, and did so following the Anzio invasion. It could not concede control of the daylight skies over the Reich without courting disaster. Forced to give battle over the Reich, the accumulative and synergistic effects of the Eighth Air Force bomber and fighter commands combined combat effort reduced the *Luftwaffe* fighter arm to ruin.

A direct product of the B-17's ability to penetrate German airspace in massed formations, hit its targets with useful accuracy, and do so without prohibitive losses forced the *Luftwaffe* to meet that fatal challenge. Ultimately the provision of long range fighter escort enabled strategic bombers to accomplish their designed mission--high altitude daylight precision bombing. The only available substitute, the B-24, was a useful supplement to the B-17, but had to be employed with circumspection in a high threat environment. With a service ceiling some 5,000 feet lower than that of the B-17,¹³ the B-24 was considerably more exposed to anti-aircraft artillery, a liability multiplied by the B-24's greater vulnerability to battle damage.¹⁴ Moreover, the B-24 was significantly more difficult to fly. The problem was particularly acute in the earlier versions and made the assembly of large formations above the undercast after individual instrument takeoffs difficult and at times impossible. As a concrete example, the B-24 equipped 2nd Bombardment Division tasked to participate in the 14 October 1943 Schweinfurt raid, managed to assemble only 21 of 58 bombers launched, too small a formation to be tactically viable, and the force diverted to a diversionary raid.¹⁵ In short, the B-17 could have done the job alone. The B-24 could not have.

At this point I will present my rank ordering accompanied by a skeletal rationale for each aircraft's place within it followed by a brief discussion of the way in which the design of the aircraft in question contributed to its strategic significance. These discussions must be preceded by the caveat that in many cases we know little about the design process beyond what we can infer from physical characteristics, performance data and the operational record. I do not pretend that the ranking is definitive and have no doubt that it will be controversial. It does, however, raise important questions concerning aircraft design and how it was turned to strategic advantage—or disadvantage—that we will address in concluding.

World War II Aircraft in Order of Strategic Importance

Bf 109

The Messerschmitt Bf 109¹⁶ provided the battlefield air superiority essential to German victory in the Battle of France and the initial successes on the Eastern Front that inflicted horrendous losses on Soviet forces and materially lengthened the war. With Germany on the defensive, the Bf 109 was the *Luftwaffe's* most important daylight interceptor and the only one capable of contesting the high altitude daylight skies over *Festung Europa* with the long range USAAF fighters that began penetrating German airspace from the end of 1943.

While aircraft were not designed to ideological specifications, the Bf 109 fit Hitler's strategic vision like a hand in a glove. The smallest airframe that could be built around the most powerful engine available, the Bf 109 owed its early success largely to the excellence of its Daimler-Benz 601 engine. While the DB 601's closest equivalent, the British Rolls-Royce Merlin, offered better performance at high altitudes, the German engine held a progressively greater advantage as combat altitudes dropped below 15,000 feet. This was a product of the DB 601's hydraulically driven, variable speed supercharger. The Merlin's supercharger had a mechanical clutch; it therefore ran full speed or not at all, and engaging it at too low an altitude would overboost the engine. By contrast, the Bf 109's supercharger

gradually throttled back as altitude decreased and continued to yield the maximum boost that the engine could absorb right down to the deck. Moreover, the Bf 109E, the principal version employed in the Battle of France and the Battle of Britain, had the most effective armament of any contemporary operational fighter in the form of two wing-mounted high velocity 20 mm cannon, supplemented by two 7.92 mm machine guns mounted in the engine cowling. The Bf 109's cannon yielded major tactical advantages over machine-gun armed opponents, particularly in fighter-versus-fighter combat. Not only did each round inflict far more damage, the destructive effect did not diminish with range. Of considerable operational importance to the early German victories, ground crews easily maintained the Bf 109 in the field: an engine change could be accomplished in fifteen minutes. Finally, the simple and efficient design was well suited to mass production.

The only putative alternative to the Bf 109, the Heinkel He 112, had a heavier airframe and, in its initial versions, inferior flight characteristics. It would have been more difficult to maintain in the field. Finally, its more complex structure would have been more difficult to produce, the factor that ultimately led to its rejection. Significantly, the decision to reject the He 112 in favor of the Bf 109 was made in 1936 within the inner circles of the Nazi Party under the pressure of Hitler's strategic agenda.¹⁷

An important component of the Bf 109's early successes was the development in the Spanish Civil War of tactics based on the use of air-to-air voice radios that enabled element leaders to rely on wingmen to cover their tails and gave formation leaders a means of coordinating attacks. Called "finger four" because the spacing of the four fighters in the basic *schwarm* formation resembled that of the tips of the fingers of an outstretched hand, these tactics were later widely imitated, but gave the *Luftwaffe* an enormous initial advantage.

On the down side, a light and simple design gave the Bf 109 exceptional performance at the expense of a restricted radius of action and entailed compromises in handling characteristics. The Bf 109 lacked a rudder trim that could be adjusted in flight, placing significant demands on pilot strength and skill. The main landing gear, attached to the fuselage rather than the wing, permitted a lighter structure, but was inherently weak and placed the main wheels close together near the center of gravity. As a result, unless in the hands of an experienced pilot, the Bf 109 was susceptible to ground looping during takeoff or landing roll. In such an event, the landing gear was prone to collapse with the aircraft rotating horizontally around the landing gear. This was a significant cause of operational losses, particularly when operating from unprepared grass strips.

The net result was an aircraft capable of controlling the airspace over fast-moving armored columns, albeit at a considerable cost in operational wastage. The underlying technological strategy—implicit, but integral to the Nazi ethos—assumed that the ensuing victories would be quick and decisive, making high loss rates acceptable since they would only be sustained for brief periods. Except for the Battle of Britain, that logic remained operationally valid through the summer of 1942. Then, with the turn of the tide of the air war, first in the Mediterranean, then in the east and finally in the west, high losses in the absence of quick victories plagued the *Luftwaffe*. Although handicapped by short range, later versions of the Bf 109 remained tactically viable until war's end and German aircraft industry produced it in greater numbers than any other World War II aircraft, more than 33,000, with the sole exception of the Soviet Il 2 *Shturmovik*.¹⁸

In the final analysis, the *Luftwaffe* lost the war in the air by virtue of its inability to make good the loss of skilled pilots, particularly fighter pilots. While aircraft production outpaced losses almost to the bitter end, the *Luftwaffe*'s shortsightedness in fielding a robust and dynamic pilot training establishment kept it from absorbing operational pilot losses. Shortages of aviation fuel caused by allied bombing likewise contributed to a reduction in training tempo. As a consequence, by 1945 the *Luftwaffe* defended German skies with a reduced number of fighter pilots with less experience and inadequate flight training. Pilot losses incurred as a direct product of the Bf 109's design flaws was a major factor as well. Both the failure to create a capable training establishment and the Bf 109's design deficiencies accurately reflected the *Wehrmacht*'s—and Hitler's—strategic mindset.

Ju 87

The Junkers Ju 87's combination of bombing accuracy and psychological shock effect—an effect magnified by wind-driven sirens mounted on the landing gear and “screamers” on the bombs—made essential contributions to German victory in the Battle of France and to German ground offensives on the Eastern Front through the summer of 1942. Although not employed in a true close air support role, it provided the mobile heavy artillery that the Panzer divisions lacked. It proved highly effective in attacks on ships, inflicting major losses on the Royal Navy in the Battle of Crete and on convoys on the Murmansk run. The *Stuka* performed as a divisional organic mobile artillery reserve--stacked at altitude over the armored "schwerpunkt" through the French lines, formations of Stukas rendered timely close air support and interdiction through the JFAC and permitted the armored thrusts to exploit the timely breakthroughs.

As with the Bf 109, the Ju 87 *Stuka*—from *Sturzkampffleiger*, diving battle plane—was tailored for Hitler's strategic vision. Doctrinally, the *Stuka* exaggerated the blitzkrieg tempo of an armored paralysis by adding flexible and organic firepower to the German mechanized ground maneuver force. Supremely effective in placing heavy ordnance precisely on target, it was the only World War II bomber capable of attacking in a true vertical dive with all the advantages in accuracy that entailed. That ability played large in the Battle of France and German victories on the Eastern Front through the summer of 1942. But a true vertical attack and the high “g” forces sustained in recovery called for an exceptionally robust and heavy airframe and that, in turn, compromised maneuverability and speed. The *Stuka*'s exceptional accuracy and bomb carrying capability thus came at a price: it was horribly vulnerable to fighter attack, a lesson the *Luftwaffe* learned to its chagrin in the Battle of Britain, when Goring elected to take it out of action after devastating losses. Although no longer viable in the west, the Ju 87 continued to play a useful role on the Eastern Front to the end of the war both as a dive-bomber and as a "tank buster" with a pair of 37 mm cannon mounted beneath the wings.

Hurricane

Designed as part of an integrated, radar-controlled, air defense system, the Hawker Hurricane was essential to British victory in the Battle of Britain. Intended to bring firepower to bear against bomber formations, the Hurricane area interceptor acted in concert with its Spitfire sister, the better air superiority interceptor of the two.

A competent, workmanlike, design, the Hurricane was a straightforward development of the Hawker Fury biplane fighter, built with a traditional structure (in the early models only the fuselage from the cockpit forward had an aluminum skin) that lent itself to mass production and easy repair. It derived its tactical effectiveness from the excellence of its Rolls-Royce Merlin engine, about which an additional word is in order. A product of the Rolls-Royce company's systematic development of high-performance liquid cooled V-12 engines that went back to World War I, the Merlin was a scaled-up development of the Kestrel that powered the Fury. The Merlin's design was also influenced by the Rolls Royce "R" racing engine of 1931, the product of a government-subsidized program to compete in the Schneider Trophy seaplane races. The Merlin's debt to the "R" included the adoption of American-developed 100-octane fuel (about which more below) and a mechanical supercharger of unprecedented efficiency that give the Merlin exceptional performance at altitudes from 15,000 feet up.¹⁹ The firepower of the Hurricane's massed battery of eight, and in later versions twelve, wing-mounted .303 caliber machine guns, contributed to its aerial successes against *Luftwaffe* medium bomber formations.

The Hurricane's strategic effect as an interceptor was a product of its design specification, one that called for a high rate of climb and heavy firepower at the expense of loiter time and radius of action.²⁰ Integral to the Hurricane's design and to its success as an interceptor was its use in ground-controlled radar intercepts directed by voice radio. Serendipitously, the peculiar circumstances of the Battle of Britain, fought at altitudes of 20,000 feet and above where the Merlin outperformed the DB 601 mitigated the Hurricane's tactical liabilities *vis a vis* the Bf 109. Moreover, the Hurricane's .303 caliber armament, inferior to the Bf 109's cannon in fighter-versus-fighter combat, proved brutally effective at close range against lightly armed and armored *Luftwaffe* bombers. Finally, as already noted, the Hurricane was eminently producible. In addition to its key role in the Battle of Britain, the Hurricane performed yeoman duty as a fighter-bomber in North Africa and when deployed aboard merchant ships as expendable catapult-launched interceptors Hurricanes helped counter the depredations on Allied shipping inflicted by Focke Wulf Fw 200 reconnaissance bombers that reached epidemic proportions in the final months of 1940. Carrier-based Sea Hurricanes played a small, but significant, role in the war at sea.

While the Hurricane's usefulness as a ground attack fighter bomber was mitigated by a short radius of action and the inherent vulnerability of liquid cooled engines to battle damage—a single hole in the coolant system can drain the engine, leading quickly to seizure—it was the best the RAF had until the advent of the Hawker Typhoon, which shared the same liability. Fitted with intake filters to protect the engine from sand particle erosion and armed with a variety of wing- and underwing-mounted cannon, the Hurricane was effective in the ground attack role in North Africa. The Supermarine Spitfire had significantly better performance and would in principle have been available as a substitute, but was significantly harder to produce and repair. In consequence, it is doubtful that enough Spitfires could have been built and kept in commission to defeat the *Luftwaffe* in the Hurricane's absence. The figures bear this out: during the Battle of Britain the number of Hurricane squadrons increased from twenty-five to thirty-three while the number of Spitfire squadrons remained constant at nineteen.²¹ Given inspired leadership—which Fighter Command had—Britain could probably have prevailed in the Battle of Britain without the Spitfire. British victory is difficult to imagine without the Hurricane.

