A WARTIME NECESSITY

The National Advisory Committee for Aeronautics (NACA) and Other National Aeronautical Research Organizations' Efforts at Innovation During World War II

EDITED BY
ALEX M SPENCER

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FOREWORD

Engineering the Air War

Tom D. Crouch

The Second World War began and ended with attacks from the sky. The Japanese first demonstrated their capacity to deploy carrier-based aviation against Shanghai in January 1932. Italy, Germany, and the Soviet Union tested their emerging air arms in Ethiopia and Spain. Luftwaffe strikes against Poland ignited the conflict and cleared the way for the Wehrmacht blitzkrieg that swept through the low countries and France six months later. Japan drew America into the conflict with aerial attacks on Pearl Harbor and other Allied bases in the Pacific and Asia. During the conflict, air power would reshape the very nature of war. Tactical air power revolutionized the ground war. From the Coral Sea to Midway and beyond, great naval engagements were fought entirely from the air. Strategic bombing redefined the notion of a battlefield to include civilians in the enemy's heartland. A global war demanded airfields and air routes stretching around the globe and long-range transport aircraft to make use of them. It ended with two airplanes dropping two weapons to destroy two cities.

The airplane was just 36 years old when the war began in 1939. During those years, technological advances transformed the wood, wire, and fabric machines of the pioneering era into complex, all-metal craft capable of flying as high, as far, and as fast as piston-engine propeller-driven airplanes would ever go. Government research dollars played a critical role in fueling the extraordinary progress of flight technology. Before the First World War, European nations established aeronautical research centers to ensure that they did not fall behind potential rivals. Unfortunately, the United States came late to the game, creating the National Advisory Committee for Aeronautics (NACA) in 1915 and that organization's Langley Memorial Aeronautical Laboratory in Hampton Roads, Virginia, two years later.

Research organizations in Europe and America, working with universities, industry, and the military, played vital roles in aeronautical advances during the years between the wars. They conducted studies in aerodynamics, propulsion, structures, instrumentation, flight equipment, human factors, and the range of other areas required to improve performance and safety in the air. Continued progress in aviation required the development of support systems, including in-flight radio, improved instrumentation, and ground- and air-based systems that opened the way to night and all-weather flying.

With the threat of war looming on the horizon, scientists and engineers sought the means of defending against attacks from the air. At the height of WWII, the night skies over Europe were a web of electronic beams designed to locate approaching aircraft, guide bombers to their targets, help them navigate home again, lead night fighters to enemy bombers, and help those bombers to spot the enemy fighters stalking them. For every measure, there was a countermeasure in a constantly escalating technological competition.

The warring nations adopted very different aerial strategies. German and Soviet air planners emphasized aircraft that would support ground units, conduct bombing missions against medium-range objectives, protect their airspace, and prevent enemy bombers from reaching their targets. The American and Japanese navies, faced with conducting a war across the broad Pacific, focused on developing aircraft carriers, carrier-borne aircraft, and equipment and procedures to fight a new kind of naval war. While seeking to match the Axis in terms of fighters, transports, and ground-attack aircraft, the United States and Great Britain invested heavily in four-engine bombers capable of striking industrial targets and reducing entire cities to ashes.

National research and development strategies differed, as well. As the war began to turn against them, both Germany and Japan developed advanced aerial weapons with which they hoped to stave off total defeat. Japan introduced innovative night fighters, experimented with jet-powered aircraft, and built the rocket-propelled Yokosuka MXY-7 Ōka, designed to conduct high-speed suicide attacks on the American fleet.

German research in high-speed aerodynamics and advanced propulsion systems began before the war. By 1944, with Nazi armies in retreat on every front and British and American bombers conducting devastating around-the-clock attacks on the cities of the Reich, the Luftwaffe introduced the first operational turbojet-powered fighters and medium bombers, the Me 262, He 162, and Arado 234, as well as the Me 163, the first rocket-propelled interceptor. In addition, special research groups produced the V-1, an effective pulsejet-powered terror weapon, and the V-2, the world's first ballistic missile. The most advanced aerial weapons of the war, these technological marvels were uniformly bad investments, entering combat too late and in too few numbers to have any effect on the outcome of the war. Nevertheless, the ultimate result of the substantial German investment in advanced technology was to provide their enemies, the victorious Allied nations, with a foundation for a postwar leap forward in aerospace science and technology.

Since the 1920s, the NACA had established a tradition of providing basic technical information to support aircraft designers and manufacturers. In 1933, the NACA issued detailed descriptions of 78 airfoils, listing their geometric properties and performance. It served as an encyclopedia of airfoils from which American and foreign engineers could select shapes that met their needs. Both Allied and Axis aircraft flew into battle with derivatives of NACA airfoils. Drag reduction was another special area of research, from the introduction of the NACA cowling in 1927 to the development of efficient laminar flow wing designs and wind tunnel studies of full-scale aircraft.

By 1941, the NACA was operating two new centers, a facility at Moffett Field, California, which focused on aircraft structures, and another in Cleveland, Ohio, which would take the lead in propulsion research. As the essays in this volume demonstrate, the wartime NACA prioritized finding solutions to the problems facing wartime industry and the military services. Rather than pushing toward the distant future, the leaders of the organization worked to improve the performance of existing aircraft and those coming into service that would see the war to a successful conclusion. They sought to increase propeller efficiency, reduce drag, and improve performance through wind tunnel studies and flight testing of instrumented aircraft. Specific research projects addressed immediate problems, ranging from developing de-icing systems to improving the cooling airflow within the tight confines of the cowlings housing the complex 18-cylinder R-3350 engines powering the B-29 Superfortress.

Historians have taken the wartime NACA to task for its failure to recognize the importance of turbojet engine technology, pioneered in Great Britain and Germany, which would transform postwar aviation. Layne Karafantis and Roger Launius consider this issue in their contributions to this volume. That lapse was offset to a degree by fundamental studies of the problems of compressibility in high-speed flight. The organization addressed aerodynamic problems that plagued specific aircraft approaching transonic speeds, as John Anderson explains. In addition, NACA engineers, partnering with researchers in industry, the Army Air Forces, and the Navy Bureau of Aeronautics participated in initial design studies for a series of postwar high-speed experimental aircraft that would pave the way for the next-generation military and commercial airplanes.

The NACA's postwar role in operating experimental piloted and robotic aircraft marked a new and final era in the history of the organization. While the full range of ground-based research would continue, the NACA was now in the business of developing and testing the world's most advanced research aircraft. With the coming of the Space Age, this experience eased the transition to the National Aeronautics and Space Administration, which would partner with industry to design, build, and fly spacecraft that carried human beings into space and send robot explorers to the planets and beyond. In war and peace, the NACA had served the nation well.

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INTRODUCTION

Alex M Spencer

The story of Stefan Cavallo illustrates the breadth of the contributions of the National Advisory Committee for Aeronautics (NACA) to the war effort. In April 1942, Cavallo graduated from New York University with a bachelor's degree in aeronautical engineering. Before the war, Cavallo had learned to fly and earned his private pilot's license through the Civilian Pilot Training Program. The Roosevelt administration established this program with the aim of expanding civil aviation by subsidizing the civilian flight schools and student expenses, with a larger goal of expanding the pool of the nation's general aviation or private pilots by over 20,000. The program would also enable the expansion of the United States' military aviation by having a large pool of ready-trained aviation cadets for the both the Army Air Corps and the Navy. Cavallo was just one of thousands of such pilots, and he was scheduled to serve as a pilot with the Army Air Corps. When the war broke out, even though the military was in desperate need of pilots, Cavallo's unique résumé as an aeronautical engineer with pilot training made him even more valuable to the aeronautical research efforts of the NACA. The NACA immediately offered him a position as an engineer in the Flight Section at Langley Field, Virginia. As Cavallo drove from New York to Virginia, he did not know if he would be arrested for circumventing his service obligation to the Army in favor of working for the NACA. Fortunately for Cavallo, working for the NACA was viewed as essential for the American war effort. For his first six months at Langley, he evaluated engineering data from the flight-test program to improve aircraft design. With his previous flying experience, Cavallo transitioned into the NACA's Pilots Office.

For the remainder of the war, Cavallo was one of the agency's principal test pilots. The flight testing at Langley that Cavallo experienced was diverse, and he evaluated a wide range of aircraft types, from the Consolidated PBY-5A flying boat to one of the first American jet aircraft, the Lockheed XP-80. Most of Cavallo's work on these aircraft involved first assessing and then improving their stability and control. In all, he was involved with testing nearly 75 different aircraft. He could explain their problems to NACA personnel and the aircraft manufacturers with the voice of both a pilot and an engineer. The events surrounding Cavallo's wartime service were exceptional. They demonstrate how continued aeronautical research was as critical to the war effort as serving in combat. It was a wartime necessity.

Technological advances witness most of their most rapid developments during wartime. In the realm of aviation, these advances appear to be the most evident. The aircraft that flew at the beginning of World War I (WWI) were barely armed and could not reach speeds of 100 miles per hour (mph). By the end of the war, aircraft manufacturers had designed aircraft with specialized missions, such as air superiority, long-range bombing, and ground attack. Heavily armed with multiple machine guns, aircraft could reach altitudes well above 10,000 feet and fly faster than 125 mph. To many in the United States, it became clear that the improvements made to European aircraft during WWI rapidly outpaced and clearly surpassed American designs. In response, Woodrow Wilson's administration supported legislation to create "an advisory committee for aeronautics to supervise and direct the scientific study of the problems of flight with a view to their practical solution."[1] With this broad mission statement but limited budget, the NACA would produce groundbreaking aeronautical research that took place in the interwar period and during World War II.

There was one dramatic difference in the manner which these advances during WWII took place. During the First World War, improved designs came from an individual engineer or from the staffs of the private aircraft-manufacturing firms. One does not have to look beyond Anthony Fokker's design of the synchronized machine gun and how it revolutionized aerial combat. During the Second World War, improvements to aeronautical designs were institutionalized. All the powers established government-sponsored research laboratories such as the NACA or directed research money to universities. The groundbreaking research represented by the NACA's Technical Reports became one of the first instances of the government's "open sourcing" of technological innovation. Just one example was the airfoil profiles created by the NACA. These airfoil design data were adopted by aircraft engineers around the world and found their way into the wing designs of both the Allied and Axis powers' aircraft. It was not unusual for combatant aircraft flying against one another to be using the identical wing profiles.

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[1] Frank Winter and F. Robert van der Linden, *100 Years of Flight: A Chronicle of Aerospace History, 1903–2003* (Reston, VA: American Institute of Aeronautics & Astronautics, 2003), p. 27.

This volume investigates a broad range of topics associated with aeronautical research and development that took place during WWII, both in this country and with its allies and enemies. It also demonstrates not only how the technological improvements conducted from their research were critical to those on the frontline of combat, but also how wartime expedience and technology required these institutions to adapt to the world crisis.

One aspect of the NACA's research during the interwar years was its efforts to investigate and gather information on aeronautical research conducted by other nations. This aeronautical intelligence provided vital insight into planning against the opposition during the war. Richard Hallion's chapter, "Observation in Context," provides a unique and previously unknown assessment of the important role that both Charles and Anne Lindbergh played in helping the United States gather this intelligence. Their celebrity status in aviation opened many doors that would have been unavailable to others. Many postwar assessments focus on Charles Lindbergh's observations on the capabilities of the newly formed German Luftwaffe. However, as Hallion demonstrates, Lindbergh was given access to critical aeronautical research taking place in Germany, and he passed this crucial information along to the NACA.

Aeronautical research was critical to all of the major powers during the war and was demonstrated by the engineering work that continued throughout the conflict. The chapters by Roger Launius, Juergen Melzer, and F. Robert van der Linden illustrate the wartime developments by focusing on three different national research organizations. They provide insight on how different political ideologies shaped the scope and priorities of these countries' aeronautical research during the war.

Roger Launius, in his chapter, "The NACA and American Aeronautical Research in World War II," summarizes the growth and importance of the NACA during the war. He illustrates how the NACA grew from a small laboratory in coastal Virginia during the interwar period to a massive organization with numerous facilities spread throughout the United States, each with its own specific research mission. He demonstrates not only how critically important the NACA research was for the war effort, but also how important the war was for the evolution and growth of the NACA.

Largely forgotten or unknown in the West are the advances in aeronautical achievements by Japan and the Soviet Union during the war. The chapters by Juergen Melzer and F. Robert van der Linden help to bridge this critical gap and provide an interesting comparison and contrast to the wartime aeronautical research of the NACA. Melzer's chapter, "Japanese Aeronautical Innovation During World War II," highlights the advances of aeronautical design in Japan during the war.

Just as in the United States, Melzer outlines the important connection between the Japanese government researchers, the military and its requirements, and manufactures to advance the country's aviation capabilities. Too often, Japanese aeronautical engineers are accused of copying western designs, but in fact they were in many ways original and a response to their military's needs and philosophy. In addition, he points out how the Japanese continued to push forward with new and innovative aircraft designs even as the pressure from military setbacks began to strangle the Japanese military economy.

Also, often unnoticed were the aviation advances coming out of the Soviet Union. These developments were not intentionally overlooked in the West but were unavailable because of how the Soviets sealed off much of their work to the West. As the thaw in the Cold War took place in the 1980s and 1990s, more information concerning Soviet aeronautical research became available. Robert van der Linden's chapter, "TsAGI During the Great Patriotic War," discusses these important aeronautical innovations that came out of the Soviet Union from their Central Aerohydrodynamic Institute (TsAGI—Tsentral'nyi aeroghidrodinamicheskyi Institut), formed in 1918 by Nikolay Yegorovich Zhukovsky. Much of their work was driven by the demands of the powerful centralized government.

World War II widened society's traditional roles relating to both race and gender. The demand for labor in every aspect of the wartime economy meant that everyone was essential to making the national war machine operate. Emily Gibson's chapter, "Essential, Not Supportive," looks beyond the traditional examination of the Rosie the Riveter role or women who filled a vital labor shortage in the country's aircraft assembly lines. Gibson highlights and provides an analysis of the important work of women as aeronautical engineers at the NACA and Beech Aircraft Company. These engineers provided a critical but unnoticed contribution to the United States' aeronautical research and development during the war.

Following these chapters, *A Wartime Necessity* includes three chapters that provide specific case studies of critical wartime research that illustrate how the NACA improved aeronautical designs and ultimately improved the performance of American aircraft during the war.

In a little-known area of aeronautical innovation, Jeremy Kinney's chapter, "Blades for Victory," examines the work of all of the war's major powers and how each of them approached propeller design. World War II was the apex of propeller-driven aircraft, and propeller innovation was critical to the overall performance of the aircraft that fought in the war. The designs and engineering of these propellers was just as critical as the advance in airframe and powerplant design and were a vital component to an aircraft's combat capability.

For the United States, the NACA proved vital to the American war effort in the advances of aeronautical research. Robert van der Linden's chapter, "The NACA Drag Reduction Program," looks at the important and innovative work that took place at the Langley Aeronautical Laboratory in Hampton, Virginia. Specifically, he highlights the work that took place within its full-scale wind tunnel. Here, NACA engineers came to the assistance of the American aircraft manufacturers by finding "solutions to immediate problems" and "extract[ing] the maximum performance possible from these designs." To accomplish these goals, the laboratory's engineers improved these basic designs through detailed drag reduction. In every case, these engineers made good designs even better.

John Anderson's chapter, "The Tuck-Under Problem," looks at the specific work of the NACA on the performance of the Lockheed P-38 Lightning. This aircraft entered the realms of speed performance not previously experienced. At these higher speeds, the airframe began to experience the adverse effects of aerodynamic compressibility. Anderson examines how the NACA discovered and corrected the problem that could have killed hundreds of American pilots who were unaware of this hazard.

The rigors of war bring unanticipated consequences when the realities of combat occur. Often the strategy or technology must change to accommodate the operational realities of the battlefield. William Trimble's chapter, "The Evolution of the U.S. Navy's Fast Carrier Task Force in World War II," examines how the United States Navy transitioned to focus its strike capabilities through aviation rather than the heavy gun of the surface battleships and cruisers. As the aircraft carrier replaced the battleship as the primary element of the fleet, this required the transition to fast strike fleets. The Navy had to adjust its mobile supply structure to accommodate this new operational reality.

Breanna Lohman's work, "Resighting the Norden Bombsight," focuses on the Norden Bombsight as a critical wartime component for the American strategic bombing strategy. During the interwar period, the U.S. Army Air Corps focused on the concept of precision aerial bombing. Lohman demonstrates how the rigors of combat brought this strategic concept into question because the bombsight performance did not meet expectations.

During the war, the NACA provided critical research to improve the performance of the county's aircraft. The organization saw unprecedented expansion to provide this service. What would the role of the NACA be in the postwar world? Layne Karafantis's "What About Aeronautics?" addresses how this organization transitioned itself from a wartime to peacetime research organization and how the agency would continue to make itself relevant to the country's aeronautical industry in a time when the space race came to dominate the agency's principal focus in the new Cold War.

Overall, with premonitions of and then the actual onset of WWII, the NACA adapted and contributed to the war effort in numerous significant ways. As Alex Roland has noted, "For the NACA, World War II began in 1937 with the discovery of the aeronautical research being conducted in Germany.... By the time Germany invaded Poland in 1939, the NACA was on a self-imposed war footing."[2] The NACA dramatically "scaled up" its staff approximately 12-fold by expanding from 500 employees in 1939 to more than 6,000 in 1945.[3] While fundamental research was at the NACA's core, mobilization for World War II meant a shift toward applied research and development, as well as much tighter Government-industry cooperation.[4]

During the war, the NACA took over testing of virtually all military aircraft models, whereas previously the military services had done this themselves. While its signature Technical Reports and Technical Notes had been publicly available before the war, the vast majority of these publications issued during the war were classified,[5] making it more difficult for wartime enemies to assess what technical innovations the NACA was developing and how much progress it was making.

Beyond its specific accomplishments in areas such as strategic bombing, carrier aviation, and propellers, the NACA's testing of a wide variety of new military aircraft in a relatively short period of time and its ability to pivot beyond fundamental research to partner with industry were invaluable to the war effort. Airplane designers on all sides relied on the NACA's innovations, often either adapting or reverse-engineering aviation technologies.

Despite its sterling record of accomplishment, relatively few scholars have examined the NACA's history and, specifically, its contributions to the World War II effort. Hopefully, the case studies examined in this volume will stimulate readers to do further research amongst dozens of specific subjects, such as the design and testing of individual aircraft, powerplants, electronics, aerodynamic surfaces, and so forth, that deserve additional research and consideration by scholars of the NACA.

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[2] Alex Roland, *Model Research: The National Advisory Committee for Aeronautics, 1915–1958* (Washington, DC: NASA SP-4103, 1985), p. 173.

[3] Robert Ferguson, *NASA's First A: Aeronautics from 1958 to 2008* (Washington, DC: NASA SP-2012-4412, 2013), p. 26.

[4] Ferguson, *NASA's First A*, pp. 29–30.

[5] Roland, *Model Research*, pp. 179–180.

CHAPTER 1

Observation in Context

The Interwar Rebuilding of German Aviation, the Lindberghs, and the Challenges of Air Intelligence and Assessment

Richard P. Hallion

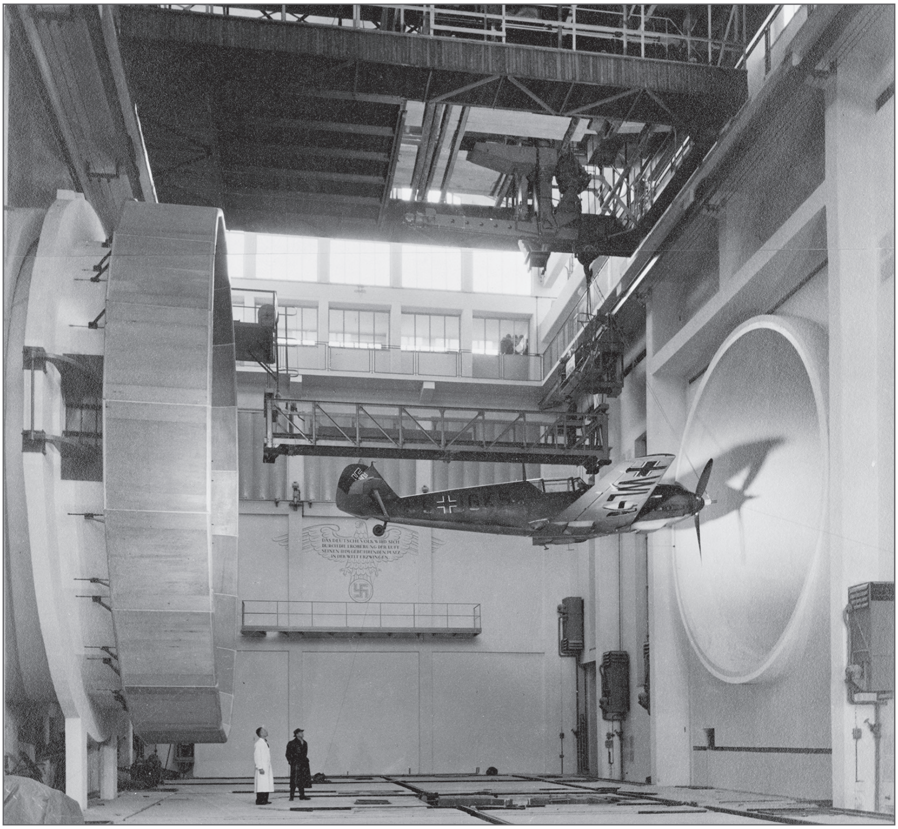

Figure 1: A Messerschmitt Bf-109 in the wind tunnel at the Hermann Göring Aviation Research Institute in Braunschweig, Germany, ca. 1940. Much was made of Charles Lindbergh's visits with Nazi leaders during his trip there in 1938, but he also gained access to this and other German aeronautical research facilities. (Image credit: Library of Congress)

INTRODUCTION: WHAT LINDBERGH—AND OTHERS—SAW AND SAID

Generally, American military intelligence limped along in the interwar years. Most talented officers gravitated toward combat commands, and those that chose intelligence went overseas with little training and few resources. No consensus existed on collection protocols, attachés often just submitting questionnaires to foreign contacts.[1] One notable exception to this general pattern was Major (later Lieutenant Colonel) Truman Smith, a gifted and experienced infantry officer who arrived in Berlin as Military Attaché in August 1935. Smith blended his military intellectual's insight with a combat officer's instincts and quickly realized he faced challenges requiring immediate resolution: his office was receiving contradictory inputs on the state of German aeronautics, and the office's air intelligence effort was at best sporadic. The office focused on preparing an annual report with limited value. (Indeed, the chief of the attaché section of the War Department's intelligence branch had "expressed dissatisfaction with the quality of the air reports of the Berlin office.")[2]

Smith immediately instituted some changes in office procedures to improve the quality of intelligence servicing and accompanied his assistant (Captain Theodore Koenig, a dedicated and hardworking officer, but no aviation expert) on trips to German aeronautical facilities. The trips convinced him that he needed an expert

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[1] See Col. Stanley H. Ford, "Organization and Functions of the Military Intelligence Division, G-2," an address to Course 1927–1928, The Army Industrial College, Washington, DC, 14 October 1927, copy in library of the National Defense University, Washington, DC; Thomas G. Mahnken, *Uncovering Ways of War: U.S. Intelligence and Foreign Military Innovation, 1918–1941* (Ithaca: Cornell University Press, 2002), pp. 18–41; Scott A. Koch, "The Role of U.S. Army Attachés Between the World Wars," *Studies in Intelligence* 38, no. 5 (1995); and Thomas A. Fabyanic and Robert F. Futrell, "Early Intelligence Organization," in *Piercing the Fog: Intelligence and Army Air Forces Operations, in World War II*, ed. John F. Kreis (Washington, DC: Air Force History and Museums Program, Bolling Air Force Base, 1996), pp. 18–20.

[2] Col. Truman Smith, U.S. Army (USA) (ret.), "Air Intelligence Activities, Office of the Military Attaché, American Embassy, Berlin, Germany, August 1935–April 1939, with Special Reference to the Services of Colonel Charles A. Lindbergh, Air Corps (Res.)," (1954–56), p. 13, a privately prepared report in the "Air Intelligence Activities" folder, Truman Smith Collection, Hoover Institution on War, Revolution and Peace, Stanford, CA. This report (hereafter Smith summary) is also reproduced in Robert Hessen, ed., *Berlin Alert: The Memoirs and Reports of Truman Smith* (Stanford, CA: Hoover Institution Press, 1984); the quotation is on p. 84.

aeronautical observer to furnish the information the War Department required. Learning that Charles Lindbergh had visited some French aircraft plants, he invited the famed aviator to Berlin, if the German air leadership and aviator would be receptive. Lindbergh was, writing, "I am particularly interested in various types of low-wing monoplanes; the development of high-altitude flying, including supercharging of both engines and fuselage; and methods of landing in fog.... There is nothing I would enjoy as much as visiting the various air establishments quietly and being able to talk to a few of the Germans who are interested in the various developments."[3] After some adjustment to schedules and final arrangements, Lindbergh and his famous wife, author and aviator Anne Morrow Lindbergh, arrived in Germany in late July 1936, flying their own little Miles Mohawk.

Despite the Lindberghs' desire to visit "quietly," they were instead extensively feted, with Anne Morrow Lindbergh recording incisive portraits of those they met. (She found Hermann Göring to be "an inflated Alcibiades.")[4] It was evident from the Smith-Lindbergh correspondence that both viewed the trip as a means of assessing not Germany's *force structure* and *military posture*, but rather its *technology*, which constituted the visit's thrust. Over the 12-day trip, Lindbergh piloted both a Luft-Hansa Ju 52 trimotor and the Junkers G 38. He visited a fighter wing at Döberitz equipped with the Heinkel He 51 (an obsolescent biplane fighter), the Deutsche Versuchsanstalt für Luft-fahrt (D.V.L.) at Adlershof, and the Heinkel factories at Rostock and Warnemünde. Here Charles and Anne witnessed flying displays of new Heinkel airplanes, including the He 111 and the He 112. (The latter, a new Heinkel fighter, broke up in flight, forcing its pilot, Ernst Udet, to bail out.) He visited famed aircraft designer Willi Messerschmitt and then toured Junkers' Dessau plant, where he inspected the Ju 86 bomber, the Ju 87 dive bomber, the Jumo engine concern, and the ubiquitous Ju 52 trimotor. Then he finally journeyed to the Rhinow soaring center. Every morning, Lindbergh would meet with Smith and his assistant attaché, go over the previous day's visits, and prepare notes for reports to be sent to the War Department. From Smith's standpoint, the Lindbergh trip served his purposes admirably, for it raised the attaché's office's public profile, consequently gaining Smith and his assistant frequent access to the highest levels of the Reichsluftfahrtministerium (R.L.M.) and the German aircraft industry. Overall, on this first visit, Lindbergh judged German aviation vigorous and promising, but also with evident weaknesses. The older He 51 biplane he rightly considered deficient to American practice. The G.38 airliner was large, if otherwise

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3. Charles A. Lindbergh to Maj. Truman Smith, 5 June 1936, in Smith summary, Truman Smith Papers, Hoover Institution on War, Revolution and Peace, Stanford, CA, pp. 25–26.
4. Anne Morrow Lindbergh (AML), *The Flower and the Nettle: Diaries and Letters, 1936–1939* (New York: Harcourt Brace Jovanovich, 1976), p. 85.

unimpressive, in an era when the Douglas DC-2 and the new DC-3 constituted the international design standard. The He 112 he rightly judged as inferior to the latest British fighter, the Vickers-Supermarine Spitfire.[5]

The Lindberghs' trip coincided with a sharp ramping-up of interest in German aeronautics. In 1934, the Chief of Air Staff of the Royal Air Force, Air Chief Marshal Sir Edward Ellington, summarized what was known and anticipated about German aviation—the Luftwaffe would not be unveiled for another year—concluding, "I should not expect them to reach our present standard of efficiency [in] under 10 years."[6] Now, just two years later, things were far less certain. In April 1936, three months before the Lindbergh tour, a British test pilot had likewise visited the Heinkel plant, reporting afterward to the Air Ministry that while Germany "have nothing at the present time," nevertheless "[o]ne would cede, however, that with their aerodynamic knowledge, their keen appreciation for perfectly clean aeroplanes and the fact that all the engine contractors are working hard on new types, that they will have in the very near future, maybe, some of the most modern aeroplanes in the world from the point of view of performance."[7] Al Williams, a former Marine airman, air racing and demonstration pilot, and aeronautical commentator, likewise visited Germany in 1936. He also visited the D.V.L., Döberitz, and Dessau, meeting with Udet and other officials, discussing applications of high technology to advanced structures and propulsion (including the prospect of turbine engines—jets—that had not come up even in Lindbergh's meetings), coming away convinced that "[t]he Germans in 1936 are about five years ahead of England and America in aeronautical research and about eight or nine years ahead of France."[8]

A little over a month after the Lindberghs left Germany, Dr. George Lewis, Director of Aeronautical Research of the National Advisory Committee for Aeronautics (NACA), also arrived in Berlin. In March 1936, a select NACA committee concluded that "[t]he existing aeronautical research facilities in the United States are no longer fully adequate to meet the growing needs of aviation." The committee predicted that European laboratories would, "within a few years, enable European countries to surpass the United States in the technical development of

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[5] Smith summary, pp. 33–50.

[6] Minute, Air Chief Marshal (ACM) Sir Edward Ellington to Sec. State for Air, 9 March 1934, attached to Great Britain, Air Ministry, Air Staff (Intelligence), "Appreciation of the Situation Regarding the Military Aspect of German Aviation," 6 March 1934, p. 3, AIR 40/1999, The National Archives of the United Kingdom (TNA).

[7] Report of Lappin visit to Heinkel Factory, 20 April 1936, p. 4, AIR 40/2101, TNA; see also Wesley Wark, *The Ultimate Enemy* (Ithaca, NY: Cornell University Press, 2010), p. 65.

[8] Major Al Williams, *Airpower* (New York: Coward-McCann, Inc., 1940), pp. 44–70.

aircraft," concluding by "urgently recommending" an increase in NACA appropriations for expansion of its research facilities.[9] Over the next few months, the NACA's European observer, John Jay Ide, had toured nine government, academic, and industrial aviation development centers. His report of "a new large wind tunnel" (a variable-density design) at Göttingen particularly interested Lewis. He crossed over on the Hindenburg, then flew from Frankfurt to Berlin on the G.38, finding it as regressive compared to the DC-2 as had Lindbergh. During his trip, Lewis was given detailed tours of the D.V.L. and Göttingen and had surprisingly frank discussions with Adolf Baeumker of the R.L.M., who admitted that Germany's reinvigoration of its aeronautical research establishment owed much to the example of the NACA at Langley. This was somewhat ironical given that it had been a German research scientist, Max Munk, who had effectively enabled the NACA to achieve the impressive reputation that it possessed. The D.V.L. itself was "completely equipped with every conceivable device and facility," and its conference facilities were "excellently equipped and beautifully designed."[10] After returning to America, Lewis wrote to Reginald Cleveland, aviation editor of the *New York Times*,

> I know only too well that unless something is done, within the next year and a half or two years, the lead in technical development resulting from research will cross the ocean and probably be taken by Germany. Aeronautical research in Germany is considered of such importance that it ranks equally with the problem of national defense.[11]

Even as Lewis was still overseas, two Royal Air Force (RAF) test pilots, Squadron Leader H. V. Rowley and Flight Lieutenant R. L. Atcherley, flew on their own to Germany in a Percival Gull. Despite the "rather skeptical" view of RAF intelligence that they would see anything of "real interest," they met with Baeumker, Udet, Ernst Heinkel, and other dignitaries (including Heinrich Koppenberg, the head of Junkers). They attended the Lilienthal-Gesellschaft's inaugural meeting as Baeumker's guests and made the acquaintance of many American attendees,

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[9] NACA, "Report of Special Committee on Aeronautical Research Facilities" (27 March 1936), pp. 2–3, in Folder "Special Committee on Aeronautical Research Facilities 1936," Numeric Files, box 68, 20-2, record group 255, National Archives and Records Administration (NARA), Archives II, College Park, MD.

[10] G. W. Lewis, "Report on Trip to Germany and Russia, September–October 1936," p. 17, in folder "Lewis folder, July–Dec. 1936," box 182, 38-4, record group 255, NARA Archives II. See also John Jay Ide to NACA, "Visits to Germany," 23 October 1936, Ide Papers, folder 5, box 2, National Air and Space Museum (NASM)–Smithsonian Institution (SI) Archives.

[11] G. W. Lewis to Reginald M. Cleveland, 4 January 1937, Folder "For. Aero Off. German, 1936–1937," Numeric Files, 20-19D, record group 255, NARA, Archives II.

Figure 2: Charles Lindbergh, seated front row left, is posed with the National Advisory Committee for Aeronautics. The committee met at the Ninth Annual Aircraft Engineering Conference held at Langley Field, Virginia, May 26, 1934. During his many travels internationally, Lindbergh was able to pass valuable information back to the NACA about other nations' aeronautical technology and capabilities. (Image credit: National Air and Space Museum, Smithsonian Institution, image NASM 77-3102)

including Arthur Nutt of Curtiss-Wright, Clark Millikan of the California Institute of Technology (Caltech), and Lester Gardner, an aviation editor.[12] They inspected the D.V.L.; witnessed flying exhibitions; discussed tactics with German fighter pilots; and toured Heinkel (flying there in a He 70) and Junkers, where they saw the Ju 87. Atcherley even flew a Ju 86 bomber, something even Lindbergh had not done. Seeing the sophistication of the Heinkel and Junkers plants, they came away wishing that "we had a Koppenberg in England." They also believed that "in one or two years, at its present rate of expansion, the German Air Force will be able to close the ports of England and keep them closed long enough to starve us out." Summarizing their conclusions, Rowley wrote ominously, "The advent of airpower

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[12] Arthur Nutt, the Vice President of Engineering of the Wright Aeronautical Corporation, prepared an excellent examination of comparable European industrial capabilities, especially in Germany; see his "Report of European Trip, October 8 to December 4, 1936" in the Arthur Nutt Papers, folder 3, box 2, NASM-SI Archives. For American participation at the 1936 Lilienthal-Gesellschaft, see *Journal of the Aeronautical Sciences* 4, no. 1 (November 1936): 19–27.

has placed a weapon in their hands by which they can impose the same pressure on England which the British Navy imposed on them in the last war. In an amazingly short time, they have developed an Air Force, which is the most powerful in Europe.... England's only chance of keeping the peace is to balance against this force an Air Force of comparable strength.... [O]ur only hope of peace is to prepare for war."[13] This "most dismaying report" swiftly reached the desk of Winston Churchill, then stewing out of power and rightly worried about Germany's growing air strength. He wasted no time using it to savage the Baldwin government's failure to support the long-planned but never-executed expansion of the Royal Air Force and Britain's defense needs more generally. Speaking in the House of Commons on 11 November 1936, he excoriated the drift of British policy, "staggered" at "the dangers that have so swiftly come upon us."[14]

Lindbergh returned to Germany in 1937, by which time Smith had a new assistant, Major Albert Vanaman, an officer knowledgeable in aircraft production. Smith and Lindbergh had an understanding that the aviator would return to Germany at some point. Thus both were pleased when, in September, the R.L.M. informed the attaché that Reichsmarschall Göring wanted Lindbergh to attend the second Lilienthal-Gesellschaft Congress, scheduled for mid-October. Lindbergh kept a longhand record of his trip. While it is incomplete, when combined with Smith's recollections and Anne Morrow Lindbergh's diary, a reasonably complete itinerary of the trip can be assembled. The Lindberghs flew from Reading, England, to Frankfurt, Germany, on 10 October 1937, arriving in Munich the next day. Officers friendly with an anti-Nazi nobleman had arranged for the Lindberghs to stay with his family as a means of gaining him some measure of security against future Nazi harassment (the ploy subsequently worked). Lindbergh was heavily involved with the conference, which included several technical presentations on the state of German aeronautical development. In addition, he maintained a busy schedule away from the conference.[15]

On 17 October, he and Udet flew to Rechlin, the newest and most comprehensive of all German flight-testing centers. Once there, Lindbergh witnessed various flying demonstrations and inspected a variety of new German aircraft, considerably more advanced than those he had seen just a year before: the Heinkel He 111

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[13] Sqdn. Ldr. H. V. Rowley and Flt. Lt. R. L. Atcherley, "Report on a Visit to Germany by Squadron Leader H. V. Rowley and Flight Lieutenant R. L. Atcherley, October 6th to October 15th 1936," particularly pp. 34, 36, 41, and 44, AIR 40/2086, TNA.

[14] William Manchester, *The Last Lion—Winston Spencer Churchill: Alone, 1932–1940*, pp. 208–215.

[15] Charles A. Lindbergh, Diary for October 1937, file 207-423, LP, Archives at Yale; see also AML, *Flower and Nettle*, pp. 153–163; Smith summary, passim.

and Dornier Do 17 bombers, the Messerschmitt Bf 109 fighter, the Fieseler Fi 156 liaison airplane, the Junkers Ju 87 dive bomber, and the Henschel Hs 123 ground-attack biplane; all were then fighting in Spain, and later versions of them would play significant roles in the Blitzkrieg of Western Europe to follow. Udet arranged for him to fly the little Fieseler, a remarkably controllable and slow-flying airplane. His comments on performance, bomb capacity, and other characteristics indicate that he generally received accurate information. However, the top speeds quoted for the Dornier and Messerschmitt were higher than each could attain (more so for the bomber than the fighter), suggesting deliberate exaggeration by his hosts.

On the whole, however, Lindbergh learned a great deal of accurate information, including the Luftwaffe's faith in a new long-range twin-engine fighter, the Messerschmitt Bf 110, and in the Ju 87 Stuka dive bomber. Udet openly discussed the Luftwaffe's commitment to dive-bombing (already demonstrated by the Legion Condor in Spain), stressing its "great importance." He was remarkably frank in his comments regarding German acquisition practices and how programs were structured from prototype development through initial operational test and evaluation and full-scale production. As well, Lindbergh journeyed to Bremen to inspect the Focke-Wulf complex, observing (with amazement) the Focke-Achgelis FA 61, an early twin-rotor helicopter, and writing extremely detailed comments about it. He inspected the Daimler-Benz engine factory at Marienfelde and the Henschel factory at Schönefeld (near Berlin). The Henschel plant previously manufactured a small "Schlacht" (ground-attack) biplane, the Hs 123, and produced a licensed production of Dornier's Do 17. Lindbergh computed the number of Dorniers—approximately 60—then undergoing fabrication, given the number of wing spars, subcomponents, and fuselages scattered about the production line.[16]

The Lindberghs left Germany near the end of October, and the aviator submitted a trip report through the London attaché's office, following this with a more detailed German air estimate that he had drafted with Smith before he left Germany. This document, prepared over three days, was written in a style and language guaranteed to secure attention. Though it has been criticized as alarmist, it was remarkably sober in retrospect.[17] The estimate stated, accurately, that "Germany is once more a world power in the air. Her air force and her air industry have emerged from the kindergarten stage. Full manhood will still not be reached for three years." It concluded that the Luftwaffe, as of 1 November 1937, numbered "probably from 175 to 225 squadrons," with "a total of 2,400 planes." These figures

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[16] Lindbergh Diary, file 207-423, LP.

[17] This report, "General Estimate as of November 1, 1937," is reprinted in Smith, "Air Intelligence Activities."

were again accurate: at that time, the Luftwaffe had 213 squadrons and a first-line air strength of approximately 2,356 planes.[18] It projected a potential annual production rate "of probably 6,000 planes." Again, this was accurate: Germany was *already* producing over 5,000 airplanes per year and, in 1939, would top 8,000; by the end of 1944, its workers would be producing nearly 40,000 airplanes annually.[19]

"Behind this industry," Lindbergh, Smith, and Vanaman wrote, "stands a formidable group of air scientists, with large and well-equipped laboratories and test fields, constantly pushing forward the German scientific advance. This advance is remarkable. The fact that the United States still leads in its air science and manufacturing skill must not be allowed to overshadow the German achievements between 1933 and 1937 and above all, not to lead to an underestimate of what Germany will achieve in the future."[20]

Indeed, Germany was far more advanced than even they knew, and while the report concluded that trends indicated "Germany should obtain technical parity with the U.S. by 1942 or 1943," already in the field of high-speed aircraft design it was well ahead: technologists had already bench-tested their first jet engine; had the design of the world's first jet airplane under way; were working assiduously on rocketry and the aerodynamics of high-speed flight; had placed supersonic wind tunnels into service and had more advanced ones in design; were busily studying the problems of flight within the stratosphere; and had already identified, in addition to the jet engine, a critical technological development that would prove essential to exploiting transonic and supersonic velocities, the low-drag sweptback wing.

In March 1938, Nazi Germany occupied Austria, and the American ambassador, William Dodd, was recalled to Washington, replaced by Hugh Wilson. Dodd had little feel for intelligence or appreciation for his various attachés, and Smith thus welcomed the assignment of a new, and hopefully more supportive, ambassador. With Austria swallowed up, Czechoslovakia now fell under the lethal Nazi gaze; thus, interest in German military strength, particularly its air strength, increased significantly. Until late 1938, British predictions of German air strength lagged badly behind the Luftwaffe's reality. In September 1938, the Luftwaffe possessed not quite 3,000 combat aircraft, having added roughly 600 since the time of Lindbergh's visit the previous year.

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18. "General Estimate"; German figures from Wark, *The Ultimate Enemy*, Appendix 3, "The Growth of the *Luftwaffe*, 1933–1939," p. 244.
19. United States Strategic Bombing Survey, *Aircraft Division Industry Report* (Washington: USSBS Aircraft Division, January 1947 ed.), Figure VI-1, "German Airplane Production by Type and by Year."
20. "General Estimate."

At the request of the military air attaché in London, Colonel Raymond Lee, Lindbergh had visited Russia that August, a visit plagued by problems. While he was allowed to see some genuinely front-line combat aircraft such as the Polikarpov I-15 and I-16 fighters and the Tupolev S.B. twin-engine bomber, his hosts employed a heavy-handed off-putting "Soviet life is wonderful" approach, clumsily surrounded him with internal security officers posing (unconvincingly) as aviation experts, and generally rushed him along from one engagement to the next.[21]

At the embassy, American Ambassador Alexander Kirk presented a bleak picture of a nation riven by purges, starvation, and a death toll already exceeding 30 million. In contrast, his military attaché, Army Lieutenant Colonel Philip R. Faymonville, presented such a curiously rosy and insistent counterpoint ("He is evidently bitterly afraid we are going to be prejudiced by Alexander Kirk against the U.S.S.R.," Anne Morrow Lindbergh confided) as to raise questions over his political loyalties, not to mention his common sense and powers of observation.[22] The Lindberghs flew to Czechoslovakia, witnessing an "exceptionally fine" aerial demonstration at Kbely airfield outside Prague that convinced him that Czech airmen were far better than their obsolescent biplane fighters and Russia-purchased SB bombers. Swinging through France, he had dinner with the French air minister, Guy de la Chambre, who presented such a morose picture of French aviation that Lindbergh wrote in his diary, "The French situation is desperate. Impossible to catch up to Germany for years, if at all. France is producing about forty-five or fifty warplanes per month. Germany is building from 500 to 800 per month, according to the best estimates. England is building in the vicinity of seventy per month.... One *is forced* to the conclusion that the German air fleet is stronger than that of all other European countries combined [emphasis added]."[23]

Back in England, Lindbergh prepared a letter to the American ambassador to Great Britain, Joseph P. Kennedy, warning "in essence" that "Germany's strength in military aviation was greater than that of all other European countries combined."

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[21] See Charles A. Lindbergh (CAL), *The Wartime Journals of Charles A. Lindbergh* (New York: Harcourt Brace Jovanovich, Inc., 1970), pp. 48–66; AML, *Flower and Nettle*, pp. 303–343; Grigori A. Tokaev, *Comrade X* (London: The Harvill Press, 1956), p. 117. Tokaev, later a defector who took up a teaching position in aeronautics at the Imperial College of Science and Technology, participated as Lindbergh's technical guide and related the story of NKVD surveillance.

[22] AML, *Flower and Nettle*, p. 310. Faymonville's apologias for Stalinism earned him the nickname "the Red General." For two viewpoints on this enigmatic character, see James S. Herndon and Joseph O. Baylen, "Col. Philip R. Faymonville and the Red Army, 1934–43," *Slavic Review* 34, no. 3 (September 1975): 483–505; John Daniel Langer's "The 'Red General': Philip R. Faymonville and the Soviet Union, 1917–1952," *Prologue: The Journal of the National Archives* 8, no. 4 (winter 1976): 209–221.

[23] CAL, *Wartime Journals*, p. 70.

He added that "the U.S. was the only country in the world capable of competing with Germany in aviation." Kennedy immediately cabled it to Washington.[24] Lindbergh presented the heart of this grim picture when he met with Air Ministry officials on 22–23 September 1938, coincident with Prime Minister Neville Chamberlain's journeying to Germany to meet with Adolf Hitler. The officers he met—most notably Air Marshals Sir John Slessor, the former the Air Staff's Deputy Director of Plans, and Sir Wilfred Freeman, the former Air Member for Development and Production—generally considered his views too pessimistic (particularly on German aircraft production capacity). They also considered him "entirely sympathetic to the British, so much so that one occasionally forgot that one was not speaking to an Englishman."[25] Lindbergh's assessment of both Germany's military dominance in European aviation and its productive capacity was mostly accurate, as its rising force structure and production figures—and its combat performance after August 1939—clearly show.[26]

On 30 September, Hitler and the French, British, and Italian leaders executed the Munich accord, effectively destroying Czechoslovakia less than two decades after its creation. Having consistently underestimated German air strength, the Air Ministry *overshot* its estimate, crediting the Germans with approximately 4,000 in service, almost 500 more than the Luftwaffe would possess a year later when Hitler launched his Blitzkrieg (see table 4).

France was in dismal shape, despite well over a decade of continuous warnings of growing inferiority made by French aviation advocates. The French air ministry failed to act with any decisiveness. Indeed, socialist air minister Pierre Cot consciously distorted French air strength, claiming he had increased France's air power 80 percent when, in fact, new aircraft deliveries had actually declined by 30 percent under his regime.[27]

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[24] Ibid., p. 73.

[25] "Note on Conversation with Colonel Lindbergh on September 22, 1938," in Marshal of the RAF Sir John Slessor, *The Central Blue* (New York: Frederick A. Praeger, 1957), pp. 218–223.

[26] For an excellent analysis of Lindbergh's meetings and the context within which they occurred, see Lt. Col. Raymond H. Fredette, U.S. Air Force (USAF) (ret.), "Lindbergh and Munich: A Myth Revived," *Missouri Historical Society Bulletin* 33, no. 3 (April 1977): 197–202, an essay triggered by Leonard Mosley's inaccurate portrait in *Lindbergh: A Biography* (Garden City: Doubleday & Company, Inc., 1976). I thank Dr. Marie E. Hallion of the University of Maryland University College for locating this essay for me.

[27] Peter Jackson, *France and the Nazi Menace: Intelligence and Policy Making, 1933–1939* (Oxford: Oxford University Press, 2000), pp. 232–233. Predictably, Cot wrote a self-serving defense of his actions; see his "The Defeat of the French Air Force," *Foreign Affairs* 19 (July 1941): 3–18. For the collapse of the French air service, see Lt. Col. Faris R. Kirkland, USAF (ret.), "The French Air Force in 1940: Was It Defeated by the Luftwaffe or by Politics?" *Air University Review* (September–October 1985), passim.

In their September 1937 maneuvers, French leaders had already concluded that "their air force would be unable to defeat the *Luftwaffe* in the air."[28] In the summer of 1938, the French air chief, General Joseph Vuillemin, had visited Germany. Witnessing legitimate disparities between the state of German and French aviation and the carefully crafted propaganda displays emphasizing German might, he returned, convinced Germany could overwhelm France's Armée de l'Air in just two weeks. Vuillemin subsequently submitted a "terrifying report" to government ministers that summarized the dangers.[29] French intelligence authorities, thoroughly alarmed, went far further than their British colleagues, concluding that the Germans already had at least 6,000 aircraft in service, possibly as many as 9,000 including older models, and that it could build 24,000 airplanes per year. Popular air advocates stressed—quite rightly—France's growing air inferiority.[30]

That same month, Germany held its third meeting of the Lilienthal-Gesellschaft, inviting a number of foreign attendees, including Lindbergh. This third trip to Germany coincided with an uproar over his Russian visit, following some blunt remarks he had made over the state of the Soviet Union and its aviation capabilities. While the controversy forever shattered his relations with the Soviet Union (one wonders what became of the various escort officers and handlers who accompanied him), those with the Nazi air establishment were as warm as ever. Luft-Hansa's senior leaders discussed the future of long-range aviation, confessing their belief that the future belonged to the landplane, not the seaplane, something he agreed with (though fellow countryman Igor Sikorsky, there to present a paper on long-range flying boats, dissented). He inspected the Heinkel factory at Oranienburg, estimating He 111 production at "probably in the vicinity of two

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[28] Eugenia C. Kiesling, *Arming Against Hitler: France and the Limits of Military Planning* (Lawrence: University Press of Kansas, 1996), p. 177.

[29] Eugene M. Emme, "German Air Power, 1919–1939" (Ph.D. diss. submitted to the Department of History, State University of Iowa, June 1949), p. 398. Copy in Smithsonian Institution National Air and Space Museum Library. See also Jacques de Launay, *Major Controversies of Contemporary History* (Oxford: Pergamon Press, 2001 ed.), pp. 168–169.

[30] CAL, *Wartime Journals*, p. 83, reporting on a conversation with French air minister Guy de la Chambre and French finance officer Roger Hoppenot. Interestingly, after Munich, French intelligence shifted yet again, stressing German deficiencies almost to the point of complacency. For the various twists and turns of French intelligence projections, see Jackson, *France and the Nazi Menace*, pp. 232–235, 270–275, and 338–342. For popular air activism, see, for example, Philippe Roland, *La Crise de Matériel de l'Aviation Militaire Française* (Paris: Sociéte d'Études et d'Informations Économiques, November 1938), pp. 13–20, 64–72, copy in the "French Military Aviation (General Publications-1931-1939) (Documents)" file, NASM-SI Archives.

per day."[31] (While the Oranienburg plant's production was less than this, overall, indeed, total German production of the He 111 averaged two per day over this period.) Lindbergh and another American test pilot had the opportunity to fly two new German four-engine airliners, the Focke-Wulf FW 200 (soon to gain notoriety as a remarkably successful maritime patrol bomber and ship-killer) and the Junkers Ju 90, a 40-passenger airliner. Both men experienced flight control surface flutter on the Junkers, a potentially hazardous condition that Lindbergh surprisingly minimizes in his diary.[32]

In an agenda filled with social events, two dinners stand out. On the night of 16 October, Lindbergh dined with British Ambassador to Berlin Sir Neville Henderson, who "said he hoped I would do all I could to make the people in England realize the quality and magnitude of the aviation program in Germany." He complained to Lindbergh that "[t]hey did not believe him when he described it."[33]

Remarkable as this was, it was the second that made the news. On 18 October, at a dinner at the American embassy, while Lindbergh was "standing in the back of the room," Reichsmarschall Göring sidled up and abruptly presented him with the Verdienstkreuz der Deutsche Adler, the "Service Cross of the German Eagle," for his work on behalf of world aviation and his 1927 flight.

To Lindbergh and others in the room at the time, it hardly seemed momentous: he had received many foreign awards for the Paris flight and his aviation activities, and none previously from Germany. It would be, of course, a defining event in Lindbergh's life, one his critics would seize upon, some alleging—as historian William Manchester would—that it represented an award for his strong views on the state of German aviation. At the time, it was simply one more event in a highly productive trip. At the Messerschmitt plant at Augsburg, Lindbergh inspected the Bf 109 production line and saw a demonstration of this "most impressive" fighter. He then flew its predecessor, the Bf 108 four-place monoplane, which he pronounced "by far the best plane of its type I have flown," with "excellent control characteristics—very light stick and rudder loading."[34] At Rechlin, he inspected the new Junkers Ju 88, a *schnellbomber* (high-speed bomber), the new twin-engine

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31. CAL, *Wartime Journals*, p. 99; for He 111 production over this time period, see Ferec A. Vajda and Peter Dancey, *German Aircraft Industry and Production, 1933–1945* (Shrewsbury, U.K.: Airlife Publishing Co., 1998), Table 3-D, p. 44.
32. CAL, *Wartime Journals*, pp. 95–100; the other pilot was D. W. "Tommy" Tomlinson; he returned convinced that "Germany is unquestionably the master of Europe today"; see his "Notes on Trip to Germany," a speech presented to the Air Transport Meeting of the Institute of the Aeronautical Sciences, Chicago, 18 November 1938, copy in the "German Air Force (*Luftwaffe*) (1933–1939) (II) (Documents)" file, NASM-SI Archives.
33. CAL, *Wartime Journals*, p. 98.
34. Ibid., p. 192.

Bf 110, and two Bf 109s, then flew the 109, to his evident delight, writing subsequently that "the 109 takes off and lands as easily as it flies." It was a comment on his piloting ability, for the 109 was, by every measure, a difficult and demanding airplane to land smoothly, prone to ground-looping and upset. That he had such a reaction is an indication that Lindbergh indeed possessed a "golden arm" among fighter and test pilots.[35]

Lindbergh left Germany by train at the end of October, recalling years later:

> If any doubt had remained in my mind about Germany's current leadership in military aviation, that visit in October 1938 removed it. The slowness of France, Britain, and other farther-west countries to face the implications of the *Luftwaffe*'s strength was to me astounding and depressing.[36]

It was a judgment with which few, if any, would have quarreled in 1938, whether made by Lindbergh or any other observers who had visited Germany. The following month, he inspected various French factories and the flight-test center at Villacoublay. However, although some of the aircraft he saw appeared "reasonably good," he was "not at all impressed" by the factories or other facilities that he saw, save for a new streamlined experimental bomber developed by the Amiot company.[37] Again, these were hardly judgments unique to the Lone Eagle.

In early November 1938, Lindbergh wrote to the NACA's Dr. Joseph S. Ames, warning that

> Germany's aviation progress is as rapid as ever. Her production facilities are tremendous, and new factories are still being built. Germany is even today as supreme in the air as England is at sea, and I see no sign of any other nation in Europe catching up to her.... Even now, Germany is far ahead of us in military aviation. When she turns her present resources to the field of commercial aviation, we will have a competition such as we have never experienced in the past.[38]

By the end of the month, he had penned another missive, urging that "we should be working on prototypes with top speeds in the vicinity of 500 miles per hour, more if possible... [I]t is even more important for the United States to lead in the

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[35] Ibid., p. 108.

[36] Charles A. Lindbergh, *Autobiography of Values*, ed. William Jovanovich and Judith A. Schiff (New York: Harcourt Brace Jovanovich, 1978), p. 180.

[37] CAL, *Wartime Journals*, pp. 118–119.

[38] CAL to Joseph S. Ames (JSA), 4 November 1938, Folder "Foreign Aero Officials—German, 1938," box 75, 20-19D, record group 255, NARA, Archives II.

quality of design than in quantity of service aircraft...we can gain eventual strength by devoting relatively more time to research and the development of prototypes."[39]

In one of those strange episodes that accompany real desperation, the French now sought his assistance to procure German engines, even airplanes! In December 1938 and January 1939, he returned quietly to Germany to meet with Erhard Milch, Udet, and other senior officials to assist both parties in transacting such a deal, but nothing came of it. France, Germany, and Lindbergh went their own way. He would not return to Germany until the summer of 1945, and then as part of an intelligence team sifting through the rubble of the industry he had so assiduously examined less than a decade before.

In early 1939, Army Air Corps Chief Major General Henry H. "Hap" Arnold requested the NACA's views on new aeronautical research facilities and proposed a new laboratory at Sunnyvale, California. (This would become the NACA Ames Aeronautical Laboratory.) The response—that "[t]he peace of Munich indicates that wars may be won before they are fought.... They may be waged in laboratories and factories without bloodshed.... [And t]o have inferior aircraft is but to invite disaster"—were words with which Lindbergh would have concurred.[40] Arnold, needing expert technical advice, recalled Lindbergh to active duty, and the aviator returned to America in April 1939, meeting with Arnold the next day. Arnold immediately arranged for him to participate in a high-level Air Corps board to assess, as Arnold recalled, "what changes we should make in our own airplane development.... The value of the findings of that Board was inestimable."[41]

By this time, there was a growing military-civilian consensus of American air inferiority. In Paris in mid-June 1939—less than 90 days from war—George Lewis addressed the Aéro-Club de France, somberly pronouncing that Germany led the world in aviation progress and research, and conceding, "They are making greater efforts than America at present."[42] By this time, Lindbergh had thrown himself into the struggle to reshape and refocus American aeronautical research within both the Air Corps and the National Advisory Committee for Aeronautics. Participating in key boards, he testified before Congress and sped around the

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[39] CAL to JSA, 28 November 1938, folder "Foreign Aero Officials—German, 1938," box 75, 20-19D, record group 255, NARA, Archives II.

[40] Response to Gen. Arnold request, 23 February 1939, in folder "War Dept. Air Service Jan-June 1939," box 159, 25-37, record group 255, NARA, Archives II.

[41] General Henry H. Arnold, *Global Mission* (Blue Ridge Summit, PA: TAB Books, 1989 ed.), p. 189.

[42] "Germany Leads in Air Progress Says U.S. Expert," *New York Herald Tribune*, Paris (15 June 1939); "Germany Put at Top in Aviation Research," *New York Times* (15 June 1939).

country in an Air Corps Curtiss P-36 Hawk fighter that Hap Arnold had thoughtfully assigned to him.

Ironically, at this point in his life, Lindbergh believed that he was moving away from aviation! In November 1939, writing why he did not wish to remain any longer as a member of the prestigious NACA, he penned: "Aviation, however, is past the stage which held greatest interest for me—that of pioneering and development.... I realize and have for a long time realized that my mind is turning to a diverging path. Where it will lead I do not yet know."[43] Where it would lead, of course, was to center stage of the isolationist-interventionist battle. In the uproar that followed, Lindbergh's prewar role as an air observer and commentator would be minutely dissected, and, despite his inner feelings, aviation would continue to exert a powerful hold on him—air intelligence in particular—for years to come.

LINDBERGH AND PREWAR AIR INTELLIGENCE: THOUGHTS AND REFLECTIONS

Looking back from the perspective of over 70 years, what can be said of Lindbergh as an air observer of German aeronautical development?

Lindbergh, by any measure, was an uncommonly dedicated and proficient observer of the aeronautical scene. His experience as an airline executive, airman, and member of the NACA (with access to the latest in scientific and technical information); his awareness of industrial practices; his knowledge of the state of military and commercial aeronautics; and his proximity to other leading figures in the aeronautical scene all worked to make him uncommonly influential. Simply stated, he was, as intelligence historian David Kahn has assessed, "the most famous" of all the "private individuals who provided information on Axis countries."[44]

Lindbergh's many critics have seen his fame and image as a mega-celebrity as ensuring that he became, in effect, a "high value" target for Nazi disinformation, for any pronouncement he made regarding German superiority would necessarily have a profound impact. Critics portrayed him as having been dazzled, in effect, by ephemera: cavorting airplanes, smartly tailored uniforms, manufactured hoopla. The more sinister allege darker motives, such as a basic sympathy to the Nazi cause

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[43] CAL, *Journals*, p. 286. Ironically, he would arguably be even more involved in aviation in the future than in the past, though not so dramatically as flying solo across the Atlantic in a fabric-covered monoplane.

[44] David Kahn, "The United States Views Germany and Japan in 1941," in Ernest R. May, ed., *Knowing One's Enemies: Intelligence Assessment Before the Two World Wars* (Princeton: Princeton University Press, 1984), p. 486.

or a desire to do the Hitler regime's bidding by over-portraying its strengths. None of these portrayals stand up under historical scrutiny. All are misleading and inaccurate, and certainly not fair to the complex personality that was Charles Augustus Lindbergh. If anyone was a supreme rationalist, it was Lindbergh. While he had a poet's soul, he had an engineer's focus and a realist's view of the world around him. Delusion was not part of his make-up.

A review of his notes, correspondence, and published memoirs afterward indicate that he was a careful observer and a forthright commentator. He would note his observations and comment upon them, including doubts and misgivings. He carried into the international security arena the same analytic style that one sees in his reports on commercial aviation. Lindbergh's writings indicate that he did far more than simply listen and record what was said to him. He assessed it as well, and his judgments were generally sound. He was not a trained intelligence officer, nor was he a trained strategist or air power doctrinal expert. (He had not, for example, attended the Air Corps Tactical School, or the Command and General Staff College, or the Army War College). Very much a technologist and pilot, he concentrated on the technical and industrial and their implications for overall policy. Thus, it is his technical judgments that are the most valid and useful. However, having said this, his overall views on air strategy and national air survival coincide generally with what occurred. His larger societal views—including his genuine concerns for the future of Western civilization, a civilization he cherished above all—frame much of his commentary.

Lindbergh's role as air intelligence gatherer is muddied by his connection to the significant controversies of the time: the buildup to Munich and war, his long-standing disagreements with the Roosevelt administration on aeronautical matters, and the battle against American intervention in the Second World War culminating in his work for the America First movement.

Commonly implied by critical literature is that Lindbergh made a quick 1938 trip to Germany, was dazzled by German legerdemain, and then strongly influenced French and British policy to abandon Czechoslovakia at the time of Munich. However, such is not the case, of course: Lindbergh's most influential German trip, the third, came *after* the Munich accord, not *before*. Lindbergh witnessed the sequential growth of German aeronautics in 1936 and 1937, including its rebuilding and expansion. He observed the corresponding lack of enthusiasm in the United Kingdom and France; then he went to Russia and Czechoslovakia in 1938 and received information from the French air minister himself that pointed to French inferiority. Whatever views Lindbergh offered to the British and French, they can hardly have had any strongly deterministic influence upon those countries' policies at the time of Munich. Indeed, Lindbergh hardened his attitudes on

German aviation's superiority only *after* Munich, when he returned for the third time to Nazi Germany and had yet another opportunity to place the growth of German military aviation (and the corresponding reaction of the other European nations) into a proper context. Thus, it was the cumulative summation of his observations and not any single "slice in time" visit that led him to the pronouncements he made.

Intelligence is a cumulative process that is dependent upon the mutually reinforcing collection of individual bits of data. In this regard, it is well to remember that Lindbergh was far from alone in his judgments of German superiority. Other notable aviation figures, whether airmen, military officials, or technologists, had reached many similar conclusions. Those conclusions, taken together, formed the intelligence picture that emerged of German air strength and capabilities. Indeed, for the British, the Rowley-Atcherley visit constituted an essential indication of Germany's rising power and potential threat. For the United States, the many visits by leading industrial figures, research scientists, and notable airmen—individuals such as John Jay Ide, George Lewis, Arthur Nutt, Clark Millikan, Al Williams, Eddie Rickenbacker, Tommy Tomlinson, and others—all resonated with, and buttressed, what Lindbergh, more memorably than them, put into print and pronouncement.

The undoubted—and deserved—shame of France and Britain for having to back down at the time of Munich reflects not upon the estimates of German strength, but upon the very real disastrous states of their societies and how those charged with responsibility for safeguarding national security had failed to do so. France never did possess the will to fight and win, despite some whistling-by-the-graveyard bluster on the eve of the Second World War. That the German military itself was unready for a general war and achieved its victory at Munich through intimidation is beside the point. Among those three nations, undoubtedly Germany was, in its ability to project Continental power, more substantial than the rest. It had the morale; it had the doctrine; it had the better training; it had an appropriate (and growing) force structure. Could Germany have subjugated Britain from the air in 1938? No, certainly not, not any more than it could in 1940 after multiple campaigns and steady losses. With a highly professional military establishment, particularly its air force, Britain had a better reason to feel fairly secure. However, it was hardly the nation it would be a year later, in the late summer of 1939. Could Germany have achieved victory over France? Arguably yes, though not as easily as it did less than two years later.

Put another way, nothing France did after 1938 prevented its defeat in 1940. Years of mismanagement, governmental feuds, failed socialist labor experimentation, interservice rivalries, and doctrinal confusion had already taken too significant a toll. In September 1940, John Ide attended a briefing by Colonel Horace Fuller, the former military attaché at the American embassy in Paris of the previous five years, on the fall of France. Fuller noted that "instead of spending the eight months of grace since war was declared in intensive training of French troops, 90% of the effort of the higher officers appeared to be spent in efforts to entertain the troops."[45] A country exhibiting such behavior cannot save itself, nor can others save it.

Lindbergh was, of course, not a perfect air observer or intelligence collector: no one is. For example, he missed the significant silence of German technologists on the subject of rocketry, even though he had worked closely with Robert Goddard, thus missing that Germany was making a heavy investment in this new field. He did not understand grand strategy and the formulation of integrated joint-and-combined military policy. He had no insight or comprehension into the rivalries and conflicts tearing at the Luftwaffe, its acquisition system, and the German scientific and technology research and development community. He tended to see air power as too much a "stand-alone" quantity, unconnected from other forms of military power projection. After January 1939, he could not speak with the same authority he possessed in 1936–38, for intelligence is cumulative, finite, and perishable. Thus, except for those of the United States, he missed the firsthand knowledge of internationally evolving air power force structure and capabilities, particularly Britain's, as the RAF and British aircraft industry rapidly transformed over 1939 and 1940. Nevertheless, even granting all of these, in all "big picture" aspects, he was remarkably accurate and prescient.

Certainly, others missed much as well, both large and small matters. Lindbergh's reportage of Udet's emphasis upon ground attack and dive-bombing and its implications against surface targets on land and sea were missed by higher military intelligence. (They even missed the significance of actual German combat experience in Spain.) The devastating effectiveness of German ground attack and dive-bombing in the Blitzkrieg brought it to the fore. For all his skill as a research administrator, George Lewis missed completely the revelation that Germany was building a major new aeronautical research establishment at Braunschweig, which effectively remained hidden from the Allies until discovered by intelligence teams after the Nazi collapse. Eastman Jacobs missed the swept wing's significance (to be fair, so did virtually everyone else) even though it was presented in an open forum at the Volta Conference in 1935. The two enthusiastic Britons, Rowley and Atcherley, missed how dismissively German fighter pilots treated the RAF tactical notion of employing fighters in a three-aircraft "Vic." They failed to appreciate that German

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45. Ide to NACA Headquarters, Wartime Report 4, "Talk by Military Attaché, American Embassy, Paris," 26 September 1940, p. 1, Ide Papers, folder 5, box 6, NASM-SI Archives.

fighter tactics were rapidly evolving to match aircraft flight speeds. The Germans created the more fluid "finger four" formation emphasizing the pairing of a wingman and leader that the Luftwaffe would use to such devastating effect in the Blitzkrieg (which would subsequently be emulated by the British and Americans).

In remembering Lindbergh as an air intelligence collector, it is only necessary to look at what he said and what occurred. He said Germany was more advanced than other nations in the science and technology of flight. He said it would sweep to victory in any European war; in this, he was correct save only for the important exception of the United Kingdom. In September 1939, Poland fell in less than a month, and Scandinavia (excepting neutral Sweden and ignored Finland, left by Hitler to be invaded and partially overrun later that year by Stalin) and Continental Western Europe (excepting neutral Switzerland and fellow dictatorships Spain and Portugal), fell from April 1940 through June 1940.

Visiting the French front late in May 1940, foreign correspondent William L. Shirer wrote, "You have to see the German army in action to believe it," adding:

> It has absolute air superiority. It seems incredible, but at the front I did not see a single Allied plane during the daytime. *Stuka* dive bombers are softening the Allied defense positions, making them ripe for an easy attack. Also, they're wrecking Allied communications in the rear, bombing roads filled with trucks, tanks, and guns, wiping out strategic railroad stations and junctions. Furthermore, reconnaissance planes are giving the German command a perfect picture of what is going on.[46]

All this was predicted by Lindbergh. That Britain saved itself was, arguably, in no small measure due to the alarm and warnings he helped raise. This stimulated a near-too-late re-arming and re-equipping of the Royal Air Force. (Even so, to John Slessor, "those lovely summer days of glorious weather were an exhausting nightmare.")[47] Across the Atlantic, the United States reformed and reshaped its military air power, recast and reinvigorated its research and development establishment, and developed foreign study teams to visit Britain and shape the grand Anglo-American air alliance—again mainly due to Lindbergh's reports and air advocacy.

As we know today all too well, intelligence is never—can never be—perfect, and neither are its practitioners. An open mind, keen eye, keen instincts, and keen judgment are critical, as is the willingness to stake a claim, engage in debate, and hold to a position. In all those attributes, Charles Lindbergh excelled. They were at first appearance far different skills from those he had needed to fly a frail

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[46] William L. Shirer, *Berlin Diary: The Journal of a Foreign Correspondent, 1934–1941* (New York: Popular Library, 1961 ed. of 1940 work), p. 281.

[47] Slessor, *The Central Blue*, p. 297.

little airplane across the North Atlantic at the very dawn of transoceanic aviation. Nevertheless, they required the same dedication, the same preparation, the same self-confidence, and even the same courage.

TABLE 1: German Aircraft Production, 1920–41

YEAR	CIVIL AIRCRAFT	MILITARY AIRCRAFT	TOTAL
1920	95	0	95
1921	est. 71	0	est. 71
1922	40	7	47
1923	An estimated 2,283 civil aircraft were built in the 1923 through 1930 time period.	Manufacturers secretly built 247 military aircraft from 1923 through 1930, part of an overall total of 365 manufactured between 1920 and 1933. These consisted of 65 fighters, 93 bombers and torpedo-droppers, and 207 observation and reconnaissance aircraft.	est. 95
1924			248
1925			406
1926			est. 360
1927			301
1928			409
1929			379
1930			332
1931	254	56	310
1932	176	55	231
Weimar Era Total	**2,919 (88.89%)**	**365 (11.11%)**	**3,284 (100%)**
1933	172	196	368
1934	1,128	840	1,968
1935	1,360	1,823	3,183
1936	2,582	2,530	5,112
1937	2,955	2,651	5,606
1938	1,885	3,350	5,235
1939	3,562	4,733	8,295
Prewar Hitler Era Total	**13,644 (45.84%)**	**16,123 (54.16%)**	**29,767 (100%)**
Combined Weimar and Prewar Hitler Era, Civil and Military	**16,563 (50.11%)**	**16,488 (49.89%)**	**33,051 (100%)**
1940	3,723	7,103	10,826
1941	3,694	8,082	11,776

Sources: Compiled from data in Vajda and Dancey, *German Aircraft Industry and Production*, Tables 1-A through 3-G, pp. 9–49; Deist et al., *Germany and the Second World War*, Table II.iii.4, p. 232; Overy, *The Air War*, Table 1, p. 26; Homze, *Arming the Luftwaffe*, Table 9, p. 159; Hooten, *Phoenix Triumphant*, Table 3, p. 54; Murray, *Luftwaffe*, Table I, p. 14; Emme, "German Air Power 1919–1939," Table VI, p. 308; and United States Strategic Bombing Survey, *Aircraft Division Industry Report,* p. 78.

TABLE 2: Nazi Military Service Expenditures with Luftwaffe Portion, 1933–39, in Reichsmarks (R.M.)

YEAR	TOTAL EXPENDITURE (ARMY, NAVY, AIR)	LUFTWAFFE EXPENDITURE	LUFTWAFFE EXPRESSED AS A PERCENTAGE
1933/34	746,000,000	76,000,000	10.2%
1934/35	1,953,000,000	642,000,000	32.9%
1935/36	2,771,000,000	1,036,000,000	37.4%
1936/37	5,821,000,000	2,225,000,000	38.2%
1937/38	8,273,000,000	3,258,000,000	39.4%
1938/39	17,247,000,000	6,026,000,000	34.9%

Source: Extracted from Budraß, *Flugzeugindustrie und Luftrüstung*, Tabelle 15, p. 364.

TABLE 3: Comparative Aircraft Production: Europe, America, and the Soviet Union, 1933–41

	1933	1934	1935	1936	1937	1938	1939	1940	1941
Germany	368	1,968	3,183	5,112	5,606	5,235	8,295	10,826	11,776
Britain	633	652	893	1,830	2,218	2,828	7,940	15,049	20,094
France	1,251	1,152	1,052	1,028	1,092	1,595	3,338	1,765	1,001
Italy	386	328	895	1,768	1,749	1,610	1,750	3,257	3,503
U.S.	1,324	1,615	1,710	3,010	3,773	3,623	5,856	12,804	26,277
USSR	4,115	4,455	2,529	4,270	6,039	7,690	10,342	10,565	15,735

Sources: Overy, *The Air War*, Table 1, p. 26; Vajda and Dancey, *German Aircraft Industry and Production,* pp. 11, 25, 40, 54–55; Ritchie, "Aircraft Production Between the Wars," in Jarrett, *Biplane to Monoplane*, p. 239; Ritchie, *Industry and Air Power*, Tables 1, 10, 41, pp. 9, 90, 235; Chadeau, *De Blériot à Dassault: L'industrie aéronautique en France, 1900–1950*, p. 435; Clouzot post, 26 August 2007, *http://www.comandosupremo.com/forum* (accessed 7 November 2007); C.A.A., *1957 Statistical Handbook*., p. 58; Aircraft Industries Association, *Aviation Facts and Figures, 1953,* Tables 2-3 and 2-6, pp. 22–24; Higham et al., *Russian Aviation,* Tables 6.2, 6.4, pp. 138, 146.

TABLE 4: Luftwaffe Force Structure, 1934–39

YEAR	SQUADRONS	FRONT-LINE COMBAT AIRCRAFT
1934	19	228
1935	48	576
1936	96	1,152
1937	213	2,356
1938	243	2,928
1939	302	3,541

Source: Wesley Wark, *The Ultimate Enemy,* Appendix 3, "The Growth of the *Luftwaffe,* 1933–1939," p. 244.

CHAPTER 2

The NACA and American Aeronautical Research in World War II

Roger D. Launius

Figure 1: The National Advisory Committee for Aeronautics (NACA) Aircraft Engine Research Laboratory, located in Cleveland, Ohio, was established in 1941 and was critical to the NACA's wartime expansion. At the Cleveland Laboratory, NACA engineers improved the performance of reciprocating engines, propellers, fuel additives and mixtures, and de-icing systems. (Image credit: NASA image GRC-1946-C-14736)

INTRODUCTION

In May 1944, John F. Victory, the longtime executive secretary of the National Advisory Committee on Aeronautics, or the "NACA," as it was universally known, sat down at his desk and penned a letter describing his agency's activities to support the war effort. "Never was life more interesting," he told his friend Porter Adams. "Never have I been so busy. I take a keen delight in getting work done, and we are rendering service of truly great value to the war program." Victory promised to keep up the "volume of the work," seeing it through as "its urgency continue[s] to increase."[1]

The first employee hired by the NACA upon its creation in 1915, Victory was a guiding hand for the organization throughout its existence. He retired in 1960, after the NACA had been transformed into a new aerospace research and development (R&D) agency with a broad charter to explore space, the National Aeronautics and Space Administration (NASA). While Victory's comments about wartime NACA efforts must be taken with some skepticism because of his insider boosterism, the organization's executive secretary poignantly expressed the intensity of the agency's work on behalf of the war effort.

To this end, this essay surveys the NACA's role in this defining event of the 20th century. It focuses on the agency's prewar maturation from a sleepy R&D organization tucked away in the federal bureaucracy. The NACA experimented and solved the problems of flight for a clientele that included the military, the aviation industry, and the airlines. The agency evolved into a much larger institution that was more firmly wedded to larger aerospace initiatives after 1945. During this period, a significant transformation took place in the agency; it accommodated the needs of the armed services and contributed to a discussion of postwar approaches toward aeronautical R&D. This essay also reviews some of the most significant aeronautical research problems the NACA dealt with before and during the war, one of those being the debate surrounding the development of jet aircraft. Finally, it examines some of the critical postwar demobilization issues faced by the NACA and the difficulties presented in disentangling itself from the military.

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1. John F. Victory, NACA Executive Secretary, to Porter Adams, 27 May 1944, John F. Victory Papers, Special Collection, United States Air Force Academy Library, Colorado Springs, CO. A much earlier version of this paper appeared as "'Never Was Life More Interesting': The National Advisory Committee for Aeronautics, 1936–1945," *Prologue: Quarterly of the National Archives* 24 (winter 1992): 361–373.

VOICES OF WARNING

In 1936, the NACA was a small, loosely organized, and elitist non-bureaucracy that provided aeronautical research services on an equal basis to all. An exceptionally small headquarters staff in Washington directed by Victory—so small that it could be housed in the corner of the Navy Building—oversaw the political situation and secured funding for research activities. The fact that it was governed by a committee of appointees who served without pay made it one of the most nontraditional organizations in Washington.[2] Moreover, its small Langley Memorial Aeronautical Laboratory, with only 370 employees in 1936, collocated with the Army Air Corps near Hampton, Virginia, conducted pure research, mostly related to aerodynamics. They received advice and support from the headquarters Director of Research, Dr. George W. Lewis, another employee associated with the NACA since its earliest years.[3] Those who remember the agency between the two world wars speak of it in idyllic terms. They developed their own research programs along lines that seemed to them the most productive, handled all test details in-house, and carried out experiments as they believed appropriate. They issued "Technical Notes" partway through many investigations containing interim results and "Technical Reports" with major research conclusions at the end of the effort. No one and no political issue, the old NACA hands recollected, infringed upon their work. Thus, they believed that, partly for this reason, the organization was the premier aeronautical research institution in the world during the early 1930s.[4]

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[2] The NACA was a unique agency of the Federal government throughout the interwar period, but it must be acknowledged that much of Franklin D. Roosevelt's New Deal government was loosely structured. His constant use of ex officio diplomats and representatives is well documented. See Robert Dallek, *Franklin D. Roosevelt and American Foreign Policy, 1932–1945* (New York: Oxford University Press, 1979).

[3] An excellent history of this organization is Alex Roland, *Model Research: The National Advisory Committee for Aeronautics, 1915–1958* (Washington, DC: National Aeronautics and Space Administration, 1985), 2 volumes. See also George W. Gray, *Frontiers of Flight: The Story of NACA Research* (New York: Alfred A. Knopf, 1948); Arthur L. Levine, "United States Aeronautical Research Policy, 1915–1958: A Study of the Major Policy Decisions of the National Advisory Committee for Aeronautics" (Ph.D. diss., Columbia University, 1963); Ira H. Abbott, "A Review and Commentary of a Thesis by Arthur L. Levine Entitled 'United States Aeronautical Research Policy, 1915–1958: A Study of the Major Policy Decisions of the National Advisory Committee for Aeronautics,'" April 1964, HHN-36, NASA Historical Reference Collection, Washington, DC (hereafter "NASA HRC"); Roger E. Bilstein, *Orders of Magnitude: A History of the NACA and NASA, 1915–1990* (Washington, DC: NASA SP-4406, 1989); Michael H. Gorn, *Expanding the Envelope: Flight Research at NACA and NASA* (Lexington: University Press of Kentucky, 2001).