Spitfire

Like the Hurricane, the Supermarine Spitfire was procured as part of an integrated, radar-controlled air defense system. Capable of meeting the Bf 109E on an even footing at 15,000 feet and with an increasing advantage as altitudes rose, it made a vital contribution to British victory in the Battle of Britain. Fighter Command employed Spitfires to defeat the *Luftwaffe* fighter escorts while Hurricanes attacked and shot down the *Luftwaffe* bombers. From the end of the Battle of Britain until late 1943, it was the only Allied day fighter available in numbers in the European theater that could match the performance of first-line German fighters and remained in front-line service until the end of the war. During 1941-42, Spitfires played a major role in wresting air superiority over North Africa and the Mediterranean from the *Luftwaffe* and the Italian *Regia Aeronautica*, a matter of no small strategic importance. In addition, specially modified Spitfires were the most important Allied strategic photo-reconnaissance aircraft at the outbreak of hostilities in 1939—and the *only* ones capable of deep penetrations of Axis territory—and so remained until the debut of reconnaissance versions of the Mosquito in the autumn of 1941.²² The Spitfire remained effective and important in that role until war's end. As with the Sea Hurricane, Seafires, as the carrier-based Spitfire was called, played a small but significant role in the war at sea.

Designed to a specification that called for a high rate of climb and heavy firepower at the expense of range and loiter time, the Spitfire, and, like the Hurricane, owed its tactical success to its Rolls-Royce Merlin engine fueled with 100 octane aviation gas. The Spitfire too was a lineal descendant of the Rolls Royce "R" powered Supermarine S 6 racer that won the Schneider Trophy in 1931. To an even greater extent than the Hurricane, the peculiar circumstances of the Battle of Britain negated the Spitfire's tactical liabilities. More aerodynamically refined than the Hurricane—its elliptical wing planform increased aerodynamic efficiency by some two to three percent.²³ Inferior to the Bf 109E at low altitudes, the Spitfire Mark II enjoyed appreciable advantages in maximum speed and turn radius at the altitudes at which the combatant pilots fought the critical engagements of the Battle of Britain. As the war progressed, the Spitfire was given remarkable longevity as a first line air-to-air fighter by progressive improvement of its Merlin engine, but the Spitfire was more difficult to produce and repair.

Comparison with the Daimler-Benz powered Bf 109 is instructive in this regard. While early versions of the DB 601 were superior to contemporary Merlins in power to weight ratio and in performance at medium and low altitudes, the DB 601 proved unable to accept increases in compression ratio that the more solidly built Merlin absorbed with ease. In consequence, the G model of the Bf 109, fielded from the summer of 1942 and the most important variant in numbers produced, required an entirely new engine, the DB 605.²⁴ Moreover, while engineers increased the Spitfire's armament from late 1940 to include two wing-mounted 20 mm cannon, and later four, wing-mounted cannon had to be abandoned on Bf 109s beginning with the F model in 1941 to avoid fatally compromising performance in air-to-air combat. The final production versions of the BF 109 had only a single cannon firing through the propeller hub supplemented by two 12.7 mm machineguns in the engine cowling. The British parallel to the DB 605 was the Rolls Royce Griffon, a development of the "R" racing engine that was begun in 1933, then set aside until 1939.²⁵ Like the DB 605, the Griffon developed more power than its predecessor in the same space, 2,035 to 1,700 horsepower in late 1943 versions. Unlike the DB 605, the Griffon was strategic insurance rather than a necessity. While Griffon-powered Spitfires and Seafires were tactically

superior to Merlin-powered versions, the latter remained tactically viable. Only in photo-reconnaissance Spitfires did the Griffon's added power and efficiency yield strategically important dividends.

The Griffon-powered Spitfire PR XIX (PR for photo-reconnaissance), which entered service in the spring of 1944, provides a final commentary on the Spitfire's importance. The Griffon's superior high altitude performance and a pressurized cockpit combined with the Spitfire's refined aerodynamics to give the PR XIX a service ceiling of no less than 48,000 feet—the highest of any operational piston-engined aircraft—rendering it effectively immune from interception. At that point photo-reconnaissance versions of the P-38 were horribly vulnerable to interception by later versions of the Bf 109 and the PR XIX, though produced only in small numbers, satisfied a vital strategic requirement at a critical time. The aerial edge in battle early shifted between allied air forces and the *Luftwaffe* as the Spitfire underwent growth in engine power, aeronautical performance and increased firepower.

B-17

The Boeing B-17 Flying Fortress was the anvil against which the USAAF fighter force hammered the *Luftwaffe* fighter arm to destruction in the skies over Germany. That was of immense strategic importance above and beyond the destruction that B-17s visited on military and industrial targets, threatening a level of damage to key industries that the Third Reich's leaders could not tolerate. The B-17 was a singular design for which there would have been no viable substitute until the B-29 became available in quantity... if Boeing could have designed the B-29 without the experience gained from the B-17. Even before long range fighters were available to escort deep penetrations, massed formations of B-17s took a significant toll of the *Luftwaffe* fighter arm, both physically and psychologically, helping to make subsequent the German air arm's recovery impossible.

The B-17 was an uncompromising 1934 design intended to produce the fastest, highest-flying heavy bombardment aircraft extant. Boeing's design team adopted those objectives in response to stated Army Air Corps requirements, but pushed them to the limit as a conscious high risk, high gain strategy to deliver blows against an industrial enemy. For a variety of reasons involving internal Army politics and blind luck—the loss of the first prototype to a pilot error accident—that strategy nearly failed and most of the initial Army bomber contract went to the mediocre twin-engine B-18, a derivative of the DC 3 civilian transport. That having been said, Boeing's boldness reaped huge strategic dividends in range, bomb load and ability to absorb battle damage.

The excellent Wright R-1820 nine-cylinder engine, re-engineered at Air Corps insistence to burn 100-octane gasoline, was an essential cornerstone of the B-17's success.²⁶ Another was the development of the turbo supercharger by General Electric on an Air Corps contract, the only discrete Army research and development program to receive funding through the Great Depression. The importance of the turbo supercharger lies in the fact that the War and Navy departments stopped subsidizing the development of military aero engines during the Great Depression. American military aircraft would henceforth be powered by engines designed for civilian use, and while high altitude performance had obvious military importance it had little civilian value. The European solution, gear-driven superchargers designed as an integral part of the engine, was an obvious non-starter for economic reasons.²⁷ The military market was simply too small. American superchargers therefore would be add-

on accessories and the only evident way to power such a supercharger was a turbine driven by engine exhaust gasses. The extremely high temperatures and rotational speeds to which the turbines were subjected posed obvious problems. A further complicating factor was the lack of full-sized high altitude wind tunnels: turbo superchargers could only be tested in actual flight with the obvious risks that entailed. Beginning work in 1919, General Electric eventually surmounted these problems and by the mid-1930s was fielding increasingly reliable turbo superchargers.²⁸ The B-17 was slated for them from the beginning.

The result was a bomber capable of delivering a two-ton bomb load over a thousand miles from its base—the figures are approximate, based on data from missions flown over Germany in 1943-44—penetrating enemy air defenses *in formation* at altitudes of 25,000 to 29,000 feet.²⁹ The emphasis in the preceding sentence is warranted since a formation's speed and ceiling are dictated by its most poorly performing aircraft. Such performance, unprecedented in the mid- to late 1930s, speaks volumes both for the soundness of the B-17's design and for the excellence of Wright, General Electric, and Boeing production line quality control. The excellence of the B-17's design is highlighted by comparing it to that of the Consolidated B-24 *Liberator*, the closest thing to an available substitute. A newer design by five years and similarly powered,³⁰ the B-24 was nonetheless inferior to the B-17 in every critical performance parameter that counted in the European theater of operations save maximum range.

A final factor contributing to the B-17's success was the decision by the Air Corps during the 1920s to adopt the .50 caliber machine gun as its standard aircraft weapon. Designed toward the end of World War I as a heavy infantry machine gun, the Browning .50 caliber was an uncompromising design with exceptional ballistic performance.³¹ Not only was its projectile nearly four times as massive as that of .30 caliber weapons, its superior ballistic coefficient and streamlined shape gave it the best velocity over distance characteristics of any commonly used aerial machine gun of World War II.³² As a result, the Fortress's effective defensive fire ranged well beyond the practical hitting distance of any Axis air-to-air gun. While unescorted B-17 formations proved unable to sustain deep penetrations of German airspace without incurring prohibitively heavy losses, they inflicted serious losses on the German fighter arm in the process. To be sure, the Air Corps initially underestimated the need for defensive armament and Boeing engineers resisted the addition of turrets that spoiled the aircraft's aerodynamic shape. Ultimately, however, tactical logic and superior engineering prevailed and from early 1942 on B-17s were well provided with heavy defensive armament, much of it mounted in power-operated turrets.

Facilitated by intercom and radio connections, the Fortress' aircrew arrangement throughout the cockpit, crew compartment and fuselage ensured that the dispersed crewmen retained their group cohesion in air to air combat. Compartmentalized responsibilities and specialized training demanded aircrew discipline in coordinating defensive fire and fighting battle damage to the airframe, engines and subsystems. This dispersed crew arrangement provided for more defensive armament that could protect the bomber from all flight attitudes of fighter attack, especially with the B-17G modified "chin" turret model giving frontal attack defense. The size of the airframe and engineering capacity enabled the Fortress to grow in defensive firepower from ten .50 caliber machine guns aboard the "E" model to the "G" model with thirteen machine guns providing all around defense. The porcupine firepower gave large formations of B-17s overlapping fields of fire that enabled adjacent

elements and squadrons to cover one another. The result was the fifty-four aircraft combat box formation that dealt severe blows against the industrial strength Nazi Germany.

The final analysis, bombers exist to drop bombs, and a late war USAAF study showed that the B-17 was the most accurate Army bomber (the second most accurate being the B-29), enjoying a small, but significant, advantage over the B-24 despite the fact that B-24s bombed from lower altitudes.³³ In *ex post facto* validation of the Air Force's preference for heavy bombers, the study showed that four engine bombers were significantly more accurate than twin engine bombers across the board.³⁴ That the B-17, a 1934 design, was still in front line service in 1945 speaks volumes for the quality of its design.

Lancaster

The AVRO Lancaster was the backbone of RAF Bomber Command's night area bombardment campaign, and while that campaign failed to defeat the Third Reich in isolation, it wrought immense destruction, forced strategically important diversions of resources, and—a critical point often forgotten—was Britain's only means of taking the war directly to Germany until D-Day. Without the Lancaster, it is unlikely that the night area bombardment campaign could have been sustained during 1943-44 without unbearable losses. The only available substitute, the Handley-Page Halifax, was a far less capable aircraft with a much lower service ceiling and a significantly higher loss rate: Lancasters dropped 107 tons of bombs for every one lost in combat, Halifaxes only 48. Moreover, the Halifax was more difficult to produce and maintain, consuming 11,000 man-hours of labor per ton of bombs dropped to 4,000 for the Lancaster.³⁵ Lancasters also made major contributions to the preparations for D-Day and to the destruction of the German oil production in 1944 and German rail transportation net during the winter of 1944-45. In addition to its positive contributions to Allied victory, the Lancaster program absorbed an immense quantity of vital resources, a matter of considerable strategic significance.

The Lancaster was a derivative of the AVRO Manchester, a heavy night bomber designed to a 1936 contract and powered by two Rolls-Royce Vulture engines.³⁶ By mating two V-12 Merlin equivalents belly-to-belly around a common crankshaft,³⁷ the Vulture doubled the engine power output while halving the number of engine nacelles, thus reducing aerodynamic drag. As with virtually all liquid-cooled, in-line engines having more than twelve cylinders, the Vulture suffered extensive development problems³⁸ and, though these were eventually technically solved, it still suffered from being badly overweight.³⁹ RAF Bomber Command consequently withdrew the Manchester from operations after a brief career, but the airframe showed promise and a substantial investment had been made in production facilities. In an inspired decision to salvage the investment, four Merlin engines, mounted on a larger wing; a redesigned empennage and a name change to Lancaster produced a strategic bomber capable of carrying the largest possible bomb load at medium altitudes better than any other World War II bomber. Beyond gross bomb carriage capacity, the Lancaster was designed and modified to carry an unprecedented variety of bombs, ranging from 4 lb incendiaries through conventional high explosive 500 lb and 1,000 lb bombs and the 4,000 lb light case "blockbuster" to the 12,000 lb Tallboy and 22,000 lb Grand Slam. The small incendiaries were particularly effective in attacks on oil refineries when used in combination with high explosive bombs and played a significant role in the strategically decisive 1944 campaign against German oil. The Tallboy and Grand Slam,

though not available until 1944, proved devastatingly effective in the 1944-45 campaign against German transportation. The Lancaster's effectiveness as a bombing platform was multiplied from 1942 by the development of effective blind-bombing aids to penetrate to the German heartland.