[4] William Phillips, "Recollections of Langley in the Forties," n.d., oral presentation, History Collection, Langley Research Center, VA; oral histories with Paul E. Purser, Walter S. Diehl, and W. Kemble Johnson by Michael D. Keller, all in NASA HRC.

Of course, the NACA veterans have remembered their efforts in somewhat rosy hues, but they were indeed members of a unique organization. It was perhaps a little sleepy until the first part of 1936, when John J. Ide, the NACA's European representative since 1921, fired off an alarming report on the state of aeronautical science on that continent. Ide, the sometime technology expert, sometime intelligence analyst, and sometime expatriate socialite, reported on significantly increased aeronautical research activities in Great Britain, France, Italy, and Germany. He observed that new and quite modern wind tunnels had been built to aid in developing higher-performing aircraft and suggested that the NACA review its equipment to determine if it met contemporary demands.[5] Charles A. Lindbergh, an executive committee member living in seclusion in England, confirmed Ide's report in a May 1936 letter to Committee chairman Dr. Joseph S. Ames.[6] In 1936, Lewis inserted a deft warning to the government in the NACA's annual report, commenting on the arms race in Europe that followed Hitler's coming to power in Germany and suggesting that "increased recognition abroad of the value and of the vital necessity of aeronautical research has led to recent tremendous expansion in research programs and to multiplication of research facilities by other progressive nations. Thus has the foundation been laid for a serious challenge to America's present leadership in the technical development of aircraft."[7]

In part because of these developments and in part because of an invitation from the Deutsche Zeppelin-Reederei, in September–October 1936, George W. Lewis traveled to Europe via the German airship Hindenburg to learn about aeronautical development. While there, he toured with Dr. Adolf Baeumker, the German government's R&D head, several aeronautical facilities in Nazi Germany, and he was both impressed and disquieted by their activities. He learned that Luftwaffe chief and Hitler stalwart Hermann Göring was "intensely interested in research and development."[8] With Göring's support, Baeumker greatly expanded aeronautical R&D, decentralizing it at three major stations: one for research on new aircraft, one for fundamental research without application to specific aircraft designs, and one for the development of new propulsion systems. It was a powerful combination,

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[5] "John Jay Ide, 69, Air Pioneer, Dies," *New York Times* (13 January 1962); NACA Executive Committee Minutes, 3 March 1936, pp. 8–9, record group 255, National Archives and Records Administration, Washington, DC; Gray, *Frontiers of Flight*, pp. 22–23.

[6] Charles A. Lindbergh to Dr. Joseph S. Ames, 20 May 1936; John F. Victory to Charles A. Lindbergh, 18 June 1936, both in NASA HRC.

[7] *Twenty-Second Annual Report of the National Advisory Committee for Aeronautics, 1936* (Washington, DC: Government Printing Office, 1937), p. vii.

[8] George W. Lewis, "Report on Trip to Germany and Russia, September–October, 1936," NASA HRC.

especially when Reichsmarks were flowing to fund accelerated experimentation. Lewis remarked:

> It is apparent in Germany, especially in aviation, that everyone is working under high pressure. The greatest effort is being made to provide an adequate air fleet. Every manufacturer is turning out as many airplanes as possible, and the research and development organizations are working on problems that have an immediate bearing on this production program.[9]

While "the equipment at Langley Field is equal to or better than the equipment in the German research laboratories," Lewis concluded, "the personnel of the German research laboratories is [*sic*] larger in number, and the engineers have had an opportunity of having special training, which has not been afforded to many of our own engineers." To maintain American primacy in aviation, Lewis advised that the nation immediately start the NACA's expansion.[10]

These epistles of warning brought moderate action by the NACA. It started in 1936 with constructing another wind tunnel at Langley and the lengthening of a tank used for seaplane research. It obtained additional funding through a special "Deficiency Appropriation Act" to fund the construction of new facilities. It also, and these were both important and peculiarly bureaucratic decisions, created two committees to review the situation. The first was a Special Committee of Aeronautical Research Facilities with Rear Admiral Ernest J. King as chair. Charged with surveying the country's research needs, the committee quickly responded with a detailed critique of the NACA's capabilities and recommended rapid expansion. This found tangible expression in a significantly increased budget request for 1938, a request adopted in Congress because of Europe's anticipation of war.[11]

The NACA also established a Special Committee on the Relation of NACA to National Defense in Time of War, also known as the Westover Committee because it was chaired by the Chief of the Army Air Corps, Major General Oscar Westover. This select committee began operation on 22 December 1936. More than 18 months passed before it took any action, submitting a report on 19 August 1938 that declared the NACA an essential agency in a time of war to support the Army and Navy's aviation development needs. It also said that the agency's

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[9] Ibid.

[10] Ibid.

[11] "Some Important Facts Regarding Expansion of NACA Research Facilities and War-time Status of NACA," 17 January 1946, NASA HRC; A. Hunter Dupree, *Science in the Federal Government: A History of Policies and Activities to 1940* (Cambridge, MA: Harvard University Press, 1957), p. 363.

activities should be expanded and become an adjunct of the Aeronautical Board. Simultaneously, its workforce should remain mostly civilian and deferrals from a draft be granted on a case-by-case basis. "Such a position," the report stated, "would [essentially] make the NACA part of the Armed Forces."[12]

While the agency would remain independent in a legal sense, this committee allowed that it would be "in a more subordinate position than that which it now enjoys."[13] Most important, the Westover Committee found that aeronautical R&D was being hampered by "the congested bottle neck of Langley Field" and that an additional laboratory was required to meet increasing expansion in response to the perceived foreign threat and to limit the agency's vulnerability to attack.[14] No doubt partly in response to the renewed emphasis on defense issues acknowledged in the April 1939 Military Appropriations Bill, this report was approved by the President as a mobilization plan for the NACA on 29 July 1939 and set the stage for the actions of the organization throughout the early 1940s.[15]

Meantime, a real fear arose about the possibility that the United States was losing its technological edge or at least parity in military aviation because the major European powers were conducting aeronautical R&D on a wartime footing. Lindbergh again expressed his distress at advances in European aeronautics to Joseph Ames in November 1938:

> Germany's aviation progress is as rapid as ever. Her production facilities are tremendous and new factories are still being built. Germany is ever today as supreme in the air as England is at sea, and I see no sign of any other nation in Europe catching up to her. I believe we should accept the fact that Germany will continue to be the leading country in Europe in aviation. She will be the leading country in the world if we do not increase our own rate of development. Even now Germany is far ahead of us in military aviation. When she turns her present resources to the field of commercial aviation, we will have a competition such as we have never experienced in the past.... [T]he present quality of German military planes indicates what we may look forward to in the future, and necessitates our devoting much more effort to our own aviation development if we are to keep pace. To give some idea of the development which is going on there, I think I need only mention the fact that the German engineers are now thinking of speeds in the vicinity of 800 kilometres per hour at

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[12] "Westover Committee Report, 19 Aug. 1938," reprinted in Roland, *Model Research*, vol. 2, p. 676.

[13] Ibid.

[14] *Twenty-Fifth Annual Report of the National Advisory Committee for Aeronautics, 1939* (Washington, DC: Government Printing Office, 1940), p. 38.

[15] NACA Executive Committee Minutes, 15 September 1939, pp. 9–10, NASA HRC.

> critical altitude for service airplanes. Their latest bombers are now flying at more than 500 kilometres per hour. It is really necessary to visit Germany and to see the development at first hand in order to fully realize its magnitude.[16]

Lindbergh continued to harp on these advances in German aeronautics and urge the NACA to redouble efforts to recapture the lead in aeronautical research and development, especially in relation to its need to emphasize aircraft propulsion.[17]

DOING ITS PART FOR THE "ARSENAL OF DEMOCRACY"

As the United States' leaders began to sense the potential of war in Europe during the later 1930s, they immediately recognized the need to strengthen the nation's air arm, which was woefully inadequate. General George C. Marshall recalled that it "consisted of a few partially equipped squadrons serving the continental United States, Panama, Hawaii, and the Philippines; their planes were obsolescent and could hardly have survived a single day of modern aerial combat."[18] Harry Hopkins, President Franklin D. Roosevelt's longtime confidant, commented that "[t]he President was sure that we were going to get into the war and believed that air power would win it."[19]

Because of these inadequacies, in 1934, Congress appropriated $23.3 million for the use of the Army Air Corps, 8.4 percent of all Army appropriations. In 1936, Congress funded the construction of another wind tunnel at the NACA's Langley Aeronautical Laboratory and the lengthening of a tank used for seaplane research. It provided the impetus for additional funding through a special "Deficiency Appropriation Act" to fund the construction of new R&D facilities, all because of the likelihood of war in Europe. In 1938, Roosevelt suggested that the Air Corps

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[16] Lindbergh to Ames, 4 November 1938, NASA HRC. See also Lindbergh to Ames, 23 August 1937, 26 August 1937; Lindbergh to George W. Lewis, 23 September 1937; Victory to Lindbergh, 27 October 1937, all in NASA HRC.

[17] Lindbergh to Ames, 28 November 1938; John J. Ide to NACA, "Visit to Germany, June 1938," 12 August 1938, both in NASA Historical Reference Collection; Clinton Macauley, "Millions for Research—Abroad," NACA publication, October 1938, pp. 22–23.

[18] Gen. George C. Marshall, "For the Common Defense: Biennial Report of the Chief of Staff, July 1, 1943 to June 30, 1945," *The War Reports* (Philadelphia: J.B. Lippincott, 1947), pp. 289–296.

[19] Quoted in Robert E. Sherwood, *Roosevelt and Hopkins: An Intimate History* (New York: Harper and Brothers, 1950 ed.), p. 100.

Figure 2: An aerial view of the NACA's Ames Aeronautical Laboratory ca. 1943. In 1939, the NACA established the Moffett Field laboratory adjacent to the U.S. Navy's lighter-than-air facility. Equipped with new wind tunnels, the facility helped improve the high-speed performance of American fighter aircraft flown during World War II. The laboratory also conducted critical research relating to de-icing of aircraft. The laboratory was named Ames Aeronautical Laboratory for Joseph S. Ames, the former chairman of the NACA, in 1940. (Image credit: NASA image ARC-1943-AAL-4799)

was operating with what could be politely called "antiquated weapons" and advocated increasing its strength to 30,000 airplanes.[20]

Although he had suggested a much higher target, Roosevelt could obtain funding only for an additional 3,000 planes in 1939. In April 1939, when Congress passed the National Defense Act of 1940, it authorized the Army Air Corps to develop and procure 6,000 new airplanes, increase personnel to 3,203 officers and 45,000 enlisted, and spend $300 million. As a result, the Army Air Forces (AAF) received $70.6 million, 15.7 percent of the Army's direct appropriations. This was only the beginning of a massive wartime expansion of the United States Army Air Forces during World War II.[21] (See table 1.)

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[20] Report of the Secretary of War, FY 1938, pp. 26–27, USAF Historical Research Center, Air University, Maxwell Air Force Base, AL; *Congressional Record*, 76th Cong., 1st sess., p. 219.

[21] Wesley Frank Craven and James L. Cate, eds., *The United States Air Force in World War II*, 6 vols. (Chicago, IL: University of Chicago Press, 1948), 1:104, 6:171–173.

Between 1940 and the end of World War II in August 1945, the Army Air Forces received approximately $43.5 billion in air materiel, of which 82.5 percent consisted of aircraft. This represented 37 percent of the total value of all war materiel procured by the War Department and 25 percent of the nation's $185 billion outlay for military procurement of all types during the war.[22] This did not represent the American aviation industry's entire production during the war, however, as it produced a total of 295,959 aircraft for both the American military and allies (shown in table 2).

TABLE 1: Aircraft Deliveries to Army Air Forces, 1940–45

TYPE	1940*	1941	1942	1943	1944	1945	TOTAL
Very Heavy Bombers	0	0	4	91	1,147	2,657	3,899
Heavy Bombers	19	181	2,241	8,695	13,057	3,681	27,874
Medium Bombers	24	326	2,429	3,989	3,636	1,432	11,836
Light Bombers	16	373	1,153	2,247	2,276	1,720	7,785
Fighters	187	1,727	5,213	11,766	18,291	10,591	47,775
Reconnaissance	10	165	195	320	241	285	1,216
Transports	5	133	1,264	5,072	6,430	3,043	15,947
Trainers	948	5,585	11,004	11,246	4,861	825	34,469
Communication/Liaison	0	233	2,945	2,463	1,608	2,020	9,269
Total by Year	1,209	8,723	26,448	45,889	51,547	26,254	160,070

*Last half of year.

Source: Irving B. Holley, Jr., *Buying Aircraft: Materiel Procurement for the Army Air Forces* (Washington, DC: Office of the Chief of Military History, 1964), p. 554.

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[22] Irving B. Holley, Jr., *Buying Aircraft: Materiel Procurement for the Army Air Forces* (Washington, DC: Center for Military History, 1964), p. 556; Patrick Coffey, *American Arsenal: A Century of Waging War* (New York: Oxford University Press, 2014), pp. 55–72; Arthur Herman, *Freedom's Forge: How American Business Produced Victory in World War II* (New York: Random House, 2013), pp. 334–345.

TABLE 2: American Aircraft Production, 1940–45

RECIPIENT	NUMBER OF AIRCRAFT
U.S. AAF	158,880
U.S. Navy	73,711
U.S. Other	3,714
U.K. Commonwealth	38,811
Soviet Union	14,717
China	1,225
Other Foreign	4,901
Total	**295,959**

Source: Irving B. Holley, Jr., *Buying Aircraft: Materiel Procurement for the Army Air Forces* (Washington, DC: Office of the Chief of Military History, 1964), p. 560.

Concomitantly, by the time of the attack on Pearl Harbor, the NACA was willing to give up much of its independence for the good of the war effort. Relations between the NACA and the military had always been amiable, but this was especially the result of wholesale changes on the committee, reorienting it toward acquiescence in military prerogatives. In 1938, Major General Henry H. "Hap" Arnold, Jerome Hunsaker, and Vannevar Bush became members of the main committee. They brought strong and ably expressed pro-military sympathies to the committee, as well as skepticism about some of the NACA's traditional ideas about how to accomplish aeronautical R&D. Near the same time, several members of the committee were replaced with representatives from industry who were intimately involved in the military buildup of the latter 1930s and approached the committee's work with resulting biases.

As the NACA attempted to expand for a potential war, one of the committee's great and recurring problems arose almost to paralyze the effort. The NACA had never been a traditional government agency. It was a committee and suffered from all the problems and benefited from all of such an organization's positive attributes. Most significantly, it had no firm line of authority, and this meant that it was something of a stepchild in the world of U.S. government organizations. It also possessed no unique place in the aeronautical world; it had a function, to be sure, but just what form it might take and for whom the function was performed were open questions. The NACA had fought a series of bureaucratic skirmishes over these issues almost from its inception, but they arose especially in the later 1930s as the nation prepared for possible war.

The committee's mission began to be an issue in the fall of 1938, when Robert A. Millikin, head of the Guggenheim Aeronautical Laboratory, California Institute of Technology (GALCIT), in Pasadena, California, asked the federal government for help in expanding his facility's research capability to keep pace with military research requirements. He asked that the War Department fund the construction of a new wind tunnel at GALCIT for "applied research," dealing "with questions arising in the development and design of a particular machine." Specifically, he thought this type of work would help the aircraft industry, which was becoming more and more a West Coast–based concern and was swamping GALCIT with requests for research into specific aircraft characteristics, most of which were military designs.[23]

This request aroused a long-standing NACA bugaboo. The committee had fought long and hard for its role as a research institution. It had made its reputation based on "fundamental research" not specifically oriented toward an aircraft design. While Millikin conceded the "fundamental research" mission to the NACA, he opened the larger question of just what research the government should fund and, by implication, the committee's role in that research. He also stirred up several members of Congress and leaders of several government agencies to consider these issues anew.[24]

Hap Arnold, who took over following Oscar Westover's death in September 1939 as Chief of the Army Air Corps, advocated dividing aeronautical research into three segments. The NACA had primacy in only one part: basic research on fundamentals of flight. Military laboratories would conduct applied research, and the manufacturers would conduct research for the "application of new aerodynamic theories, principles, and discoveries to the particular problems of military aircraft." "Production research," Arnold thought, should be "conducted in the facilities available at Universities or other private or civilian institutions in the vicinity of the manufacturer concerned." While Arnold believed that the NACA could coordinate some of this research, he wanted to minimize its role.[25]

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[23] Robert A. Millikin to Maj. Gen. H. H. Arnold, Chief of Army Air Corps, 10 December 1938, H. H. Arnold Papers, Library of Congress, Washington, DC; Robert A. Millikin, *The Autobiography of Robert A. Millikin* (London, England: Macdonald and Co., 1951), p. 253.

[24] George W. Lewis to Henry Reid, 2 February 1939; George W. Lewis to Robert A. Millikin, 25 February 1939; George W. Lewis to NACA Chair, "Visit of Major A.J. Lyon," 14 December 1938; Robert A. Millikin to Congressman John Costello, 29 March 1939; Jerome C. Hunsaker to E. E. Wilson, 6 January 1940, all in NASA HRC.

[25] "Maj. Gen. H.H. Arnold to George W. Lewis, 5 January 1939, enclosing 'Discussion of a Proposal to Establish an Aeronautical Laboratory for Applied Research,'" in Roland, *Model Research*, vol. 2, pp. 678–683. See also Edward P. Warner to Royal S. Copeland, 25 May 1938, record group 255, NARA.

The GALCIT proposal, and the consideration that it engendered in Washington, forced the NACA into a defensive posture. The committee had always tried to define its work so that it had a broad primary mission duplicated by no other agency, public or private. Millikin and Arnold and some congressmen struck at an Achilles' heel in the organization and a tender nerve, suggesting that the NACA had a role in aeronautical research only in certain specific "basic" aspects.

NACA officials responded to this perceived challenge to the institution's mission on two fronts. First, they rebutted the insinuation that the NACA primarily conducted "basic research," arguing that the committee was engaged in a spectrum of aeronautical research in concert with other organizations and concentrating whenever appropriate on "basic research." Agency leaders also asserted that theory, basic research, and application might be conducted at any aeronautical R&D organization. Any attempt to categorize and limit particular agencies' involvement in aspects of research was an unnecessary and possibly unfruitful exercise. The NACA might embrace "fundamental research" as its area of special expertise, but it was also intimately involved in other R&D activities.[26]

All of this discussion came together in a unique way. The NACA's true strength since the 1920s had been its basic research in aerodynamics, made possible by several wind tunnels at Langley. It had appropriately focused its research in areas that prompted the best use of its unique resources, particularly the wind tunnels. It had hired or developed leading aerodynamicists to work for the committee.[27] To give GALCIT a government-sponsored wind tunnel was to arm a potential rival with a means of competing directly with the NACA. It also would foster the primacy of GALCIT as the chief supplier of research services to the West Coast aircraft industry.[28] The NACA's leadership was certainly not interested in doing that, but it could not say so directly and searched for another reason to kill the proposal. Even so, many suspected that the sound heard from the NACA about the GALCIT proposal was more like a rice bowl breaking than an honest appraisal. Congressman Carl Hinshaw of Los Angeles remarked:

> There seems to be a certain feeling on the part of the NACA, which I can hardly describe, but the best way to describe it is that they would like to retain a

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[26] "Memorandum, John F. Victory to Dr. Lewis, 'General Arnold's Letter of January 5, 1939, re basic research, applied research, and production research,' 9 January 1939," in Roland, *Model Research*, vol. 2, pp. 683–684.

[27] On the Langley tunnels, see James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917–1958* (Washington, DC: NASA SP-2305, 1987), pp. 441–478.

[28] The NACA already had strained relations with GALCIT and good ones with industry. Allowing this proposal to go forward would have exacerbated that situation. See Charles A. Lindbergh to Jerome C. Hunsaker, 4 August 1939, NASA HRC.

> concentration of research facilities entirely within the NACA. They do not seem inclined to favor allowing these facilities to be spread out among the several qualified educational institutions. I do not just know whether it is the old question of professional jealousy or the old question of expanding bureaucracy or some other queer incomprehensible angle.[29]

Jerome C. Hunsaker, the Massachusetts Institute of Technology (MIT) professor who was an NACA member and became its chairman in 1941, offered the conclusion that the aircraft industry indigenous to southern California wanted a wind tunnel but was not willing to build one itself. He remarked in private: “If S. California industry wants more wind tunnel facilities, let them provide them themselves.”[30]

These political machinations aside, the means for the NACA to defeat the GALCIT proposal without looking like an organization of bureaucratic infighters was readily at hand. It did not take agency officials long to employ it. On 19 August 1938, the NACA had empowered another committee to study the feasibility of developing a second research center. This Special Committee on Future Research Facilities, chaired by Rear Admiral Arthur B. Cook, then chief of the Navy’s Bureau of Aeronautics, came forward with a recommendation on 30 December 1938 to construct a new NACA facility adjacent to the Moffett Field naval air station at Sunnyvale, California. Ensconced near the West Coast aircraft industry, the new research site would be able to provide the kind of assistance to industry demand in a potential wartime environment. It was also a preemptive strike against GALCIT. Why should the War Department fund the GALCIT proposal when the NACA had a facility that could provide the same research capability? John Victory wrote to a friend about this move, leaving out a discussion of the bureaucratic battle that had in part prompted the decision. “So whatever pride we may take in our present research effort,” he wrote,

> we must realize that Germany has laid well a foundation for enduring supremacy in technical development. Our plan for a second major research station at Sunnyvale was arrived at after months of sober reflection on the responsibilities facing us. We must look not only at the present, but at the situation that will exist three years from now, ten years from now. The present German advantage will have

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[29] *Congressional Record*, 77th Cong., 1st sess., vol. 87, pt. 1, 1941, p. 416.

[30] Jerome C. Hunsaker to E. E. Wilson, United Aircraft Corp., 6 January 1940, Jerome C. Hunsaker Papers, National Air and Space Museum, Smithsonian Institution, Washington, DC.

> cumulative results with the passing of time unless America takes adequate measures to strengthen the research foundations for its air development.[31]

Although it took some swift action on the part of the NACA to win congressional approval, because of Washington's crisis environment during the summer of 1939, it received permission to build the Sunnyvale laboratory. It did so immediately, and the new NACA facility opened the following year.[32]

At the same time that the NACA was fighting a rearguard action against GALCIT and potential encroachments into its R&D prerogatives, Charles Lindbergh was asked to head another NACA committee on research facilities. He took the opportunity to hammer on a particular area of concern that he had registered many times before, propulsion research. In a report sent to the NACA on 19 October 1939, Lindbergh "urgently recommend[ed] that an engine research laboratory be constructed at the earliest possible date, in a location easily accessible to the aircraft-engine industry." Quickly agreed to by the committee, this proposal prompted a site selection committee to begin meeting under the leadership of Vannevar Bush. In late 1940, it selected Cleveland, near the northeastern-based engine industry, as the place for the new laboratory. The NACA had little trouble obtaining the new facility's funding—although considerable regional politics and industrial priorities entered into the episode—and in 1941, construction began.[33]

With these issues resolved, the NACA pursued a research agenda during the war, not unlike what had been the case earlier, but with national security as a primary focus.

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[31] John F. Victory to Russell Owen, 16 February 1939, record group 255, NARA.

[32] This laboratory was eventually named for Joseph S. Ames, longtime member of the NACA. On the facility's history, see Elizabeth A. Muenger, *Searching the Horizon: A History of Ames Research Center, 1940–1976* (Washington, DC: NASA SP-4304, 1985), and Glenn E. Bugos, *Atmosphere of Freedom: Sixty Years at NASA Ames Research Center* (Washington, DC: NASA SP-2000-4314, 2000). See also "Statement by Dr. Joseph S. Ames, Chairman, National Advisory Committee for Aeronautics," 31 March 1939, and Smith J. DeFrance to Hugh L. Dryden, 29 July 1948, both in the NASA Historical Reference Collection; and Joseph S. Ames to Rear Adm. Arthur B. Cook, 24 October 1938, record group 255, NARA.

[33] For a discussion of the formation of this laboratory, see Virginia P. Dawson, *Engines and Innovation: Lewis Laboratory and American Propulsion Technology* (Washington, DC: NASA SP-4306, 1991). See also John F. Victory to NACA Chairman, "Origins and Status of the Aircraft Engine Research Laboratory," 7 October 1941, Record Group 255, National Archives; and William S. Knudsen, Office of Production Management, to Jerome C. Hunsaker, 2 December 1941, NASA HRC.

WARTIME PRIORITIES

Arnold, Hunsaker, Bush, and other pro-military members of the committee guided NACA research policy in the two years immediately before the United States entered World War II, and their influence throughout the war remained strong. They agreed that when war came, the NACA should place its total resources at the military's disposal but that it should remain a civilian science and engineering institution. As Hunsaker wrote to George Mead in 1940, the NACA's proper role in wartime would be to serve "as an unbiased technical advisor to any branch of the government on aeronautical matters."[34] Mead agreed, and the NACA became part of the "science team" that went to war, the "Scientists Against Time" who became famous in the aftermath of the successful military campaigns.[35]

The NACA had difficulty providing unbiased technical advice throughout the war, however. Its members and staff sought to keep an especially close relationship with the uniformed services. However, this relationship was never fully satisfactory, and senior members of both parties repeatedly urged closer coordination.[36]

The same was true of the committee's relations with two other organizations created by President Franklin D. Roosevelt to harness scientific and technical knowledge for the war effort. Vannevar Bush had met with one of Roosevelt's key advisors, Harry Hopkins, about concerns he and other scientists had about the nation's lack of preparedness for war and offered to take charge of an effort to organize scientific activities for Victory. He was motivated to this end, he recalled, by "the threat of a possible atomic bomb [that] was in all our minds, and time might well determine whether it became ours or a means for our enslavement." This resulted in the creation of the National Defense Research Committee (NDRC),

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[34] Jerome C. Hunsaker to George J. Mead, 8 August 1940, record group 255, NARA.

[35] Jerome C. Hunsaker to George J. Mead, 23 September 1940, and George J. Mead to Jerome C. Hunsaker, 28 August 1940, 2 October 1940, all in record group 255, National Archives; Levine, "United States Aeronautical Research Policy, 1915–1958," pp. 84–85; Holley, *Buying Aircraft*, p. 256; Wesley Frank Craven and James L. Cate, eds., *The Army Air Forces in World War II* (Chicago: University of Chicago Press, 1955), 6:308; James Phinney Baxter III, *Scientists Against Time* (Boston: Atlantic-Little, Brown, 1946). More recently, Paul Kennedy, *Engineers of Victory: The Problem Solvers Who Turned The Tide in the Second World War* (New York: Random House, 2013), has evocatively analyzed the critical responsibility for military success beginning in 1943 of the workaday activities of thousands of engineers and others whose creativity, decision-making, tactical ingenuity, and organizational capabilities made possible victory in World War II.

[36] Jerome C. Hunsaker to Gen. Henry H. Arnold, 2 May 1940, record group 255, NARA.

established by the President on 27 June 1940, with Bush as chairman.[37] Modeled on the NACA structure, this committee coordinated all defense-related research in the United States—except the aeronautical work that the NACA handled—until June 1941, when it was transformed into the Office of Scientific Research and Development. That new organization continued with broader powers to direct national defense research efforts until the end of the war.[38]

A second key organization that the NACA worked with was the Advisory Commission to the Council of National Defense. This agency oriented itself more toward production than R&D, but it also had significant interchange with the NACA. The Vice-Chairman of this agency was George J. Mead, a member of the NACA as well, and he worked hard in 1940 and 1941 to establish lines of coordination and cooperation. He complained to Jerome Hunsaker in October 1940 that the NACA "is not occupying its proper place in government councils at the present time." He urged greater coordination and a move away from basic research toward solving specific problems associated with individual aircraft design.[39]

These groups defined a basic policy on research that respected all groups and left no areas uncovered. Indicative of this process was the agreement between the NACA and the National Defense Research Committee:

> [I]t would usually be easy to assign proposed research problems to the three classes, (a) those which fall definitely within the field of the NACA, (b) those which fall definitely within the field of the NDRC, and (c) those which might be appropriately investigated by either committee. As an example of the problem of class (a), we may take the development of a plastic material for use in covering aircraft, which

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[37] Vannevar Bush, *Pieces of the Action* (New York: William Morrow and Co., 1970), p. 34; Irvin Stewart, *Organizing Scientific Research for War: The Administrative History of the Office of Scientific Research and Development* (Boston: Little, Brown, 1948), pp. 52–78.

[38] The history of this organization is documented in Daniel J. Kevles, *The Physicists: The History of a Scientific Community in Modern America* (New York: Vintage, 1979), pp. 287–301; Larry Owens, "The Counterproductive Management of Science in the Second World War: Vannevar Bush and the Office of Scientific Research and Development," *Business History Review* 68 (winter 1994): 515–576; Stuart W. Leslie, *The Cold War and American Science* (New York: Columbia University Press, 1993); G. Pascal Zachary, *Endless Frontier: Vannevar Bush, Engineer of the American Century* (New York: Free Press, 1997), pp. 147–188; and Roy M. MacLeod, "Combat Science: OSRD's Postscript in the Pacific," in *Science and the Pacific War: Science and Survival in the Pacific, 1939–1945*, ed. Roy M. MacLeod (Boston: Kluwer, 2000), pp. 13–26.

[39] George J. Mead to Jerome C. Hunsaker, 2 October 1940, Hunsaker Papers, National Air and Space Museum. See also George J. Mead to Jerome C. Hunsaker, 28 August 1940, and Jerome C. Hunsaker to George J. Mead, 16 August 1940, both in Hunsaker Papers, Smithsonian Institution; Vannevar Bush to George J. Mead, 10 December 1940, and Robert P. Patterson, Asst. Secy of War, to Vannevar Bush, 5 December 1940, both in record group 255, NARA.

> would naturally fall within the scope of the NACA Committee on Materials. As examples of problems of class (b), we may take the development of weapons for use on airplanes, or studies of the aerodynamic behavior of projectiles and bombs, which would naturally fall within the scope of the Division of Armor and Ordnance of the NDRC. As an example of a problem of class (c), we may take the problem of noise in combat vehicles, which is important both in airplanes and in tanks. In a case like this it would be appropriate for either committee to make investigations, but in the interest of economy of effort it would be natural to make some division of effort between the two committees. Thus, in the case of the particular example mentioned, since the problem is acute at the moment in connection with tanks and since the NACA had no group working on acoustics, it might be natural for the NDRC to undertake the main part of the investigation.[40]

In those areas of potential mutuality, the two committees were to determine by common consent which organization would take on the research effort. All the memoranda and agreements between these agencies would have been worthless had not those involved in leadership positions wanted to cooperate with each other. That was never an issue during the war.[41]

RESEARCH EFFORTS GREAT AND SMALL

The NACA deemphasized its prerogatives in response to the wartime effort, and such institutional blinders as seen in the GALCIT wind tunnel episode were subsumed in the larger struggle. That is not to say that all was harmony. Jerome Hunsaker, who had acceded to the chair of the NACA in 1941, expressed concern that his organization's traditional emphasis on fundamental research had given way to helping solve specific problems with military aircraft in development. By the time of Pearl Harbor, he reported, 71 percent of the NACA's work was on specific military projects. NACA Director of Research George Lewis testified to Congress in 1943 that the agency was involved in applied military aeronautical research 100 percent of its time. While this is a questionable conclusion, a large majority of NACA effort went into this direct support. This subsuming of the NACA mission under broader charters by other organizations would create difficulties for the

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[40] Vannevar Bush to George J. Mead, 20 December 1940, NASA HRC.

[41] "Memorandum on the Fields of Activity of the National Advisory Committee for Aeronautics and of the National Defense Research Committee," 12 February 1941, record group 255, NARA.

agency at the end of the war. However, at that time, it was allowable because of the national emergency.[42]

Throughout the war, the NACA aeronautical research program pursued an accelerated pace and focused on solving specific flight problems in the interest of the war effort. Requests for answers to specific problems came in to the committee. They were then sent to subcommittees that ranked them, coordinated with other agencies that might have a stake in the project, and assigned them to a laboratory for resolution. The researchers worked closely with those seeking the information to provide it on a timely basis.

As the NACA conducted research, it printed its findings, and this proved to be the most significant output from the agency's activities. The NACA issued several types of reports describing research findings:

- Technical Reports (TRs): The most prestigious, most polished, most important, and most widely distributed type of report, Technical Reports described the final results of a research effort and made "lasting contributions to the body of aeronautical knowledge."
- Technical Notes (TNs): These reported on work in progress, offered interim findings, or served as final reports for less significant research activities.
- Bulletins: These were short progress reports on limited phases of larger research projects.
- Memorandum Reports (MRs): These reported on pieces of aeronautical research of interest to a very small group of clients, generally on a specific type of aircraft or engine design.
- Technical Memoranda (TMs): These reported on aeronautical research conducted somewhere other than at the NACA and often were translations of technical articles published in a foreign language.

During World War II, the NACA issued more than 8,000 research reports of one type or another. Technical Reports were publicly available; readily accessible to anyone with a need to know the information; and distributed to a huge mailing list that included laboratories, libraries, factories, and military installations worldwide. They became famous for their thoroughness and accuracy and served as the rock upon which the NACA built its reputation as one of the world's

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[42] "National Advisory Committee for Aeronautics," 23 January 1941, text of appropriations testimony to Congress, Record Group 255, National Archives; House Committee on Appropriations, Independent Offices Appropriation Bill for 1944, Hearings, 78th Cong., 1st sess., 1943, p. 149, and minutes of regular meeting of NACA Executive Committee, 24 June 1941, both in NASA HRC.

best aeronautical research institutions. While the principal means of transferring this research knowledge was through its research reports, an important secondary means of transferring this information was through the annual conferences sponsored by the NACA after 1926.[43]

The NACA was appropriately pleased with its contributions in both applied and fundamental research during World War II.[44] These related to research on the shape of wings and bodies, the devices to improve engine power and propeller thrust, the measures to safeguard stability and control, and the technology necessary to protect the planes against ice and other natural hazards.[45] These involved all types of experiments at all the NACA research institutions. The NACA periodically issued statements about its general work for the war. A January 1944 issue of *Aviation* described in proper patriotic fashion the agency's efforts and urged support for it:

> How much is it worth to this country to make sure we won't find the Luftwaffe our superiors when we start that "Second Front?" We spend in one night over Berlin more than $20,000,000. The NACA requires—now—$17,546,700 for this year's work. These raids are prime factors in winning the war. How can we do more towards Victory than by spending the price of one air raid in research, which will keep our Air Forces in the position which the NACA has made possible?[46]

John F. Victory remarked that "[t]he employees of the NACA have a big and important job to do. They are at war with similar research organizations in Germany, Japan, and Italy. It is their responsibility, and they are using their technical knowledge and skill to make sure that the airplanes that are given to American and allied flyers are better and more efficient instruments of war than those flown by enemy airmen."[47]

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[43] Roland, *Model Research*, pp. 115, 127–129, 551–567; John B. Rae, *Climb to Greatness: The American Aircraft Industry, 1920–1960* (Cambridge, MA: MIT Press, 1968), pp. 35–38; Peter W. Brooks, *The Modern Airliner: Its Origins and Development* (London, U.K.: Putnam, 1961), p. 32.

[44] Many of these activities, described in a celebratory tone, have been detailed in Grey, *Frontiers of Flight*; "Research and Air Supremacy," *New York Times* (3 April 1945).

[45] William M. Leary, *"We Freeze to Please": A History of NACA/NASA's Icing Research Tunnel* (Washington, DC: NASA SP-2002-4226, 2002); Glenn E. Bugos, "Lew Rodert, Epistemological Liaison, and Thermal De-Icing at Ames," in *From Engineering Science to Big Science: The NACA and NASA Collier Trophy Research Project Winners*, ed. Pamela E. Mack (Washington, DC: NASA SP-4219, 1998), pp. 29–58.

[46] "NACA: The Force Behind Our Air Supremacy," *Aviation* (January 1944): 22–23.

[47] John F. Victory, "National Advisory Committee for Aeronautics," 24 June 1942, pp. 2–3, Victory Papers, Record Group 255, National Archives. See also "NACA Research and the Nation's War Planes: A Brief History of the Efforts of the NACA to Improve the Performance of Military Airplanes," 9 September 1942, record group 255, NARA.

While these efforts resulted in many important developments, there is space to discuss only three critical ones. The first was the NACA's effort to create cleaner aerodynamic fuselage designs and wing configurations to increase fighter aircraft speeds. The NACA employed its many wind tunnels with direct benefit to this endeavor.[48] Old NACA hands liked to recall how the committee had been approached by Hap Arnold in June 1939 asking for a 400-mph fighter that could go head to head with and beat the best German aircraft. Arnold spoke at length with George Lewis about this requirement, and Lewis promised that the NACA could give the Army a plane with a 400-mph top speed.[49]

Designed as a 400-mph fighter, the Bell P-39 could not attain that level of performance, although a stripped-down prototype had flown as fast as 390 mph at Wright Field, Ohio. During the summer of 1939, engineers at Langley investigated ways to eliminate drag on the aircraft and increase its speed. They used the full-scale wind tunnel to test various configurations and eventually came up with several modifications that pointed toward 400-mph flight under optimum conditions. NACA engineers increased the speed of the P-39 by about 16 percent. Because of the weight of production models, it never did fight or even fly at 400 mph.[50] A more successful aerodynamics effort was the development of low-drag wings for the P-51 Mustang, the Cadillac of the airways, which helped it to be one of the great fighters of World War II. During the war, Langley performed such research for 23 aircraft in production for the military. The drag cleanup it achieved provided the edge that Arnold had wanted for his fighter pilots. A 10 percent increase in performance was often enough to outrun or outmaneuver an enemy in a dogfight.[51] This was a significant aspect of the NACA's wartime role in applied research.

A second important R&D effort, but more in the NACA's traditional basic research mode, was its de-icing investigations. Icing on aircraft had long been a

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[48] "National Advisory Committee for Aeronautics Utilization of Wind Tunnels from January 1939 to June 1945," n.d., and George W. Lewis, "Survey of Future Needs in Aeronautical Research," 1 March 1940, both in record group 255, NARA.

[49] Interview of John F. Victory by Eugene M. Emme, 29 August 1960, NASA HRC.

[50] This story is well told in Hansen, *Engineer in Charge*, pp. 198–202. See also Clinton H. Dearborn to Langley Director, "Information on Langley Laboratory Research During War Period on B-17, P-39, and B-29 Airplanes as Requested by Mr. John F. Victory on September 14, 1949," 21 September 1949, Victory Papers; NACA Director to G. E. Ramsay, Jr., Bureau of the Budget (BOB), "NACA Activities in Aid of National Defense During Current Fiscal Year," 17 January 1941, and John F. Victory to G. E. Ramsay, Jr., BOB, "Outstanding Improvements in Aircraft During the Past Year, and the Contribution of NACA," 28 July 1941, in NASA HRC.

[51] The Langley effort here is described in Paul L. Coe, Jr., *Review of Drag Cleanup Tests in Langley Full-Scale Tunnel (from 1935 to 1945) Applicable to Current General Aviation Airplanes* (Hampton, VA: Langley Research Center, NASA TN D-8206, 1976).

problem, increasing the plane's weight, putting a strain on propellers and engines, and changing the plane's aerodynamics. NACA research on this problem had begun in 1927 and had made significant progress under Lewis A. Rodert. The war, and the increasing number of high-performance aircraft it engendered, prompted the NACA to redouble its efforts. All three NACA laboratories worked on this problem and carried the effort through the actual design of de-icing systems that pumped hot air from the engines into sections of the aircraft most prone to icing. For these efforts, Rodert received the prestigious Collier Trophy in 1946; the second Collier Trophy awarded for research by the NACA.[52]

Finally, something must be said of the NACA's involvement in jet propulsion research during the war. Perhaps no technological innovation has been more significant for the development of aviation of all types than the turbojet engine. A relatively simple engine in its principles, the jet required a unique combination of metallurgical capability, cooling and velocity control, and an unconventional understanding of Newton's third law of motion. The NACA and many other aeronautical research institutions had dallied with the concept in the 1920s. They abandoned it because the combination of factors required to make it a viable option was not present. Whereas other individuals and agencies returned to the concept periodically thereafter and found success in its development at least by the mid-1930s, the NACA ignored the jet propulsion problem and was notoriously left behind in jet development. It had to make a crash effort in the 1940s, in some cases literally, and get help from the British to catch up with developments elsewhere.[53]

Virtually every historian who has dealt with jet propulsion and the United States has asked the same question: why did the leading aeronautical nation in the world misjudge the potential of jet propulsion so badly? Those interested in the history of the NACA posit several reasons for its blinders in dealing with this subject, and their explanations represent the best wisdom available on this problem. They

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[52] The development of the thermal icing research program is described in Bugos, "Lew Rodert, Epistemological Liaison, and Thermal De-Icing at Ames," pp. 29–58; Grey, *Frontiers of Flight*, pp. 307–329; Robert McLarren, "NACA Research Ends Ice Age," *Aviation Week* 47 (22 December 1947): 24–27; Hansen, *Engineer in Charge*, pp. 110–112; Dawson, *Engines and Innovation*, pp. 109–115; and Muenger, *Searching the Horizon*, pp. 19–22.

[53] Critical studies of this subject are Edward W. Constant II, *The Origins of the Turbojet Revolution* (Baltimore, MD: The Johns Hopkins University Press, 1980); Jack Connors, *The Engines of Pratt & Whitney: A Technical History* (Reston, VA: American Institute of Aeronautics and Astronautics, 2009); Sterling Michael Pavelic, *The Jet Race and the Second World War* (Annapolis, MD: Naval Institute Press, 2010); and Hermione Giffard, *Making Jet Engines in World War II: Britain, Germany, and the United States* (Chicago: University of Chicago Press, 2016).

suggest four interrelated factors.[54] First, few Americans were interested in tackling the jet problem because of the nation's overall approach to aviation. Most research into the problems of propulsion were conducted by or for the engine manufacturers, and it was in their best economic interest to make incremental improvements to existing engines. Consequently, few asked the question in the 1920s and 1930s, and the NACA saw little reason to proceed independently. When it created a special committee under the leadership of Stanford University's William F. Durand to study jet propulsion in 1941, the NACA explicitly omitted industry representatives because they were economically wedded to the propeller.

Second, in contrast to European renegade engineers like Frank Whittle and Hans von Ohain, no Americans perceived the combination of compressor and turbine as a powerplant for flight. Whittle and von Ohain were drawn to the turbojet because its simplicity and unique characteristics made it a system ideally adapted to flight. Although the NACA had some of its engineers investigate jet power, they explored avenues, such as the Campini ducted-fan powerplant, that had very little practical application. When their work hit a dead end, the committee terminated the research. No one in America, it seems, grasped the turbojet's potential until Hap Arnold returned from Britain with plans for the Whittle engine, and a collective light bulb went on over the head of the NACA and other American R&D organizations.

Third, the economics of aeronautical R&D weighed against the NACA's heavy involvement in the development of the jet engine. The small and poor organization had always been forced to pursue research questions upon which it was uniquely suited to make significant contributions. The NACA engineers made conscious decisions to work in directions that might be more immediately productive. Jet propulsion research was, for many of them, a luxury they could not afford to pursue even if they had thought it worthwhile. Numerous projects swamped the Langley facility and created a bottleneck in R&D in the 1930s. By the time the Sunnyvale and Cleveland laboratories opened, the wartime increase in work was in full swing.

Finally, and this is by far the most significant area of concern, there was a problem of leadership among those who were interested in aeronautical R&D that mitigated against the NACA's timely and effective research into jet propulsion. The principal clients of the NACA were the military services, and they neither appreciated the potential of jet propulsion nor asked the committee to work on the

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[54] The following discussion is based on the observations of Roland, *Model Research*, pp. 186–194; Muenger, *Searching the Horizon*, pp. 33–37; Hansen, *Engineer in Charge*, pp. 219–247; Dawson, *Engines and Innovation*, pp. 41–63; and I. B. Holley, "Jet Lag in the Army Air Corps," in *Military Planning in the Twentieth Century*, ed. Harry R. Borowski (Washington, DC: Office of Air Force History, 1986), pp. 123–153.

problem. To appreciate the jet engine's full potential, individuals had to possess a sensitivity to the convergence of thermodynamic and aerodynamic principles. Few Army officers, even aviators, had the technical background to grasp this situation. This was, of course, part of a broader trend in the prewar Army; it did not understand the implications of the scientific revolution that was transforming warfare through such developments as radar, jet propulsion, atomic weapons, and other similar technological developments. Until the war was under way in Europe, and Britain shared the Whittle engine with the United States, they did not press for work in jet propulsion.

The NACA leadership was little better. It did not exploit its self-proclaimed primacy and foster basic research in the theoretical studies of jet propulsion. It failed to pick up on European work in turbojets, even though some professional conferences addressed these issues in the 1930s. It always possessed, it seems, a bias against engine research regardless of the type of engine. Perhaps the fact that it had built its many wind tunnels—and had developed world-leading expertise in aerodynamic research because of them—prompted the NACA to give shorter shrift to engine research. Charles Lindbergh was piqued that the NACA was ignoring R&D of propulsion systems, and he consequently pressed for the establishment of a separate research laboratory to undertake that work. He was successful in the early 1940s with the creation of the laboratory in Cleveland. A failure of leadership extended over the issue and fostered American complacency in the area of jet propulsion R&D.

These factors and others of a more subtle nature came together to retard American efforts in this aspect of aeronautical R&D. The British developments shook both the NACA and other American aviation agencies out of their complacency, however. During the war, significant improvements were brought both to the turbojet and to the aircraft that they would propel, for the higher speeds necessitated significant aircraft redesigns. It was not efficient to strap a turbojet on an aircraft designed for propellers. In this way, the NACA contributed significantly during the war toward resolving the transonic barrier that the United States cracked in 1947.[55]

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[55] John V. Becker, *The High Speed Frontier: Case Histories of Four NACA Programs, 1920–1950* (Washington, DC: NASA SP-445, 1980).

THE NACA PLANS FOR PEACE

Jet lag for the NACA notwithstanding, the committee had found a useful niche for itself during World War II, but it was one among many organizations performing similar types of work. That was acceptable for the war effort; everyone needed and welcomed all the help they could get. Nevertheless, it raised a specter for the agency in the postwar era. Traditionally, the committee had specialized in fundamental research and left most development to other organizations, in the process claiming a unique role in the R&D system that was not duplicated by anything else. This critical distinction made by the NACA ensured its prewar survival. Could it find the same or similar niche in the postwar world? It tried to do so, much as did the Army Air Forces, which planned for peacetime autonomy even while the war was going on. Committee leaders sought to define the agency's relationship with the military, industry, and other research institutions in such a way as to preserve its autonomy.[56]

It was never really able to do so. The NACA changed during the war, and even more importantly, its clients and the federal government overall had changed. The most serious change was, without question, the institutionalization of science and technology into virtually every aspect of government operations. World War II brought that about in a way that would not have happened until much later otherwise. This development ensured that the military services and other government organizations created vehicles to obtain the advice they believed necessary to survive in the postwar world. The model they used was not the one pioneered by the NACA, and explicit rejection took place even while the war was still under way. The traditional friends and clients of the NACA—the military and manufacturers—were generally supportive of a postwar role for the NACA. However, they were less willing to turn over exclusive responsibilities for R&D to the NACA than before the war.

By 1945, the federal government directed less than 10 percent of the R&D investment toward the NACA, far below the 1940 figure of about 45 percent. Some saw no use for the NACA at all; Senator James M. Mead, who headed an investigation of the National Defense Program, recommended in 1944 that the committee pass entirely out of existence, but most others did not share this view. They

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[56] On the Army Air Force's struggles in this regard, see Perry McCoy Smith, *The Air Force Plans for Peace, 1943–1945* (Baltimore, MD: Johns Hopkins University Press, 1970); Herman S. Wolk, *The Struggle for Air Force Independence, 1943–1947* (Washington, DC: Office of Air Force History and Museums Program, 1997); and Herman S. Wolk, *Reflections on Air Force Independence* (Washington, DC: Office of Air Force History and Museums Program, 2007).

were content to let it operate as a small institution without a unique charter.[57] The postwar NACA was a humble institution, and it was an easy target for consolidation into the new National Aeronautics and Space Administration in 1958 in the aftermath of the Sputnik crisis.

CONCLUSION

After a slow start, the NACA's accomplishments during World War II were genuine. While air power has never taken a single foot of ground and cannot by itself win any war, its contributions to the success of the American war effort were not small. Without the NACA, the American aerial supremacy won and held at least by the first part of 1944 would have been less robust. Every American airplane that fought in the war was tested and improved in NACA laboratories. While much of this work was incremental, evolutionary, difficult to evaluate, and unknown to most people, it was certainly significant. For its work, the NACA received its share of awards and other forms of recognition, and its members congratulated themselves for their good work. With all of the organization's successes during the war, there were also failures, near-failures, and instances where bureaucratic priorities got in the way of significant aeronautical research and development. These shortcomings should not be minimized, but neither should they overshadow the agency's positive contributions.

Almost as important, the NACA emerged from the war a transformed organization. As a result of World War II, during which the NACA focused almost entirely on military R&D, the structure of the aeronautics research system in the United States changed, and the prewar NACA approach became outmoded. During the war, aircraft companies and the Army Air Forces developed a significant in-house R&D capability, and the NACA's research infrastructure became less critical.[58]

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[57] Senate Special Committee Investigating the National Defense Program, "Investigation of the National Defense Program: Hearings Pursuant to S. Res. 55," 79th Cong., 2nd sess., part 31, July and August 1945, pp. 15375–15459; Grover Loening, BOB, "Criticism of the NACA," 23 October 1945, and Jerome C. Hunsaker, "Notes on Discussion at Meeting of NACA, July 27, 1944," 8 August 1944, both in record group 255, NARA; David C. Mowery and Nathan Rosenberg, *Technology and the Pursuit of Economic Growth* (Cambridge, England: Cambridge University Press, 1989), p. 179.

[58] This was the specific goal of such technological thinkers as Theodore von Kármán, as demonstrated in *Toward New Horizons* (Washington, DC: U.S. Army Air Forces, 1945), the umbrella title for 12 separate volumes on the military R&D arena. On von Kármán's efforts, see Michael H. Gorn, *Harnessing the Genie: Science and Technology Forecasting for the Air Force, 1944–1986* (Washington, DC: Office of Air Force History, 1988), pp. 11–58; and Michael H. Gorn, *The Universal Man: Theodore von Kármán's Life in Aeronautics* (Washington, DC: Smithsonian Institution Press, 1992).

Despite expansion in its annual budget, which by 1944 exceeded the committee's appropriations' cumulative total from its establishment through 1940, the NACA declined relative to other R&D agencies. It was easily consolidated into another institution, something NACA leaders had always tried to avoid before the war. Regardless of these developments, World War II was an important transition point for the NACA. It conducted its research mission, fought its bureaucratic battles, and sought to find a place in the postwar world, not always successfully.

CHAPTER 3

Japanese Aeronautical Innovation During World War II

Juergen Paul Melzer

Figure 1: A magnificent example of Japanese exotic design: the tailless Kyūshū Shinden interceptor. (Image credit: Japan Aeronautic Association)

Japan's wartime aeronautical innovation can be read as a tale of "too little, too late." It also can be interpreted as a unique story of ingenuity, contingency, and unexpected outcomes. Conventional wisdom often assumes that victory in war is a result of innovative technology. One, therefore, might assume that Japan's defeat signaled the country's technological inferiority. However, this is far from the truth. What makes the history of Japan's aviation so interesting is the breathtaking pace of Japanese aeronautical innovation that accelerated right up until the last days before Japan's surrender. Continually increasing pressure led to a burst in innovative energy that resulted in an astonishing variety of aircraft. Many of them matched and often even surpassed their American counterparts.

This chapter follows the advances in Japanese wartime aviation and describes to ever more radical designs. In its initial phase, a wide range of motives drove aeronautical innovation in Japan. Many engineers engaged in basic research, while others were chasing new world records. More often than not, aircraft with cutting-edge technology were used as public showpieces to promote national aviation enthusiasm and secure funding for further research.

The start of the Pacific War in 1941 catapulted aeronautical research into its second phase. Pressing for a new generation of high-performance aircraft, Army and Navy officials offered new opportunities to Japan's aeronautical engineers. As it turned out, the military's obsession with aircraft performance provided a unique environment for advanced aeronautical innovation that ignored mundane concerns about production technology, maintenance requirements, or operational use.

In summer 1944, Japan's aeronautical innovation entered its third and final phase. Large-scale U.S. air raids on the Japanese homeland began, and submarine attacks devastated Japan's seaborne supply lines. Japanese engineers now had to cope with a severe shortage of material, and relentless bombing runs targeted the country's aircraft industry. Rather than coming to a halt, the efforts of Japan's engineers accelerated. Their search for substitute materials and propellants intensified, while their aircraft designs shifted toward last-ditch attempts to turn the tide of war.

This chapter explores Japan's diverse aeronautical research landscape and its wide range of academic, commercial, and military institutions. It continues with a short excursion into the realm of "exotic" Japanese designs. Rather than attempting complete coverage of all aspects of Japanese aeronautical innovation, this chapter will center on aeronautical performance: altitude, speed, and flight range.

A focus on these critical concepts combined with the above-mentioned three-stage chronology will provide the analytical framework to illuminate the gradual development from research aircraft to advanced military prototypes. It will also reveal how, during the final stage of the war, these incremental advances gave way to entirely new designs that pushed the three performance parameters to new limits. A final section shows how the increasing radicalization of Japanese aeronautical innovation culminated in designing the ultimate weapon for the defense of the homeland: jet-driven suicide aircraft that were to be catapulted out of their secret hideouts to crash-dive into the enemy's invasion fleet.

SETTING THE STAGE: PREWAR AERONAUTICAL RESEARCH IN JAPAN

Japan's aeronautical research originates in 1918 when the Aeronautics Department of Tokyo Imperial University set up its laboratory. The new Aeronautical Research Institute (A.R.I.), relieved of all teaching duties, entirely concentrated on their research. Being under the Ministry of Education's direct jurisdiction, the institute was free from the military's influence. As a result, its researchers had great latitude in choosing their specific field of investigation. The price for such academic freedom was a chronic shortage of funding that put limits on the A.R.I.'s research activities.

In the same year, the Imperial Japanese Navy opened its first Aircraft Test Laboratory (Kaigun Kōkūki Shikensho) at Tsukiji in central Tokyo, a place well-known for the navy's first balloon launch in 1877. After the devastating 1923 Kantō earthquake destroyed most of the laboratory, naval aeronautical research moved to the Kasumigaura Air Base, around 60 kilometers northeast of Tokyo. The new facilities included a wind tunnel for advanced experiments in flight performance and airframe structure. In April 1932, the navy merged its aeronautical research with the design, prototype evaluation, and production of new aircraft types at the recently established Naval Air Arsenal (Kaigun Kōkūshō) at Yokosuka.

The Imperial Japanese Army built up its own research center at the Tokorozawa Flight School in 1919, 30 kilometers northwest of Tokyo. Initially, the army's research department engaged in the development and construction of prototypes. In 1925, the army's Aviation Headquarters (Rikugun Kōkūhonbu) made the far-reaching decision to leave airplanes' development and manufacture entirely to civil companies. The army limited aeronautical investigation to the examination and adoption of new aircraft types.

Thus, in the early 1930s, Japan's aeronautical research landscape was geographically scattered and thematically uncoordinated. Under the A.R.I. leadership, academia limited itself to basic research; the navy heavily endowed its arsenal with capital and workers to consolidate its technological lead. The army had withdrawn from virtually all research activities and relied on the civilian sector.

Then, in the mid-1930s, several new developments led to far-reaching alliances and power shifts in Japan's aeronautical research.[1] To reestablish its technological expertise, the army set up its Air Technical Research Institute (Rikugun Kōkūgijutsu Kenkyūsho) in August 1935. During the following five years, the institute's budget and staff numbers quickly increased. Its research activities included ordnance, fuel, and material—and even aviation medicine and psychology. However, the institute did not engage in aircraft design. The army still wholly depended on civil companies like Kawasaki, Mitsubishi, and Nakajima, which designed all of the army's new aircraft and engines, built the prototypes, and carried out their series production.

Furthermore, the army's Air Technical Research Institute had no say in the army's aviation procurement policy. All major decisions were made at the army's Aviation Headquarters by career officers who had only a limited understanding of technology.[2] As a result, Japan's aviation industry had to follow even the most unrealistic requests for aircraft with ever-increasing flight performance. With no technical support from the Army Air Technical Research Institute, the sheer number of these projects put a massive strain on the manufacturers' engineering departments.

Things were different with the Japanese navy. Unlike the army's Air Technical Research Institute, the Naval Air Arsenal became a hotbed of aeronautical innovation. The arsenal's activities covered the whole range, from basic theoretical studies to prototype design, test flights, and aircraft production. By the mid-1930s, the Naval Air Arsenal was pursuing its aim to catch up with Western aviation with great effort and an almost missionary zeal. The arsenal's chief, Admiral Maebara Kenji (1882–1963), urged in his 1935 New Year's address:

> We have to make sure that we do our best to develop excellent engines, bombs, radios, and torpedoes. U.S. aircraft stand on an entirely different level. Who can

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1. Japanese institutional history can be confusingly complicated. The author therefore has relegated the mentioning of the Central Aviation Research Institute (Chūōkōkūkenkyūjo, established by the Communications Ministry in 1939) and of the Technology Board (Gijutsuin, est. 1942) to this footnote. Both institutes became mostly known for their cumbersome bureaucracy and inter-ministerial rivalries that, until the end of the war, presumably produced more red tape than aeronautical blueprints.
2. *Rikugun kōkūgijutsu enkakushi* [The historical development of the Army's aviation technology], written in 1947 by an unknown author of the First Demobilization Bureau, p. 25.

> be sure that our aviation technology as one pillar of Japan's naval power will not collapse? During the last few years, it has become obvious that we can neither rely on our major civil manufacturers nor on the Army's aviation technology. Therefore, our Naval Air Arsenal has to shoulder an even heavier responsibility.[3]

The Naval Air Arsenal became Japan's fastest-growing aeronautical research center. By the end of the war, the number of its employees exceeded 14,000.[4] The Naval Air Technical Arsenal designed, built, and tested prototypes according to the navy's specifications before entrusting civil manufacturers with the mass production of these aircraft.

The year 1935 also marked a turning point for the fate of the Aeronautical Research Institute of Tokyo Imperial University. New regulations made it possible for the institute to engage in contract research for civil and military clients. This newly gained leeway allowed the A.R.I. to cooperate with Gasuden (Tokyo Gas and Electrical Industry Co., Ltd.) to build the Kōkenki (Aeronautical Research Airplane), a long-range aircraft with an advanced airfoil design. In May 1938, the airplane set a new world distance record of 11,651 kilometers. It became a public showcase of advanced Japanese aviation technology and effectively demonstrated the practical application of research done at the A.R.I.

The design of wings with low drag and high lift became a significant research field at the A.R.I. By the late 1930s, a group of scientists under the leadership of Tani Ichirō (1907–90) closely examined the interaction between a wing's surface and its surrounding airflow.[5] Their research resulted in breakthrough innovation: the so-called laminar flow airfoil. The curved surface of the new wing dramatically improved its lift-to-drag ratio. An aircraft with a laminar flow wing could fly considerably faster than any other airplane equipped with the same engine but using a conventional wing.

Such was the situation when the Pacific War began: a Japanese army with limited aeronautical expertise pestering civil aircraft makers with requests for increasingly demanding aircraft designs, a fast-growing Naval Air Technical Arsenal that

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3. Quoted in Sawai Minoru, *Kindai Nihon no kenkyū kaihatsu taisei* [The completion of the development of research in modern Japan] (Nagoya: Nagoya Daigaku Shuppankai, 2012), p. 259.
4. Ibid., p. 255.
5. Tani was aware of similar investigations in England and the United States. In 1939, the National Advisory Committee for Aeronautics (NACA) reported the successful design of a laminar flow airfoil. But most of the U.S. results were classified, so no specific details were available to Tani and his team. For details on Tani's research, see Hashimoto Takehiko, *Hikōki no tanjō to kūki rikigaku no keisei: Kokkateki kenkyū kaihatsu no kigen o motomete* [The invention of the airplane, the emergence of aerodynamics, and the formation of national systems of research and development] (Tokyo: Tōkyōdaigakushuppankai, 2012), pp. 247–296.

was on the brink of doing "big science," and an academic Aeronautical Research Institute with a recent publicity stunt and a new wing.[6]

SMALL FIRMS UNVEILING EXOTIC DESIGNS

After the outbreak of the Pacific War, Japanese aeronautical innovation frequently emerged from rather unexpected places. With all major aircraft manufacturers concentrating their efforts on large-scale production, relatively small companies began to play an increasingly important role in research and development.[7] When Allied submarines increasingly wreaked havoc on Japan's seaborne supply lines, the small company Kayaba designed and built an autogiro aircraft, a predecessor of the helicopter. The Kayaba Ka-1 that made its first flight in May 1941 was the world's first autogiro to be deployed for anti-submarine missions. To eliminate the submarine threat, another small-scale aircraft maker came up with an unusual innovation. As an alternative to marine shipment, Japan International Aviation Industries remodeled its transport gliders into long-range tanker aircraft that were to fly fuel from the Dutch East Indies to Japan.

Kawanishi's 1943 Shiden (Flash of Lightning) was a response to a new generation of U.S. fighters.[8] The Shiden was the world's first fighter to be equipped with automatic combat flaps, drastically improving its dogfight capability. To counter the threat of high-flying U.S. bombers, the Kyūshū Aircraft company presented in April 1945 one of the most unusual World War II (WWII) designs. Its interceptor Shinden (Magnificent Lightning) was a fast-climbing tailless canard aircraft with its elevator attached to its nose section and driven by a rear propeller.

Most of the above designs would qualify as exotic or as unorthodox responses to specific challenges. Japanese aeronautical innovation pushed the three most fundamental aeronautical categories—altitude, speed, and flight range—to new limits.

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[6] Japanese aircraft makers repeatedly argued that by getting rid of the military's close oversight, a new aircraft's experimental phase could be shortened by two-thirds and the production cost could also be considerably lowered. See *Nihon kōkū gakujutsushi (1910–1945)* [Aeronautical research in Japan (1910–1945)] (Tokyo: Nihon Kōkū Gakujutsushi Henshū Iinkai: Hatsubaijo Maruzen, 1990), p. 213. My view on the Naval Air Technical Arsenal is different from that of Walter Grunden, who argues that "there was no Big Science revolution in Japan." Walter E. Grunden, *Secret Weapons and World War II: Japan in the Shadow of Big Science* (Lawrence, KS: University Press of Kansas, 2005), p. 5.

[7] In addition, as David Nye has argued, major innovations often originate from outsiders who are not affected by the establishment's "path dependency." David E. Nye, *Technology Matters: Questions To Live With* (Cambridge, MA: MIT Press, 2006), p. 38.

[8] "Shiden" also translates into "the flash of a sword."

"FASTER, HIGHER, FARTHER"

Despite the Kōkenki's spectacular success, the Aeronautical Research Institute still suffered from its ivory-tower image. As one of its members gloomily observed, "[E]ven excellent research faded away at the laboratory and was never put to practical use."[9] It seemed as if some new showpiece projects could boost the A.R.I.'s public image and even procure the military's support. In 1940, the institute's head, Professor Wada Koroku (1890–1952), announced the institute's new research policy: in a slight deviation from the Olympic motto "Faster, Higher, Stronger," he proclaimed three straightforward goals that should direct future research: "Faster, Higher, Farther." Accordingly, three separate projects were to engage in the design of record-breaking airplanes. One research group was to develop a high-speed airplane. The other two groups would design a pressurized cabin for a high-altitude aircraft and a long-range research aircraft that incorporated the latest advances in aerodynamic research.

These projects' timing could not have been more unfortunate. After the outbreak of the war with America, the Japanese military decided on a strict division of labor. The military research institutes focused on urgent projects that required immediate implementation and expected the A.R.I. to concentrate wholly on basic research. Furthermore, with many specialists and skilled workers drafted, the A.R.I. was chronically understaffed, often running on less than half of its actual capacity. At the end of the war, the A.R.I. had a total workforce of about 600.

Despite all these difficulties, Professor Wada's ambition, matched by his scientists' and engineers' ingenuity, teamed up with the aircraft makers Tachikawa and Kawasaki to build three remarkable research aircraft. Even more importantly, the knowledge and experience gained from the "Faster, Higher, Farther" project would enable the two companies to develop an entirely new generation of high-performance fighters and bombers.

Flying Higher: The SS-1 High-Altitude Research Aircraft

High-altitude flight has ever fascinated pilots, engineers, and air power strategists: a high-flying aircraft could easily avoid detection and anti-aircraft fire. Furthermore, with the lower air density at these altitudes, air resistance decreases, allowing higher speeds and longer flight ranges. However, high-altitude flight comes at a high price: it poses enormous challenges to aircraft design and the human body. Without proper countermeasures, such as a pressurized cabin, an

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[9] Awano Seiichi, quoted in *Nihon kōkū gakujutsushi (1910–1945)*, p. 264. Awano had been working at A.R.I. since 1934; in 1939, he became an assistant professor at Tokyo Imperial University.

airman is incapacitated within minutes by lack of oxygen, barotrauma, and decompression sickness.

In 1938, the Aeronautical Research Institute had procured the Army's support for a study of the basics of high-altitude flight. The research under the leadership of Professor Ogawa Taichirō (1899–1952) showed such promising results that in 1940, Professor Wada could convince the Army to reverse its research policy and to fund the A.R.I.'s new project of an experimental aircraft with a pressurized cabin. Army officials now considered developing a high-altitude aircraft of such military importance that they classified the project as "especially top secret."

The Army's design specifications asked for an aircraft that could operate for up to 6 hours at an altitude between 8,000 and 10,000 meters. Dr. Kimura Hidemasa (1904–86), who had already participated in the development of the Kōkenki, was in charge of the pressurized cabin's basic design.[10] Even though he was well aware of ongoing U.S. experiments, almost no information about the structure and the function of a pressurized cabin was available in Japan.[11] As a result, Kimura had to start from scratch. To accelerate the project, Kimura made an unusual decision. Designed by the Kimura team, the pressurized cabin fitted with the wings and tail assembly of a Lockheed 14 passenger aircraft that already was produced under license by Tachikawa Hikōki.[12] To improve its high-altitude performance, the aircraft equipped with two powerful Mitsubishi Ha-102 supercharged engines fitted with propellers specially designed for high altitudes.[13]

Work on the pressurized cabin started in spring 1940. The Aeronautical Research Institute carried out the overall development while Tachikawa was to take care of the design details. Preliminary calculations showed that the most obvious solution, a cocoon-shaped airtight capsule, would be too heavy. Instead, two engine-driven compressors were to supply pressurized air to maintain a minimum cabin air pressure equivalent to an altitude of 3,000 meters. In three years, the engineers refined the compressors' design and developed air cleaners, temperature-regulating valves, and automatic pressure regulators. They also solved problems of cabin air leakage and defects in the supply system.

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10. Kimura was a fellow student of Kawasaki's chief designer, Doi Takeo, and Horikoshi Jirō, the famed designer of the *Zero-sen*. He would also become the future designer of the Ōka suicide plane.
11. Akimoto Minoru, *Kenkyūki kaihatsu monogatari* [The development of research engines] (Tokyo: Kōjinsha, 2003), p. 133.
12. Tachikawa started the licensed production of its Lockheed Type LO in 1940.
13. Kimura Hidemasa, *Waga hikōki jinsei* [My life with aircraft] (Tokyo: Nihon Tosho Sentā, 1997), pp. 133–135.

Two SS-1 (SS for sub-stratosphere) experimental aircraft were completed in July 1942.[14] On 1 June 1943, the SS-1 made its first flight. Subsequent experiments showed that a "cabin altitude" of 3,000 meters could be maintained up to a flight altitude of 8,000 meters. By early 1944, six test flights had been carried out to a maximum altitude of 9,000 meters. A second aircraft with an improved pressure cabin made its first flight in summer 1944. On 9 October 1944, it climbed to an altitude of 11,000 meters, reaching the stratosphere.

Even though the SS-1 was Japan's first high-altitude aircraft featuring the new technology of cabin pressurization, very little information on the project survived. Due to their classified nature, the A.R.I. destroyed all results of the experiments and test flights at the end of the war. The success of the SS-1 project was to have immediate consequences. It provided the technological foundation for Tachikawa's advanced Ki-94 high-altitude fighter.

Tachikawa's High-Altitude Fighter Ki-94

At the early stages of the Pacific War, the Japanese military imagined that Japan might face high-altitude bombing attacks. An analysis of downed U.S. bombers had shown that their engines allowed them to operate at altitudes of more than 10,000 meters. In July 1944, these fears materialized when, with Saipan's loss, Tokyo came within the United States Army Air Forces' B-29 bombers' flight range.

The new high-altitude fighter Ki-94-II was Tachikawa's antidote to such anxieties. It was custom-designed to climb to altitude and then detect and shoot down high-flying U.S. bombers. The Ki-94-II project started in May 1944. The aircraft was to have a service ceiling of more than 14,000 meters and a maximum speed of 710 kilometers per hour (kph) and easily outperform the B-29s and their escort fighters. It could climb to 10,000 meters in 17 minutes, well within the limits of a 20-minute advance warning time for approaching bombers.

The most remarkable design feature of the Ki-94 was its pressurized cabin that allowed the pilot to perform without a cumbersome pressure suit and oxygen mask. The Tachikawa engineers made full use of their experience acquired during the SS-1 high-altitude research aircraft development. They also devoted special attention to the Ki-94's wing design. To optimize the aircraft's high-speed and high-altitude characteristics, it featured a tapered wing with a relatively small surface area.[15] For the first time, Tachikawa adopted a high-speed laminar-flow wing cross-section. To implement the wing's new airfoil design, the engineers built it with

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[14] Sub-stratosphere is generally defined as the air layer located between 4,300 and 11,000 meters.

[15] Hasegawa Tatsuo and Yamazaki Akio, *Maboroshi no kōkōdo sentōki Ki-94: B-29 yōgekiki no kaihatsu hiroku* [The phantom high-altitude fighter Ki-94: Secret memoirs of the development of an interceptor of the B-29] (Tokyo: Kōjinsha, 2002), pp. 61–63.

painstaking care. According to the chief designer, Hasegawa Tatsuo (1916–2008), its "workmanship was strikingly beautiful."[16] The designers equipped the aircraft with a turbosupercharged 2,400-horsepower Nakajima Ha-44, the most powerful engine for high-altitude flight available in Japan.

Intensifying air raids forced Tachikawa to disperse most of its activities. In November 1944, Hasegawa and his team had to continue their work in a spinning factory in Kanamachi, about 15 kilometers northeast of Tokyo.[17] The work went on, and in early August 1945, they completed a prototype. However, three days before the scheduled first test flight, Japan surrendered. Even though the aircraft never saw deployment, one can surmise its strong military potential, and the aircraft's technological significance remains undoubted. In the words of aviation expert Nozawa Tadashi, the Ki-94-II was an "epoch-making innovative masterpiece."[18]

Flying Faster: The Ki-78 High-Speed Research Aircraft

Since the early days of aviation, speed has been one of the defining features of aeronautical progress. Air races attracted thousands of spectators, and competitions like the Schneider Trophy became immensely popular and inspired high-speed research.[19] In the late 1930s, the quest for speed reached a new stage. In April 1939, the German company Messerschmitt established a new speed record of 755 kph, an achievement that was widely exploited by Nazi propaganda. In the same year, in an obvious attempt to join the high-speed boom, Lieutenant General Yasuda Takeo (1889–1964) of the Army Air Technical Research Institute approached Wada Koroku (1890–1952), the chief of the A.R.I. Yasuda suggested starting research on a high-speed aircraft that could serve as a prototype for a future fighter. Yamamoto Mineo (1903–1979), an assistant professor at Imperial Tokyo University who had participated in the Kōkenki design, became chief of the new Ki-78 project, which consisted of 13 A.R.I. researchers and 10 Army officers.[20]

The design of the Ki-78 followed two simple principles: minimize air resistance and maximize engine power. Tani Ichirō, it should be recalled, was Japan's leading expert in designing laminar flow wing profiles. He joined the team and tested his

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[16] *Nihon kōkū gakujutsushi (1910–1945)*, p. 14.

[17] Nozawa Tadashi, *Nihon kōkūki sōshū: Tachikawa, rikugun kōkūkōshō, Manpi, Nikkoku hen* [Encyclopedia of Japanese aircraft: Tachikawa, Army Aviation Arsenal, Manpi, Nikkoku], vol. 7 (Tokyo: Shuppankyōdōsha, 1980), p. 93.

[18] Ibid.

[19] See John David Anderson, *The Airplane: A History of Its Technology* (Reston, VA: American Institute of Aeronautics and Astronautics, 2002), pp. 268–273, for a discussion of the air races' effects on aircraft development.

[20] Hashimoto Takehiko, "Aerodynamic Researches at the Aeronautical Research Institute at Tokyo and the Invention of Laminar Flow Airfoil," unpublished paper, 2010, p. 25.

Figure 2: The sleek Ki-78 High-Speed Research Aircraft. Note the narrow air inlets behind the cockpit. (Image credit: San Diego Air & Space Museum)

theoretical calculations with several wind tunnel experiments. High-speed turbulences rendered wind tunnel data unreliable. Tani then decided to run a series of flight tests on the airplane that resulted in airfoils that came very close to the theoretical optimum. To further minimize air resistance, the aircraft was to have an unusually short wingspan of only 8 meters. Its fuselage featured a front area of less than 1 square meter and a tiny streamlined windscreen. Narrow inlets provided air for the fuselage-embedded coolers. As such, a high-speed aircraft would be notoriously difficult to land. A sophisticated combination of two different wing flaps and drooping ailerons provided additional lift during the landing.

Due to its small diameter, the fuselage could not house a radial engine—the standard Japanese engine type at that time. The best choice would be a liquid-cooled inline engine with a small frontal area. Rather than develop such a powerplant from scratch, the design team decided to upgrade and install an imported German DB-601 aeroengine. It is a testimony to Japanese engine designers' skill that they successfully increased the power of an already sophisticated engine by nearly 50 percent to 1,500 hp.[21]

The army selected the aircraft maker Kawasaki for the prototype's production. The company was Japan's only aircraft maker that had experience with high-power liquid-cooled engines. The company just had begun producing its Ki-61 Hien fighter powered with the same license-built DB-601 engine. The first Ki-78

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[21] Several innovative measures taken by the engineers led to this remarkable power surge. They installed a water-methanol injection device to avoid engine knocking, which allowed them to increase the engine's boost pressure. They also improved the effectiveness of cylinder filling, minimized the power needed for turbocharging and engine cooling, and used exhaust gas for additional thrust.

prototype was completed in December 1942 (figure 2). The aircraft then underwent more than 30 test flights that led to continuous refinement of the Ki-78's engine cooling, flight controls, and propeller adjustment. Then, on 27 December 1943, the Ki-78 set a new Japanese speed record of 699.9 kph. Even though the German speed record remained unchallenged, the Ki-78 clearly could outrun, at low altitudes, advanced U.S. fighters such as the P-47 Thunderbolt or the P-51 Mustang.[22] In early 1944, the project came to a halt, and the company abandoned plans for building a second prototype aiming at a speed of 850 kph.

Kawasaki's High-Speed Fighter Ki-64

In August 1940, when the Ki-78 research project was already under way, the army asked Kawasaki for a high-speed fighter with exceptional climb performance. Kawasaki's chief designer, Doi Takeo (1904–96), eagerly accepted the challenge. He had been toying with the design of such an aircraft since 1936. Making good use of the advanced design features of the Ki-78, he decided to use the same laminar flow airfoil and a similar powerplant.[23]

The new aircraft was to put the high-power/low-drag principle to a new extreme. To increase the available engine power twofold, the engineers installed two Kawasaki Ha-40 engines in front of and behind the cockpit.[24] With a total of 2,300 hp, these motors were to drive two propellers. This arrangement had several additional advantages. The two counter-rotating propellers counteracted each other's torque effect, thus solving a problem experienced by single-propeller aircraft, and greatly improved the fighter's flying characteristics. Two independent engine units provided a high degree of redundancy. With one engine installed behind the cockpit, the nose section was relatively short and improved the pilot's field of vision.

An innovative method for engine cooling further enhanced the aircraft's performance. A conventional liquid-cooled engine uses a radiator for heat exchange. To eliminate the radiator's drag, the new aircraft used a so-called steam-vapor cooling system. Water absorbed the engine's heat and turned it to steam. The steam was then pumped to cooling panels installed on the upper and lower wing surfaces, where it condensed and then returned to the engine. Doing away with a separate air-exposed cooler substantially reduced air resistance and resulted in a speed increase of 40 kph.

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[22] The P-47 Thunderbolt reached a speed of 654 kph at 1,500 meters (802 kph at 9,000 meters) with a 2,600-horsepower engine; the P-51 Mustang's maximum speed at 1,500 meters was 624 kph (708 kph at 9,000 meters) with a 1,500-horsepower engine.

[23] Nozawa Tadashi, *Nihon kōkūki sōshū: Kawasaki hen* [Encyclopedia of Japanese aircraft: Kawasaki], vol. 4 (Tokyo: Shuppankyōdōsha, 1960), p. 122.

[24] The Ha-40 was a licensed production of the German DB 601 aeroengine.

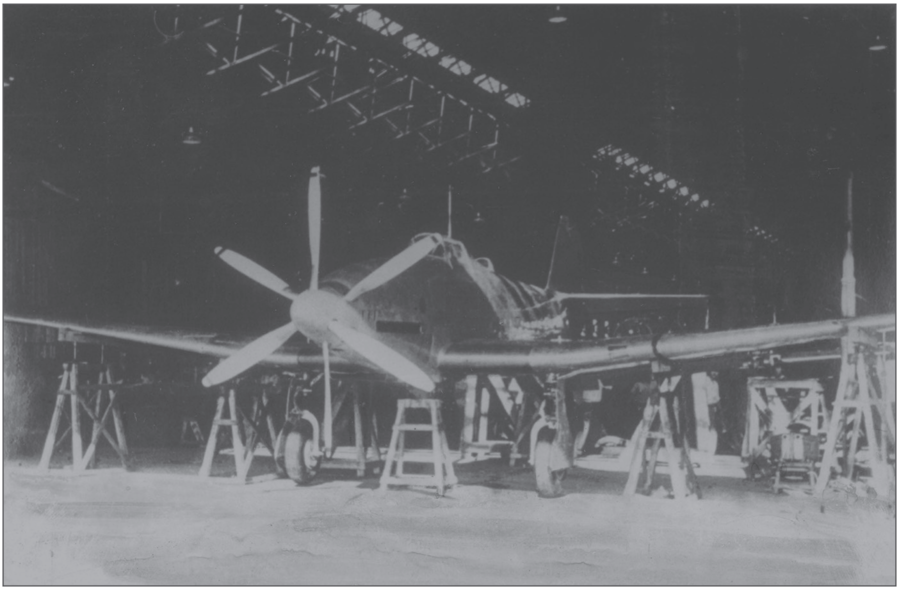

Figure 3: Kawasaki's High-Speed Fighter Ki-64 with its counter-rotating propellers. (Image credit: Japan Aeronautic Association)

After extensive motor unit tests and the addition of the new cooling system, the prototype was ready in December 1943 (figure 3). On the fifth test flight, the rear engine caught fire, but the pilot returned to the airfield. The engine's and propeller's massive damage required extensive repairs and finally led to the project's official termination. While it is hard to know what other factors led to this decision, considerable doubt about building such a sophisticated aircraft in large numbers was certainly one. In the words of the Kawasaki engineer Nakano Takayoshi, "even though we received the full support of the military, we agonized over how to mass-produce such a complex machine as a front-line fighter aircraft."[25]

Flying Farther: The Long-Range Research Aircraft A-26 (Ki-77)

Long-distance flight always held a unique position on the Japanese aircraft makers' agenda because of the vast expanses associated with flight in the Pacific. Since the 1920s, they had responded to the dual challenge of overcoming the Pacific Ocean's "tyranny of distance" and outranging any hypothetical enemy. As part of its "Faster, Higher, Farther" project, the Aeronautical Research Institute decided to push back this aeronautical frontier. In stark contrast to the "especially top secret" high-altitude project, the development of a new long-range research

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[25] *Nihon kōkū gakujutsushi (1910–1945)*, p. 128.

aircraft became a public showpiece that featured cooperation among academia, private enterprise, the military, and—most notably—the press.

In 1940, Japan celebrated the 2,600th anniversary of the mythic Emperor Jimmu's accession. The Tokyo newspaper *Asahi Shinbun* decided to honor the event with a "Tokyo–New York nonstop friendship flight." The paper hoped to attract the public's attention and measure up with its arch-rival Mainichi Shinbun of Osaka, which had enthralled the Japanese with the successful 1939 round-the-world flight of its Nippon-gō.

Asahi's president, Murayama Nagataka (1894–1977), met with Lieutenant General Yasuda Takeo, head of the Army Air Technical Research Institute, and Wada Koroku, director of the A.R.I., in February 1940. The three men agreed to build a new aircraft to establish a new long-distance world record of more than 15,000 kilometers. Both the army and the newspaper agreed to contribute ¥500,000 to the project. As with the SS-1, the basic design was to be done by the A.R.I.; the detailed design and the construction of the aircraft, by Tachikawa. Just three days later, *Asahi* publicly announced the ambitious project, duly called "A-26"—a combination of *Asahi*'s initial letter and the first two digits of the year 2600.

Once again, Kimura Hidemasa became the designated leader for A.R.I.'s design team. Kimura could refer to his experience gained from the record-breaking Kōkenki aircraft. Like its predecessor, the A-26 was to have a high-aspect-ratio wing with an integrated fuel tank. The new wing was about the same size as that of the Kōkenki but able to carry twice the weight. In order to minimize the wing's drag, Kimura chose a laminar cross-section. Incorporating these advanced features posed several challenges. To create a lightweight wing that nevertheless was strong enough to carry 12,000 liters of fuel, Kimura and his team used the wing's skin as a part of the load-bearing structure; this choice allowed them to incorporate just a single wing spar. To match the engineers' efforts, Tachikawa's workmen built the wing with a perfectly smooth surface that precisely integrated the airfoil's laminar flow shape.

In a determined effort to further minimize air resistance, the slender fuselage featured a circular cross section with a diameter of less than 1.2 meters and a tiny integrated windscreen. As the flight was to be carried out at high altitude, a quasi-airtight oxygen-filled cabin was built and tested for the first time in Japan. The engineers modified the compact but powerful Nakajima Ha-105 engine with improved cooling fins and covered it with special streamlined engine cowlings. To minimize the engine's fuel consumption, it ran on an extremely low fuel-to-air ratio. In spring 1941, the production began on the first experimental prototype. With the start of the Pacific War, the military shifted its priorities and put the project on hold.

Figure 4: Back on the tarmac: The A-26 after the completion of its 16,435-kilometer world record flight. (Image credit: Japan Aeronautic Association)

Then, a spectacular air attack on Japan revived the A-26 program. On 18 April 1942, 16 B-25 bombers under the command of Lieutenant Colonel James Doolittle (1896–1993) launched from the deck of the aircraft carrier U.S.S. Hornet and conducted the first U.S. air raid on the Japanese homeland. The soon-to-be-famous Doolittle Raid had such a devastating impact on Japanese morale that the Japanese army decided to retaliate with a new long-range bomber based on the A-26's technology to attack the American homeland. The army ordered Tachikawa to finish construction of the A-26 by the end of 1942. The A-26 successfully made its first flight on 18 November 1942. During the next four months, the aircraft logged more than 100 flight hours for test flights before making its first long-range journey, a 5,330-kilometer nonstop flight from Tokyo to Singapore.

By the end of April 1943, a second experimental aircraft was completed. Rather than bombing America, Prime Minister Tōjō Hideki (1884–1948) now envisioned the A-26 establishing a new air route between the Axis powers. Carrying out its new assignment, the aircraft left Tokyo on a secret mission and arrived in Singapore on 30 June. It took off for a nonstop flight to the Crimean Peninsula before continuing to Berlin. However, the airplane never arrived at its destination. It disappeared, together with its crew of eight, over the Indian Ocean.[26]

The army and *Asahi* then decided to use the remaining A-26 for setting up a new nonstop distance record. Captain Omata Toshio expressed the hope that such a record-breaking flight should bring “at least a small bright light to the dark mood of the people.”[27] On 2 July 1944, he took off with his A-26 from Changchun in Manchuria, from where the aircraft began to proceed on triangular flight patterns via Baicheng and Harbin. Overcoming early autopilot failure and oxygen shortage, the crew of five landed the aircraft safely after 57 hours with almost empty tanks and a new world record (figure 4). In their narrow fuselage, the Japanese airmen had covered a range of 16,435 kilometers, more than 1.5 times the distance between Tokyo and New York.

Building on their valuable experience gained with the A-26 long-range research aircraft, Tachikawa’s engineers embarked on an even more ambitious project. As early as spring 1939, the Japanese army had toyed with the idea of a top-secret long-range reconnaissance plane that could penetrate deep into Soviet territory. The conclusion of the 1941 Soviet–Japanese Neutrality Pact made the army officials change their plans. They now wanted a high-flying aircraft that could reach the United States for reconnaissance missions. The airplane should also carry a moderate 1,000-kilogram bomb load to drop over the U.S. homeland. By the end of 1941, Tachikawa received the detailed specifications for the new Ki-74 Long-Distance Reconnaissance-Bomber. Even though Tachikawa could make maximum use of its A-26 production jigs, it took the company more than two years to build a prototype. In March 1944, the first Ki-74 was ready for flight testing. The company built a total of 14 Ki-74s by the end of the war. Starting from the third prototype, these aircraft incorporated nearly all the advances in Japanese aviation technology. A laminar flow wing section directly adopted from the A-26 provided the low drag and high lift for a long flight range, and a pressurized cabin allowed the crew to operate at an altitude of up to 12,000 meters. Powerful supercharged engines could accelerate the airplane to a speed of up to 570 kph, and self-sealing tanks and

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[26] Decrypted Magic (code name for decoded radio communications) intercepts informed the British about the Se-gō’s takeoff date and flight route. However, there seem to be no reports of the aircraft having been shot down by the RAF or by anti-aircraft artillery. See Peter Herde, *Der Japanflug: Planungen und Verwirklichung einer Flugverbindung zwischen den Achsenmächten und Japan 1942–1945* [The Japan flight: Planning and realization of an air link between the Axis powers and Japan, 1942–1945] (Stuttgart: F. Steiner, 2000), pp. 213–216.

[27] Various authors, *Nihon no kōkū runesansu* [The renaissance of Japan’s aviation] (Tokyo: Kantōsha, 2000), pp. 39–40.

armor protection provided a better chance of survival after enemy attacks.[28] While the Ki-74 was still in its evaluation phase, the Army decided to use it for reconnaissance flights over Saipan with the eventual aim to bomb the B-29 bases on the island. The war ended before these attacks could be carried out.

RADICALLY NEW TECHNOLOGIES

Aeroengines were arguably the most complex artifacts of the period. In their effort to fulfill the seemingly incompatible criteria of low weight, high power, and high reliability, engineers had to cope with temperatures over 2,000°C and high-speed flow processes that occur in less than 1 millisecond. Soon after the start of the Pacific War, a new class of Japanese aeroengines outclassed most of their U.S. counterparts. Mitsubishi completed the prototype of its 2,200-horsepower Ha-43 engine in February 1942.[29] Nakajima developed under enormous time pressure its 2,000-horsepower Homare engine and put it into production in September 1942.

Such engineering feats notwithstanding, metallurgists might be the unsung heroes of aeronautical innovation. Increases in engine power intensified the strain and thermal stress on crankshafts, bearings, pistons, and cylinder valves. Metallurgists all over the world set off on a feverish quest for heat- and fatigue-resistant steel alloys. Nevertheless, the Japanese metallurgists were facing even more significant challenges. While their Western counterparts focused on developing alloys for improved engine performance, the Japanese had to put up an increasingly desperate fight against the growing scarcity of strategic alloys. By 1943, acute shortages of nickel, molybdenum, and tungsten not only hampered the development of a new generation of high-powered engines but even threatened to bring current engine production to a halt. The metallurgists at the Naval Technical Air Arsenal played a crucial role in discovering carbon and nitride steel alloys as a substitute material.[30] Extensive research on aluminum alloys led to the invention of

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[28] For comparison: The four-engine heavy U.S. bomber B-29 had a ceiling of 9,710 meters and a similar maximum speed of 574 kph. However, its 9,000-kilogram bombload put it clearly in a different category.

[29] Matsuoka Hisamitsu and Nakanishi Masayoshi, *Mitsubishi kōkū enjin-shi: Taishō rokunen yori shūsen made* [The history of Mitsubishi aeroengines, 1915–1945] (Tokyo: Miki Shobō, 2005), p. 125.

[30] A very detailed account by Kawamura Kōi, a metallurgist at the Naval Technical Air Arsenal, can be found in Okamura Jun, *Kōkū gijutsu no zenbō 2* [An overall picture of the aviation technology, vol. 2] (Tokyo: Hara Shobō, 1976), pp. 356–417. The Naval Air Technical Arsenal's research for substitute materials included the following fields: special metals to reduce the use of nickel, molybdenum, and tungsten; non-nickel, heat-resistant steel;

many new alloys that minimized the use of copper, magnesium, and nickel while maintaining or even improving strength and thermal properties.[31]

Even the most sophisticated aeroengine delivers its maximum power only when running on high-grade fuel.[32] During the first two years after the outbreak of WWII, the Japanese navy fought against the United States by using its stockpile of imported U.S. fuel. After the Japanese occupation of the Dutch East Indies, it turned out that crude oil from this region was of such inferior quality that even advanced refining methods could not reach the minimum octane level required for aviation fuel. Tackling this problem, the Naval Air Technical Arsenal researchers found out that additives like aniline, acetone, or isopropyl benzene made it possible to obtain high-octane gasoline.[33]

Amid dwindling fuel supplies and severe material shortages, two revolutionary propulsion technologies promised an ingenious solution. Rocket engines that ran on chemical fuel would not need high-grade aviation fuel. Jet engines could burn low-grade fuel. As the Japanese researchers found out, even a mixture of gasoline and pine root would suffice. A small but powerful rocket engine required only a fraction of the advanced piston engine's material.

In contrast, the jet engine's relatively uncomplicated design seemed to make it ideal for mass production, even by untrained workmen. The brute force of both propulsion systems also allowed a radical departure from an earlier design philosophy that emphasized aerodynamic sophistication. Now a simple and easy-to-produce airframe, together with a powerful motor, would bring about a high-performance aircraft.

Japan's First Jet Fighter: Kikka

Japanese jet engine design traced its origin to the development of turbosuperchargers. These superchargers were exhaust gas–driven air compressors to boost the power of a conventional piston engine. In the early 1940s, while working on such a supercharger, the Naval Technical Air Arsenal engineers under the leadership of

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low-tungsten, high-speed steel; cobalt substitution; ways of dealing with low-grade bauxite; use of steel for propeller blades; and countermeasures against the lack of platinum. *Nihon kōkū gakujutsushi (1910–1945)*, pp. 237–238.

[31] For details on the HD (Honda's duralumin), ND (Nippon Duralumin), and Y alloy, see Okamura Jun, *Kōkū gijutsu no zenbō 2*, pp. 394–400.

[32] According to Edward Constant, about half of the rapid progress in engine power until WWII resulted from advances in the chemistry of aviation fuel. Edward W. Constant, *The Origins of the Turbojet Revolution* (Baltimore, MD: Johns Hopkins University Press, 1980), p. 120.

[33] The wide range of fuel-research topics at the Naval Air Technical Arsenal included fuel substitutes, such as alcohol fuel and pine root fuel; oil substitutes; synthetic oil; and oil additives. *Nihon kōkū gakujutsushi (1910–1945)*, pp. 239–240.

Tanegashima Tokiyasu (1902–87) had the idea to replace the piston engine with a gas turbine. This supercharger-turbine combination went through several improvements but—partly because of its complicated internal gas flow—still suffered from the disastrous cracking of turbine blades.

In this technological deadlock, a single piece of paper arriving from Germany changed everything. In July 1944, the naval engineer Iwaya Eiichi (1903–59) brought one blueprint that showed a longitudinal cross section of a BMW-003 jet engine to the navy's Aviation Bureau. The blueprint provided only one line of text, no numbers, not even a scale. Nevertheless, the engineers welcomed the document "with wild joy," and Tanegashima famously noted:

> This one single picture that Commander Iwaya showed me was enough. When I saw it, in a split second I understood it all. The principle was completely the same as ours. But instead of a centrifugal compressor, an axial-flow compressor was used; moreover, the speed of rotation was low, and the turbine was designed with [masterly] ease. The combustion chamber allowed an unrestrained airflow. By just looking at it, I thought: Well done![34]

The Japanese jet engineers' expertise had already reached a level that allowed them to incorporate the new design ideas right away. Simultaneously, they solved technological challenges such as high-grade steel selection, the design of heavy-duty bearings, and the optimum layout of the combustion chamber and fuel injection. In June 1945, the new jet engine Ne-20 was ready for flight.

The airframe of the jet fighter, named Kikka (Orange Blossom), was built by Nakajima. The designers followed the navy's request for a low-cost aircraft that could be easily mass-produced. They minimized the necessary production steps and—wherever possible—replaced valuable aluminum alloys with wood, steel, or even tinplate. In response to intense U.S. air raids, Nakajima dispersed the prototype production, and by a quirk of fate, the final assembly of Japan's first jet fighter was carried out in a silkworm nursery shed.

On 7 August 1945, test pilot Takaoka Susumu (1912–99) made the Kikka's maiden flight, during which the aircraft and its two jet engines operated satisfactorily. Four days later, a second flight was to test the deployment of booster rockets. These wing-mounted rockets were to provide additional thrust. However, during the aircraft's takeoff run, these rockets caused an unexpected nose-up momentum that made the pilot abort the takeoff. The aircraft overshot the runway and suffered massive damage.

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[34] Ishizawa Kazuhiko, *Kikka: Nihon hatsu no jetto engin Ne-20 no gijutsu kenshō: Kaigun tokushu kōgekiki* [Kikka: Japan's first jet engine; A review of the Ne-20: The navy's special attack plane]. (Tokyo: Miki Shobō, 2006), p. 105.

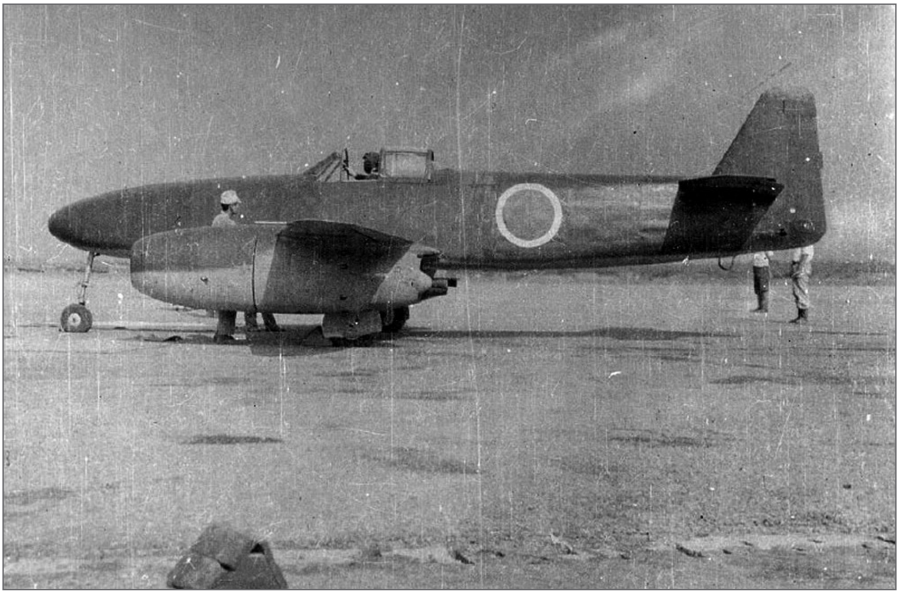

Figure 5: The Kikka jet aircraft preparing for takeoff. (Image credit: National Air and Space Museum, Smithsonian Institution)

Radically Higher and Faster: The Shūsui Rocket Interceptor

In July 1944, the navy decided to build a rocket interceptor based on the German Messerschmitt Me 163. Even though the Germans had already proved the project's feasibility, the Japanese engineers' challenge was enormous. They could refer only to a very vague German design description and had to design both the airframe and rocket motor basically from scratch. The navy requested that the new aircraft, named Shūsui (Polished Sword), reach an altitude of 12,000 meters within less than 4 minutes while accelerating up to 900 kph and that a prototype should be ready for flight within one year.

Mitsubishi received the order to develop the Shūsui's airframe in August 1944. Even though the design of a tailless high-speed aircraft required intensive experimentation, the company had already finished its first airframe by December. However, in the same month, a devastating earthquake followed by a large-scale air raid forced the company to disperse the aircraft's design and construction to three different locations.

The development of the rocket engine was an even more ambitious undertaking. Mitsubishi's engineers, headed by Mochida Yūkichi (1912–2002), engaged in an entirely unfamiliar technology. They had to work under intense time pressure and constant fear of testbed explosions and U.S. air attacks. Nevertheless, Mochida and his team ran a long series of experiments that led to the rocket engine's successive improvements. The engineers mastered the complicated pump unit design and a combustion chamber that endured temperatures of up to 1,800°C.

In the early morning of 7 July 1945, the Shūsui was ready to open up a new chapter in Japanese aviation history. Captain Inuzuka Toyohiko (1922–45), who already had flown an unpowered glider version of the Shūsui, took off from the Oppama Air Field. When he pulled the aircraft's nose up to initiate a steep climb, the engine began to discharge smoke and stopped. Inuzuka went into a descent and tried to glide back to the airfield. Unfortunately, shortly before touchdown, he hit an obstacle that badly damaged the aircraft. He survived the crash landing but died from his injuries the next day.

As it turned out, the Shūsui's engine failure resulted from a misplaced fuel supply line, a fault that could have been easily corrected. Therefore, even with its tragic outcome, the Shūsui's maiden flight had proved that the Japanese could master advanced rocket technology.

Taking Operational Range to New Extremes: The Submarine-Borne Attack Bomber Aichi M6A Seiran

After the Pearl Harbor attack, Admiral Yamamoto Isoroku (1884–1943) planned to take the war to the American homeland. As one of Japan's most air-minded officers, he envisioned a series of submarine-launched air raids on U.S. cities on the East Coast and West Coast.[35] This idea was not as eccentric as it seems. Yamamoto could convince the Japanese Navy that such attacks would have a considerable psychological impact on the American public, while at the same time raising the morale of the Japanese navy. Furthermore, it would force the U.S. military to withdraw troops from the Pacific theater to protect the homeland.

As it turned out, Japan's dockyards and aircraft factories could provide the hardware for such an ambitious endeavor. The navy planned for 18 large-size submarine aircraft carriers, each capable of carrying three attack aircraft in a watertight hangar. With a displacement of up to 6,565 tonnes, the so-called I-400–class submarines would become the world's largest submarines. Carrying enough fuel for a nonstop voyage of 77,000 kilometers, these submarine aircraft carriers could launch air attacks on any coastal town in the world.

In May 1942, the navy ordered the Aichi Aircraft Company to design and build a suitable bomber. The new aircraft, the Seiran (Storm from a Clear Sky), was to be launched by a catapult from the submarine's forward deck.[36] Aichi already

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[35] Nihon Kaigun Kōkūshi Hensan Iinkai, *Nihon Kaigun kōkūshi 1 Yōhei hen* [The history of Japanese naval aviation 1 (strategy)] (Tokyo: Jiji Tsūshinsha, 1969), pp. 227–228.

[36] The Seiran has attracted the attention of many (mainly Western) aviation historians. See, for instance, Robert C. Mikesh, *Monogram Close-Up 13: Aichi M6A1 Seiran, Japan's*

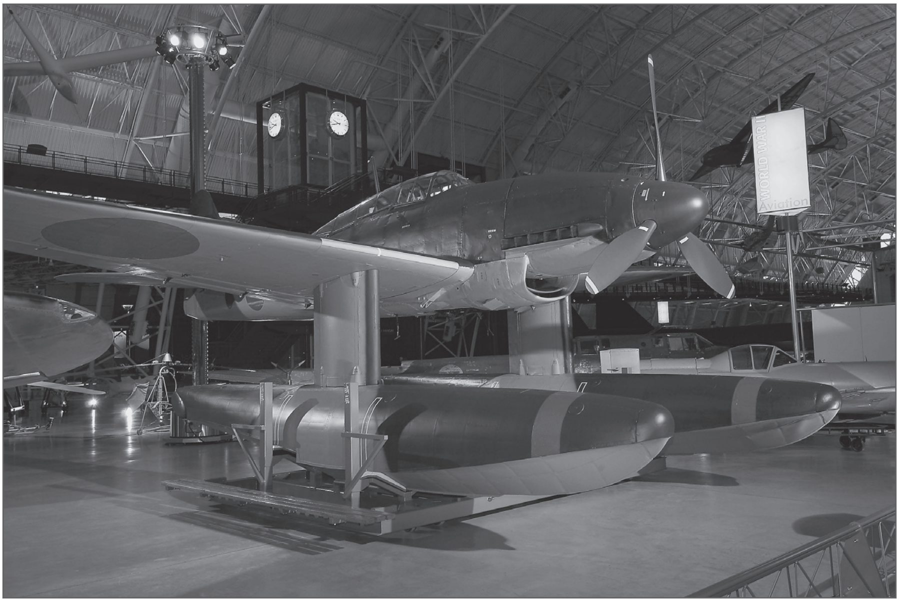

Figure 6: A beautifully restored Seiran attack bomber. Note the slot near the wing root hinting at the aircraft's unique folding mechanism that allowed it to be stored in a submarine. (Image credit: National Air and Space Museum, Smithsonian Institution)

had experience building seaplanes and dive bombers for the navy, but the Seiran confronted the engineers with several new challenges. The aircraft was to combine a high-altitude dive bomber's flight characteristics with those of a low-flying torpedo bomber. Furthermore, while stored on board the submarine, the aircraft was to require as little space as possible. The Aichi engineers came up with an ingenious mechanism that allowed swiveling each wing along its main spar by 90 degrees and then folding it back parallel to the aircraft's fuselage. The tail fin and elevator folded downward to reduce storage size further. Simultaneously, to expose the surfaced submarine as little as possible to detection and attack by the enemy, it was vital to make the bomber ready for launch as fast as possible. After a series of trial runs, Aichi's engineers had developed a system that allowed a well-trained crew to pull the aircraft out of its hangar and have it ready for takeoff within 7 minutes. The Seiran made its first test flight in November 1943, and production began in autumn 1944.

In March 1945, the first two submarines, I-400 and I-401, were completed. In the meantime, the Naval General Staff abandoned its initial plans to attack

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Submarine-Launched Panama Canal Bomber (Boylston, MA: Monogram Aviation Publications, 1975); and John J. Geoghegan, *Operation Storm: Japan's Top Secret Submarines and Its Plan To Change the Course of World War II* (New York: Crown, 2013).

the U.S. homeland in favor of a surprise attack on the Panama Canal. Bombing the canal's locks would cut a vital supply line and prevent the passage of the U.S. Atlantic Fleet to the Pacific after the Allied victory in Europe. However, the loss of Okinawa in June 1945 forced yet another change of plans. Now the Seiran bombers were to fly suicide attacks on the U.S. fleet at the Caroline Islands. In late July, the I-400 and I-401 departed for their final mission. However, before the submarines were ready for attack, Japan capitulated, and the submarine crew followed the order to dump all aircraft, weapons, and ammunition into the sea.

SUICIDE PLANES: A QUINTESSENTIALLY JAPANESE INNOVATION?

It is repugnant to label any suicide weapon as "innovative," so much more an airplane specifically designed to kill its pilot. Nevertheless, the Japanese "special attack" aircraft received ample attention from military experts. Some commentators even expressed approval of their efficiency. They argued that—compared to conventional bombers—these planes not only could be quickly built and operated but also, due to their close approach to the target and their heavy bomb load, deliver "greater potential damage."[37]

In August 1944, Japanese Ensign Oota Shōichi (1912–94) envisioned a piloted bomb whose pilot would start a high-speed dive and crash into his target after being released from a carrier aircraft. Oota, who was neither a pilot nor an engineer, gained the support of the Naval Air Arsenal and the experts at the Aeronautical Research Institute. The arsenal's engineers and the university researchers teamed up, and within a few weeks, they finished several prototypes of the suicide plane. The Navy Suicide Attacker Ōka (Cherry Blossom) was the antithesis of aeronautical sophistication (figure 7). It was a 1,200-kilogram bomb with two short plywood wings and a tiny cockpit attached. The rear part contained three solid-fuel rockets and had a simple tail unit fastened to it. The whole design reflected the idea of a disposable weapon produced cheaply and in large numbers.

Flight tests showed that during its dive, the Ōka could accelerate to an impressive speed of over 900 kph. Only 15 seconds would elapse between the visual detection by an observer on the target and the actual impact at such a speed. Production and recruitment of volunteers also made quick progress.[38] By the end of 1944, the

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[37] *Strategic Bombing Survey*, vol. 63, *Japanese Air Weapons and Tactics. Reports. Pacific War* (Washington, DC: The Division, 1947), pp. 25–26.

[38] Recent publications emphasize the role of coercion and peer pressure in staffing the Tokkōtai (special attack) units. See, for instance, Emiko Ohnuki-Tierney, *Kamikaze Diaries: Reflections of Japanese Student Soldiers* (Chicago: University of Chicago Press, 2006).

Figure 7: The Navy Suicide Attacker Ōka. (Image credit: National Air and Space Museum, Smithsonian Institution)

Naval Air Arsenal had built more than 150 Ōkas. However, the first significant deployment revealed the shortsightedness of the suicide-plane strategy. The Ōka's limited flight range of 40 kilometers required a carrier airplane to transport it close to their target. Both the carrier and the attack aircraft were vulnerable to the enemy's air defense. On 21 March 1945, 15 Ōka carriers were shot down even before bringing their deadly load into target range.

To increase the Ōka's flight range, the arsenal's engineers sacrificed explosive force for fuel load and engine power. In its most potent version, the Ōka 43B was to be driven by the new jet Ne-20, which also powered the jet fighter Kikka. According to Wada Misao (1889–1981), chief of the Naval Air Technical Arsenal, this new generation of jet-powered suicide bombers were hidden along Japan's coastline. From there, they would be "all launched together from catapults and send the enemy's invasion troops to the ocean's bottom."[39]

The construction of the world's most powerful catapults began in April 1945. The navy's planners envisioned nearly 100 catapults installed along the Pacific coast and the Tsushima and Tsugaru straits. Each of them was able to launch half a dozen suicide planes in rapid succession. These rocket-driven catapults accelerated the Ōkas to nearly 200 kph.[40] In July, several catapults, including one on Japan's sacred Mount Hiei, were ready for launch. The manufacturers' failure to deliver sufficient jet engines terminated the project before the end of the war.

CONCLUSION: INGENUITY, INNOVATION, AND A LOST WAR

Putting Japan's wartime aeronautical innovation in a strategic context demonstrates that innovations alone cannot transform the battlespace. Recent research on present-day military policy emphasizes the potential of so-called disruptive military technology to "radically alter the symmetry of military power."[41] Why, then, were Japan's radical innovations not disruptive?

Japan's basic aeronautical research neither benefited from a consistent research policy nor received the necessary funding and workforce. Even with its longstanding research tradition and academic expertise, the Aeronautical Research Institute was constantly understaffed. Throughout the Pacific War, America systematically mobilized its scientists and engineers for the war effort; many Japanese specialists and skilled workers had to leave their work and were sent to the war front. Furthermore, with the lack of a national research policy, the A.R.I. could easily switch its priorities between basic research and practical aircraft design. The institute's constantly shifting cooperation with the military, various aircraft makers, and even the press reflected opportunistic short-term alliances rather than a consistent research strategy.

Lack of coordination severely hampered Japanese aeronautical innovation. The perennial army-navy rivalry resulted in wasteful redundancies. Due to different standards and specifications, aircraft makers like Nakajima and Mitsubishi, which produced aircraft for both the army and the navy, had to manage two separate

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[39] Quoted in Naitō Hatsuho, *Ōka: Hijō no tokkō heiki* [Ōka: A merciless special attack weapon] (Tokyo: Bungei Shunjū, 1982), p. 163.

[40] Okamura, *Kōkū gijutsu no zenbō 2*, p. 316.

[41] Shawn Brimley, Ben FitzGerald, and Kelley Sayler, *Game Changers: Disruptive Technology and U.S. Defense Strategy* (Washington, DC: Center for a New American Security, 2013), p. 11.

design, prototype construction, and production lines.[42] One could argue that having poor coordination rather than central management might have boosted Japanese designers' creativity and led them to engage in a bewildering variety of research projects. Nevertheless, poor coordination took a heavy toll on the industry's resources. During the Pacific War, Japan's aircraft makers designed approximately 90 basic aircraft types with 164 variations.[43]

The military's erratic procurement policy reflected short-term developments rather than long-term goals. As we have seen, the A-26 aircraft's intended use changed three times from a Tokyo–New York nonstop "friendship flight" to a trans-Pacific long-range bomber to an airliner connecting Japan and Germany. Similarly, the submarine-launched Seiran's targets dramatically shifted from America's East and West Coasts to the Panama Canal before ending up on the Caroline Islands. While these adjustments were in large part due to Japan's increasingly desperate efforts to turn the tide of the war, procurement orders for ever more aircraft seemed to have lost all touch with reality. During the final months of the war, Japan's aircraft makers received an order for a grueling production plan aiming to supply over 1,200 *Shūsui* rocket interceptors by September 1945. An overall total of 3,600 Shūsui were to be delivered by March 1946.[44]

Such unrealistic aims emphasize the considerable chasm between Japan's advanced aircraft designs and its backward production methods. While Japanese designers excelled in aerodynamics, aircraft structure, and aeroengine technology, their outsized visions did not match Japan's industrial capabilities. As one engineer of the Army Air Technical Research Institute put it: "Japanese designers were envisioning record-breaking racing aircraft rather than military [aircraft] that could be mass-produced and operate under harsh conditions."[45] Most efforts to translate the overreaching prototype designs into mass production were bound to fail. The engineers' neglect to consider future mass production already during the early design phase, together with the generally low standard of Japan's production technology, often led to inferior aircraft output. The low operational capability and

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[42] Nihon Kōkū Kyōkai, *Nihon kōkūshi. shōwa zenkihen* [The history of Japanese aviation in the early Shōwa period], vol. 2 (Tokyo: Nihonkōkūkyōkai, 1975), p. 887.

[43] *Strategic Bombing Survey*, vol. 15, *The Japanese Aircraft Industry* (Washington, DC: The Division, 1947), p. 2.

[44] René J. Francillon, *Japanese Aircraft of the Pacific War* (Annapolis, MD: Naval Institute Press, 1987), p. 88.

[45] Ikari Yoshirō, *Kaigun gijutsushatachi no Taiheiyō Sensō* [The Pacific War of the navy engineers] (Tokyo: Kōjinsha, 1989), p. 97.

poor reliability of these airplanes became a nightmare for mechanics and pilots on the front lines.[46]

Thus, the increasing radicalization of Japanese aircraft design was the engineers' response to the military's pressing demands and the exhaustion of materials and resources. Even under intensifying air raids and the resulting chaos caused by the aviation industry's dispersal, Japanese engineers continued their efforts literally up until the last days of the war.

Japan's defeat discredited its engineers and their all-out wartime endeavors. Simultaneously, ironically, Japan's postwar reconstruction once more called for the engineers' service in a national effort. With the war's lessons in mind and the pressure of wartime conditions gone, Japan's engineers put their talents to work again to lay the foundation for the country's postwar industrial growth. When Japanese innovation directly translated into commercial success, the nation could create its new narrative of military defeat turned into postwar economic victory.

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46. According to *Nihon kōkū gakujutsushi (1910–1945)*, p. 214, in February 1944 only one-third of the new aircraft delivered to the army were considered operational.

CHAPTER 4

TsAGI During the Great Patriotic War

F. Robert van der Linden

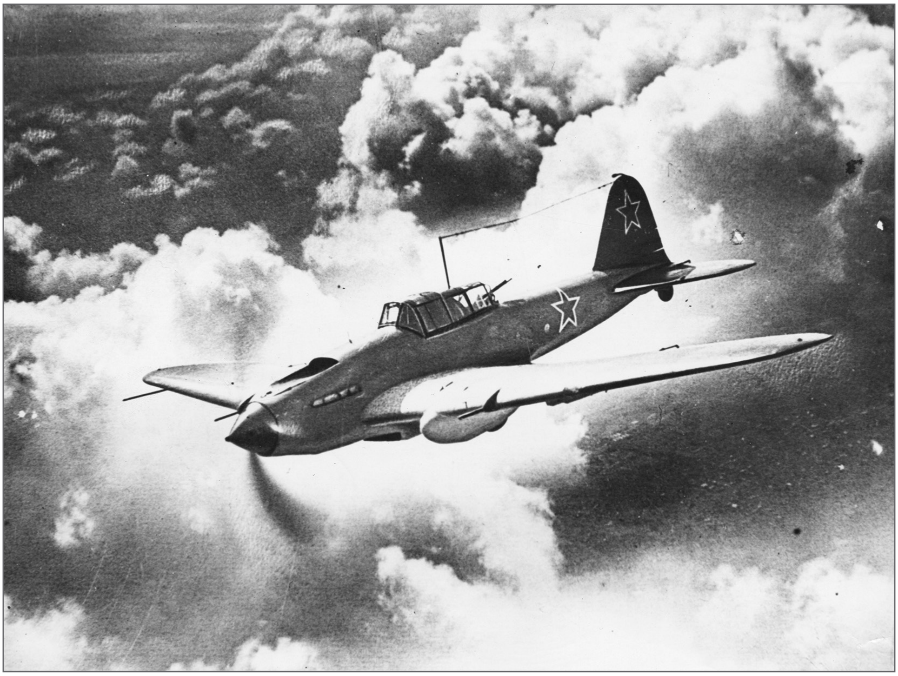

Figure 1: Built in greater numbers than any warplane, the Ilyushin Il-2 was the premier ground attack aircraft of the Red Air Force. Heavily armed and armored, the Il-2 devastated Axis armies, spearheading the victory of the Soviet Union on the Eastern Front. Shown here, the Il-2m3 featured an improved wing installation developed by TsAGI. (Image credit: National Air and Space Museum, Smithsonian Institution, image NASM 82-8315)

Paris in late November 1936. The autumn weather is getting colder and damper. Life in the French capital is good despite the growing uncertainty of a recently remilitarized Germany on the French western border. Across the Pyrenees Mountains in the southwest, Spain is embroiled in a brutal civil war that serves as a proxy battlefield between fascist Germany and Italy and the communist Soviet Union and threatens to drag other countries into the conflict. Spain also serves as a proving ground for the latest weapons. Italy is well-known for its highly maneuverable Fiat biplane fighters and swift Savoia Marchetti bombers, providing the aircraft, crew, and ground personnel to operate them. Nazi Germany does the same with its Heinkel biplane fighters and Junkers corrugated bombers. Surprisingly, the Soviet Union sends Polikarpov fighters and Tupolev bombers, which, to the shock and surprise of many, are equal or superior to their fascist counterparts.

In Paris, the world had an opportunity to view and compare these and other airplanes in the Fifteenth International Aero Exhibition. Held in the heart of Paris close to the Seine River in the Grand Palais des Champs Elysees, the Aero Show featured aircraft from most of the industrialized countries of Europe, including Great Britain, France, the Netherlands, Czechoslovakia, and Poland, as well as Italy, Germany, and the Soviet Union.[1]

To the surprise of many, one of the show's stars was the latest version of the Polikarpov I-17, the TsKB-19. This aircraft was based on the highly successful Polikarpov I-16, the first modern fighter aircraft produced by any country when it first took to the skies in late 1933 and was now in combat over Spain. The I-16 was made of aluminum alloy, plywood veneer, steel, and fabric. It featured a low-wing, cantilevered (i.e., internally braced) monoplane wing, retractable landing gear, and a closely cowled air-cooled engine.[2] When it entered service in 1935, it was the most advanced fighter flying, despite the limitations of the struggling Soviet economy. The I-17 was based on this design but incorporated a license-built, liquid-cooled V-12 Hispano-Suiza 12Y, known as the M-100, and an enclosed cockpit. The result was a graceful, well-balanced design that looked very similar to the later British Supermarine Spitfire.[3] The Paris Air Show allowed the rest of Europe to see up close what the aviation industry in the Soviet Union was capable of producing, and they were reluctantly impressed. According to *Flight*, "The U.S.S.R. presents one

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1. "The Paris Aero Show," *Flight* XXX, no. 1456 (19 November 1936): 540–541.
2. William Green, *Warplanes of the Second World War*, vol. 3 (New York: Doubleday & Company, 1971), pp. 161–165.
3. Ibid., pp. 166–167.

of its high-speed, stressed skin fighters of which we have heard so much but seen so little…. [It] is somewhat reminiscent of a Spitfire. Its ground angle seems abnormally large, but, all things considered, the machine seems quite a sound design."[4] While the I-17 did not enter production, it demonstrated that the Soviet aviation industry was capable of producing world-class designs, many of which would be widely used in the coming world war.

Mounted high on a stand behind the I-17 was the massive ANT-25 long-range monoplane. This aircraft was the creation of Andrei N. Tupolev (whose initials form the designation), a key figure in Soviet aeronautics. Reacting to the spate of long-distance flights in other nations, in 1931, Tupolev began designing a massive single-engine monoplane with an extremely long, almost sailplane-like wing with a 13:1 aspect ratio for maximum lift. He had the support of the Soviet leader Joseph Stalin, who wanted to use technology, particularly aviation, to legitimize his rule and demonstrate the supposed superiority of communism over the West.[5]

The ANT-25 set a series of records after its first flight in 1933, culminating in two incredible transpolar flights in the summer of 1937: a 6,200-mile direct flight from Moscow to Vancouver, Washington, and a 6,306-mile nonstop flight from Moscow to San Jacinto, California. The respective command pilots Valery Chkalov and Mikhail Gromov became international celebrities.[6] The ANT-25 was an all-metal design that featured a stressed skin, aluminum alloy fuselage, and corrugated aluminum alloy wing, patterned after the German Junkers model. *Flight* was impressed: "This machine…is of very daring design. Aerodynamic efficiency is the chief consideration in the layout of a long-range aeroplane, and in the A.N.T. 25, the reduction of induced drag has been carried to the utmost extent. The wingspan being no less than 112 feet…. That Tupolev did succeed in constructing a cantilevered monoplane of this aspect ratio in so large an aircraft (gross weight 25,000 lb) is evidence of his skill as a designer."[7]

Of more modern design was the ANT-35 civil airliner, which was on display underneath the ANT-25. According to *Flight*, the design "shows that Russia has been making real solid progress technically during the last couple of years."[8] Based on the SB-2 medium bomber that was fighting against the Nationalist forces in Spain, this twin-engine 10- to 12-seat monoplane airliner was built of stressed-skin

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4. "The Paris Aero Show," p. 544.
5. K. E. Bailes, "Technology and Legitimacy, Soviet Aviation and Stalinism in the 1930s," *Technology and Culture* 17, no. 1 (January 1976): 55–59.
6. R. E. G. Davies, *Aeroflot: An Airline and Its Aircraft* (Rockville, MD: Paladwr Press, 1992), pp. 32–33.
7. "The Paris Aero Show," p. 554.
8. Ibid., p. 541.

aluminum alloy and powered by two air-cooled engines fitted with NACA cowlings, giving the aircraft a reported top speed of 268 miles per hour. The Soviets used this aircraft as a transport and liaison aircraft through World War II, until the larger license-built Douglas DC-3 version, the PS-84/Lisunov Li-2, superseded it.

The one thing each of these three exhibit aircraft had in common was that they were designed and engineered at the same place, Tsentral'nyi aeroghidrodinamicheskyi Institut (TsAGI), or the Central Aerohydrodynamic Institute, where the Soviet Union conducted most aviation and aeronautical technical research and development and Russia continues to do so to this day. TsAGI was formed in 1918 by one of aeronautics' great names—Nikolay Yegorovich Zhukovsky.[9]

Born in Orekhovo, Russia, in 1847 and inspired by Otto Lilienthal's work, pioneer aerodynamicist Nikolay Y. Zhukovsky was the first scientist to study airflow. Using mathematics, he was the first to explain aerodynamic lift with his circulation theory.[10] In 1902, he constructed the first wind tunnel in Russia at Moscow University, and in 1904, he established the Institute of Aerodynamics, the first aerodynamics school, in Kachino. He taught for many years at the Moscow Imperial Technical College.

Zhukovsky continued his work during the First World War and the subsequent Russian Revolution. Unlike other Russian designers and engineers, such as Igor Sikorsky and Alexander de Seversky, Zhukovsky stayed in Russia. In March 1918, he founded the Flight Laboratory at the Moscow Higher Technical School. By this time, Zhukovsky and two of his best students, Andrei Tupolev and I. A. Rubinsky, recognized the need for a national aeronautical research center. They recommended a unified research facility for the study of aerodynamics and hydrodynamics for aircraft and engines.[11] On 1 December 1918, Vladimir Lenin approved their request, creating TsAGI by combining the Flight Laboratory with the Red Air Fleet's design bureau. Zhukovsky, whom Lenin described as "the father of Russian aviation," served as its first director.[12]

TsAGI immediately became the primary aeronautical research and development center, studying the science of aeronautics and applying it through its design bureau. TsAGI also became the center for engineering, construction, and the

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9. Yefrim Gordon and Vladimir Ringmat, *OKB Tupolev: A History of the Design Bureau and Its Aircraft* (Hinckley, England: Midland Publishing, 2005), p. 5.
10. Higham et al., *Russian Aviation and Air Power in the Twentieth Century* (London: Frank Cass Publishers, 1998), p. 157.
11. Gordon and Ringmat, *OKB Tupolev*, p. 5
12. Higham et al., *Russian Aviation and Air Power in the Twentieth Century*, p. 157.

education of the Soviet Union's designers, engineers, and technicians.[13] The new organization was composed of eight departments:

1. General Theoretical
2. Aviation
3. Wind-Driven Motor
4. Communication
5. Design, Engineering, and Researching
6. Aerohydrodynamics
7. Application for Structures of Research
8. Technological Specialization in Aerohydrodynamics

TsAGI itself reported to the Research and Technology Department of the Supreme Council of National Economy.[14]

Work began in 1919 using the aeronautical facilities at the Moscow Technical School. Despite the deprivations caused by the ongoing civil war and a bitterly cold winter, progress was made, first in the development of a propeller-driven sledge for potential use in carrying goods over Russia's poorly developed road network. By the end of the year, the school had built 20 sledges and had 54 people employed at the facility.[15]

S. A. Chaplygin was appointed to lead TsAGI after Zhukovky's sudden death on 17 March 1921. A brilliant mathematician and scientist, Chaplygin would lead TsAGI for the next 10 years. Under his direction, TsAGI expanded and developed well-organized teams of engineers to solve the various problems of powered flight, establishing the organizational model for the Institute's operations.[16] Andrei Tupolev was promoted to assistant director and became the principal designer, with his initial ANT prefacing most of TsAGI's future designs well into the 1930s.[17]

On 22 March 1923, TsAGI requested funding from the new Soviet government to expand its facilities, requesting the construction of a new laboratory in Moscow. By the following year, work had begun on a new engine and propeller,

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[13] Ibid.

[14] Sergei Leonidovich Chernyshev and G. S. Bushgens, *TsAGI: Russia's Global Aerospace Research Center: History of the Establishment and Future* (Zhukovsky, Moscow: Central Aerohydrodynamic Institute, 2011), p. 20.

[15] Bill Gunston, *Tupolev Aircraft Since 1922* (Annapolis, MD: Naval Institute Press, 1995), p. 10.

[16] Chernyshev and Bushgens, *TsAGI*, p. 42.

[17] Ibid., p. 22.

and a materials laboratory was finished by the end of 1925.[18] Of particular significance was the completion of TsAGI's first wind tunnel, T-I/T-II.[19]

A. M. Cheremukhin directed the construction of the new tunnel based on the work of Gurgen Musiniants and B. N. Yuriev. A design team led by K. K. Baulin and Musiniants built a prototype model at the Moscow Technical School beforehand. The T-I part of the tunnel was fitted with a quaternary balance. It tested wing shapes and airfoil sections, particularly foreign aircraft, including the Fokker F-II single-engine, cantilevered wing transport. At the time of its completion, T-II was the largest wind tunnel in the world. It was large enough to hold the fuselage of a single-engine aircraft and significant other parts of complete aircraft.[20] The tunnel itself had two pressure-type test sections of an octagonal cross section. The T-I test section had a 3-meter diameter and an airflow rate of 60 meters per second with a honeycomb latticework to smooth the flow or 100 meters per second without one. The T-II test section had a larger cross section of 6 meters and a flow rate of 27 meters per second with the honeycomb. The tunnel tested propellers and aircraft spin characteristics.[21]

Considerable research was conducted in T-I/T-II for many years, particularly in studying drag reduction in wings and fuselages. Particular attention was paid to the study of wing fillets; the effects of retractable landing gear and fairings; the beneficial results revealed by careful elimination of excess openings; and the increased drag caused by added aircraft components, such as radiators and air intakes.[22]

Following the opening of T-I/T-II, Musiniants visited German aerodynamics pioneer Ludwig Prandtl at Prandtl's laboratory in Göttingen. Inspired by what he had learned, Musiniants recommended constructing another wind tunnel, designated T-5, patterned after one of Prandtl's tunnels. T-5 had an open test section, a circular section of 2.25 meters, and a flow rate of 50 meters per second with a back channel and six-component balance. It also was fitted with a turntable. The primary advantage of T-5 was the extremely low turbulence number.[23]

This cooperation with Germany was not unusual. After the First World War, Weimar Germany and communist Russia were pariah nations. Following the turmoil of civil war in former Imperial Russia and several uprisings in Central and Eastern Europe, an uneasy peace descended upon Europe. Germany was saddled with crippling reparations and runaway inflation while the Bolsheviks in Russia

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[18] Ibid., p. 22

[19] Ibid., p. 23.

[20] Ibid., p. 24.

[21] Ibid., p. 24.

[22] Ibid., p. 37.

[23] Ibid., p. 24.

were shunned by Europe and the United States and left destitute to rebuild their bankrupt economy.

On 16 April 1922, Germany and Russia signed the Treaty of Rapallo, renouncing all territorial and financial claims against each other. The two governments also agreed to normalize diplomatic relations and, according to the text of the treaty, to "co-operate in a spirit of mutual goodwill in meeting the economic needs of both countries." Part of the normalization of relations was the secret agreement for both parties to provide military aid.[24]

As part of the treaty, Russia offered Germany the use of Russian facilities deep inside the country and far from the eyes of the former Allies. The Germans were thus able to circumvent the Versailles Treaty restrictions and begin to rebuild and train their army and air force. In turn, the Russians requested and received invaluable technical assistance on all forms of military technology, especially aviation.

Before the ink was dry on the Treaty of Rapallo, Weimar Germany sent aircraft pioneer Hugo Junkers and a team of engineers to design and build an aircraft factory at Fili, just west of Moscow. The plant was a joint operation with the Russian government with the promise by Russia to purchase several hundred aircraft. Junkers was the world's leading and advocate of all-metal aircraft and pioneered the use of duralumin, the strong yet lightweight aluminum alloy invented by German Albert Wilm in 1906. Junkers's unique corrugated duralumin provided additional strength to his designs. It became a hallmark feature of his aircraft through the late 1930s, copied by many, including William Stout in the United States with the famous Ford Tri-Motor. He also invented the cantilevered wing, which significantly reduced drag because its support structure was internal, and the thick airfoil provided significantly more lift than conventional thin airfoil shapes.[25] This advanced technology was delivered to TsAGI's doorstep, and they were quick to exploit it.

While the relationship between Junkers and Russia (after December 1922, the Soviet Union) was complicated and not as productive as hoped, it did provide invaluable technology transfer that greatly assisted the Soviets' nascent aviation industry. The leading proponent of all-metal aircraft in Russia was none other than TsAGI's chief designer, Andrei N. Tupolev, who embraced this construction material long before most designers from around the world were willing to accept it.

With the supply of duralumin heavily restricted by sanctions imposed by the French government, Tupolev formed a committee at TsAGI to promote metal

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[24] Higham et al., *Russian Aviation and Air Power in the Twentieth Century*, p. 129.

[25] John Anderson, *A History of Aircraft Technology* (Reston, VA: American Institute of Aeronautics and Astronautics, 2002), pp. 171–179.

aircraft production and the development of the Russian equivalent of duralumin, which they called "armored-aluminum."[26] In pursuing this new material, Tupolev began his work on creating TsAGI's first aircraft, and the first aircraft of his illustrious career and subsequent design bureau, the ANT-1.[27] This diminutive, single-seat, cantilevered low-wing sport monoplane featured Junkers's corrugated sheet metal and demonstrated this new metal alloy's utility and first flew in 1923. Tupolev and others in the Soviet aviation industry would rely on corrugated armored-aluminum for years to come.[28]

With the success of the experimental ANT-1, Tupolev and TsAGI designed and built a succession of larger and ever more capable aircraft, starting with the ANT-2 three-seat, high-winged light passenger aircraft that featured an enclosed passenger cabin. The ANT-3 was a successful all-metal biplane military reconnaissance bomber and mailplane and the first TsAGI aircraft built in significant numbers for the Red Air Force. Some 15 of the military R-3 versions were constructed.[29]

On 9 July 1924, the Soviet government's Special Technical Bureau for New Defense Technology gave TsAGI the task to build a new heavy bomber using its newly acquired technology. Unable to acquire a large all-metal bomber from Britain, Tupolev undertook his own design that could meet the requirement to carry at least 2,000 kilograms of bombs, mines, or torpedoes. A huge and very advanced aircraft for its time, the ANT-4 was a twin-engine low-wing bomber that could operate from conventional landing gear or floats. The ANT-4 flew many significant long-distance, record-setting flights, rescuing the crew of the trapped ship Chelyushin in 1931.[30] It is still widely, though incorrectly, believed in Russia that the appearance of an ANT-4 in the United States in 1929 inspired Boeing and other American manufacturers to use the all-metal twin-engine configuration for the new generation of bombers for the U.S. Army Air Corps.[31] Its arrival and its high level of technological sophistication surprised Tupolev's American peers.

Known as the TB-1 when in service, the aircraft fought in several conflicts with China in 1929 along the Chinese Eastern Railway. Later, as a transport, the TB-1 fought the Japanese at Khalkin-Gol in 1938–39; the Finns in 1939–40; and the Germans during World War II, as a transport, reconnaissance aircraft, glider tow, and parachute drop aircraft, serving well despite its obsolescence—a fine tribute to a design from the mid-1920s. It was also the first Soviet aircraft built at the Fili

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[26] Chernyshev and Bushgens, *TsAGI*, p. 22.

[27] Gordon and Ringmat, *OKB Tupolev*, p. 5.

[28] Ibid., pp. 15–16.

[29] Ibid., pp. 1–19.

[30] Davies, *Aeroflot*, pp. 26.

[31] Chernyshev and Bushgens, *TsAGI*, p. 26.

factory.[32] After 1932, a special TsAGI pilot plant built all Tupolev aircraft and developed and tested new techniques.

TsAGI underwent a significant reorganization in late 1931 that reflected the organization's growing responsibilities and capabilities. On 30 September 1931, A. I. Nekrasov became the head of the scientific and research sector because of his academic experience teaching theoretical mechanics at Moscow University. This new unit complemented the existing design and production sectors headed by Tupolev. In addition, G. A. Ozerov was placed in charge of the Airframe Strength Department at its inception in 1931. Under his leadership, TsAGI created the basic airframe strength research laboratories in Moscow and Tupolev's experimental design bureau.[33]

TsAGI's integrated approach from research to construction optimized decision-making for Tupolev and the other design bureaus. Therefore, Tupolev led the experimental aircraft construction at TsAGI, assigning designs to numerous young engineers, many of whom would later lead their own design bureaus, such as Polikarpov, Sukhoi, Myasishchev, Petlyakov, and Ilyushin.[34] Thus, Tupolev led the design team but allowed this younger generation the freedom to develop their skills, creating subassemblies of these aircraft, eventually assuming the design lead for the next generation of aircraft.

In 1930, Tupolev produced his ANT-6, a larger four-engine aircraft, which served as a heavy transport during the early 1930s and as a polar research aircraft. At this time, Tupolev began work on his famous ANT-25, which impressed Paris in 1936. Of great significance, the design bureau created the ANT-40, which was a high-speed medium bomber that was faster than contemporary fighters when it entered service with the Red Air Force. In service as the SB-2, this aircraft gained fame fighting in Spain and China and later during the Second World War.[35] The SB-2 also provided considerable technology to the new ANT-35 airliner.

With the ANT-40/SB-2 series, Tupolev and TsAGI had moved on from the Junkers style of corrugated duralumin construction to the building of modern aircraft composed of sleek, stressed-skin configuration, which continues today as the standard for all-metal aircraft.

Under orders from Soviet leader Joseph Stalin, TsAGI and Tupolev undertook designing and constructing a series of massive multi-engine aircraft for propaganda

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[32] Gordon and Ringmat, *OKB Tupolev*, pp. 22–28.

[33] Chernyshev and Bushgens, *TsAGI*, p. 29.

[34] Gunston, *Tupolev Aircraft Since 1922*, pp. 10–12.

[35] Mikhail Maslov, *Tupolev SB: Soviet High Speed Bomber* (Old Saybrook, CT: Icarus Aviation Press, 2004), pp. 103–163.

purposes.[36] Engineers Vladimir M. Petlyakov and Alexander Archangelsky were two of the primary designers for this machine. The eight-engine ANT-20, known as the Maxim Gorky, broadcast propaganda from the skies while carrying a printing plant to print the latest editions of *Pravda*, the Communist Party newspaper. It was the world's largest aircraft when it flew in the summer of 1934.[37]

During the mid-1930s, the Red Air Force recognized the potential for new long-range strategic bombers. Under the leadership of Iakov Alksnis in the Voyenno-Vozdushnyye Sily (VVS), the Red Air Force adopted the ideas of Italian bomber advocate Giulio Douhet, as had the Royal Air Force and the U.S. Army Air Corps. That the Red Air Force remained a purely tactical power during the forthcoming world war was a function of political intrigue, not of technological incompetence, for the Tupolev design bureau produced an impressive aircraft in 1936, the ANT-42.

Primarily designed by Petlyakov's design group under Tupolev's oversight, the ANT-42 was a large, four-engine, midwing monoplane made of stressed-skin duralumin. Its performance rivaled that of its American Boeing B-17 contemporary in speed, range, and payload. Known in service as the TB-7, it was later redesignated as the Petlyakov Pe-8. During the war, Pe-8s bombed Berlin in 1941. However, few were built after the Red Air Force turned to tactical bombardment following the arrest and execution of Red Air Force chief Alksnis. The need for Petlyakov Pe-2 high-speed twin-engine tactical bombers outweighed the need for strategic heavy bombers, and Petlyakov built only 93 of these aircraft.[38] A Pe-8 flew the People's Commissar of Foreign Affairs, Vyacheslav Molotov, from Moscow to Washington, DC, by way of Britain to meet with President Franklin Roosevelt in May 1942.

The ANT-42/TB-7/Pe-8 was the last significant aircraft produced by Andrei Tupolev as part of TsAGI. In 1936, TsAGI reorganized once again, this time as a purely research-focused organization. Tupolev continued his work, but now as the head of his own design bureau (OKB) as TsAGI's experimental OKB disbanded.

Other changes had taken place. In February 1931, S. A. Chaplygin stepped down as the chairman of TsAGI, although he stayed with the organization to continue his research in TsAGI's newly formed facilities in Novosibirsk, Siberia. N. M. Kharlamov was appointed in his place and would lead TsAGI through the early

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[36] Scott Palmer, *Dictatorship of the Air: Aviation Culture and the Fate of Modern Russia* (New York: Cambridge University Press, 2006), pp. 204–219.

[37] Gordon and Ringmat, *OKB Tupolev*, pp. 46–49.

[38] Yefim Gordon, *Soviet Air Power in World War II* (Hinckley, England: Midland Publishing, 2008), pp. 390.

and mid-1930s during a period of significant change that required his leadership and expertise.[39]

TsAGI understood that the key to an aircraft's performance was the efficiency of its propeller. By 1930, serious research efforts were under way to learn how to increase the thrust of fixed-pitch propellers, particularly the work of G. I. Kuzman. TsAGI gathered data on the complex airflows generated by propellers around the wings and fuselage in the hope of reducing interference and thereby reducing drag. Following the lead of Frank Caldwell in the United States, TsAGI examined the potential improved efficiencies of the new variable-pitch propeller technology pioneered by the Hamilton Standard Company.[40]

Work also examined the utility of flaps and other aerodynamic devices to improve lift at low speed to shorten takeoff and landing distances.[41]

TsAGI wrestled with the problem of flutter beginning in 1931 and formed a special unit for the express purpose of studying this dangerous phenomenon. Many engineers worked on this and, by 1937, were able to develop aerodynamic flutter theory and a methodology to predict flutter through the use of modeling.[42]

TsAGI did not ignore aircraft structures and, over time, developed a series of "Aircraft Strength Standards" for the industry based on the examination of flight loads on aircraft. The first standards were published in 1926 and updated with new standards in 1934. An improved version was distributed in 1937.[43] Interestingly, a report on static strength, strength analysis, and the validation of aircraft strength through testing was produced by Sergei V. Ilyushin in 1931. Ilyushin would create the famous Ilyushin Il-2 Shturmovik attack bomber during World War II, the most widely produced aircraft in history. He would also lead a design bureau that specialized in large military and commercial transports. The Ilyushin design bureau, like that of Tupolev, is still in existence.[44]

Under Kharlamov's direction, TsAGI developed a series of design requirements for various potential aircraft designs based on the accumulation of the first 15 years of research. In 1937, TsAGI published its first user's manual for aircraft designers. Entitled *Airplane Designer Manual—Volume 1—Airplane Aerodynamics*, this work became the textbook of aeronautical information for the Soviet aircraft industry. The manual extensively covered the aerodynamics of wings and propellers, stability

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[39] Chernyshev and Bushgens, *TsAGI*, p. 30.

[40] Ibid., pp. 37–38.

[41] Ibid., p. 38.

[42] Ibid., p. 41.

[43] Ibid., pp. 39–41.

[44] Yefim Gordon, Dmitriy Komissarov, and Sergey Komissarov, *OKB Ilyushin: A History of the Design Bureau and its Aircraft* (Hinckley, England: Midland Publishing, 2004), pp. 14–46.

and control, spin, engine cooling, and testing methods used in wind tunnels and actual flight tests.[45] By 1939, TsAGI had published the third manual (and the second devoted to aircraft), *Aircraft Designer Manual—Aircraft Strength*, which laid out the guidelines for structures and structural testing.[46]

Working in the confines of Moscow limited the ability of TsAGI to conduct the research it wished to do. New facilities built in large, underdeveloped areas were required to allow the organization to expand and continue providing the science and engineering the Soviet aviation industry demanded. TsAGI especially needed additional testing facilities to validate their theoretical discoveries. With engines becoming more powerful and propellers more efficient, significant increases in speed were possible. Unfortunately for TsAGI, it was becoming an increasing challenge to produce flight-test results that reflected laboratory results. Newer and larger wind tunnels were needed.[47]

In 1931 and 1932, teams of TsAGI designers and scientists toured Europe and the United States to learn about those countries' research facilities. In particular, Andrei Tupolev visited the NACA Langley Memorial Aeronautical Laboratory's facilities in Hampton, Virginia, and returned home impressed. Of particular interest was the NACA's newest tool, the Full-Scale Tunnel, which opened in 1931. This massive double-return atmospheric pressure tunnel with a 30- by 60-foot (9- by 18-meter) open throat tested complete actual aircraft at speeds of up to 118 miles per hour, which would produce the most accurate data by far—vastly superior to models. It featured two large fans, each driven by a 4,000-horsepower electric motor.[48]

On 21 April 1933, TsAGI chief Kharlamov applied to P. I. Baranov, the People's Commissar Deputy of Heavy Industry, for the funds to build a full-scale tunnel. Four months later, the Labor and Defense Council approved the construction of the "new TsAGI" near the train station at Otdykh near Ramenskoi (now Zhukovsky). Established along the Kazan railroad track, the new location provided easy access to Moscow to the west and provided an extensive level expanse for new facilities. It was also near a reservoir so that TsAGI's other work in hydrodynamics could also benefit.[49] On 31 October, Kharlamov authorized the construction of the full-scale tunnel, designated T-101, and a smaller, though equally significant,

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[45] Chernyshev and Bushgens, *TsAGI*, p. 41.

[46] Ibid., p. 41.

[47] Ibid., p. 43.

[48] Joseph R. Chambers, *Cave of the Winds: The Remarkable Story of the Langley Full-Scale Wind Tunnel* (Washington, DC: NASA, 2014), pp. 16–24.

[49] Chernyshev and Bushgens, *TsAGI*, pp. 43–44.

propeller tunnel designated T-104. Actual construction began in the spring of 1935, with its completion four years later.[50]

T-101 was similar to the NACA's Full-Scale Tunnel. It, too, was a double-return type with an open throat with two four-bladed fans and two reverse channels. The test section was 77 by 45 feet (24 by 14 meters) and powered by 30 kilowatts of electricity, which provided a maximum airflow rate of 157 miles per hour, significantly larger than the NACA's tunnel.[51]

In order to design such a large tunnel, TsAGI wisely constructed a 1:6 scale version to test the efficacy of their plans. This tunnel, T-102, was similar in design but much smaller. T-102 was used to examine the phenomenon of flow pulsation, a critical problem that had to be solved before building a large tunnel. Flow pulsation was detected earlier in the T-5 tunnel in Moscow and was inherent because of the creation of circular vortices coming off the tunnel's nozzle. This was an inherent problem with any tunnel with an open test section, but it was particularly dangerous in large tunnels where the pulsation created destructive vibrations inside the wind tunnel and even the building. Using T-5, TsAGI engineers learned to use modified diffusers downstream of the test section to stabilize the airflow. Using T-102, S. P. Strelkov used thin blades to split the vortices, thus smoothing the flow and eliminating the problem.[52] Once the design of T-101 was verified, T-102 was used for research, providing additional data on large-scale models.[53]

Concurrent with the development of T-101, TsAGI proceeded with the smaller T-104. T-104 was intended for propeller research and required higher speeds. Using two 15-kilowatt electric motors driving two eight-bladed fans, the smaller tunnel was a continuous-operation type with a 22.5-foot circular cross section with two blowers and one reverse channel. It could generate wind speeds of up to 268 miles per hour. This ability would provide TsAGI with an invaluable tool for its propeller research as they could now explore the upper reaches of propeller efficiencies that previously had been difficult to achieve.[54] This tunnel's design was also tested with a smaller iteration, T-103, which had a single 10-bladed fan and motor that could produce an airflow of up to 246 miles per hour.[55]

T-101 and T-104 used aerodynamic balances manufactured by Toledo in the United States. These took measurements at various angles of attack and other

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[50] Ibid., p. 50.

[51] "Wind Tunnel T-101," Central Aerohydrodynamic Institute, *http://tsagi.com/experimental_base/wind-tunnel-t-101/*.

[52] Chernyshev and Bushgens, *TsAGI*, pp. 47–48.

[53] Ibid., p. 46.

[54] Ibid., p. 45.

[55] Ibid., p. 47.

angles relative to the airflow. The equipment also allowed engineers to vary the center of gravity of the test aircraft with the tunnel running, saving a great deal of time during experiments.[56]

T-101 and T-104 opened in August 1939, just days before Nazi Germany invaded Poland to start World War II in Europe. While these were under construction, in 1938, TsAGI gained approval to design and build a vertical aerodynamic tunnel to study the problem of spin. Designated T-105, this tunnel was designed to test free-flying models. It had a 22.5-foot open cross section and a single 450-kilowatt motor that generated a continuous 90-mile-per-hour airflow. T-105 opened in August 1941, two months after the German invasion of the Soviet Union.[57]

This massive spending did not go unnoticed at the highest levels. On 5 May 1938, members of the TsAGI leadership were summoned to the Kremlin to report directly to Soviet dictator Joseph Stalin. Stalin took a particular interest in all aviation matters, often berating or encouraging designers to improve their aircraft. The consequences of displeasing Stalin were often severe. In this case, after lengthy and intense questioning, professors Gurgen Musiniants and A. K. Martynov defended their expenditures to Stalin's satisfaction.[58]

With Stalin's approval, TsAGI secured additional funding for a more audacious project, the construction of T-106, an alternating-pressure transonic wind tunnel. At Tupolev's suggestion, TsAGI reached out to prominent aerodynamicist Dr. Theodore von Kármán at the Guggenheim Aeronautical Laboratory at the California Institute of Technology in the United States for help in designing the new tunnel.[59] Working with TsAGI, von Kármán, a student of Ludwig Prandtl and the leading aerodynamicist concerning supersonic flight, helped design the new tunnel completed in 1942 after four years of work.

T-106 was a continuous-flow tunnel with an enclosed 9.5-foot-diameter test section. The 20-kilowatt motor drove a compressor that could produce a range in pressure from 0.15 to 6.7 atmospheres. The airflow circulated at speeds between 0.15 and 0.9 Mach. This was later increased to 1.2 Mach.[60] This new tunnel made it possible for TsAGI to study transonic flow and, in particular, seek ways of solving the problem of compressibility of the airflow around airfoils. This phenomenon

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[56] Ibid., p. 49.

[57] Ibid., p. 51.

[58] Ibid., p. 52.

[59] Michael Gorn, *The Universal Man: Theodore von Kármán's Life in Aeronautics* (Washington, DC: Smithsonian Institution, 1992), p. 103.

[60] Malinda Goodrich, Project Manager, *Wind Tunnels of the Eastern Hemisphere* (Washington, DC: Federal Research Division, Library of Congress), p. 375.

dangerously hampered control and prevented propeller-driven aircraft from exceeding speeds of 500 miles per hour.

As the performance of wind tunnels improved, TsAGI discovered that the existing quality of model-making was insufficient to gather accurate data. Conventional models carved from hardwood deviated as much as 0.4 millimeters from the intended design. These simply would not work in T-106 with its high Mach and Reynolds numbers. All metal models were accurate but difficult to make and very difficult to modify. TsAGI developed new models with the All-Russia Institute of Aircraft Material by making models with a solid steel core covered in resin-impregnated wood skin. This resulted in more accurate models, with only a 0.01- to 0.02-millimeter deviation that could also be quickly modified.[61]

In 1941, as World War II began in the Soviet Union, TsAGI opened a new research laboratory at their Airframe Strength Department. The new facility included a sizable static test room, a mechanical lab for material and structures testing, and a dynamic test room that conducted drop tests on landing gear. All were built of reinforced concrete to withstand the heavy stress on the aircraft and aircraft parts. The static test room had 11 moving cranes.[62]

Remarkably, the new TsAGI laboratory was built within the span of only seven years. For the most part, it was built by hand under the most trying conditions of a totalitarian state because the Soviet Union lacked significant quantities of modern construction equipment. The results were, nonetheless, impressive. According to TsAGI's official history: "All the above mentioned developed a strong foundation for research investigations in the aviation field and played a tremendous role in the subsequent years for strengthening this country's defensive ability."[63]

The dedicated work of Kharlamov and Andrei Tupolev paid huge dividends in building Soviet aviation and a viable air force for the conflict to come. Their work was not rewarded.

As Joseph Stalin consolidated his power after Vladimir Lenin's death in 1924, the Soviet Union slipped deeper into the nightmare of a total dictatorship. He crushed all forms of dissent and imprisoned, tortured, and executed enemies, real and imagined. In the Ukraine and other agricultural regions, he forced the peasantry to surrender their land and join collective farms under state control as Moscow sought to crush regional dissent. Millions of citizens died of starvation as production dropped, and Stalin sent the grain from these regions overseas in return for currency. The Soviets used this currency to pay for his first two Five-Year Plans

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[61] Chernyshev and Bushgens, *TsAGI*, p. 55.

[62] Ibid., p. 57.

[63] Ibid., p. 57.

to industrialize the nation, which included subsidizing Junkers and the Germans at Fili. A massive prison system spread throughout the nation as Stalin's drive for total power and paranoia grew. Whole classes of industry, agriculture, and military professionals were eliminated and replaced with rigid, inexperienced party functionaries. By 1941, Stalin was in complete control. According to TsAGI's history: "The 1930s was a time of relentless state centralization of the aviation industry and aviation science administration. This enabled the achievement of tremendous results in technological expansion by the beginning of the war.

Strict discipline and responsibility, especially at that time, played a positive role in the prewar years, especially during the war period. Simultaneously, in some cases, the system generated formalism in handling the directive problems and constrained the scientists' initiative. The administration at the top level was sometimes not equipped with professional technological skills. "Indefensible administration methods using repression that was harmful to the development of science and technology was a tragic consequence of the era."[64]

Stalin's purges touched every part of Soviet society. By the late 1930s, the secret police, the NKVD, focused their attention on weeding out nonexistent "enemies of the people" in science and industry. TsAGI's turn came in 1937, when TsAGI chairman N. M. Kharlamov—the architect of the new TsAGI—was arrested on trumped-up charges and shot.[65] His replacement lasted four months. Kharlamov had promoted TsAGI engineer A. M. Cheremukhin to head the experimental aircraft design bureau in 1931. From 1935 until 1937, he oversaw the myriad construction projects at the new location. He was imprisoned in 1938.[66] A. I. Nekrasov, the Deputy Head for Research Science and a distinguished professor, was arrested in 1937.[67]

Perhaps the most egregiously unfair arrest was that of Andrei Tupolev himself. Despite a life dedicated to TsAGI, Soviet aviation, and his long list of advanced aircraft, he was falsely accused of spying for the Germans and for giving them the plans for the Messerschmitt Bf-110 twin-engine fighter. His dedicated colleague, Vladimir M. Petlyakov, was arrested and thrown in prison, as were Nikolai Polikarpov, Vladimir Myasishchev, Robert Bartini, and others. Sergei P. Korolev, the future architect of the Soviet space program, served time with Tupolev. Konstantin Kalinim and Vladimir Chizhevsky were executed.[68]

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[64] Ibid., p. 58.

[65] Ibid., p. 30.

[66] Ibid., p. 50.

[67] Ibid., p. 29.

[68] Gunston, *Tupolev*, p. 12.; L. L. Kerber, *Stalin's Aviation Gulag: A Memoir of Andrei Tupolev and the Purge Era* (Washington, DC: Smithsonian Institution Press, 1996), pp. 149–240.

Tupolev was held in the infamous Lubyanka prison in Moscow for almost a year after his arrest on 21 October 1937. Sukhoi took over his work on the ANT-46 attack bomber, but progress was slow without the team leader. Eventually, Lavrenti Beria, the head of the NKVD, summoned Tupolev and reassigned him to a small prison near Moscow, and here he started designing aircraft while under armed guard. Realizing that the Red Air Force needed a fast attack bomber to replace his aging SB-2, Tupolev began designing "Airplane 103." He could not use his name or former designation for this or any aircraft designed while incarcerated.

Despite his prisoner status, Tupolev was widely respected. The NKVD granted his request for larger quarters. With extreme irony, he and his team returned to their original experimental design office building in Moscow, only under lock and key, where they continued their work under the eyes of their NKVD guards. Despite constant interference and questioning from Beria, the design of Airplane 103 quickly took shape and flew in January 1941. Fortunately, it flew beautifully, and the resulting aircraft, redesignated the Tu-2 after Tupolev was freed following the German invasion of the Soviet Union, became one of most outstanding attack bombers of the war.[69] By this time, the other prisoners also had been released and were allowed to return to work unescorted. One of them, Vladimir Petlyakov, also had designed an aircraft while in prison, the Pe-2 dive bomber, which became a mainstay of the Red Air Force during the war. Its success won Petlyakov his freedom.[70]

The Purges crippled TsAGI's work at one of the critical periods in Russia and the Soviet Union's history. With Hitler's menacing forces gathering in the east, the Soviet Union should have prepared a new series of modern aircraft. Unfortunately, its best scientists and engineers were either in prison or threatened with violence. Regardless, TsAGI did the best it could with the resources at hand. According to its official history, "TsAGI members personally directed and made recommendations regarding aerodynamic improvements as well as maintenance of stability and controllability of any given aircraft. During the pre-war period, work on the creation of combat aircraft used in the Great Patriotic War (Yak-1, MiG-1, LaGG-3, and others) were also based mainly on tests in the aerodynamic tunnels at TsAGI in the Moscow territory."[71]

New aircraft were on the horizon, especially fighters from new design bureaus such as Yakovlev and Lavochkin, as well as the famous Il-2 "Shturmovik" ground attack bomber from Ilyushin. However, it took time to develop these aircraft and

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[69] Ibid., p. 13.

[70] Gordon, *Soviet Air Power*, pp. 364–368.

[71] Chernyshev and Bushgens, *TsAGI*, p. 39.

get them produced in sufficient numbers. Time was not a luxury when the Nazis invaded the Soviet Union on 22 June 1941.

Fortunately, one year earlier, General I. F. Petrov had been appointed chairman of TsAGI. While he resigned to rejoin the army after the invasion, his 11-month tenure marked the return of professionalism to ranks as he replaced party appointees with qualified scientists throughout the organization. His successor, Ivan V. Ostoslavsky, guided TsAGI through the war and paid particular attention to improving the quality of life at the new TsAGI. The rise of Ostoslavsky to Deputy Director of TsAGI placed one of the Soviet Union's most gifted scientists in a critical position. He led TsAGI's efforts to study drag reduction, propeller efficiency laminar flow, and improved aerodynamics.[72]

Driven by the exigencies of war, TsAGI reorganized again to streamline its work. This time, the Aerodynamic Laboratories were consolidated from three to two facilities. Laboratory #1 was responsible for aircraft aerodynamics, including the airframe, propellers, and propulsion. Led by S. S. Sopman and later I. V. Ostoslavsky until the end of the war, Laboratory #2 handled airframe sections' aerodynamics, including airfoils and wing design. S. A. Kristianovich led studies on payload aerodynamics.

Known as the Great Patriotic War in the Soviet Union, World War II in Eastern Europe swept over European Russia. In a matter of months, the German ground and air forces mauled the Red Army, which suffered millions of casualties, and the obsolescent Red Air Force was virtually wiped out. Nazi troops advanced swiftly and, by the late fall of 1941, were at the gates of Moscow and Leningrad. In a desperate and audacious attempt to salvage their economy, the Soviet government moved hundreds of factories and their workers east toward the Ural Mountains and even further into Siberia and the Soviet Far East. Although terribly disruptive, these efforts preserved the Soviets' production capacity and enabled the crippled nation to continue fighting. This and timely aid from the western Allies enabled the Soviets to survive.

For a time, TsAGI had to leave Moscow. Earlier, Sergey A. Chaplygin had left the new TsAGI. He had moved to Novosibirsk in the heart of Siberia, where he led the establishment of a new arm of TsAGI, safely behind the Urals and far from the Germans. Facilities were also opened in Kazan, far from Moscow. After the Germans were hurled back from Moscow's gates by the Red Army in December 1941, most of TsAGI's staff returned to Moscow and their new laboratories in Ramenskoy and got back to work.[73]

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[72] Ibid., pp. 59–61.

[73] Ibid., pp. 69–70.