Against the Lancaster's unparalleled ordnance carriage capabilities, the design tradeoff was a modest service ceiling of around 24,000 feet that made daylight operations infeasible except in the most permissive of environments and calls into question the pre-war Royal Air Force's appreciation of the lethality of German anti-aircraft artillery. The Royal Air Force's reliance on .303 caliber machine guns for defensive armament further constrained the Lancaster's effectiveness. These were badly outranged by the high velocity 20 mm cannon carried by *Luftwaffe* night fighters, all but reducing British gunners to lookouts. To compound matters, the British did not field an effective belly turret and Bomber Command decided to eliminate downward firing armament altogether on the mistaken assumption that *Luftwaffe* night fighters would not attack from that quarter. In fact, the *Luftwaffe* installed upward-firing cannon in its night fighters, mounted in the fuselage and firing forward at a 10°-20° angle from the vertical so that the pilot could aim by means of a sight mounted in the top of the canopy. These went undiscovered for an extended period and inflicted heavy losses on Bomber Command. In combination with American long range daylight bombers the Lancaster forced dispersal of the German armaments factories, forced Germany to deploy a million man air defense force to protect the homeland, diverted German industrial production from offensive weapons and contributed to the effects of attrition on the Eastern front.

Zero

The Mitsubishi A6M Zero was the linchpin of early Japanese strategic success. Without the Zero's range and effectiveness in air-to-air combat, the Pearl Harbor attack and the conquest of the Philippines and Netherlands East Indies would have been problematic at best. The Zero was an improbably good design, and one for which there was no available substitute. On the negative side of the strategic ledger, the Zero's remarkable performance was gained at the expense of vulnerability to battle damage. Its tactical effectiveness was thus heavily dependent upon pilot skill, magnifying the strategic impact of the loss of the Japanese Navy's cadre of experienced aviators in the Solomons campaign.

A combat aircraft designed to a tight and seemingly impossible specification calling for unprecedented range and maneuverability in a carrier fighter, the Mitsubishi A6M Zero is the rare example of a first-rate combat aircraft powered by a mediocre engine. Indeed, Japanese engineers consciously compensated for the fact that Japanese aero engines were, quoting the Zero's designer Horikoshi Hiro, "20 to 30 percent less powerful than those of the more advanced countries."⁴⁰ That notwithstanding, the Zero was the first carrier-based fighter capable of besting its land-based equivalents. This is remarkable in light of the fact that the design of carrier-based aircraft is inherently more difficult than that of the land-based equivalents. Not only do arrested carrier landings call for a considerably stronger, and hence heavier, structure; final approach speeds must be low by land-based standards and handling characteristics must be exceptionally good if high operational losses are to be avoided. The Zero's range, an essential precondition to early Japanese victories in the Pacific, was the compromise of an extremely light, yet strong, structure and the provision of a jettisonable

centerline external fuel tank. The Zero's remarkable maneuverability in air-to-air combat combined a low wing loading and excellent power-to-weight ratio⁴¹ with a potent armament of two wing-mounted 20 mm cannon plus two 7.7 mm machine guns in the engine cowling, mainly to help the pilot aim the cannon. In order to obtain the remarkable wing loading and power-to-weight ratio that made the Zero formidable, designer Horikoshi dispensed with protective armor and self-sealing fuel tanks and Zero pilots wore no parachutes. This was not, as is commonly imputed, because the Japanese Navy placed a low value on the lives of its pilots or because of a "kamikaze mentality," but due to a rational assessment of pilot survival factors. Unlike its main allied opponents, the Zero, with flotation bags in the wings, had excellent ditching characteristics.⁴²

The Zero's critical dependence upon pilot skill was its Achilles heel. Once the Japanese Navy had expended its cadre of skilled aviators in the Solomons campaign, the Zero's prime liability, extreme vulnerability to battle damage, made it a death trap.

Wildcat

The only battle-worthy American fighter in operational service in 1941, the F4F Grumman Wildcat assumed strategic importance by virtue of its ability to take the Zero's measure. This had two principal strategic effects, one intangible, the other attritional and both of great importance. Though the evidence is circumstantial, it is clear that confidence in the Wildcat and the men who flew it emboldened our naval commanders to challenge the Japanese aggressively in the early days of the war. This led to victory at the Coral Sea and Midway. Second, the Wildcat played a dominant role in the destruction of the flower of the Japanese naval air arm in the Solomons campaign, particularly in the critical early stages. That the Wildcat's tactical effectiveness was largely due to remarkable pre-war tactical innovation within the US Navy fighter community in no way lessens its strategic importance. The Brewster F2A Buffalo, the only putative substitute until the operational debut of the Grumman F6F Hellcat in August 1943,⁴³ was a deathtrap. A superior design, the Hellcat added significantly to Japanese losses and lessened American casualties, but entered service only after the Japanese naval air arm had been effectively destroyed.

Like the Hurricane, the Wildcat was the lineal development of a biplane precursor, the F3F, and was a conservative design structurally. The Wildcat owed its robust performance to its Pratt and Whitney R-1830 fourteen cylinder twin-row radial engine, fitted with a two-stage, two-speed mechanical supercharger in the initial operational versions. So powered, the Wildcat was inferior to the Zero in turn radius, rate of climb and climb angle, deficiencies that should have placed it at a severe tactical disadvantage. It could match the Zero in service ceiling and—almost—in maximum speed in level flight. It could easily outstrip the Zero in a dive. Given the Japanese fighter's vulnerability to battle damage, the Wildcat's four .50 caliber machine guns were a match for the Zero's comparatively low-velocity 20 mm cannon. With shorter wings, the Wildcat also had a higher initial roll rate, essential for breaking contact with an enemy on your tail. Finally, with self-sealing tanks and armor protection for the pilot, it was far more resistant to battle damage and lessened pilot combat attrition meaning more American pilots survived lost engagements to become battle hardened and experienced for their next aerial combat.

The Wildcat's performance might have gone for naught had the US Navy's fighter community not developed remarkably innovative tactics during the late 1930s. First, the US

Navy's air service was effectively alone among the world's air forces in systematically training its fighter pilots in wide off-angle deflection shooting, meaning that they were trained to lead their targets by as much as 60°.44 Second, eschewing the then-*de rigueur* three-ship "Vee" and echelon formations prevalent in every air force but the *Luftwaffe*, the Navy embraced a system of mutually-supporting two-ship two-element formation tactics developed by Commander James Thatch in which each pilot in the four ship formation continually checked one another's blind spots astern, the so-called "beam defense position" or "Thatch weave."⁴⁵ The Wildcat's design serendipitously enhanced its tactical effectiveness in that the pilot sat high in the cockpit above the wing and engine, primarily for better visibility in carrier landings, and downward visibility over the nose, already good by design, was enhanced by the R-1830's small diameter. The result was an important tactical advantage: when "pulling lead" in attacking a turning enemy from astern, Wildcat pilots could maintain visual contact at closer ranges and thus press home their attacks more aggressively than could their Japanese opposites, seated low behind the Zero's larger engine.

SBD

The Douglas SBD Dauntless' strategic importance derives first and foremost from the destruction of the heart of the Japanese fast carrier force in the Battle of Midway. Victory at Midway precluded a massive re-deployment of American resources to the Pacific that would have undercut the Allied Europe First strategy and lengthened the war by six months to a year. The Dauntless also played a pivotal role in the Guadalcanal campaign, blunting the power of the Japanese Navy when it still enjoyed a measure of operational freedom, wreaking havoc on Japanese warships and shipping. The Dauntless remained the Navy's principal dive-bomber until well into 1944 and accounted for a greater tonnage of Japanese warships sunk than any other American aircraft.

Designed for one thing and one thing only, the destruction of enemy warships, the Douglas Dauntless was a less efficient dive bombing platform than the Ju 87, but a far superior aircraft in every other regard. Edward Heinemann, although not formally trained as an aeronautical engineer, conceived of a light, strong airframe, first incorporating it into the wing for the Douglas DC 3, and then into the Northrop A-17 attack aircraft. He extrapolated this sturdy and light design into the SBD. Underpowered, the SBD had a low rate of climb with a full bomb load and was not particularly fast, but had sterling flight characteristics in all other respects and was an excellent instrument platform. Of considerable importance, its carrier landing characteristics were excellent, a fact that reduced operational wastage.

P-47

The Republic P-47 Thunderbolt was the first American fighter available in significant numbers in the European Theater that was capable of reaching German airspace and outperforming first line *Luftwaffe* fighters at high altitudes. That made it possible for USAAF heavy bomber formations to attack targets inside Germany without prohibitive losses and forced the *Luftwaffe* fighter arm to accept battle on unfavorable terms, leading ultimately to its defeat. The Lockheed P-38, with a significantly greater radius of action than the P-47, entered operational service earlier and could have done the job in principle, but was never wholeheartedly embraced by the USAAF and was not available in quantity at the critical

time. The North American P-51 could have done the job as well and ultimately did, but became available in numbers only after the P-47 had turned the tide. Produced in larger numbers than any other American fighter, 15,579, the P-47 was a highly effective as a fighter bomber in the European Theater and played a major role in interdicting German lines of communication and in supporting friendly ground forces.

The P-47 was the end product of an evolutionary series of fighter designs by Russian émigré designer Alexander Kartveli that combined a powerful radial engine, an all-metal structure, and an elliptical wing in the smallest airframe feasible. Starting with the P-35 of 1935, Kartveli's fighters became progressively larger and more aerodynamically refined, acquiring a turbo-supercharger in 1939 with the R-1830-powered P-43. Within the parameters of his basic design, Kartveli perceived that the full benefits of turbo supercharging could only be realized with an engine in the 2000 horsepower range. In 1940, he turned to the eighteen-cylinder twin-row radial Pratt and Whitney R-2800 just entering production to harness the raw power of a turbo supercharger. The Pratt and Whitney was engineered, like all high performance US aero engines to exploit the properties of high-octane gasoline. The integration resulted in the P-47, the largest single-engine, piston-powered fighter ever built. Remarkably clean and sophisticated, the P-47 was one of the few successful mid-wing fighters of the war and, like the Spitfire, benefited from the greater efficiency of an elliptical wing.⁴⁶

In fighter installations, the turbo supercharger offered advantages similar to those of a variable clutch mechanical supercharger that could be progressively disengaged to obtain maximum power at lower altitudes without over boosting the engine. Achieving the benefits of the turbo's inherent characteristics required superior thermodynamic-mechanical and aerodynamic engineering and the P-47's supercharger installation, although necessarily complex, was remarkably efficient and reliable. Taking full advantage of the R-2800's power, Kartveli gave the P-47 an armament of no less than eight wing-mounted .50 caliber machine guns.

The P-47 could carry a significant bomb load and that, combined with its heavy firepower and the remarkable ability of the R-2800 to absorb battle damage, made it one of the most effective fighter-bombers of the war. Of greater strategic importance, the P-47 could also carry over 200 gallons of fuel in jettisonable external tanks. In late 1943 when the USAAF came belatedly to an appreciation of the value of long range fighter penetrations of *Festung Europa* in support of heavy bomber operations, the P-47 was the only US fighter available in significant numbers that possessed the requisite capabilities. At that point, P-47s based in southeast England could penetrate only as far as an arc running through Lübeck and Frankfurt. P-38s could penetrate as far as Leipzig from the beginning and by February 1944, were equipped with larger external tanks, enabling them to reach Berlin, but USAAF production and deployment decisions limited their availability to small numbers. P-51s, capable of reaching well beyond Berlin to as far as Prague and, eventually, Vienna, only became available in significant numbers from March 1944.⁴⁷ In the meantime, the P-47 filled the gap. Had Air Force leaders appreciated the importance of long-range escort fighters sooner than they did, the P-47 could have been readily modified to match the radius of action of the P-38 and P-51. The longer-ranged Thunderbolt, in the form of the P-47N, saw action in the Pacific in the final days of the war.

Yak 1-9

The first Soviet fighters capable of meeting the Bf 109 and Fw 190 on even terms, Yak fighters were produced in large numbers and played a major strategic role in denying the *Luftwaffe* the unimpeded exploitation of the air it had enjoyed to great effect until Stalingrad. The Soviet Union possessed only ninety-four Yak-1s on the eve of Barbarossa, but by the end of the war, the rejuvenated Soviet aircraft industry had manufactured over 16,700 Yakovlev fighters, some fifty-eight percent of all Soviet single-seat fighters, distributed among many *Protivovozdushnaya Oborona* air defense units. The Lavochkin La 5-7 series could have done the job, but entered service later, offered no tactical advantages over contemporary Yak fighters, and was not, in the final analysis, essential.

The Yak-1 was an unremarkable, straightforward, and competent design, in many ways reminiscent of the Hurricane, which it superficially resembled. The circumstances of aerial combat on the Eastern Front dictated that it would fight only at low to medium altitudes, for which its liquid-cooled Klimov V-12 engine, developed from a French Hispano-Suiza original, was more than adequate. Indeed, the Yak-3, with a reduced wingspan for greater low-altitude maneuverability, was one of the best low-altitude dog-fighters of the war, a fact attested to by *Luftwaffe* flight evaluations of captured examples. The Yaks' armament, typically a 20 mm cannon firing through the propeller hub and two synchronized 12.7 mm machine guns in the engine cowling, was somewhat lighter than that of its principal *Luftwaffe* opponents, but was adequate. Better than they needed to be, Yak fighters contributed to the aerial battle by providing an environment of air superiority that permitted the *Shturmoviks* ground attack units to support the highly Il-2 mobile Soviet armored forces in their counteroffensives from Stalingrad to Berlin.

Mosquito

The de Havilland Mosquito's strategic importance derives in the first instance from its effectiveness as a photo reconnaissance aircraft. Effectively immune to interception by virtue of its speed and service ceiling and with a significantly greater radius of action than any competing design, the Mosquito provided Allied intelligence staffs and operational planners with information of immense value, almost all of which could have been obtained in no other way. In addition, the Mosquito made important contributions to the Combined Bomber Offensive as a bomber, particularly marking targets in the pathfinder role.⁴⁸ The Mosquito also enjoyed significant success as a low altitude precision daylight bomber, as a night fighter, as a daylight intruder fighter, and in the maritime strike role.

The Mosquito's genesis lay in a 1935 RAF specification stimulated by reports that the Germans were building an extremely fast twin-engined bomber. It called for a bomber powered by two Rolls-Royce Merlins with a defensive armament of three .303 calibre machine guns in streamlined mounts. Geoffrey de Havilland's interest in the project and his firm's experience in building high performance multi-engined aircraft with wood structures resulted in the Mosquito. The decision to delete all defensive armament—de Havilland's preference from the start—was made by Air Vice Marshall Wilfred Freeman, the Air Ministry official in charge of production and development, in August 1939.⁴⁹ That decision was central to the Mosquito's success.

The Mosquito was a rarity: a genuinely successful multi-role combat aircraft. Although the Mosquito excelled in its intended role (it had the lowest loss rate over Germany of any British bomber) it played a significant part in the multiple roles mentioned above. Rendered safe from interception by speed, photo-reconnaissance Mosquitoes had sufficient range to cover most of Germany from bases in the United Kingdom, and after the capture of the Foggia airfield complex in Italy in September 1943 provided coverage of the entire Third Reich. Progressive development of the Mosquito and its Merlin engines kept a step ahead of German defenses, particularly for photo-reconnaissance. The Mosquito PR XIV, which entered service in late 1943, had a fully-pressurized crew compartment and a service ceiling above 35,000 feet that rendered it effectively immune to interception. Only 432 PR XIVs were produced, but they rendered strategically vital intelligence.⁵⁰ Despite the need for exotic glues and highly skilled workers, De Havilland manufactured nearly 8,000 Mosquitoes. The Mosquito's drawbacks included short airframe life in tropical conditions and the difficulty of exiting a damaged aircraft in flight.

PBY

The Consolidated PBY was ubiquitous as a patrol aircraft for the US and Royal navies, entering service with the latter in early 1941, well before America's entry into the war. PBY crews located the *Bismarck*, gave the Royal Navy warning of the April 1942 Japanese incursion into the Indian Ocean, located the Japanese carrier force before Midway, were omnipresent in tracking Japanese task forces and convoys in the Solomons campaign, and played a major role in the Battle of the Atlantic. Allied effectiveness in dealing with Axis naval surface forces owed much to US and Royal Navy emphasis on patrol operations in which the PBY excelled and played a disproportionately important role.

A twin-engine flying boat of conservative design, the Consolidated PBY (Catalina in British service) entered service in 1936 and possessed unremarkable performance except in range, endurance, and handling qualities. A competent design, it was the right aircraft for the job at the right time and was procured in adequate numbers by the US Navy and for British and Canadian forces. That the PBY's strategic significance was due as much to the US and Royal Navy's emphasis on reconnaissance in support of the battle fleet as to the excellence of its design takes nothing away from the PBY's luster. It was slow, with a cruise speed of only 179 mph, but had a radius of action of nearly 2,000 miles and an endurance of no less than 17.6 hours.⁵¹ Less effective as an anti-submarine patrol aircraft than the B-24 by virtue of the latter's greater speed and the ease with which it could be modified to carry electronic equipment and offensive ordnance, it was still useful in that role. Later versions were amphibians, fitted with retractable landing gear. In addition to reconnaissance, it was used for air-sea rescue by US Army Air Forces in the later stages of the Pacific war.

C-47

The Douglas C-47, "Skytrain," (Dakota in British service) was far and away the most important, and best, tactical transport and paratroop deployment aircraft of the war. Produced in large numbers, it provided the bulk of the airlift that dropped two American and one British airborne divisions behind the D-Day invasion beaches and would make the list on that basis alone. In fact, the C-47 did a great deal more, hauling key personnel, spare parts, supplies and fuel. Provided in significant numbers to the British and Soviets, it was used

most innovatively and in the largest numbers by US forces, but served as a potent Allied logistical force multiplier in all theaters.⁵²

The military version of the 1937 Douglas DC 3, the first commercially successful airliner, the C-47 was beyond doubt the most successful tactical transport of World War II.⁵³ A scaled up extrapolation of the DC 2 of 1934 (itself developed from the prototype DC 1 of 1933), the DC 3 varied from its predecessors in the provision of a cabin sufficiently spacious to permit passengers to stand up and walk around. The DC (for Douglas Commercial) series of transports extracted the full benefit of stressed skin aluminum construction, the wings being particularly efficient. Designed in response to a Trans World Airlines specification that stipulated that a safe takeoff at design weight following the loss of an engine could be completed from the highest airfield served by TWA following loss of an engine, the DC 3 had adequate reserves of power and was inherently safe. Modifications for military use were minimal, the most important being the provision of easily removable (and spartan) passenger accommodations, provisions for securing heavy cargo inside the cabin, and a spacious loading door. Powered by two 1,200 horsepower R-1830 engines, the C-47 was fast for a transport with a cruise speed of 185 mph; it had a useful load of as much as 14,000 pounds and a radius of action of over 700 miles.⁵⁴ It had excellent flight characteristics and was easily maintained in the field. The rear cargo door could be opened in flight, making it far and away the best mass produced paratroop deployment aircraft of the war. Total US production reached 10,926, of which 10,123 were specifically manufactured as military transports; to this we can add 6,157 built under license in the Soviet Union.⁵⁵ As a tribute to the C-47's efficiency and durability, it formed the backbone of the Soviet internal air transport network into the 1960s.

P-51

Entering service after the P-38 and P-47, the North American P-51 had greater range and, partly in consequence, enjoyed a better kill ratio than either of the other two fighters. It was also the more agile of the three, a fact that its pilots exploited to great effect. From March of 1944 the P-51 broke the back of the *Luftwaffe* fighter arm, probably shortening the war and surely reducing the cost to the United States.⁵⁶ The P-38 *could* have done the job—the P-47's range was inadequate—and given time would have, albeit at greater cost in blood and treasure. The P-51 *did* it. Finally, the photoreconnaissance version of the P-51, the F-6, was the most successful low altitude photographic imagery collector of the war.

The most successful long-range piston-engine air-to-air fighter of the war, the North American P-51 was one of a handful of strategically significant aircraft to be designed after the commencement of hostilities in 1939. Ironically, the P-51's designer, Edgar Schmued, was Austrian by birth and did his engineering apprenticeship in Germany.⁵⁷ Designed in response to a request by the British purchasing commission in 1940, the North American P-51 (Apache in British service) benefited from the most recent NACA drag reduction and airfoil data, a fact that put it in a class by itself. The efficiency of the P-51's laminar flow wing and engine installation resulted not only in an excellent turn of speed, but in dramatically greater range than existing single-engine fighters. The exceptionally compact engine installation and associated engine cooling resulted in remarkably low drag. The P-51's principal liability in its early production versions stemmed from the altitude limitations of its Allison engine. Virtually identical to the Rolls Royce Merlin in configuration, size,

and development potential, the Allison was anemic by comparison due to the low rated altitude of its mechanical supercharger, the product of an Air Corps decision to rely on turbo supercharging for high altitude performance. In the event, shortages of the high temperature alloys needed for turbo supercharger turbine blades initially limited production to little more than that required for heavy bombers and the P-38 was the only fighter powered by turbo supercharged Allisons.

The RAF began taking delivery of Apaches in November 1941 and used them for long-range low altitude operations from July of 1942 with considerable success.⁵⁸ Impressed by the aircraft's performance, the British experimentally re-engined an Apache with a Rolls Royce Merlin in the spring of 1942. The results were spectacular, yielding outstanding high altitude speed and range, but might have lead to nothing had not USAAF Major Thomas Hitchcock, assigned to the American Embassy as an attaché, been invited to fly the aircraft.⁵⁹ An instant convert, Hitchcock was both persuasive and well connected. Re-engined with the Merlin, providentially produced in the United States under license by Packard, the Mustang became the best long range, high altitude fighter of the war to be manufactured in large numbers, 14,819 by the end of the war. The P-51 was not without vices. The vulnerability of its liquid coolant system limited its usefulness in the ground attack role and careful management of the fuel system was necessary to avoid exceeding the rearward center of gravity limit with a full fuel load. On balance, however, it was a remarkably well designed aircraft that exceeded all expectations.

P-38

The Lockheed P-38 Lightning rendered US air superiority in the Pacific unassailable from the autumn of 1942 and made significant contributions to the defeat of the *Luftwaffe* in the skies over *Festung Europa* in the spring of 1944. The first USAAF—or any other—fighter capable of high altitude escort operations deep within enemy territory, the P-38 was not used effectively in that role until the P-47 was available in larger numbers and was then superseded by the faster, more maneuverable and longer-ranging P-51. For the USAAF, the P-38 was the greatest missed strategic opportunity of the war. Because it entered operational service nine months later than it should have, because it was produced in smaller numbers than any other battle-worthy USAAF fighter, because few pilots in the European Theater learned to exploit its peculiar strengths, and because it was belatedly employed in the long range escort role, the P-38's strategic impact was substantially less than it might have been. The photo reconnaissance version of the P-38, the F-5, though inferior to the Mosquito in range, speed and service ceiling, made significant contributions to Allied victory.

Lockheed's Clarence "Kelly" Johnson designed the P-38 in response to a January 1937 Army Air Corps' specification for a long-range interceptor so demanding as to deter other would-be contractors.⁶⁰ Perceiving that the required speed, climb and service ceiling could not be met by orthodox means, Johnson turned to a radical twin-engine design powered by a pair of turbo supercharged twelve-cylinder, liquid-cooled Allison V-1710 engines. A central fuselage-pod housed the cockpit situated between the engines mounted in mid-wing booms that supported the tail surfaces. This configuration offered the significant ancillary benefit of grouping the armament of four .50 caliber machine guns and a 20 mm cannon closely together in the nose. Unlike wing-mounted guns that were "harmonized" so that their fire converged at a pre-determined distance and dispersed thereafter, the P-38

delivered a concentrated stream of fire regardless of range. Johnson and his team were the only pre-war designers to fully exploit the notion that powering a single seat fighter with two engines had the advantage of halving the per-engine weight penalty of pilot, armament, instrumentation, and flight controls, though the Lightning's success owed at least as much to Johnson's unorthodox approach as to the inherent advantages of the scheme.⁶¹

The XP-38 (X for experimental) first flew in January 1939 and proved to have spectacular performance, but mismanagement at Lockheed delayed development. Battle-worthy versions of the P-38 did not enter service until the summer of 1942, over nine months behind schedule.⁶² The source of the problem was cash-and-carry orders from Britain for patrol bomber versions of the twin-engine Electra transport, desperately needed to stem the U-boat menace. These produced immediate profits for a cash-starved Lockheed, but stripped the YP-38 (Y for service test) program of first-line engineers, draftsmen and machinists. The resultant delay had the doubly adverse effect of depriving the USAAF of a world-class fighter at the outbreak of hostilities and of souring the Army Air Forces on Lockheed as a contractor, a fact that no doubt played a role in restricting P-38 procurement. Moreover, the AAF initially misused the P-38 as a low altitude battlefield air superiority aircraft in North Africa where it was outclassed by the Bf 109 and Fw 190, suffering a taint to its reputation that was never completely erased.