For TsAGI, the first priority was to find ways of improving the performance of existing aircraft. The most pressing need was for the scientific examination of the problem of drag. Working 14-hour days for the duration of the war, TsAGI sought ways to identify the hidden sources of drag that robbed supposedly sleek aircraft of their expected performance. The NACA had earlier noticed that many high-performance fighters at the time, such as the Brewster F2A Buffalo and the Seversky XP-41, failed to exceed 300 miles per hour, despite their engineers' careful calculations. The NACA used its Full-Scale Wind Tunnel to gather the most accurate data possible; their efforts revealed numerous unexpected sources of additional drag and allowed them to take measures to eliminate it.[74] TsAGI engineers recognized the same problems and conducted extensive tests on virtually every single- and twin-engine aircraft that could fit in the massive T-101 tunnel.[75]

Recognizing the need for an easily produced high-performance fighter built from non-strategic materials, designers Semyon Lavochkin, Vladimir P. Gorbunov, and Mikhail Gubkov joined forces and designed a compact single-engine fighter. They were engineers from the People's Commissariat for the Aircraft Industry (NKAP). Formed in 1938, this organization was responsible for constructing aircraft, engines, propellers, weapons, and systems. TsAGI had stopped designing and building its own aircraft in 1936, when Tupolev organized his design bureau.[76] Their new aircraft, the Lavochkin LaGG-3, had a contemporary design with a cantilevered, low-mounted wing; retractable landing gear; and an enclosed cockpit. Despite Tupolev's advocacy of all-metal construction, the LaGG-3 was made primarily from wood, plywood, and "delta timber," impregnated with birch veneer tar. Since Hitler's rise to power in 1933, the Soviet Union's supply of strategic materials such as duralumin was cut off, and the Soviet metals industry had not yet expanded to fill the gap. In the meantime, these three designers and others sought to use the Soviet Union's inexhaustible supply of high-quality lumber in its place.[77]

The LaGG-3 first flew in 1940 and, by 1942, was numerically the most important Soviet fighter on the Eastern Front. The prototype's performance was excellent, with a top speed of 376 miles per hour, as good as or better than its German counterparts. Unfortunately, the production version fared poorly. In service, the aircraft was overweight, climbed slowly, and was 10 percent slower than promised. The workmanship was poor on production versions because of a lack of suitable

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[74] Chambers, *Cave of the Winds*, pp. 96–102, 113–114.

[75] Chernyshev and Bushgens, *TsAGI*, p. 71.

[76] Gordon, *Soviet Air Power*, p. 3.

[77] Ibid., p. 199.

carpenters. This, in turn, had a deleterious effect on the aircraft's aerodynamics by causing unexpected drag.[78]

The state gave TsAGI the task to help Lavochkin fix the LaGG-3's flaws. Using the T-101 full-scale tunnel, TsAGI started a rigorous drag reduction program. By carefully testing the existing airframe and methodically removing or fairing over all possible areas of drag, they were able to ascertain baseline drag data. Then they reintroduced the potentially problematic features to measure the increase in drag and, lastly, modified or redesigned the most egregious parts to improve the aircraft's aerodynamics.

A liquid-cooled Klimov V-105 V-12 engine of 1,200 horsepower powered the LaGG-3. Its installation was the most significant cause of excessive drag. After lengthy testing in T-101, TsAGI recommended changes in the oil radiator tunnel design and the coolant radiator tunnel. This improvement alone bought them 10 miles per hour. Sealing the fuselage and fully enclosing the retractable landing and tail wheel gained another 10 miles per hour; improving the wing finish and making the wing more accurately follow the airfoil shape provided 10 more miles per hour. Once the exhaust fairing and cockpit canopy were improved, TsAGI increased the top speed of the LaGG-3 by more than 30 miles per hour.[79] Once TsAGI learned of these additional sources of unexpected drag, it circulated its findings throughout the industry to improve other aircraft.

The LaGG-3 was a decent fighter, but it did not perform as well as its foreign contemporaries. Aware of its shortcomings, Lavochkin teamed with Arkadiy Shvetsov, the chief designer of the Perm engine plant Number 19 that made the powerful M-82 14-cylinder, twin-row radial engine. Shvetsov had a backlog of engines that needed to find a home; Lavochkin had an airframe that needed more power. By September 1941, an M-82 powered version of the LaGG-3 had taken to the sky.[80]

Combining a wide radial engine with a slim fuselage of an aircraft initially intended to have an inline "V" engine was challenging. The center of gravity of the aircraft shifted forward. The forward fuselage required a complete redesign and reengineering to accept the heavier powerplant. Engine cooling required an NACA-style cowling with pronounced cooling flaps. After an arduous gestation, the new fighter appeared on the front lines in June 1942 and quickly proved itself in combat.[81]

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[78] Ibid., pp. 202–203.

[79] Chernyshev and Bushgens, *TsAGI*, p. 71.

[80] Gordon, *Soviet Air Power*, pp. 218–219.

[81] Ibid., pp. 222–223.

Now known as the La-5, the new fighter was a marked improvement over the LaGG-3. However, like its predecessor, the performance difference between the prototype and actual production aircraft was significant. Rushed assembly played a role, but the critical problem was with the engine and its installation. The La-5 was prone to overheating, and, as such, the engine could not operate at its maximum output for fear of failure. The cowling was not as streamlined as it needed to be, and the blending of the radial with the slender fuselage was not as aerodynamic as possible. TsAGI estimated that 30 percent of the engine's output was lost to excessive heat and drag through its engine development program.[82]

Immediately before the war, TsAGI undertook a program to confront the problem of engine cooling and drag. Using the T-101 tunnel, in particular, they made a series of discoveries and subsequent recommendations to redesign oil coolers to decrease frontal drag and streamline the NACA-style cowling's interior and exterior to improve airflow. These lessons were applied by TsAGI when they evaluated the La-5 on behalf of the government.[83]

In early 1943, TsAGI conducted a series of flight tests and numerous experiments of the La-5 in the T-101 full-scale wind tunnel. Concurrent with these studies, Shvetsov developed an improved M-82 to solve the recurring problem of burned spark plugs; the short, 10-hour engine life; and burned exhaust pipes. TsAGI recommended several changes, including sealing the engine cowling joints, lengthening the air inlet above the cowling, increasing the exhaust pipes' diameter for better cooling, and strengthening the tailwheel doors. These seemingly small changes reaped significant benefits, providing an additional 12 miles per hour to the La-5. When fitted with the new M-82 FNV fuel-injected engine, the new La-5FN became a world-class fighter with an additional 21 miles per hour and a new top speed of 402 miles per hour, comparable in performance to the best aircraft from the western Allies and Germany.[84]

Despite their success, TsAGI continued to work on improvement to this fighter. In summer 1943, TsAGI began a detailed analysis of the La-5FN in cooperation with the Lavochkin design bureau. Extensive testing in T-101 and flight trials until early 1944 produced a superlative fighter with significantly cleaned-up lines and better aerodynamics. They sealed the cowling more thoroughly, relocated the air intake to inside the leading edge of each wing, and moved the oil cooler to the lower fuselage under the cockpit. Individual exhaust stacks were fitted to the engine, and the exhaust system was redesigned for better efficiency. TsAGI also recommended

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[82] Chernyshev and Bushgens, *TsAGI*, p. 66.

[83] Gordon, *Soviet Air Power*, p. 226.

[84] Ibid., p. 227.

cutting the aircraft's weight to improve its climbing ability and maneuverability. To this end, a duralumin spar replaced the impregnated wooden wing spar, which saved several hundred pounds.[85]

The new 1944 version of the La-5, soon redesignated the La-7, was also fitted with what TsAGI called a "Mach resistant blade airfoil."[86] TsAGI applied many of its resources and much of its technical expertise to the question of propellers. Using T-104, their full-scale propeller wind tunnel, TsAGI explored the problem of compressibility on propeller blades. This enabled the institute to create new blade configurations and airfoil shapes, as well as better finishes to delay the onset of compressibility and improve propeller efficiency.[87] A "Mach-resistant airfoil" propeller was fitted to the new aircraft. Lavochkin accepted all of these recommendations and produced one of the best fighters of the war. Most of the top aces—including Ivan Kozhedub, the leading Soviet and Allied ace with 62 victories—flew the La-7.[88]

TsAGI worked tirelessly through the war, tackling many other challenges as well. The famous Ilyushin Il-2 Shturmovik ground-attack aircraft ravaged the German invaders throughout the war. Heavily armed and armored, the Il-2 had a deserved reputation for ruggedness and devastating firepower. TsAGI improved the aircraft's aerodynamics, particularly for the Il-2m3 two-seater, which featured counterbalances for better elevator control and a slightly swept wing to improve center of gravity shortcomings in the original design.[89] More importantly, TsAGI led the redesign of the Il-2 into the more powerful, all-metal Il-10 that saw service toward the end of the war and into the Korean conflict. After their thorough evaluation and subsequent recommendations, the much-improved Il-10 could fly almost 100 miles per hour faster than its predecessor could.[90]

The series of fighters produced by Alexander Yakovlev did not escape TsAGI's attentions. Yak fighters were all low-wing monoplanes, each powered by a single Klimov M-105 V-12 engine of various models and horsepower. Yaks were famous for their lightweight, superb maneuverability, as well as their excellent climbing ability. The Yak-1 entered service in early 1941, just before the war began, followed by the improved Yak-7 type. These high-performance aircraft bore the brunt of air combat in the early days of the Great Patriotic War, performing with distinction despite the odds.

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[85] Ibid., p. 235.

[86] Ibid., p. 235.

[87] Chernyshev and Bushgens, *TsAGI*, p. 66.

[88] Green, p. 135.

[89] Gordon, *Soviet Air Power*, p. 294.

[90] Chernyshev and Bushgens, *TsAGI*, p. 91.

Figure 2: TsAGI's recommendations to clean up the aerodynamics of the Yak-7B resulted in the excellent Yak-9 fighter. The long-range Yak-9D, shown here, featured mixed wood and metal construction and was a match for contemporary Messerschmitt Bf 109s and Focke Wulf Fw 190s. (Image credit: National Air and Space Museum, Smithsonian Institution, image NASM 85-17696)

Regardless of its qualities, Yakovlev fighters suffered similar performance deficiencies between prototypes and production models. As with the Lavochkin series, Yaks were thoroughly tested by TsAGI in the T-101 and T-104 wind tunnels. TsAGI was able to increase the top speed of the Yak-1 by an additional 25 miles per hour, a considerable difference that could mean the difference between life and death for its pilot in combat.[91]

TsAGI played a crucial role in developing the widely used Yak-7B, recommending improvements to its air intakes and oil and coolant lines, as well as a smoother polished finish on the wings.[92] Fitted with aluminum alloy spars, the Yak-7B became the famous Yak-9 (figure 2), which in turn became the most widely used

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[91] Ibid., p. 71.

[92] Ibid., p. 71; Yefim Gordon, Dmitriy Komissarov, and Sergey Komissarov, *OKB Yakovlev: A History of the Design Bureau and Its Aircraft* (Hinckley, England: Midland Publishing, 2005), pp. 93–94.

fighter in the Red Air Force by the summer of 1944. Following in TsAGI's pioneering efforts, the Yak-9 and particularly its last versions, the powerful Yak-9T and Yak-9U, were built with a large proportion of duralumin, which, by 1944, was no longer in short supply.[93]

TsAGI conducted considerable analyses of the fastest version of the Yakovlev fighter series, the Yak-3. Designed as a lightweight low-altitude fighter and fitted with a more powerful 1,500-horsepower VK-107 engine, it was smaller, significantly faster, and aerodynamically cleaner than its diminutive Yak brethren. Testing in the TsAGI wind tunnels showed engineers how to gain an extra 18 miles per hour, giving the Yak-3 a maximum speed of 447 miles per hour and making it the fastest Soviet fighter of the war,[94] faster than the superlative North American P-51D Mustang from the United States.

The P-51's excellent performance was correctly attributed to its revolutionary airfoil design. For years, the NACA worked to develop a laminar flow wing that would smooth the boundary layer and significantly reduce drag at high speeds. The P-51 was the first production to feature such an airfoil. Although pure laminar flow was almost impossible to achieve in practice, the new airfoil did lower drag, thereby improving range and high-speed lift. This new wing cross section intrigued TsAGI's engineers with its possibilities; they conducted numerous tests with their version of a laminar flow wing. The engineers fitted a wing to a Yak-7B for flight tests, and another fitted to an La-7 for tunnel testing in T-101.[95] TsAGI converted an Ilyushin Il-4 medium bomber as a flying laboratory and attached a laminar flow wing section vertically over the fuselage center.[96] Using the bomber, TsAGI was also able to experiment with the possibility of boundary layer control that held the promise of markedly improving lift, especially at low speeds. Engineers also conducted work on a specially built glider that had a laminar flow wing. These efforts created a series of new airfoils and a much better understanding of the boundary layer and the transition from laminar to turbulent flow. These efforts were later used on a series of new airfoils developed exclusively by TsAGI during and after the war.

During the war, Red Air Force pilots frequently encountered the phenomenon of compressibility as the aircraft approached transonic speeds in a dive. TsAGI studied this phenomenon at great length, first with propellers and later with aircraft. As early as 1941, Soviet aircraft designers were experimenting with rocket-powered aircraft. The Berezniak-Isaev BI-1 was approved by Stalin as a point-defense

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[93] Gordon et al., *OKB Yakovlev*, pp. 102–130.

[94] Ibid., p. 144.

[95] Chernyshev and Bushgens, *TsAGI*, p .64.

[96] Ibid., p. 63.

interceptor and first flew on 15 May 1942. The design benefited from substantial work in TsAGI's T-101 and T-5 wind tunnels. Powered by a 1,100-pound-thrust rocket, the BI-1 made several successful test flights.[97] However, on 27 March 1943, the BE-1 nosed over and struck the ground during a high-speed run at low altitude. The aircraft had experienced compressibility, which forced it to tuck under or pitch down, causing its destruction.[98] S. A. Khristianovich's work was crucial to understanding compressibility, especially his theoretical work about how to decrease the intensity of wave growth and delay its formation to higher speeds. He studied and published his work concerning the compressible gas flow around an airfoil, based mainly on his research in the T-106 transonic wind tunnel.[99]

T-106 proved a beneficial asset during the closing years of the war. With victory on the horizon, Joseph Stalin summoned Artem Mikoyan, the lead designer for the Mikoyan Gurevich design bureau, to Moscow in February 1945 and directed him to build an original jet-powered aircraft, following the success of the German Messerschmitt Me-262 and the British Gloster Meteor. Sukhoi built an Me-262 copy while Yakovlev expediently modified his Yak-3 with a German Junkers 004 jet engine. Mikoyan took another route.

Using a new series of airfoils developed by TsAGI in its wind tunnels during the war, he produced the MiG-9, a straight-wing jet fighter. Before this, virtually every aircraft built in the Soviet Union, Germany, Great Britain, Japan, and the rest of the world depended on versions of the famous American Clark Y airfoil or, more likely, the NACA four-digit and five-digit series. With the coming of transonic flight in conjunction with the jet engine, TsAGI did not wait to see what the United States would produce. Instead, they developed their own series of airfoils that were the hallmark of all Soviet high-performance aircraft after the war. TsAGI also examined the relative merits of straight-wing jets versus swept-wing jets and determined that all future jet fighters would use TsAGI's swept-wing design.

In March 1942, TsAGI's former head, S. A. Chaplygin, who was now running the institute's facility in Novosibirsk, proposed that TsAGI assume responsibility for the development of jet-powered aircraft. As a result, in November 1942, G. N. Abramovich formed the first Jet Engine Department at TsAGI's Moscow offices under his leadership, just a month after Chaplygin's death. By early 1944, the Jet Engine Department had merged with the Research Institute; the combined organization worked on various types of jet propulsion.[100] Although not as advanced as

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97. Green, pp. 125–126.
98. Bill Gunston, *The Encyclopedia of Russian Aircraft, 1875–1995* (Osceola, WI: Motorbooks International, 1995), p. 44.
99. Chernyshev and Bushgens, *TsAGI*, p. 83.
100. Ibid., p. 82.

contemporary German or British jet research, the Jet Engine Department was in a strong position to benefit from the capture of much German technology at the end of the war and the fortuitous acquisition of British Rolls-Royce Nene and Derwent engines soon thereafter.

The culmination of TsAGI's wartime research became apparent in Korea when the superlative MiG-15 stunned the West with its excellent performance. The MiG-15 resulted from TsAGI's groundbreaking work during the Great Patriotic War and provided proof that Soviet aerodynamics had come of age.

TsAGI's most significant contribution during the Great Patriotic War was their work in drag reduction and airfoil research, but this was not all they did. They not only tested Soviet aircraft but also those of their allies and their enemies. Typically, captured German aircraft were flown and examined in wind tunnels to determine their flight characteristics. The lessons learned quickly disseminated throughout the Soviet aviation industry to improve current and future designs.[101] In the case of American aircraft, TsAGI thoroughly examined the Bell P-39 Airacomet, which had become a top-rated fighter with the Red Air Force. It did suffer from a structural weakness in the tail and was susceptible to high-speed stalls. TsAGI evaluated P-39s in their structural testing facility and wind tunnel T-101 and recommended reinforcing the tail to prevent failure. Changes were made to all of the P-39s in service and those subsequently received from the United States.[102]

During the war, TsAGI spent great effort examining structural stress. Testing aircraft components to the point of destruction revealed many points of weakness in many aircraft. TsAGI developed sophisticated evaluation techniques that helped create more robust and more durable designs. Work on composite wood and metal and phenol-impregnated plywood improved the durability of most Soviet combat aircraft.[103]

TsAGI also studied aerodynamics around enclosed canopies. Many pilots found that they could not jettison the canopy during emergencies because the pressure of the airflow was too strong for the pilot to overcome when pulling back the canopy at speed. TsAGI tested the aircraft in T-101 and other tunnels and had the design bureaus modify the problematic canopy designs, preventing further loss. TsAGI also researched the placement of air-to-ground rockets on attack aircraft, the cooling of fuel tanks, and even the placement and finish of camouflage patterns to eliminate any chance of additional drag from the use of multiple colors.[104]

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[101] Ibid., p. 74.

[102] Gordon, *Soviet Air Power*, p. 448.

[103] Chernyshev and Bushgens, *TsAGI*, p. 77.

[104] Ibid., p. 74.

TsAGI also provided help to the Red Army by examining and improving the flight characteristics of the famous Katyusha surface-to-surface rockets. Launched in salvo from Lend-Lease Studebaker and Chevrolet trucks, these unguided rockets struck with devastating effect. They were one type of weapon most feared by the Germans despite their lack of accuracy and wide-dispersal landing pattern. TsAGI's efforts significantly improved the accuracy of this weapon, greatly increasing its effectiveness.[105]

Born from the turmoil of revolution and civil war, TsAGI served the Soviet Union well despite severe challenges. It provided the struggling aviation industry of the new nation with expertise and innovation that played an essential role in improving the many aircraft designs that helped defeat Germany during the Great Patriotic War and was instrumental in expanding the Jet Age. TsAGI was and is a major aeronautical research institution that continues to serve the interests of its country long after the collapse of the Soviet Union.

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105. Ibid., p. 74.

CHAPTER 5

Essential, Not Supportive

Women and World War II Aeronautical Research and Development at the NACA's Langley Aeronautical Research Laboratory and Beech Aircraft Company

Emily Gibson

Figure 1: Before World War II, the Langley Laboratory had never employed more than 100 women at any one time. They worked primarily as secretaries, clerks, telephone operators, and receptionists. By the end of the war, nearly 1,000 women worked at Langley: practically one-half of the nonprofessional staff and one-third of the entire staff. (Image credit: NASA image LRC-1943-B701_P-33028)

When history books have recorded their presence or popular culture has celebrated their image during World War II, working women have often been credited with temporarily occupying "supportive" roles in the absence of men serving overseas in combat. This chapter highlights women's essential contributions to various facets of aeronautical research and development during the war. From the aircraft production lines at factories such as Beech Aircraft Company to various research departments at the Langley Aeronautical Research Laboratory, women directly contributed to the United States' aeronautical industry's strength and innovation during World War II.

This chapter is in no way meant to be exhaustive in its coverage of women in the aviation industry during World War II. That history has already been written, in great detail and attention, covering the wide-ranging roles women occupied within the aeronautics industry. Deborah Douglas's *American Women and Flight Since 1940* serves as the most comprehensive history of women in aviation, whose analysis of the topic also pays careful attention to questions of gender, race, and technology.[1] Douglas documents the many ways women were involved in the development of the American aviation industry from its inception. This essay seeks to provide a more micro-level look at the specific ways women contributed to aeronautical research and development during the war through two case studies looking at the NACA's Langley Aeronautical Research Laboratory and the Beech Aircraft Company.[2] This analysis of women at the NACA and Beech Aircraft Company represents a relatively small slice of a larger story detailing women's contribution to the United States' aeronautical research and development program during the war.

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1. Deborah Douglas, *American Women and Flight Since 1940* (Lexington: The University Press of Kentucky, 2004), p. 40.
2. The case-study approach was also chosen in an effort to avoid the infamous "lists of great women" that are often the starting place for historians working to uncover women in masculine-dominated fields where their presence is often under-documented or even obscured. Suffice it to say, though, that a number of women served in outstanding positions in the aviation industry during World War II (despite not being covered here)—ranging from aeronautical engineer for the Navy Bureau of Aeronautics or the United Aircraft Corporation to test pilots for Grumman Aircraft Company and production workers for a whole host of companies, including Boeing.

PART I: "I FELT LIKE I WAS HELPING TO WIN THE WAR. I FELT LIKE I WAS HELPING TO GO THROUGH THE TRANSONIC BARRIER"—HUMAN COMPUTERS AND TRANSONIC AERODYNAMICS RESEARCH AT THE NACA LANGLEY LABORATORY DURING WORLD WAR II

Scholars concerned with the history of computing and the NACA history more generally have noted the existence and importance of women working as computers at Langley during the war. This section draws on the work of such scholars while aiming to contextualize human computers within two larger stories: 1) the aeronautical research program at Langley and 2) the broader experience of women's wartime work in America. Above all else, this section argues that we should view these women as central to Langley's research program. More specifically, the women of the Langley Aeronautical Laboratory staff were central to the production of theoretical and technical solutions to the problems faced by transonic aerodynamics, as opposed to support staff engaged in unskilled computational work.

The National Advisory Committee on Aeronautics represented the leading edge of aeronautical research in the United States from its founding in 1915 well through World War II. The war exigencies served as a significant boost for the lab's research agenda and rapid growth of facilities and staff. In 1941, at the beginning of the war, Langley had fewer than 1,000 employees; by the war's end, the total number of employees at Langley had more than tripled to 3,200.[3] The lab's wartime mission remained relatively the same as its peacetime mission but was pursued with increased vigor and urgency. Jim Hansen, historian of the lab, characterized that mission as such: "to find practical ways for American aircraft to achieve improved performance, i.e., higher speeds and altitudes, longer range, more maneuverability, and better handling characteristics."[4] In total, Langley tested 137 different types of airplanes during the war that represented over half of the planes contracted for by the army and navy. Langley played a leading role in the research and development of the majority of the nation's air force and had a hand in the research and design of nearly all of the different plane types that saw combat service during World War II.[5]

It is no surprise that growing from a lab staffed with 1,000 employees to a lab capable of playing such a leading role in maintaining the country's military air power posed several challenges. Meeting these demands required that Langley greatly expand its research into transonic aerodynamics and greatly expand its workforce

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[3] James Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917–1958* (Washington, DC: United States Government Printing Office, 1987), p. 203.

[4] Hansen, *Engineer in Charge*, p. 219.

[5] Ibid., p. 220.

in the face of wartime labor shortages. Testimony given by the NACA in front of Congress in 1944 reflected these challenges. In justifying the NACA's then-current federal funding and making a case for an increased budget for 1945, testimony outlined the necessity of funding further NACA research. "Superior speed is still the most valuable single characteristic of military aircraft," the testimony declared; "as speeds increase, new problems are introduced by the enormous aerodynamic loads imposed upon the airplane structure, especially in violent maneuvers and in pulling out of dives. In some cases, the attainment of terminal velocities in dives causes structural failures resulting in loss of lives and airplanes."[6] Designing aircraft that could withstand high speeds from a structural standpoint while also affording supreme maneuverability and handling became the key technical challenge of the NACA's wartime research. Nevertheless, as of the time of the 1944 testimony before Congress, the NACA report explained, "The workload imposed upon the National Advisory Committee for Aeronautics is about two and one-half times as great in volume as can be met with the personnel and facilities available."[7]

The increase in demands placed on the NACA during the war and the limited supply of men because of the draft forced the NACA into new strategies for maintaining a supply of workers to respond to research demands. Langley sought to increase personnel by several means. As of 1944, the NACA had received 1,292 war deferments for its engineers, physicists, and chemists on the basis that they were engaged in work essential to the war effort.[8] Additionally, the NACA recruited employees from seemingly unrelated disciplines to increase its workforce. Several documents detail that NACA recruiters traveled up and down the East Coast to recruit and retrain auto mechanics to work on aircraft engines for research purposes at Langley. Finally, and perhaps of most interest for this story, the NACA also worked to reduce its research engineers' workload by training new employees in the methods of data collection and computation.[9] The employees hired to relieve engineers of such work were primarily women and were referred to as "computers." Hiring women as computers to collect and process experimental data began before the war and increased rapidly during the war. By 1944, of the total 2,183 employees at Langley, 850 were women—representing around 39 percent of the lab's total workforce. These women were critical elements in the breakthroughs that the NACA made in transonic aerodynamics, including the development of the Bell X-1 and Douglas D-558, the first two aircraft to travel faster than the

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[6] NACA testimony to Congress, *Congressional Record*, 91st Cong., 1945, p. 100.

[7] Ibid., p. 100.

[8] Ibid., p. 115. This number is out of the total number of NACA employees at all of the labs, not just Langley (4,289).

[9] Ibid., p. 125.

speed of sound. They also helped develop the dive flaps for the P-38, which greatly increased its combat speed and maneuverability, saving countless pilots' lives. Who were these women, and how did they come to work at the NACA during the war?

Helen Willey, a Newport News, Virginia, resident who worked for the NACA for 31½ years, represents one example of the diverse paths that brought many women to work in one of the premier aeronautics labs in the world. "I really didn't plan to work," Willey explained in an oral history interview; "I thought I would like to stay home and keep house."[10] After some convincing from her neighbor who planned to go in for an interview, Helen decided to ride along to the NACA laboratory at Langley, Virginia. While her neighbor ended up not getting a job, Helen Willey started work at the NACA on 5 December 1941, "and of course you know what happened on Sunday…," she later reported. After the bombing of Pearl Harbor on 7 December, Helen turned what was initially supposed to be a six-month post into a lifelong career.

With a bachelor's and master's degree in mathematics, Helen quickly rose to the rank of "head computer," which meant she supervised as many as 20 other women working as computers. However, the level of experience that she brought to the job was not necessarily typical. According to a 1942 Langley memo on computers' hiring and organization, the minimum qualification for working as a computer was completing a Civil Service exam.[11] The memo explained that while preference was given to women with "major interests" in mathematics or science, the requirements were not very rigid. Having taken at least one college course in mathematics was considered a sufficient demonstration of relevant experience. Regardless of whether or not a woman held an advanced degree in mathematics or physics, all computers were initially hired with the rating of minor laboratory apprentice, noted one 1943 Langley memo. Also referred to as junior computers, these women were hired to "serve as mechanics' helpers as well as to relieve hard-pressed junior engineers of many duties associated with tunnel operation and laboratory procedure."[12] Discussing the process of being hired, Helen Willey, Vera Huckel, and Marie Burcher (the latter two started working as computers at Langley in the early 1940s) noted the distinctions between men and women who were hired

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[10] Women Computers @ Langley, *https://www.youtube.com/watch?v=otFNR1a0o3A* (accessed 23 January 2023).

[11] "Computing Group Organization & Practices at NACA," 24 April 1942, p. 2. The text of the memo is available in the online article "Hidden Figures and Human Computers," 26 January 2017, *https://airandspace.si.edu/stories/editorial/hidden-figures-and-human-computers* (accessed 23 January 2023).

[12] "Organization of SP-1 Female Employees by the Aerodynamics Division," NACA Memorandum for Engineer-In-Charge, Record Group 6, 21 April 1943.

with similar qualifications to perform nearly the same work. Vera Huckel recalled that a man with the same qualifications would be hired as a professional and could earn anywhere from $200 to $400 more per year. Computers were considered subprofessionals within the administrative hierarchy. “That was before women’s lib,” Helen Willey quipped. The NACA classified the men tasked with doing the same calculations and taking the same measurement readings in the pursuit of producing crucial experimental data as junior engineers rather than computers, Willey explained. “Computers were women because they were paid less,” she surmised.[13]

According to an article published by the NASA History Program Office, titled “When the Computer Wore a Skirt: Langley’s Computers, 1935–1970,” by the end of the war in 1946, the NACA had hired around 400 women trained to work as computers in various sections across the Langley laboratory.[14] Training for new computers lasted two weeks and was rigorously technical. NACA organizational correspondence describing in detail the type of training computers were to receive quickly betrays the fact that the term “computer” was hardly an accurate description of the scope of activities assigned to these women or the level of skill they were required to possess. When one attempts to form the image of a computer, it is tempting to picture a woman seated at a desk scribbling away, making calculations, occasionally making use of the automatic adding machine of the day. However, training descriptions reveal that computers were tasked with participating directly in the experimentation process in Langley’s wind tunnels. The training involved learning to read and manipulate various instruments used in wind tunnel experiments, including electrical gauges, scales, rheostats, and manometers. Computers also had to become familiar with various laboratory tools, airplane nomenclature, and wind tunnel equipment and procedures.[15] A description of computer training by aeronautical engineer E. H. Derring explained that computers were “taught to read vernier scales and adjust fluctuating manometers as well as to take average readings from vibrating balance scales.”[16] Additionally, he highlighted the fact that women were “taught the art of finishing wing surfaces, soldering, and other work that necessitated the use of elementary mechanic’s tools,” before finally adding that “[p]lotting curves was also included in the course.”[17]

Understanding the skill behind the work performed by computers at the NACA first requires at least a cursory understanding of the nature of aerodynamics

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[13] James Hansen interview, ca. 1990s, *https://www.youtube.com/watch?v=Dh-EHz3RtM8*.

[14] “When the Computer Wore a Skirt,” *NASA History Program Office News & Notes* 29, no. 1 (first quarter 2012): 25.

[15] “Organization of SP-1 Female Employees by the Aerodynamics Division,” p. 2.

[16] Ibid., p. 2.

[17] Ibid., p. 2.

research conducted with wind tunnels at Langley. In his article "When Computers Were Human," historian Paul Ceruzzi explains that "the empirical nature of aerodynamics research implied an enormous amount of computational work."[18] Citing a description of the experimental process by aeronautical engineer Walter Vincenti, Ceruzzi relates that "engineers would begin by selecting a trial shape for, say, a wing" before building a scale model and placing it inside a wind tunnel to test. "In the tunnel," he continued, "a battery of instruments measured its performance; after the test, that data was reduced and analyzed." Based on these test results, only one parameter of the initial design would be changed. The effects of the alteration would again return to the tunnel for measurement and analysis. This method was called "parameter variation." It produced a large amount of data that had to be gathered by "reading" pressure values from manometers, instruments designed to measure the pressure placed on various aircraft designs by differing wind speeds inside the wind tunnels and visible through portholes or on photographic film.

As Helen Willey explained, determining the pressure levels indicated by the manometers was a bit more complicated than the term "reading" would imply. Women either worked from the manometer board that she described as a 12-foot-high panel covered with hundreds of tubes filled with a liquid or photographic film that captured the manometers' fluid levels. Calculations could be done remotely or after the tests were completed. Willey unpacked the process of reading the gauges, explaining that using known equations, computers would use "proper calibrations" to convert the height of the liquid in the tubes into pressure coefficients. "Reading" the manometers thus required mathematical calculations to interpret raw data into useful pressure readings. After calculating the pressure levels on the manometers, computers plotted and analyzed the results on graph paper. Willey explained, "We could plot several different pressure distributions of several different airfoils on one sheet. We had reduced that from manometer readings."[19] Another computer who worked at Langley, Marie Burcher, added, "[A]fter you plotted [the pressure distributions], you had to integrate that curve and then return the data to the engineers."[20] While NACA documents from the period tend to underemphasize the work of computers "reading" instruments, these documents substantiate the mathematical skill required for this process. NACA memos state that the analysis of wind tunnel data required "advanced knowledge of mathematics, including trigonometry and sometimes calculus." [21] If women did not already have this level

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[18] Paul Ceruzzi, "When Computers Were Human," *Annals of the History of Computing* 13, no. 3 (July–September 1991): 237–244, quotation on p. 238, doi:10.1109/MAHC.1991.10025.

[19] Hansen interview.

[20] Ibid.

[21] Computing group organization and practices at NACA, pp. 3–4.

of mathematics training before being employed as a computer at Langley, head computers (such as Helen Willey and Vera Huckel) were tasked with leading mathematics instruction to bring everyone up to speed.[22]

Virtually all of the innovations in aerodynamic theory and aircraft design produced by Langley during the war involved some degree of wind tunnel testing and, therefore, relied on the expertise and calculations of computers.[23] In addition to a central "computing pool" where new computers trained and performed general calculations, smaller groups of women were assigned to specific tunnels to work on particular research projects. When one pieces together NACA documents, histories of research performed at Langley, and oral history interviews of computers, a more detailed account of computers' specific contributions to aeronautical developments begins to take shape. These sources reveal that computers participated in essential research to solve the "high-speed breakthrough," which historian Richard P. Hallion has referred to as "a singular milestone in the evolution of flight, enabling the achievement of routine rapid global air transport and access to space."[24]

As the previously cited 1944 NACA congressional testimony highlighted, the unanticipated problems encountered by aircraft traveling at increasingly faster speeds constituted the most pressing challenge to the field of aeronautics during the war. Historian Jim Hansen explained, "[B]y 1939, flying speeds had increased to the point where the fastest aircraft were encountering a unique set of potentially dangerous aerodynamic phenomena known as *compressibility effects*."[25] Put simply, pilots and researchers began to discover that aircraft behaved in different and unexpected ways at higher speeds as a result of energy being transferred from the plane to the surrounding air, increasing its density or "compressing" the air and, thus, increasing the force acting on the aircraft. This change in airflow around aircraft traveling at high speeds resulted in increased drag and loss of lift, creating severe problems for the performance fighter and bomber aircraft.[26]

Solving the problems posed by compressibility effects became a key concern for Langley during the war. Histories of the lab reveal that one engineer and his wind tunnel research group, in particular, became a driving force behind the advancement of high-speed aerodynamics research at Langley: John Stack and the 8-Foot

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[22] Hansen interview.

[23] Robert Ferguson, "Evolution of Aeronautics Research at NASA," in *NASA's First 50 Years: Historical Perspectives*, ed. Steven J. Dick (Washington, DC: NASA SP-2010-4704, 2010), p. 206.

[24] Richard P. Hallion, "The NACA, NASA, and the Supersonic-Hypersonic Frontier," in *NASA's First 50 Years*, p. 224.

[25] Hansen, *Engineer in Charge*, p. 220.

[26] Ibid.

High-Speed Tunnel (HST) group. A group of computers (numbering upwards of 20 at one point) was assigned to collect, compute, and plot research data produced by the 8-Foot HST experiments. Helen Willey, Marie Burcher, and Rowena Becker were part of this group and have left accounts of what they experienced during this time and what their work entailed. Their reports of working on transonic aerodynamics research are colorful and reveal the degree to which computers participated in research beyond the computations in the process of data reduction.

Helen Willey, who served as the head computer of the women assigned to the 8-foot tunnel, remembered the excitement she felt when she was transferred from the general computing pool to work in a division. In reference to the comparatively better accommodations and the excitement of working under a well-known engineer such as John Stack, Willey related, "I thought: a wooden desk and cursing boss! The best thing that ever happened to me in my whole career!"[27] Marie Burcher was also sent to the 8-foot tunnel and described working with a group of "exceptional girls" who toiled in the summer without air conditioning and on New Year's Day with rarely a complaint.[28] Rowena Becker left a teaching job in North Carolina in 1942 to be a computer at Langley because it paid almost three times her teaching salary. She worked on the 8-foot tunnel and married an engineer she met in the research group.

All three women described working in close collaboration with the engineers on the 8-foot tunnel. As the head computer of the 8-foot tunnel, Willey remembered that division heads generally selected who would serve as the head computer. In her case, John Stack appointed her as head computer and personally trained her on the job. Willey recounted, "It made for more interest and loyalty in the job when you were working directly for an engineer. It gave [the computers] a more physical understanding of the work."[29] Similarly, Rowena Becker recalled reporting computations and experiment results directly to the engineers. Becker's account revealed that computers were not merely performing calculations divorced from any knowledge of the research program at hand. Rather, Becker described a process of collaboration in which computers played an essential and trusted part. Becker explained that after reading the dials and running the calculations, she would "let the engineer know how his test there was working out…whether it was running the true line he expected or what the picture was. And he might want to re-run the point again…. They tell me there's nothing like getting under a good engineer and working up…."[30] Willey and Becker's accounts revealed that comput-

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[27] "Women Computers @ Langley," *https://www.youtube.com/watch?v=o-MN3Cp2Cpc.*

[28] "Women Computers @ Langley."

[29] Hansen interview.

[30] "Women Computers @ Langley."

ers worked closely with engineers and that they viewed collaboration with various engineers as essential to learning more about research at Langley and moving up in their careers.

Vera Huckel, a computer in the physical research division headed by Dr. Theodore Theodorsen, provided evidence of the roles computers played in experiment formation in other divisions at Langley as well. Unlike wind tunnel research, Huckel explained that the physical research division's work was "all theoretical." Working in this division, Huckel recalled, required "a good mathematical understanding and a good understanding of the physical problems involved [in a research project] because lots of times you helped make a new procedure in a solution. The engineers would give us the problem, and it was up to us to come around."[31] While it is not clear how many computers were tasked with such direct involvement in influencing experiment design and execution, evidence suggests that this practice was not wholly uncommon. Marie Burcher remembered a "very cooperative work relationship" with engineers. Though, as Helen Willey noted, it was not always smooth sailing. "When we first went to work," she recalled, "some of our engineers were sitting and plotting all day long and wouldn't trust us to the integration."[32] While often meeting with initial distrust and skepticism, many computers created careers for themselves with the NACA that moved beyond the duties prescribed for computers. Huckle remembered, "[T]here were quite a few computers who went on to do individual research, writing reports, collaborating with engineers, etc." Willey concurred, explaining, "[M]ost of the girls that got their name on a report were collaborating with engineers, though some wouldn't allow it."[33] Doris Cohen, who worked at Langley during the period, coauthored along with an engineer a technical report titled "An Analysis of the Stability of an Airplane with Free Controls."[34]

Although their names cannot be found on any technical reports nor in any historical works recounting the great minds involved, Marie Burcher and Helen Willey participated in the research and development of the Douglas Model 558 High-Speed Test Airplane (the D-558 for short) and the Bell X-1—the first two aircraft to aircraft to fly through the sound barrier. Burcher and Willey recalled processing aeronautical test data to develop both of these aircraft during their time working with engineer John Stack. While records documenting their specific roles

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[31] Hansen interview.

[32] Ibid.

[33] Ibid.

[34] Robert T. Jones and Doris Cohen, "An Analysis of the Stability of an Airplane with Free Controls," NACA-TR-709, 1 January 1941, *https://ntrs.nasa.gov/search.jsp?R=19930091787* (accessed 2 June 2022).

in this research effort simply do not exist, the general principle of inference suggests the likelihood that their contributions far exceeded the performance of rudimentary computational work. There is no reason to believe that the well-documented "collaborative" working relationship between computers and engineering teams, in which computers often had direct involvement in the experiment process, did not exist in the development of the Bell X-1 and D-558. Willey also recalled her involvement in testing and developing an additional aeronautical innovation credited to Stack's 8-foot tunnel group: the dive recovery flaps for the P-38. It was not surprising that she found that particular project to be "exciting," as the problem was turned over to Langley's research efforts in 1941 after a test pilot died when he lost control of a P-38 during a test dive and crashed.[35] Within four months of testing, Willey and the 8-foot tunnel solved the P-38's dive-recovery problem by implementing a fixture to the wing that prevented the loss of aircraft control during dives.[36] It is no wonder that witnessing a research project with which she had been involved come to such fruition in the form of saving pilots' lives left her with the following impression of her time at Langley: "I felt that I was helping to win the war, I felt like I was helping to go through the transonic barrier."[37] Similarly, Marie Burcher described, "It was a team effort, and we all felt like we were making our own contribution, and we weren't as interested in seeing yourself than the whole job done."[38]

The story of computers at the NACA is not uncharacteristic of women's work experience during World War II, often categorized as "supportive" rather than vital. For example, women who worked in the Women's Airforce Service Pilots during the war were considered aircraft ferry pilots and not given military benefits upon disbandment.[39] A closer analysis of the work performed by computers at Langley reveals that women played a vital role in the research conducted on high-speed aerodynamics that resulted in several technical innovations that saved many lives. As historian Paul Ceruzzi astutely argues, "Historians of technology recently have attempted to uncover the significant fraction of technical activity embodied in the tacit, unwritten, and non-verbal skills of a craftsman (Post 1989, Staudenmeier 1989). To that, we must add crafts-women as well. The Langley computers' work was vital to the entire research effort, but it remained largely invisible."[40]

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[35] Hansen interview.

[36] Hansen, *Engineer in Charge*, p. 251.

[37] Hansen interview.

[38] Ibid.

[39] Douglas, *American Women and Flight Since 1940*, p. 103.

[40] Ceruzzi, "When Computers Were Human," p. 239.

Another common misconception of women's wartime work experience was that it was homogeneous. However, women of different class, education, and racial backgrounds had different and highly stratified work opportunities. While the war opened up opportunities for women to pursue higher-skilled and higher-paying defense-related positions, minority women still found themselves on the periphery of a hierarchical system based on their skin color.[41] During the war, the NACA employed African American computers for the first time, but rather than having them sit in the general computing pool, the NACA segregated them in their own computing pool known as the west section.[42] West Virginia native Kathryn Peddrew came to work at the NACA in 1943 after graduating college. While Peddrew recalls being taught that she could grow up to do anything she wanted, she encountered the limitations placed on her due to her gender and race early in her career. After graduation, Peddrew sought a research job on the effects of quinine deafness with her professor in New Guinea but was turned down because there were reportedly no facilities for the women who would have been research members on-site.[43] Dismayed by the rejection, Peddrew stumbled across an NACA job advertisement and was hired in 1943 to work in Langley's chemistry division. Despite her meeting the qualifications for the chemistry division's job, when the NACA discovered that she was African American, they moved her to the west section of the computing division because "the chemistry laboratory did not employ African-Americans."[44] In addition to work facilities, African American computers at Langley also reported having segregated dining and restroom facilities.[45]

While not all of the white computers at Langley were aware of the segregated west section for African American computers, sources reveal that some knew of the segregated section and recalled its place within the lab's research structure. In an oral history interview conducted by Jim Hansen around 1990, the West computing section came up in conversation—somewhat interestingly at the close of the interview after the camera had reportedly stopped rolling. As each of the women chatted about what she should have mentioned or covered in more depth, Hansen commented that he had thought about asking about the segregated computing section but had decided not to in case it made anyone uncomfortable. Both Helen Willey and Vera Huckel responded that they had anticipated being asked about it

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[41] Sherna Berger Gluck, *Rosie the Riveter Revisited: Women, War, and Social Change* (New York: Meridian, 1988), p. 38.

[42] Beverly Golemba, "Human Computers: The Women in Aeronautical Research," unpublished manuscript, 1994, p. 42, available in the NASA Langley archives.

[43] Ibid., p. 18.

[44] Ibid., p. 18.

[45] Ibid., p. 43.

but were trying to avoid the topic during the interview. Speaking of the African American women assigned to the west section, Marie Burcher volunteered, “I think they kind of got not as good of treatment. They got work that was what you didn’t want to do. Which was normal, you kept the work that was most challenging and sent out the work that was least challenging.”[46] Other sources confirm that the work performed in the west section was often sent from the general computing pool or research divisions because it was deemed “less interesting” or “more tedious” in nature.[47] Despite their segregated facilities, however, these women also contributed to aeronautical research and development during World War II.

PART II: ROSIE THE RIVETER REDUX: WOMEN AND AIRPLANE PRODUCTION AT BEECH AIRCRAFT COMPANY—FROM THE BOARDROOM TO THE SHOP FLOOR

The development of efficient aircraft production plants across the country was crucial to the aviation industry’s growth and the American war effort during World War II. In a not-so-metaphorical sense, the production process (which included procuring government contracts, financial backing, facilities, raw materials, and skilled labor to build the nation’s combat aircraft) constituted the actual “stuff” of aeronautical development. Just as important as the research that went into solving aerodynamics’ fundamental problems, the production process put real planes in the air in remarkable quantities and with remarkable speed. The Beech Aircraft Company serves as an interesting example to explore women’s role in aircraft production during the war. The company’s workforce—40 percent of whom were women—built many aircraft that proved crucial to the American war effort. The individual that oversaw the company’s remarkable wartime expansion of production was a woman—Olive Ann Beech, the first woman to serve as an executive of an aviation company.

As historian Deborah Douglas has documented, “The demands of the war led to a huge expansion in the aircraft industry and enormously enlarged the opportunities in it for female employment.”[48] Women served variously as flight attendants, mechanics, sales representatives, public relations employees, and engineers (to name a few). The vast majority of women working in the aviation industry

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[46] Hansen interview.

[47] Golemba, “Human Computers,” p. 43.

[48] Douglas, *American Women and Flight Since 1940*, p. 30.

during World War II worked on the production lines of aircraft manufacturing plants. Just as the war exigencies had significantly boosted interest in aeronautical research at Langley, the war requirements led to an immense expansion of American aircraft production facilities. Total employment of all aircraft manufacturing plants receiving government contracts to build planes jumped from 460,356 in 1942 to 1,027,914 in 1943.[49] Like Langley, production plants found themselves increasingly drawing on a limited labor pool due to the draft and turned to women to fill the gap. In 1942, women represented just 5 percent of the total aircraft-manufacturing workforce. By 1943, that number had risen to 31.3 percent—an increase of nearly 1,300 percent in just one year.[50]

Beech Aircraft Company was no exception to the national trend—with women constituting 40 percent of peak wartime employment in 1945 (14,110 total).[51] Like other companies, Beech experienced impressive levels of growth during the war. Such growth came quickly and necessitated rapid shifts in hiring strategies. In May 1940, after the Nazi invasion of France, President Franklin D. Roosevelt requested an astonishing 50,000 planes from the aircraft industry, compared with a previous request from Congress in April 1940 for just 47 new warplanes.[52] As one company publication declared, Beech responded by "preparing for all-out military production."[53] With a mere 660 employees on its payroll at the beginning of 1940, Beech had $1.2 million worth of backlogged orders by midyear.[54] It was clear that a massive expansion of Beech production facilities and the staff was in order. Tragedy struck the Beech Aircraft Company in the summer of 1940 while planning for an unprecedented expansion. Walter Beech, the company's president, contracted encephalitis—an illness characterized by an acute swelling of the brain—and was hospitalized for nearly a year. Olive Ann Beech, Walter's wife, with whom he had cofounded Beech Aircraft in 1932, quickly stepped forward to run the company in his absence.

Olive Ann Beech began her career in the aviation industry in 1925, when she accepted a position as secretary and bookkeeper of the Travel Air Manufacturing Company, formed by Clyde Cessna, Lloyd Stearman, and Walter Beech earlier that

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[49] Ibid., p. 44.

[50] Ibid., p. 44.

[51] "A Chronicle of Aeronautical Achievement," excerpt from *The Home of Beechcraft, Wichita, Kansas* (1 April 1949), clipping located in FF-1, box 56, MS 97-02, Walter and Olive Anne Beech Collection, Wichita State University Special Collections.

[52] Dennis Farney, *The Barnstormer and the Lady: Aviation Legends Walter and Olive Ann Beech* (Kansas City, MO: Rockhill Books, 2010), p. 72.

[53] "A Chronicle of Aeronautical Achievement."

[54] Farney, *The Barnstormer and the Lady*, p. 72.

Figure 2: Walter and Olive Ann Beech overlooking the production line of Beech AT-11 bomber/gunnery trainers at the Beech Aircraft factory in Wichita, Kansas. (Image credit: Kansas Historical Society item number 209298)

year. In addition to handling the books, Olive Ann eventually became Walter's personal secretary. After a "stormy" courtship, they eventually wed in 1930—a year after the Travel Air Manufacturing Company had merged with the Curtiss-Wright Corporation. By 1931, however, Walter had grown weary of Curtiss-Wright's depression-era, risk-averse production program. Walter resigned from his position with the company to cofound Beech Aircraft Company with Olive Ann. The decision to make Olive Ann cofounder speaks to the degree to which Walter considered her essential to the company and reflects her determination and self-assurance. She later reported to the *Saturday Evening Post*, "I made him pay me a salary or I wouldn't work. I wasn't willing to give my life's blood and not have it properly evaluated."[55]

This self-confidence and power to command respect (which, it should be noted, gained her many enemies over the years) would serve Olive Ann well in the face of

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[55] Cited in Farney, *The Barnstormer and the Lady*, p. 53.

Walter's health crisis.[56] In Walter's absence, Olive Ann assumed the daily responsibilities of running the company and faced the pressing issue of expanding aircraft production to meet government contracts with great success. The first order of business was to secure the financial backing that would fund the construction of new facilities and increase production required to meet the $82 million backlog of military aircraft orders. While previous histories have neglected to credit Olive Ann for overseeing this massive wartime transition,[57] author Dennis Farney reports, "It was Olive Ann who negotiated the loans necessary to gear up for wartime production. From the Federal Reconstruction Finance Corp., she secured a $13.5 million revolving line of credit. She also negotiated a $50 million loan from a syndicate of thirty-six banking firms."[58] As a result, the plant expanded by 525,610 square feet between 1939 and 1941 and started turning out aircraft that would prove essential to the war effort.[59]

Before the new production facility had even gotten a chance to install heating, Beech ramped up production of the AT-11.[60] The AT-11 served as a bombing trainer for the U.S. Army and, along with the AT-10, dominated wartime military contracts.[61] In 1942 alone, Beech produced and delivered 615 AT-11s to the army.[62] This aircraft's importance to the war effort was critical, as it is estimated that over 90 percent of American bomber pilots trained on the AT-11.[63] The second aircraft in high military demand was the brand-new AT-10, designed by lead Beech engineer Ted Wells and his team. Remarkably, the AT-10 was constructed almost entirely of plywood to conserve aluminum, which was heavily rationed and in limited supply during the war. As Beech historian Walter Phillips detailed, "[T]he AT-10 helped train military pilots to fly complex, multi-engine aircraft such as the Boeing B-17 and Consolidated B-24 heavy bombers."[64] The AT-10 was also a huge success, with Beech producing a total of 1,360 in 1943—amounting to nearly half of all aircraft produced in that year. Attesting to its popularity, Farney estimates that "at least half of U.S. multi-engine pilots received some of their training in the

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[56] Peter Wyden, "Danger: Boss Lady at Work," *Saturday Evening Post* (8 August 1959).

[57] Phillips states that Walter secured this financial backing in Edward H. Phillips, *Beechcraft Pursuit of Perfection: A History of Beechcraft Airplanes* (Eagan, MN: Flying Books, 1992), p. 5.

[58] Farney, *The Barnstormer and the Lady*, p. 79.

[59] "A Chronicle of Aeronautical Achievement."

[60] Farney, *The Barnstormer and the Lady*, p. 72.

[61] Phillips, *Beechcraft Pursuit of Perfection*, p. 5.

[62] "A Chronicle of Aeronautical Achievement."

[63] Farney, *The Barnstormer and the Lady*, pp. 72–73.

[64] Phillips, *Beechcraft Pursuit of Perfection*, p. 5.

AT-10."[65] Additionally, in 1943, Douglas Aircraft Company contracted Beech to construct wing and nacelle assemblies for the A-26 Invader produced at Douglas's Tulsa, Oklahoma, plant. When production of the A-26 ceased in 1945, Beech produced and delivered 1,635 wing-sets to Douglas "on or ahead of schedule thanks to a massive company-wide mobilization."[66]

That Beech's gross sales jumped from $1,328,296 in 1939 to a staggering $126,587,384 in 1943 was no small feat and undoubtedly thanks in large part to the efforts of Olive Ann Beech.[67] During this period, Olive Ann reportedly worked 10- to 12-hour days poring over the company books, securing much-needed funding, and even fighting off at least one coup organized by a group of employees set on taking over the company in Walter's absence. A testament to her unyielding resolve, Olive Ann insisted on meeting with company directors at her bedside while in the hospital for her daughter's birth. She successfully staved off the threat—firing 13 employees in the process.[68] Olive Ann's position as managing director at Beech Aircraft was unprecedented for a woman within the aviation industry at the time, and certainly uncommon for a woman in business writ large. In 1942, *Newsweek* touted her as a "topflight executive." In 1943, the *New York Times* listed her as "one of the twelve most distinguished women in America."[69] Beech kept Walter's illness out of the prying eye of the press for fear of inciting panic amongst financial backers and government inspectors over the company's fate. He was often shuttled back and forth from home or the hospital in time to make a big meeting to give the illusion that he had never left command. As a result, it is unclear exactly how long Olive Ann formally held the reins in his absence. However, what is clear is that even after Walter regained his health enough to return to business, Olive Ann did not relinquish her control. As Walter's nephew would later report when asked how long Olive Ann ran the company in his stead: "She's always been running it."[70]

However, Beech Aircraft Company's ability to meet aircraft production goals during the war resulted not from Olive Ann's leadership alone. Instead, a whole host of employees working on Beech manufacturing plants' production lines—a near majority of whom were women—supplied the labor that proved equally essential to the company's success. Remarking on the centrality of women in the company's production workforce, an article in the company newsletter titled "Beechcraft Salutes Its Women Soldiers of Production" explained: "No bands play for women

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[65] Farney, *The Barnstormer and the Lady*, pp. 71–73.

[66] Phillips, *Beechcraft Pursuit of Perfection*, p. 5.

[67] "A Chronicle of Aeronautical Achievement."

[68] Farney, *The Barnstormer and the Lady*, pp. 75–76.

[69] Ibid., p. 78.

[70] Ibid.

factory workers. Their bugle is an alarm clock, their uniform a pair of coveralls or slacks. These women never make headlines, but the world sees the result of their labor every time an American fighting man's story reaches the home front."[71] While employment statistics listing the number of women working in each division of Beechcraft plants do not exist, the employee newsletter (called the *Beech Log*) gives the best representation of women's working experience during the war. Throughout Beech's manufacturing plants, women in various departments volunteered to be reporters for the *Beech Log* and published editions regularly throughout the war years. Its pages provide vital information regarding women's activities and concerns, which were not recorded anywhere else in official corporate documents.

Constituting 40 percent of Beech's employees during the war, according to the *Beech Log*, women occupied a variety of positions on the manufacturing line, including "machine operators, welders, dopers, painters, platers, sanders, sheet metal workers, assemblers, riveters, skin fitters, electricians, woodworkers, upholsterers, [and] tool crib clerks, to mention just a few."[72] The article reported that at the time of the attack on Pearl Harbor, Beech employed only 25 women. From November 1942 to March 1943, however, the number of women at Beechcraft increased by a stunning 96.5 percent. An article highlighting the importance of their work testified, "The production rate at Beechcraft is in itself the highest tribute that can be paid to our women factory workers. If they were not doing their part, production would reflect it. But they are doing their job superbly, as our production increases month after month so clearly show."[73] Though considered vital to Beech production's success, women entering aircraft manufacturing plants (as was the case in other industries) faced entrenched notions of women's inherent unsuitability for mechanical work. Some critics argued that women would not be able to endure the demands of war production work, claiming that "the work is too hard and broken fingernails, bruised fingers and aching muscles are too much for them to stand."[74]

Refuting such criticism, the *Beech Log* devoted countless articles to emphasizing the many Beech women performing men's work daily on the production line. "'Welding is a man's job' they used to say. 'Not Anymore,' says Beechcraft. Many

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[71] "Beechcraft Salutes Its Women Soldiers of Production," *Beech Log*, 3, no. 11 (12 March 1943): 6, Wichita State University Special Collections, Walter and Olive Anne Beech Collection, SC 4876, vol. II.

[72] Ibid., p. 8.

[73] Ibid.

[74] "Sure It's Hard Work but Beechcraft Women Can Take It!" *Beech Log* 3, no. 35 (27 August 1943), Wichita State University Special Collections, Walter and Olive Anne Beech Collection, SC 4876, vol. II.

women, like E.M. Sampson, are carrying the welder's torch for victory, building fittings and parts for Beechcraft," one article explained.[75] "There's nothing feminine about the massive radial drills used in fabricating aluminum alloy parts for Beechcraft—except the operator," the article continued. In another article titled "Sure It's Hard Work but Beechcraft Women Can Take It," radial drill operator Florence McCann reported that while it was true that her fingernails broke off and her fingers got bruised, she had "no intention of falling down" on her job.[76] Accounts even emphasized cases where women were considered more capable than the men they replaced. One article documented the work of Mrs. D. L. Harramier, who toiled away on the production line assembling wiring harnesses for the AT-10. Because "women excel in tedious, complex work of assemblies of all kinds," the article explained, departments that required detailed work had high percentages of women.

Similarly, the article noted the work of Anne Huff, who was photographed attaching an antenna to the tail of an AT-11. The article explained that the final assembly department supervisors often touted women like Huff for "showing up the men" in the department because of their attention to detail.[77] Such attention to detail also secured some women, such as Geraldine Shelly, positions within the Beech engineering department, "performing tasks usually associated with masculine talents."[78]

Stories like these from the *Beech Log*, chronicling the difficult work many women performed on the production line during the war, have received much attention in the history books and popular culture. Today, the iconic "Rosie the Riveter" image, created to represent women such as those working in Beech production, can be found on clothing, bumper stickers, and coffee mugs alike. Her image is a reminder that women occupied men's jobs during the war and served as a testament to the power women can collectively wield. However, what is not often emphasized in histories is the role women played in advancing the fields of work with which they were engaged. Furthermore, literature relating to aeronautical research and development history pays little attention to women as aircraft production workers. If production is considered a part of the late-stage development process—a step in which technical modifications are sometimes made to an aircraft—then women's contributions should be given more consideration. The place of workers in debates about the source of technological innovation and development is not new to the history of technology. Scholars have already begun to ask questions about the value

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[75] "Beechcraft Salutes Its Women Soldiers of Production," p. 8.

[76] "Sure It's Hard Work but Beechcraft Women Can Take It!"

[77] "Beechcraft Salutes Its Women Soldiers of Production," p. 7.

[78] Ibid.

added by the often unwritten, tacit knowledge that workers bring to various technological developments.[79] More scholars, however, should start to ask the same question about the innovations made by the multitudes of "Rosies" who built the aircraft that proved so essential to the allied victory. A significant challenge to answering this question is that documentation of innovations or modifications made at the production point is often scarce. Workers may notice a problem in the production process and fix it themselves and perhaps spread the word to fellow workers.

While it is not clear how common the practice was in other plants, Beech employee newsletters reveal that during the war, the company instituted an incentive program to encourage employees to improve the aircraft production process. This documentation provides crucial evidence that women working on the production lines of aircraft manufacturing plants might have been more of a source of innovation and development than previously thought. "The gals have 'went and done it' again, at least one did," an article in the *Beech Log* declared. "Evelyn Johanson, while in Department 05 [Sheet Metal Parts] has received two Suggestion Contest awards for her suggestions as to improvements to her machine, a three-foot shear," it continued. Johanson reportedly received "two nice checks" for offering her ideas, which led to her work improvement.[80] The Suggestion Contest was part of a larger effort made by the various departments in the plant to encourage women to turn in suggested improvements. The effort highlighted the difficulty women faced in feeling comfortable and confident in making such suggestions while operating in a place they were repeatedly told was "a man's world." The article explained that "Miss Johanson said she hesitated for four days before turning in her first suggestion because she was afraid it would not be given much attention, coming from a woman, but she did get up her nerve, and she was rewarded for doing so." Imploring more women to follow Johanson's lead and turn in suggestions of their own, the article ended on an encouraging note: "Women are operating more machines every day at Beechcraft…and they need not be afraid to compete with men in suggesting improvements in their own work."[81] Whether or not additional women followed suit is hard to say. This single recorded instance of a woman's innovation on the production line is insufficient evidence to build an argument for such a practice's generality. However, this example suggests that women's lasting contributions to the production work in which they were engaged may be underestimated and provides a fruitful area for further research.

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[79] Ibid.

[80] *Beech Log* (26 March 1943): 20, Wichita State University Special Collections, Walter and Olive Anne Beech Collection, SC 4876, vol. III, no. 13.

[81] Ibid.

PART III: CONCLUSION: DEMOBILIZATION

Despite being lauded as heroes of production, as early as 1943, women war workers became the subject of growing anxieties over the postwar labor market. President Roosevelt's Secretary of the Interior, Harold Ickes, warned in the *Saturday Evening Post* that "when the war is over, the going will be a lot tougher, because [men] will have to compete with women whose eyes have been opened to their greatest economic potentialities."[82] Concerned with men coming home from war to find their jobs still occupied by women, the government propaganda machine flew into action, creating films that warned women of the dangerous effects of strenuous work. At the beginning of the war, government films assured women that cutting sheet metal was no different from shearing dress material. By the end of the war, the same films featured men in white coats pointing to charts that explained the harm that such work could cause to a woman's body. Many women, however, had no choice but to leave their wartime positions. With the end of the war, production slowed, and layoffs ensued.[83] All told, over half of the women who entered the workforce in 1941 left at the war's close, the vast majority of whom left the manufacturing sector.[84]

The mass mobilization of women during the war did have lasting effects on women's employment patterns—by 1950, more women participated in the workforce than in 1940.[85] Moreover, while women left wartime production work in large numbers, historian Deborah Douglas notes that women working in aircraft manufacturing, on the whole, fared slightly better. Douglas reports that while the overall number of workers employed in the aircraft manufacturing industry decreased by half from 1941 to 1947, the percentage of women working in those jobs did not drop proportionately. The percentage of women in aircraft manufacturing increased from 5 percent in 1941 to 11.8 percent in 1947.[86] Why did women working in the aircraft industry experience slightly different prospects from those of the average wartime working woman? Brief examinations of the postwar

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[82] Harold Ickes, "Watch Out for Women" *Saturday Evening Post* (20 February 1943), cited in Sherna Berger Gluck, *Rosie the Riveter Revisited: Women, the War, and Social Change* (New York: Meridian, 1988), p. 15.

[83] *The Life and Times of Rosie the Riveter*, directed by Connie Field (Clarity Films, 27 September 1980).

[84] Claudia Goldin and Claudia Olivetti, "Shocking the Labor Supply: A Reassessment of the Role of World War II on US Women's Labor Supply" (working paper, Cambridge, MA: National Bureau of Economic Research, January 2013), p. 1.

[85] Mary M. Schweitzer, "World War II and Female Labor Force Participation Rates," *Journal of Economic History* 40, no. 1 (March 1980): 90.

[86] Douglas, *American Women and Flight Since 1940*, p. 109.

trajectories of Beech Aircraft Company and the NACA's Langley Aeronautical Research Laboratory suggest potential explanations.

Beech Aircraft Company

Despite a financial slump at the close of the war, Beech experienced a near-total recovery due to renewed military contracts fueled by the outbreak of the Korean War. By 1952, Beech employed nearly as many workers as it had during the peak of World War II employment.[87] Without access to specific employment statistics during this period, it is impossible to say what percentage of that total workforce was composed of women. However, it is somewhat reasonable to assume that if Beech followed national trends, women were employed in production at Beech in more significant numbers than in other industries. In addition to Beech's production workers, its cofounder Olive Ann Beech enjoyed much professional success in the postwar period. After her husband Walter's death in 1950, Olive Ann assumed the company's president and CEO positions. Olive Ann served as president until 1981, when her nephew Frank Hedrick was appointed head of the company—though she never relinquished her position as CEO.[88]

The NACA's Langley Aeronautical Research Laboratory

The close of the war did not significantly impact the pace or intensity of Langley's research into high-speed aircraft. While total employment numbers fell by 500 from 1944 to 1947, by 1952, total employment at Langley had rebounded to 3,557—surpassing the peak wartime employment of 1944 by 269 employees.[89] Without specific numbers, it is hard to say whether the numbers of computers working at Langley decreased following the war. However, one indication lies in the fact that the NACA categorized computers as sub-professional employees. Employment statistics report only a minor decrease in the number of sub-professional employees following the war, which followed the overall employment trend and began to climb again starting in 1947. Likewise, the number of computers employed at Langley remained relatively stable. Qualitative evidence confirmed by previously cited oral history interviews conducted by Jim Hansen and Beverly Golemba found that of the women who worked as computers during the war, seven continued their

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[87] Farney, *The Barnstormer and the Lady*, pp. 106–107. This success would be short-lived as Beech would ultimately struggle to find a profitable place for itself in the postwar, private-use aviation market.

[88] Ibid., pp. 98–100.

[89] Hansen, *Engineer in Charge*, p. 413.

careers at Langley after the war. All seven of these women witnessed the 1958 change from the NACA to NASA—working well into the 1970s and ’80s.[90]

The spotlight recently shone on one of the Langley computers for her contributions to human spaceflight provides a vivid example of the contributions computers made to the field of aerospace research overall. An African American woman, Katherine Johnson, came to work at Langley after World War II in 1953. Many of the women mentioned in this essay worked at NASA well into the 1980s. Not only has Johnson been awarded the Presidential Medal of Freedom, but the book and film that share the same name, *Hidden Figures*, document her accomplishments.[91] The growth of attention around mathematicians who were women involved in the space race certainly speaks to the rich stories beginning to be told about women’s contributions to aerospace research and development. In many ways, the women working as computers at Langley during the war were the forerunners of later involvement by women in research focusing on human spaceflight.

Mobilization efforts drew many women into the aeronautics industry’s research and development efforts. Their significant contributions undoubtedly paved the way for women who would work as researchers during NASA’s early years. The examinations of women at Langley and Beech have documented the sheer rise in numbers of women involved in aeronautical R&D during World War II and showed that women’s contributions in these fields were not merely supportive. They were essential to the advancement of aeronautics during the period. From the wind tunnels at Langley to the boardroom and production lines at Beech, women not only participated but also directly enriched aeronautical research and development.

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[90] Golemba, “Human Computers,” pp. 128–140.

[91] Margot Lee Shetterly, *Hidden Figures: The American Dream and the Untold Story of the Black Women Mathematicians Who Helped Win the Space Race* (New York: HarperCollins, 2016).

CHAPTER 6

Blades for Victory

Propeller Innovation, Production, and Use During World War II

Jeremy R. Kinney

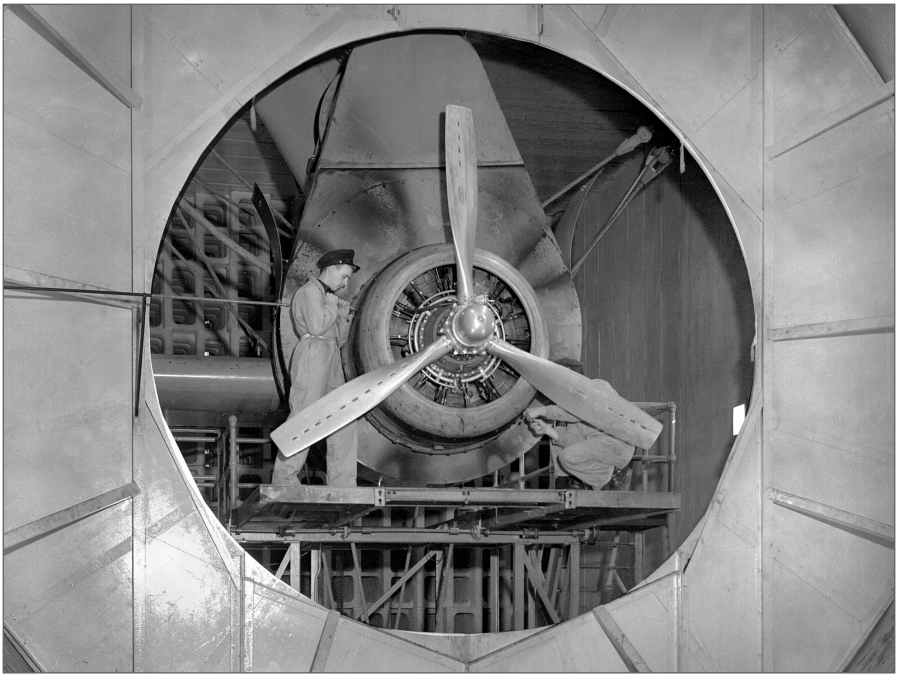

Figure 1: A Wright Aeronautical R-2600 Cyclone engine installed in the NACA's Engine Propeller Research Building or Prop House. The research conducted here during the war was critical to the development, performance, and refinement of the United States' aircraft propellers. (Image credit: NASA image GRC-1943-C-01379)

U.S. Army Air Forces First Lieutenant Robert S. Johnson of the 56th Fighter Group of the Eighth Air Force took to the air in his Republic P-47D Thunderbolt named Lucky on New Year's Day, 1944. His Thunderbolt's four-blade Curtiss Electric propeller was different that day. The blades were wider from the leading edge to the trailing edge and had fairings in the shape of airfoils near the hub. He was skeptical initially about the "fuss" being made over his new propeller by the engineering officers. He quickly experienced an overwhelming boost in performance, which, in his words, was "worth 1,000 horsepower, and then some," as he was now able to outclimb and outdive both the Luftwaffe's deadly Messerschmitt Bf 109 and Focke-Wulf Fw 190 fighters in combat.[1] The refinement of his propeller transformed the Thunderbolt into an overall better and more lethal weapon. Johnson went on to be one of the leading American aces of World War II with 27 victories.

The air forces of World War II conducted strategic and tactical bombing campaigns, maintained air superiority, and operated worldwide supply networks with propeller-driven airplanes. By the end of the war, manufacturers for the major combatants produced over 780,000 bombers, fighters, transports, and trainers. The United States, Great Britain, Germany, and Japan alone produced approximately 1.4 million propellers to help wage their global aerial war.[2] The specialist communities in those countries created and manufactured propellers that were vital components of their national war machines. A discussion of Allied and Axis propeller design and production programs during the late 1930s and 1940s reveals how each nation's approach to innovation and operational use in those areas differed and how that contributed to the overall outcome of World War II.

TECHNOLOGY AND PRODUCTION

A propeller is a mechanism that converts a piston engine's power into thrust, the force that propels an airplane forward—much like a wing produces lift, albeit in a rotary path. It was a central technology to the international aeronautical community as it reinvented the wood, strut-and-wire-braced biplane of World War I

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1. Robert S. Johnson, *Thunderbolt!* (New York: Rinehart, 1958), pp. 239–241.
2. Jeremy R. Kinney, *Reinventing the Propeller: Aeronautical Specialty and the Triumph of the Modern Airplane* (New York: Cambridge University Press, 2017), pp. 319, 324.

into the modern, all-metal, and streamlined monoplane of the late 1930s used to fight World War II. Engineers took the laminated piece of wood invented by the Wright brothers to operate in one fixed operating regime—either takeoff, climb, or cruise—and made it capable of varying its blade angle, or pitch, in-flight to meet all three efficiently. The ultimate form of a variable-pitch mechanism was the constant-speed propeller, which changed blade pitch automatically according to varying flight conditions while the engine speed remained the same, which maximized propeller, engine, and fuel economy and offered hands-off operation. These propellers, as found on military and commercial airplanes in the late 1930s, were a product of a modern industrial age, made from the latest alloys, steel, and composite materials, and incorporated a sophisticated design that gave increased altitude, speed, and range performance over a variety of conditions.

Manufacturing such advanced aeronautical technology involved a significant amount of handwork and training. Hydraulic and electrical pitch-changing mechanisms required exact assembly and operating tolerances for the reliable operation that pushed the limits of machine work. It took six months for a worker to become fully versed in one operation, such as blade making. Regardless of whether the material was solid duralumin; hollow steel; or composite wood, mesh, and resin laminates, shaping them into a blade was a time-consuming, labor-intensive process. The *Wall Street Journal* noted in 1941 that the modern propeller was "a highly complicated mechanism" requiring "the most delicate kind of craftsmanship."[3]

THE ALLIES: UNITED STATES

For the United States, the quantity production of aircraft propellers became a significant element of its rapidly mobilizing war machine in the late 1930s, which coincided with President Franklin D. Roosevelt's labeling the country as an "arsenal of democracy" in December 1940. To supply itself and its European and Asian allies, American military planners chose the propeller and piston engine as its primary aircraft propulsion system. They wedded it to large-scale production programs to avoid the strategic mistake of putting too much emphasis on new technologies.[4] For them, a revolutionary new technology, the jet engine, would only be practical in the long term and after costly research and development,

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[3] "Propeller Producers Widening Bottleneck Despite Unusual Dependence on Hand Labor," *Wall Street Journal* (16 May 1941): 28.

[4] Wesley F. Craven and James L. Cate, *The Army Air Forces in World War II*, vol. 6, *Men and Planes* (Chicago: University of Chicago Press, 1955; repr., Washington, DC: Office of Air Force History, 1983), pp. 228–230.

not immediately on aerial battlefields around the world.[5] As a result, the United States entered World War II with readily available constant-speed propellers for its high-performance bombers and fighters produced by three manufacturers—Hamilton Standard, Curtiss, and Aeroproducts—that were capable of considerable refinement through the help of government research from the National Advisory Committee for Aeronautics (NACA).

Hamilton Standard

Hamilton Standard was the premiere American propeller manufacturer and emerged from the interwar period best prepared to offer Allied air forces advanced technologies. Formed in November 1929, the company resulted from the merger of pioneering manufacturers Standard Steel and Hamilton Aero Manufacturing under the corporate umbrella of the United Aircraft and Transport Corporation.[6] Hamilton Standard dominated the world propeller market in the early 1930s with its two-position variable-pitch propeller that earned it the nickname "No. 1 Propeller Company" and garnered the prestigious 1933 Collier Trophy for achievement in aeronautics.[7]

Hamilton Standard's first constant-speed propeller, introduced in late 1935, employed counterweights to vary pitch in one direction. Engineering manager Frank Caldwell and chief engineer Erle Martin led a team to develop a new propeller that relied on hydraulic pressure for all pitch actuation and, as a result, utilized engine power even more efficiently. Introduced in early 1938, the Hydromatic propeller—the name was a combination of "*hydr*aulic" and "aut*omatic*"—employed major improvements over earlier variable-pitch designs. The propeller offered better control of pitch variation and multi-engine synchronization, and it removed the risk of "over-speeding" the engine while diving.[8]

Most importantly, the Hydromatic also offered blade feathering, an important safety feature for multi-engine airliners, bombers, and transport aircraft in the upcoming global air war. In the event of engine damage and failure during a flight,

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5. Edward W. Constant, *The Origins of the Turbojet Revolution* (Baltimore: Johns Hopkins University Press, 1980), pp. 15, 117, 120; James O. Young, "Riding England's Coattails: The U.S. Army Air Forces and the Turbojet Revolution," in *Innovation and the Development of Flight*, ed. Roger D. Launius (College Station, Texas: Texas A&M University Press, 1999), p. 271.
6. "UAT Propeller Firms Now Hamilton Standard," *Aviation* 27 (30 November 1929): 1080.
7. "No. 1 Airplane Company," *Fortune* 5 (April 1932): 47; Carl B. Allen, "Hamilton Standard Wins Collier Trophy for Controllable-Pitch Propeller," *Bee-Hive* 8 (June 1934): 1.
8. Frank W. Caldwell, "Hamilton Standard Hydromatic Propeller," *Aviation* 37 (July 1938): 28; "A Review of the Hydromatic Propeller," *Bee-Hive* 14 (July 1939): 3–5; "Hydromatic Aircraft Propeller," *Automotive Industries* (23 July 1938): 114.

the slipstream flowing through the dead engine's propeller made it "windmill." A windmilling propeller produced an enormous amount of drag and severely limited the speed and altitude performance of a stricken airplane, rendering it virtually uncontrollable. Severe windmilling resulted in the disintegration of the airplane from structural failure through extreme vibration. Feathering set the blades to a position parallel to the slipstream so they would not disrupt the airflow over the wing after an engine failure, which improved the airplane's lift/drag coefficient and made it more controllable. Tests conducted by American Airlines with a Douglas DC-3 powered by a single engine in 1938 revealed that a feathered propeller increased the airliner's altitude by 300 feet.[9]

Hamilton Standard was the most prepared manufacturer in terms of the transition to wartime production. During the period 1935 to 1939, the East Hartford factory produced approximately 380 propellers a month. The company committed itself to delivering 60,000 propellers to the U.S. government by June 1942. After the expansion of the shop floor to 310,000 square feet, the workers produced 1,900 propellers per month by the spring of 1941. The conversion of an old textile mill into a 200,000-square-foot satellite factory at Pawcatuck, Connecticut, added another 1,000 propellers a month by the following September. Besides this initial expansion, Hamilton Standard's production strategy included subcontracting individual components and assemblies out to 75 different manufacturers and licensing its products to makers of non-war-related products.[10]

Virtually the entire frontline inventory of the Army Air Forces and the Navy's Bureau of Aeronautics, from multi-engine bombers to fighter and transport aircraft, employed Hydromatic propellers. Hamilton Standard and its three licensees—refrigerator manufacturers Frigidaire and Nash-Kelvinator, as well as office equipment maker Remington-Rand—produced 530,135 Hydromatic propeller assemblies during the war.[11] All told, Hamilton Standard accounted for approximately 76 percent of all American propeller production in World War II.

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[9] W. P. Keasbey, "Did You Ever Wonder What a 'Full-Feathering' Airplane Propeller Is?," *Christian Science Monitor* (24 September 1941): 23; George Rosen, *Thrusting Forward: A History of the Propeller* (Windsor Locks, CT: United Technologies Corporation, 1984), pp. 46, 49; O. P. Echols to Curtiss Aeroplane Division, 12 February 1938, folder "Curtiss Electric Propeller, 1934–1938," box 6302, RD 3330, record group 342, National Archives and Records Administration.

[10] "Propeller Producers Widening Bottleneck," p. 28; "Propellers from Pawcatuck," *Bee-Hive* 16 (May–June 1941): 1.

[11] "Hartford Fosters World Air Group," *Montreal Gazette* (5 May 1943): 7; Hamilton Standard Propellers, *Wherever Man Flies* (Hartford: United Aircraft Corporation, 1946); Irving Brinton Holley, Jr., *Buying Aircraft: Matériel Procurement for the Army Air Forces* (Washington, DC: Government Printing Office, 1964), p. 563.

For the United States, the Hydromatic was a central technology in the Army Air Forces' strategic bombing campaigns over Europe and Japan. Young pilots and aircrew flew Boeing B-17 Flying Fortress and Consolidated B-24 Liberator heavy bombers in a long-distance aerial war against the Axis. During combat operations, the successful operation of Hydromatic feathering systems was commonplace. The Army Air Forces exhibited much more concern over isolated failures. Pilots and flight engineers in both the European and Pacific theaters of operation identified a significant problem with having the engine and the propeller share the same oil. Damage inflicted on an engine or oil tank from anti-aircraft artillery fire could result in the loss of the oil supply, which deprived the propeller of the needed hydraulic pressure for feathering.[12]

The deadliest bomber of them all was the world's most advanced propeller-driven airplane in 1945, the Boeing B-29 Superfortress. The Army Air Forces' Twentieth Air Force used them to attack Imperial Japan from the Mariana Islands 1,500 miles away to the southeast in the Pacific. Combat formations of B-29s carried 20,000 pounds of bombs or aerial mines each to Japan at a cruising speed of 220 mph and altitudes reaching 30,000 feet.[13] A crucial component of the B-29 was its four Hydromatic propellers. Each had four blades spanning a diameter of 16 feet 6 inches and weighed 870 pounds, making them the largest ever installed on an airplane up to that time. They gave the necessary performance that ensured that the heavily laden lumbering aircraft operated in and out of airfields safely and cruised at high speeds with their deadly cargoes.[14]

Curtiss

While Hamilton Standard was the dominant propeller manufacturer for the Allies, its long-standing rival, the Curtiss-Wright Corporation, started production from a much smaller scale. Entering production in 1934, the Curtiss Electric propeller utilized an electric motor and gearing for changing blade pitch. By mid-1938, the company employed 111 workers in a 17,000-square-foot corner of the Curtiss aircraft plant in Buffalo, New York. The creation of a dedicated Propeller Division led to the move to a 64,000-square-foot factory in northern New Jersey

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[12] Joseph V. LeBarbera, "Feathering Props on B-17," 30 May 1944; Allan R. Willis, "Auxiliary Feathering System," 30 October 1944; and Donald C. Burrows, "Feathering Fuel," 9 November 1944, all in Collection A1276, Roll 116002, United States Air Force Historical Research Agency.

[13] John M. Campbell, *Boeing B-29 Superfortress* (Atglen, PA: Schiffer Military/Aviation History, 1997), p. 27.

[14] "Target—Tokio [*sic*]," *Bee-Hive* 20 (June 1944): 12–13; "Biggest Props Drive B-29," *Atlanta Constitution* (5 July 1944): 18.

in July 1938. By the end of the year, 300 workers were producing an average of 25 propellers a month. To meet its commitments to the American military, Curtiss expanded its workforce to 3,400 to produce 650 propellers a month by May 1941. Curtiss was producing on a large scale on the eve of America's entry into World War II. Unlike Hamilton Standard, which subcontracted out to other firms, Curtiss-Wright expanded its manufacturing base to meet its production contracts. The ultimate goal was 1,000 propellers a month from 15,000 employees working in 1.3 million square feet of manufacturing space divided among five factories by the spring of 1942.[15]

The Propeller Division never achieved the high-volume production it anticipated at its primary factories in Caldwell, New Jersey, and Neville Island and Beaver, Pennsylvania. They accounted for only 21 percent of the total American propeller output. Curtiss manufactured 144,863 electric propellers for Allied frontline aircraft, including the Curtiss P-40 Warhawk, Lockheed P-38 Lightning, Republic P-47 Thunderbolt, and Grumman F4F Wildcat fighters; the Martin B-26 Marauder bomber; the Consolidated PB2Y Coronado flying boat; and the Curtiss C-46 Commando transport.[16]

The Curtiss Electric propeller played an essential role in a defining moment of World War II. Army Air Forces Colonel Paul Tibbets, commander of the world's first atomic bomber force, the 509th Composite Group, ordered their installation as part of a series of modifications to the unit's B-29s. Unlike other bomber crews, a 509th crew could not simply drop their payload into the sea in the event of an aborted mission. The Curtiss Electric propeller's reversible-pitch feature created opposite thrust would help slow down an overloaded bomber carrying a 5-ton atomic weapon after landing on one of the 8,500-foot runways at North Field on Tinian. He also needed the feature to facilitate easier taxiing and positioning of the bombers over dedicated bomb pits for loading their sensitive cargo. The Curtiss Electric provided the added performance and flexibility to operate the 509th's B-29s. The atomic bombers, Enola Gay and Bockscar, ushered in another era in human history, the Atomic Age, when they attacked the Japanese cities of Hiroshima and Nagasaki in August 1945.[17]

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15. "Propeller Producers Widening Bottleneck," p. 28.

16. "Curtiss Wright: When the Difference Depends on a Split Second or Less!," *Life* 7 (9 August 1943): 93; "The Third Part of a Plane: Curtiss Electric Propellers," n.d. [1942], file B5-260140-01, Propulsion Technical Files (hereafter cited as PTF), National Air and Space Museum (hereafter cited as NASM; Holley, *Buying Aircraft*, p. 563.

17. Propeller Division, Curtiss-Wright Corporation, "Curtiss Propellers: Thirty Years of Development," 4 September 1945, file B5-260000-01, PTF, NASM; Richard H. Campbell, *The Silverplate Bombers: A History and Registry of the Enola Gay and Other B-29s Configured To Carry Atomic Bombs* (Jefferson, NC: McFarland, 2005), p. 14.

Figure 2: Langley Memorial Aeronautical Laboratory's Number 3 Propeller Research Tunnel in the early 1930s. This Propeller Research Tunnel was used to test propellers and to solve problems associated with cooling. The majority of the propeller research moved to the NACA facility at Cleveland, Ohio. (Image credit: National Air and Space Museum Smithsonian Institution, image NASM 77-11380 NACA 16952)

Aeroproducts

Besides the Hydromatic and Curtiss Electric, the American war machine produced a third constant-speed propeller. Pete Blanchard and Charles MacNeil of Engineering Projects developed their hydraulically actuated Unimatic propeller in the late 1930s. Seeing an opportunity, General Motors (GM) acquired the company and formed the Aeroproducts Division in June 1940. Blanchard and MacNeil continued as general manager and chief engineer, respectively. One of Blanchard's new hires was Glenn Peterson, the first African American engineer to work at GM.[18]

GM provided for a new factory in what was originally a cornfield in Vandalia, Ohio, just north of Dayton and across the road from the city's municipal airport.

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18. "Better Idea for Aircraft Propeller Design Led to Formation of Aeroproducts Division," n.d. [1950], GM; Aeroproducts Division, General Motors Corporation, "Propellers," n.d. [1950], Charles Kettering Collection (hereafter cited as CKC), Kettering University Archives (hereafter cited as KUA), Flint, MI; "Werner J. Blanchard" and "Charles Seward Jadis MacNeil," *Who's Who in Aviation* (New York: Ziff-David Publishing Company, 1973); Richard A. Tunney, "The Aeroproducts Division of General Motors Corporation," n.d. [1950], in Juliet Blanchard, "A Man Wants Wings: Werner J. Blanchard, Adventures in Aviation," unpublished manuscript [1986], pp. 81–82, 85, Juliet Stroh Blanchard Collection, Wright State University Special Collections and Archives.

The factory became operational in May 1941 after months of chaotic work. Blanchard and MacNeil initiated a five-year plan to develop the Unimatic as a practical propeller, but the Japanese attack on Pearl Harbor in December dramatically accelerated the program. The Vandalia factory, full of machinery specifically designed to fabricate Unimatic components, produced 73 propellers that same month. The following year, the Unimatic, better known as the "Aeroprop," saw service on Bell P-39 Airacobra and P-63 Kingcobra and North American P-51 Mustang fighter aircraft. Aeroproducts workers produced 12,500 propellers by February 1944. Overall, Aeroproducts' 2,500 employees, 99 percent of whom had never made a propeller before, produced 20,773 three- and four-blade constant-speed propellers, which was approximately 3 percent of total American production during World War II.[19]

The NACA

In support of the American propeller industry and the war effort, the NACA, under the leadership of Chairman Jerome C. Hunsaker, refined an already revolutionary technology by providing solutions to specific problems, and this interwar propeller legacy centered primarily at the Langley Memorial Aeronautical Laboratory in Hampton, Virginia.

Langley researchers first worked to refine the aerodynamic properties of a propeller blade along its entire length. Blade design reflected a compromise where most of the blade was an airfoil, but the portion where it attached to the hub called the shank, or root, was round for structural strength. Beginning in 1939, researchers in the Langley Full-Scale Tunnel fabricated streamlined cuffs in the profile of an airfoil for each blade root that covered over 45 percent of the blade. They calculated that the increased blade area enabled a future fighter to reach speeds of 400 mph at 20,000 feet.[20] Researchers David Biermann, Edwin P. Hartman, and Edward Pepper conducted concurrent tests of propeller spinners, cuffs, airfoil- and round-shaped roots, and NACA 16-series blade sections in the Propeller Research Tunnel throughout 1940. They estimated that a propeller with a spinner and cuffs increased efficiency and power absorption characteristics by 2–4 percent compared

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[19] Aeroproducts Division, General Motors Corporation, *Blades for Victory: The Story of the Aeroproducts Propeller and the Men and Women Who Build It* (Dayton: Aeroproducts Division, General Motors Corporation, 1944), pp. 22, 34; Aeroproducts Division, "Propellers," n.d. [1950], CKC, KUA; Holley, *Buying Aircraft*, p. 563.

[20] NASA Cultural Resources, "Langley Facility 643 (30 ′ 60 Full Scale Tunnel): Test 128-XP-47 Stability, Cooling (Part 1)," 1941, *http://crgis.ndc.nasa.gov/historic/643_Test_128_-_XP-47_Stability,_Cooling_(Part_1)* (accessed 16 February 2018).

to a "conventional" propeller without those innovations.[21] The use of cuffs facilitated increased cooling for radial engines and the installation of de-icing equipment for high-altitude and cold-weather operation. NACA researchers investigated wider, or paddle, blades that featured a larger chord length from the blade's leading edge to its trailing edge to increase thrust further. Langley discovered that blades one and a half times wider than conventional blades led to increased efficiency at higher altitudes and speeds.[22]

Propeller manufacturers introduced paddle blades and blade cuffs as part of their contribution to the refinement of military aircraft. Following what they believed to be the best practice, Hamilton Standard and Aeroproducts favored only paddle blades, while Curtiss used both cuffs and paddle blades on their designs. Regardless of the manufacturer, high-performance aircraft like the North American P-51 Mustang escort fighter and the Boeing B-29 Superfortress strategic bomber benefited from their application.

Cuffs and paddle blades transformed the performance of one of America's frontline fighters in the air war against Nazi Germany, the Republic P-47 Thunderbolt, in late 1943. Combat units like the 56th Fighter Group of the Eighth Air Force were experts at maximizing the P-47's superior diving capability, rugged construction, and unrivaled firepower of eight .50-caliber machine guns through aggressive tactics. However, Army Air Forces evaluations and combat operations revealed that the Thunderbolt exhibited poor climb and maneuverability against the Luftwaffe's Messerschmitt and Focke-Wulf fighters below 25,000 feet.[23] The installation of a Curtiss Electric propeller 13 feet in diameter with cuffed paddle blades and water-injection equipment for the 2,000-horsepower Pratt & Whitney R-2800 radial engine increased top speed by 10 mph and the rate of climb at low altitudes to 600 feet per minute. The improved Thunderbolt could climb to 30,000 feet in approximately 13 minutes rather than 20.[24] All of the 56th's Thunderbolts, including Robert S. Johnson's Lucky, had new propellers by 4 January as the group flew

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[21] David Biermann, Edwin P. Hartman, and Edward Pepper, "Full-Scale Tests of Several Propellers Equipped with Spinners, Cuffs, Airfoil and Round Shanks, and NACA 16-Series Sections," NACA Special Report 168 (October 1940), pp. 1, 11–12.

[22] Louis H. Enos, "Recent Developments in Propeller Blade Design," *Aero Digest* 37 (August 1940): 50–51; George W. Gray, *Frontiers of Flight: The Story of NACA Research* (New York: Alfred A. Knopf, 1948), pp. 212–213, 217–218.

[23] Army Air Forces Proving Ground Command, "Final Report on the Tactical Suitability of the P-47C-1 Type Aircraft," 18 December 1942, *http://www.wwiiaircraftperformance.org/p-47/p-47c-tactical-trials.html* (accessed 16 February 2018).

[24] Roger A. Freeman, *Zemke's Wolf Pack: The Story of Hub Zemke and the 56th Fighter Group in the Skies over Europe* (New York: Orion, 1989), p. 138.

a bomber escort mission to Münster in northwestern Germany. The group went on to be one of the highest-scoring American fighter units of World War II.[25]

Long-time competitors Hamilton Standard and Curtiss, along with the upstart Aeroproducts Division of GM, produced 695,771 constant-speed propellers on a massive scale during World War II. The American people recognized their contribution. Each company received the U.S. government's Army-Navy "E" award for excellence in the production of material for the overall war effort at least once during the conflict. James H. L. Peck wrote in *Popular Science* that as early as 1943, the "amazingly ingenious" propellers pulling American fighters and bombers through the air in four major theaters of operations worldwide were "more than a little responsible" for growing Allied air superiority over the Axis.[26]

THE ALLIES: GREAT BRITAIN

The technical development of the variable-pitch propeller in Great Britain followed a different path than in North America. As American propellers took to the air in the mid-1930s, there had yet to be a British-designed variable-pitch propeller put into production even though engineers Henry Selby Hele-Shaw and Thomas E. Beacham had patented a hydraulic constant-speed propeller in 1924. American Hamilton Standard variable-pitch propellers satisfied the void left unfilled by manufacturers of British metal and wood fixed-pitch propellers for commercial and military operators. The heroic modification of Supermarine Spitfire and Hawker Hurricane fighters to constant-speed operation during the summer of 1940 coincided with the final community-wide acceptance of the variable-pitch propeller in Great Britain. That transformation revealed the crucial role of users in shaping technology as the Royal Air Force (RAF) Fighter Command pilots successfully worked to incorporate constant-speed propellers into their aircraft for more performance.[27]

Having survived the tense days of 1940, the British war machine committed itself to the volume production of constant-speed propellers. The aircraft production program gained momentum, which allowed Great Britain to take the war to

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[25] David R. McLaren, *Beware the Thunderbolt!: The 56th Fighter Group in World War II* (Atglen, PA: Schiffer Military/Aviation History, 1994), p. 52.

[26] James H. L. Peck, "Propellers for Our Fighting Planes," *Popular Science* 143 (November 1943): 122.

[27] Kinney, *Reinventing the Propeller*, pp. 274–304; Ronald Kline and Trevor Pinch, "Users as Agents of Technological Change: The Social Construction of the Automobile in the Rural United States," *Technology and Culture* 37 (October 1996): 764–765.

the enemy. Operational fighter and bomber units ventured out to far-flung combat zones such as North Africa, confident that they could get the requisite spare propellers since those areas lacked adequate repair facilities. Unfortunately, at one crucial moment or another, there was a shortage in the supply of propellers for almost every type of aircraft flown by the RAF and Fleet Air Arm until production stabilized in 1943. The situation became so extreme at certain points that once an airplane was delivered from the factory to an operational unit, fitters removed the propellers and shipped them back to the manufacturer for installation on the next airplane coming off the production line so that new aircraft could be delivered.[28]

The root causes of the production problems were logistical and cultural. Great Britain had two propeller manufacturers. Formed in 1937 from the Rolls-Royce and Bristol programs created to develop the Hele-Shaw-Beacham propeller, Rotol was not even close to volume manufacturing with a practical product until the fall of 1940. The other, de Havilland, which had built Hamilton Standard designs under license since 1934, was not planning to produce the constant-speed Hydromatic until 1941. The focus was on the outdated constant-speed counterweight, or “bracket,” propeller as an expedient. The small size of the industry and the immediate need for propellers impaired a quick expansion program. There was also competition with the overall war industry for raw materials, skilled labor, and machine tools.[29] Moreover, there was a long-standing nationalist desire to support innovation at Rotol, a British company, over de Havilland and its licensed American-origin designs.[30] National pride put the British in a deadly and precarious position in the early 1940s.

Despite their bias, the Air Ministry and the Ministry of Aircraft Production focused on enlarging the capacity of both de Havilland and Rotol. The two manufacturers reacted to their situations differently. De Havilland initially faced the problematic transition from manufacturing the three-blade bracket propeller to the much more complicated Hydromatic in both three- and four-blade versions. Nevertheless, the company produced 97,773 bracket and Hydromatic propellers at its Stag Lane and Lostock factories, which accounted for approximately half of all British propellers during the war. Its workers assembled an additional 37,801 Hydromatics from imported American-made components. The RAF also imported complete Hamilton Standard propellers for use on its primary strategic bomber,

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[28] Ministry of Supply, “Propellers: Development and Production, 1934–1946,” n.d. [1950], AVIA 46/211, The National Archives of the United Kingdom (hereafter cited as TNA), pp. 27, 32, 40–41, 51.

[29] Ibid., pp. 14, 41.

[30] W. R. Freeman to A. H. R. Fedden, 11 August 1938; and Notes of Meeting of Air Council Committee on Supply, “Rotol Airscrews, Ltd.,” 8 September 1938, AVIA 10/223, TNA.

the four-engine Avro Lancaster. Overall, 40 distinct aircraft-engine combinations used three- and four-blade de Havilland propellers, including the Lancaster, Bristol Blenheim, Beaufort, Beaufighter, de Havilland Mosquito, Handley Page Hampden and Halifax, Hawker Typhoon and Tempest, Short Sunderland and Stirling, and Vickers Wellington. All of the RAF and Fleet Air Arm aircraft equipped with de Havilland propellers featured duralumin blades.[31]

With the Ministry of Aircraft Production's help, Rotol had several subcontractors to rely upon in 1941. The foundries and machine shops of the Armstrong-Whitworth, David Brown, and Laystall Engineering companies produced hubs, gears, and components. As the demands increased in 1942, vacuum cleaner manufacturer Hoover; Vickers-Armstrong; and the No. 1 Shadow Group, which included automobile manufacturers Austin, Daimler, and Rover, initiated production of complete propellers. By the end of the war, workers produced approximately 98,034 propellers in three-, four-, and five-blade versions for more than 60 types of production aircraft. Of that number, Rotol provided 30,000 propellers for Great Britain's most famous fighters, the Spitfire and Hurricane.[32]

Unlike de Havilland and in contrast to American practice, Rotol propellers featured composite wood blades due to duralumin shortages. Without a market for its two-blade fixed-pitch propellers in the late 1930s, the Airscrew Company, under the leadership of propeller pioneer Henry C. Watts, went on to specialize in manufacturing composite wood detachable blades for Rotol.[33] The company licensed the patent for the German Schwarz system in 1936. In 1938, the Airscrew Company's new division, Jicwood, pioneered joining compressed wood roots to birch laminates that resulted in blades as strong and light as duralumin components. By war's end, the company had produced an estimated 200,000 individual blades for British military aircraft, including the Fairey Barracuda, Halifax, Hurricane, and Wellington. Two other, much smaller wood-blade companies, Horden Richmond and Jablo Propeller, specialized in Lancaster and Spitfire blades, respectively.[34]

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31. Ministry of Supply, "Propellers: Development and Production, 1934–1946," pp. 12–13, 17, 28, 32; C. Martin Sharp, *D.H.: A History of de Havilland* (Shrewsbury, England: Airlife, 1982), pp. 156, 208.

32. Ministry of Supply, "Propellers: Development and Production, 1934–1946," pp. 28, 30, 63.

33. "News in Brief," *Flight* 50, no. 1959 (11 July 1946): 35.

34. The Airscrew Company, Ltd., "Wooden Airscrews," *Flight* 37, no. 1631 (14 March 1940): 65; Tony Deeson, *The Airscrew Story, 1923–1998* (n.p.: Airscrew Howden, n.d. [1999]), pp. 30–32; Ministry of Supply, "Propellers: Development and Production, 1934–1946," p. 58.

THE ALLIES: FRANCE AND THE SOVIET UNION

Other Allied nations innovated some of their own designs and used a mixture of licensed American and British technology. Ratier in France built hydraulic and electric propellers before the fall of France in June 1940. The American-built North American B-25 Mitchell, Curtiss P-40 Warhawk, and Bell P-39 Airacobra aircraft flown to the Soviet Union through the Lend-Lease program featured Hamilton Standard, Curtiss, and Aeroproducts propellers. The Soviet Union also produced licensed versions of Hamilton Standard and Rotol propellers for its fighter, ground attack, and bomber aircraft.

THE AXIS

The primary Axis powers, Nazi Germany and Imperial Japan, equipped their aircraft with propellers of German and American origin as they executed their planned conquests all over the world. Unlike the Americans and the British, Germany failed to continue to innovate and refine their propeller technology throughout the war. The reasons included the distraction of new technologies, primarily jet and rocket propulsion, and the lack of a substantial interwar legacy of design and development that facilitated technical creativity, innovation, and leadership.

Nazi Germany

Rising from the ashes of the Weimar disaster and ignoring the Versailles Treaty's restrictions, Nazi Germany introduced to the world a revived air force, the Luftwaffe, and an aviation industry capable of producing state-of-the-art aircraft.[35] The Luftwaffe's modern airplanes served as potent aerial symbols of Adolf Hitler, National Socialism, and the Deutsches Reich's technological prowess. By the end of the Spanish Civil War, most of those menacing warplanes featured constant-speed propellers manufactured by Vereinigte Deutsche Metallwerke (VDM), which gave them ultimate performance as Nazi Germany used them to intimidate the rest of Europe.

Vereinigte Deutsche Metallwerke, or United German Metalworks, was a society of family-owned firms formed in August 1930 to sell copper, brass, aluminum, stainless steel, and nickel to European industry.[36] One of VDM's member com-

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[35] James S. Corum, *The Luftwaffe: Creating the Operational Air War, 1918–1940* (Lawrence, KS: University Press of Kansas, 1997), pp. 125, 225.

[36] George C. McDonald, "Report on the Manufacture of Aircraft Propellers by Vereinigte Deutsche Metal Werke, Heddernheim, Frankfurt-Am-Main," 23 May 1945, B5-90000-01,

panies, the Heddernheimer Metal Company of Frankfort am Main, initiated the development of metal propellers in Germany in the late 1920s.[37] VDM's leadership, particularly Bernard Unholtz, recognized that the propeller's aluminum alloy blades would be even more desirable to the European aeronautical industry if connected to a variable-pitch hub. VDM lured mechanical engineer Dr. Hans Ebert away from the Deutsche Versuchsanstalt für Luftfahrt (German Research Center for Aviation) in Berlin in early 1933, just as the Nazi Party took over the German government, to develop a new variable-pitch propeller design.[38]

Ebert's design featured a small reversible electric motor mounted on the engine crankcase that provided actuation via a flexible shaft connected to a small primary drive reduction gearbox and a large annular gearbox fitted to the rear of the propeller hub.[39] The design required no modifications to the engine, which avoided costly conversion programs. The decentralized location of the pitch actuation mechanism away from the propeller hub meant that the propeller's shaft was hollow. This hollow-shaft construction meant ready adaptation of cannon armament into the design of military, primarily fighter, aircraft. A blade pitch indicator in the cockpit gave the pilot instant information.[40] The first VDM constant-speed propellers appeared during the spring of 1937, with full-scale production in Hamburg planned for a year later.[41]

Nazi Germany's industrial landscape was a battleground. As American and British strategic bombers consistently targeted the German industry, planners dispersed critical manufacturers' production efforts like VDM beginning in 1943. They located plants responsible for the production of blades and hubs in safer and

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PTF, NASM; *25 Jahre Vereinigte Deutsche Metallwerke A.G.* (Frankfurt am Main: Vereinigte Deutsche Metallwerke, 1955), pp. 1–2; Thyssen Krupp, VDM, "History," 2011, *https://www.vdm-metals.com/en/our-company/vdm-metals/history/* (accessed 21 February 2018).

[37] Jacob W. S. Wuest to Assistant Chief of Staff, G-2, War Department, "RS Light Propeller Hub," 9 December 1932, B5-900060-01, PTF, NASM.

[38] Hans Ebert, "Bericht über die VDM-Verstelluftschraubenentwicklung [Report on the Development of the VDM Controllable Propeller]," 6 January 1943, German/Japanese Captured Air Technical Documents (hereafter cited as CATD), NASM; A. H. Metcalfe to J. S. Buchanan, 17 January 1937, AIR 2/2406, TNA; John D. Waugh, "Investigation of the VDM Propeller Works," 15 August 1945, p. 1, CATD, NASM; "The German VDM Electric Propeller 1940 Model Used on the Heinkel 115 Twin-Engined, Mine-Laying Seaplane," n.d., B5-900010-01, PTF, NASM; *25 Jahre Vereinigte Deutsche Metallwerke*, pp. 1–2.

[39] John D. Waugh, "Details of the German VDM Electric Propeller, Part I," *Industrial Aviation* 1 (July 1944): 33.

[40] A. H. Hall to the Air Ministry, "Relative Merits of Curtiss and VDM Variable-Pitch Airscrews," 3 January 1938; and H. B. Howard, "VDM Airscrew Designed for Battle-Merlin—General Report," 14 November 1937, both in AIR 2/2406, TNA.

[41] A. H. Metcalfe to J. S. Buchanan, 17 January 1937; and H. S. Royce, "The VDM Airscrew," n.d. [April 1937], both in AIR 2/2406, TNA.

less-concentrated areas. Blade production increased in 1944. The high point was the production of 30,000 individual blades a month from August to October 1944.[42]

In August 1944, Allied bombers attacked Hamburg and Frankfurt and destroyed the VDM factories. The main manufacturing effort moved to Marburg. Hans Ebert took his design and, along with the experimental group, fled Frankfurt to the safety of a new manufacturing complex hidden in a railway tunnel near Hasselborn. Inside the tunnel, they investigated new ideas and solutions, while approximately 1,500 forced laborers produced propellers for the Nazi war effort. The manufacturing equipment included a 30-ton hydraulic press that turned out aluminum blades in a single operation.[43]

The war ended for VDM on 30 March 1945, the day after Frankfurt fell to advancing U.S. Army infantry and armored units. Even though exact numbers are not available, the manufacturing record of VDM was impressive. The aerial arsenal of Nazi Germany's Luftwaffe—from the Messerschmitt Bf 109 fighter to the Heinkel He 219 night fighter—fought World War II almost exclusively with VDM propellers. The estimation that 95 percent of the Luftwaffe's approximately 140,000 aircraft used VDM propellers between 1934 and 1945 suggests that production was between 260,000 and 400,000.[44]

In the wake of the Nazi collapse during the spring of 1945, Allied technical intelligence personnel scrambled to harvest the Luftwaffe's aeronautical legacy. They collected VDM propellers and any reports and information available and shipped them west for evaluation. U.S. Army intelligence officers found Hans Ebert wandering among the ruins of the Hasselborn railway tunnel. Ebert's interview revealed that developmental work on propellers stopped when the German aviation industry moved toward jet- and rocket-powered craft in 1943, which was in stark contrast to the American emphasis on winning the war by refining established technology like the constant-speed propeller. Hitler's orders to restrict the distribution of technical data between manufacturers further curtailed innovation

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42. United States Strategic Bombing Survey (hereafter cited as USSBS), *Aircraft Division Industry Report*, 2nd ed. (Washington, DC: USSBS, 1947), pp. 107, 110–111.

43. McDonald, "Report on the Manufacture of Aircraft Propellers by Vereinigte Deutsche Metal Werke"; L. H. G. Sterne, G. A. Luck, and H. G. Ewing, "Propeller Development at VDM, Frankfurt," August 1945, CATD, NASM; USSBS, *Aircraft Division Industry Report*, pp. 110–111; *25 Jahre Vereinigte Deutsche Metallwerke*, pp. 1–2.

44. There were other German propeller manufacturers. Both Argus Motorenwerke and Junkers Flugzeug und Motorenwerke produced variable-pitch propellers, but in much smaller numbers and primarily for trainers and transports. Ferenc A. Vajda and Peter Dancey, *German Aircraft Industry and Production, 1933–1945* (Warrendale, PA: SAE International, 1998), pp. 133, 312.

in propeller design. Plans to develop high-speed scimitar-shaped blades and a hydraulic propeller capable of instantaneous pitch change never materialized.[45]

American intelligence and engineering personnel inspecting and evaluating German aeronautical developments found Nazi propeller technology inferior. Adam Dickey, the civilian head of the Army Air Force's propeller program at Wright Field, confirmed that while the Germans were ahead of the United States in many areas, they were dramatically behind in propeller development.[46] Unlike other German technologies and the engineers and scientists that developed them, specifically jet and rocket propulsion, as well as transonic and supersonic aerodynamics, there was no post–World War II legacy in Nazi propeller innovation.[47]

Imperial Japan

For its war of conquest in the Pacific and Asia, Imperial Japan adapted and modified foreign variable-pitch designs for its Army Air Force and naval aircraft. Purchasing and licensing American and British propeller technology was part of the vibrant Japanese aeronautical industry all through the interwar period.[48] The two primary manufacturers were the Propeller Division of Sumitomo Metal Industries and musical instrument manufacturer Nippon Gakki (now Yamaha Corporation).

Sumitomo acquired the license for both Hamilton Standard and VDM constant-speed propellers in the late 1930s as Japan continued its military expansion into China. The company had two plants in the Osaka area producing 672 propellers a month by January 1941. The majority were the Hamilton Standard counterweight design and for use on the Imperial Navy's aircraft, including the Mitsubishi A6M2 Reisen fighters, the Aichi D3A1 dive-bombers, and the Nakajima B5N torpedo bombers used in the 7 December 1941 attack on Pearl Harbor. Production of the VDM propellers began in 1942 for aircraft such as the Mitsubishi Ki-67 Hiryu medium bomber and the Kawanishi N1K2 Shiden Kai fighter. Seen as more advanced, the VDM required 70 percent more work than the Hamilton Standard to manufacture. By July 1944, Sumitomo was operating four manufacturing plants producing 5,247 propellers a month under the direction of long-time general manager Osamu Sugimoto, an aeronautical engineer educated at the Massachusetts Institute of Technology.

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[45] McDonald, "Report on the Manufacture of Aircraft Propellers by Vereinigte Deutsche Metal Werke."

[46] D. A. Dickey, "Messerschmitt Propeller Activity," July 1945, CATD, NASM.

[47] Michael J. Neufeld, "The Nazi Aerospace Exodus: Towards a Global, Transnational History," *History and Technology* 28 (March 2012): 57.

[48] "1,000th Controllable," *Bee-Hive* (December 1934): 4; Derek N. James, *Gloster Aircraft Since 1917* (London: Putnam, 1971), pp. 16–17.

Using its expertise in making pianos, Nippon Gakki began manufacturing wood two-blade fixed-pitch propellers in 1921. Imperial Japan's need for propellers increased after the invasion of Manchuria in September 1931. The company began producing ground-adjustable pitch propellers with aluminum alloy blades at its main factory in Hamamatsu. Nippon Gakki sent a delegation of engineers to the United States and Europe to survey manufacturing processes before the Imperial Japanese Army took over the company in 1937. Three factories employing 10,000 people fabricated constant-speed counterweight-type, wood fixed-pitch, and hybrid propellers with metal hubs and wood blades during the war.[49]

Material and labor shortages, design changes, and poor planning led to a dramatic reduction in output during the fall of 1944. Continued bombings by the U.S. Twentieth Air Force led to the dispersal of the overall Japanese propeller industry to new areas, including the basement of the Sogo Department Store in downtown Osaka. B-29 attacks during June and July 1945 destroyed the Japanese propeller industry permanently. Overall, Sumitomo produced 89,885—or 66 percent of all—propellers for Japan's aerial war effort, while Nippon Gakki produced 46,304, or 34 percent, to account for 136,189 propellers. The intelligence personnel of the United States Strategic Bombing Survey estimated that the state of Japanese propeller technology was five or more years behind developments in the United States.[50]

CONCLUSION: THE TRIUMPH OF THE PROPELLER IN WORLD WAR II

World War II was a global conflict where propeller-driven aircraft played a central role. The United States, Great Britain, Germany, and Japan approached the design and production of propellers differently. American manufacturers and government organizations capitalized on an interwar legacy of revolutionary propeller innovation and development, refined the technology for more performance, and dominated the skies. Great Britain foundered initially, but with the production of a dedicated British and a licensed American design, persevered after the tense days of 1940. Hamilton Standard, the Propeller Division of Curtiss-Wright, Aeroproducts,

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[49] Jeffrey W. Alexander, *Japan's Motorcycle Wars: An Industry History* (Vancouver, Canada: University of British Columbia Press, 2008), pp. 146–148.

[50] USSBS, *Sumitomo Metal Industries, Propeller Division*, Corporation Report No. VI (Washington, DC: USSBS, 1946), pp. 1, 3, 10, 12; *The Japanese Aircraft Industry* (Washington, DC: USSBS, 1947), pp. 100–102.

Rotol, and de Havilland produced an astonishing 891,578 propellers for the 430,000 aircraft produced in American and British factories during the war.[51]

A look at Axis propeller design and development reveals another reason for the German and Japanese defeat. After its own late, but successful, start, Germany failed to continue innovating and refining VDM propellers for its operational propeller-driven aircraft as it focused on jet- and rocket-powered aircraft. Japan's reliance upon foreign designs ensured that Sumitomo Metal Industries and Nippon Gakki never could update the country's propellers as the war dragged on. The Allies also bombed both German and Japanese propeller makers into oblivion, a reality no American or British manufacturer faced.

Despite the triumph of Allied industrial might and operational performance, the lasting legacy of the propeller in World War II is mixed. In the immediate postwar period, the widespread transition to jet engines for even higher military and commercial aircraft performance began. The so-called "turbojet revolution" cast doubt on the persistence of the propeller as a modern technology culturally acceptable to an aeronautical generation accustomed to going "higher, faster, and farther" that lingers to this day. Progress-oriented interpretations aside, for the Allies to have won World War II, they needed propellers.

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[51] Kinney, *Reinventing the Propeller*, p. 319.

CHAPTER 7

The NACA Drag Reduction Program

F. Robert van der Linden

Figure 1: A Curtiss-Wright XP-40 prototype in the NACA Full-Scale Tunnel at Langley Field, Virginia, in April 1939. NACA engineers made a number of improvements to reduce the aircraft's drag characteristics; these included combining the radiator and oil-cooling air scoops, as well as changes to the exhaust manifolds and landing gear doors. These small changes resulted in an increased air speed of 53 miles per hour. (Image credit: NACA 17472)

In early 1936, the U.S. Navy sought to re-equip its fighter squadrons with a new generation of monoplane aircraft suitable for operations from its expanding fleet of aircraft carriers. Previously, the navy had stayed with highly maneuverable but slower biplane designs that permitted more controlled takeoffs and landings from narrow carrier decks. By this time, it was clear that the advantages of biplane design were rapidly fading as high performance and significantly faster monoplane fighter designs were becoming the international standard. To keep pace with its potential competition, the U.S. Navy requested proposals for a fighter capable of a maximum speed of at least 300 miles per hour to replace the Grumman F3Fs currently in service. Three companies responded: navy stalwart Grumman quickly redesigned its proposed biplane into a monoplane; the Seversky Aircraft Corporation offered the NF-1, a navalized version of its P-35 then entering service with the U.S. Army Air Corps; and a new company previously known for building high-end automobiles, bespoke auto bodies, and aircraft parts for other manufacturers, the Brewster Aeronautical Corporation, responded with the XF2A.

On 22 June 1936, the U.S. Navy ordered a prototype of the new Brewster F2A Buffalo. The new aircraft was a portly, all-metal, midwing cantilevered monoplane with an enclosed cockpit, retractable landing gear, and a cowled 950-horsepower Wright R-1820 nine-cylinder radial engine; it was a very advanced carrier-based fighter for its time. The new F2A, the Grumman XF4F-1, and the Seversky XFN-1 were all flying and undergoing testing and evaluation by their manufacturers and the navy by the following winter.

The navy quickly rejected the Seversky design, which had a top speed of only 250 mph and suffered from lateral instability. At Grumman's request, the navy approved a redesign of the biplane Grumman XF4F-1 into the monoplane XF4F-2, which would eventually become the famous Wildcat of World War II. Its maximum speed was 290 mph, 10 mph under the requirement. It also suffered engine-overheating problems that convinced the navy to award the winning contract to Brewster on 11 June 1938.

The navy now had the modern monoplane fighter it wanted, but the aircraft also underperformed. Designed to reach 300 mph, the F2A-1 could only struggle to 277.5 mph during its tests. The power and the lower drag of the monoplane design should have enabled the Buffalo to reach its goals. What was wrong? Desperate to find a solution, the navy approached the National Advisory Committee for Aeronautics (NACA) for help.

The NACA was formed in 1915 "to supervise and direct the scientific study of the problems of flight with a view to their practical solution."[1] Despite its small size and budgets during the early years of the 20th century, the NACA conducted significant aeronautical research that led directly to the development of a new generation of high-performance military and civilian aircraft that revolutionized warfare and air travel. Fewer than 500 people conducted research at the Langley Memorial Aeronautical Laboratory in Hampton, Virginia.

In 1938, with war clouds gathering, the NACA expanded its work from fundamental research into specific testing to find swift solutions to immediate problems. Starting with the Brewster Buffalo, the NACA assumed responsibility for testing and analyzing America's combat aircraft to extract the maximum performance possible from these designs.

This critical work completed the design revolution begun in the late 1920s and early 1930s that produced the first truly modern aircraft capable of carrying significant payloads over significant distances at significant speeds, realizing, at last, the vast potential of the aircraft.[2] The innovations of powerful engines, all-metal monocoque construction with cantilevered wings, retractable landing gear, and closely cowled powerplants significantly increased the performance of a new generation of aircraft. As speeds increased, designers and engineers encountered new problems associated with increased drag. They produced new aircraft that, according to their calculations, should have reached their design goals but did not.

At level speeds approaching 300 mph, drag became a particularly significant part of the equation. While the obviously high-drag designs of the biplane, fixed-landing-gear, exposed-engine past were receding into history, new aircraft designs were increasingly bedeviled by what appeared to be minor drag issues—but they were becoming increasingly implicit in degrading the performance of the latest generation of aircraft.[3] Reliable data gathered from careful research addressed this burgeoning problem. The answer to this question was the NACA's Full-Scale Wind Tunnel (FST), also known as the 30- by 60-foot tunnel.

While the NACA possessed its excellent Variable Density Tunnel (VDT), which could simulate different atmospheres, it could test only models. Despite the extraordinary accuracy of these models, only data for airfoils could be accurately

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1. "World War II and the National Advisory Committee for Aeronautics: U.S. Aviation Research Helped Speed Victory," Langley Research Center fact sheet, July 1995, *http://www.nasa.gov/centers/langley/news/factsheets/WWII.html* (accessed 21 June *2022).*
2. James R. Hansen, *The Bird Is on the Wing: Aerodynamics and the Progress of the American Airplane* (College Station, TX: Texas A&M University Press, 2004), p. 77.
3. John A. Anderson, Jr., *The Airplane: A History of Its Technology* (Reston, VA: American Institute for Astronautics and Aeronautics, 2002), pp. 230–231, 235.

acquired.[4] The results were nevertheless impressive as the NACA used the VDT to gather and publish extensive data on 78 different airfoils that provided invaluable assistance to aeronautical engineers the world over.[5] In fact, most of the aircraft flown during World War II—both Allied and Axis—flew with NACA airfoils.

In 1927, the difficulty in collecting accurate data on propellers in traditional small wind tunnels prompted the NACA to build a new tunnel large enough to test full-size propellers as well as actual aircraft parts. Designed by Dr. Max Munk and Elton Miller, the new 20-Foot Propeller Research Tunnel (PRT) provided invaluable data.[6] Under Fred Weick's direction, the NACA developed the so-called "NACA cowling" that markedly reduced drag while improving airflow around bulky air-cooled piston engines. The breakthrough, for which the NACA won the coveted Collier Trophy, increased the speed of an air-cooled powered Lockheed Vega by 12 percent.[7] The cowling, coupled with the air-cooled engine's excellent reliability and durability, made these engines competitive with liquid-cooled designs.[8]

Buoyed by the VDT's and PRT's success, in 1928, the NACA under George Lewis, the Director of Aeronautical Research, began work on a massive wind tunnel that could test actual aircraft. Built in 1931, the Full-Scale Wind Tunnel could hold an aircraft with a wingspan of up to 40 feet and provide unprecedentedly accurate data.

The tunnel itself was the first open-throat, double-return design with a semi-elliptical entrance cone. It featured two 4,000-horsepower electric motors, each fitted with a four-bladed propeller that was 35 feet 5 inches in diameter. This prodigious power could generate airspeeds between 25 and 118 mph.[9] Built at a cost of $1 million, the FST covered 2.4 acres, was 434 feet 6 inches long and 222 feet wide, and rested on a 5-inch base of concrete. Constructed with a steel frame that supported large corrugated asphalt sheets for strength and fire protection, the tunnel proved to be one of the most significant and versatile research tunnels ever built.[10]

Almost immediately after it opened in 1931, the U.S. Army and Navy requested the testing of many of its existing and proposed aircraft. The first aircraft tested

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[4] Joseph R. Chambers, *Cave of the Winds: The Remarkable Story of the Langley Full-Scale Tunnel* (Washington, DC: NASA, 2014), p. 5.

[5] Ibid., pp. 5–6.

[6] Ibid., p. 7.

[7] Donald D. Baals and William Corliss, *Wind Tunnels of NASA* (Washington, DC: NASA, 1981), p. 22.

[8] F. Robert van der Linden, *The Boeing 247: The First Modern Airliner* (Seattle: University of Washington Press, 1991), pp. 24–25.

[9] Baals and Corliss, *Wind Tunnels of NASA*, p. 22.

[10] Chambers, *Cave of the Winds*, pp. 15–17.

was a Vought OS3U-1 Corsair designed as a scout and observation aircraft that could operate from navy warships, mainly cruisers and battleships. It could be fitted as a landplane or a floatplane, depending on the mission. Unfortunately, no adequate data were acquired as the tunnel had significant aerodynamic difficulties that required significant modifications. A difficult recontouring of the walls that required three months of work solved the turbulent flow problems, and the FST returned to operation in September 1931.[11]

From that point onward, the FST rarely rested. Intriguingly, the first project involved testing a Vought O2U-1, not for the navy, but to help settle a patent dispute. French designer Robert Esnault-Pelterie received a French and U.S. patent for his "stick and rudder" control system before World War I. In 1924, he sued Vought and the U.S. government for infringement on his patent and reached a settlement with the Fairchild Company. However, the government argued that Esnault-Pelterie's system, as patented and designed, could not independently control pitch and roll. A week of tests on the highly modified O2U-1 supported the government's claims, and the case was dismissed, saving the government from paying $2.5 million—an auspicious beginning.[12]

Throughout the 1930s, the NACA tested numerous aircraft in the FST to examine aerodynamic problems, load problems, stall issues, angle-of-attack concerns, and many other essential questions. Drag reduction, where new designs are modified to lower drag, and drag cleanup, where existing aircraft are examined with the object of solving unexpected drag problems, were also conducted. With a now-solid base of research testing in hand, the NACA was well prepared to respond to the U.S. Navy's and Army Air Corps' pressing need to solve the increasingly vexing drag reduction problem.

In early spring of 1938, U.S. Navy Commander Walter S. Diehl contacted the NACA to investigate why the Brewster F2A Buffalo was not reaching its expected performance parameters despite its thoroughly modern all-metal monocoque design, powerful cowled air-cooled engine, and retractable landing gear. The aircraft should have easily reached its intended top speed of 300 mph but fell short by a very disappointing 9 percent. This was of particular concern because the XF2A-1 was the first U.S. military aircraft designed from the NACA's new 230 series of airfoils.[13] On 21 April, the navy flew its sole XF2A-1 to Langley and quickly installed it in the FST to look for, in the words of James Hansen, "kinks" or "bugs" that

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[11] Ibid., pp. 30–34.

[12] Ibid., pp. 35–37.

[13] James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917–1958* (Washington, DC: NASA SP-4305, 1987), p. 195.

might be the root of the problem.[14] Time was of the essence as the NACA had less than a week to complete its task.

Clinton H. Dearborn directed the tests. He and his team needed to determine the Buffalo's minimum and high-speed drag coefficient, figure out the possible reductions in drag by improving the numerous fairings on the aircraft, and investigate where deadly carbon monoxide was entering the cockpit.

According to Dearborn's report, the engineers first mounted the Buffalo on the FST's balance. With the propeller removed, all of the control surfaces locked in their neutral position, and the aircraft in its normal condition, the first force test ran at four different speeds between 60 and 100 mph at minimum and high-speed angles of attack. This process helped determine that the mean angle of 1.05 degrees was best suited to calculating further force tests for high speeds at sea level and at 15,000 feet.

Critical to this investigation was the determination of the aircraft's general flow conditions. For this, engineers affixed a series of wool tufts at regular intervals over the entire fuselage, around the opening in the lower tail of the fuselage for the arrester hook, and around the tail wheel to ascertain the possible entry points for carbon monoxide. An observer sat in the aircraft with a rod with wool tufts at its tip to locate entry points of carbon monoxide in the cockpit. The engineers conducted flow tests at speeds of 60 mph, observed and recorded the effects on film for further study. The results of this initial test gave the engineers a baseline for the subsequent examinations.

Following this, a series of tests were conducted at the high-speed attitude at the four test speeds. During the first, the aircraft remained in its standard condition except for the installation of streamlined fairings around the engine's exhaust stack. Next, technicians fitted cover plates over the space between the wheels and the landing gear strut with the gear retracted. During the third force test, engineers removed the wheels and covered the open-wheel wells with sheet metal.

For the fourth test, engineers returned the XF2A-1 to its original configuration but now, with their changes to the engine cowling, specifically improving the fairing around the carburetor and oil cooler intakes. They made alterations to the forward part of the machine gun blast tubes on the top of the cowling and smoothed out the indentations on the lip of the cowling. The work conducted on the cowling was based on earlier data gleaned from a series of low-drag cowlings. The engineers added plasticene filler where they felt it appropriate and were able to eliminate the observed turbulent wake. They also sealed the forward opening of

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[14] Ibid., p. 194.

the two blast tubes to cut off the movement of air from within the cowling. This apparently worked very well.

The next test involved removing the external gun sight to calculate what, if any, difference to the drag this device caused. In addition, the team placed a sheet metal fairing on the trailing edge of the sliding canopy hood and fitted a new curved windscreen.

After these force tests were complete, Dearborn and his team examined the wing of the Buffalo. Detailed measurements were taken of the airflow at five spanwise locations over the left-wing at a test speed of 90 mph and at angles of attack from zero lift to high-speed configuration. Once the initial examination was complete, they sealed the gaps around the ailerons and took new measurements.

Dearborn's team completed their detailed analysis within five days, and on 17 May, they published their stunning results. In less than a week, they were able to identify several significant areas of unexpected drag and reduce the high-speed drag coefficient for the XF2A-1 by a remarkable 27 percent. Their work translated into a 30-mph increase in speed, which could easily be the difference between life and death for the aviator in combat. Specifically, Dearborn and his team found that the turbulent flow on the top of the engine cowling and around the blast tubes up from the cowling was exceptionally high. Also, there was significant turbulence around the exhaust stacks and the wheel wells. The team recommended turning the stacks 90 degrees to the rear and away from the fuselage. They did discover that the fuselage itself was relatively clean, with an adequate airflow around it. The flow around the wing roots was also quite good. The wing tests demonstrated that the typical aileron installation did not add to the aircraft's overall drag in any meaningful way.[15]

As for the vexing problem of carbon monoxide, the investigation showed that air entered the cockpit particularly from the fuselage opening for the aileron control tube and the significant opening around the arresting and tail wheel in the rear of the fuselage.[16]

Based on the NACA's findings, the navy and Brewster made most of the necessary changes to improve the Buffalo's performance. This should have had a happy ending, and in a way, it did, although not for the navy. As modified, the Brewster F2A-1 was now a satisfactory fighter. With world war looming, several threatened

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[15] James R. Hansen, ed., *The Wind and Beyond: A Documentary Journey into the History of Aerodynamics in America*, vol. 2, *Reinventing the Airplane*, Document 3-29 (a), C. H. Dearborn, "Full Scale Wind Tunnel Tests of Navy XF2A-1 Fighter Airplane," NACA Confidential Memorandum Report, 17 May 1938 (Washington, DC: National Aeronautics and Space Administration, 2007), pp. 578–581.

[16] Ibid., p. 581.

nations ordered Buffalos from the United States. Finland purchased several squadrons of de-navalized F2A-1s. While these did not arrive in time to fend off the Soviet invasion during the Winter War of 1939–40, they did arrive in time for the Continuation War of 1941–44, where they gave exemplary service. Light and maneuverable, and now with a top speed of over 300 mph, these Finnish Brewster B-239s gave an excellent accounting of themselves, downing 32 Soviet aircraft for every Buffalo lost. Some 38 Finnish pilots became aces in their Buffalos.[17]

The story for the U.S. Navy and the other operators was not as positive. Following the tests, the NACA returned the XF2A-1 to Brewster for modifications, including installing a more powerful Wright R-1820 radial engine. An improved propeller, as well as flotation gear, was also installed. These changes increased the aircraft's top speed to 323 mph, but the added weight hurt its climb performance. Nevertheless, the F2A-2 was commended for its light controls and excellent maneuverability.

Following the first test's success, the navy sent the improved XF2A-2 to Langley for another round of experimentation in May 1940. The changes made by Brewster at the NACA's recommendation encouraged the navy and the NACA to conduct a series of tests with the aircraft to determine the effects of compressibility, a problem that members of the latest generation of fighters were beginning to encounter as their aircraft were approaching the speed of sound in prolonged dives. While no solution was found as the phenomenon was not fully understood, the F2A-2 survived an 8-g pullout after reaching a terminal velocity of 560 mph.[18]

In October 1940, the XF2A-2 and XF2A-1 returned to the FST for a more exhaustive study, particularly of the drag created by the numerous small protuberances from the antenna, masts, air intakes, and other fittings, as well as the actual surface of the aircraft. The aircraft was also equipped with instruments to measure air pressure in areas subject to compressibility effects. The NACA conducted additional tests to learn the amount of drag caused by wing-mounted automatic weapons. The results proved intriguing; internally mounted guns that did not protrude ahead of the wing leading edge had virtually no effect, while cannons, suspended in pods underneath the wings, registered significant drag. It is interesting to note that most U.S. fighters during World War II had flush machine guns, and none carried guns slung under the wings. In all, the NACA learned that a phenomenal 44-mph improvement from the original design was possible if Brewster made all the recommended changes. Many, though not all, were incorporated.[19]

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[17] Jim Maas, *F2A Buffalo in Action* (Carrolton, TX: Squadron Signal/Publications, 1987), pp. 15–20.

[18] Chambers, *Cave of the Winds*, p. 98.

[19] Ibid., pp. 98–99.

Had the navy stopped with the F2A-2, history might have been kinder to the portly Buffalo. The problem came with the F2A-3 version. This variant added extra fuel for longer range but at a significant weight penalty. Brewster installed a self-sealing wet wing and a larger fuselage tank, armor plating, and additional ammunition that increased the Buffalo's wing loading. While combat experience in Europe dictated many of these changes, the Buffalo design could not absorb the extra weight without a significant loss of performance and a dangerous propensity for collapsing landing gear. Consequently, Buffaloes fell victim to the superior Japanese Mitsubishi Zeros when the Pacific War began in late 1941.

The unfortunate fate of the Buffalo in no way reflected on the NACA's groundbreaking drag cleanup work. Impressed with the quality and speed of Dearborn's team, the U.S. Navy (and later the U.S. Army Air Corps) sent its latest single-engine fighter and bomber designs to the FST to search for any improvements in lowering drag that could give a pilot an edge in combat. The results were impressive and critically important to the nation's war effort.

Each subsequent investigation followed procedures similar to those used on the Buffalo and based on the NACA's previous work with cowling and airfoil research.[20] According to Joseph Chambers in his superlative history of the Full-Scale Wind Tunnel, its service, or "as is," condition determined the aircraft's actual drag. Using wool tufts affixed throughout the aircraft, observations, measurements, photographs, and movies were made to record the data. The engineers studied aircraft at various speeds and angles of attack, generally with the propeller removed. An exception to this state was when the propellers were reattached occasionally and the engines were started to see what, if any, interference was being caused by the propeller wash, especially around the nose of the fuselage. Once the baseline was determined, the engineers identified potential turbulent flow sources and meticulously took steps to isolate these problematic areas. Engineers used tape, plasticene putty, sheet metal, and other materials to fair over the offending location and removed protuberances until the aircraft was as aerodynamically clean as possible. Wooden plugs inserted into the cowling of air-cooled aircraft minimized the turbulent flow around the cylinders. Measurements were then taken off the streamlined configuration, thus determining the theoretical objective. Once the cleanest configuration was determined, engineers carefully removed each fairing and took new readings. Sometimes data from as many as 18 different configurations of a test aircraft were collected. Measurements were also made of the wing profiles, and pressure measurements were gathered to examine the potential onset of compressibility

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[20] Hansen, *Engineer in Charge*, p. 196.

and make recommendations for its amelioration. In this meticulous manner, 35 aircraft underwent thorough cleanup and drag reduction investigations.[21]

The next subject aircraft was the Grumman F3F naval fighter as it was currently in service, and the navy sought to find ways to improve its performance. Though an obsolescent biplane, the F3F was rugged and highly maneuverable. As with the Buffalo, they discovered significant turbulent airflow around the exhaust stacks and the machine gun blast tubes on the top of the engine cowling. As the F3F's days were numbered with the fleet, no modifications were made to existing aircraft, although more useful data were collected.[22]

The third test was incredibly significant and proved critical to the U.S. battles in the Pacific from 1941 through 1943. The Navy and Grumman were impressed with the drag cleanup results for the Brewster Buffalo. Earlier, Grumman had submitted a biplane design developed from the F3F for the competition eventually won by the Brewster F2A. Brewster was a novice in the aircraft business and suffered perpetual problems dealing with poor management, bad labor relations, and questionable business practices. Eventually, this would lead to the dissolution of the company in 1944 despite a wartime economy flush with cash for defense contractors.[23] The navy wisely encouraged Grumman to modify its entry if Brewster could not deliver a quality product in time and sufficient numbers. Redesignated the XF4F-2 Wildcat, the new Grumman was now a rotund midwing monoplane design with rounded wings and tail surfaces and powered by a single Pratt & Whitney R-1830 radial engine.

Grumman was an established manufacturer of naval aircraft with a deserved reputation for building robust, well-designed machines. They were as concerned as the navy when their new Wildcat lost the competition to Brewster and encountered similar, unexpected performance issues. With the F2A test program's revelations fresh in everyone's minds, Grumman flew the prototype XF4F-2 aircraft to Langley and installed it in the FST. The navy was particularly interested in improving the aircraft's top speed, which was inferior to that of the Buffalo, and decreased its stall speed, which was affecting its handling. They were also concerned that the engine did not respond well as the aircraft approach its stall speed. Particularly worrisome was the recurring problem of deadly carbon monoxide intrusion into the cockpit, which the NACA also investigated.

Using the methodology devised for the F2A tests, Langley engineers carefully measured the drag of the F4F-2 in both service and clean condition, thereby

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[21] Chambers, *Cave of the Winds*, pp. 100–101, 196.

[22] Ibid., p. 103.

[23] William Green, *Warplanes of the Second World War: Fighters*, vol. 4 (New York: Doubleday and Company, 1971), pp. 28–33.

Figure 2: The Navy's Brewster Buffalo fighter was the first military aircraft to benefit from Langley's drag reduction program. This practical engineering research at Langley proved to be so successful that almost all American combat aircraft went through the full-scale tunnels to discover or improve their aerodynamic flaws. (Image credit: NACA 22532)

determining the baseline for both. Their observations with the wool tufts showed several problem areas and allowed them to recommend changes. Specifically, the airflow was especially turbulent around the carburetor intake on the cowling, the exposed wheels on the landing gear that retracted into the fuselage, and the underwing oil cooler intake. The NACA estimated that a 9 percent improvement in top speed to 288 mph was possible by fairing the intakes, covering the wheel wells, and removing the antenna wires. Tests also revealed that the stall speed could drop 6 mph to 71 mph if the wingtips were squared off and the flaps extended. As for the carbon monoxide problem, significant airflow was revealed from the rear of the fuselage, the aileron control tubes, and around the forward fuselage fuel tank and firewall. That was not the last investigation of the Wildcat.[24]

Grumman took these recommendations to heart. Back in their factory in Bethpage, Long Island, the Wildcat was quickly redesigned, with its intakes cleaned up and its wingtips, fin and rudder, and elevators squared off. They also took the opportunity to install a more powerful version of the Pratt & Whitney

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[24] Chambers, *Cave of the Winds*, p. 103.

R-1830, which now gave the Wildcat a competitive top speed of 331 mph. The U.S. Navy immediately purchased this new version, the F4F-3, in quantity in August 1939, just days before the Second World War broke out in Europe.[25]

Grumman and the navy, not willing to take any chances, submitted the latest Wildcat to the NACA for further scrutiny. Throughout September, just as Germany and the Soviet Union were carving up Poland, the XF4F-3 underwent a new series of tests in the FST. The investigation confirmed the previous trials' finding that the wing's recorded lift significantly improved over the XF4F-2's. The team also suggested that Grumman install a smaller antenna mast and seal several small but noticeable gaps in the fuselage. Data suggested that the alterations could provide an additional 15 mph in top speed. The elevator and tailplane were also moved to the fin from the lower fuselage for greater effectiveness. With the previous results validated, production continued of this new, improved version of the Wildcat.

Fortunately for the navy and the nation, as modified based on the NACA's recommendations, the F4F-3 Wildcat succeeded where the Brewster Buffalo had failed. Wildcats held the line for three years fending off Imperial Japan's attacks, and then, after the Battle of Midway in June 1942, they helped the United States take the initiative and go on its relentless offensive. While the Mitsubishi A6M Zero was still a superior fighter, the improved Wildcat could more than hold its own in combat until the new Grumman F6F Hellcat entered service in August 1943.[26] While counterfactual, it is chilling to think what could have happened if the Buffalo or the original version of the Wildcat had been in frontline service following the attack on Pearl Harbor. Neither would have stood a chance against the vaunted Zero. The NACA's unheralded contribution to the improved performance of the Wildcat made the F4F a viable combat aircraft and contributed significantly to America's ultimate victory.

From 1938 until the end of the war in 1945, the NACA tested virtually every single-engine aircraft in the military and large models of combat aircraft too big even for the FST. The results were as significant as those of the Wildcat.

During the late 1930s, the standard frontline pursuit aircraft for the Army Air Corps was the Curtiss P-36. Powered by a Pratt & Whitney R-1830, it was a delightful aircraft to fly and reach level speeds of 300 mph. With the advent of the Allison V-1710 liquid-cooled engine, which promised higher horsepower and lower drag, Curtiss sought to exploit this new powerplant and produce a new fighter based on the P-36 but incorporating the new engine. The result was the Curtiss XP-40.

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[25] Ibid., p. 102.

[26] Rene Francillon, *Grumman Aircraft Since 1929* (Annapolis, MD: Naval Institute Press, 1989), pp. 113–141.

Despite designer Don Berlin's best efforts, at 315 mph, the new fighter was not appreciably faster than its radial-engine predecessor. However, his calculations predicted a maximum speed of 350 mph. Lieutenant Benjamin Kelsey, the Air Corps' Flight Project Officer, ordered that the XP-40 be sent to Langley to see if the engineers there could rectify the problem.

As with the Wildcat, the changes made on the recommendations of the NACA made the P-40 a competitive, if not a superior, fighter when confronting early German Messerschmitt Bf 109s and Japanese Mitsubishi A6M Zeros. Before the company sent the aircraft to Langley, Curtiss modified it by moving the radiator from the underside of the fuselage behind the pilot to a position immediately underneath the engine. This alteration alone improved the drag to a point where the top speed of the XP-40 was now 342 mph. The XP-40 arrived at Langley for testing in the FST in April 1939.

Abe Silverstein and Clint Dearborn subjected the XP-40 to a detailed examination with a particular emphasis on reducing the drag around the new location for the radiator.[27] They predicted an additional 23 mph with the now-routine sealing of the typical gaps present in the airframe. Dearborn and Silverstein concluded that a total of 42 miles per hour could be gained if the radiator was modified to optimize the airflow through it and make changes to the carburetor inlet, the oil-cooler, and the wing fillets.[28] Curtiss adopted many of the recommendations that resulted in the XP-40's top speed increasing to 360 mph. While the P-40 did not generally realize that speed in the combat-ready version, the drag cleanup enabled the aircraft to more than hold its own when the United States entered the war after December 1941.

Work continued unabated at Langley and the FST. Next up was the Seversky XP-41. While not well known, as it did not enter service with the U.S. Army Air Corps, it provided much useful information later incorporated in the highly successful Republic P-47 long-range escort fighter. Based on the Seversky P-35 already in service with the U.S. Army Air Corps, the XP-41 featured a more powerful turbosupercharged engine that gave the aircraft a good, but not outstanding, 323-mph maximum speed.

Despite the aircraft's sleek appearance, the XP-41 suffered from exceptionally high drag around its engine, exhaust, and cowling—accounting for an almost 45 percent increase over its cleanest test configuration. Improvements by the NACA team reduced this to 27 percent. Additional drag caused by an unusually large number of gaps and protuberances around the landing-gear doors and the

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[27] Chambers, *Cave of the Winds*, p. 111.

[28] Ibid., p. 112.

machine-gun blast tubes added another 20 percent. The NACA reduced the drag to a remarkable 2.5 percent after completing their work.[29] These efforts inspired the aircraft manufacturers to pay much more attention to minor drag sources' adverse cumulative effects—subsequent designs with impressive results incorporated these lessons.

One of the most significant and particularly challenging drag cleanup investigations helped to improve the performance of a radical new fighter that was not living up to its expectations. The Bell P-39 Airacobra was a highly innovative design that maximized maneuverability by locating its turbosupercharged Allison V-1710 engine behind the pilot to concentrate the aircraft's mass near its center of gravity. Power was routed through a long driveshaft under the cockpit floor to the propeller in the nose. Designed as a high-altitude interceptor to destroy attacking bombers, the P-39 featured a powerful 37-millimeter automatic cannon firing through the propeller hub and rifle-caliber machine guns in the nose and one in each wing. The Airacobra was also the first American fighter equipped with tricycle landing gear, which improved ground handling and eliminated inadvertent ground loops on landing.

Its innovations were also a source of its problems. At first, the P-39 program looked very promising. In trials at the Army Air Corps' Wright Field, the prototype XP-39 peaked at 390 mph. The results were tempered because the aircraft was unarmed and unarmored; thus, its gross weight was only 5,500 pounds, almost 2,000 pounds lighter than the proposed production version. In reality, an actual top speed of just 340 mph was expected when the full weight was factored into the equation.[30]

Regardless, the Army Air Corps placed a large order for the new fighter while requesting that the Airacobra undergo detailed testing at Langley. The XP-39 arrived on 6 June 1939, and the NACA assessment quickly revealed that a potential 26 percent drag improvement was possible between the service version and the completely faired version of the aircraft.[31]

For two months, Silverstein and the other engineers at Langley subjected the aircraft to scrutiny, paying particular attention to how the engine and its accessories were installed behind the cockpit and near the trailing edge of the wings. A large duct for the turbosupercharger intercooler dominated the left side of the fuselage. The turbosupercharger was installed underneath the centerline of the fuselage between the exposed wheels of the landing gear. Four engine exhaust stacks that

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[29] Ibid., p. 114.

[30] Hansen, *Engineer in Charge*, p. 199.

[31] Ibid., p. 199.

drove the supercharger intruded clumsily into the airstream. The carburetor intake protruded awkwardly out of the wing root fillet. The engine's radiator intake was placed below the leading edge of the left wing, with some of the aircraft's structure partially blocking it. Mounted on the fuselage's right side was a bulky air intake and exhaust for the oil cooler. All of these installations produced significant turbulent airflow and drag around the wing root.[32]

Because the pilot had to sit above the propeller shaft, the cockpit sat higher than most comparable fighters. Bell designers created a large canopy that provided excellent visibility but, unfortunately, also produced inordinate drag. Compounding this additional concern was that, although the XP-39 had retractable landing gear, each wheel's outer part remained exposed even when stowed within the wing. At the same time, significant gaps existed between the fuselage and the nose wheel door.[33]

Silverstein's report recommended numerous changes, many of which Bell accepted. They reduced the canopy's height; the mainwheels were made smaller and faired to fit entirely inside the wing; the large intakes were removed from the fuselage sides; and the oil cooler intake was repositioned to within the leading edge of the right wing. The carburetor intake was relocated just behind the cockpit.[34]

The report also strongly suggested the redesign of the intercooler. If that was not possible, then Silverstein's team recommended replacing the existing Allison powerplant with one fitted with an engine-driven supercharger, which required much less space. Neither of these changes was made. Instead, the Army Air Corps decided to remove the turbosupercharger, which was not thoroughly proven; that solved the drag problem, saved much-needed weight, and improved reliability. But there were consequences.

The changes reduced drag considerably. Top speed did increase, but nowhere near the predicted 410 mph.[35] More importantly, without the engine boost from the turbosupercharger, the P-39 no longer had the high-altitude performance that the Army Air Corps demanded. For its efforts, critics attacked the NACA for apparently wasting valuable resources in a vain attempt to improve a flawed design.

On the surface, this seemed to be the case. The Bell P-39's low service ceiling and poor high-altitude climbing ability hampered it when it entered service with the Army Air Corps and the Royal Air Force. Because it lacked a turbosupercharger, it was not suitable for aerial combat on the Western Front in Europe, much of which occurred well above 20,000 feet. Action in the Pacific Theater was no better as the vaunted Mitsubishi Zero could easily outclimb the P-39. The only

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[32] Chambers, *Cave of the Winds*, p. 116.

[33] Ibid., p. 116.

[34] Hansen, *Engineer in Charge*, p. 199.

[35] Ibid., p. 200.

points in its favor were its extraordinary firepower of its 37-millimeter cannon and immense strength, making it suitable for ground-attack duties. Consequently, the Army relegated most U.S. P-39s to ground-support missions or advanced training, or supplied them to other allies.

While the British, French, and later Italians reluctantly received the Airacobra, the Red Air Force of the Soviet Union welcomed it. Air combat on the Eastern Front mirrored the intense violence of the ground war. Locked in a titanic struggle for its very survival, the Soviet Union was desperate for weapons as Nazi Germany overwhelmed most of European Russia in 1941 and 1942, forcing the withdrawal of factories to the east and leaving the Red Air Force with a dearth of modern fighters until the relocated factories could resume production. The United States was happy to send thousands of unwanted P-39s to the Soviet Union, where, surprisingly, they excelled.

Because the air war on the Eastern Front was primarily tactical, combat took place at low and medium altitudes where the lack of a turbosupercharger was not significant. In this environment, the excellent roll rate and maneuverability of the P-39, coupled with its decent top speed of 368 mph, modern gunsight, and radio equipment, quickly made the Airacobra a legend on the Eastern Front. Contrary to western assumptions, the Soviets did not use the P-39 for ground attack. Instead, it was a highly prized fighter, flown by most of the Soviet Union's top aces, including Alexander Pokryshkin, the second-highest-ranked Allied ace, who downed 59 German aircraft, 48 of which while flying the Airacobra.[36]

With a total of 4,719 Airacobras delivered, most of which arrived during the desperate earlier years of the Great Patriotic War, the P-39 directly contributed to the Allied victory by providing vital air cover for the Red Air Force and Red Army as they systematically destroyed the Nazi invaders. This would not have been possible without the NACA's contribution to improving the P-39's design.

The drag reduction and cleanup program continued unabated throughout World War II on prototypes as well as production aircraft. The Curtiss XP-42, which was a P-36 fitted with a streamlined cowling, was tested, and significant drag reduction was realized, especially with an NACA-designed annular cowling. The Curtiss intended to have the XP-46 replace the venerable P-40 and realized similar improvements, which proved moot because neither aircraft ever entered production as better types were already in service.[37]

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[36] Yefim Gordon, *Soviet Air Power in World War 2* (Hinckley, England: Midland Publishing, 2008), pp. 439–448.

[37] C. H. Dearborn and Abe Silverstein, *Wartime Report: Drag Analysis of Single-Engine Military Airplanes Tested in the NACA Full-Scale Wind Tunnel* (Washington, DC: October 1940), pp. 1–33; Chambers, pp. 121, 123–125.

The navy sent the Grumman TBF Avenger torpedo bomber and its controversial Curtiss SB2C Helldiver dive-bomber to Langley. The Avenger's test was the (by now) simple drag cleanup, which indeed improved its performance.[38] Interestingly, the test was conducted in early June 1942 as the Battle of Midway was unfolding, and the initial Avengers met an untimely fate despite the United States' overwhelming victory.

The work performed on the Helldiver was part of a long process to sort out the myriad of problems of SB2C (known as the "Beast" in the navy). The Helldiver suffered from numerous issues that the navy asked Langley to examine. First, the aircraft's drag was disappointingly high. Once again, work at the FST in February 1943 revealed areas of improvement, particularly in the engine exhaust stacks, that promised a 30-mph increase in top speed. Furthermore, other tests revealed the poor design of the leading-edge slats. The NACA's recommendations dramatically improved the Helldiver's aileron effectiveness, solved the wing's premature stalling issue, and significantly improved its lift.[39] After lengthy trials and modifications, the SB2C entered service in 1943 and eventually replaced the famed Douglas SBD Dauntless, as it could carry twice the bombload at a speed of 294 mph and a range of nearly 1,200 miles. As a result, the Helldiver became a deadly dive bomber that devastated the Japanese fleet in the Pacific battles of 1944 and 1945.

The controversial work performed on the Bell P-39 bore fruit in its subsequent redesign, the P-63 Kingcobra. In August 1943, the new P-63 was tested at Langley and revealed how far industry had come, as the aircraft was remarkably clean as delivered. Bell carefully sealed the gaps; the duct was well designed; and the overall finish was much improved. Now fitted with an engine-driven supercharger, a four-bladed propeller, and a new NACA laminar flow airfoil, the Kingcobra could easily reach 400 mph and perform well at high altitudes. The results showed that, because of the great care now taken in identifying small sources of drag in the initial design, an improvement of only 10 mph was possible.[40] Unfortunately for Bell, the P-63, while vastly superior to its P-39 forebear, was not as good as the incomparable North American P-51 Mustang. Once again, the United States sent the unwanted Bell fighters to the Soviet Union, where they once again performed sterling service.

As shown by the P-63, the U.S. aircraft industry quickly adopted the NACA's drag-reducing program's lessons into subsequent combat aircraft design and production. Many, if not all, of this next generation of aircraft were much cleaner in their original configurations than their immediate predecessors, which, ironically,

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[38] Chambers, *Cave of the Winds*, pp. 140–141.

[39] Ibid., pp. 148–149.

[40] Alain J. Pelletier, *Bell Aircraft Since 1935* (Annapolis, MD: Naval Institute Press, 1992), pp. 42–49; Chambers, *Cave of the Winds*, pp. 159–160.

led to new problems as the new machines were much faster than before. With lessons learned from the earlier XP-41 testing, the new Republic P-47B came to Langley to learn why this and other high-speed aircraft were suffering tail failures. Because of its massive 2,000-horsepower engine and very clean design, the P-47B could reach a speed well above 400 mph. Stability, control, and tail load tests revealed that the fabric covering the rudder and elevator was failing when the aircraft reached 460 mph. Fabric-covered control surfaces were the standard means of eliminating deadly flutter; only now, the fabric was the source of the problem. The NACA recommended the use of metal surfaces, which solved the problem for the P-47.[41]

In November 1942, the U.S. Navy requested that Langley study its 400-mph fighter, the Vought F4U-1 Corsair. An auspicious design that became one of the war's best fighters, the F4U-1 featured the wing leading-edge oil cooler and supercharger inlets previously recommended by the NACA. Further tests revealed a potential improvement of 12 miles per hour. Other tests solved the aircraft's dangerous sharp stall of its left wing at low speed and at high angles of attack typical of carrier landings. A simple triangular spoiler affixed to the opposite wing's leading edge gave the aircraft uniform stall characteristics.[42] Once finished with these and other modifications not directly related to the drag cleanup program, what had started as a very good airplane emerged as one of World War II's all-time great airplanes.

In March 1943, it was the turn of the Corsair's stablemate, the Grumman F6F-3 Hellcat, in the FST testing chamber. Langley determined that significant airflow separation occurred at the wing root, which was causing drag and less lift than was possible with wing fillets installed.[43] Recommendations to cover the gap at the wheel wells and at the juncture where the wing folded were not feasible and therefore not adopted. Engineers determined that the extent of the work involved was not worth the additional 13 miles per hour that was theoretically possible with this already very clean design. It was not necessary as the Hellcat quickly gained the upper hand over the Mitsubishi Zero as it was rugged, easy to fly, and could easily outdive its adversary.

Interestingly, the NACA tested an actual Mitsubishi A6M-2 in the FST just before the Hellcat arrived. This Zero was captured intact after a fatal crash landing on the Alaskan island of Attu in June 1942, as part of the Battle of Midway. It was discovered and brought to the United States later that summer for extensive flight

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[41] Ibid., pp. 129–130.

[42] Chambers, *Cave of the Winds*, pp. 145–146.

[43] Ibid., p. 153.

testing. These analyses revealed its flaws and helped U.S. naval aviators develop successful tactics to fight it. In great secrecy, the navy flew the Zero to Langley on 5 March 1943, where it remained until 11 March. While drag cleanup was not an objective, Abe Silverstein and the NACA staff performed their drag analysis and other tests to learn what they could about this remarkable fighter.[44]

The results of the NACA's effort bore fruit when they tested the North American P-51B Mustang. The graceful Mustang, initially designed for the Royal Air Force, was a replacement for the Curtiss P-40s they had acquired through Lend-Lease. It was originally fitted with an Allison V-1710 that gave it very good low- to medium-altitude performance, but the Rolls-Royce V-1650 Merlin engine transformed the aircraft. The Merlin had a two-stage supercharger that gave the new P-51B outstanding speed and climb at any altitude; it quickly became the backbone of the U.S. Army Air Forces and was the only fighter capable of escorting strategic bombers deep into Germany.[45]

In September 1943, three months before the P-51B joined the Eighth Air Force in Britain, the NACA subjected an example to a drag cleanup evaluation. The Mustang proved to be an excellent design, with its new NACA laminar flow "high-speed" wing, tight seals and gaps, and an innovative radiator under the rear fuselage that protruded away from the airframe and away from the boundary layer, thus reducing drag. After thorough testing, the engineers concluded that an insignificant 3-mph improvement was possible, clear evidence that industry had learned that significant improvements were possible if close attention was paid to the little details.

The NACA examined 30 military aircraft during its drag cleanup and reduction program during the Second World War. In many cases, these efforts paid off handsomely, producing combat aircraft capable of fighting the Axis on an equal or better footing. Designers passed these lessons on to a succeeding generation of aircraft that helped keep the United States at the forefront of aeronautics.

One of the last aircraft tested introduced the American aviation industry to a new technology—jet propulsion. Trailing Germany and Great Britain in the race to introduce jet-powered combat aircraft, the United States acquired working examples and production drawings of Frank Whittle's W-1 centrifugal flow engine, Britain's first flying jet engine. The U.S. Army Air Forces through General Henry H. Arnold contracted with Bell aircraft to construct America's initial jet fighter. First flown on 1 October 1942, the Bell XP-59 Airacomet blazed the trail

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[44] Ibid., pp. 152, 153.

[45] Norm Avery, *North American Aircraft: 1934–1998*, vol. 1 (Santa Ana, CA: Narkiewicz/Thompson, 1998), pp. 109–141.

for all American jet-powered aircraft to follow, but its performance was surprisingly not up to par.

Bell had produced a safe design that promised outstanding performance but failed to deliver as expected. The aircraft's design was inherently stable to ease the pilot's transition to flying and learning the idiosyncrasies of the temperamental jet engine. The aircraft was a straightforward design with a thick, shoulder-mounted wing with two engines installed underneath near the fuselage centerline. The tailplane was mounted above the fuselage so that the hot exhaust would not damage the aluminum tail nor interfere with the elevator and rudder.[46]

Despite the aircraft laminar flow wing and excellent thrust-to-weight ratio, the maximum speed of the Airacomet was only 404 mph—fast—but not faster than conventional piston engine fighters such as the Corsair or Mustang. It should have been capable of speeds of over 500 mph.

In March 1944, Bell sent a service-test YP-59 to the Langley FST for investigation. After three months, the YP-59A revealed its secrets. As suspected, the thick wing produced a significant amount of profile drag in exchange for its good low-speed handling. More telling, and of great potential use for the future design of jet-powered aircraft, the test revealed significant turbulent flow and boundary-layer separation around the air intakes in the engine nacelles. The NACA conducted its now-standard cleanup protocol and redesigned the intakes, which theoretically increased the Airacomet's top speed by 27 mph.

Even a 27-mph improvement was not enough to exceed the speed of contemporary piston-engine fighters, but the research helped the next generation of jets dominate the skies. The Lockheed XP-80 Shooting Star, America's first jet fighter to enter service, had a much thinner wing and better-designed engine intakes. It was capable of speeds of over 500 mph, relegating the P-59 to its role as an advanced trainer.

Nevertheless, much was learned from the P-59 investigations, the 30 detailed drag cleanups, and the drag reduction program. The results had a marked positive effect on America's frontline combat aircraft's performance and materially aided the war effort on every front.[47]

On 1 July 2016, the National Air and Space Museum opened its new Boeing Milestones of Flight Hall, which commemorates a host of historic aerospace artifacts. Just behind the prototype Bell XP-59 hangs one of the two huge wooden four-bladed fans that ran for decades in the FST—a fitting tribute to the NACA's work in Langley's Full-Scale Wind Tunnel and its critical drag cleanup program.

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[46] Pelletier, *Bell Aircraft Since 1935*, pp. 50–54.

[47] Chambers, *Cave of the Winds*, pp. 164–167.

CHAPTER 8

The Tuck-Under Problem

An Aerodynamic High-Speed Compressibility Disaster for the Lockheed P-38 and How NACA Engineers Fixed It

John D. Anderson, Jr.

Figure 1: An early prototype of the Lockheed P-38 Lightning. The aircraft's performance moved into realms not seen before. Pilots experienced the forces of the transonic region on the aircraft and its control surfaces. (Image credit: NASM HGC-968)

In the late morning of 4 November 1941, in the sky over Southern California, Lockheed test pilot Ralph Virden was conducting high-speed dive tests in the first YP-38, a new fighter airplane designed by the iconic Kelly Johnson. At the same time, the Lockheed Aircraft Company was hosting a noontime outdoor luncheon at its Burbank factory, in honor of visiting high-ranking Army Air Corps and War Department representatives. According to the *Los Angeles Times*, 25,000 Lockheed employees attended the luncheon. Suddenly, not far away, the peaceful neighborhood surrounding 1147 Elm Street in Glendale, California, was jarred at noon by a massive explosion—Ralph Virden and his YP-38 had crashed into the home of Jack Jensen. The attendees at the Lockheed luncheon did not observe the crash and had no clue that it had happened. Nevertheless, Jensen, who was at home at the time, tried valiantly to free Virden from the burning wreckage. Driven back by the flames, he was not able to save Virden's life. According to the *Times* in a dispatch published the next day, witnesses said that the airplane was flying at "near-maximum speed" when the duralumin tail assembly "simply floated away." A moment later, the airplane "seemed to put on a burst of speed, the high whine of its engines rising." Without the vertical tail, Virden had no longitudinal control of the airplane. He managed to glide to an altitude of about 1,500 feet when the YP-38 went into a flat spin, flipped over on its back, and shot earthward.