The P-38's tactical profile was utterly unlike that of any other World War II fighter: it had a good rate of climb and excellent speed, a high service ceiling, a spectacular zoom climb, a good turn radius, and heavy firepower. Equipped from the start with jettisonable drop tanks for range extension it had by far the longest radius of action of any US fighter until the debut of the P-51. A slow initial roll rate, the product of the mass of its two in-line engines mounted well outboard of the center of gravity handicapped the P-38's air to air capability. These characteristics called for tactics that were quite different from those that worked well with other US fighters. P-38 pilots in the Pacific generally adapted well—getting into a turning dogfight with the lighter Japanese fighters was a critical mistake for *all* US fighters, not just the P-38—but only a minority of pilots in the European theater learned to exploit the P-38's capabilities effectively. Complicating matters, the P-38's size and complexity intimidated many pilots and its high wing loading called for initial climb speeds higher than those to which neophyte pilots were accustomed if loss of an engine on takeoff were to be survived.

In addition, technical problems—all fixable—reduced the P-38's effectiveness over Europe: its cockpit heater was inadequate for winter operations over Germany and its intercoolers, the ducting that cooled the outflow from the turbo superchargers, were *too* efficient, reducing the air/fuel mixture to sludge in frigid, moist winter air at high altitudes. This led to blown engines deep in enemy territory when they were most needed, and twin-engined redundancy had little value in a dog fight. In consequence, the P-38 fought over northern Europe at a serious disadvantage: in 90 days of combat beginning 28 December 1943, the 20th Fighter Group, the most highly decorated P-38 group in the European theater, suffered 54 pilots lost to 52 kills awarded.⁶³ There is bitter irony in the consideration that if the two groups of P-38s operating over Germany in December of 1943 had been deployed six months earlier, something entirely within the realm of the feasible, they would have been available for both Schweinfurt missions and would have fought in the warm skies of summer and early autumn. The problem was one of vision, not design.

The P-38's slow initial roll rate was partially ameliorated by the provision of hydraulically boosted aileron control. Used aggressively in larger numbers and with appropriate tactics, the P-38 had the potential to have done in mid- to late 1943 what the P-47 did and more. In the event, the P-38 played a significant, albeit subsidiary, role in the defeat of the *Luftwaffe* fighter arm. Under the designation F-5, the P-38 was the USAAF's most important American-produced photoreconnaissance aircraft.

IL 2

Produced in huge numbers, the heavily armored, single-engine Illushyn Il-2 *Shturmovik* was the most important Soviet ground attack aircraft of the war and inflicted serious losses on the *Wehrmacht* from the summer of 1944 to the end of the war.

A 1938 design powered by a liquid cooled Mikulin V-12 engine in the 1,700 horsepower range, the result of progressive development of a late 1920s BMW original,⁶⁴ the IL -2 entered service in the summer of 1941 and was built for one thing and one thing only: low altitude ground attack. A straightforward design, the IL-2 incorporated little that was novel beyond the extensive structural use of hardened steel to provide armor protection to the engine, cooling system and crew. It was armed with two unsynchronized wing-mounted 23 mm cannon and, in two seat versions, with a flexible 7.62 mm or 12.7 mm machine gun fired by the rearward-facing observer. The IL-2's bomb load was not particularly impressive: 600 kg (1,321 lb) of bombs and rockets carried externally on underwing mounts—the P-47 carried a heavier weight of ground attack ordnance by some twelve percent. This was more than compensated for by its resistance to battle damage and the numbers in which it was produced, more than 36,000 by war's end.⁶⁵

B-24

The strategic importance of the Consolidated B-24 Liberator derives in the first instance from its success as an anti-submarine patrol aircraft in the Battle of the Atlantic and in the second instance from the immense amount of resources the B-24 program absorbed, both in absolute terms and relative to the aircraft's operational effectiveness as a bomber. The B-24 had many technical and tactical deficiencies, but possessed one critically important virtue, range, that was of critical importance in anti-submarine patrols, particularly in combination with a relatively high cruise speed. Small numbers of VLR (for very long range) Liberators were deployed in this role by the British from June of 1941. Progressively upgraded in capabilities, they were procured in modest numbers but to decisive effect; a mere two squadrons of later VLR versions of the Liberators closed the mid-Atlantic "air gap" south of Greenland in the spring of 1943, sounding the death knell of the U-boat force.⁶⁶ Early versions of the Liberator, though not battle worthy, were the premier Allied long range VIP transport and served in this role in small numbers throughout the war. Though substantially less effective as a high altitude daylight bomber than the B-17, the B-24 made a significant contribution to the Combined Bomber Offensive. From late 1942 until the operational debut of the B-29, the B-24 was the principal USAAF heavy bomber in the Pacific where its superior radius of action conferred important benefits and where its vulnerability to battle damage could be tolerated.

Produced in larger numbers than any other US aircraft of World War II—over 18,000 were built⁶⁷—the B-24 was designed to a March 1939 contract and first flew that December, but was not fielded as a battle-worthy bomber until mid-1942. Procured by the USAAF to supplement the B-17 with a more modern aircraft, the B-24 was powered by four Pratt and Whitney R-1830s, a hedge against demands on production of the Wright R-1820. A large part of the B-24's appeal lay in the supposed efficiency of its wing's Davis airfoil. Designed by California entrepreneur David Davis in a pseudoscientific process of inspired guesswork, the airfoil did not differ appreciably in performance from similar NACA airfoils. That, however, was not appreciated at the time, and Convair's decision to give the B-24 a wing of unusually high aspect ratio, that is a wing that was long as a function of its span, resulted in a wing that was uncommonly efficient at low and medium altitudes and was largely responsible for the aircraft's superior range.⁶⁸ The B-24 proved amenable to modifications that enhanced its effectiveness in the anti-submarine role, notably radar installations and a variety of forward-firing ordnance, ranging from 20 mm cannon to stub wing-mounted 5-inch high velocity rockets.

Early models of the B-24 had neither turbo supercharged engines, self-sealing fuel tanks, nor effective defensive armament, and extensive modifications were required to make the aircraft battle worthy, a threshold reached in mid-1942 with the B-24D.⁶⁹ At that point, the B-24 was armed with power operated twin .50 cal. dorsal and tail turrets, but, unlike contemporary B-17s had no belly turret. Later models were fitted with a retractable belly turret and were as heavily armed as the B-17. Not until the J model of 1944 were problems with the flight controls largely worked out, and problems with the leaky fuel system were never completely resolved.

As noted earlier, the B-24 was inferior to the B-17 as a high altitude daylight bomber in every tactically meaningful parameter except range. That, however, became apparent only with accumulated combat experience, by which time the USAAF had committed itself to procuring the B-24 in large numbers. That decision in itself produced problems, notably in efforts by the Ford Motor Company to mass-produce the B-24 using automotive production methods at the enormous Willow Run facility built specifically for the purpose. In fact, automotive and aircraft production methods were fundamentally different and by the time Ford engineers had mastered the new medium, the B-24 was approaching obsolescence.

Bf 110

The Bf 110's strategic importance lies first and foremost in its failure as a heavy day fighter, a major reason for German defeat in the Battle of Britain. Fitted with air intercept radar, the Bf 110 proved to be an excellent night fighter and exacted a heavy toll on RAF Bomber Command from 1942 on, a matter of lesser, but still considerable, strategic importance. In addition, rocket-armed Bf 110s were effective against American heavy bombers during the USAAF unescorted daylight precision bombardment campaign of 1943.

Designed to a 1934 specification calling for a long-range heavy fighter, the twin-engine Bf 110 first flew in 1936, powered by two DB 600s. The DB 601 engine and, later, the DB 605 powered the operational versions. Fast for the time, well armed, and with excellent handling characteristics, the Bf 110 was handicapped by the fact that it was a multi-place aircraft with provisions for a gunner and radio operator, provisions that meant greater size and weight. In consequence, the Bf 110 had insufficient maneuverability to survive in

combat against single-engine fighters although this did not become apparent until the Battle of Britain. The Bf 110 turned out to be a superior night fighter since it had sufficient power and payload capacity to carry the requisite air intercept radar and specialized receivers, a radar operator, and heavy armament. Of equal importance, it was an excellent instrument platform. The provision of upward-firing fuselage-mounted 20 mm cannon from August 1943 gave Bf 110 night fighters an unprecedented lethality that the RAF recognized only belatedly. That the installation was developed in the field by an enlisted armorer speaks volumes for low level German initiative and the basic soundness of the Bf 110's construction.⁷⁰

The same power and payload capacity that made the Bf 110 a superior night fighter supported the provision of two under-wing launchers for 210 mm bombardment rockets for daylight use against USAAF heavy bomber formations. This was the *Luftwaffe* only air-to-air weapon that outranged the American bombers' .50-caliber defensive armament and the only one capable of degrading the integrity of B-17 defensive formations. Brutally effective when employed in combination with single-engined fighters, the rocket-armed Bf 110 enjoyed a brief heyday before it was put out of business by drop tank-equipped US fighters.

B-29

Boeing B-29s reduced the major Japanese cities to ashes in firebombing attacks from March of 1945 and dropped the two nuclear bombs that ended the war. Also of considerable strategic significance, the B-29 program absorbed immense quantities of resources, outspending the Manhattan Project that produced the A Bomb by some \$3.75 billion to \$2 billion in 1945 dollars.⁷¹ Finally, B-29s played a major role in cutting off Japanese maritime commerce by means of aerial mines.

Power plants aside—a point that is debatable—the B-29 was far and away the most technologically advanced production aircraft of World War II. Indeed, save for its piston engines and unswept wings, it had more in common with the jet bombers of the 1960s than with contemporary designs. In addition to an unprecedented radius of action in excess of 2,000 miles and a service ceiling above 30,000 feet, the B-29 was the first mass-produced operational bomber with a fully pressurized crew compartment and effective, remotely controlled, defensive armament. The power plants, four R-3350 four row radial engines, each with two turbo superchargers, were an impressive technological achievement in their own right, and posed major developmental problems stemming partly from sheer complexity and partly from the altitudes at which they had to operate. The B-29 was the USAAF's second most accurate bombing platform next to the B-17.⁷² Ironically, Hiroshima and Nagasaki aside, it had its greatest strategic impact dropping incendiaries at low altitudes, a mission where many of its advanced design features were irrelevant.

Ju 52

A handful of Ju 52 transports forwarded to Spain by Hitler in the early days of the 1936-1939 Spanish Civil War provided the critical increment of support that prevented the collapse of the Nationalist cause by ferrying elements of the regular Army of Africa from Morocco to Seville. Although the subsequent drive on Madrid stalled in November 1936, the Nationalists ultimately prevailed, keeping Spain out of World War II and placing the

diplomatic tenacity of Spanish dictator Francisco Franco between Hitler's armies and Gibraltar. In addition, German paratroops dropped from Ju 52s or descending in gliders towed by them played a major role in the May 1940 conquest of the Low Countries and the preeminent role in the April 1941 capture of Crete. Finally, the success of the *Luftwaffe* transport arm in supplying the Demjansk pocket, cut off by the Soviet 1941-42 winter offensive, encouraged *Luftwaffe* chief Hermann Göring to believe that he could similarly supply Stalingrad the following winter. Perversely, the Ju 52's successes, all functions of its sound design, led Göring and the Third Reich into disaster.

A late 1920s design with corrugated aluminum skin, three engines and fixed landing gear, the Ju 52 had modest performance in comparison with its principal Allied counterpart, the C-47. Its maximum and cruising speeds were 168 mph and 124 mph to the C-47's 185 mph and 230 mph and it carried a payload amounting to about 38% of its maximum takeoff weight in comparison to the C-47's 45%.⁷³ On the plus side, it was exceptionally rugged, possessed excellent handling characteristics, and was easily maintained in the field under the most primitive of conditions, virtues that kept it in production well after the termination of hostilities in 1945. Among mass-produced World War II transports, it was second only to the C-47 as a parachute deployment aircraft and was capable of handling surprisingly bulky loads.

Conclusions

What conclusions can we draw from the preceding analysis? First, our exercise in rank ordering supports and gives substance to the proposition that aircraft design *was* a major driving factor in the conduct and outcome of World War II. How many aircraft a country produced was important, but which aircraft it fielded and how well suited they were to their respective nations' grand strategies was crucial. Timing was also a critical factor, which is another way of saying that those establishments which accurately anticipated their strategic needs and allocated their resources accordingly were able to deploy the aircraft they needed in time to have strategic effect. Numbers were important, but it had to be the right aircraft at the right time. To be sure, talented designers were essential to the process, but as we have seen the availability of first-rate aero engines was more likely to be the limiting factor than airframe design talent, a point we shall expand on below. To anticipate another point to be expanded upon, Nazi Germany and the Imperial Japanese Navy did a brilliant job of anticipating their short-term aircraft needs, taking full advantage of the fact that the strategic initiative was theirs to begin with. By contrast, Britain and the United States, more precisely the Royal Air Force, US Army Air Force and US Navy, did a far superior job of planning and preparing for a long war. That is particularly impressive in light of the fact that, as our exercise makes clear, the design of aircraft for strategic applications was inherently more demanding than that for tactical applications and much of the pre-war RAF and USAAF effort was directed toward strategic applications, both defensively and offensively on the part of the RAF and offensively by the USAAF.

At a lower level of abstraction, a breakdown of aircraft by nationality underlines just how important American airpower was to World War II and how much of that importance was directly dependent on the quality of power plant and airframe design. It also underlines the importance of America's massive commitment of engineering skill and economic

resources to the air war. No less than ten of the twenty-one aircraft on the list are American, followed by four British, four German, two Soviet and one Japanese. Note, however, that six of the ten American aircraft are in the bottom half of the list and the seventh, the P-47, is at the middle, an accurate reflection of the time needed to mobilize American resources, intellectual as well as productive. Conversely, the fact that the top two aircraft on the list are German provides eloquent testimony to the operational benefits accruing to an aggressor who attacks at the time and place of his choosing. That the second, the Ju 87 Stuka, was operationally effective *only* at the time and place of the aggressor's choosing further underlines the point. That the other two German aircraft on the list are near the bottom, and that both make the list largely because of their contribution to strategic failure, testifies to the incoherence of Nazi strategy and resource allocation when applied to a prolonged war. The location of the only Japanese aircraft on the list, the A6M Zero, makes the same point with regard to Japan. By contrast, the fact that three of the four British aircraft are in the top third of the list provides eloquent testimony to the remarkable prescience of those responsible for Britain's technical preparations for war in the air. So, too, does the fact that one of the American aircraft, the P-51 Mustang, was designed in response to a British requirement and achieved tactical success and strategic importance by virtue its British engine.

In functional terms, the list includes two transports, one specialized patrol aircraft and eighteen combat aircraft. Of the eighteen combat aircraft, no less than eleven were designed as day fighters, including three of the top four and eight of the top eleven, although one of the eighteen, the Bf 110, makes the list primarily because it failed in its primary role. The preeminence of day fighters confirms conventional wisdom concerning the importance of air superiority, both as perceived before the war and as things played out, but with an interesting twist: the importance of long range fighters was almost entirely unanticipated during the interwar years and only the *Luftwaffe* entered the war with an aircraft, the Bf 110, designed for that role. From the standpoint of those who wrote the specifications, the long-range capabilities of the P-38, P-47 and P-51 were entirely serendipitous. From the standpoint of those who designed them, they were anything but, if only because they took full advantage of their remarkable engineering skills and the impressive power plants available to them to build in a great deal of payload reserve.

Interestingly, four of the remaining eight combat aircraft are four engine bombers, B-17, Lancaster, B-24 and B-29, although one of the four, the B-24, was included in large part because of its success in an ancillary role. That, too, is more or less in accordance with conventional wisdom, at least as promulgated by the USAAF and RAF. Three of the remaining four combat aircraft are single-engine attack aircraft, the Ju 87 Stuka, SBD Dauntless, and Il 2 Shturmovik, all designed to tight specifications written with specific mission requirements in mind and all outstandingly successful in terms of those specifications... and not much else. No surprises there.

What *is* surprising is the relative absence of twin-engine combat aircraft. The only two to make the list by virtue of operational success, the P-38 and the Mosquito, were remarkably radical and uncommonly successful designs. Particularly striking is the absence of twin-engine bombers. One reason for this phenomenon lies in the fact that certain essential items of equipment, notably defensive armament installations and the gunners who manned them, were of a fixed size and weight and could not be scaled down. Each such installation thus comprised a greater proportion of the gross weight of a smaller aircraft than a larger one. Every bomber on the list except for the Mosquito was defended by powered

gun turrets, and turrets could only be made so small, so the same point applies to drag as well.⁷⁴ Another reason is that structural materials, notably the rolled aluminum sheet of which most aircraft on the list were constructed,⁷⁵ were made to a standard thickness. Although the point needs to be investigated more thoroughly, the skin on a four-engine bomber would thus be thinner and lighter relative to the total weight of the aircraft than that of a twin-engine bomber. To exploit these realities in the design process clearly posed major engineering challenges—only Britain and America fielded operationally successful four engine bombers—but the payoff in greater range, bomb load, service ceiling, or some combination thereof, clearly had great strategic importance. That is not to say that twin-engine bombers were unimportant strategically. Rather it is to say that such aircraft had substantially more modest operational capabilities, and thus less strategic importance. They were also more or less interchangeable. Light and medium bombers performed useful work, but they did not and could not carry the fight to the enemy as did their larger brethren.

Progressing from the general to the specific, engines were the critical limiting factor in aircraft design where extreme performance was required. With the sole exception of the Zero, every aircraft on the list with outstanding high altitude performance and/or with exceptional range and payload characteristics was powered by an exceptionally capable engine. In concrete terms, the aircraft in question were powered by the Daimler Benz 601 or Daimler Benz 605 (Bf 109); by the Rolls Royce Merlin (Hurricane, Spitfire, Lancaster, Mosquito and P-51); or by turbo supercharged American engines (B-17, P-47, P-38, B-24 and B-29). To this short list we can add the Rolls Royce Griffon-powered Spitfire PR XVI, mentioned earlier. Going beyond our list, mediocre aircraft powered by first-class engines were numerous: to cite two prominent examples, the Handley Page Halifax and some versions of the Curtiss P-40 were powered by Merlins. With the sole exception of the Zero, the converse was not true: insofar as combat aircraft were concerned mediocre engines powered mediocre aircraft.

Moreover, the strategic importance of high performance aero engines was magnified by the time required for their development—a minimum of three years by the beginning of World War II⁷⁶—and it is in this context that the remarkable farsightedness of British preparations for war becomes manifest. Government subsidies for the development of high performance aero engines with military potential were maintained throughout the 1920s and '30s, although ironically development of the Rolls Royce R was financed with a private contribution of £100,000.⁷⁷ Nor was Rolls Royce Britain's only producer of high performance aero engines. Bristol developed and fielded a family of high performance air cooled radial engines that powered some versions of the Lancaster and Halifax and by 1944 could have provided a capable substitute for Rolls Royce engines in fighter applications had one been needed.⁷⁸ In addition, Napier developed the liquid-cooled 24 cylinder "H" Sabre, the most powerful aero engine to see operational service until the debut of the Wright R-3350, and if the strategic impact of the Sabre-powered Hawker Typhoon and Tempest was comparatively modest, it was not because of the inadequacies of their power plants.⁷⁹ Finally, Rolls Royce developed a more powerful successor to the Merlin, the Griffon, in time to see operational service in later versions of the Spitfire. As noted earlier, it was insurance that was not needed.

The American achievement was equally farsighted and more innovative, much of it the product of Army Air Corps initiatives. Considering the United States safe behind its ocean frontiers, Congress stopped subsidizing the development of high performance aero

engines with the onset of the Great Depression, forcing the Army and Navy to depend on engines developed for the civilian market.⁸⁰ That meant air cooled radial engines designed for maximum cruise efficiency at low and medium altitudes, a path down which the Navy had already started as a result of the air-cooled engines' superior power to weight ratios, reliability, and ease of maintenance. For likely Navy missions, attack and defense of ships and maritime patrol, none of them requiring a particularly high service ceiling, that made perfect sense. But Army airmen, looking ahead to a European war, with their utter unpreparedness for World War I clearly in mind and with an eye on developments abroad, saw the need for higher speeds and service ceilings than any conceivable civilian requirement would demand. As already related, their response was on two fronts: contracting with General Electric to develop the turbo supercharger and working aggressively in cooperation with the oil industry to develop aviation gasolines that would support higher compression ratios without pre-ignition "knock." Despite strong resistance on the part of the Army Staff—high octane gasoline was considerably more expensive than that in common use—the Air Service prevailed, and by the 1930s had managed to obtain supplies of 100 octane aviation gasoline and engines modified to take full advantage of the higher compression ratios it permitted. Integral to this achievement was success in convincing the airlines that greater speed meant more profits, thus providing a civilian market for high-octane fuels, a market ensured by the surprisingly robust health of the American aviation industry during the Depression.⁸¹ A final factor in the triumph of 100 octane aviation gasoline was America's position as a major producer of crude oil, for the reason that the production of a barrel of 100 octane fuel required many more barrels of crude oil than the production of a barrel of 87 octane gasoline, the standard aviation fuel for the oil-starved Third Reich and Japanese empire.

Meanwhile, to hedge its bets, the Army, understanding that high performance liquid cooled engines offered higher maximum speeds in fighter applications given the state of the art in the mid-1930s, was able to provide the Allison division of General Motors with a modest subsidy to develop its twelve-cylinder V-1710. For reasons already addressed, the V-1710 never achieved its full potential except in the P-38 and then only when turbo supercharged.

In the greater scheme of things, the V-1710 was a minor chord in a great symphony. The major chords were struck by 100-octane aviation gas and the turbo supercharger. Not least among the Army's achievements lay in apprising the Royal Air Force of the benefits of 100 octane gasoline, benefits that perfectly fit the tactical demands that would fall on Fighter Command's Hurricanes and Spitfires in the Battle of Britain. The responsible British authorities saw their opportunity clearly, arranged for the appropriate modifications to their engines, and 100-octane fuel played large in the Battle of Britain. It was to play large in the subsequent successes of the allied air forces in general.

As for the turbo supercharger, the high altitude skies above Western Europe were the critical theater of the air war, and until the P-51's operational debut at the very end of 1943 the only US aircraft capable of engaging in combat there were powered by turbo-supercharged engines. Simply put, without the turbo supercharger, the application of America's aerial might against the allies' most dangerous opponent would have been delayed by at least a year. Good as it was at low and medium altitudes, The F4F was outclassed in service ceiling and high altitude speed by contemporary versions of the Bf 109 and Fw 190. Even the second generation of US Navy fighters that entered service from the late summer of

1943, the Grumman F6F Hellcat and the Vought F4U Corsair, would have been outclassed at high altitudes by later versions of the Bf 109 and Fw 190 and at low altitudes would have fought at little better than a par.⁸² More crucially, the United States would have had no bomber with the service ceiling needed to survive in daylight over Europe. Would the USAAF and American industry have found other avenues to high altitude performance? Perhaps, though it is difficult to see how they could have been deployed quickly or that they would have worked as well.

What lessons can we distill from our exercise? First and most basic, technological competence and strategic vision are essential, but only if applied in conjunction with one another. The Allies won World War II in the air largely because the leaders of the Royal Air Force, the US Army Air Forces and the US Navy's aviation establishment had a clear strategic vision and a good sense of what was feasible in terms of the aircraft performance needed to make their respective visions reality. That their strategic visions were imperfect in important particulars was inevitable. What was important was that they *did* have a vision and that it drove technology in positive directions. Technological cleverness in isolation is not enough, as the *Luftwaffe* and Nazi Germany's aviation industry clearly demonstrated. Indeed, it can be counter-productive.

In the case of World War II, the combination of strategic vision with technological competence was rendered particularly important by the considerable amount of time needed to develop certain critical technologies. One hundred-octane aviation gas and the turbo supercharger are salient examples with British development of high performance aero engines not far behind. The development of high performance engines in the United States is a special case since they were developed for civilian applications, but it only adds to the luster of the Army Air Forces planners that they were able not only to effectively harness a civilian technology to their needs, but advance the civilian technology in the process.

That having been said, it is important to remember that our exercise underlined the considerable advantages accruing to the strategic aggressor. In being able to determine the time and place of their attack, and in obtaining aircraft suitable for their chosen operational methods, the Third Reich and Imperial Japan came closer to success than we commonly admit today or was comfortable then. The fact that it is easier to design for tactical than for strategic advantage—and this applies to technologies other than aircraft—renders ideologically-motivated aggressors all the more dangerous however unbalanced their world views may be. In that there is surely a lesson for today.