Virden, one of Lockheed's best test pilots, was the first fatality due to adverse compressibility effects, and the P-38 was the first airplane to suffer from those effects. Virden's YP-38 had exceeded its critical Mach number in the power dive and had penetrated well into the compressibility regime at its terminal dive speed. The problem encountered by Virden and other Lockheed P-38 pilots was that, beyond a certain speed in a dive, the horizontal tail suddenly experienced an unexpected increase in lift that caused the airplane to go into an even more severe dive from which recovery was not possible. The whole airplane simply tucked under the vertical direction, and this problem, therefore, acquired the label "the tuck-under problem." The existence of hundreds of P-38s already in service and many more hundreds on the Lockheed production lines emphasized the seriousness of the problem.

THE COMPRESSIBILITY PROBLEM: WHAT IS IT?

Air density is defined as the mass of air per unit volume, in units of kilograms per cubic meter or pounds-mass per cubic foot. (For engineering readers, the more consistent engineering unit of mass is slugs, not pounds-mass, and the density can be expressed in terms of slugs per cubic foot.) Until the beginning of World War II, most airplanes flew at speeds on the order of 350 miles per hour or slower. At these relatively low velocities, the density of the air flowing over the aircraft changed little, no more than about 5 percent. For all practical purposes, this change is so small that the density can be considered *constant* throughout the flow—defined as incompressible flow. The fluid dynamics of incompressible flows had been studied for centuries; such flows were generally smooth and without significant physical complications. Up to the beginning of World War II, virtually all aerodynamic applications assumed the existence of incompressible flow. In contrast, for airplanes flying faster than 350 miles per hour, the change in density of the flow around the airplane progressively became too large to be ignored; flow wherein the density is variable (not constant) is defined as *compressible* flow.

In a compressible flow, the local flow velocity can be everywhere less than the local speed of sound (a subsonic compressible flow), or everywhere greater than the local speed of sound (a supersonic flow), or a mixture of subsonic flow in some parts of the flow and supersonic flow in other parts of the flow (called a transonic flow). In the supersonic regions of the flow, shock waves can occur. The "compressibility problem" is intimately linked to these shock waves in a transonic flow.

EARLY HISTORY: HARBINGERS OF THE COMPRESSIBILITY PROBLEM

In 1673, the French physicist Edme Mariotte gave a paper to the Paris Academy of Science that contained experimental data proving for the first time that the force on an object moving through the air varied as the square of the velocity of the object. Before this time, conventional wisdom adopted the idea that the force varied directly with the velocity. After Mariotte's finding, the velocity-squared law for aerodynamic force became widely accepted. Then, in the early 18th century, the English ballistics expert Benjamin Robins, while experimentally measuring the aerodynamic drag on artillery projectiles, observed for the first time that, when the projectiles were moving through the air at speeds near the speed of sound, the aerodynamic force (drag in this case) began to vary as the velocity cubed, not velocity squared as in the lower-speed case. This is the first time in history that transonic drag rise was observed. In 1742, he gave a paper to the Royal Society on this phenomenon entitled "Resistance of the Air and Experiments Relating to Air Resistance." However, he had no idea what was causing this large drag increase. We know today that the culprit came from the resulting shock waves.

By the middle of the 19th century, shock waves were shown to be a mathematical possibility. In 1858, the German mathematician G. F. Bernhard Riemann first attempted to calculate shock properties, but he neglected an essential physical feature and obtained incorrect results. Twelve years later, William John Rankine, a noted engineering professor at the University of Glasgow, correctly derived the proper equations for the flow across a normal shock wave. Not cognizant of Rankine's work, the French ballistician Pierre Hugoniot rediscovered the normal shock wave equations in 1887. To the present day, the governing equations for flow across a shock wave are called the Rankine-Hugoniot equations, in honor of these two men.

In 1887, the Austrian physicist Ernst Mach took a photograph of the flow over a supersonic projectile—a .22 caliber bullet—as it streaked down a range in his laboratory. Employing a special optical system, Mach was able to photograph a shock wave emanating from the projectile's nose. This was the first time a shock wave

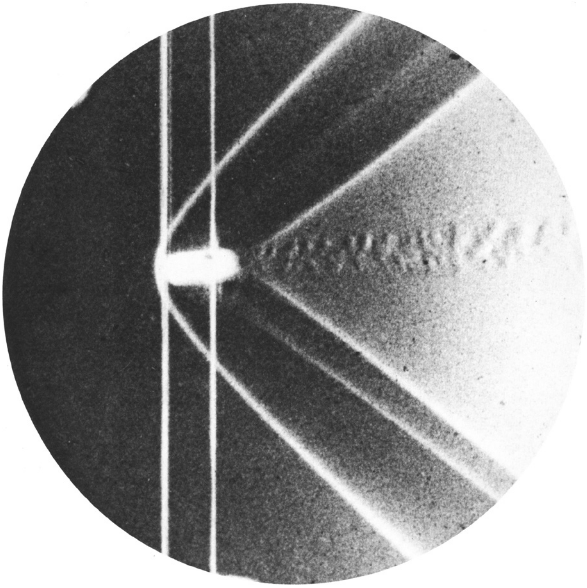

Figure 2: In this first photograph of a shock wave, the wave is generated in front of a .22 caliber bullet moving at supersonic speed. The two vertical lines are trip wires designed to time the photographic light source (a spark) with the passing projectile. (Image credit: Ernst Mach, 1887)

was seen by human beings, proving that shock waves exist. Mach's photograph is shown in figure 2.

By the beginning of the 20th century, the large drag increase on projectiles as their velocity passed through the speed of sound was well known. For example, ballistics measurements on projectiles carried out by Bensberg and Cranz in Germany in 1910 yielded the variation of drag coefficient with velocity for the transonic and supersonic regimes. Those measurements showed a considerable rise in drag coefficient near the velocity of 340 meters per second (Mach 1) and a gradual decrease in the drag coefficient in the supersonic region. Also, it was suspected that the large drag rise was caused by a shock wave generated at the nose of the projectile, as shown in Mach's photograph. The air pressure behind a shock wave is larger (sometimes much larger) than the pressure in front of the wave. It is easy to understand that this high air pressure just behind the bow shock wave is exerted directly on a supersonic projectile's nose, significantly increasing the aerodynamic drag. At the beginning of the 20th century, therefore, the source of the considerable drag rise observed on projectiles as they flew faster than the speed of sound was understood.

THE FOCUS SHIFTS: COMPRESSIBILITY EFFECTS ON AERODYNAMIC LIFT

At the turn of the 20th century, however, other humanmade objects began to fly through the air—namely airplanes. In contrast to projectiles (artillery shells, bullets, etc.), airplanes had to generate aerodynamic lift to counterbalance their weight to remain in the air for long periods. Although no airplanes were flying even remotely close to the speed of sound, a new question arose: what happens to the lift on an airfoil or wing moving near, at, and beyond the speed? Nobody had looked into this question. That is, not until Frank Caldwell and Elisha Fales, two engineers at the U.S. Army Air Service Engineering Division, McCook Field, in Dayton, Ohio, began a series of experiments to examine the question. In 1918, Caldwell and Fales had designed and built the first high-speed wind tunnel in the United States. The tunnel was large for its time, with a length of 19 feet and a test section with a 14-inch diameter—a big, powerful machine for its day. Its velocity range was from 25 mph to a stunning 465 mph. At the time, the fastest speeds of fighter airplanes were on the order of 130 mph. So, in the design of a wind tunnel to achieve a test stream velocity of 465 mph, were Caldwell and Fales and the U.S. Army so prescient to envision the 400-mph speeds to be achieved by fighter airplanes 25 years later? Not really. Caldwell and Fales were in the propeller section of McCook Field, and even for an airplane flying at 130 mph, the relative airspeed over the tip of a rotating propeller could reach near the speed of sound. When this occurred, the propeller efficiency would suddenly decrease, causing the thrust to decrease precipitously and the torque exerted on the engine drive shaft to increase markedly. The cross section of a propeller blade is an airfoil shape. An intelligent method to examine the cause of this degradation of propeller efficiency was to test airfoils in a high-speed wind tunnel.

Thus, in 1918, Caldwell and Fales were the first investigators to measure the effects of high speeds on the lift of airfoils. The newly created National Advisory Committee for Aeronautics (NACA) initiated and sponsored research under contract and carried it out at McCook Field. Caldwell and Fales's investigation was the first time that the NACA researched the compressibility problem. The results were stunning. They observed that not only did the drag of the airfoil increase dramatically when the airspeed reached a certain high value (similar to the case with projectiles), the lift decreased precipitously beyond this speed—it simply "fell off the cliff," as clearly seen in figure 3, taken directly from their technical report. They labeled this speed as the "critical speed," which later became the source of the term "critical Mach number." (The critical Mach number is defined as that free stream Mach number at which sonic flow first occurs at some point on the surface of the body.) This plot and others like it for other angles of attack were the first published data on the adverse compressibility effects on airfoils. However, at that time, nobody understood what physical phenomena were causing these adverse effects.

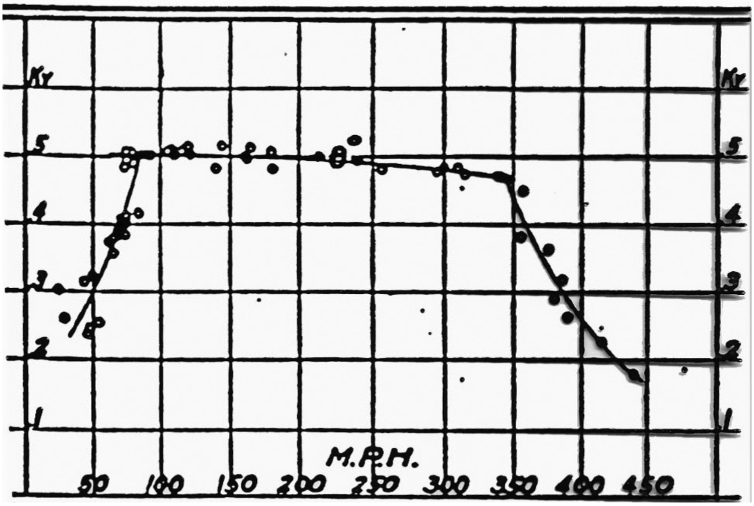

Figure 3: Lift coefficient versus velocity. (Image credit: F. W. Caldwell, and F. M. Fales, "Wind Tunnel Studies in Aerodynamic Phenomena at High Speeds," NACA Technical Report 83 [1920])

During the 1920s, the NACA initiated research to find out. It sponsored a series of fundamental experiments in high-speed aerodynamics at the Bureau of Standards conducted by Lyman J. Briggs and Hugh L. Dryden. In 1919, at age 20, Dryden earned a Ph.D. in physics from Johns Hopkins University, the youngest to obtain that degree from Johns Hopkins by that time. Moreover, the subject of his dissertation was the investigation of high-speed aerodynamic flows. (Dryden would later become Director for Research for the NACA, 1947–58.) At first, Briggs and Dryden jury-rigged a high-speed tunnel by connecting a vertical standpipe 30 inches in diameter and 30 feet high to a large centrifugal compressor at the Lynn works of the General Electric Company in Massachusetts. At the other end of the pipe was a cylindrical orifice that served as a nozzle. Briggs and Caldwell reported that air speeds approaching the speed of sound were obtained with this device. Rectangular planform models, with a span of 17.2 inches and a chord length of 3 inches, were placed in the high-speed airstream, and the lift, drag, and center of pressure were measured. The findings supported the earlier trends observed by Caldwell and Fales. In particular, they found that

1. The lift coefficient for a fixed angle of attack decreased rapidly as the speed increased beyond the critical speed.
2. The drag coefficient increased rapidly.
3. The center of pressure moved back toward the trailing edge.
4. The critical speed at which those changes occurred decreased as the angle of attack increased and the airfoil thickness was increased.

However, again at this stage, they had no clue what was causing these adverse compressibility effects.

Continuing under another NACA contract, Briggs and Dryden carried out a second series of experiments at the U.S. Army's Edgewood Arsenal in Maryland because the compressor at the Lynn works was no longer available to them. At the Edgewood Arsenal, they constructed another high-speed wind tunnel, much smaller, with an airstream only 2 inches in diameter. By careful design, two pressure taps could be placed in each of the seven small wing models of identical shape, but with different locations of the taps. With that technique, Briggs and Dryden measured the pressure distribution over the airfoil at Mach numbers from 0.5 to 1.08. The findings were dramatic: Beyond the critical speed, the pressure distributions over the top of the airfoil exhibited a sudden pressure jump at about one-third to one-half the distance from the leading edge, followed by a relatively long plateau toward the trailing edge. Such a pressure plateau was familiar—it was similar to that found over the top surface of an airfoil in a low-speed flow when the airfoil stalls at high angles of attack. It was well known that separation caused airfoil stall of the flow off the airfoil's top surface. Briggs and Dryden concluded that the adverse effects of compressibility were caused by flow separation over the top surface of the airfoil, even though the airfoil was at low (even zero) angles of attack. To substantiate that, they conducted oil-flow tests: An oil, with pigment added to make it visible, was painted on the model surface. By placing the model in the high-speed airstream, the oil pattern then revealed the telltale line of flow separation. Clearly, beyond the critical speed, flow separation was occurring on the top surface of the airfoil. This was a dramatic discovery—flow field separation was causing the adverse compressibility effects. But what was causing the flow to separate? The answer to that question was eight years in the future.

NACA COMPRESSIBILITY RESEARCH SHIFTS TO AN IN-HOUSE FOCUS

In July 1928, a young New Englander, born and raised in Lowell, Massachusetts, began his career with the NACA Langley Memorial Laboratory in Hampton, Virginia. Having just graduated from the Massachusetts Institute of Technology (MIT) with a B.S. degree in aeronautical engineering, John Stack was assigned to the Variable Density Tunnel, the premier wind tunnel in the world at that time. Absolutely dedicated to aeronautical engineering, Stack, while in high school, earned money so that he could take a few hours of flight instruction in a Canuck biplane. Stack helped out with the maintenance of a Boeing biplane owned by one of his part-time employers. Before he went to college, he had made up his mind to be an aeronautical engineer. However, his father, a carpenter who was also very successful in real estate, wanted his son to study architecture at MIT. Against his father's wishes, Stack enrolled in aeronautical engineering, keeping it a secret from his father for the first year, but with his mother's understanding approval. Stack later commented: "[W]hen Dad heard about it, it was too late to protest."[1]

When Stack first walked into the Langley Laboratory that July of 1928, a year's worth of design work had already been done on Langley's first high-speed tunnel. The facility was already operational with an open-throat test section. Briggs and Dryden's work had achieved some success in studying the compressibility problem, and the growing importance of high-speed research was already perceived by some visionaries. Because of this perception, Joseph S. Ames, president of Johns Hopkins University and the new chairman of the NACA, in 1927 gave priority

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[1] Lou Davis, "No Time for Soft Talk," *National Aeronautics* (January 1963): 9–12.

to high-speed wind tunnels and research. Eastman Jacobs, who had joined the NACA in 1925 after receiving his B.S. degree in mechanical engineering from the University of California, Berkeley, was the chief designer of the open-throat 11-inch High-Speed Tunnel. (Jacobs would later earn an international reputation for his work on the famous NACA airfoil sections in the 1930s and his conception of, and pioneering research on, the NACA laminar flow airfoils just before the beginning of World War II.) An innovative aspect of the 11-inch High-Speed Tunnel from the 20-atmosphere-pressure tank of the Langley Variable-Density Tunnel drove it. For a change in models in the Variable-Density Tunnel, the 20-atmosphere tank that encased the entire tunnel was blown down to 1 atmosphere; this represented a wasted energy source that the Langley engineers ingeniously realized could be tapped for the 11-inch High-Speed Tunnel. The high-pressure tank's 5,200-cubic-foot capacity allowed about 1 minute of operation for the tunnel. The NACA gave John Stack gave the responsibility for improving the High-Speed Tunnel by designing a closed throat. This improved facility, shown in figure 4, was operational by 1932. His participation in the design and development of the 11-inch High-Speed Tunnel launched John Stack on his life-long career in high-speed aerodynamics.

While Stack was working on the High-Speed Tunnel, he was impressed by an event in England that would lead to a rapid refocusing of the NACA high-speed research program: On 13 September 1931, a highly streamlined airplane, the Supermarine S.6B, flashed through the clear afternoon sky near Portsmouth, along the southern English coast. Piloted by Flight Lieutenant John N. Boothman, that racing airplane averaged a speed of 340.1 mph around a long, seven-lap course, winning the coveted Schneider Trophy permanently for Britain. Later that month, Flight Lieutenant George H. Stainforth set the world's speed record of 401.5 mph (Mach 0.53, over half the speed of sound) in the same S.6B. Suddenly, in the face of that kind of speed, the previous concern over propeller compressibility effects, which for propeller tips posed a significant but tolerable problem, became transformed into a vital concern about the compressibility effects on the entire airplane, and the complexities of these effects raised a problem of show-stopping proportions.

Stack was acutely aware of the new compressibility challenge. In 1933, he published the first data to come from the newly modified, closed-throat High-Speed Tunnel. Although the airfoils tested were propeller sections, Stack obviously had the Schneider Trophy racer in mind: "A knowledge of the compressibility phenomenon is essential, however, because the tip speeds of propellers now in use are common in the neighborhood of the velocity of sound. Further, the speeds that have been attained by racing airplanes are as high as half the velocity of sound. Even at ordinary airplane speeds, the effects of compressibility should not be disregarded if

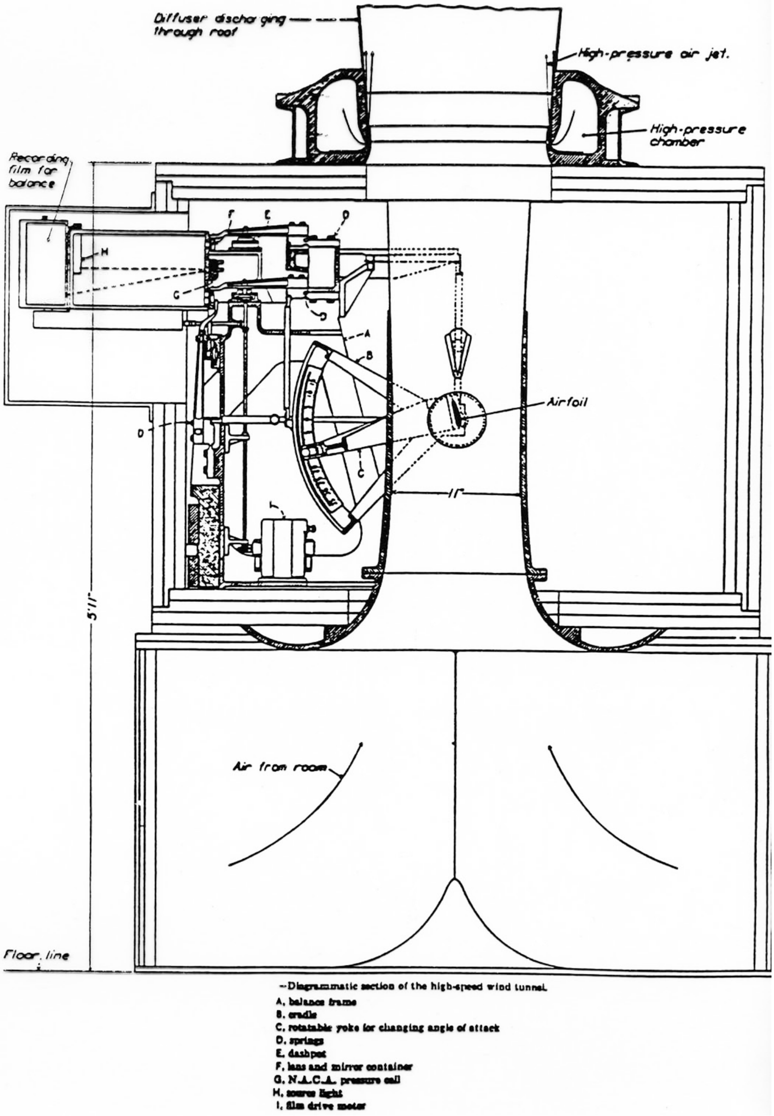

Figure 4: NACA High-Speed Tunnel with closed-throat test section, ca. 1932. (Image credit: NACA Technical Report 463)

accurate measurements are desired."[2] For the most part, Stack's data in 1933 confirmed the trends observed earlier. These measurements were carried out with the usual detail and accuracy that characterized the NACA's work. Stack's report was

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2. John Stack, "The N.A.C.A High-Speed Wind Tunnel and Tests of Six Propeller Sections," NACA Technical Report 463 (1933).

the most definitive compilation of airfoil properties in the compressible regime to date. His measurements of the variations of the lift, drag, and moment coefficients with Mach number for a Clark Y airfoil showed the precipitous drop in lift and the large increase in drag at high speeds. He also confirmed that when there were increases in airfoil thickness or angle of attack, or both, the adverse compressibility effects began to appear at lower Mach numbers.

At this time, there was virtually no theoretical solution to the high-speed flow over an airfoil. One such approximate theory, labeled the Prandtl-Glauret compressibility correction, applied to the "correction" of low-speed data for lift coefficient and moment coefficient to consider high speeds. He insightfully realized that this theory was only reasonably accurate for speeds below the compressibility burble. The Prandtl-Glauret theory applied only to the attached flow over the airfoil, not to the higher-speed regime where the flow became separated from the surface, which of course is the regime where the adverse compressibility effects occur. This conclusion presaged almost 40 years of a theoretical void. The aerodynamic equations applicable to the transonic flight regime, Mach numbers between about 0.8 and 1.2, are nonlinear partial differential equations that defied solution until the 1970s. Moreover, even then, the solution was by brute force—numerical solutions using the power of the newly developed discipline of computational fluid dynamics carried out on high-speed digital computers.

Stack coined the phrase "compressibility burble" in an NACA Technical Report he wrote:

> The lift coefficients increase as the speed is increased, slowly as the speed is increased over the lower portion of the range, then more rapidly as speeds above half the velocity of sound are exceeded, and finally at higher speeds, depending on the airfoil section and angle of attack, the flow breaks down as shown by a drop in lift coefficient. This breakdown of the flow, hereinafter called the compressibility burble, occurs at lower speeds as the lift is increased by changing the angle of attack of the model.[3]

Driven by the conviction and foresight of John Stack, the NACA waved the red flag of compressibility problems to the whole world of aeronautical engineering. In January 1934, the first significant professional aeronautical society in the United States, the Institute of Aeronautical Sciences, published the first issue of its premier journal, the *Journal of the Aeronautical Sciences*. It contained an article by Stack entitled "Effects of Compressibility on High-Speed Flight." In the first paragraph,

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[3] Ibid.

Stack makes clear the theme that would be played out by the NACA for the next several decades:

> The effects of compressibility have commonly been neglected because until the relatively recent development of the last Schneider trophy aircraft the speeds have been low as compared with the velocity of sound, and the consequent local pressures over the surfaces of high-speed airplanes have differed but slightly from atmospheric pressure. At the present time, however, the speeds associated with the fastest airplanes approach 60 percent of the velocity of sound, and the induced velocities over their exposed surfaces lead to local pressures that differ appreciably from the pressure of the atmosphere. When this condition exists, air can no longer be regarded as an incompressible medium. The effects of compressibility on the aerodynamic characteristics of airfoils have been under investigation by the N.A.C.A. in the high-speed wind tunnel, and it is the purpose of this paper to examine the possibility of further increases in speeds in the light of this relatively recent research.[4]

By this time, it was clear that the NACA was the leading research institution in the world in the area of compressibility effects. Through its influence and sponsorship of the fledgling experiments in 1918 by Caldwell and Fales at McCook Field, by Briggs and Dryden at the Bureau of Standards, and now by its own carefully conducted experiments at Langley, the NACA had been able to identify the first two aspects of the fundamental nature of compressibility effects, namely that 1) above a certain "critical speed," the lift decreased dramatically and the drag skyrocketed almost beyond comprehension, and 2) this behavior was caused by sudden and precipitous flow separation over the top surface of the wing or airfoil. There remained one question, the most important of all: *Why?*

John Stack and the NACA focused their efforts on this question and achieved a breakthrough in 1934. At this time, Stack had a new instrument with which to work—a schlieren photographic system. This optical system made density gradients in the flow visible. One of nature's mechanisms for producing very strong density gradients is a shock wave; hence, a shock wave should be visible in a schlieren photograph. Stack's boss, Eastman Jacobs, was familiar with such optical systems through his hobby of astronomy. Jacobs suggested to Stack that using a schlieren system might make visible some of the compressible flow field's unknown features over an airfoil and might shed some light on the nature of the compressibility burble. It did just that, and more!

With the 11-inch tunnel running above the "critical speed" for an NACA 0012 symmetric airfoil mounted in the test section, and with the aid of the schlieren

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[4] John Stack, *Journal of the Aeronautical Sciences* 1 (January 1934): 40–43.

system, Stack and Jacobs observed for the first time in the history of aerodynamics a shock wave in the flow over the surface of the airfoil. It became immediately apparent to these two experimentalists that the presence of a shock wave caused the separated flow over the airfoil's surface and resulting compressibility burble with all its adverse consequences. They observed that the shock wave interacted with the thin, friction-dominated boundary layer adjacent to the airfoil's surface. This caused the boundary layer to separate from the surface in the region where the shock impinged on the surface. A massive region of separated flow trailed downstream, significantly increasing the drag and decreasing the lift. The quality is poor by present-day standards, but it certainly is sufficient for identifying the phenomena. (The windows of the wind tunnel made of celluloid compromised the clarity; today, the windows are made of ultra-high-quality optical glass.) This is a historic photograph in the annals of aerodynamics and led to the final understanding of the physical nature of the compressibility burble. Stack and Jacobs's breakthrough was of enormous intellectual and practical importance at a time when most airplanes of the day were lumbering along at 200 mph or slower.

As with many discoveries in science and technology, there are always those who are skeptical at first. One of those was Theodore Theodorsen, the best theoretical aerodynamicist in the NACA at the time, with a worldwide reputation for his pioneering papers on airfoil theory. John Becker, who joined the NACA in 1936 and who went on to become one of the most respected high-speed aerodynamicists at Langley, tells the following anecdote about Theodorsen's reaction to the schlieren photographs taken by Stack. It is repeated here because it reflects just how much of a radical departure from the expected norm the results were.

> The first tests were made on a circular cylinder about ½ inch in diameter, and the results were spectacular in spite of the poor quality of the optics. Shockwaves and attendant flow separations were seen for the first time starting at subsonic stream speeds of about 0.6 times the speed of sound. Visitors from all over the Laboratory, from Engineer-in-Charge H.J.E. Reid on down, came to view the phenomena. Langley's ranking theorist, Theodore Theodorsen, viewed the results skeptically, proclaiming that since the stream flow was subsonic, what appeared to be shock waves was an "optical illusion," an error in judgement which he was never allowed to forget.[5]

An interesting confluence of events occurred in 1935 that allowed the NACA to inform the international research community of this intellectual breakthrough in

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[5] John V. Becker, *The High-Speed Frontier: Case Histories of Four NACA Programs, 1920–1950* (Washington, DC: NASA SP-445, 1980), p. 16.

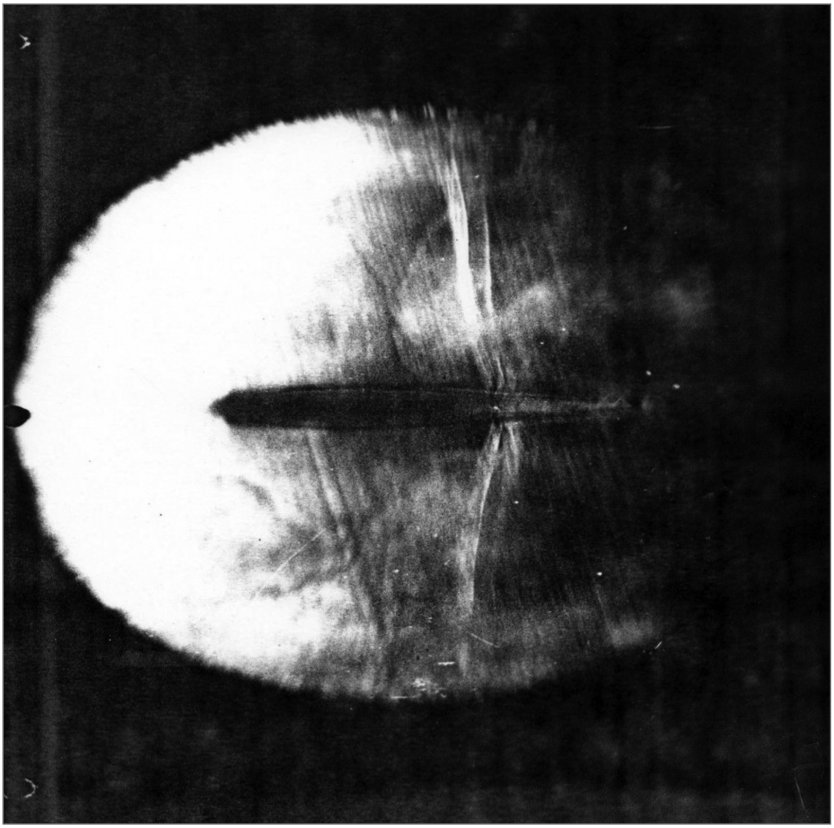

Figure 5: An early schlieren photograph of the shock pattern on an NACA 0012 airfoil in a freestream above the "critical speed." Flow is from left to right. Shock waves are visible, propagating above and below the airfoil at about 0.6 chord length downstream from the leading edge. From the first group of schlieren photographs of the compressibility burble taken by John Stack. (Image credit: From the Stack Archives, Langley Research Center)

understanding compressibility effects and the compressibility burble. One was the existence of the data itself—fresh, exciting, and revolutionary. The other was the scheduling of the fifth Volta conference in Italy. Since 1931, the Royal Academy of Science in Rome had conducted a series of important conferences sponsored by the Alessandro Volta Foundation. The first conference dealt with nuclear physics; later meetings then rotated between the sciences and humanities on alternate years. The second Volta conference had the title "Europe"; in 1933, the third conference was on immunology.

A conference on "The Dramatic Theater" followed in 1934. During this period, the influence of Italian aeronautics gained momentum, led by General Arturo Crocco, an aeronautical engineer. He became interested in ramjet engines in 1931 and was therefore well aware of the potential impact of compressible flow theory and future aviation experiments. This research led to the choice of the fifth Volta conference topic: "High Velocities in Aviation." Participation was by invitation only, and the select list included all the leading aerodynamicists at the time. Because of his reputation in the design and testing of the famous NACA four-digit airfoil series and as the Section Head of the NACA Variable Density Tunnel, which had put the NACA on the international aerodynamic map in the 1920s, Eastman Jacobs received an invitation. He took the opportunity to present a paper on the new NACA compressibility research. During the period between 30 September and 6 October 1935, the major figures in the development of high-speed aerodynamics of the 1930s (except for John Stack) gathered inside an impressive Renaissance building in Rome that had served as the city hall during the Holy Roman Empire. Discussions centered on flight at high subsonic, supersonic, and even hypersonic speeds took place. The fifth Volta Conference was to become the springboard for new thought on the development of high-speed flight.

In these discussions, Eastman Jacobs represented the NACA. His paper entitled "Methods Employed in America for the Experimental Investigation of Aerodynamic Phenomena at High Speeds" was both tutorial and informative. He took the opportunity to derive and present the basic equations for compressible flow, assuming no friction and no thermal conduction. Then he described the NACA High-Speed Tunnel, the schlieren system, and the airfoil experiments carried out in the tunnel. Then came the blockbuster. He showed, for the first time in a technical meeting, some of the schlieren pictures taken at Langley. One of these was the photograph shown in figure 5. Conscious of the NACA's penchant for perfection, especially in its publications, Jacobs apologized for the quality of the photographs, a very modest gesture considering their technical and historical importance. "Unfortunately, the photographs were injured by the presence of bent celluloid windows forming the tunnel walls through which the light passed. The pictures nevertheless give fundamental information in regard to the nature of the flow associated with the compressibility burble."[6] With this, the NACA high-speed research program was not only on the map; it was leading the pack.

By this time, Stack had a newer, larger facility—the 24-inch High-Speed Tunnel equipped with an improved schlieren system. The primary testing of compressibility effects on flows over airfoils continued in this facility. In 1938, Stack published

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[6] Eastman Jacobs, "Methods Employed in America for the Experimental Investigation of Aerodynamic Phenomena at High Speeds," NACA Misc. Paper No. 42, March 1936. A copy of this paper, which is the printed version of Jacobs's presentation at the fifth Volta conference, is available in the Technical Documents Section; Mathematics, Engineering and Physical Sciences Library; University of Maryland, College Park.

the most definitive document yet on the nature of high-speed compressible flows over airfoils, “The Compressibility Burble and the Effect of Compressibility on Pressures and Forces Acting on an Airfoil.” This technical report included many detailed surface pressure measurements. It solidified the NACA as the undisputed leader in the study of the effects of compressibility and consequences of the compressibility burble.

THE LOCKHEED P-38

In 1936, the U.S. Army Air Corps issued a design competition for a twin-engine high-altitude interceptor. At that time, Kelly Johnson, the Chief Research Engineer for the Lockheed Aircraft Company, immediately played the role of conceptual airplane designer, along with the help of his boss, Hall Hibbard. After considering several possible configurations, Johnson decided on a somewhat unorthodox design—a twin-boom configuration with an engine in each boom with the booms extending back to the tail, sprouting a vertical tail from each boom, and a horizontal tail spanning the distance between the booms. The pilot was situated in a central nacelle mounted on the wing between the booms. In this fashion, the P-38 Lightning was born; its unconventional configuration is seen in a test model variant shown in figure 6. About the P-38 Lightning’s configuration, Kelly Johnson wrote:

> It was considered a radically different design—even funny looking, some said. It wasn’t to me. There was a reason for everything that went into it, a logical evolution. The shape took care of itself. In design, you are forced to develop unusual solutions to unusual problems.[7]

Emphasis has been placed on the last sentence because it might be considered Kelly Johnson’s mantra as a “grand designer”; it explains his design philosophy and the novel aircraft he designed later during the Cold War. The P-38 was the first reflection of his different and innovative philosophy. He employed the first use of high-lift maneuvering Fowler flaps in a fighter aircraft. The two counter-rotating propellers eliminated the torque effect experienced in propeller-driven airplanes. Johnson designed the airplane with flush rivets, the ploy so effectively used a few years earlier by British airplane designer R. J. Mitchell for his Supermarine racers and the Spitfire. The power required to meet the specifications for the new Army fighter dictated the use of two engines. During the conceptual design process,

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[7] C. L. Johnson, with Maggie Smith, *Kelly: More Than My Share of It All* (Washington, DC: Smithsonian Institution Press, 1986), p. 71.

Figure 6: A test model variant of the P-38 showing its unconventional twin-boom configuration. (Image credit: NACA AAL-2125)

different configurations were examined, including one with an engine at the front of the fuselage "pulling" the airplane and the other at the rear "pushing" the airplane, called a tractor-pusher configuration (a push-pull arrangement). A more conventional arrangement called for both engines mounted in the usual style in the wings. However, the liquid-cooled Allison engine required a long Prestone radiator and a turbocharger. This, along with making room for the landing gear to retract into the engine nacelle, made the nacelle so long that it reached far back behind the wing, almost to the tail. In this case, sensible design dictated that the nacelles become twin booms with the tail attached at the end.

The Air Corps was pleased with the Lockheed design and issued a contract for one XP-38 prototype on 23 June 1937. Lockheed entrusted the detailed designs to project engineer James Gerschler, and the prototype was ready in December. The first flight of the XP-38 took place on 27 January 1939, with Army Lieutenant Benjamin S. Kelsey at the controls. Kelsey was the Project Officer for the Army at Wright Field, and the very fact that he flew the XP-38 on its first flight was indicative of his excitement with the new fighter design. The first flight was only 34 minutes. The airplane suffered from a violent vibration of the flaps and failure of three out of the four flap support rods. Lockheed engineers corrected these problems before the next flight, and the XP-38 was considered a success. Kelsey's excitement about the XP-38 continued; just 15 days after the first flight, he attempted an unprecedented cross-country flight from March Field in California to Mitchell Field in New York. He almost made it. After an elapsed time of 7 hours and 43 minutes—just 15 minutes more than the transcontinental record set by Howard Hughes in his H-1 racer two years earlier—with Mitchell Field in sight, the XP-38 lost power and crashed on a golf course just 2,000 feet away from the runway. The prototype was a total loss, but Kelsey escaped unhurt. Moreover, his enthusiasm for the P-38 continued undaunted; on 27 April 1939, he awarded Lockheed an Army contract for $2 million for 13 YP-38s. The P-38 program was under way, to end after nearly 10,000 (inclusive of all models) were produced during World War II.

Beyond its technical firsts, the P-38 was the right airplane at the right time for service during World War II. It was

1. Lockheed's first military aircraft to go into series production;
2. the first twin-engine fighter to go into service with the U.S. Army Air Corps;
3. the first fighter with a top airspeed of more than 400 mph (the XP-38 had a maximum speed of 413 mph, and the last model to go into production, the P-38L, could reach 414 mph);
4. the first fighter to be flown from the United States to Europe;
5. the first American airplane to shoot down a German aircraft;
6. the first American fighter to carry out an escort mission to Berlin;
7. the first American airplane to land in Japan after the surrender;
8. the heaviest American fighter of the war (the gross weight of the P-38L was 17,500 lb); and
9. the only American fighter that was in production on the first and last days of the war.

The P-38 made Lockheed a household word during the war. Its designers, Hall Hibbard and Kelly Johnson, were not so. Except for R. J. Mitchell in England, whose national and international fame started with the Schneider Trophy racers and solidified with the Spitfire, most substantive airplane designers were not household names. For the most part, they stayed behind the scenes, although they were usually well known by the professional aeronautical engineering world in their time. This held true for the young Kelly Johnson. By 1941, he had published six papers in the *Journal of the Aeronautical Sciences* and was elected as an Associate Fellow of the Institute of the Aeronautical Sciences. (Hall Hibbard was an I.A.S. Fellow by that time.) Johnson's position as Chief Research Engineer at Lockheed provided him with an early professional status, but he was still not a household name.

The P-38's high speed led the plane to encounter another first—one not so glorious—the first airplane that suffered from massive aerodynamic compressibility problems. As related earlier, beginning as early as 1918, the NACA carried out a program of definitive research on the high-speed aerodynamic characteristics of airfoils. These studies attempted to explain why, beyond a certain freestream Mach number (the critical Mach number), a given airfoil would exhibit a drastic increase in drag and loss of lift. By 1935, John Stack and his NACA colleagues at the Langley Memorial Aeronautical Laboratory had uncovered the basic physical phenomena causing these adverse compressibility effects. During his conceptual design of the P-38, Kelly Johnson was fully aware of the NACA research and the problem posed by compressibility for high-speed airplanes. He used the knowledge and data generated by the NACA during his conceptual design of the P-38. In his proposal to the Air Corps, Johnson wrote a discourse on the probable effects of compressibility on the P-38 and referenced two NACA documents: John Stack and A. E. von Doenhoff's NACA Technical Report 492, "Tests of 16 Related Airfoils at High Speeds," and Stack's 1934 Technical Note 543, "The Compressibility Burble." Johnson knew that the adverse compressibility effects could be delayed to a higher Mach number by using a thinner airfoil from this research. Lockheed successfully used the NACA 23018 airfoil on Lockheed's Super Electra Model 14, but this 18 percent thick airfoil was too thick for high-speed use. So the P-38 was designed with a thinner 16 percent NACA 23016 airfoil in the center section of the wing between the two booms and an even thinner 12 percent NACA 4412 airfoil for the wing shape outboard of the booms. With this thinner wing, Johnson hoped to minimize the compressibility problems for the P-38. The production models of the P-38 began to encounter massive and sometimes fatal compressibility problems in high-speed power-dives. This was disappointing too and somewhat unexpected by Johnson and the Lockheed engineering team.

The compressibility effect caused large drag-divergence beyond the critical Mach number on the P-38. Although this large increase in airplane drag did occur, the conceptual design of the P-38 accounted for it. Phil Coleman, an aerodynamicist working with Johnson, predicted speed versus altitude dive trajectories for the P-38. He compared the analytical results for no compressibility effect with those for the assumed compressibility effects.[8] To verify these results, Lockheed began a flight-test dive program in the summer of 1941, which is when things began to unravel. During some of these tests, the pilots could not pull out of the dive, no

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[8] R. L. Foss, "From Propellers to Jets in Fighter Aircraft Design," American Institute of Aeronautics and Astronautics (AIAA) Paper 78-3005, in *Diamond Jubilee of Powered Flight: The Evolution of Aircraft Design*, ed. Jay Pinson (Dayton-Cincinnati Section, AIAA, Reston, VA, December 1978), pp. 51–64.

matter how hard they pulled back on the control stick. As described at the beginning of this chapter, one of Lockheed's most valuable test pilots, Ralph Virden, crashed to his death during one of these tests in November. The problem being encountered by Virden and other P-38 pilots was beyond a certain speed in a dive; the elevator controls suddenly felt as if they were locked, and to make things worse, the tail suddenly produced more lift, putting the P-38 into an even steeper dive. This became known as the "tuck-under problem," and at the time, nobody, including Kelly Johnson, knew how to explain it, much less how to fix it.

Lockheed consulted various aerodynamicists, including Theodore von Kármán at Caltech, but to no avail. The new Lockheed wind tunnel could not get to the high speeds required to study the problem. However, the NACA 8-foot High Speed Tunnel (HST) at Langley could produce an airstream of 575 mph (Mach 0.75). In December 1941, just a few weeks after Ralph Virden was killed, a 1:6 scale model of the P-38 was mounted in the NACA HST, and extensive testing began. Under the direction of John Stack, it was not long before the NACA engineers observed shock waves forming on the upper surface of the P-38 wing, with the expected consequent loss of lift and increase in drag. More importantly, John Stack, with his accumulated experience in compressibility effects, was the only one to properly diagnose the problem: When the shock waves formed on the P-38 wing, causing a loss of lift, the downwash angle of the flow trailing behind the wing decreased. In turn, that increased the effective angle of attack at which the flow encountered the horizontal tail, increasing the lift on the tail and pitching the P-38 to a progressively steeper dive, totally beyond the pilot's control. The NACA's solution was to place a special small, wedge-shaped flap located under the wing about 30 percent of the chord distance downstream of the leading edge. The flap only deployed when the aircraft encountered those compressibility effects. The flap, called a dive-recovery flap, was not a conventional dive flap intended to reduce the airplane's speed. It maintained lift in the face of the compressibility effects, thus reducing or eliminating the change in the downwash angle, allowing the horizontal tail to function properly.

This solution was a graphic example of the vital importance of the NACA compressibility research as real airplanes began to sneak up on Mach 1. Indeed, the P-38 was the first airplane to penetrate well beyond its critical Mach number in a powered terminal dive. However, Johnson and his staff did not understand the specific cause of the tuck-under problem. Indeed, as late as 1985, Johnson wrote:

> We decided that if we could not solve compressibility, we would discover a way to slow the airplane to a speed where the effect was no longer a factor. The answer was

> external dive flaps or brakes. Put in the right place, they would cause the nose to come up out of a dive and stop buffeting.[9]

In reality, the dive-recovery flap's function on the P-38 was not to slow the airplane to a speed below the critical Mach number but rather to increase the lift—hence the downwash angle while still flying beyond the critical Mach number. John Stack and his colleagues at the NACA fully understood the aerodynamic effect of the dive recovery flap. They were responsible for this aerodynamic palliative that mitigated the P-38 tuck-under problem.

For the rest of his life, Johnson never saw it that way. Johnson was the official Chief Research Engineer of Lockheed at this time. He was supposed to know and understand the answers, especially to aerodynamic problems. He co-opted the dive-recovery flap as the *Lockheed* dive-recovery flap and gave the NACA little credit. Indeed, writing in 1985, well after his retirement, Johnson derides the NACA:

> The agency charged with assisting, coordinating, and instituting this nation's aeronautical development did not want to acknowledge the work as industry-initiated. Later, N.A.C.A. did do some testing on its own but had contributed nothing to solving the problem of compressibility on the P-38 except allowing the use of its wind tunnel. And this only under orders from the Army Air Corps. The successor agency, National Aeronautics and Space Administration (N.A.S.A), by contrast, has been very aggressive and eager to assist and work with industry. I am happy to report that I enjoy excellent relations with N.A.S.A.[10]

Here, Johnson showed his miffed feelings about being originally stood up by the NACA when he first requested wind tunnel time for testing the P-38 in the agency's high-speed wind tunnel. By nature, a conservative agency now entrusted with a massive wartime wind tunnel program for all U.S. aircraft, the NACA was rightfully concerned about the P-38 model coming loose and damaging the high-speed tunnel. In a few preliminary tests, the P-38 model did indeed violently thrash around. So Johnson found the ear of the head of the Army Air Forces, General H. H. "Hap" Arnold, who guaranteed the NACA that the Army would fix any damage to the tunnel that might occur. The NACA proceeded with the tests, and John Stack and his colleagues threw themselves into solving the tuck-under problem, ultimately coming up with the dive-recovery flap.

Thirty-five years later, Richard L. Foss, of the Lockheed-California Company in Burbank, in his survey paper on Lockheed's fighter aircraft design, takes a middle-of-the-road position:

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[9] Johnson, *Kelly: More Than My Share of It All*, p. 76.

[10] Ibid., p. 76.

> Further P-38 wind-tunnel testing finally resolved the means for dive recovery. A dive flap was perfected, mounted on the lower surface of the main beam of the wing. When deployed, it generated a positive pressure field that created a lift and nose-up moment at high Mach numbers and assisted in dive recovery. The device was installed on production P-38 aircraft in 1944. It did not break the descent speed—its purpose was to provide a means for recovery, and actuation was almost instant, being electrically activated. Because of their effectiveness and simplicity of operation, they permitted the use of an expanded flight envelope and increased the dive capability of the P-38 airplane.[11]

Foss gave no explicit credit to either Kelly Johnson or the NACA for the solution to the problem. He implied that by working jointly, they found the solution.

Johnson's negative view of the NACA is an aspect that put him on the wrong side of history. From its beginning in 1916 to its amalgamation into NASA in 1958, the NACA had been held in an almost iconic status by aeronautical engineers worldwide. In particular, the NACA was essential to airplane designers with its work on its own series of airfoils, including the pioneering laminar flow airfoils and with the stunning, drag-reducing cowling design for air-cooled piston engines. Johnson readily used these and other NACA-produced technologies for his airplane designs during the 1930s. Things came to a head, however, with the P-38 tuck-under compressibility problem. Johnson faulted the NACA for "contributing nothing to solving the problem of compressibility on the P-38 except allowing the use of its wind tunnel."[12] Throughout the 1930s and into World War II, however, the NACA had become the world's research leader in understanding the aerodynamic causes and consequences of the compressibility problem. Through its research engineers with this knowledge, it was the NACA that came up with the solution to the P-38 tuck-under problem, namely, the small flap under the wing. However, Kelly Johnson did not see it that way. In his mind, the research carried out in the NACA high-speed wind tunnel was Lockheed's work, principally his own. In his autobiography, Johnson reflected:

> Because of the importance of compressibility as an aviation industry problem and the wide interest in it, I prepared a technical paper covering our own research and what we thought the solutions might be for presentation to the American Institute of Aeronautical Sciences. It was duly cleared by the War Department, and I presented it at a meeting in January 1943. Naturally, there were many requests from other companies for copies, and I supplied them.[13]

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[11] Foss, "From Propellers to Jets in Fighter Aircraft Design," pp. 58–59.

[12] Johnson, *Kelly: More Than My Share of It All*, p. 78.

[13] Ibid. The paper was later declassified.

Then the paper was recalled and labeled secret.

Smith J. DeFrance, Engineer-in-Charge of the NACA Ames Aeronautical Laboratory, clearly states the NACA version of this matter in a strong letter he wrote to Dr. George Lewis, then the Director of Aeronautical Research for the NACA, dated 26 April 1943. In this letter, he railed against Johnson:

> Through the grapevine, a representative of one of the aircraft companies on the Coast has been informed that the Lockheed company installed an auxiliary flap approximately at 33 percent of the chord of the center section of the P-38 wing and flight-tested the combination in high-speed dives. The information I have is that Colonel Kelsey made the flight test and that after reaching an uncontrolled condition in a high-speed dive, he possibly became frantic and operated the flaps suddenly with full deflection. The flaps tore off from the wing, probably struck the tail surfaces, and the tail disintegrated. Fortunately, Colonel Kelsey was able to bail out, but the airplane, which was the Lockheed Company's special test plane, was lost with all of their flight instruments.
>
> Kelly Johnson still thinks apparently that the auxiliary flaps are the answer to his uncontrolled dive condition on the P-38, and it is understood that he is making another installation for further flight tests.[14]

To this point, DeFrance merely is relating an experience that is consistent with Kelly Johnson performing the role of an airplane designer. However, then DeFrance's letter turns combative. He writes that "I think everything possible should be done to stop the Lockheed company from obtaining a patent on the auxiliary flap arrangement because in the first place, it is not Lockheed's idea, and in the second place, the primary development was carried out by the Committee."[15]

The "Committee" he refers to is the NACA. DeFrance then goes on to state: "As I told you some time ago, I got the idea of the auxiliary flap while reading the German report which commented on the adverse effect of the flap on the lower surface of the wing as a dive break." Then Smith DeFrance's real feelings came out as he ends his letter to Lewis as follows:

> Kelly Johnson apparently is not satisfied with having lifted the data from the 16-foot tunnel tests on the P-38 and used them in his paper before the Institute of Aeronautical Sciences, but now he would like to patent the work of the Committee.

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[14] Smith J. DeFrance, Engineer-in-Charge, NACA Ames Aeronautical Laboratory, to Dr. George Lewis, Director of Aeronautical Research, NACA, 26 April 1943, record number 2967, NASA HRC.

[15] Ibid.

> Unless it is stopped, the next thing, he will be trying to make the Committee a subsidiary of the Lockheed Company.[16]

Clearly, there was no love lost between the NACA and Johnson. This author knows of no other influential airplane designer during the first half of the 20th century with such negative feelings toward the NACA. Indeed, part of the original 1915 charter of the NACA was "to supervise and direct the scientific study of the problems of flight, with a view to their practical solution." The NACA carried out a great deal of research and development in support of the aircraft industry. Indeed, it held an annual conference during the 1930s at the Langley Aeronautical Laboratory for industry and government members, during which it shared its research results and solicited suggestions for work that the NACA could and should be doing for the "practical solutions" of problems of flight. During World War II, the NACA focused on work aimed almost exclusively at improving the performance of existing U.S. aircraft. This author knows of no situation where the NACA willfully hindered the work of airplane designers; indeed, the agency was there to help. The NACA's intellectual grasp of the causes and effects of compressibility on high-speed airplanes, so effectively acquired by its systematic research program during the 1920s and '30s, is clear. Finally, it provided the engineering solution to the P-38's tuck-under problem in the early 1940s. Had the problem not been solved, it would have significantly compromised the high-speed performance of one of America's most important fighter aircraft during World War II.

Author's Note

Portions of this chapter were patterned after the author's presentations in the following books:

Anderson, John D., Jr. *A History of Aerodynamics*. Cambridge, England: Cambridge University Press, 1998.

Anderson, John D., Jr. "Research in Supersonic Flight and Breaking of the Sound Barrier." In *From Engineering Science to Big Science*, edited by Pamela E. Mack, pp. 59–90. Washington, DC: NASA SP-4219, 1998.

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[16] Ibid.

CHAPTER 9

The Evolution of the U.S. Navy's Fast Carrier Task Force in World War II

William F. Trimble

Figure 1: Aircraft carriers as far as the eye can see. CV-14 USS Ticonderoga, in the foreground, highlights a row of Essex-class aircraft carriers at anchor in Ulithi Atoll in 1944. These aircraft carriers were the centerpiece of the Navy's new Fast Carrier Task Force. (Image credit: National Air and Space Museum, Smithsonian Institution, image NASM 00149990)

On the afternoon of 26 May 1944, the heavy cruiser Indianapolis stood out from Pearl Harbor, making up a little task group with the destroyers Selfridge and Ellet. Their destination was Majuro in the southern Marshall Islands, about halfway between Hawaii and the Marianas. Vice Admiral Raymond A. Spruance flew his flag on the Indianapolis as commander of the Fifth Fleet forces arrayed for Operation Forager, the invasion of the Mariana Islands. Spruance and other top brass on the cruiser could not help but feel a sense of awe when the Indianapolis anchored in Majuro's deep and spacious lagoon on the morning of 2 June. Compared to the naval forces they had led in the fight against Japan only two years before, the armada of gray steel in the anchorage looked more like an entire navy than anything else. At Majuro, there were no fewer than 111 warships, the majority of them constructed since the Japanese carrier attack on Pearl Harbor, out of a total of 535 ships and amphibious craft brought together to deliver more than 127,000 marines and soldiers onto the beaches. Planners considered the Marianas, strategically located east of the Philippines, essential for basing long-range Army Air Forces bombers capable of attacking the Japanese Home Islands. The first objective of the invasion force was the island of Saipan in the northern part of the archipelago, to be quickly followed by Tinian (also in the north) and Guam in the south.[1]

Spearheading Spruance's fleet as it sortied from Majuro was Task Force (TF)–58, composed of 93 ships, more than 900 aircraft, and nearly 100,000 sailors and airmen, led by pioneer naval aviator Vice Admiral Marc A. "Pete" Mitscher. His 15 fast carriers were organized into four roughly equal task groups (TGs): four carriers in group 58.1 (Rear Admiral Joseph J. "Jocko" Clark), four in 58.2 (Rear Admiral Alfred Montgomery), four in 58.3 (Rear Admiral John W. Reeves, Jr.); and three in 58.4 (Rear Admiral William K. Harrill).[2]

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1. "USS INDIANAPOLIS," War Diaries, May, June 1944, 26 May, 2 June 1944, World War II War Diaries, Records Relating to Naval Activity During World War II, Records of the Office of the Chief of Naval Operations, Record Group 38, National Archives and Records Administration, Archives II, College Park, MD; Barrett Tillman, *Clash of the Carriers: The True Story of the Marianas Turkey Shoot of World War II* (New York: NAL Caliber, 2005), pp. 16, 51; Samuel Eliot Morison, *History of United States Naval Operations in World War II*, vol. 8, *New Guinea and the Marianas, March 1944–August 1944* (Boston: Little, Brown and Company, 1953), pp. 158–159.
2. Morison, *New Guinea and the Marianas*, pp. 158–159, 233; Tillman, *Clash of the Carriers*, pp. 51, 301–305; W. D. Dickson, *The Battle of the Philippine Sea* (London: Ian Allan, Ltd., 1975), pp. 186–187.

By the summer of 1944, the fast carrier task force had evolved from a tactical arm of a battle fleet to achieve sea control into a mobile strategic force capable of a "sustained forward presence" and projecting power from the sea.[3] Among the elements contributing to the emergence of the fast carrier task force were planning, organizational, administrative, and technological changes that led to multicarrier forces, some including five carrier groups, screened by an amalgam of battleships, cruisers, and destroyers. For example, operational experience, along with innovations in search radars, radio links, navigation, and command and communication, allowed carriers to maneuver in groups to coordinate literally hundreds of strike and combat air patrol aircraft simultaneously. So-called "blanket" operations smothered enemy airfields with nearly round-the-clock coverage, made possible by improvements in launch and recovery procedures, carriers dedicated to night operations, and coordinated fleet anti-aircraft defenses. Mobile logistical support forces, themselves covered by task groups centered on small escort carriers, brought unprecedented flexibility that allowed the carriers to stay at sea for weeks and months at a time before having to return to advance bases.

These changes were the result of an iterative, empirical, and nonlinear process that synthesized planning, organization, tactics, doctrine, and technology within the crucible of a conflict stretching across the vastness of the Pacific. It was, as the historian Thomas C. Hone related, a "messy" process; the developments did not come about without debate or controversy. As late as the middle of 1943, there was no general understanding about how best to use the fast carriers in support of amphibious operations, or even if a task force with more than two carriers could coordinate offensive and defensive air operations. Determining the fast battleship's place in the task force defensive screen took time before it and other supporting ships were fully integrated into what Hone concluded was a "total" force.[4] Nor by 1945 was there agreement about the makeup of carrier air complements. Whereas carrier air groups in 1942 were generally evenly divided among bomber, torpedo, and fighter squadrons, by the end of the war carrier complements were mostly made up of bombers and fighters. Some task force commanders wanted to eliminate torpedo bombers altogether and rely exclusively on bombers and fighter-bombers, the latter often armed with air-to-ground rockets. Another question that remained open was whether it was best to incorporate night carriers in the task force or to include night-capable aircraft into each carrier's complements.

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[3] Capt. C. C. Felker, introduction, "CVN Debate," U.S. Naval Academy, Annapolis, MD, 9 January 2015.

[4] Thomas C. Hone, "Replacing Battleships with Aircraft Carriers in the Pacific in World War II," *Naval War College Review* 66 (winter 2013): 72–73.

Prewar maneuvers, or "fleet problems," provided indications that the aircraft carrier, operating independently or with the battle fleet, had considerable offensive striking power. In one of these exercises, Fleet Problem IX in 1929, Rear Admiral Joseph Mason Reeves led the carrier Saratoga on a surprise strike on the Panama Canal. Even more instructive was a joint Army-Navy exercise in 1932, highlighted by Rear Admiral Harry E. Yarnell's dawn attack on Pearl Harbor with the Saratoga and its twin ship the Lexington. In Fleet Problem XIX, two fleets opposed each other in the Pacific in early 1938, one force including the Lexington and Saratoga and another the Ranger, the Navy's first carrier built as such from the keel up. In the Caribbean in 1939 Fleet Problem XX for the first time included four carriers, sometimes cruising together in formation. The maneuvers underscored the importance of concentrating air power in early strikes on the enemy's carriers and the effectiveness of dive and torpedo bombers, provided they had sufficient fighter escort. Instructive as they were and important for providing experience in independent operations and demonstrating that carriers were offensive weapons that could attack enemy ships and defend themselves against air attacks as well as inflict damage on heavily defended shore targets, the exercises showed that carriers were vulnerable to gunfire and torpedo attacks from surface ships, especially at night, when they were unable to launch defending aircraft. Moreover, they did not resolve the fundamental question about whether it was best for carriers to operate together in formations to exploit the principle of concentration or singly, where dispersal complicated enemy air or surface attacks.[5]

In the aftermath of the disaster at Pearl Harbor, which destroyed or damaged most of the Pacific Fleet's battle force, the aircraft carrier became what the historian Clark Reynolds termed a defensive "weapon of expediency." With only five carriers in the Pacific (soon reduced to four in January, when the Saratoga was torpedoed and damaged by a Japanese submarine), there was little to be done other than to conduct limited hit-and-run raids. Risky, but successful in keeping the Japanese off balance, the carriers, operating under the dynamic leadership of Vice Admiral William F. Halsey, struck enemy bases in the Marshalls and Gilberts, as well as Wake, Marcus, and New Britain Islands. In March, Admiral Wilson Brown commanded a force consisting of the Lexington and Yorktown against Japanese positions at Lae and Salamaua on the north coast of New Guinea. Brown delegated tactical control of the carriers to Captain Frederick C. "Ted" Sherman of the Lexington, who operated the carriers together tactically during the strikes.

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5. Albert A. Nofi, "Aviation in the Interwar Fleet Maneuvers, 1919–1940," in *One Hundred Years of U.S. Navy Air Power*, ed. Douglas V. Smith (Annapolis, MD: Naval Institute Press, 2010), pp. 100–119; Craig C. Felker, *Testing American Sea Power: U.S. Navy Strategic Exercises, 1923–1940* (College Station: Texas A&M University Press, 2007), pp. 49–56.

Most spectacularly, in April, Halsey's task force consisting of the Enterprise and the Hornet launched Army North American B-25 Mitchell medium bombers from the Hornet against Tokyo and other targets in Japan itself.[6]

Based on intelligence gleaned from intercepted coded naval messages, Admiral Chester W. Nimitz, Commander in Chief, Pacific Fleet (CINCPAC), knew that the Japanese planned to assault Port Moresby on the south coast of New Guinea. He sent a task force under Rear Admiral Frank Jack Fletcher with the carriers Lexington and Yorktown to meet the three Japanese carriers (Shokaku, Zuikaku, and Shoho) covering the operation. During the ensuing engagement on 7–8 May, Fletcher attempted to keep his carriers together within the same defensive screen, only to have them maneuver apart and lose the Lexington to Japanese torpedoes and bombs and see the Yorktown badly damaged. In turn, the Americans sank the Shoho while mauling the Shokaku and forcing the Japanese to abandon the Port Moresby operation. A month later (4–6 June) at Midway, under the overall tactical command of Fletcher, leading two task forces (TF-16 with Fletcher and the hastily repaired Yorktown and TF-17 with the Enterprise and Hornet under then–Rear Admiral Spruance), the Japanese lost all four of their big carriers (Akagi, Kaga, Soryu, and Hiryu) in return for the loss of the Yorktown. Japanese doctrine stipulated that carriers operate together in a tight box formation during air operations, then diverge when under air attack, a factor that contributed to the American success. At the same time, Spruance allowed his two carriers to separate while Fletcher held the Yorktown force some distance away in reserve. In some respects, the lack of coordination of the American attacks on the Japanese carriers at Midway inadvertently led to triumph in what most historians conclude was the turning point of the Pacific war.

As the Navy prepared to undertake a limited offensive in the South Pacific in the aftermath of the Battles of the Coral Sea and Midway, the jury remained out as to the best means of prosecuting a carrier war. To block a Japanese advance into the Solomon Islands that threatened to interdict the Allied lines of communication to Australia and New Zealand, Admiral Ernest J. King, wearing two hats as the Commander in Chief, United States Fleet, and Chief of Naval Operations, determined to take the island of Guadalcanal before the Japanese could consolidate a foothold in the archipelago. To cover the 7 August 1942 invasion, Fletcher had the carriers Saratoga, Enterprise, and Wasp arrayed in separate task forces according to specific orders from King. Without adequate land-based air power, Fletcher had to hold his carriers close to the Solomons, losing the advantage of mobility to

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[6] Clark G. Reynolds, *The Fast Carriers: The Forging of an Air Navy* (1968; repr., Annapolis, MD: Naval Institute Press, 1992), pp. 22–29.

the Japanese. In the subsequent Battle of the Eastern Solomons on 24–25 August, three Japanese carriers (Shokaku, Zuikaku, and Ryujo) encountered Fletcher's Saratoga and Enterprise task forces. (Fletcher had just dispatched the Wasp task force to refuel.) Airmen from the Saratoga sank the Ryujo, and the remaining Japanese carriers suffered crippling losses to their air groups, but the Enterprise was heavily damaged and had to withdraw. Less than a week later, a Japanese submarine torpedoed the Saratoga, causing damage so severe that the carrier had to retire for extensive repairs. In early September, another enemy sub penetrated the Wasp's task force screen, torpedoed and sank the carrier and a destroyer, and extensively damaged the battleship North Carolina (BB-55).[7]

One more carrier clash marked the attrition warfare in the Solomons. On 26 October, two task forces centered on the Hornet and Enterprise, both under the tactical command of Rear Admiral Thomas C. Kinkaid, fought four Japanese carriers, three of which operated in a single formation. In what became known as the Battle of Santa Cruz Islands, the Hornet was sunk and again the Enterprise suffered bomb damage, and the Shokaku, Zuikaku, and Zuiho were damaged to the extent that they had to be withdrawn from the theater for extensive repairs. Despite that setback, the Japanese had won a tactical victory, and Halsey now had only one carrier left—the damaged Enterprise. But the Japanese had lost valuable aircraft and elite airmen, none easily replaced, and could no longer afford to risk their remaining carriers in support of operations to retake Guadalcanal.[8] More months of fighting remained at sea and ashore before the bloody campaign ended in American victory in February 1943.

The searing experience of the Solomons campaign left both adversaries exhausted and in need of rebuilding their forces and reassessing their strategies. It was also time for lessons learned in light of the three carrier battles that had been fought since the Coral Sea in May 1942. To Sherman, the engagements confirmed his belief that dispersal diluted protection under air attack and that it was imperative for carriers to remain together in the same defensive screen. At the end of the year, when he received command of TF-16, with the Enterprise and Saratoga, Sherman, now a rear admiral, exulted that "now is my chance to operate a two-carrier task force which I have been advocating since the war started over a year ago." He went even further to declare that he thought a five-carrier task group "looks feasible and fine for defense." Fletcher joined Sherman as an adherent to the advantages of

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[7] John B. Lundstrom, *Black Shoe Carrier Admiral: Frank Jack Fletcher at Coral Sea, Midway, and Guadalcanal* (Annapolis, MD: Naval Institute Press, 2006), pp. 308–482; Norman Polmar, *Aircraft Carriers: A History of Carrier Aviation and Its Influence on World Events*, vol. 1 (Annapolis, MD: Naval Institute Press, 2006), pp. 290–291.

[8] Polmar, *Aircraft Carriers*, pp. 292–299.

multicarrier forces, believing that radar and more fighters in the carriers' air groups allowed the ships to concentrate "for mutual support and protection." Kinkaid saw offensive advantages: "by having two carriers together one carrier can take care of all routine flying while the other maintains her full striking group spotted and ready to launch on short notice."[9]

Not everyone agreed. King remained unconvinced about the merits of bringing two or more carriers together in a single task group and even questioned how a commander could coordinate multiple task groups within a task force. Among many things on the agenda when King and Nimitz met in San Francisco in late May 1943 to plan for the offensive in the Pacific were carrier task force organization, night operations, training, and command responsibilities. Meanwhile, Halsey, as a theater commander in the South Pacific with no recent experience in carrier command, was most concerned about continuing the advance up the Solomons to the Japanese stronghold of Rabaul. He left the matter of multicarrier doctrine open in the spring of 1943. Rear Admiral Dewitt C. Ramsey thought a multicarrier formation would complicate flight operations and interfere with carrier maneuvers when the task force was under attack. He concluded that it was "imperative that carriers separate," staying at least 5 miles apart, with the individual carriers controlling their "own air operations and fighter direction." Vice Admiral John H. Towers, Commander Aircraft, Pacific Fleet (COMAIRPAC) in Pearl Harbor, studied analyses of carrier operations in the Solomons campaign and determined in March that carriers should disperse as soon as they were threatened with air attacks.[10]

Frustrated with the indecision by his superiors, Sherman complained that "the Navy high command…shows no proper conception of handling carriers." At Pearl Harbor, in command of the Enterprise, he conducted a series of training exercises with new Essex-class carriers then joining the Pacific Fleet. As a result, he found that individual ships could vary their maneuvers so that they did not interfere with one another during launch and recovery evolutions and that their air groups could coordinate with one another with little difficulty. Much depended on training and new command, control, and communication technologies and procedures.

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9. Reynolds, *Fast Carriers*, pp. 33–35; Hone, "Replacing Battleships with Aircraft Carriers," pp. 60–61; Lundstrom, *Black Shoe Carrier Admiral*, pp. 299, 497.

10. Message 111819, May 1943, Cominch to Cincpac; message 270001, May 1943, Cominch to Cincpac; both in War Plans, Cincpac Files, Captain Steele's "Running Estimate and Summary, 1 Jan.-30 June 1943," Archives Branch, Naval History and Heritage Command, Washington, DC, p. 1557 (hereafter cited as Graybook); Lundstrom, *Black Shoe Carrier Admiral*, pp. 476, 482; Hone, "Replacing Battleships with Aircraft Carriers," pp. 61–62; Reynolds, *Fast Carriers*, pp. 34–35.

It was now necessary to codify the results in formal doctrine and validate them in combat.[11]

Nimitz wanted resolution of the problem before initiating the planned offensive in the Central Pacific and directed COMAIRPAC Towers to draft a proposal for a new carrier doctrine. Closely monitoring Sherman's trials, Towers convened a conference with his staff and carrier flag officers and captains in Pearl Harbor. The result, issued on 10 June as *Pacific Fleet Tactical Orders and Doctrine* (PAC-10), envisaged carriers playing a dominant role in future offensive operations in the Pacific. More specifically, the doctrine was, as Hone asserted, a "dramatic innovation" that operationally combined up to four heavy and light carriers with fast battleships and other supporting ships into fully integrated task groups. Because all elements of the force were interchangeable and adhered to a common doctrine, PAC-10 brought the tactical flexibility and operational mobility Nimitz considered essential for a fast-moving offensive against the Japanese.[12]

The first objective was the Japanese-held Marcus atoll, 2,700 miles from Hawaii. Task Force–15, under the command of Rear Admiral Charles A. Pownall, flying his flag in the new Essex-class Yorktown, included the new light carrier Independence. Accompanied by the oiler Guadalupe, the three carriers were in the middle of a screen that included the battleship Indiana, light cruisers Mobile and Nashville, and 11 destroyers. Lightly defended Marcus allowed Nimitz to see how well a multicarrier task force formation functioned in combat. Pownall's force closed on Marcus on 30–31 August, reaching a position 125 miles north of the island before the big carriers launched dawn strikes; aircraft from the Independence provided search and combat air patrols. The carriers flew three more strikes that day before the task force withdrew. Nimitz was pleased with the results. The carriers had worked together efficiently, their aircraft damaging the runway and destroying enemy communication and other installations, along with at least seven twin-engine aircraft on the ground. No enemy aircraft challenged the task force, which lost five planes and six aircrew to anti-aircraft fire and accidents.[13]

In September, Pownall led TF-15 with the Essex-class Lexington and two light carriers, Princeton and Belleau Wood, to strike Tarawa in the Gilberts. For the

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[11] Reynolds, *Fast Carriers*, pp. 36, 72; Hone, "Replacing Battleships with Aircraft Carriers," p. 63; Lundstrom, *Black Shoe Carrier Admiral*, p. 498.

[12] Hone, "Replacing Battleships with Aircraft Carriers," pp. 63–64; Clark G. Reynolds, *Admiral John H. Towers: The Struggle for Naval Air Supremacy* (Annapolis, MD: Naval Institute Press, 1991), pp. 430–431.

[13] "Commander Task Force FIFTEEN," War Diary, 22 August 1943 to 24 September 1943, 22, 23, 27–31 August 1943; Commanding Officer, USS Yorktown, to Cominch, 6 September 1943, Air Attack on Marcus Island on 31 August 1943; Commanding Officer, USS Essex, "Action Report–Marcus Island Raid," 3 September 1943; Reynolds, *Fast Carriers*, pp. 80–83.

first time, the carriers faced Japanese air attacks, although they were largely inconsequential and did not offer much of a test for task force fighter direction. The raid was generally a success despite some reservations about Pownall's composure and decision making in combat. A better experiment came in a similar raid on Japanese-held Wake Island on 5–6 October. Commanded by Rear Admiral Alfred E. Montgomery, Task Force–14 had six carriers—the heavy Essex, Yorktown, and Lexington and the light carriers Independence, Cowpens, and Belleau Wood—organized into three units. Montgomery successfully interchanged the ships and their air groups, sometimes operating two together, other times three, and even at one point all six concentrated in the same screen. Not only did fighters escorting the strike units defeat a concerted Japanese challenge in the air over Wake, but the carriers' combat air patrols defended the force against enemy retaliatory attacks. Yet the operation was not without cost, for Montgomery's force lost 27 aircraft, more than half of them operationally, and 21 aircrew were dead or missing.[14]

The fast carrier raids in the summer and fall achieved their purpose in proving the concept of the multicarrier task force. As important, the strikes complicated Japanese plans for defending their positions in the South and Central Pacific and presaged an unrelenting American offensive that began with the invasion of Tarawa and Makin in the Gilberts scheduled for 20 November. For the Gilberts, code-named Operation Galvanic, Nimitz chose Spruance to command the Central Pacific Force. Pownall, again, was in charge of the fast carriers, now numbering six Essex-class and five Independence-class ships organized into Task Force–50. Spruance fretted that the Japanese might counter with a carrier-battleship force staged from their bases in the Marshall Islands and from Truk in the Carolines. He decided to hold the carriers in defensive positions close to the beaches, despite some of the aviators believing it was "dangerous" to deny carriers their chief asset of mobility. Galvanic was a success, but it came at a cost both to the marines of the invasion force and to the supporting carriers. Japanese bombers torpedoed and damaged the Independence, and a Japanese submarine torpedoed and sank the escort carrier Liscome Bay. It was obvious that there were still deficiencies in task force air defense, and there were questions about Spruance's decision to tie down the fast carriers and deny them the freedom to strike Japanese sea and air forces.[15]

COMAIRPAC Towers in Pearl Harbor was critical of the way Spruance had handled the carriers in the Gilberts, believing he should not have held them back in

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[14] Entry 9, October 1943, Graybook, 1 July 1943–31 December 1943, p. 1671; Reynolds, *Fast Carriers*, pp. 84–88; Hone, "Replacing Battleships with Aircraft Carriers," p. 65.

[15] Reynolds, *Fast Carriers*, pp. 92–96, 102–109, 111–112; Reynolds, *Towers*, p. 464; Gerald E. Wheeler, *Kinkaid of the Seventh Fleet: A Biography of Admiral Thomas C. Kinkaid, U.S. Navy* (Washington, DC: Naval Historical Center, 1995), pp. 363–366.

anticipation of an engagement with the main Japanese fleet that never materialized and that the carriers would have been more effective had they been unleashed to assault the Japanese in the Marshalls. Towers was also unhappy with Pownall, who appeared to be suffering from the strain of combat and had been overly cautious in his employment of the carriers in support of Galvanic. Nimitz concurred. To replace Pownall, he turned to Marc Mitscher, then a rear admiral, who had skippered the Hornet in the Halsey-Doolittle Tokyo raid and at the Battle of Midway.[16] Despite Towers's reservations, Nimitz stood by Spruance, who remained in command of what was now designated the Fifth Fleet. Spruance was responsible for developing plans for Operation Flintlock, the invasion of the Marshalls, considered a crucial waypoint to the Carolines and the big Japanese fleet base at Truk. Initially the islands of Kwajalein, Wotje, and Maloelap were to be invaded simultaneously, but Nimitz decided to bypass Wotje and Maloelap and go straight to Kwajalein, although he agreed to seize Majuro in the southern Marshalls, which Spruance coveted as an advanced fleet anchorage.[17]

In preparation for the assault planned for 1 February, Mitscher's Task Force–58, operating independently, struck Wotje and Maloelap. Two of Mitscher's task groups also hit Eniwetok in the western Marshalls, deterring the Japanese from using that island to surge aircraft from the Marianas. In preparation for the invasion, two other carrier groups eliminated what remained of Japanese air power on Roi and Kwajalein. Carrier planes and Army Air Forces bombers from the Gilberts softened up Roi and Kwajalein in preparation for the invasion, which went smoothly, with a minimum of casualties for the landing forces and no losses among the carriers or other supporting ships. Considering the relative ease of taking Kwajalein, Nimitz determined that either Truk or the Marianas could be assaulted sometime in June, but not before he decided to take Eniwetok, using the reserve troops left over from Flintlock. Before that operation, TF-58's fast carriers descended on Truk. Over two days (17–18 February), three task groups, with nine carriers, destroyed or damaged more than 200 aircraft in the air and on the ground and sank 200,000 tons of shipping. Meanwhile, one of Mitscher's task groups covered the invasion of Eniwetok, which fell to a combined Army and Marine Corps force on 22 February. The historian Clark Reynolds concluded that the Marshalls and Truk "changed the

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[16] On 18 April 1942, Lt. Col. Jimmy Doolittle led a raid of a small group of B-25 medium bombers launched from the deck of the Hornet. This was the first aerial bombardment of Japanese cities in World War II.

[17] Reynolds, *Fast Carriers*, pp. 114–115, 122; Reynolds, *Towers*, pp. 450–452; Craig L. Symonds, "Mitscher and the Mystery of Midway," *Naval History* 26 (June 2012): 46–52. The most recent biography of Mitscher is Paolo E. Coletta, *Admiral Marc A. Mitscher and U.S. Naval Aviation* (Lewiston, NY: The Edwin Mellen Press, 1997).

complexion of the war in the Central Pacific," whereby the fast carrier task forces allowed Japanese island strongholds to be leapfrogged and accelerated the offensive against the strategically important Marianas and Japanese defenses even closer to the Home Islands. Thomas Hone added perceptively that TF-58 operations in early 1944 demonstrated that TF-58 functioned as "both sword and shield" and verified PAC-10 combined-force doctrine.[18]

Reynolds, Hone, and other historians acknowledge that the success of TF-58 and the fast carriers as they sailed from Majuro for the Marianas in the spring of 1944 was due not only to the evolution and verification of strategy and doctrine, but also the convergence of disparate technologies and techniques. Definitions vary; at the risk of oversimplification, technology comprises the "hardware," and technique involves the physical and intellectual skills needed to effect results from the hardware. Both, however, in the broadest sense, are interconnected elements of technology as a holistic complex of machines and processes.[19]

Carriers and the supporting ships in the task force were central to the technological changes that took place in 1943 and 1944. The Essex originated in carrier studies in 1939 that focused on a follow-on to the Yorktown class, limited by international naval arms agreements. The Essexes were built to a standardized design in five different shipyards, were larger at 27,500 tons than the Yorktowns, were as fast at 33 knots, featured an armored hangar deck, and accommodated an air group in excess of 90 (mostly larger and heavier) aircraft. Largely an expedient stopgap to fill in as the Essexes came into the fleet were the 11,000-ton Independence-class light carriers (CVLs), built on light cruiser hulls. Speedy enough at 32 knots, the CVLs were compromises with small air groups (31 aircraft) and handling characteristics that sometimes limited their air operations in unfavorable wind and sea conditions. Fast battleships anchored the task force screen. The North Carolina and South Dakota classes were designed and built to standards stipulated by the London Treaty of 1936, and at 27 knots were not quite fast enough to operate effectively with the task force. In contrast, the 45,000-ton, 33-knot Iowa-class dreadnoughts were ideal, stable, and fast, making them suitable as task force flagships and offering enough space for mixed heavy, medium, and light anti-aircraft ordnance.[20]

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18. Reynolds, *Fast Carriers*, pp. 114–115, 122, 130–141; Hone, "Replacing Battleships with Aircraft Carriers," p. 63.

19. Reynolds, *Fast Carriers*, pp. 53–59; Hone, "Replacing Battleships with Aircraft Carriers," p. 68. For a discussion of technology and technique, see Andrew Murphie and John Potts, eds., *Culture and Technology* (New York: Palgrave Macmillan, 2003), pp. 3–5, 28–29.

20. Reynolds, *Fast Carriers*, pp. 54–55; Norman Friedman, *U.S. Aircraft Carriers: An Illustrated Design History* (Annapolis, MD: Naval Institute Press, 1983), pp. 133–157, 177–191, 394–395, 403; Norman Friedman, *U.S. Battleships: An Illustrated Design History* (Annapolis, MD: Naval Institute Press, 1985), pp. 243–327.

With new carriers came new aircraft. Through 1942, the Grumman F4F Wildcat was the mainstay of carrier fighter squadrons, yet even with modifications and improvements, it was inferior in many respects to the Japanese Mitsubishi A6M Zero. Not so the Wildcat's successor, Grumman's F6F Hellcat. Its design based in part on wartime experience, the Hellcat first flew in June 1942, with production aircraft reaching the fleet early in 1943; its baptism of fire came in the Marcus raid in August 1943. Joining the Hellcat by the middle of 1944 as the standard carrier fighter was the Vought F4U Corsair, featuring a distinctive gull-wing that permitted a large-diameter propeller and short, sturdy landing gear. Both fighters with well-trained pilots over-matched the Zero in nearly all aspects of aerial combat. As a strike aircraft, the superb Douglas SBD Dauntless dive-bomber had been the mainstay through all of 1942 and most of 1943. Its replacement was the Curtiss SB2C Helldiver, capable of hauling heavy ordnance in an enclosed bomb bay but troubled by development problems. The crash of the first experimental model in early 1941 delayed the program while Curtiss made extensive modifications to the production version, the first of which was not delivered until June 1942. Not until December 1942 did the first examples reach operating units, and nearly another year passed before the airplane got into combat. Even then, aviators scorned the SB2C's handling characteristics, and carrier commanders found them hard to maintain, although the much-maligned airplane went on to have a sound operational record. Meanwhile, the rugged Grumman TBF Avenger, which flew in combat for the first time at Midway, continued in various iterations throughout the war as the U.S. Navy's only torpedo bomber despite efforts to field a more modern replacement.[21]

Communication was one of technologies and techniques that were essential to the organization and functioning of the fast carrier task force, both for individual ships and aircraft and for coordinating their movements and operations. By 1944, carriers and ships in the task force screen relied on four-channel very-high-frequency (VHF) radio sets, linked by "nets" that provided real-time interchange of information among hundreds of ships and aircraft. VHF radio was short-range, so for the most part it was secure from enemy eavesdropping. By 1944, improved air search radars gave carriers and ships in the task force screen early warning of Japanese attacks while at the same time allowing the carriers to direct and coordinate both offensive strikes and fighters in the task force combat air patrol (CAP). A major development was a system known as Identification Friend or Foe (IFF), a transponder on carrier aircraft that was interrogated by search radar and

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[21] Gordon Swanborough and Peter M. Bowers, *United States Navy Aircraft Since 1911*, 3rd ed. (Annapolis, MD: Naval Institute Press, 1990), pp. 166–168, 222–227, 230–233, 234–237, 449–453.

replied with a code that determined whether the airplane was or was not an enemy intruder. Most important, however, was a means of coordinating the immense amount of ship and aircraft data on board the carrier, all of which was channeled through the ship's Combat Information Center, or CIC.[22]

The CIC was the nerve center, or "brain" of the ship, where the acquisition, analysis, and dissemination of tactical information from other vessels and aircraft took place. Initially, a team of officers and enlisted men handled radar data streaming in through shipboard long-range air search radars in a space designated Radar Plot. Combat experience in 1942 verified the importance of shipboard radar plots while at the same time demonstrating that something more comprehensive was necessary for efficient information management. Late in the year, Nimitz recommended that warships be equipped with Combat Operations Centers where "information from all available sources" could be collected, analyzed, and made available to commanding officers. King followed up in February 1943 with a directive to place such facilities, now identified as Combat Information Centers, in all surface ships. By the summer of 1943, the Navy had drafted standardized layouts for CIC spaces that were to be installed in existing ships when they were modernized or refitted and that were to be incorporated into the design and construction of new vessels. Initially, CICs in escort carriers proved their worth in processing information from disparate sources, facilitating decision-making, and directing ships and weapons in the high-tech war against the German U-boat in the Atlantic. All Essex-class carriers had CICs, and most of the older ships and the light carriers in the Pacific had the installations by the end of 1943. Initially, CICs were located in the carrier's island close to the bridge, but later they were placed in the gallery deck just above the hangar deck, less convenient in some respects for officers responsible for ship and aircraft operations, but more protected than in the exposed island.[23]

Not least of the activities in the hectic and congested carrier CIC was fighter direction, which was heavily dependent on radar. Air defense before the advent of radar relied on an outer patrol of fighters that made visual contact with approaching enemy aircraft while a close-in CAP engaged adversaries before they came within range of the ships' anti-aircraft batteries. Direction and control came from an airborne fighter director. Air search radars, which could locate attackers more accurately and at a greater distance, made the outer patrol no longer necessary. On the carrier, a Fighter Director Officer (FDO) tracked and controlled fighter patrols using voice radio and by monitoring search radar plots from the carrier and other

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[22] Reynolds, *Fast Carriers*, pp. 53–54.

[23] Timothy S. Wolters, *Information at Sea: Shipboard Command and Control in the U.S. Navy from Mobile Bay to Okinawa* (Baltimore: Johns Hopkins University Press, 2013), pp. 175, 186–187, 204–212.

ships. Inadequate radar and radio equipment, poor doctrine and training, and lack of experience in fighter direction contributed to the loss of the carriers Lexington and Yorktown at the Coral Sea and Midway, respectively. In later battles in 1942, fighter directors found it difficult to coordinate with air groups and share data with their counterparts in other carriers in the formation. This was one of the major problems leading to skepticism about concentrating carriers during enemy air attacks.[24]

By the fall of 1943, the new Essexes and light carriers in the task force enjoyed far more effective fighter direction than was possible just a year before. A task force fighter director officer analyzed radar plots from the flagship and other CICs and coordinated individual carrier and surface ship FDOs; his and others' jobs were made possible by improved technology and more and better-trained personnel. Carriers were now equipped with SK and SM air search radars to supplement early SC units; multichannel VHF radio allowed the FDOs to have near-continuous contact with their fighters; and CICs had the ability to control strike and patrol aircraft while simultaneously communicating with other CICs in the task force and with the task force fighter director officer. Radar-equipped picket destroyers ranging outside the task force screen detected incoming enemy aircraft, and their own FDOs directed fighter interceptors. Individual low-flying attackers could sneak in below task force radar, thus making visual fighter directions imperative under some circumstances. Specially trained radio-equipped FDOs and enlisted men were therefore stationed on carriers and other ships to detect and warn of intruders.[25]

Less well known and generally underappreciated by historians was Loran (Long Range Navigation), first used operationally by anti-submarine aircraft in the Atlantic in 1942 and extended to ships and aircraft in most parts of the Pacific theater by the end of 1944. The system used "pulses" of low-frequency radio waves that could be detected at distances of up to 1,500 miles by relatively simple receiving equipment. Two Loran stations transmitted signals within milliseconds of one another. A navigator receiving the signals from the paired stations measured the time delay between them on an oscilloscope, using that time delay to plot their intersection on special charts, which allowed him to determine his position easily and with unprecedented accuracy. By the end of 1944, eight Loran stations were

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[24] World War II Administrative History, Office of the Deputy Chief of Naval Operations DCNO (Air), *History of Naval Fighter Direction*, vol. 1 (Washington, DC: Aviation History Unit, Office of the Chief of Naval Operations, 1946), pp. 139–146, 163–165 (hereafter cited as DCNO [Air] World War II Admin. History); Wolters, *Information at Sea*, pp. 195–201.

[25] DCNO [Air] World War II Admin. History, *History of Naval Fighter Direction*, pp. 191–194, 197–199, 212–214.

in operation in the Marshalls and Marianas, all constructed and operated by the Coast Guard and invaluable to the ships and aircraft of the fast carrier task force.[26]

At Majuro in the spring of 1944 was the At Sea Logistics Service Group, a component of the Service Force, Pacific Fleet, under the command of Vice Admiral William L. Calhoun. Vital to the mobility of the fast carrier task force, Service Squadrons (Servrons) 8 and 10 provided logistical support for the force as it advanced across the western Pacific. Thirty-four oilers, 11 escort carriers, and more than 50 destroyers and destroyer escorts rotated in support of the fast carrier forces. Escort carriers, themselves organized in task groups that mirrored those of the fast carriers, provided air cover and anti-submarine defense and ferried replacement aircraft and personnel. Servron 8 at Pearl Harbor was primarily responsible for administration of the Service Group and for the ships transporting fuel, ammunition, and other supplies to the advance fleet bases, while Servron 10 handled most operations, including under way replenishment of fuel, dry stores, and other supplies; by February 1945, Servron 10 had perfected ammunition resupply at sea, which allowed the carrier task forces to stay at sea virtually indefinitely. For Clark Reynolds, the Service Force was one of the Navy's "open secret weapons" that helped ensure the success of the fast carrier force in the Pacific.[27]

Another "open secret weapon" was the Carrier Aircraft Service Unit (CASU), a self-contained mobile supply and maintenance organization assisting the operating squadrons. Shore-based CASUs and their carrier-based counterparts had been brought together administratively under COMAIRPAC in September 1943 to help centralize aviation logistics in the Pacific. By 1944, the rapid influx of new aircraft in the Pacific had caused logistical bottlenecks, and it had become apparent that a policy would have to be promulgated to remove or return damaged, worn out, or obsolescent aircraft to make room for the new planes coming through the pipeline. It would also be necessary to ensure that supply, maintenance, and repairs were done efficiently and in concert with production and logistic support, especially in the Pacific. In the spring of 1944, Vice Admiral John S. McCain, Jr., Deputy Chief of Naval Operations (Air), appointed Rear Admiral Arthur W. Radford to chair a committee to grapple with the problem. Following up with the

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[26] World War II Administrative History, Bureau of Aeronautics, Summary, vol. 1 (Washington, DC: Director of Naval History, 1957), pp. 362–363 (hereafter cited as BuAer World War II Admin. History); *The Coast Guard at War, Loran IV*, vol. 2 (Coast Guard Headquarters, 1946), pp. 143–147, *http://www.loran-history.info/LORAN_Implementation_Planning_Installation_and_Termination/1942-1949/THE%20COAST%20GUARD%20AT%20WAR.pdf* (accessed 20 July 2016).

[27] Worrall Reed Carter, *Beans, Bullet, and Black Oil: The Story of Fleet Logistics Afloat in the Pacific During World War II* (1953; repr., Newport, RI: Naval War College Press, 1998), pp. 95–99; Reynolds, *Fast Carriers*, pp. 128–129.

board's recommendations, the Navy implemented a plan to coordinate the work of the forward-based CASUs with the aircraft maintenance and repair operations of aircraft Assembly and Repair (A&R) units at naval air stations. It was not easy to provide for the smooth flow of aircraft into and out of the fleet, but in general the carrier forces were beneficiaries of a logistical support system that ensured they had reliable and up-to-date aircraft as they began the Marianas campaign.[28]

With nine carriers organized into the Mobile Fleet under Vice Admiral Ozawa Jisaburo, the Japanese were prepared to engage and defeat the American forces in the waters west of the Marianas. Although at a numerical disadvantage in ships and aircraft, Ozawa planned to launch his planes out of the range of the American carriers and shuttle them to airfields on Guam, striking American ships again on the way back. On 15 June, as two Marine Corps divisions, supported by TF-58, landed on Saipan's west coast beaches, intelligence sources gave Spruance an understanding of the size and composition of the Japanese carrier forces. His plan was to have Mitscher's TF-58 defeat the Japanese carriers, destroy the enemy battleships and cruisers, and then organize the fast battleships into a separate task force to pursue and crush any remaining elements of Ozawa's force. When he received word late on the 17th that a submarine was shadowing the Mobile Fleet about 350 nautical miles east of the Philippines, Mitscher surmised that if the Japanese continued to the east and TF-58 steered west, the enemy force would be within the extreme range of TF-58's aircraft late in the afternoon of the 18th. Yet he could not attack until TF-58 aircraft spotted the Mobile Fleet. Instead, with their range advantage, Ozawa's searchers found the Americans first, locating elements of TF-58 on the afternoon of the 18th.[29]

Spruance now knew that the Japanese were committing to battle, but he still did not know exactly where the Mobile Fleet was, and he feared that a separate element of their force might attempt an "end run" or flanking maneuver to get behind TF-58 and disrupt the invasion forces. So he ordered the vulnerable amphibious ships to assume a "safe" distance to the east of Saipan and determined to have TF-58 cruise in position just west of the Marianas. Mitscher was furious with the orders and asked Spruance for permission to speed westward during the night of

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[28] BuAer World War II Admin. History, Summary, vol. 1, pp. 92–93, 95, 597, 600–601, 642–645; BuAer World War II Admin. History, vol. 5, pp. 207; Reynolds, *Fast Carriers*, pp. 129–130; Vern A. Miller, "Our Coral Carriers Helped Turn the Tide of Battle," *http://www.wartimepress.com/archive-article.asp?TID=This%20is%20CASU&MID=68&q=114&FID=7* (accessed 26 Nov. 2012).

[29] Tillman, *Clash of the Carriers*, pp. 39, 48–51, 65–66, 76–77, 88–97, 101–102; Morison, *New Guinea and the Marianas*, pp. 179–183, 242; W. D. Dickson, *The Battle of the Philippine Sea* (London: Ian Allan, Ltd., 1975), pp. 48–50, 53, 55, 62, 63, 70, 77–78, 80.

18–19 June and strike the Japanese at first light. Spruance remained firm: TF-58 would stand off the Marianas and absorb the Japanese strikes.[30]

Ozawa launched his strike aircraft early on the 19th, when his carriers were beyond Mitscher's reach. With favorable prevailing winds, the Japanese carriers enjoyed the advantage of remaining on course to the east when launching and recovering aircraft, whereas the American carriers had to double back from a westerly heading to gain enough wind over their decks for takeoffs and landings. About 9:50 a.m., TF-58 search radars detected the attackers, and within less than an hour, 200 F6Fs were in the air ready to intercept the Japanese planes. The Japanese followed their initial strike with three more, the last of which ended about 3 p.m. In the meantime, two American submarines torpedoed and sank the carriers Taiho and Shokaku. None of Mitscher's carriers suffered a direct hit, although some were damaged by near misses. Fighters and anti-aircraft fire accounted for 261 Japanese aircraft, the most ever in a single day of aerial combat; in return, the Americans lost 31. Compared by one of the Lexington's fighter pilots to an "old-time turkey shoot," the 19 June battle was a stunning American aerial victory.[31]

As the Mobile Fleet retired to the northwest, Spruance, still worried that a detached element of the Japanese force might pounce from an unexpected direction, hesitated in granting Mitscher permission to pursue. Mitscher's carriers were more than 300 miles behind Ozawa, and they would have to make good time to the west to bring the Japanese force within range, all while conducting air operations. Nevertheless, Spruance ordered TF-58 to steam westward in hopes of contacting the Japanese, while releasing one task group to refuel and stay close to Saipan. Mitscher's searchers sighted Ozawa's carriers, barely within range, late on the 20th. Knowing that his aircraft would have to be recovered after dark, he ordered his three carrier task groups to launch full deck load strikes against Ozawa's remaining carriers. Just before sunset, the Americans located and attacked Ozawa's force, damaging the Zuikaku, Junyo, and Chiyoda and sinking the Hiyo; another 60 aircraft were lost defending the Mobile Fleet. Low on fuel and enveloped by darkness, TF-58 aviators now had to find their way back home. With the task force carriers illuminated to guide the fliers, 140 of them landed safely, while another 86 planes and aircrew were missing, the majority of whom were rescued.[32]

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[30] Tillman, *Clash of the Carriers*, pp. 98, 100–101, 108; Reynolds, *Fast Carriers*, pp. 186–187.

[31] Tillman, *Clash of the Carriers*, pp. 108–109, 119, 125, 129–131, 135–136, 139, 146–160, 162–182, 196, 199, 322; Dickson, *Philippine Sea*, pp. 108, 119, 121; Reynolds, *Fast Carriers*, pp. 192–193.

[32] Tillman, *Clash of the Carriers*, pp. 197, 201, 204, 207–209, 213–214, 219, 238–240, 242–262, 265–269, 276–284; Dickson, *Philippine Sea*, pp. 140–141; Reynolds, *Fast Carriers*, pp. 202–204.

It was not long before there was critical assessment of what became known as the Battle of the Philippine Sea. Towers offered that he was "terribly disappointed about recent naval actions west of the Marianas," later blaming Spruance for "ultra-conservatism" that allowed the Japanese carrier force to avoid annihilation. Mitscher's action report summarized much of the sentiment at the time that Spruance had made a mistake in not ordering TF-58 to pursue the Japanese on the night of 18–19 June. It ended cryptically: "The enemy had escaped. He had been badly hurt by one aggressive carrier air strike, at the one time he was within range. His fleet was not sunk." In reply to those who believed that Spruance had been right to keep Mitscher close to Saipan to cover the invasion force, other aviators responded that the best defense would have been to take the battle directly to the Japanese Mobile Fleet.[33]

It cannot be denied that the Battle of the Philippine Sea was a decisive victory, the pivotal battle of the Pacific war that for all intents and purposes marked the demise of Japanese carrier-based air power. In another sense, it was the culmination of PAC-10 and the fully integrated fast carrier task force as well as a validation of the effectiveness of fighter direction doctrine and training.[34] Yet no one was certain that Japan's carriers were finished as a fighting force, nor could they guarantee that there would never be another encounter of this type or scale. They did know, on the other hand, that the Japanese still had at least six operational carriers, that their army and air forces had not been defeated, and that there was much more to do as naval sea and air power led the offensive beyond the Marianas.

Among the Joint Chiefs of Staff there was general consensus on the plans and means to bring the war in the Pacific to an end. Nimitz's Central Pacific forces and those of General Douglas MacArthur in the South West Pacific were to converge on the southern Philippines, from which Allied forces could advance on either the Philippine island of Luzon or on Formosa off the coast of China, penetrate the Japanese inner defense perimeter by assaulting Okinawa in the Ryukyu Islands, and advance from there to Kyushu, the southernmost Home Island. The southern Philippine island of Mindanao was to be invaded first—tentatively on 15 November—followed by Leyte, a potential fleet anchorage and site for air bases. To isolate the Philippines, Peleliu in the southern Palaus and Morotai in the Halmaheras would need to be taken, and Yap and Ulithi in the western Carolines either occupied or neutralized.[35]

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[33] Reynolds, *Towers*, p. 476; Reynolds, *Fast Carriers*, pp. 205–206.

[34] DCNO [Air] World War II Admin. History, *History of Naval Fighter Direction*, pp. 217–219; Wolters, *Information at Sea*, pp. 212–213.

[35] Reynolds, *Fast Carriers*, pp. 244–246.

In August, following the "two-platoon" rotation scheme devised by Nimitz and King, Halsey assumed command of Spruance's force, now designated the Third Fleet. The idea was that when Spruance and his Fifth Fleet completed an operation (in this case the Marianas), he and his staff would retire to plan the next phase of the Central Pacific offensive; meanwhile, Halsey would take over the fleet, which remained basically the same as far as ships and aircraft were concerned. Task Force–58 under Mitscher therefore became Task Force–38, the command of which was to fall to Vice Admiral John McCain. Yet when Mitscher insisted on staying with the fast carriers for the next phase of the offensive, King decided to compromise: Mitscher would become the new Commander First Fast Carrier Task Force Pacific, while McCain became Commander Second Fast Carrier Task Force Pacific, as well as commander of TG-38.1 under Mitscher.[36]

When reports indicated that Japanese air power in the southern Philippines was weaker than anticipated, Halsey suggested that the Mindanao operation be canceled and Leyte invaded instead. Moreover, Halsey disagreed with planners that a forward position in the Palaus was necessary and that other than Ulithi, no other islands in the western Carolines need to be taken; unfortunately, the invasion of Peleliu went forward—a costly mistake that did nothing to expedite the advance into the Philippines. King, Nimitz, and MacArthur concurred about Mindanao and Leyte, but they did not agree about Luzon. The Joint Chiefs favored Luzon but were unwilling to make a commitment until after the Leyte landings scheduled for 20 October. Under MacArthur, now–Vice Admiral Thomas Kinkaid's Task Force–77 would carry out the landings in Leyte Gulf. Air cover would come from Mitscher's TF-38, now with 4 task groups, 17 fast carriers, and nearly 1,100 aircraft; one of the task groups (TG-38.1) included five carriers. The divided command dictated that there was no direct line of communication between Halsey and Kinkaid and that they would only be able to communicate through their superiors, Nimitz and MacArthur.[37]

Nimitz's operation plan called for TF-38 carriers to neutralize enemy air and shipping in Formosa and the Philippines, then provide close air support for the ground forces. Nimitz did not want the Japanese fleet to escape as it had after the Battle of the Philippine Sea and directed Halsey that "in case opportunity for destruction of major portion of the enemy fleet is offered or can be created, such destruction becomes the primary task." Halsey reciprocated: "My goal is the same as yours–to completely annihilate the Jap fleet if the opportunity offers...." He further specified that TF-38 in "strategic support" would "seek out the enemy and

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[36] Ibid., pp. 232–233, 238.

[37] Ibid., pp. 245–246, 255–256.

launch a concerted air strike against his major units." Halsey's plan anticipated the possibility of a surface battle, in which his fast battleships would organize into a separate task force to counter the Japanese, as well as a unit of destroyers and light cruisers to engage Japanese night forces should they appear. As Thomas Hone stresses, Halsey presented a "whole-force plan" that fully incorporated the doctrinal principles of PAC-10.[38]

Leading up to the amphibious operation, Mitscher's carriers blasted Japanese airfields in Okinawa, Formosa, and northern Luzon, resulting in the destruction of more than 1,200 enemy aircraft. On schedule, TF-38 aircraft launched fighter sweeps and strikes against Japanese defensive positions to provide direct cover when Army troops went ashore on 20 October. Lacking intelligence about the movement of major Japanese units and convinced there would be no major fleet engagement, Halsey decided to rotate TF-38's groups to Ulithi to rearm and replenish stores. On the 22nd, McCain's TG-38.1 was the first to leave for Ulithi. At this juncture, no one at CINCPAC or Third Fleet knew that the Japanese had implemented plan Shō-1, which involved four of Ozawa's Mobile Fleet carriers, largely devoid of their air groups, acting as decoys to lure Mitscher's carriers away from Leyte. Once that happened, heavy surface ships under the command of Vice Admiral Kurita Takeo would cut through the Philippines to converge on and destroy Kinkaid's transports and support ships off the beaches. A contingency, to be implemented only if absolutely necessary, were the kamikaze suicide pilots assembled by Vice Admiral Onishi Takajiro, whose planes would in effect function as deadly guided missiles.[39]

Early on 24 October, Mitscher's airmen struck Kurita's warships threading through the Sibuyan Sea west of Leyte. They delivered devastating blows that sank the super battleship Musashi and badly damaged a heavy cruiser, but other ships were not seriously hurt. In the Battle of the Sibuyan Sea, the American fliers overestimated the damage they had inflicted and reported that the Japanese appeared

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[38] Reynolds, *Fast Carriers*, pp. 259–260; Hone, "Replacing Battleships with Aircraft Carriers," p. 71; E. B. Potter, *Bull Halsey* (Annapolis, MD: Naval Institute Press, 1985), pp. 279–280; Wheeler, *Kinkaid*, pp. 386–387; Samuel Eliot Morison, *History of United States Naval Operations in World War II*, vol. 12, *Leyte, June 1944–January 1945* (Boston: Little, Brown and Company, 1961), pp. 57–58, 424–428.

[39] Reynolds, *Fast Carriers*, pp. 220, 253–254, 259–264; Morison, *Leyte*, pp. 130–156; Potter, *Bull Halsey*, p. 287; Richard W. Bates, *The Battle for Leyte Gulf, October 1944, Strategical and Tactical Analysis*, vol. 2, *Operations from 0719 October 17th Until October 20th D-Day* (Newport, RI: Naval War College, 1955), pp. xl, 209; Richard W. Bates, *The Battle for Leyte Gulf, October 1944, Strategical and Tactical Analysis*, vol. 1, *Preliminary Operations* (Newport, RI: Naval War College, 1953), p. 450; Commander Task Group THIRTY-EIGHT POINT ONE, Action Report, 2 October–29 October 1944, Enclosure A, pp. 12–14, folder GTG 38.1–Action Report 2–29 October 1944, box 92, Com 2nd Carrier TF (Blue 627), Naval Operating Forces, RG 313, NARA Archives II.

to be retreating to the west. To Halsey, it looked like a major Japanese defeat that ensured no further threat from that quarter to Kinkaid's Seventh Fleet forces at Leyte. Even if the remaining enemy ships did manage to break through the San Bernardino Strait to the north of Leyte, Halsey reasoned that his battleships were more than adequate to defeat them and informed his battleship commander that four of his heavies would be formed by subsequent message as TF-34. Kinkaid picked up the signal, which he wrongly interpreted to mean that TF-34 had already been organized to cover the exit of the San Bernardino Strait. At the same time, Halsey was worried about the possibility that a Japanese carrier force might jump his three task groups from somewhere to the north. He therefore recalled McCain's group with orders to refuel and send out searches to the north and northwest at daylight on the 25th. A reminder of the threat of Japanese land-based aircraft came when Japanese bombers struck the light carrier Princeton, which had to be sunk following a massive internal explosion.[40]

Halsey assumed that Kinkaid's heavy ships and his escort carriers could deal with any residual Japanese surface ships that might threaten the amphibious force at Leyte. He was right. In a night gun duel that ended in the predawn darkness on the 25th, Kinkaid's superannuated battleships virtually wiped out a Japanese force entering the Surigao Strait to the south of Leyte. Halsey also thought that Kinkaid's battleships could deal with the depleted Japanese force in the Sibuyan Sea, which, according to scouting reports, had turned back east on the evening of the 24th. Determined to get Ozawa's carriers, Halsey decided to take TF-38 north and launch a dawn strike, accompanied by all of Vice Admiral Willis Lee's battleships now assembled in TF-34. By daybreak on 25 October, Kinkaid lacked any heavy ships or fast carriers at the moment when the Japanese charged out of San Bernardino and down the coast of Samar toward Leyte.[41]

As TF-38 launched its first strike on Ozawa's carriers off Cape Engaño, Kurita's big ships emerged from San Bernardino and fell on Kinkaid's TF-77 escort carrier groups. Kinkaid called for assistance, but due to communication delays and his position far to the north, Halsey was unable to help. Only the valiant sacrifice of Kinkaid's escort carriers and destroyers and the surprise retreat of the Japanese battleships and cruisers saved the day for the invasion force. Puzzled that Kinkaid was having difficulties with a Japanese force that he thought was capable of nothing

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[40] Morison, *Leyte*, pp. 130–156, 169–176; Potter, *Bull Halsey*, p. 287; Reynolds, *Fast Carriers*, pp. 262–266; Commander THIRD Fleet, Action Report, 23–26 October 1944, Enclosure A, pp. 2, 4, 6; Richard W. Bates, *The Battle for Leyte Gulf, October 1944, Strategical and Tactical Analysis*, vol. 5, *Battle of Surigao Strait, October 24th–25th* (Newport, RI: Naval War College, 1958), pp. 44, 46, 163–165, 168, 178, 179.

[41] Reynolds, *Fast Carriers*, pp. 266–269, 271–273.

more than harassment, Halsey hesitated. Meanwhile, Nimitz, who had been monitoring developments from Pearl Harbor, sent the message: "Where is rept Where is Task Force Thirty-Four RR The World Wonders." Halsey seethed at what he considered an unprofessional gratuitous insult until he realized that the last sentence was leftover cryptological padding. At that point, he ordered one of Mitscher's task groups to provide support for two of TF-34's battleships as they steamed south to relieve Kinkaid, while the remaining TF-38 carrier forces finished off Ozawa's carriers and Mitscher's two task groups inflicted more damage on the Japanese ships retreating through the Sibuyan Sea. By late on the 26th, all four of Ozawa's carriers had been sunk, and Kinkaid's invasion force was safe from attacks from the sea, if not from Japanese land-based aircraft and kamikazes.[42]

Considered by some the greatest naval battle in history, the Battle of Leyte Gulf had concluded in an overwhelming American victory. But that did not preclude controversies and finger-pointing. Foremost was the essentially political decision to divide the command between MacArthur and Nimitz, which had led to miscommunication between the Third and Seventh Fleets, fostered confusion, and hindered cooperation, especially in the crisis facing Kinkaid on 25 October. Halsey justified his decision to pursue Ozawa, explaining that it was illogical to keep Mitscher's carriers "statically" off Samar and that, at the time, it appeared as if Ozawa's force was the main threat to Kinkaid. Nimitz was judicious in his criticism of Halsey, but King was more direct in blaming Halsey for the near-debacle. For the most part, historians have taken a balanced interpretation of the people and events of October 1944. Clark Reynolds acknowledged that Halsey had made a mistake in failing to draw on the experience of his subordinates, especially Mitscher, and that his command lacked efficient planning and coordination. Kinkaid "took too much for granted" in assuming that TF-34 had indeed been formed to guard San Bernardino and never fully comprehended the tactical situation on 24–25 October. Kinkaid's biographer, Gerald Wheeler, asserted that of the two—Halsey and Kinkaid—the latter paid more "attention to the mission," that is, how the carrier and amphibious forces needed to work together to assure the success of the operation. Lessons still remained to be learned—some at considerable cost. Regardless, the reality is that the Japanese Navy was no longer an effective sea and air force.[43]

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[42] Potter, *Halsey*, pp. 302–304; Morison, *Leyte*, pp. 296–300, 309–310, 330; Commander THIRD Fleet, Action Report, 23–26 October 1944, Enclosure A, p. 34; Commander Task Group THIRTY-EIGHT POINT ONE, War Diary, 1 October–31 October 1944, 25 October 1944.

[43] Reynolds, *Fast Carriers*, pp. 278–280, 282–283; Bates, *Battle for Leyte Gulf*, vol. 2, pp. 30–32; Morison, *Leyte*, p. 175; Reynolds, *Towers*, p. 493; Wheeler, *Kinkaid*, pp. 405–406, 489.

When the Joint Chiefs decided to bypass Formosa and invade Luzon, the fast carrier task force now had the responsibility for gaining control of the air over the northern Philippines and preventing the Japanese from interfering with the amphibious operation at Lingayen Gulf, scheduled for January 1945. In contrast to Spruance, Halsey wanted the fast carriers to undertake a broad strategic defense, exploiting the mobility of the task force and not tying it to the landing beaches. From November 1944 to the end of the year, Halsey's Third Fleet, with Vice Admiral McCain replacing Mitscher in command of TF-38, the fast carriers struck airfields, aircraft, and transportation systems in Luzon, Formosa, and the Ryukyus. TF-38 devastated Japanese air power, shipping, and infrastructure, but the success came at a price, exacted in part by Japanese suicide attacks that damaged six carriers, three so severely that they had to be pulled off the line for major repairs.[44]

McCain's solution to the problem was to have his task groups initiate new defensive tactics and formations. In "Moose-trap" exercises, one or two fighter or dive-bomber units mimicked suicide strikes while the task force concentrated fighter defenses to counter the attacks. Another innovation was to assign radar picket destroyers (called "Tomcats") to stations 50 to 60 miles in front of the task force to warn of attackers and vector their own CAP ("RapCap") to intercept them. In a tactic known as "de-lousing," friendly aircraft orbiting the destroyers were separated from enemy planes ("parasites") that might hide in the formation, which then could be shot down by anti-aircraft fire or the carriers' CAP scouting ahead of the task force ("ScoCap"). In addition to the ScoCap, so-called Jack patrols were dispatched at dusk to intercept Japanese planes approaching at low altitude in the darkness; "DadCap" fighters covered the force during daylight; and "BatCap" aircraft took over at nightfall.[45] McCain's tactical innovations worked, although neither he nor anyone else anticipated that in subsequent operations, the Tomcat destroyers would become targets of a disproportionate share of suicide attacks.

New task force offensive tactics complemented defensive measures. McCain suggested that the carriers "blanket the threatening enemy air opposition day and night with the most air power available." This "blanket" over the enemy's airfields would smother air opposition and free carrier planes to pursue secondary objectives while minimizing the threat of air assault on the fleet. "The enemy must never be permitted to lift even one corner of the 'blanket' over his airfields, or the safety of

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[44] Reynolds, *Fast Carriers*, pp. 285–290.

[45] Ibid., p. 290; Steve Ewing, *Thach Weave: The Life of Jimmie Thach* (Annapolis, MD: Naval Institute Press, 2004), pp. 146–148; Commander Task Force THIRTY EIGHT to Task Group Commanders, 11 November 1944, Enclosure A, folder P11-1, box 88, Com 2nd Carrier TF (Blue 627), Naval Operating Forces, RG 313, NARA Archives II.

the entire Task Force is jeopardized," McCain insisted. "Regardless of the attractiveness of other targets, responsible commanders must not be lulled into diverting so much of their air strength from the 'blanket' that the enemy's air is no longer thoroughly held helpless while it is being systematically destroyed." He concluded, "The stake is too high." A "three-strike" system enhanced the coverage of McCain's "blanket." After launching half their aircraft in their first strikes of the day, carriers waited until those strikes were about to land before flying off their second deckloads. The interval sometimes gave the Japanese a chance to attack the task force. Better for the carriers to launch two-thirds of their aircraft in the first strike: half of the planes in the strike carried bombs ("Strike A"), and half did not ("Strike B"), allowing them to carry more fuel. The Strike B aircraft remained over the targets to engage any enemy aircraft that survived the strike while protecting the bombers as they returned to the carriers. Before those first strikes returned to the carriers, the remaining third of the air group was launched as Strike "C," adhering to the same pattern as the first and splitting into two smaller strikes. The new tactic maximized the carriers' offensive power and resulted in near-continuous coverage of the enemy airfields, but the intensity of air operations demanded well-trained aircrew, sufficient numbers of front-line aircraft, and standardized replacement air groups. Another innovation was to restructure the task force into three task groups instead of four, two with four carriers each and one with five, which allowed entire task groups to rotate out on a regular basis for rest and replenishment.[46]

"Round the clock" carrier operations were essential for McCain's "blanket" coverage. As Chief of the Bureau of Aeronautics in 1942, he had called for the development of a specialized night fighter, which eventually materialized as the twin-engine Grumman F7F Tigercat. Because the F7F did not reach combat units until late in the war, an interim capability was essential. A radar-equipped TBF and two fighters flew a night mission from the Enterprise in November 1943, followed in January 1944 by night fighter units deployed on the Enterprise and Intrepid (CV-11). Yet integrating a night capability into the carrier task force occurred in fits and starts. Problems with night fighter direction in the February raid by TF-58 on Truk led to the torpedoing of and heavy damage to the Intrepid. Thereafter, Mitscher was skeptical about night operations, which demanded specialized training, complicated task force maneuvers, and precluded airmen and ships' crews from getting the rest they needed. In December 1944, the Enterprise and the Independence

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[46] Ewing, *Thach Weave*, pp. 148–149; *Reminiscences of Admiral John Smith Thach, U.S. Navy (Retired)*, vol. 1 (Annapolis, MD: U.S. Naval Institute Press, 1977), pp. 401–404; Commander Task Force THIRTY-EIGHT, Action Report, 30 October 1944–26 January 1945, p. 5, box 92, Com 2nd Carrier TF (Blue 627), Naval Operating Forces, RG 313, NARA Archives II.

came together into a separate night fighter task group within TF-38. By February, the old Saratoga had been converted to a night carrier, replacing the Independence, only to be damaged and withdrawn after a kamikaze strike. In May, the Enterprise was taken out of action by a kamikaze strike off Okinawa but was replaced in June by the Bonhomme Richard (CV-31). Mitscher remained opposed to night carrier groups and recommended that each carrier have its own night squadron, while McCain concluded at the end of the war that the "results have been exceptional" when a night carrier or group was with the task force.[47]

Through the end of 1944 and into the late winter of 1945, the fast carriers ranged widely, striking airfields, aircraft, shipping, and infrastructure in the Philippines, Formosa, and the Ryukyus. In January, TF-38, now including the two-carrier night group, attacked a continent for the first time when they penetrated into the South China Sea to attack warships, convoys, and land targets in Indochina and China. In time for the next operation, the assault on the heavily defended island of Iwo Jima in February, Mitscher rotated back to the fast carriers, taking over TF-58 in Spruance's Fifth Fleet. Including the night group, the task force had 16 carriers in five groups, with two groups operating 4 carriers each. Before the landings, Mitscher's carriers struck targets in and around Tokyo, destroying more than 300 enemy aircraft. Thereafter, TF-58 covered the Iwo Jima operation with close air support of the Marines ashore and defended the invasion force against determined attacks by land-based Japanese bombers and kamikazes.[48]

Okinawa in the Ryukyus was the next objective in a strategy that viewed the island as a springboard for operations that called for the destruction of Japanese naval and air power, followed by a massive sea and air blockade, and finally an invasion of the Home Islands. Leading up to the 1 April invasion of Okinawa, Mitscher's force launched strikes on airfields and other installations on Kyushu, followed by a week of attacks on positions in the Ryukyus. Japanese aircraft from Kyushu and the Ryukyus retaliated against TF-58 with unrelenting fury. In a little more than a month, suicide planes and bombers damaged 10 fast carriers and sank or damaged more than 350 other ships and smaller craft, with more than 4,900 Fifth Fleet officers and enlisted men killed. Only two days after the landings on Okinawa, the Joint Chiefs directed MacArthur and Nimitz to begin planning for the invasion of Kyushu, later named Operation Olympic and tentatively set for 1 November. In late May, Spruance and Mitscher rotated out of Fifth Fleet and TF-58 respectively, and Halsey and McCain rotated in—for what turned out to

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[47] Reynolds, *Fast Carriers*, pp. 59, 102, 131, 139–140, 147, 290–291, 295, 330, 335, 358; DCNO [Air] World War II Admin. History, *History of Naval Fighter Direction*, pp. 205, 209–211.

[48] Reynolds, *Fast Carriers*, pp. 292, 332–336.

be the last time. Halsey's Third Fleet operations plan (Op Plan 3-45) included McCain's TF-38 with 12 fast carriers in three task groups and the recently arrived British TF-37 with 4 fast carriers under the command of Vice Admiral H. Bernard Rawlings. The fast carrier task forces had a strategic mission, specifically the destruction of Japan's industrial fabric, in addition to the elimination of all potential naval and air threats in preparation for Olympic.[49]

With plans to assault Japan in place and the need to maximize the offensive capability of the fast carriers to support land operations, it was time to rethink the composition of air groups, which for most of the war had been made up of a mix of fighters, dive bombers, and torpedo planes. By the end of 1944, McCain and others saw advantages in reducing the number of torpedo aircraft, which were no longer necessary since the defeat of the Japanese Navy. He was also ready to jettison the troublesome SB2C Helldiver. Instead of torpedo planes and dive bombers, the carrier air groups could employ more fighters to counter the threat of enemy land-based air power, including Japanese suicide units, and to function as strike aircraft when armed with bombs and rockets. The F4U Corsair, for example, had shown itself to be an excellent fighter-bomber. "In view of critical operation[s] in near future, the nature of which will require all possible VF strength in the Task Force for wide spread offensive missions," he recommended in December 1944 that the Essex-class ships include no fewer than 91 Hellcats and Corsairs. Nimitz subsequently agreed to increase the air groups of all large carriers to 73 fighters, but they would still retain 15 dive bombers and 15 torpedo planes. Mixed air groups continued through the end of the war, although Nimitz did concede that all new light carrier air groups should be made up exclusively of fighters and fighter-bombers (Hellcats, Corsairs, and ultimately the new high-performance Grumman F8F Bearcat).[50]

During the last two and a half months of the war, Halsey's Third Fleet and McCain's TF-38, in combination with British carriers and fast battleships, destroyed

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[49] Ibid., pp. 338–346; Samuel Eliot Morison, *History of United States Naval Operations in World War II*, vol. 14, *Victory in the Pacific, 1945* (1960; repr., Annapolis, MD: Naval Institute Press, 2012), p. 89; Reynolds, *Towers*, p. 507; Richard B. Frank, *Downfall: The End of the Imperial Japanese Empire* (New York: Random House, 1999), pp. 117–118; Operation Plan Cincpoa No. 4-45, 15 May 1945, folder Operation Plan 4-45, box 37, Military File, Halsey Papers, MDLC; message 200400, May 1945, Com3rdFlt to CTF51…info Cincpac, Graybook, 1 January 1945–1 July 1945, pp. 3130–3132; Commander THIRD Fleet, War Diary, 1 February to 31 May 1945, 16–18 May 1945.

[50] Message 250550, December 1944, CTF38 to Comairpac; message 030321, January 1945, Cincpac to Com3rdFlt, Com2ndCarrierTaskForce; both in Graybook, 1 January 1944–31 December 1944, pp. 2475, 2737; message 120245, June 1945, CTF38 via Com3rdFlt to Comairpac; message 232208, June 1945, Comairpac Admin; message 260352, June 1945, Cincpoa; all in Graybook, 1 January 1945–1 July 1945, pp. 2709, 2711, 3173; Reynolds, *Fast Carriers*, p. 357.

what little remained of the Japanese Navy, decimated Japan's air power, and delivered hard hits on the country's infrastructure. With carrier fighters and bombers blanketing Japanese airfields and suppressing the kamikaze threat, the task forces ranged up and down the coast, attacking aircraft and electronics factories, iron and steel works, aluminum processing plants, bridges, and rail lines. An outstanding example of the strategic capability of the multicarrier task force was the destruction of the railroad ferry network that transported coal from the northern island of Hokkaido to the main island of Honshu, crippling Japan's electricity-generating capacity and major industries dependent on electric power. The historian Richard B. Frank concluded that "this blow by carrier planes ranks as the most devastating single strategic-bombing success of all the campaigns against Japan." Only persistent adverse weather over Honshu and a vicious typhoon that lashed the Fifth Fleet in June limited what the carriers accomplished before Japan agreed to surrender terms in the aftermath of the atomic bombs that leveled Hiroshima and Nagasaki in August.[51]

Had the atomic bombs not brought about the end of the war, the fast carriers were prepared for the blockade of Japan and ready to cover the invasion of Kyushu and perhaps the Tokyo Plain (Operation Coronet) in March 1946. New technologies, including jet- and rocket-powered guided missiles for strike and fleet air defense, would have been deployed. Airborne early warning systems had been developed but were not operational before the end of the war, and electronic countermeasures, such as the "jamming" used against Japanese airborne radar, would have taken on more importance. The immediate reality was that nuclear weapons and long-range delivery systems, monopolized by the Army Air Forces, would present new challenges for the U.S. Navy in the immediate postwar years. Thomas Hone is right that victory in the Pacific was made possible by combined arms, with the fast carrier task force the major, but not the only, factor in the triumph.[52] In fact, American fleet submarines destroyed more Japanese naval and merchant shipping than carrier-based air power. Yet, even before the end of the war, the fast carriers had completed a fundamental transformation and had become the focal point of a fleet with unprecedented capability for projecting power from the sea. In another sense, the fast carriers represented a complex, synergistic technology, where multiple human and machine components functioned together in a three-dimensional, rapidly evolving, and highly lethal environment demanding unprecedented flexibility in the Pacific as well as the hot and cold wars that punctuated the rest of the 20th century.

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[51] Frank, *Downfall*, p. 157.

[52] Hone, "Replacing Battleships with Aircraft Carriers," p. 73.

CHAPTER 10

Resighting the Norden Bombsight

Precision Tool or Area Bomber?

Breanna Lohman

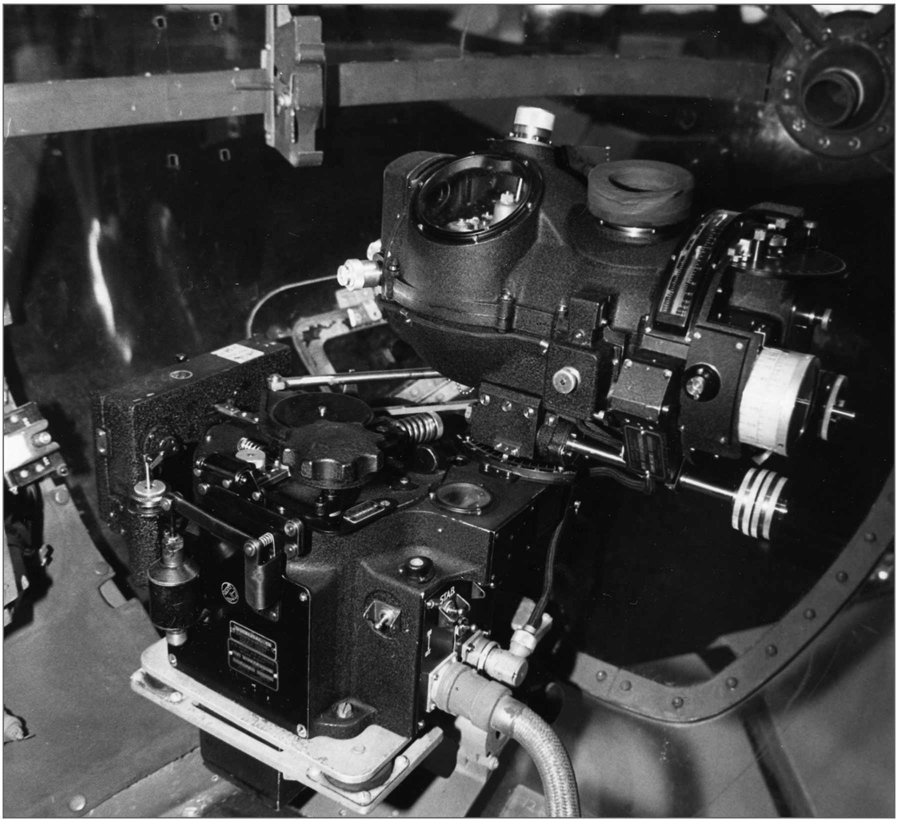

Figure 1: Originally designed for the U.S. Navy, the Norden bombsight was soon adopted for use by the U.S. Army Air Corps in 1934. Its perceived accuracy helped confirm the Air Corps doctrine of daylight strategic bombing. (Image credit: National Air and Space Museum, Smithsonian Institution, image NASM 82-1711-15)

I. A TALE OF TWO BOMBSIGHTS: THE NORDEN BOMBSIGHT IN THE AMERICAN IMAGINATION AND ABOVE EUROPEAN CITIES

It was a strange sight, a motley display of patriotism. Before an audience, 15,000 strong, clowns, dressed in the billowing costumes of the American harlequin, aimed a peculiar contraption at a pickle barrel. This was no ordinary event; the Ringling Brothers and Barnum & Bailey Circus, "The Greatest Show on Earth," had organized a special show to recognize the men and women who manufactured "the famed and highly secret Norden bombsight."[1] As the indefatigable Theodore Barth, President of Carl L. Norden, Inc., and self-described "tycoon," admitted, these workers were part of a grand project that employed "more than 20,000 workers in four modern plants," generating more than $250,000,000, according to the executive—and that was in 1943.[2]

What was this device, this strange sight?

First designed in the 1920s by the austere and cantankerous Dutch transplant Carl L. Norden, the bombsight that bears his name ostensibly transformed the complex stratagems of aerial war into "principles of geometry."[3] Capable of computing aircraft speed, altitude, and distance to the target, the site precisely determined when to drop a plane's payload of bombs over a target. Housed in the nose of heavy bombers, the Norden bombsight was the weapon of the bombardier. It consisted of two principal components: the sight head and the directional stabilizer. Together, it permitted the bombardier to strike his target with a degree of accuracy from a high altitude. This technological innovation was so seemingly significant that it compelled the Chief of the Air Corps to proclaim that the Norden bombsight was "the most important military secret project under development by the Air Corps."[4] The instrument was used in the first American aerial bombardment mission of the war

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[1] "How Bombsights Work Is Told for First Time," *Chicago Daily Tribune* (13 December 1944).

[2] Theodore Barth in a letter to John J. Ballentine, 19 March 1943, folder 6: "November 1941–September 1942," box 8, Papers of John J. Ballentine, Library of Congress, Washington, DC.

[3] Caren Kaplan, "Precision Targets: GPS and the Militarization of U.S. Consumer Identity," *American Quarterly Special Edition Rewiring the "Nation": The Place of Technology in American Studies* 58, no. 3 (September 2006): 700.

[4] Virginia G. Toole, "The Norden M-Series Bombsight and the C-1 Automatic Pilot," in "Development of Bombing Equipment in the Army Air Forces" (unpublished report), p. 79, call number (box) 201-11 (vol. 2) to 201-15 (vol. 3), Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, AL.

on 17 August 1942, as well as the final two atomic raids on Japan in August 1945. By the end of the war, the U.S. government had spent the equivalent of $1.5 billion on the bombsight's development, 65 percent of the total invested in the secretive Manhattan Project.[5] By the war's end, over 50,000 sights had been manufactured.

Heralded as a marvel of modern warfare—"both a magician and mathematician"—the instrument promised to do the impossible: high-altitude precision bombing during daylight hours.[6] The Norden bombsight (hereafter referred to as the NBS), as tests from Maxwell Air Force Base had seemingly proved, could indeed "pluck a pickle barrel from 20,000"—or, more presciently, the interlocking tracks of a marshaling yard or the heavy machinery of a ball-bearing factory.[7] The oft-cited pickle-barrel quip was apocryphally attributed to Norden himself.[8] With the signature exaggerated gestures, the Barnum & Bailey troupe pantomimed the bombardier's job: sighting the target, inputting the calculations, and releasing the projectile. The prop bomb landed in the pickle barrel, striking "not only the barrel but a special pickle that had been announced as the target."[9] The show's climax was, indeed, appropriate. Norden's answered refrain to the question of whether the bombsight's celebrated accuracy was true was, "Which pickle would you like to hit?"[10]

What, precisely, was the war record of the NBS? Was it the marksman that its proponents, Theodore Barth (the CEO and marketing extraordinaire) and Carl Norden (the designer), claimed it to be? Was "the bomb's destination…a mathematical certainty"?[11] Could it "pluck a pickle barrel from 20,000"? The technological capabilities of the bombsight could not match the rhetoric of its publicity. As is well documented, the NBS seldom managed to hit "the broad side of a barn."[12] On 8 November 1942, more than 20 bombs struck near a factory about 3 miles

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5. See Donald L. Miller, *Eighth Air Force: The American Bomber Crews in Britain* (London: Aurum Press, Ltd., 2007), *https://www.google.com/books/edition/Eighth_Air_Force/zOpmAAAAMAAJ?hl=en&gbpv=0* (accessed 26 January 2023).
6. Volta Torrey, "How the Norden Bombsight Does Its Job," *Popular Science Monthly* (June 1945): 70.
7. "Norden Laboratories Classified Ad 9," *Newsday* (14 November 1979).
8. Carl L. Norden, quoted by Don Sherman in "The Secret Weapon," *Air & Space* 9, no. 6 (February/March 1995): 80.
9. "Circus Honors Norden Plant: Company Gets Its Third E Award at Garden," *New York Times* (14 April 1943): 19.
10. Graham Simons, *Consolidated B-24 Liberator: The Consolidated B-24* (Barnsley, U.K.: Pen and Sword Aviation, 2012), *https://www.google.com/books/edition/Consolidated_B_24_Liberator/EXbfj27Bi3MC?hl=en&gbpv=0* (accessed 18 August 2022).
11. Torrey, "How the Norden Bombsight Does Its Job," p. 70.
12. Stephen L. McFarland, *America's Pursuit of Precision Bombing, 1910–1945* (Washington, DC: Smithsonian Institution Press, 1995), p. 168.

short of the intended target, the German U-boat pens at St. Nazaire. Eleven days later, St. Nazaire was bombed "under the impression" that it was a different place altogether; the actual target was 300 miles away.[13] Major General Hayward S. Hansell, who flew on one of the first bombing raids, lamented that "the bombing was regrettably bad."[14] By the end of 1942, the Eighth Air Force had flown 30 missions over Europe, suffering a staggering loss of 8.9 percent of all dispatched aircraft.[15] Results did not justify the toll. Attrition over the skies of Regensburg and Schweinfurt on 17 August 1943 shattered the prewar American doctrine of precision bombing without fighter escort.

The NBS could not deliver on its promise and its marketing. In the years after the war, it earned itself the derision of many. To Kurt Vonnegut, author of the anti-war novel *Slaughter House 5*, the lauded precision of the NBS was snake oil, will-o-the-wisp, "hokum."[16] In *Catch-22*, a classic satire of the Second World War, Joseph Heller mocks the oft-cited refrain of the bombsight, its accepted "pickle barrel" accuracy:

> Yossarian took his flight of planes in over the target a second time. The group had missed the bridge at Ferrara again for the seventh straight day with the bombsight that could put bombs into a pickle barrel at forty thousand feet, and one whole week had already passed since Colonel Cathcart had volunteered to have his men destroy the bridge in twenty-four hours.[17]

II. DISMANTLING THE BLACK BOX OF THE NORDEN BOMBSIGHT

The NBS was revered during the war as a masterpiece of American ingenuity. Howard Nemerov's poem is representative of how the NBS is remembered today: "The ancient bombsight here enshrined in glass is the relic left us of a robot saint

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[13] "Preliminary Report on Bombing Accuracy," 4 January 1943, p. 5, folder 6: "Bombing," box 78, Papers of Carl A. Spaatz, Library of Congress Washington, DC.

[14] "U.S. Air Force Oral Interview of Major General Haywood S. Hansell, Jr.," p. 6, call number (box): K293.0512-0624 to K293.0512-0642, Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, AL.

[15] Robin Neillands, *The Bomber War: The Allied Air Offensive Against Nazi Germany* (New York: Barnes & Noble Press, 2001), p. 200.

[16] George Plimpton, David Hayman, David Michaelis, and Richard Rhodes, "The Art of Fiction No. 64, Kurt Vonnegut," *Paris Review*, *http://www.theparisreview.org/interviews/3605/the-art-of-fiction-no-64-kurt-vonnegut* (accessed 15 November 2016).

[17] Joseph Heller, *Catch-22* (New York: Simon & Schuster, 1955), p. 60.

with a passion for accuracy, who long ago saw towns as targets miniature and quaint, townsfolk invisible that far below."[18] During the war, the instrument toured the country with experts who expounded on its unsurpassed accuracy. It was celebrated in the 1943 film *Bombardier* with enthusiasm and touted in a work the United States government commissioned John Steinbeck to write. "The nation is at war," Steinbeck intoned. "It is a war of finding the target in the crosshairs of the bombsight and setting the release, and it isn't a war of speeches and frothy hatred."[19] It was the subject of hundreds of articles, featured in many specialist magazines, and even dramatized in serials. One comic from 1943, titled "The Negroes' Pride," depicted an African-American soldier captured behind Japanese lines after crash-landing on a Pacific island. His captor presses him to reveal the "hiding place" of the NBS. "[Y]ou will be striking a blow [for] oppressed blacks all over the world," his captor urges. Instead of betraying (what the public believed was) the most closely guarded secret of his country, the protagonist resists, "taking the hard way out—an overdose of morphine," but not before killing his captor with a concealed, deux ex machina blade. His suicide note reads, "No colored woman has ever given birth to a traitor." This was the highest act of patriotism: to sacrifice one's life to protect state secrecy.

The Norden Company, its sole contractor, and the United States government skillfully cultivated this image of guarded ingenuity. Barth, the tireless CEO and promoter of the NBS, aggressively marketed it as a technological marvel to the public. He boasted of its exquisite craftsmanship: "its parts are held to such close tolerances as to make the finest watch a crude gadget by comparison."[20] Only American craftsmen could achieve "such close tolerances." German bombsights were "hastily made" and too "cumbersome."[21] Their Japanese counterparts were "primitive, hodgepodge."[22] The United States government, too, popularized the bombsight. The instrument was famously kept under lock and key, stored in vaults patrolled by armed guards around the clock. Every bombardier swore an oath, beckoning to the imagined romanticism of long-ago chivalric wars, to "keep inviolate the secrecy" of

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[18] Howard Nemerov, "The Air Force Museum at Dayton," *The Selected Poems of Howard Nemerov* (Athens, OH: Swallow Press, 2003), p. 131.

[19] John Steinbeck, *The Moon Is Down* (New York: Viking Press, 1942), p. 66.

[20] Theodore Barth, quoted in "Sees Precision Bombing from Unheard of Height," no publication title given, 20 July, year not listed, box 159: "American Institute of Aeronautics & Astronautics Newspaper Clippings Norden, Carl L. Co.," Library of Congress, Washington, DC.

[21] Theodore Barth, quoted in "Nelson Lauds U.S. Workers as Norden Gets 'E,'" *New York Herald Tribune* (11 April 1942).

[22] Theodore Barth, quoted in "Japan Sought Norden Sight Plans in 1932," *New York Herald Tribune* (23 June 1945).

the instrument, "if need be, with my life itself."[23] Carl Norden, the famed inventor, was awarded numerous commendations, including the coveted "E" medal three times. The sight's operation was public knowledge and its designs pilfered by spies. A German spy, Herman W. Lang, worked in the facility contracted to assemble the bombsights and conveyed the designs back to Germany. The Germans inspected and studied the Norden and found it lacking and inferior to their own Lotfernrohr 7. According to the postwar House on Un-American Activities Committee, the Soviets also had access to the NBS as early as 1938. The Japanese, French, and British all made public requests to procure the sight before 1942. If the bombsight was a secret, it was the worst-kept one of the Second World War.

That is not to say that the NBS contained no secrets. While the public knew of its existence, they did not know how it worked or, for that matter, whether it worked at all. Comprehensible only to the modern priesthood of industry, science, and the military, the NBS was a black box for the American public. As historian of technology Donald MacKenzie writes, a black box is a "technical artifact" that "performed its functions, without any need for, or perhaps any possibility of, awareness of its internal workings."[24] The public admired but did not understand this "machine with a startling mental grasp" and the "split second's computation" it performed.[25] As one publication observed, "Opened up, it becomes—to the layman—a bewildering confusion of gears, mirrors, cams, lenses, wires, prisms, bearings and a myriad of tiny parts." This "electromechanical analog computer" was bafflingly complex, its concepts comprehended only in the abstract.[26]

Press releases, government assurances, and popular propaganda mediated the public knowledge of the bombsight; its operation remained unknown; its results remained beyond the pale of a public inquiry. The Norden Company and the United States government's proclamations of precision inured the public to the dangerous fallacy that a black box could, independent of human intervention, win a war without savagery and save lives without the dread of moral misgiving. Of course, the NBS was not a black box, only socially constructed as such. It was operated in conjunction with bombardier and bomber, aircrew, and air squadron, each performing as a single unit, relying upon the collective training and expertise of those involved.

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[23] C. G. Sweeting, "Not-So-Secret Weapon," *Aviation History* (March 2004): 34.

[24] Donald MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (Boston: MIT Press, 1993), p. 26.

[25] "How Bombsights Work Is Told for First Time: 20 Engineers Tell Its Secrets," *Chicago Daily Tribune* (13 December 1944).

[26] Frederik Nebeker, *Dawn of the Electronic Age: Electrical Technologies in the Shaping of the Modern World, 1914 to 1945* (Piscataway, NJ: IEEE Press, 2009), p. 446.

III. THE PROMISE OF PRECISION: THE INTERWAR YEARS

On 2 December 1941, the Bureau of Aeronautics' acting chief enthusiastically wrote to the Secretary of the Navy, "The Norden bombsight is considered to be the principal single factor of superiority which the air forces of this country possess over those of potential enemy countries."[27] That the instrument became as crucial to the framers of both policy and procurement as it did is, in retrospect, a remarkable feat. Mutual animosity between the Norden executives and the Air Corps festered. Barth loathed the "hysteria [that] prevails in Government procurement circles."[28] After a visit to one of the company's factories, one Air Corps official said, "If I never enter the Norden factory again and deal with their executive personnel again, it will be too soon."[29] Exacerbating relationships between industry and government further, the Air Corps, the principal purchaser of the bombsight, was forced to submit requisitions through the Navy, an arrangement that was, by all accounts, a humiliating affair. Worse still, production shortages were endemic. In January 1936, the Air Corps purchased 206 bombsights but received only 100. Only by June 1944 was bombsight production in excess of requirements. Many of these bombsights were shoddily made. Quality-control spot checks often noted defects.[30] On one occasion, 600 instruments were recalled.[31] Overwhelmed by the demands of mass production, manufacturers produced inferior sights.

The doctrinal centrality and wartime celebrity of the NBS was not a fait accompli. It was contingent on all historical events, subject to accidents of happenstance and the participants' intentional decisions. Many scholars have suggested that the bombsight was an inevitability of engineering due to the advent of the air doctrine. One historian wrote, "[T]he evolution of the specifically American concept of high-level precision bombing…led to the perfecting of elaborate computing

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[27] Extracted from "The Secret Weapon," by Don Sherman, *Air & Space* 9, no. 6 (February/March 1995): 80; and "The Norden Bombsight: Accurate Beyond Belief?" by Roaul Drapeau, *Warfare History Network*, 21 July 2016, from ***http://warfarehistorynetwork.com/daily/wwii/the-norden-bombsight-accurate-beyond-belief/*** (accessed 15 November 2016).

[28] Theodore Barth in a letter to Lieutenant Commander J. J. Ballentine, 1 May 1951, p. 1, folder 4: "January–August 1941," box 8, Papers of John J. Ballentine, Library of Congress, Washington, DC.

[29] Toole, "The Norden M-Series Bombsight and the C-1 Automatic Pilot," p. 92.

[30] Ibid.

[31] Ibid., p. 95.

bombsights."[32] Indeed, the instrument became a buttress of the B-17 bomber architecture that girded American doctrine. Moreover, it found its doctrinal niche within industrial web theory, which posited that industrial societies' inherent fragility rendered them particularly vulnerable in an air war.

Its interwar rise depended upon the alignment of war discourses, budgetary concerns, and cultural affinities within the Air Corps. As David Nye observed, "A technology is not merely a system of machines with certain functions; it is part of a social world."[33] The NBS was designed in a social world that venerated technological innovation and economies of scale. The bombsight was ostensibly cost-effective. One well-aimed bomb against a military target seemingly amounted to more than a hundred craters ringing the site. Likewise, the rationale of budgetary constraint was an essential consideration for a tax-averse society during the threadbare years of the Great Depression.

The social world of the Air Corps and the United States valued precision for reasons that were less material. Thomas Greer contended that "the traditional American respect for marksmanship, going back to frontier days," had predisposed strategists within the Air Corps to the NBS.[34] Whereas the bomb was indiscriminate, the bombsight was its antithesis, containing the circumference of destruction. For a brief period between 1933 and 1943, it seemed possible to resolve the oxymoron of "humane war," of the cratering blast with a sharpshooting eye in the sky. Because it was ostensibly precise, the NBS also was ostensibly humane, an anti-Guernica. For a country that viewed itself as a beacon of liberal ideals, this was vital. The presumed precision of the bombsight eased the Air Corps's concerns of "general public opposition to mass civilian bombings."[35] In the 1930s, the results seemed promising. At the Naval Proving Ground in Dahlgren, Virginia, the bombsight achieved decent accuracy. "Of the 42 bombs" dropped within an enclosure, "20 fell within a 100 ft. band of range variation"—results that were replicated and improved in later tests.[36] In the coming years, various accoutrements were added to

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[32] Eugene Hollon, *The Preflight Schools in World War II*, 1953, p. 11, call number (box): 101-88 (1941–1951 [CY1]) to 101-88 (1941–1953 [CY1]), Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, AL.

[33] David Nye, *Electrifying America: Social Meanings of a New Technology, 1880–1940* (Boston: MIT Press, 1990), p. ix.

[34] Thomas H. Greer, *The Development of Air Doctrine in the Army Air Arm, 1917–1941*, 1 September 1955, p. 57, call number (box): 101-88 (1941–1951 [CY1]) to 101-88 (1941–1953 [CY1]), Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, AL.

[35] Ibid.

[36] "Naval Proving Ground," Dahlgren, Virginia, 11 June 1931, p. 5, folder 3: "Naval Aviation Bombsight testing 1930–32," box 18, Papers of John J. Ballentine, Library of Congress, Washington, DC.

the NBS. As Theodore Barth wrote to Lieutenant Commander J. J. Ballentine, "the Bombsight design is approaching the stage of so-called 'perfection.'"[37]

Whatever precision meant to the Air Corps in 1933, it meant something different to the Bomber Command in 1943. What, then, did precision look like during the war? Was it a bomb plot with X's inked over an aerial photograph of a derelict marshaling yard? Or was it a plunging graph line, charting the declining output of a ball bearing factory? Was it a numerical figure, such as a circular error of less than 1,000 feet, or a 90 percentile of successful strikes? Or, perhaps, was precision merely a line in the sand demarcating the acceptable threshold of the cumulative costs of a raid—justifying the loss of personnel and aircraft, as well as the investment in training, materiel, equipment, fuel, munitions, and ordnance?

IV. THE PROBLEM WITH PRECISION: THE WAR YEARS

Precision was the most elusive capability throughout the Second World War. Speed, payload, ceiling, and range all increased at a breakneck pace. Precision, however, defied mastery. In 1931, the NBS was the most accurate means for delivering a bomb to a target from high altitude. In 1945, the "football," as bombardiers called it (both affectionately and disparagingly), was still the most accurate means for high-altitude bombing, outperforming all innovations in radar technology.

Nevertheless, visual bombing accounted for only 345,697 tons, or 50.8 percent, of the American bombing campaign over Germany.[38] Just under half of the air raids over Germany were conducted "blind," using methods that could not approach even the imperfect accuracy of the NBS. In total, the Eighth Air Force reached an "accuracy ceiling" of 31.8 percent of bombs landing within a 1,000-foot radius of the aiming point for the period between January 1943 and April 1945, while the Fifteenth Air Force achieved a comparable 30.78 percent.[39] For this reason, W. Hays Park argues that the term "precision" is "inappropriate to describe USAAF [U.S. Army Air Forces, the successor organization to the U.S. Army Air

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[37] Theodore Barth in a letter to Lieutenant Commander J. J. Ballentine, 7 January 1939, folder 1: "January 1939–March 1940," box 8, Papers of John J. Ballentine, Library of Congress, Washington, DC.

[38] "Air Force Rate of Operations," in *The United States Strategic Bombing Survey: Volume III*, comp. David MacIsaac (New York: Garland Publishing, Inc., 1976), p. 38.

[39] "Bombing Accuracy of the USAAF Heavy & Medium Bombers," in *The United States Strategic Bombing Survey: Volume III*, comp. David MacIsaac (New York: Garland Publishing, Inc., 1976), p. 5.

Corps] heavy bomber practice."[40] Why, then, was the bombing campaign in the European theater so imprecise? Here, it is necessary to explain the terms used in ascertaining and measuring bombing accuracy. The initial point refers to the geographic or urban landmark that signals to the crew that the target is approaching. The aiming point refers to the coordinates of the target that the bombardier "aims" to strike. The circular error refers to the distance from the intended aiming point to the center of the bomb fall pattern.

As the report on bombing accuracy in the *United States Strategic Bombing Survey* stressed, weather was "the most important factor affecting the success of a mission."[41] The most fundamental and persistent flaw of the NBS was that it was optically sighted. The instrument relied on visual contact between the bombardier and the ground target. A bombardier could adjust for drift, account for range, measure the ballistics of the bomb based on its dimensions, and plot the distance to the aiming point through the arcane numerology of bombing tables. However, no calculation could compensate for the weather.

The costs to the bombing campaign were striking because the vagaries of European weather reduced potential effort by 45 percent.[42] Ten percent of all missions were aborted or recalled because of elemental unpredictability.[43] Rates of operation crested and troughed with the seasons: April through June averaged 13 days of visual and visual-assist bombing per month, whereas October through December averaged only 3.[44] In August 1944, visual bombardment accounted for 94 percent of all bomb tonnage unloaded on Germany; months later, it accounted for just 10 percent.[45] The advent of radar increased the rate of operations; however, it did not improve bombing results by any measure. Under poor visibility and aided by radar, only 9.4 percent of the bombs landed within 1,000 feet of the target.[46] In the last months of 1944, a shocking 42 percent of bombs fell *more than a mile* from the intended aiming points.[47]

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[40] W. Hays Park, "'Precision' and 'Area' Bombing: Who Did Which, and When?" *Journal of Strategic Studies* 18, no. 1 (1995): 146.

[41] "Bombing Accuracy of the USAAF Heavy & Medium Bombers," p. 5.

[42] "Weather Factors in Combat Bombardment Operations in the European Theater," in *The United States Strategic Bombing Survey: Volume III*, comp. David MacIsaac (New York: Garland Publishing, Inc., 1976), p. 2.

[43] Ibid.

[44] Ibid., p. 29.

[45] Ibid.

[46] McFarland, *America's Pursuit of Precision Bombing, 1910–1945*, p. 183.

[47] See "Exhibit R: Percent of Bombs Within Certain Distances of the Aiming Point," in "Weather Factors in Combat Bombardment Operations in the European Theater."

The weather was not the only hindrance to the air war; there were other obstructions. Smoke and haze—whether as a defensive screen erected by the Axis or the pluming dust from an Allied aerial offensive—diminished bombing accuracy markedly. As one postwar analysis states, smoke and haze were reported in 41.8 percent of the 98 missions reviewed, exacerbating the radial error of bombs by 281.9 feet.[48] On 17 August 1943, during the raid on Schweinfurt, clouds of dust billowed from the rubble below, cloaking the targets in a haze only the bombardier's intuition could penetrate.

The NBS required two things to operate effectively, both lacking in battle: visibility and stability. Before the shout of "Bombs away!" the bombsight's autopilot took control of the aircraft, locking it into a straight-line flight path—a necessary constant to permit the computation of the many variables factoring into the bombing raid. For what were undoubtedly harrowing moments for the crew, the instrument's computer unemotionally calculated the bomb's parabola. During this time, the heavy bomber was vulnerable to anti-aircraft fire. It was an accepted rule of thumb that flak doubled for every 5,000-foot decrease in altitude—though wrong in specifics, the principle held.[49] To avoid the flak, the formations flew higher. As a "predictor of bombing accuracy," altitude was second only to weather.[50] According to one calculation, the radial error of the bomb increased 6.1 feet per 100 feet of altitude.[51] At heights of over 20,000 feet, accuracy was strikingly low. Worse still, at elevations of 26,000 to 29,000 feet, only 4.9 percent of bombs fell within that 1,000-foot mark, and 51 percent of missions at that altitude resulted in mission failures.[52] Compounding the imprecision of high-altitude bombing, formation flight reduced accuracy. The larger the formation, the larger the error: for bombers in a formation of three combat boxes, the circular error nearly tripled, from 570 to 1,605 feet.[53]

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[48] Thomas I. Edwards and Murray A. Geisler, "The Causes of Bombing Error as Determined by Analysis of Eighth Air Force Combat Operations," 15 July 1947, p. 36, call number (box): 143.504-3(15 Jul 1947) to 143.506-2 (13 Dec 1946), Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, AL.

[49] "Flak Defensive Tactic No. 3," undated, no page number given, call number (box): 248.222-15 (n.d.) to 248.222-29 (1931), Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, AL.

[50] Edwards and Geisler, "The Causes of Bombing Error," p. 32.

[51] Ibid.

[52] "Effect of Altitude on Bombing Accuracy," in *The United States Strategic Bombing Survey: Volume III*, comp. David MacIsaac (New York: Garland Publishing, Inc., 1976), pp. 3–4.

[53] See "Exhibit C: Expected Circular Error with Respect to Altitude and Number of Attacking Boxes," in "Bombing Accuracy of the USAAF Heavy & Medium Bombers."

The chaos of aerial combat exacerbated bombing results. During raids, flak seemed to fill the sky, rattling the aluminum fuselage of bombers like "heavy hail on a tin roof."[54] Soot collected on the nose of the plane, obscuring the bombardier's field of vision. Extreme cold threatened to "impair the functioning of the release mechanism" and even the bombardier operating the bombsight.[55] One newspaper article observed that the NBS "wears an electrically heated protective cover."[56] No such luxury was afforded to the aircrew. "Manipulations which would be easy to make on the ground," writes Colonel C. G. Williamson, "are, of course, much more difficult at high-altitudes where fingers become numb with cold and where bodily motion is interfered with by the heavy clothing worn and by the oxygen apparatus."[57] Evasive maneuvers might disrupt the straight-line approach and impact mission success. Thomas Pynchon's *Gravity's Rainbow* poignantly portrays the stress of combat flight, as the crew "jettisoned all their bombs in no particular pattern, the fussy Norden device, sweat drops in the air all around its rolling eyepiece, bewildered at their need to climb, to give up a strike at earth for a strike at heaven."[58]

The Norden was indeed "fussy." The exacting and complicated design of the NBS earned the ire of bombardiers. A manual described the bombsight as "very delicate," warning that "rough handling" would damage the instrument.[59] Fragile and finicky, the NBS was an affront to field maintenance. The slightest "scratch from a file on a rotor" would "send it to the junk pile."[60] The bombsights themselves were manufactured with diminishing quality, further complicating the duties of the B-17 crews. For example, "[t]he whirling little armatures had to be within two-and-a-half ten-thousandths of an inch" to function properly."[61] Hurried production

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[54] Colonel C. G. Williamson, "The Air Force in a Task Force," March 1943, p. 35, folder: "The Air Force in a Task Force by Col. C.G. Williamson," box 76, Papers of Carl A. Spaatz, Library of Congress, Washington, DC.

[55] "Preliminary Report on Bombing Accuracy," p. 3.

[56] "Notes on Science, Bombsight Suit," *New York Times* (11 February 1945).

[57] Williamson, "The Air Force in a Task Force," p. 35.

[58] Thomas Pynchon, *Gravity's Rainbow* (New York: Viking Press, 1973), p. 151.

[59] "The Norden Bombsight: Maintenance, Calibration," B.S.M. Division, Department of Armament, Lowry Field, CO, 1 September 1943, p. 141, call number (box): 248.231-112 (1 May 1944) to 248.232-12 (Sept. 1944 to Sept. 1945), Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, AL.

[60] David O. Woodbury, *Battlefronts of Industry: Westinghouse in World War II* (New York: J. Wiley, 1948), p. 82.

[61] Ibid.

schedules struggled to replicate such tolerances. The serially produced bombsight was 5.6 times more inaccurate than its original specifications.[62]

The task of the bombardier, especially the lead bombardier, was daunting. Not only did he operate “the most intricate of the devices carried by a combat aircraft,” he was required to perform his tasks quickly, as high-altitude bombing operated under unforgiving logic, requiring an unerring exactitude of measurements.[63] During those critical minutes approaching the aiming point, the weight of the mission fell on the bombardier’s shoulders alone. As the manual on the NBS emphasized, “faulty work on his part may result in nullifying the entire mission and even in the loss of the bomber and her crew.”[64] So much could and did go wrong. A bombardier might run the disc at a low instead of a high-altitude setting, or he might forget to level the gyroscope, or he might set the intervalometer too late, or he might press the release catch too early. Did he remember to align the “dovetail parallel to the fore and aft axis of stabilizer”? Did he remember to “turn the precession level back 90° so that it reads in the transverse plane”?[65]

As the weather worsened and sorties increased, crews became more experienced and better equipped to handle the difficulties inherent in the high-altitude bombing. In the words of one Air Corps lecturer, “improvements in technique and training make the ragged experiment of yesterday, the precise operation of tomorrow.”[66] By 1945, diligence, experience, refined tactics, and innovative techniques eventually brought accuracy up to 44 percent of all bombs falling within 1,000 feet of the target.[67] The overpowering role of Allied air dominance must be acknowledged in achieving this marked improvement. Nevertheless, that increase in accuracy is directly attributable to the capability of the aircrews—not to the technical ability of the bombsight.

Accuracy was only one component in the complicated calculus of the bombing campaign. A tightly patterned bomb fall did not always result in mission success, or reduced rates of transportation, or diminished outputs of production. Much

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[62] James K. Libbey, *Alexander P. de Seversky and the Quest for Air Power* (Washington, DC: Potomac Books, 2013), p. 231.

[63] Thomas H. Greer, “Training of Ground Technicians and Service Personnel,” in *The Army Air Forces in World War II: Men and Planes*, vol. 6, ed. Wesley Frank Craven and James Lea Crate (Chicago: University of Chicago Press, 1948), p. 642.

[64] “The Norden Bombsight: Maintenance, Calibration,” p. 179.

[65] Ibid., p. 202.

[66] “Course: Bombardment Aviation,” The Air Corps Tactical School, 21 May 1940, p. 26, call number (box): 248.2209A (1939–1940) to 248.2209A-7A (1941), Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, AL.

[67] Conrad C. Crane, *Bombs, Cities, and Civilians: American Airpower Strategy in World War II* (Lawrence, KS: University Press of Kansas, 1993), p. 64.

depended on the target itself. Some sites were more strongly fortified than others, just as some were more sprawling than others. Whereas synthetic oil plants had the largest circular error averages, bridges and coastal defenses had the smallest. An oil refinery in Naples, Italy, highlighted the difficulty of striking large targets from 18,000 feet. The refinery grounds measured 280,000 square yards, only 5 percent of which, or 14,000 square yards, constituted vital areas essential to the production of petroleum products.[68] Another 21.4 percent was classified as "useful," comprising storage tanks, compounding buildings, and laboratories. A gaping 73.6 percent of the refinery, 210,000 square yards, was designated as "non-essential."[69] For another example, approximately 146,000 bombs were dropped on Germany's three largest oil-chemical plants, Leuna, Ludwigshafen-Opau, and Zeitz.[70] Only one bomb in 29 hit targets essential to the production, and 87 percent landed in the surrounding area.[71] The brute force of numbers, not targeted incisions of the NBS, ultimately decimated German oil production. When the overall bombing figures declined in August and September of 1944, German oil production "took on a new lease on life," rebounding in October. This was a striking development considering the advanced stage of the war. Only a colossal expenditure in November reversed the rising output of oil production. During that month, 2,883 tons of bombs were dropped on oil targets, registering an accuracy of only 15.4 percent. Nevertheless, it was enough.

In the fire of battle, it is impossible to isolate factors that exacerbated bombing accuracy. The most sensible argument—and the most probable—is that all contributed to this inescapable fact of the air war: bombing was seldom accurate. When visual contact was impeded, or flak prevented course stabilization, or the instrument malfunctioned, it was not merely that the NBS was compromised. The concept of precision bombing itself was compromised.