And what of aircraft design proper? It was, as I hope I have demonstrated, strategically pivotal, though in the final aggregate not as important as the underlying factors just enumerated. It is worth noting in this respect that much of America's success was attributable to the sheer depth, breadth and vitality of America's aviation industry. In hindsight, it is easy to see that in the aftermath of World War I looking forward to what most competent military professionals saw as an upcoming global conflict, aircraft technology was a critical variable, perhaps *the* critical variable. It was not so apparent at the time and airpower advocates in Great Britain and the United States had a difficult time selling their case. Today, to many aviation technology does not seem to have the same strategic primacy that it did in the interwar period, but we say this with full wisdom of hindsight and are defining aviation technology narrowly in the process. Broadly defined to include information gathering and electronic warfare capabilities across the entire aerospace

spectrum, it surely retains its importance and demands the same clear vision for the future in the aftermath of the Cold War that it did in the aftermath of World War I.

References

¹ In contrast, air power made major contributions to the defeat of the U-boat menace in the Battle of the Atlantic. Note, too, that the destruction of Japanese shipping was powerfully assisted in the final stages by B-29-dropped mines and that carrier aviation made significant contributions as well, notably in sinking eight of the twelve large rail ferries that connected Hokkaido to Honshu and rendering the other four unusable; Richard B. Frank, *Downfall: The End of the Imperial Japanese Empire* (New York: Penguin, 2001), 154-59. That having been said, submarine attacks were well on the way to reducing the size of the Japanese merchant marine below that needed to sustain the war economy before aerial mining or carrier aviation became significant factors.

² Of the examples cited, all except Stalingrad are unequivocal. The *Luftwaffe* controlled the skies above Stalingrad during the early stages of the battle, but Soviet strength in the air grew apace and by the time the Soviets launched their November 1942 counterattack the Red Air Force had achieved rough parity. Although the Red Air Force lacked the strength to drive the *Luftwaffe* from its bases, neither was the *Luftwaffe* able to contain the depredations of marauding Soviet fighters which wrought havoc on German aerial resupply operations with decisive effect. By German admission, over 320 *Luftwaffe* transports were shot down, representing a major loss in trained aircrew that had strategic implications well beyond the battle's outcome; Von Hardesty, *Red Phoenix: The Rise of Soviet Air Power, 1941-1945* (Washington, D.C.: Smithsonian Institution Press, 1991), 91-120, esp. 110.

³ The only daylight actions among these were the 13 December 1939 Battle of the River Plate in which the German pocket battleship *Graf Spee* was defeated by British cruisers *Ajax*, *Achilles* and *Exeter*; the 13 April 1940 Second Battle of Narvik, in which a British destroyer force led by the battleship *Warspite* destroyed a German destroyer flotilla; and the inconclusive engagement on 26 March 1943 between US and Japanese cruiser forces off the Komandorski Islands in the Bering Sea.

⁴ The most important of these were the 8/9 August 1942 Battle of Savo Island, a Japanese tactical victory; the 11 October Battle of Cape Esperance, an American tactical victory; and the two-phase Battle of Guadalcanal, 13 November, (a Japanese tactical victory) and 14/15 November (an American tactical and strategic victory); and, finally, the 30 November Battle of Tassafaronga, a Japanese tactical victory, the last of the war.

⁵ As the Solomons campaign progressed, Allied aerial reconnaissance became progressively more effective and ultimately constituted a major operational advantage. That having been said, particularly in the early stages of the campaign Japanese skill in avoiding or deceiving allied aerial reconnaissance yielded major tactical advantages, most notably in the Battle of Savo Island... where catapult-launched Japanese spotting aircraft rendered useful service by illuminating the American and Australian battle line with parachute flares.

⁶ Geoffrey Bennett, *Naval Battles of World War II* (New York, David McKay, 1975), 161-66.

⁷ Martin Middlebrook, *The Berlin Raids: Bomber Command, Winter 1943-44* (London: Cassell, 1988), 6-9, for a useful overview of objectives and forces committed.

⁸ Middlebrook, *The Berlin Raids*, Appendix 3, Bomber Command Statistics, for British losses.

⁹ See James Campbell, *The Bombing of Nuremberg* (New York: Doubleday, 1974), 142-45. Seven hundred and ninety-five Lancasters and Halifaxes were sent against Nuremberg, of which 94 failed to return, a loss rate of 11.8%. Of the total, fourteen were downed by FLAK and two lost to a midair over the target.

¹⁰ *Ranger*, older and smaller than the rest, was deemed unsuited for fleet operations. *Saratoga* was in dry dock undergoing repair for torpedo damage.

¹¹ This is no doubt due to the British reading public's seemingly inexhaustible appetite for accounts of the Battle of Britain and to the historical bent of the British technical aviation press. Interestingly, however, the best general account of the Battle of Britain in my view, and one of the few air campaign histories to systematically and effectively connect aircraft design to strategic consequences is by a novelist: Len Deighton, *Fighter: The True Story of the Battle of Britain* (London: Jonathan Cape, 1977). T. C. G. James, *The Battle of Britain*, Sebastian Cox, ed. (London: Frank Cass, 2000), the official RAF account written in 1943-44, is the best and most complete historical narrative, but says little about aircraft design and was published only in 2000.

¹² This point is effectively made by attritional data presented in Williamson Murray, *Strategy for Defeat: The Luftwaffe, 1933-1945* (Maxwell Air Force Base, Alabama: Air University Press, January 1983), esp. Table XXX, “German Losses by Theater, January-November 1943,” and Table XXI, “German Fighter Losses, 1943 (Number of Aircraft),” pp. 148-49.

¹³ Service ceiling is the highest altitude at which an aircraft can sustain a rate of climb of 100 feet per minute, John D. Anderson, Jr., *Introduction to Flight*, 2nd ed. (New York: McGraw-Hill, 1985), 285-88. The B-17G had a service ceiling of 35,000 feet and the B-24J a service ceiling of 28,000 feet; William Green, *Famous Bombers of the Second World War* (Garden City, New York: Hanover House, 1959). While these figures apply to individual aircraft, USAAF heavy bombers penetrated in massed formations. Formation flying involves considerable jockeying around and formation performance is dictated by the poorest performing aircraft in the formation. In consequence, actual penetration altitudes were typically in the 25,000-27,000 foot range for B-17s, although occasionally as high as 29,000 feet, and around 22,000-23,000 for B-24s. These figures in note 15, are based on examination of the records of the 2nd Bombardment Division, cited below, a B-24 unit; and the 95th Bombardment Group (Heavy), a B-17 unit, e.g. the records of 95 BG Mission #41, the 14 October 1943 Schweinfurt raid, National Archives II, College Park Maryland, Record Group 18, Stack Area 190, Row 58, Compartments 4-5, Shelves 7-3, Box 333 (henceforth given in the format NAI/RG18/190/58/4-5/7-3/333).

¹⁴ The B-24’s notoriously leak-prone fuel system was a particular problem; structural weakness was a factor as well.

¹⁵ Headquarters 2nd Bombardment Division, “Summary of Mission Number 138” and “Minutes of Critique, Mission 14 October 1943,” NAI/RG18/190/59/16/5-6/2621.

¹⁶ The Bf 109 was designed by Willy Messerschmitt in his capacity as chief designer of the *Bayerische Flugzeugwerke* (Bavarian Aircraft Works), from whence the designation Bf. The name of the company was changed to Messerschmitt AG (*Messerschmitt Aktiengesellschaft*) in July 1938 and designs subsequent to the Bf 110 received the Me prefix; J. R. Smith and Antony Kay, *German Aircraft of the Second World War* (London: Putnam, 1972), 472.

¹⁷ Dénes Bernád, *Heinkel He 112*, Aircraft Number 159 (Carrollton, Texas: Squadron/Signal Publications, 1996), 4-5.

¹⁸ William Green, *Famous Fighters of the Second World War* (London: McDonald, 1957), 16; some 36,000 *Shturmoviks* were produced, note 57, below.

¹⁹ L. J. K. Setright, *The Power to Fly: The Development of the Piston Engine in Aviation* (London, George Allen and Unwin, 1971), 101-102. So efficient was the design of the Merlin’s centrifugal flow compressor that it was incorporated into the Whittle turbojet, progenitor of the Rolls-Royce Nene of the late 1940s. Nenes produced under license in the Soviet Union powered the MiG 15 and later versions powered the MiG 17, still a competitive air-to-air fighter in the 1970s, eloquent testimony to the efficiency of the Merlin’s compressor!

²⁰ The genesis of both the Hurricane and Spitfire lay in a 1930 specification for an eight-gun fighter issued by the Royal Aircraft Establishment (RAE), the section of the Air Ministry responsible for aircraft requirements and specifications. The RAE issued a further specification for a Hawker experimental fighter in October 1934 with no further stipulations. The performance specification that led directly to the Hurricane and Spitfire was issued in April 1935; Colin Sinnott, *The Royal Air Force and Aircraft Design, 1923-1939* (London: Frank Cass, 2001), 77, 86-87. Inasmuch as the RAE’s technical expertise and operational authority was resident in its senior RAF members and worked closely with the Air Staff, I have referred to its specifications as RAF specifications for simplicity.

²¹ T. C. G. James, *The Battle of Britain, RAF Official Histories*, Sebastian Cox, ed. (London: Frank Cass, 2000), 332, 338 and 368, Appendices 2, 5, 14 and 18, addressing Fighter Command sector organization and order of battle on 7 July, 8 August, 7 September and 30 September 1940. Eight Hurricane squadrons were added between 8 August and 7 September, including one Canadian, one Czech and two Polish squadrons.

²² Owen Thetford, *Aircraft of the Royal Air Force, 1918-1957* (London, 1957), 154-58.

²³ Information to the author from John D. Anderson, Smithsonian Institution, spring 2002.

²⁴ Smith and Kay, *German Aircraft*, 486.

²⁵ Victor Bingham, *Major Piston Aero Engines of World War II* (London: Airline Publishing, 1998), 115.

²⁶ The R-1820 was originally designed to burn aviation gasoline with octane ratings in the mid- to high 80s. The Air Corps persuaded Curtiss Wright to produce a version for the Martin B-10 designed to operate at higher compression ratios, exploiting the greater resistance to “knock” provided by 100-octane gasoline. The twin-engine B-10, which entered service in 1932, proved to be substantially faster than existing bombers—and

fighters—demonstrating the value of high octane gas and engines designed for it. A significant problem was the greater cost of high octane gasoline, a problem solved by persuading the airlines that the increased speeds that the new engine-fuel combinations made possible would more than pay for the more costly fuel. A commercial market for high-octane aviation gasoline ensured a ready supply for the military. The Army Air Corps' technical development branch was the driving spirit behind these developments, powerfully assisted by reserve Air Corps Captain James Doolittle acting in his capacity as a Shell Oil Corporation executive.

²⁷ By the late 1930s, all but the smallest aero engines had integral mechanical superchargers to atomize the fuel charge and to provide a modest increase in boost. My reference here is to the provision of additional supercharging to increase power at high altitudes.

²⁸ Daniel D. Whitney, "Getting High in the Sky," *Skyways*, No. 38 (April, 1996), 16-26, for a competent summary of the General Electric turbo supercharger's development.

²⁹ See note 13, above.

³⁰ The B-24 was powered by four turbo supercharged Pratt and Whitney R-1830s. The power output of the nine-cylinder R-1820 and the twin row fourteen-cylinder R-1830 varied slightly from model to model and increased somewhat over the course of the war, but was similar from start to finish. Both were excellent engines. The R-1830 had a smaller external diameter and in a well-designed installation produced less drag; the R-1820 had a better power to weight ratio.

³¹ Ian Hogg and John Weeks, *Military Small Arms of the Twentieth Century* (Chicago, Follette Publishing Company, 1973), 5-72; David R. Mets, *Nonnuclear Aircraft Armament: The Evolution of Aircraft Guns (1912-1945)* (Eglin Air Force Base, Florida: Office of History, Armament Division, Air Force Systems Command, 1987), 60-68.

³² The ballistic coefficient is determined by the relationship between a projectile's mass and its aerodynamic drag and is generally proportional to the diameter squared. Since mass increases with the diameter cubed whereas drag increases with the diameter squared, effective range increases as a function of bore diameter given the same muzzle velocities, as was the case here. In addition, the US .50 caliber round had a "boat-tailed" bullet with exceptional aerodynamic qualities.

³³ *AAF Bombing Accuracy: Continental [and] Overseas, Report No. 1 and Report No. 2* (declassified from SECRET), not further identified as to origin and undated, though exploiting data from January through December 1944, NAI, RG 18, 190/61/24/2-5, Entry 10. Based on analysis of a mass of training and combat data, this study is analytically sound and mathematically sophisticated.

³⁴ *Op. cit. Report No. 2.*

³⁵ Brereton Greenhaus, Stephen J. Harris, William C. Johnson and William G. P. Rawling, *The Official History of the Royal Canadian Air Force*, Vol. III, *The Crucible of War, 1939-1945* (Toronto: University of Toronto Press with the Ministry of Supply and Services Canada, 1994), 754.

³⁶ Colin Sinnott, *Aircraft Design*, 142, 158-9.

³⁷ In fact, the Vulture was based on the earlier Rolls-Royce V-12 Kestrel engine, but with the blocks rebored to yield the same cylinder diameter as the Merlin; Victor Bingham, *Major Piston Aero Engines of World War II* (Shrewsbury, England: Airlife Publishing, Ltd., 1998), 134-35.

³⁸ The principal Axis examples were the German Junkers Jumo 222 and Daimler Benz 604, both twenty-four cylinder X engines; and the DB 606, consisting of two DB 601s mounted side by side and driving a single propeller through a common reduction gear. The DB 606 was the only one of these to achieve operation status, powering the He 177 heavy bomber, but was unreliable and prone to engine fires. The only successful World War II liquid-cooled aero engine with more than twelve cylinders was the twenty-four cylinder Napier Sabre that powered the Hawker Typhoon and Hawker Tempest.

³⁹ Anthony Furse, *Wilfred Freeman: The Genius Behind Allied Survival and Air Supremacy, 1939 to 1945* (Staplehurst, Kent: Spellmount, 2,000), 143. Bingham, *Major Piston Aero Engines*, 136-39.

⁴⁰ Takashi Nishiyama, "Aeronautical Technology for Pilot Safety: Reexamining Deck-landing Aircraft in Great Britain, Japan, and the United States," *Historia Scientiarum*, Vol 13, No. 1 (2003), 13-32, esp. 16.

⁴¹ The empty weight of the A6M2 Zero was less than 4,000 pounds to 6,500 pounds for the Spitfire IX, the most capable version of the Spitfire in operational service in 1943. Both were powered by engines of about 1,300 horsepower. See Pierre Closterman, *Flames in the Sky* (London: Chatto and Windus, 1956), 49-58, for a clinical evaluation by a top-scoring Allied World War II ace of the reasons for the Zero's effectiveness.

⁴² Nishiyama Takashi, *Technology for Flight Safety in Japan: The Case of the Mitsubishi Zero Fighter* (Unpublished Ohio State University MA thesis, July 19, 1995).

⁴³ William Green, *War Planes of the Second World War, Fighters*, Vol. IV (Garden City, New York: Doubleday, 1961), 102-103.

⁴⁴ Ironically, the only exception, and that a partial one, was the Imperial Japanese naval air arm, John B. Lundstrom, *The First Team: Pacific Naval Air Combat from Pearl Harbor to Midway* (Annapolis, Maryland: Naval Institute Press, 1984), 486-89. Japanese Navy fighter pilots were taught off-angle deflection shooting, but were unable to take full advantage of their training in fighter-versus-fighter combat because of poor downward visibility over the nose of the A6M Zero.

⁴⁵ Lundstrom, *The First Team*, 458-68, 477-85, for a comprehensive discussion of US Navy gunnery and tactics.

⁴⁶ In principle, the drag created by aerodynamic interference at the junction of wing and fuselage is minimized by mounting the wing near the mid-section of a fuselage of circular or elliptical cross-section. This, however, required longer landing gear to ensure propeller clearance during takeoff and landing, and longer landing gear entailed greater weight, greater mechanical complexity, or both. Kartveli solved the problem with telescoping main landing gear struts that shortened before folding upward into the wing. To the best of my knowledge, this was the only telescoping landing gear of World War II to be essentially trouble free, a tribute to Republic's second-tier engineering.

⁴⁷ John F. Kries, ed., *Piercing the Fog: Intelligence and Army Air Forces Operations in World War II* (Bolling AFB, Washington, DC: Air Force History and Museums Program, 1996), 190-213.

⁴⁸ The principal RAF electronic target marking aids, GEE (from early 1942) and Oboe (from early 1943), established a bomber's location by reference to ground-based radio transmissions. Their maximum range was thus limited by the curvature of the earth and the Mosquito's greater service ceiling, 39,000 feet to 24,500 feet for the Lancaster, meant that it could receive the guidance signals considerably further from the transmitter, thus extending Bomber Command's reach into Germany; "Electronic navigation systems," I. C. B. Dear and M. R. D. Foot, *The Oxford Companion to World War II* (Oxford and New York: Oxford University Press, 1995).

⁴⁹ Sinnott, *Aircraft Design*, 203-208.

⁵⁰ Thetford, *Aircraft of the Royal Air Force*, 156. I am indebted to Lt Col Robert Ehler, USAF, for pointing out to me the superior performance of the Mosquito PR XIV and its strategic importance.

⁵¹ Thetford, *Aircraft of the Royal Air Force*, 130-31.

⁵² Ironically, the best Axis tactical transport of the war was the Japanese LD2, a DC 3 built under license by Nakajima and Showa as the Imperial Navy's standard land-based transport, R. J. Francillon, *Japanese Aircraft of the Pacific War* (New York: Funk and Wagnalls, 1970), 499-503. Some 485 were produced by Showa and 70 by Nakajima.

⁵³ The designation C-53 was applied to the initial military conversions without the large rear door and provisions for carrying heavy cargo. For convenience and reflecting common usage, I have referred to all military versions as C-47s.

⁵⁴ Thetford, *Aircraft of the Royal Air Force*, 190-91. The payload figure represents a maximum overload and the radius of action is a conservative estimate based on a stated range of 1,500 miles.

⁵⁵ Thetford, *Aircraft of the Royal Air Force*, 190-91; R. E. G. Davis, *TWA: An Airline and Its Aircraft* (McLean, Virginia: Paladwr Press, 2000), 38.

⁵⁶ Stephen L. McFarland and Wesley Phillips Newton, *To Command the Sky: The Battle for Air Superiority over Germany, 1942-1944* (Washington, DC: Smithsonian Institution Press, 1991), 246-47.

⁵⁷ Ray Wagner, *Mustang Designer: Edgar Schmued and the P-51* (Washington, DC: Smithsonian Institution Press, 1990), 26-29.

⁵⁸ Thetford, *Aircraft of the Royal Air Force*, 344.

⁵⁹ Wagner, *Mustang Designer*, 104

⁶⁰ The specification called for a maximum speed of 400 mph at 20,000 feet and stipulated that the aircraft be able to climb to 20,000 feet in six minutes; Le Roy Weber, Jr., "The Lockheed XP-38," *Skyways*, No. 69 (January 2004), 9-17.

⁶¹ A partial exception was the British Westland Whirlwind, the only other twin-engine, single seat fighter to see operational service in World War II. A 1936 design of orthodox configuration, the Whirlwind was powered by two 885 horsepower Rolls Royce V 12 liquid-cooled Peregrine engines and had an impressive armament of four nose-mounted 20 mm cannon. The Whirlwind first flew in October 1938, but development problems with the Peregrine delayed operational deployment until mid-1941. Faster than contemporary single engine fighters at low altitudes, the Whirlwind proved to be an effective low altitude escort and ground attack

fighter, but its operational virtues were not sufficiently compelling to justify large scale production, the more so as it was the only operational aircraft powered by the Peregrine; Green, *Fighters*, Vol. II, 123-25.

⁶² David W. Ostrowski, "Early P-38 Problems," *Skyways*, No. 40 (October 1996), 54-64.

⁶³ The 20th Fighter Group Association, *King's Cliffe*, revised edition (Moore, Pennsylvania: The Sheridan Press, 2004), 112. This account is particularly valuable for documenting the P-38's strengths and weaknesses from the viewpoint of the men who flew and maintained it. The 20th was dispatched to England in late August 1943 and mounted its first operations in November. The P-38 was available in the European theater in significant numbers only from late December.

⁶⁴ Bingham, *Major Piston Aero-Engines*, 166-70.

⁶⁵ Dear and Foot, *Oxford Companion*, "bombers," 143-50, esp. 146; and "fighters," 354-63, esp. 359.

⁶⁶ The first of these were twenty Liberator Is built to British specifications and supplied to the Royal Canadian Air Force for operations from Northern Ireland; Thetford, *Aircraft of the Royal Air Force*, 132-37. These were followed by 139 Liberator IIs from August 1941 and 260 Liberator IIIs, equivalent to a B-24D, from mid-1942; Green, *Famous Bombers*, 85-90; Dear and Foot, *Oxford Companion*, "air gap, mid-Atlantic," 12-13.

⁶⁷ Dear and Foot, *Oxford Companion*, "bombers," 146.

⁶⁸ Walter G. Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore and London: Johns Hopkins University Press, 1990), Ch. 2 "Design and the Growth of Knowledge: The Davis Wing and the Problem of Airfoil Design, 1908-1945), 16-50. The B-24's wing had an aspect ratio of 11.55; that of the B-17 had an aspect ratio of 7.58.

⁶⁹ Green, *Famous Bombers*, 89-90.

⁷⁰ Smith and Kay, *German Aircraft*, 501.

⁷¹ Kenneth P. Werrell, *Blankets of Fire: U.S. Bombers over Japan During World War II* (Washington, DC: Smithsonian Institution Press, 1966), 238, 238 n. 29. A 1945 dollar was worth over twenty times as much as a 2004 dollar.

⁷² *AAF Bombing Accuracy: Continental [and] Overseas, Report No. 1*; see note 29, above.

⁷³ Smith and Kay, *German Aircraft*, 358, 370; Thetford, *Aircraft of the Royal Air Force*, 190-91. The figures for useful load as a percentage of maximum takeoff weight may be a bit high (my sources do not specify what constitutes empty weight), but should be accurately indicative of the difference in efficiency between the two aircraft.

⁷⁴ In principle, remotely controlled turrets could be made that were substantially lighter and produced less drag than their manned equivalents, but this proved to be far more difficult than anticipated. The Luftwaffe, RAF and USAAF all attempted to develop remotely controlled turrets, but only the USAAF succeeded. The first successful such installation was the twin .50 caliber chin turret installed in B-17s from late 1943. The B-29 had the first effective remotely controlled defensive armament system.

⁷⁵ The exceptions include the Yak fighters and early versions of the Hurricane that made significant use of wood and fabric; the Mosquito with its stressed plywood structure; the IL 2 with important structural elements of hardened steel; and the Ju 52 with corrugated aluminum skin.

⁷⁶ Setright, *The Power to Fly*, 110.

⁷⁷ *Ibid.*, 97.

⁷⁸ And in fact, did so in the Hawker Tempest II, a design that entered operational service shortly after the war, powered by a massive four row Bristol Centaurus radial engine; Thetford, *Aircraft of the Royal Air Force*, 308-309. The Tempest II and its naval version, the Sea Fury, were among the fastest and most capable piston engined fighters ever built.

⁷⁹ To be sure, the Sabre was more temperamental than the Merlin, but the main factor behind its limited impact on the war lay in the aerodynamic limitations of the Hawker Typhoon, limited to low altitudes by the its thick wing section. This problem was solved in the Tempest V, the fastest allied piston engine fighter of the war, but the Tempest did not enter squadron service until July of 1944; Thetford, *Aircraft of the Royal Air Force*, 306-307.

⁸⁰ Herschel Smith, *A History of Aircraft Piston Engines* (Manhattan, Kansas: Sunflower University Press, 1981), 70-76, 103-108.

⁸¹ America was becoming a motorized society and demand for gasoline engines and fuel remained strong. During 1930-38, average personal income declined by 25 percent in the United States, but the demand for gasoline declined during only two years during that period, and then by only about five percent. While only a minority of the demand was for aviation fuel, the benefits of higher octane were appreciated for automotive

fuel as well. The maximum octane rating of automobile gasoline increased from 65 to 87 during this period; William David Compton, "Internal-combustion and their Fuel: a Preliminary Exploration of Technological Interplay," *History of Technology*, A. R. Hall and Norman Smith, eds., Vol. 7 (London, 1982), 23-36, esp. 34.

⁸² Eric N. Brown, *Duels in the Sky: World War II and Naval Aircraft in Combat* (Annapolis, Maryland: Naval Institute Press, 1988). Written by a highly experienced Royal Navy test pilot who flew the aircraft about which he writes, some in combat, this work is invaluable. Brown's strategic judgments inspire little confidence, but his tactical assessments are as close to definitive as we will ever get.

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