Considering the myriad factors that stymied the NBS, under what conditions, then, could the bombsight operate effectively? Moreover, under what conditions were its limitations exposed?

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[68] "A Report on the Bombing of the Oil Refinery at Naples, Italy," Operations Analysis Section of the Fifteenth Air Force, 26 December 1943, p. 3, call number (box): 670.310-1 (26 Dec 1943 to 31 Jul 1945) to 670.317-3 (Aug 1944 to Apr 1945), Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, AL.

[69] "A Report on the Bombing of the Oil Refinery at Naples, Italy," p. 3.

[70] "Weapons Effective and Bombing Techniques," p. 2, call number (box): 248.222-15 (n.d.) to 248.222-29 (1931), Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, AL.

[71] Ibid.

V. NO. 1 AND NO. 84: CASE STUDIES IN OPTIMAL AND ACTUAL CONDITIONS

On 17 August 1942, 12 B-17Es lifted off from a runway in the bucolic English Midlands to the Rouen-Sotteville marshaling yard in northern France. The target was a German rail center unscathed by the Royal Air Force (RAF) bombing campaign; this was "Mission No. 1" for the United States Army Air Forces. Sotteville was a raid on a transportation hub outlined in the American War Plans Division's "AWPD/1"—the document set out the strategy and force needed to win the air war. It was a modest beginning. With only 12 bombers, the squadron represented "less than two-thousandths of the force called for in AWPD/1."[72] Thus, instead of an offensive, it was a probe into "the fringes of European airspace."[73] The payload of the squadron carried more than 36,900 pounds of bombs.[74] They "carried with them," in the words of historian Arthur B. Ferguson, "a long heritage of debate and controversy."[75] This first combat mission attempted to prove the untested doctrine of precision bombing fabricated on the 103-foot 9-inch wings of the B-17 and the bombsight installed behind the Flying Fortress's plexiglass nose.[76]

In the early morning hours, the squadron departed Northhamptonshire amid the flash of cameras and the scratch of pens on paper. The press "sensed a good story in the making."[77] Less than six months before, Carl L. Norden had been awarded the Navy's coveted "E" medal in New York's Waldorf Astoria for excellence in production—an award he would be given again on 3 September 1942. Finally, the pinnacles of American prewar ingenuity, the B-17 and the computerized bombsight it housed—both publicized widely in the press—were set to see action.

Under an escort of RAF Spitfires, the bombardiers sighted their targets from altitudes of 22,000 to 26,000 feet and released their high-explosive payload. A bomb, subject to atmospheric conditions, reaches terminal velocity in approximately

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[72] McFarland, *America's Pursuit of Precision Bombing*, p. 167.

[73] Tami Davis-Biddle, *Rhetoric and Reality in Air Warfare: The Evolution of British and American Ideas About Strategic Bombing, 1914–1945* (Princeton, NJ: Princeton University Press, 2002), p. 211.

[74] Stephen Bourque, "ROUEN: La Semaine Rouge," *Journal of Military and Strategic Studies* 14, nos. 3 and 4 (2012): 13.

[75] Arthur B. Ferguson, "Rouen-Sotteville No. I, 17 August 1942," in *The Army Air Forces in World War II: Plans & Early Operations, January 1939 to August 1942*, vol. 1, ed. Wesley Frank Craven and James Lea Crate (Chicago: University of Chicago Press, 1948), p. 665.

[76] Herbert S. Brownstein, *The Swoose: Odyssey of a B-17* (Washington, DC: Smithsonian Institution Press, 1993), p. 8.

[77] Ferguson, "Rouen-Sotteville No. I, 17 August 1942," p. 661.

15 seconds and strikes the earth in approximately 40 seconds. Between the shout of "Bombs away!" and the jolt a world below, the American doctrine of precision bombing underwent an irrevocable change, from untested theory to reality, subject to critique, equivocation, and, of course, failure. A collision of precision rhetoric, indiscriminating ballistics of the bomb, the mathematical exactitude of a computerized calculate, and the cratering blast of ordnance took place.

That day, the skies were clear, the flak was minimal, and the air defenses limited. Conditions were optimal for the operation of a bombsight that required a straight and steady course. The crews achieved surprisingly good results. But was it that surprising? The crews were green, but they were not untrained. While the conditions of 17 August 1942 bore little fidelity to the attrition of the coming air war, they were faithful to the training ground tests conducted in the desert sky of West Texas.

Nearly half of the bombs fell on the general target area. In a survey of the devastation, bombs had damaged "ten of twenty-four lines of track, destroyed some rolling stock, and scored direct hits on two large transshipment sheds in the center of the yard."[78] The Reich, of course, sustained no serious injury from this limited incursion. The raid was less a blow to the German war effort than a boost for American morale, vindicating, at least ostensibly, the doctrine of precision bombing.[79] Carl A. Spaatz wrote to General George E. Stratemeyer, "[W]e have certainly proved that the boys can do high-altitude bombing in the day time and really hit what they go for."[80] Ira C. Eaker, who had flown on the mission, agreed in more uncertain terms, "[W]e can do high-level accurate bombing when the weather permits."[81]

Was "nearly half" precision bombing? To the French civilians on the ground, no precision could be discerned from the wreckage. Fifty-two men, women, and children died that day. While the American public held fast to the notion that bombing could be precise, the French held reservations wrought from experience. Thus, the first aerial mission exposed the rift between the public pronouncements of the bombsight's precision and more grounded military assessments. While the raid on

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[78] Ibid.

[79] Richard Overy, *The Bombers and the Bombed: Allied Air War Over Europe 1940–1945* (New York: Penguin, 2013), p. 101.

[80] Carl A. Spaatz in a letter to General George E. Stratemeyer, 21 August 1942, folder: "[Personal] August 16–31, 1942," box 8, Carl A. Spaatz Papers, Library of Congress, Washington, DC.

[81] Ira C. Eaker in a letter to Lt. Gen. H. H. Arnold, 26 August 1942, folder 3: "General Correspondence August 1942," box 7, Ira C. Eaker Papers, Library of Congress, Washington, DC.

Rouen-Sotteville symbolized the promise of a swift victory, it had been conducted under optimal conditions—conditions that would not last.

On the first anniversary of this inaugural American raid, the air staff executed an audacious plan to hit deep into German territory. Of the missions conducted so far, this one was "the most complex, the most ambitious, and the most superlative-afflicted of all the previous eighty-three."[82] The Eighth Air Force dispatched more planes on 17 August 1943 than they had since the air war began. Unlike Mission No. 1, the USAAF flew undefended, beyond the range of RAF Spitfires and their USAAF P-47 Thunderbolts, deep into the heart of Germany. The mission was intended to be the definitive test of daylight precision bombing formalized into Allied policy at the Casablanca Conference in January 1943. In the "Case for Day Bombing," the speech that won the American doctrine the support of the United Kingdom, General Ira C. Eaker forcefully argued in favor of bombing by day. "Day bombing," he stated, "is the bold, the aggressive, the offensive thing to do." Eaker continued, "[A] successful day combined offensive to combine and conspire with the admirable night bombing of the RAF to wreck German industry, transportation and morale—soften the Hun for land invasion and the kill."[83]

The USAAF targeted Schweinfurt, sighting the Bavarian city in the crosshairs of the NBS. The industrial importance of Schweinfurt within the Third Reich is difficult to overstate. Home to the largest producer of ball bearings in Germany, Schweinfurt's factories accounted for almost half of the Reich's "total war requirements."[84] Ball bearings were, and are, essential materiel for the war effort, used as they are in aircraft, tanks, vehicles, and equipment. The ball bearing represented industrial web theory in action. Neutralize ball-bearing production, and the German war engine stalls. This critical industry was selected because of its "pivotal place in the economy" and its concentration of production facilities. Thus, they presumed its difficulty to recover.[85] The factories that manufactured German ball bearings were spread across Schweinfurt and along the River Main with its numerous subsidiary sites integrated into the city's residential and commercial districts.

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[82] Edward Jablonski, *Double Strike: The Epic Air Raids on Regensburg-Schweinfurt, August 17, 1943* (New York: Doubleday & Company, Inc., 1974), p. 3.

[83] James Parton, *"Air Force Spoken Here": General Ira Eaker and the Command of the Air* (Bethesda, MD: Adler & Adler, Publishers, Inc., 1986), p. 220.

[84] Martin Middlebrook, *The Schweinfurt-Regensburg Mission* (New York: Charles Scribner's Sons, 1983), p. 17.

[85] "The German Anti-Friction Bearings Industry," in *The United States Strategic Bombing Survey: Volume III*, comp. David MacIsaac (New York: Garland Publishing, Inc., 1976), p. 4.

In the mid-afternoon, high-explosive and incendiary bombs fell over Schweinfurt. The weather was pristine, well-suited for the imposition of the American bombing doctrine upon the city below.[86] The incoming formations flew at an altitude 3,000 feet higher than they had at Regensburg, the day's first target. The resistance that day was fierce. On their approach, agile, aggressive Messerschmitts harried the American formations. Of the 230 B-17s that departed from airfields in England, only 198 arrived at the target; some turned around, while others were shot down. Despite flying at an elevated altitude, the bombers were within the range of the 11 flak batteries stationed in Schweinfurt. Under fire, the first wave dispersed their payload over a stretch of land 4 miles long. The size of the attacking force compounded the already dismal accuracy. "This was a case," wrote Martin Middlebrook, "of an unduly large bombing force becoming confused and congested in its approach run to the target."[87] The billowing plumes of smoke and haze obscured the targets. For subsequent waves of attack, accuracy plummeted further. The NBS could not infiltrate these black clouds, save with a desperate shot in the dark; the third wave bombed the city center instead.

The raids of 17 August 1943 exposed, in the black-and-white starkness of casualty figures and aerial reconnaissance photos, the limitations of what General Eaker called "day bombing." Nineteen percent of bombers, 55 in total, did not return, and 552 men were killed in action, lost, or captured.[88] It was a grievous blow to the USAAF and the Allied war effort.

There were other sobering insights to be gleaned from the 12 minutes over Schweinfurt. The USAAF had to reconcile itself with the fact that industry was not as feeble as predicted. Industrial web theory, thus, numbered among the casualties. As it was, the productive capacity of the economy could insulate the Reich from collapse and even contraction. Over 200 tons of high-explosive bombs and over 100 tons of incendiaries fell on Schweinfurt.[89] Over 1,300,000 square feet of the city suffered damage due to the bombing; the devastation was widely felt across all of Schweinfurt.[90] The ball bearing factories suffered a 34 percent reduction in output, but the Germans quickly overcame this setback.[91] Other factories compensated for diminished production, and there was an ample supply of ball bearings in the north. Sweden, one of the few surviving neutral states in Europe, sold the

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[86] Middlebrook, *The Schweinfurt-Regensburg Mission*, p. 203.

[87] Ibid.

[88] Ibid., p. 259.

[89] Ibid., p. 206.

[90] Thomas M. Coffey, *Decision over Schweinfurt* (Philadelphia: David McKay Company, Inc., 1977), p. 54.

[91] Overy, *The Bombers and the Bombed*, pp. 340–341.

materiel to both the Allies and the Axis. As is well documented, the raids demonstrated that bombers would not always get through. Only with a fighter escort could the USAAF penetrate the aerial wall protecting Germany.

A change had occurred between 17 August 1942 and 17 August 1943: the bombsight's precision was itself compromised. The Germans' dogged defense forced the USAAF to improvise. Improvisation was antithetical to accuracy with the NBS. New tactics had been innovated to augment aerial defenses at the expense of what had proved itself unattainable—precision. Despite the colossal toll of 17 August 1943, these changes were already visible. The bomb tonnage dispersed, and the square footage damaged proved as much.

Long before the end of 1943, it was clear that the NBS was not an instrument of precision bombing, but rather something else entirely: an area bomber. The NBS improved upon bombing "by any previous standard," but its record was far from pickle-barrel precision.[92] As Geoffrey Perret observes, "[T]hose initial six months of operations consisted largely of scattering bombs over the Western European landscape. The USAAF flew the first eleven hundred sorties in good weather, against light opposition, yet the bombing was dismal."[93]

The fraught conditions of war necessitated a recalibration of accuracy and a reassessment of precision. Rates of attrition impelled the USAAF to innovate aerial tactics to more effectively guard against an air defense far more capable than they had anticipated. This new kind of precision acknowledged the weather, the smoke, the flak, the altitude, aerial combat, the stress, and the fatigue, along with all the myriad factors that defied calculation. As the air force grew in size, so, too, did the deliverable payload of bombs. Consequently, large amounts of bombs were distributed widely across the grounds of German targets—be they cities or outposts—maximizing infrastructural damage and increasing civilian casualties.

Formation bombing was a compromise between "survival and accomplishment."[94] When bombardiers sighted targets independently on their bombsights, flying fortresses almost inevitably broke formation on their approach, exchanging greater security for greater accuracy. It was one of the ironies of the air war that, in sighting their targets, the B-17s became targets themselves to the increasing accuracy of German anti-aircraft fire. Thus, the advent of formation bombing prioritized defense above offense. As a formation could span a width of 1,138 feet, a length of 640 feet, and an elevation of 900 feet, the bombs might land in an area the size of

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[92] Paul G. Gillespie, *Weapons of Choice: The Development of Precision Guided Munitions* (Tuscaloosa, AL: University of Alabama Press, 2006), p. 26.

[93] Geoffrey Perret, *Winged Victory: The Army Air Forces in World War II* (New York: Random House, 1993), p. 248.

[94] "U.S. Air Force Oral Interview of Major General Haywood S. Hansell, Jr.," p. 7.

a small urban center.[95] The more aircraft that flew within a formation, the wider the dispersal of the payload. At 21,542 feet—the "average attacking altitude" of B-17s—the circular error increased with the addition of every aircraft.[96]

First employed on 18 March 1943, dropping-on-the leader bombing, or lead-bombing, became standard operational procedure by July. The Army Air Forces devised the tactic of lead-bombing to shore up the bomber formation's defenses and obviate the chronic shortages of the NBS. As early war reports attest, the logic of lead-bombing was all too clear. The theory was based on the battle-tested truth:

> That pilots of wing aircraft are constantly changing speed and direction in order to maintain their position in formation, thus providing a very poor bombing platform, whereas the speed and altitude of the lead aircraft may be constant during the bomb run.[97]

While this tactical innovation resolved one problem, another arose in its place: the selection of lead bombardiers. "It is self-evident," began one contemporary study, "that the bombing accuracy score of a group or the Division as a whole can be raised by sending only superior bombardiers in lead ships."[98] Even for experienced bombardiers, scores varied. The marks of one bombardier's first five missions underlined the inherent unpredictability of bombing: mission 1: 70; 2: 15; 3: 18; 4: 64; 5: 0.[99] As Colonel C. G. Williamson wrote, "A gun is no better than the ability of the man shooting it, and this was never more true than of a bomber. He had to (re)act quickly to account for the delayed reaction time of the 'toggelier' bombardiers. A delay of only a single second flying at 185 miles per hour results in a bomb release 270 feet beyond the target."[100]

There was a general consensus that lead-bombing was more precise than the previous practice of individual sighting. The "'toggelier' system," so-called since bombardiers toggled the switch to release the bomb hatch, greatly improved the accuracy of the USAAF bombing.[101] However, this assumption is uninterrogated. The lead bombardier did not reduce inaccuracy but instead compensated for the

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[95] Roger A. Freeman, *Mighty Eighty War Manual* (London: Jane's Publishing Company, Limited, 1984), p. 43.

[96] "Exhibit C," "Bombing Accuracy of the USAAF Heavy and Medium Bombers."

[97] "Inauguration of Medium Altitude Bombardment Operations by B-26 Aircraft of the 3rd Bombardment Wing (M)," n.d., p. 5, folder: "Corres., Memos, & Rpts.," box 76, Papers of Carl A. Spaatz, Library of Congress, Washington, DC.

[98] "Proficiency of Bombardiers," 14 August 1944, p. 1, folder: "Bombing Accuracy Analytical Studies I," box 76, Papers of Carl A. Spaatz, Library of Congress, Washington, DC.

[99] "Proficiency of Bombardiers," p. 2.

[100] McFarland, *America's Pursuit of Precision Bombing*, p. 171.

[101] Neillands, *The Bomber War*, p. 200.

inaccuracy of his formation. It was the lead bombardier's responsibility in such formations to aim his bombs so that the pattern of the entire formation centered on the assigned target point.[102] In other words, this required the lead bombardier to release his bomber's payload later so that the mass of the formation's bombs would fall on the target. Imprecision was a core strut of dropping-on-the-leader tactics. "Bombing patterns resulted," the Summary Report of the *United States Strategic Bombing Survey* observed, "only a portion of which could fall on precision targets."[103] "The rest spilled over," the report continues, "on adjacent plants, or built-up areas, or in open fields."[104] "Built-up areas" was an indirect admission of city bombing. According to General Ira C. Eaker's biographer, the "tactic that became standard operating procedure" was "salvo bombing."[105]

What these tactical innovations in bombing amounted to was area bombing. Precision bombing, simply, was both technologically and tactically unattainable. The theoretical distinction between area and precision bombing was, from the beginning, flimsy. The latter sighted a single aiming point, while the former sighted a target area. Ostensibly, the dispersion was the difference. Area bombing sought a larger pattern resulting in a smaller bomb density.[106] As one report admitted, "the resulting bomb plot frequently resembles those which are characteristic of area bombing."[107] In June 1944, "a new type of bombing was undertaken by IX Bomber Command—area bombing."[108] Area bombing had been an unofficial practice of the USAAF since Mission No. 1, when half of the bombs struck the target and half struck the built-up areas and open fields around the Rouen-Sotteville railyard.

The USAAF dropped 194,928 tons of bombs on marshaling yards, which, as the biographer of Carl A. Spaatz has shown, was a euphemism for area bombing. Furthermore, 10.3 percent of all bombs landed in industrial areas, a category that

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[102] "Effect of Ground Speed and Size of Formation on Range Errors in B-17 and B-24 Bombing Formations," 3 July 1944, p. 2, folder: "Bombing," box 76, Carl A. Spaatz Papers, Library of Congress, Washington, DC.

[103] "The United States Strategic Bombing Survey: Summary Report," in *The United States Strategic Bombing Survey: Volume I*, comp. David MacIsaac (New York: Garland Publishing, Inc., 1976), p. 4.

[104] "The United States Strategic Bombing Survey: Summary Report," pp. 4–5.

[105] Parton, *"Air Force Spoken Here,"* p. 235.

[106] "Area Bombing for June," 7 August 1944, p. 3, call number (box): 145.81-31 (7 Jan 1944) to 145.81-49 (23 Feb 1943), Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, AL.

[107] "Tab E: Mission Strength, Effective," no page given, folder "Bombing List Data," call number box): 145.81-31 (7 Jan 1944) to 145.81-49 (23 Feb 1943), Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, AL.

[108] "Area Bombing for June," p. 1.

included "Cities, Towns, and Urban Areas."[109] Of course, industry and civilian residences were not discrete landmarks in the urban geography of Germany. That precision bombing targeted infrastructure is clear, but in doing so, it also struck civilians. As Tami Davis-Biddle wrote, "[I]t was acceptable to attack German civilians if they lived in cities with targets, but not acceptable to make German civilians targets in and of themselves."[110]

The accusation that the United States conducted area bombing is not new. Major General Hayward S. Hansell, Jr., said as much in a postwar interview. According to Hansell, 1943 exposed an age-old wartime dilemma for the USAAF, "a conflict between survival and accomplishment."[111] To protect their crews, "[t]he first thing we had to do was agree upon a formation." Formations, Hansell explained, "bombed by combat box on salvo from the lead bombardier."[112] Thus, one sight was swapped for another: the instruments of precision bombing, bombsights, were replaced with defensive armaments, gunsights. Lead-bombing, in other words, rendered additional bombsights redundant. These tactical innovations—flight formations and lead-bombing—impelled by the rigors of aerial combat, improved bombing accuracy "very materially," but they could not achieve the results of the individual sighting.[113] In peacetime, precision was a delusion that the Air Corps could afford. The wartime experience of the USAAF revealed, however, that precision was an illusion.

Area bombing is an acknowledgement that bombs, wherever they detonate, advance military aims. The target is not merely industry; it is the nation itself. So what then was the impact of area bombing?

According to *The Effects of Bombing on the Health and Medical Care in Germany*, the rate of death "rose in proportion to the increase in tons of bombs dropped."[114] Casualties possessed a far more direct relationship with the Allied bombing campaign than diminishing the Third Reich's economic output. For example, as the Reich undertook a desperate and aggressive re-armament gambit in late 1944—a period in which output rebounded—air raid deaths rose to their highest levels since the summer of 1943.[115] The bombing campaign victims died from burial in the

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[109] Ibid., p. 32.

[110] Davis-Biddle, *Rhetoric and Reality in Air Warfare*, p. 435.

[111] "U.S. Air Force Oral Interview of Major General Haywood S. Hansell, Jr.," p. 7.

[112] Ibid., p. 8.

[113] Ibid., p. 9.

[114] "The Effects of Bombing on the Health and Medical Care in Germany," January 1947, p. 6, call number (box): 137.306-9 (Sep 1939 to May 1945) to 137.3071 (Jan 1947), Air Force Historical Research Agency, Maxwell Air Force Base, Montgomery, AL.

[115] Ibid., p. 7.

rubble, injuries sustained from blasts, tetanus, carbon monoxide, radiation, respiratory blockage, extreme heat, and phosphorous burns. Delayed fuse bombs and hazardous chemicals contaminated water supplies and disrupted waste disposal.

Moreover, the relentlessness of the campaign made reconstruction, a critical component of the war, increasingly difficult. Hospitals were understaffed and undersupplied with critical resources. Increasingly, "the nutritional demands of the German people could not be met."[116] Bombing, claims the report, "did not aggrevate [*sic*] illness." Nevertheless, reason suggests that many such illnesses would go unreported in a war zone. Each bomb possessed a material, though unquantifiable, impact upon the course of the war, affecting the economy and the health of its population.

VII. CONCLUSION

One question remains outstanding: How effective was the NBS?

To the authors of the most definitive studies of the bombsight, Albert L. Pardini and Stephen McFarland, there is little agreement. For Pardini, the NBS "was able to live up to its name as a precision high-altitude bombsight."[117] In contrast, for McFarland, "America's high-altitude bombing technology in World War II was the best in the world, but inadequate for the objectives of daylight precision strategic bombing."[118] The most telling answer concerning its effectiveness comes not from what was said but what was not said about the bombsight. The authoritative *United States Strategic Bombing Survey* issued a postwar analysis titled "Bombing Accuracy of the USAAF Heavy & Medium Bombers." The report scrutinizes the impact of weather on rates of operation, compares the efficiency of the B-17 against the B-24, and evaluates how box formations and altitude skewed accuracy. It tabulates the respective records of the radar systems, Gee-H, Micro-H, and H2x.

Nevertheless, there was no explicit mention of the bombsight. It is instead analytically subsumed underneath the umbrella term "visual bombing." There is no discussion of the increasingly inferior quality of the NBS, nor consideration of the innovations that resituated the role of the NBS within the USAAF: formation flying and lead-bombing.

The NBS was effective, devastatingly so, just not in the manner that the designers of the instrument and strategists envisaged—or even in the manner that the

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[116] Ibid., p. 290.

[117] Albert L. Pardini, *The Legendary Secret Norden Bombsight* (Atglen, PA: Schiffer Military History, 1999), p. 326.

[118] McFarland, *America's Pursuit of Precision Bombing*, p. 190.

surveyors had acknowledged. It was not a "wonder weapon," and it certainly was not a precision tool.[119] The Norden bombsight was, in fact, precisely the opposite; it made the B-17s and B-24s brutally effective area bombers.

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[119] Paul Kennedy, *Engineers of Victory: The Problem Solvers Who Turned the Tide in the Second World War* (New York: Random House, 2013), p. 126.

CHAPTER 11

“What About Aeronautics?”

The NACA Forms the Nucleus of America’s Space Agency

Layne Karafantis[1]

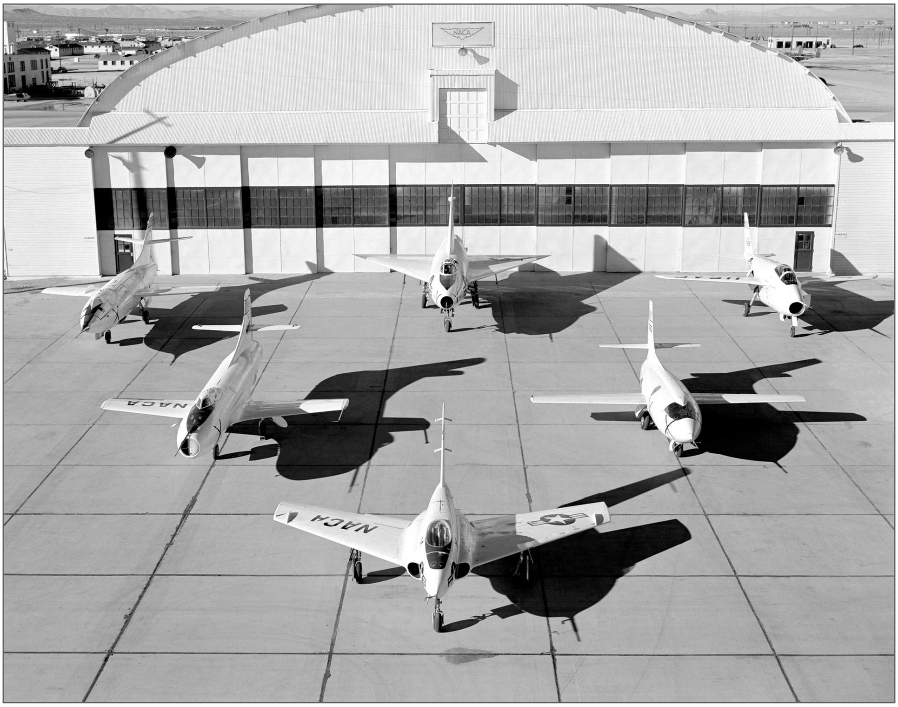

Figure 1: In the postwar period, the NACA continued groundbreaking research on the X-Plane series of aircraft. This research would soon take a back seat to rockets and spaceflight. Shown here, clockwise from the far left, at the NACA High Speed Flight Station are the D-558-II, XF-92A, X-5, X-1, X-4 and D-558-I. (Image credit: NASA E-842)

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[1] I would like to acknowledge the authors of the seminal works cited in this piece, whose painstaking archival research need not be duplicated. I would like to thank Jack Boyd and my colleagues at the NASA Ames History Office for their support of this project, as well as those who reviewed copies as this work progressed.

When one calculates the lifetime of the National Advisory Committee for Aeronautics (NACA) as over 40 years, from 1915 to 1958—born in the days of the Wright brothers and of an altogether different era in aerospace history—one might conclude that, over time, the NACA became an antiquated institution. Viewed in such terms, perhaps its absorption into the National Aeronautics and Space Administration (NASA) was overdue. However, this monolithic view of the NACA overlooks the wartime creation of additional research spaces that contributed to its dynamic nature and maintained its relevance. Beginning in the late 1930s, federal administrators began talking about the creation of additional NACA facilities to supplement Langley Memorial Aeronautical Laboratory in Hampton, Virginia. Over the next decade, these ambitions resulted in the addition of two laboratories and two stations: Ames Aeronautical Laboratory, the Air Engine Research Laboratory, Wallops Flight Test Station, and Muroc High-Speed Flight Test Station. Between these facilities, many aeronautical breakthroughs occurred during the years between the Second World War and the formation of NASA in 1958. While the NACA surely matured, its facilities were still investigating pressing problems until their dissolution and assimilation.

The waning of the NACA is often tied with its transformation during World War II, along with the introduction of competition it did not have previously. Certainly, the focus had shifted during the war from basic research to applied science and engineering. Before the war, in response to requests, the NACA conducted research, then openly distributed ensuing technical reports. During wartime, however, the Committee became a service institution to industry and the military, which significantly altered its character. In addition to this change, as asserted elsewhere in this volume, the NACA was not the only game in town by the postwar years. Its infrastructure was less critical in as much as it was no longer unique; more in-house research and development (R&D) was conducted by industry, the military, and universities. In short, its earlier approach was "outmoded."

Nevertheless, this interpretation of the NACA assigns a disproportionate amount of blame to the Committee for its disbandment. As an entity, it is typically embodied in and evaluated by the practices of its administrators; this methodology ignores the nuance revealed by investigations of specific spaces and people working at its laboratories. Throughout its existence, the NACA received conflicting criticisms—one year, it was not focused enough on practical applications, and others it was deprioritizing basic research.[2] Someone was always dissatisfied. The NACA's shortcomings have been overstated. This chapter acknowledges the challenges faced by the Committee, its achievements despite obstacles, and its oversights.

THE POSTWAR NACA

Perhaps the NACA was no longer unique by the close of the 1950s. Yes, there was a lack of manpower—skilled workers were going to industry. Yes, there was a lack of money, which is why the workers were leaving. Many employees who did not meet the needs of industry were those who had been drawn into civil service during the war, and they remained. Many of them did not meet the NACA's prewar (higher) standards for researchers, leaving the Committee with less talent in the postwar years.[3] In no small addition, many of the earliest players in the NACA were aging out in one way or another, which opened room for institutional change.[4] Nevertheless, aeronautical research had not peaked by the late 1950s. Although it had developed quickly over the previous 50 years, there still was—and continues to be—much work to be done. While the NACA no longer monopolized such research, this should not overshadow the significant science and engineering contributions made at NACA laboratories.

When we consider the beginnings of the end of the NACA, it becomes clear that this transformation was not inevitable, nor was it evident that its laboratories were eager to find sanctuary under NASA's stewardship. In fact, at the three existing labs, the movement toward space-oriented research was hastened only by necessity and a survival instinct, rather than by any collective desire to abandon aeronautical research or lack of mysteries to be solved. At the war's end, there were 31 projects awaiting flight testing. Researchers were eager to measure the extent of noise in jet aircraft, and others wanted to investigate maximum safe Mach numbers in dives or measure helicopter vibration.[5] In the final decade of NACA research, the speed of military service fighters doubled; world speed records were raised; experimental "X" aircraft grew into "a stable of diverse types to probe and analyze new problem

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[2] Steven T. Corneliussen, "The Transonic Wind Tunnel and the NACA Technical Culture," in *From Engineering Science to Big Science: The NACA and NASA Collier Trophy Research Project Winners*, ed. Pamela E. Mack (Washington, DC: NASA SP-4219, 1998).

[3] Alex Roland, *Model Research: The National Advisory Committee for Aeronautics 1915–1958*, vol. 1 (Washington, DC: NASA SP-4103, 1985), p. 237.

[4] Edwin P. Hartman, *Adventures in Research: A History of Ames Research Center, 1940–1965* (Washington, DC: NASA SP-4302, 1970), p. 223.

[5] Michael H. Gorn, *Expanding the Envelope: Flight Research at NACA and NASA* (Lexington, KY: University of Kentucky Press, 2001), p. 167.

areas"; first steps were taken toward vertical take-off and landing (VTOL), spurred by the success of the helicopter in Korea; and the "Century Series" of fighters were developed and flown, setting new performance standards.[6]

Indeed, the postwar years held new ambitions and promise, along with the solidification of roles assigned to the NACA during wartime. Hugh Dryden succeeded George Lewis as director of the NACA in 1947 and attempted to ease the transition while maintaining the Committee's historic importance. Dryden instituted managerial reforms, dealt with unfinished business from World War II, responded to requests from industry, and considered new areas of research for the NACA.[7] He gave the Committee a more public persona, hosting conferences at the Langley and Ames laboratories, and attempted to cultivate support for the NACA as it transitioned to peacetime. Dryden and other NACA leaders had Wartime Reports declassified, publishing more than 1,200 of the Committee's 3,000 reports written during World War II. They wanted a return to fundamental research at the laboratories after they "had been in military harness for more than half a decade."[8] Despite this desire, development predicated on the needs of industry continued to dominate the attention of the postwar NACA. In fact, members of industry strong-armed the NACA into publishing an annual list of all of its research projects so that they could know what studies were under way (and thus not duplicate the work in their own labs). NACA laboratories responded to increased research demands by contracting with universities.[9] Within the newly independent U.S. Air Force (July 1947), its Deputy Chief of Air Staff for Research and Development, Major General Curtis LeMay, began pursuing projects that were in direct competition with the NACA. These events laid the foundation for what would later be called the military-industrial-academic complex.

To avoid conflicts with other government agencies and hopefully secure its continued existence, the NACA proposed a National Aeronautical Research Policy that would define the areas of research for each agency. All parties—including not only the military, but the Civil Aeronautics Authority, members from the aircraft industry, and others—agreed, but the Policy was not enough to stop lines from blurring.[10] Meanwhile, the federal government wanted a national array of facilities constructed for aeronautical research, including (and benefiting) the NACA, industry, the Air Force, and universities—so that the United States would never

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[6] David A. Anderton, *Sixty Years of Aeronautical Research, 1917–1977* (Washington, DC: NASA, 1980), p. 33.

[7] Roland, *Model*, p. 225.

[8] Ibid., p. 234.

[9] Ibid., pp. 239, 245, 247.

[10] Hartman, *Adventures in Research*, p. 120.

again fall behind in aeronautical research. A committee led by Jerome Hunsaker, chairman of the NACA, proposed a congressional appropriation to facilitate new construction. The Unitary Plan Act passed Congress on 27 October 1949. The largest outcome of this plan was the construction of the massive U.S. Air Force Arnold Engineering Development Center in Tennessee, which would conduct military testing. NACA facilities were upgraded, repowered, and tasked with commercial work, and the NACA was given $75 million for new facilities. At Ames Aeronautical Laboratory, $27 million financed the creation of a complex of three interconnected tunnels—one transonic and two supersonic—all powered by a massive powerplant that could generate almost 250,000 horsepower.[11] Langley's Unitary Plan Wind Tunnel was designed to test high-speed missiles. Lewis built its tunnel to test full-scale jet and rocket engines. All NACA Unitary Plan tunnels came online in 1955 and "represented a landmark in wind tunnel design by any criterion—size, cost, performance, or complexity."[12] Such spaces were to support the top-priority projects of postwar America: "high-speed flight, missiles and rockets, and nuclear power for aircraft propulsion." High-speed flight ambitions, in particular, forced all involved into partnerships of mutual interest.[13]

WARTIME LABS: A BRIEF DISSECTION OF THE NACA

Many documents, both historical and contemporary, use "the NACA" to describe research conducted at any one of its three laboratories, but "the NACA" is often used interchangeably specifically with Langley Memorial Aeronautical Laboratory in Virginia. Granted, Langley was synonymous with the NACA for 23 years. However, calling attention to other NACA laboratories provides a contrast to the notion that by the postwar years, the Committee had become antiquated. Aside from work conducted at Langley, which was physically and politically closer to Washington, DC, than the other laboratories, considerable strides in R&D were being made in California, at Ames Aeronautical Laboratory and Muroc Flight Test Center, while propulsion research went forward at an NACA laboratory outside Cleveland.

In the years leading up to World War II, it had become clear that the United States was lagging behind Europe in aeronautical research and needed to catch up.

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[11] Elizabeth Muenger, *Searching the Horizon: A History of Ames Research Center, 1940–1976* (Washington, DC: NASA SP-4304, 1985), p. 44.

[12] Donald D. Baals and William R. Corliss, *Wind Tunnels of NASA* (Washington, DC: NASA SP-440, 1981).

[13] Roland, *Model*, p. 247.

Langley was seen as vulnerable to attack by Axis Powers (Japan was not yet deemed a threat), and Langley had run low on the land and electric power needed to meet the demand for new research. The NACA formed a Special Committee on the Relations of NACA to National Defense in Time of War, which led to the recommendation that another NACA lab be built. This request was denied, but giants of aeronautics such as Joseph Ames, Vannevar Bush, and Charles Lindbergh lobbied for its creation. Finally, the new base was approved, pushed through by John Victory, executive secretary of the NACA, only to have a great deal of bickering ensue over its location.[14] While those who had asked for the new base wanted it to be on Moffett Field, near Sunnyvale, California, the approval for the station was only gained when this particular site selection was removed from the bill.

Despite the best efforts of eastern Congressmen, the new station did not end up in Dismal Swamp, Virginia, but went to Sunnyvale.[15] Established on 20 December 1939, the Moffett Field Laboratory became the second lab of the NACA, and its work would focus on high-speed aerodynamics. As with future NASA Centers, such as Johnson Space Center in Houston, desired criteria included a nearby military base and research university, as well as ancillary industries. Moffett Field near Sunnyvale topped out the list with its clear flying weather, airfield, available power supply, and proximity to Stanford University and the West Coast aircraft industry.

Smith DeFrance, assistant chief of aerodynamics at Langley, accompanied by engineers from the lab, moved cross-country to construct the new operation.[16] At the facility that was later named Ames Aeronautical Laboratory, DeFrance would lead as "Engineer-in-Charge" (later, "Director") from 1940 to 1965. The lab was named for a former chairman of the NACA, Joseph Ames (1927–39), who had penned a request from his deathbed to Congressman Clifton A. Woodrum (D-VA), asking for the construction of the base.[17] After the creation of Ames, new additions to the NACA occurred in rather quick succession. Only a few months into 1940, Congress authorized the construction of an aircraft engine laboratory near Cleveland, Ohio, which eventually became Lewis Research Center (named after former NACA Director of Aeronautical Research George Lewis) and is now known as Glenn Research Center. The Wallops Flight Center arrived in 1945, an outpost on the Virginian seaboard from which to conduct rocket tests. A temporary Langley outpost at Muroc, California, became a permanent facility (named

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[14] Hartman, *Adventures in Research*, pp. 6, 20–21; Muenger, *Searching the Horizon*, p. 4.

[15] Hartman, *Adventures in Research*, p. 20.

[16] The base is technically located at Moffett Field. If it were located in a city, it would be Mountain View, but boosters believed the name Sunnyvale would convey a more attractive image to Congress.

[17] Hartman, *Adventures in Research*, p. 12.

the NACA High-Speed Flight Station in 1954). Over the years, this station would be managed by Langley, then briefly by Ames in the 1980s, with interspersed and eventual autonomy. Once known as the Hugh L. Dryden Flight Research Center, it is now NASA's Armstrong Flight Research Center.[18] As aerodynamic research was "at the heart of the NACA tradition," money and labor remained devoted to improving wind tunnel design, as well as to making incremental improvements in aircraft design and propulsion.

AERONAUTICAL RESEARCH: HITS AND MISSES

During World War II, the NACA began investigating jet propulsion. However, as no systems were developed or put into production, the United States found itself conspicuously behind the curve compared to European progress. Historians have often cited the lack of attention to advanced propulsion systems as an indication of the NACA's lack of foresight and, perhaps, its growing complacency. A more generous explanation for the inattention to jet engines notes that the NACA dedicated itself more to immediate wartime needs—such as those concerning propeller-driven aircraft—instead of developing entirely new systems.[19] Roger Bilstein offers: "It may have been that the NACA was not as bold as it might have been or that the agency was so caught up in immediate wartime improvements that crucial areas of basic research received short shrift."[20] The NACA had not entirely overlooked the idea of jet propulsion, however, as the Committee published a paper on the subject in 1923, and Langley staff were actively interested in the subject by the late 1930s.[21] Despite their attention, European R&D admittedly surpassed any efforts in the United States, and the NACA only fully embraced and augmented jet propulsion development in the postwar years.

Earlier in this volume, Roger Launius reiterates a few explanations historians have offered as to why the NACA did not pursue jet propulsion sooner. Perhaps most significantly, during World War II, the NACA had become fully wedded to the military services, and their clients' myopia carried over. More broadly, the NACA "emerged from the war a transformed organization." Those who later decried the NACA as short-sighted for not investigating jet propulsion need their

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[18] James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917–1958* (Washington, DC: NASA, SP-4305 1987), p. 309.

[19] Muenger, *Searching the Horizon*, p. 36.

[20] Roger E. Bilstein, *Orders of Magnitude: A History of the NACA and NASA, 1915–1990* (Washington, DC: NASA SP-4406, 1989), p. 36.

[21] Bilstein, *Orders*, p. 32.

criticisms tempered, as a great deal of practical work was accomplished at NACA facilities during the war. These laboratories were flooded with wartime work (see Launius). Ames made game-changing contributions in flight testing and simulation in its wind tunnels—a complex that would eventually grow to be one of the largest in the world. Although high-speed aerodynamics was meant to be the primary research focus at Ames, the war made testing aircraft at moderate speeds more urgent. As early as May 1940, engineers began the construction of two 7- by 10-foot wind tunnels patterned after Langley's 1930 7- by 10-foot Atmospheric Wind Tunnel. After their completion in early 1941, both tunnels were flooded with military requests, and staff were working around the clock by fall. However, they found time for some basic research, such as programs investigating propeller slipstream effects and air inlets that pioneered new technologies. The third tunnel at Ames was a giant—with a 16-foot diameter at its test section—and represented a considerable advance in wind tunnel design and construction. This tunnel operated near the speed of sound, driven by the most powerful tunnel system in operation anywhere—a 27,000-horsepower electric motor. Scientists and engineers tested warplanes in this tunnel, including the P-38, P-40, and P-51 Mustang.[22] Ames also assisted the war effort with its research on de-icing, which was a severe problem for planes flying in colder weather and at higher altitudes.[23] This de-icing research established Ames in its own right. This legitimacy was essential to those at the lab. Ames personnel felt insecurity about their relationship to the elder institution and often felt frustrated that the NACA "did not fully understand their special problems and occasionally showed favoritism to Langley."[24] However, by the war's close, Ames had established its centrality to the Committee's efforts, given its contributions to improving aircraft design and furthering high-speed research.

Nor was propulsion research absent from the ambitions of the NACA. The Aircraft Engine Research Laboratory in Cleveland was established in 1941 with a mission to improve aircraft engines. In 1944, the first test of a jet engine was performed in its Altitude Wind Tunnel. The lab also contributed to de-icing efforts, improving the cooling ability of the engine of the B-29 Superfortress, which would prove vital to America's fight in the Pacific. Renamed the Lewis Flight Propulsion Laboratory in 1948, the center expanded its efforts to investigate all types of propulsion, as opposed to focusing only on improvement of existing systems. While jet propulsion and rocket engines were not studied with great rigor until the 1950s, the creation of this center nonetheless is a testament to the NACA's efforts in this

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[22] Baals and Corliss, *Wind Tunnels of NASA*.

[23] Hartman, *Adventures in Research*, p. 77.

[24] Muenger, *Searching the Horizon*, p. 20; Hartman, *Adventures in Research*, pp. 177–178.

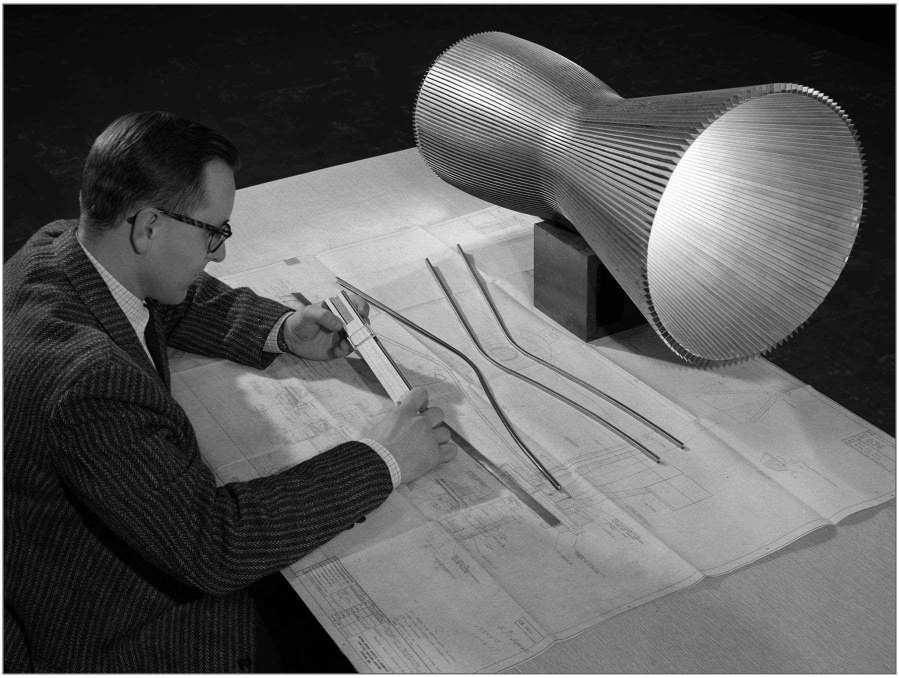

Figure 2: An engineer at NASA Lewis Research Center examines the details of a 20,000-pound-thrust regeneratively cooled rocket engine. The research at Lewis was critical to the development of the nation's newly emergent space program. (Image credit: NASA photo GRC-1958-C-49377)

field. This center has continued to contribute to studies in aeronautics and aerospace, now as part of NASA and renamed the John H. Glenn Research Center at Lewis Field in 1999.[25] For all talk of missed opportunities, the NACA contributed momentous research during the postwar years, especially in the quest to break the sound barrier. Swept wings were one such development.

DESIGNS TO GO SUPERSONIC

During the 1935 Volta Conference, an international conference on high-speed flight, German engineer Adolf Busemann asserted that "arrow" wings would have less drag at supersonic speeds.[26] Although Busemann's theory did not seem to have

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[25] See, for example, Robert S. Arrighi, *Revolutionary Atmosphere: The Story of the Altitude Wind Tunnel and the Space Power Chambers* (Washington, DC: NASA SP-2010-4319, 2010).

[26] Bilstein, *Orders*, p. 34.

much practical application at the time, after the Germans developed jet engines, the concept dramatically altered plane design, resulting in its use on the prototype Messerschmitt Me P.1101 in 1944. The same line of research was being conducted independently and simultaneously in the United States. Robert T. Jones at Langley drew inspiration from a 1924 NACA paper by former teacher Max Munk, leading to his suggestion that wings be swept back at an angle to delay the problem of compressibility (that is, drag). Years later, Jones penned a memorial for Adolf Busemann after he died on 3 November 1986, in which he lamented that "During the war years, communication with German scientists was lost, and my own somewhat belated discovery of the sweep effect, which emphasized subsonic sweep, was not immediately accepted by American aerodynamicists."[27] He persisted, however, and pitched the concept to the NACA's director of research, George Lewis, as well as at the Wright Field conference in early 1945. Wind tunnel tests at Langley soon confirmed Jones's theory that swept wings could significantly reduce drag at subsonic speeds. Jones noted that he did not simply come to an independent knowledge of Busemann's work but expanded the theory during the war to include subsonic sweep. In contrast, Busemann's 1935 theory was "incomplete in the sense that only wings having supersonic sweep were considered."[28] It was not until German engineers were captured and arrived in the United States—courtesy of Operation Paperclip—that swept wings became widely implemented. They would prove essential in the quest to go faster than the speed of sound in level flight.

One of the émigrés was, in fact, Adolf Busemann, who found himself at Langley, which soon became known as the place to consult regarding supersonic flight. According to Busemann, whereas Wernher von Braun, a fellow émigré through Operation Paperclip, was tasked with rocketry research, if he "had a question about supersonic drag or lift or whatever…of course he would direct the question to the Langley Center."[29] During his tenure at Langley, from 1947 to 1964, Busemann contributed a number of insights. Early on, he inspired a particularly groundbreaking theory in aerodynamics. He shared his expertise in transonic flight with colleague Richard T. Whitcomb, describing airflow characteristics at high speed, which led to Whitcomb's concept of the Area Rule.[30] The application of this theory led to the development of a "Coke bottle" (or "Marilyn Monroe") fuselage, one

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[27] Robert T. Jones, "Adolf Busemann, 1901–1986," in *Memorial Tributes*, vol. 3 (Washington, DC: National Academies Press, 1989), p. 65.

[28] Ibid., p. 64.

[29] Interview of Adolf Busemann by Steven Bardwell on 1979 Summer, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA, 8, *http://www.aip.org/history-programs/niels-bohr-library/oral-histories/4547*.

[30] Bilstein, *Orders*, p. 40.

with a tightened-in center to compensate for the added area of swept wings. In the words of one colleague, that innovation "made supersonic flight possible."[31] While many elements had to come together to achieve that feat, the new Coke-bottle design did increase the speed of supersonic military aircraft by up to 25 percent without any increase in engine power, enabling a plane that could fly 800 mph to now reach 1,000 mph.[32] Whitcomb won the Collier Trophy for the theory's experimental verification in 1955.[33] Several other scientists and engineers at the NACA contributed to its development and expanded the Area Rule theory to new realms.

Robert T. Jones transferred from Langley to Ames in August 1946, and the laboratory quickly embraced him as one of their own.[34] He continued to contribute NACA technical reports on swept and low-aspect-ratio wings, making wings an object of more in-depth study than simply "assemblages of largely independent airfoil sections."[35] He also augmented the Area Rule, which had a limited theoretical basis at the time of its "discovery" by Whitcomb. Jones introduced the concept of the Supersonic Area Rule, which made it possible to calculate drag at any supersonic Mach number. Barrett Baldwin and Robert Dickey, also at Ames, developed the Moment of Area Rule, which minimized drag around transonic and low supersonic speeds.[36] Experimental wing research continued at Ames Aeronautical Laboratory throughout the next decade, utilizing its ever-growing wind tunnel facilities to develop and experimentally confirm the value of new designs. One highlight often cited by Ames historians is the creation of the conical camber to reduce drag due to lift, which ultimately increased the range of supersonic airplanes. Its application in the Consolidated Vultee F-102 and F-106 fighters, as well as the B-58 Hustler designs, added considerable value to those aircraft.

Langley scientists and engineers provided their contributions toward "bridging the transonic gap," including the small model technique, as well as the center-plate and sting support systems.[37] A primary difficulty, conducting transonic research in a wind tunnel, was solved by physicist Ray H. Wright in 1946. He sought to rid a tunnel of subsonic interference, which he accomplished with a concept called the

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[31] Anderton, *Sixty Years of Aeronautical Research*, p. 35.

[32] Dennis Hevesi, "Richard T. Whitcomb Is Dead at 88; Revolutionized the Design of Jet Aircraft," *New York Times* (25 October 2009).

[33] The research was classified until 1955, so Whitcomb did not win the Collier until then, when the "Grumman F9F-9 Tiger and the Convair F-102A prototypes demonstrated just how significant the area rule was." See Lane E. Wallace, "The Whitcomb Area Rule: NACA Aerodynamics Research and Innovation" in *From Engineering*, ed. Mack, p. 147.

[34] Hartman, *Adventures in Research*, p. 127.

[35] Ibid., p. 154.

[36] Ibid., p. 208.

[37] Hansen, *Engineer*, p. 315.

"slotted throat" or "slotted wall" tunnel.[38] Discovery of the Area Rule was, in fact, dependent on this slotted-throat tunnel design, without which engineers could not have gathered the information needed to understand causes of transonic drag.[39] Wright's theory was not readily accepted at Langley, and even contemporary Adolf Busemann was sure that Wright was incorrect in his calculations.[40] However, John Stack, then head of Langley's Compressibility Research Division, believed in the potential of the slotted-throat design to assist with transonic research. His efforts would not be realized in Langley's 16-Foot Transonic Tunnel until after the XS-1 had broken the sound barrier in the field. However, soon after their implementation, slotted tunnels became standard practice in transonic research.[41] John Stack won the Collier Trophy in 1951 for his team's work on the development and practical application of the slotted-throat design.

THE BELL X-1 BREACHES THE SOUND BARRIER

Many people contributed to research that enabled breaking the sound barrier, including those in the preceding sections and many more who probably will remain unrecognized for their efforts.[42] Nevertheless, it was, in fact, John Stack, now as head of Langley Aeronautical Laboratory, who led the NACA's flight-test program for the plane that would break the sound barrier.[43] Stack theoretically conceived of a high-speed research airplane as early as 1933 and spent the next decade campaigning for NACA and military support to develop a prototype. His research airplane concept eventually provided a solid foundation for the design of the Bell X-1, the first plane that would go faster than the speed of sound. The plane did not take advantage of a swept-wing design, which was not verified in time, but instead relied on a powerful rocket engine to surpass Mach 1.[44]

Hugh Dryden was an early supporter of the development of transonic craft. During World War II, he had headed a fledgling guided-missile section within

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[38] Ibid., p. 321.

[39] Wallace, "The Whitcomb Area Rule," p. 139.

[40] Hansen, *Engineer*, p. 324.

[41] Hansen, *Engineer*, p. 329.

[42] Adolf Busemann's research contributed to the development of the X-1. Robert Gilruth was also a key player, as were Robert Jones and many others. See Dominick A. Pisano, F. Robert van der Linden, and Frank H. Winter, *Chuck Yeager and the Bell X-1* (Washington, DC: Smithsonian National Air and Space Museum, 2006), p. 49.

[43] Ibid.

[44] Hansen, *Engineer*, p. 286.

the NACA under the Office of Scientific Research and Development, where he led the team that developed the Bat guided missile.[45] After the war, Dryden resigned from the Bureau of Standards to become Director of Aeronautical Research at the NACA. From Washington, DC, he managed the Ames, Langley, and Lewis laboratories and the Muroc Flight Test Unit. Under his guidance, the NACA's primary focus dramatically shifted toward transonic and supersonic flight research, which he couched in terms of national security.[46] Theodore von Kármán later claimed that he and Dryden had invented the word "transonic." Dryden wanted it written with two *s*'s, which would have been "logical," according to von Kármán, but he did not believe it was always necessary to be "logical in aeronautics"; von Kármán wrote it with one *s* when he introduced this term in a report to the Air Force.[47]

The NACA had the facilities and experience needed to develop a supersonic research aircraft, but the Committee was missing one crucial component—money. Thankfully, the military had its own ambitions for supersonic capability, albeit for applied use in their fleet and not for pure research. The NACA's self-proclaimed interest stemmed from finding a "methodological approach to gathering data in the transonic regime." According to aerodynamicist John Anderson, "The speed of sound is one of the most important quantities in aerodynamics," because the physics of flow velocity is dramatically different in subsonic and supersonic flight.[48] Researchers were eager to gather data and begin testing theoretical models. The U.S. Air Force, admittedly, was more interested in the feat and the psychological triumph. For both parties, breaking the sound barrier would bring "visibility and justification for funding."[49]

Those involved had independent ideas about how this breach would be accomplished. John Stack wanted the aircraft to be jet-powered. Ezra Kotcher, an engineer at Wright Field, wanted to use a rocket engine. According to Stack, Langley's chief test pilot, Melvin Gough, exclaimed, "No NACA pilot will ever be permitted to fly an airplane powered by a damned firecracker!"[50] Nevertheless, that is precisely what happened, as the rocket propulsion system won out.[51]

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[45] Amy Shira Teitel, *Breaking the Chains of Gravity: The Story of Spaceflight Before NASA* (New York: Bloomsbury Sigma, 2016), p. 66.

[46] Teitel, *Breaking*, pp. 119, 123; Roland, *Model*, vol. 2, p. 713; John D. Anderson, Jr., "Research in Supersonic Flight and the Breaking of the Sound Barrier," in *From Engineering*, ed. Mack.

[47] Theodore von Kármán, *Aerodynamics* (Ithaca, NY: Cornell University Press, 1954), p. 116; Anderson, "Research."

[48] Anderson, "Research," pp. 50, 62.

[49] Roland, *Model*.

[50] Hansen, *Engineer*, p. 272.

[51] Teitel, *Breaking*, pp. 112–113.

The Bell Aircraft Corporation's design team worked closely with both Air Force and NACA engineers to create the X-1 (initially named the XS-1 for Experimental Supersonic). This marked a new era for the NACA, as "[t]his was the first time that the Langley staff had been involved in the initial design and construction of a complex research plane…[and]…this sort of collaboration marked a significant departure in NACA procedures."[52] This collaboration eventually resulted in a bright orange (highly visible), rocket-powered craft that would be dropped from the bay of a B-29 Superfortress. The narrative of the X-1 has been recounted elsewhere numerous times (see citations in this section). Eventually named for Chuck Yeager's wife, the "Glamorous Glennis" had been flown almost 50 times before Yeager broke the sound barrier in level flight, and he had personally ridden in it 8 times. It was his ninth flight, on 14 October 1947, when Yeager and the Bell X-1 went faster than the speed of sound, reaching Mach 1.06 before the engine burned out and the craft glided onto the dry lake bed of what later became Edwards Air Force Base.[53] This craft currently resides in the Boeing Milestones of Flight Hall at the Smithsonian National Air and Space Museum in Washington, DC.

The NACA's "work with the second X-1 continued in the shadow of its more famous twin but contributed much useful data on transonic flight."[54] However, the accomplishment of breaking the sound barrier dominated headlines and marked a turning point in aeronautical development and subsequent support and attention. As the Cold War emerged with the Berlin blockade and ensuing airlift, the American military and the NACA turned their attention to missile development. The former also began implementing swept-wing designs. At the war's end, North American Aviation was designing several planes with straight wings but was considering redesigns that used wings that were swept backward. This was, however, a considerable gamble at a time when jet power alone had precipitated a massive reconfiguration in aircraft design. The chance was taken with the F-86, which was modified to have its wings swept 35 degrees backward. Imagined as the jet successor to the P-51 Mustang, the F-86 first flew in fall 1947 and went on to set a new world speed record of 671 miles per hour.[55] Within a few years, the F-86 Sabre would prove a worthy adversary to the Soviets' similarly swept-wing MiG-15 in the skies over Korea, and the design became widely implemented.

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[52] Bilstein, *Orders*, p. 37.

[53] Pisano et al., *Chuck Yeager*, pp. 9–10.

[54] Ibid., p. 101.

[55] Hartman, *Adventures in Research*, p. 122.

BLUNT-BODY SOLUTION: HARBINGER OF SPACE?

One historian of Ames refers to the years from 1952 to 1957 as "The Lean Years" at the laboratory and for the NACA.[56] Undoubtedly, money had become an issue, as government salaries could not compete with those offered by private industry. The NACA, however, continued to expand and make contributions to aeronautical research. By the middle of the 1950s, the NACA could boast of "modern research facilities that had cost a total of $300 million, and a staff totaling 7200." John Stack won another Collier Trophy, along with Lawrence D. Bell (president of the eponymous company) and Captain Chuck Yeager, for breaking the sound barrier. Stack had helped implement the slotted-throat design, which made the first transonic wind tunnel possible. Testing in the new transonic and supersonic Unitary Plan facilities was in high demand. The West Coast aircraft industry quickly seized on their availability: "[I]t is not overstating the importance of the tunnels to claim that almost all high-performance US aircraft flying today or about to fly have been tested at Ames. In later years, almost all NASA manned space vehicles, including the Space Shuttle, were tested in the Ames Unitary Plan tunnel complex."[57]

In 1954, NACA Chairman Jerome Hunsaker and Hugh Dryden met with President Eisenhower to plead their case for a $13 million increase in the 1956 budget to place unitary tunnels into full operation and undertake new research.[58] Dryden was a hardline supporter of super- and hypersonic flight research and, in addition to being the NACA's Director, had recently been named the chairman of the new Air Force–Navy–NACA Research Airplane Committee.[59] The NACA got its request for 1956 and received supplemental funding in 1955; things seemed to be looking up for the NACA.[60] The Committee also began to diversify its research portfolio. Ames was an early adopter of electronic computing facilities to handle data generated by wind tunnel tests and enable advanced flight simulation. By the late 1950s, the lab had leased an IBM 704 to support theoretical research, hinting at Ames's later excellence in high-speed computing.[61] The NACA also devoted a large number of resources to study vertical flight and short-takeoff-and-landing aircraft, which many advocates saw (and continue to see) as the future of aviation.

Without a doubt, however, the Committee primarily dedicated itself to missile research in the 1950s. In 1956, Jerome Hunsaker stepped down as NACA

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[56] Muenger, *Searching the Horizon*, p. 51.

[57] Baals and Corliss, *Wind Tunnels of NASA*.

[58] Roland, *Model*, pp. 279–280.

[59] Teitel, *Breaking*, pp. 147–148.

[60] Roland, *Model*, p. 280.

[61] Hartman, *Adventures in Research*, pp. 244, 286.

chairman. He was succeeded by James H. Doolittle, a retired Air Force general with a doctorate from MIT who, according to historian Alex Roland, was "the personification of what Eisenhower was soon to label the military-industrial complex."[62] Doolittle and Director Dryden crafted a "solid, long-term, scientifically based proposal for a blend of aeronautics and space research."[63] Given Cold War military imperatives and what would soon be known as the "space race" on the horizon, priority was given to rocketry and space-related research.[64] The NACA was encouraged to study problems associated with crewed and uncrewed flight at altitudes of 50 miles and above at speeds from Mach 10 to the velocity needed to escape Earth's gravity (approximately Mach 33). As the Committee had learned from not taking the lead in jet propulsion (having instead focused on more immediate concerns), if they wanted to maintain their reputation as the organization that conducted state-of-the-art research and development, they would need to get in line with new agendas.[65]

Coupled with the issue of *getting* humanmade objects into space, another of the most vexing problems involved how to have an object survive extreme aerodynamic heating during its return to Earth. At Ames Aeronautical Laboratory, H. Julian "Harvey" Allen began researching ballistics reentry. The widespread assumption was that a slender, cone-nosed shape—such as that of contemporary intercontinental ballistic missiles (ICBMs)—would most easily withstand the high heat encountered upon reentering Earth's atmosphere. In 1952, Allen completely overturned this notion when he proposed the blunt-body theory. He calculated that a blunt body's movement through the atmosphere creates a bow-shock wave that spreads the heat encountered by the object around the body itself (see figure). This realization led to the shape of the Mercury capsules and has informed the design of all reentry vehicles since, including Gemini and Apollo spacecraft, ICBMs, and the Space Shuttle.[66]

While flight research continued at NACA laboratories and stations, notably in the design and test flights of X-planes, space-related projects began to consume more and more resources. Under Dryden's directorship, the NACA ran studies of potential human spaceflight programs in tandem with studies leading to the X-15 (a hypersonic plane that remains the world's fastest piloted craft) and other research activities. Many administrators saw space research as a natural, evolutionary new direction. After all, going into space was only further pushing the limits of velocity

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[62] Roland, *Model*, pp. 284–285.

[63] Bilstein, *Orders*, p. 47.

[64] Ibid., pp. 43–44.

[65] Roland, *Model*, p. 278.

[66] Muenger, *Searching the Horizon*, pp. 66–68.

and altitude. Many employees within the NACA felt that they could conduct space research much like business as usual, modeled on the X-15 joint program, without any large-scale organizational changes. The NACA coordinated with the Advanced Research Projects Agency—a new Department of Defense branch responsible for space activities—and was expected to add a new Space Flight Research Center to its laboratories.

Nevertheless, this was not to be. Led by science advisor James Killian, a President's Scientific Advisory Committee (PSAC) panel recommended that a new civilian agency be built around and include existing NACA facilities. On 29 July 1958, the National Aeronautics and Space Act was passed by Congress and signed by President Eisenhower. Shortly after that, Thomas "Keith" Glennan was sworn in as head of the National Aeronautics and Space Administration, with Hugh Dryden accepting the Deputy Administrator's role.[67] Many NACA employees lamented the reorientation of the laboratories within NASA and begrudged the increased—even, seemingly, exclusive—attention given to spaceflight research. To this day, NASA aviation systems scientists and engineers are quick to remind anyone that the first *A* in NASA stands for "Aeronautics."

AN ERA ENDS AND GOES OUT OF THIS WORLD

A number of historians have considered why the NACA was dissolved instead of being funded and continuing with its air and space research programs. Certainly, there were political and economic motivations for the creation of NASA—a big-budget, "all-hands" civilian space effort. Historian Alex Roland quite harshly supplemented these reasons with the assertion that the NACA simply did not deserve to continue in its own right. He argued that congressional support of the Committee had diminished because no one knew what to do with it. However, this claim overlooks the huge postwar federal investments to create new NACA laboratories and Unitary Plan facilities.[68] In a more ad hominem attack, Roland asserts: "The men and women of the NACA were not as creative, innovative, and effective as they said or believed," mostly due to absorbing their propaganda and through long careers that bred loyalty.[69] However, Roland somewhat backs away from this indictment and provides a longer analysis of why the NACA was dissolved. In short: the Eisenhower administration wanted to balance the federal

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[67] Roland, *Model*, p. 299.

[68] Ibid., p. 223.

[69] Ibid., p. 301.

budget, which resulted in widespread budget cuts. The NACA also had made an enemy in Congressman Albert R. Thomas (D-TX), chairman of the Independent Offices Appropriations Subcommittee of the House Appropriations Committee. He appeared to have a vendetta against the agency and cut the NACA's appropriations to below recommended amounts. Thomas then initiated an audit of the NACA, which reported that the Committee was no longer fit to conduct aeronautical research. Its organizational structure was inappropriate for its large size. This was not an unwarranted assessment. By the mid-1950s, the NACA had grown from 12 committeemen and a clerk in 1915 to a staff of 8,000, occupying three laboratories and subsidiary facilities valued at more than $300 million. In order to recoup its economic losses, the NACA had morphed into a service agency, as opposed to its previous status as the "autonomous, premier aeronautical research institution in America." As mentioned earlier, attracting and retaining talent became very difficult for NACA laboratories; they could not offer the same salaries as private industry. While some old-timers stayed out of loyalty, younger engineers took short apprenticeships at the NACA before moving on to careers where they could earn larger paychecks.[70]

The most convincing yet poignant reason that the NACA was eliminated, cited by Roland, is one that needs to be considered very carefully. Aviation was not a brand-new field anymore, and tons of research had already been done. Roland sympathetically notes: "In many ways, the NACA had achieved what its founders set out to do: contribute to the establishment of a thriving technology in the United States, a technology that could now survive without a government agency devoted exclusively to its nurture. Thus, in a most significant way, the NACA was laid to rest because it had accomplished what it set out to do."[71] Nevertheless, although the field had surely matured, there remained (and remain) numerous aeronautical problems that beg for solutions. Ames Aeronautical Laboratory became Ames Research Center (per NASA's conventions) rather against the will of its people. Many longtime employees chose to leave Ames rather than give in to subordination to NASA and reorientation toward spaceflight research. "What about aeronautics?" asked one engineer who did not feel enthusiastic about conducting space-related work. "There was still plenty to do."[72]

Indeed, a crucial component that is often left out of this story is the priority given to image-making objectives of the U.S. government and the psychological benefits to be reaped by accomplishing "firsts" in space, rather than anything

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[70] Ibid., pp. 263–265, 267, 273, 275–277, 287.

[71] Ibid., pp. 301–303.

[72] Muenger, *Searching the Horizon*, p. 96.

having to do with the stagnation of aeronautical research, or presence of new competitors, or any other factors. The 1957 Soviet launch of Sputnik played a huge role in catalyzing the development of NASA and the general movement away from pure aeronautical research (outside of the Department of Defense). This idea is not new, but it should play a more prominent role in understanding the dissolution of the NACA. Even Roland noted that "Sputnik provided the spark that set it off [the emphasis on space], and though it only smoldered for a while, soon the old agency [the NACA] was consumed in flames it was powerless to quench."[73] However, the NACA was less consumed and burnt to a crisp as it was integrated into what would become a much larger enterprise, serving as the foundational nugget for NASA. After President Eisenhower issued the memorandum to create NASA on 24 March 1958, James Killian's PSAC determined that the NACA would serve as the best originating system of laboratories and facilities, as it was a historic aeronautical research institution with "tempered" military ties. These attributes gave it favor over other prospects, such as the Atomic Energy Commission or the Advanced Research Projects Agency. By that fall, the NACA had restructured, and other outfits were absorbed under the NASA umbrella as well, such as the Army Ballistic Missile Association.[74] It made sense that the NACA would serve as the nucleus for the newly formed National Aeronautics and Space Administration. Its selection was obvious, in fact, due to its contributions to rocketry, high-speed research, and aerodynamic design. That it would be absorbed into a new agency rather than reimagined on its own, however, also resulted from misguided assumptions of postwar NACA administrators.

A growing consensus urged the creation of a national space program, and the Committee found itself primed to provide the foundation for such an effort. Its research-oriented ambitions made it politically more viable than a program run by the Department of Defense (DOD) or the Atomic Energy Commission, which might raise Cold War tensions. At the same time, the NACA had a history of working with the military to enable potential technology transfer between the civilian space program and DOD space efforts.[75] On the other hand, although the NACA had recovered esteem in the 1950s, as academia and industry increasingly built their own laboratories, the work of the NACA no longer seemed unique or indispensable. Nevertheless, the launch of Sputnik seemed to ensure that the NACA would be a primary actor in spaceflight research. The NACA created a Special Committee on Space Technology, headed by H. Guyford Stever, then associate

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[73] Roland, *Model*, p. 283.

[74] Teitel, *Breaking*, pp. 263–265.

[75] Bilstein, *Orders*, p. 47.

dean of engineering at MIT. This Committee produced a series of papers "in which the NACA made its formal claim to be selected as the agency that would conduct US space research." Many within the aviation community vocally asserted that the NACA was "'the Logical Space Agency' and a 'Spearhead of Progress.'" These endorsements were not enough and were overshadowed by those in scientific and political circles who considered the NACA "too small [although elsewhere described too large], too *inexperienced*, and above all *too conservative* to rise fully to the challenge of space" (emphases added).[76]

NASA, the new civilian space agency, would instead lead this effort, with T. Keith Glennan at its helm, personally nominated by Eisenhower. Glennan was president of the Case Institute of Technology and former commissioner of the Atomic Energy Commission. The three aeronautical laboratories were renamed "Research Centers" and, along with the two NACA stations, were transferred a few months later to the National Aeronautics and Space Administration. In a video appearance, newly appointed Administrator Glennan addressed the (former) employees of the NACA:

> Now NASA will be different from NACA—that is inevitable, of course—because, in many ways, NASA's job will be different. But, and this is extremely important both to you and to me as individuals, and to the success of our mission, NASA must be like NACA in the qualities of strength and character that make an organization great.[77]

Hugh Dryden was appointed Deputy Administrator of NASA and stood by Glennan in this video report. Many of the employees watching were frustrated because they had wanted Dryden to be appointed head of the Agency. According to an early historian of Ames, "For old-timers at Ames especially, far from Washington and not especially sympathetic to political realities, Glennan's appointment seemed ludicrous."[78] This was mainly because Glennan was a bureaucrat—not an engineer. However, it is worth noting that both Glennan and NASA's second Administrator, James E. Webb, accepted their posts only on the condition that Dryden would serve as Deputy Administrator.[79] This was, however, the end of an era. As NASA

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[76] Roland, *Model*, pp. 292, 294.

[77] "Creation of NASA: Message to Employees of NACA from T. Keith Glennan 1958 NASA," *https://www.youtube.com/watch?v=td482FjThYM* (accessed 27 January 2023).

[78] Muenger, *Searching the Horizon*, p. 117.

[79] Eugene Morlock Emme, "'With a View to Their Practical Solution': Sixty Years with the NACA and NASA, 1915–1975," Winter Colloquium Series, Langley Research Center, Hampton, VA, 9 February 1976, p. 80, available on microform, publisher: National Aeronautics and Space Administration, 1976, Langley Research Center, Hampton, VA.

developed, its administration grew more complex and organization charts harder to follow, showing "greater differentiation among the non-research segments…, a symptom of the growing bureaucracy." With NASA also came a huge outpouring of energy into public relations and community involvement. Ames historian Elizabeth Muenger argues that project management's introduction was the largest change (and the final straw for many).[80] Jack Boyd, senior advisor to the Ames Director, recalled that, as organizational charts became increasingly indecipherable, the first Director of Ames Aeronautical Laboratory *and* Ames Research Center, Smith De France, believed that "when you put a man in a box you might as well bury him."[81] Coupled with the denigration of aeronautical research at NASA, engineers and other workers voted with their feet as to where their loyalty and research interests lay. Such movements were not only limited to the often invisible masses of NASA workers.

The NACA's plan for Project Mercury was accepted in 1958, to be headed by Robert R. Gilruth from Langley.[82] In 1961, Collier Trophy–winning John Stack became Director of Aeronautical Research at NASA. However, one year later, Stack was certain that the first *A* in NASA was being erased forever in favor of research in space technology and funding devoted to human spaceflight. After NASA's annual R&D budget for aeronautics dipped below 1 million dollars in 1962, Stack resigned from the Agency after 34 years of government service. He became vice president for engineering at Republic Aircraft Corporation (and later Fairchild Hiller) on Long Island and served until 1971, one year before his death.[83] As of 2018, aeronautical research at NASA is down to a paltry 3 percent of NASA's total operations. While the Cold War is becoming a distant memory, NASA culture has persisted, and the Agency conducts business in much the same ways that it did during the Apollo era. There are efforts to send astronauts back to the Moon and on to Mars, but lacking the Cold War political impetus, the pursuit of such triumphs feels awkward, wasteful, and unnecessarily grandiose. Even in the 1960s, with social upheavals and movements such as civil rights occurring in America, many citizens argued that tax dollars would be better spent on domestic concerns rather than used to engage in never-ending feats boasting of technological prowess. Those at the newly renamed NASA Centers were concerned as well. They did not know if it would be possible

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[80] Muenger, *Searching the Horizon*, pp. 117, 122, 199.

[81] Glenn E. Bugos, *Atmosphere of Freedom: 75 Years at the NASA Ames Research Center* (Washington, DC: NASA SP-2014-4314, 2014), p. 2.

[82] Hansen, *Engineer*, p. 385.

[83] Ibid., p. 390; Anderson, "Research," p. 89.

to “protect NASA’s laboratory research from a starvation arising from public and political pressures for spectacular space achievements.”[84]

In today’s era of highly successful commercial spaceflight operations, the administration would do well to reconsider its purpose in American society. Space missions and planetary science deserve support, but so do NASA’s ambitions in air traffic management, aviation safety, human performance studies, and rotorcraft design. These are only a few areas currently operating with disproportionately meager budgets. A reimagining of the NACA’s methods and areas of expertise—namely, aeronautical research—might be one way that the National Aeronautics and Space Administration finds relevance in the 21st century.

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[84] Hartman, *Adventures in Research*, p. 315.

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ACRONYMS AND ABBREVIATIONS

A&R	Assembly and Repair
AAF	Army Air Forces
ACM	Air Chief Marshal
AIAA	American Institute of Aeronautics and Astronautics
AML	Anne Morrow Lindbergh
A.N.T.	Andrei N. Tupolev
A.R.I.	Aeronautical Research Institute
AWPD	American War Plans Division
BOB	Bureau of the Budget
CAL	Charles A. Lindbergh
Caltech	California Institute of Technology
CAP	combat air patrol
CASU	Carrier Aircraft Service Unit
CATD	Captured Air Technical Documents
CIC	Combat Information Center
CINCPAC	Commander in Chief, Pacific Fleet
CKC	Charles Kettering Collection
COMAIRPAC	Commander Aircraft, Pacific Fleet
CSSC	Communications Support Services Center
DOD	Department of Defense
D.V.L.	Deutsche Versuchsanstalt für Luft-fahrt
FDO	Fighter Director Officer
FST	Full-Scale Wind Tunnel
GALCIT	Guggenheim Aeronautical Laboratory, California Institute of Technology
GM	General Motors
HRC	Historical Reference Collection
HST	High-Speed Tunnel
ICBM	intercontinental ballistic missile
IFF	Identification Friend or Foe
JSA	Joseph S. Ames
kph	kilometers per hour

KUA	Kettering University Archives
Loran	Long Range Navigation
MIT	Massachusetts Institute of Technology
MPH	miles per hour
MR	Memorandum Report
NACA	National Advisory Committee for Aeronautics
NARA	National Archives and Records Administration
NASA	National Aeronautics and Space Administration
NASM	National Air and Space Museum
NBS	Norden bombsight
NDRC	National Defense Research Committee
NKAP	People's Commissariat for the Aircraft Industry
NKVD	People's Commissariat for Internal Affairs (Soviet Union Secret Police)
OKB	Soviet Design Bureau
PRT	Propeller Research Tunnel
PSAC	President's Scientific Advisory Committee
PTF	Propulsion Technical Files
R&D	research and development
RAF	Royal Air Force
R.L.M.	Reichsluftfahrtministerium
R.M.	Reichsmark
Servron	Service Squadron
SI	Smithsonian Institution
SS-1	Sub-Stratosphere-1
TF	task force
TG	task group
TM	Technical Memorandum
TN	Technical Note
TNA	The National Archives of the United Kingdom
TR	Technical Report
TsAGI	Tsentral'nyi aeroghidrodinamicheskyi Institut, or Central Aerohydrodynamic Institute
VDM	Vereinigte Deutsche Metallwerke
VDT	Variable Density Tunnel
VHF	very-high-frequency
VTOL	vertical take-off and landing
VVS	Voyenno-Vozdushnyye Sily
USA	U.S. Army
USAAF	U.S. Army Air Forces
USAF	U.S. Air Force
USSBS	United States Strategic Bombing Survey
VVS	Voyenno-Vozdushnyye Sily
WWI	World War I
WWII	World War II

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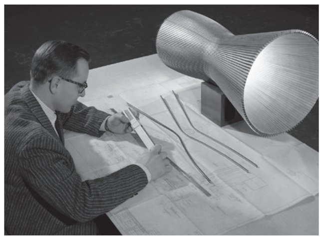
DURING WORLD WAR II, advances in aviation became unmistakable. Many nations' air forces entered the war flying biplane aircraft that were not much different from their predecessors of the previous war. They were soon eclipsed by aircraft that took advantage of new designs that utilized many aeronautical advances of the interwar period such as new powerplants, stressed-skin aluminum structures, and aerodynamic improvements. During the war, new technologies emerged and developed, such as jet-powered aircraft, which would come to dominate post–World War II military aviation.

In this volume, each chapter has been written by a recognized authority in their field and draws upon the most recent research on their topic. This volume investigates a broad range of topics associated with aeronautical research and development that took place during the war within both Allied and Axis countries. It also demonstrates how the technological improvements conducted from their research were critical to those on the front line of combat as well as how wartime expedience and technology required institutions to adapt to the world crisis.



FRONT COVER: In this 1943 photograph, a Douglas A-26B Invader airplane is tested in the 40- by 80-foot wind tunnel at Ames Aeronautical Laboratory.

BACK COVER: **Left:** An engineer at NASA's Lewis Research Center examines the details of a 20,000-pound-thrust regeneratively cooled rocket engine. **Middle:** An early prototype of the Lockheed P-38 Lightning: an aircraft that performed at a level not seen previously. **Right:** Human computers at work during World War II calculating data from the Ames 16-foot wind tunnel.

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