The Strategy of the Boffins

Lessons from Britain's Radar Innovations for Policymakers Today

Fidel Cortes

Countries must innovate in peacetime or risk confronting tomorrow's challenges with only yesterday's tools. Even more challenging is when nations must innovate to regain lost ground to rivals with more personnel and equipment who are advancing technologically. In these cases, the gap is so vast that the only hope of staying competitive is through strategic innovation. *Strategic innovation* refers to the process by which a user finds an application for a technology that fundamentally reshapes how power is generated, transforming the nature of the competition itself.[1]

In the mid-1930s, advances in aviation technology and an underfunding of the Royal Air Force (RAF) had left the United Kingdom outnumbered in the skies and defenseless from attacks by enemy bomber fleets. The RAF turned to the nascent technological discovery of radar.[2] Radar sites would use radio signals to locate enemy planes further away and more accurately than could human observers. The RAF integrated radar's radio-location capabilities with a centralized command-and-control system to orchestrate fighter engagements, developing a strategic innovation in air warfare. An outnumbered defender in the skies could conserve its scarce forces by offsetting inferiority in numbers with efficient employment of existing fighters. The investment in radar that started in 1935 allowed the British to have a new air defense system operational by the start of World War II in September 1939. This allowed the RAF to win the Battle of Britain (July to October 1940) by protracting the fighting until the Germans gave up on their goal of establishing air superiority in advance of an amphibious invasion.[3]

The story outlined above is well recounted by historians but deserves reexamination to ascertain the role that scientific and technical experts played at that time and what lessons we can learn to help address today's strategic challenges. Like the British in World War II, the United States may find the margin between victory and defeat in the early phases of a conflict depending on peacetime strategic innovations. While extensive scholarship exists on organizational traits that favor innovation, there is room to explore further how involving science and technology experts in nontechnical matters can lead to rapid and successful strategic innovations.[4]

This study contends that the RAF's decision to involve civilian scientific and technical experts in strategy, operations, and tactics was central to the British ability to innovate effectively with radar. It adapts the late US Air Force Colonel John Boyd's Observation-Orientation-Decision-Action time cycle (aka the OODA loop) to the context of innovation in strategic competition.[5] The paper highlights the vital role of civilian science and technology experts known as *boffins*—a term that the military probably first used in the late 1930s for uncertain reasons—in collaborating with military professionals in military strategy, operations, and tactics between January 1935 and September 1939, which proved essential to British success in strategic innovation with radar.[6]

INNOVATION AS AN OODA LOOP

An organization that strategically innovates quickly and effectively is an example of the OODA loop at work. Boyd's OODA paradigm explains success or failure by focusing on the speed and quality of decision making. First, a person or organization observes a vulnerability from another actor's activity or change in its environment. The actor then orients itself to understand everything it knows about the situation and consider responses using its training, education, culture, and personality. It decides on a course of action based on the available choices. And then acts on the decision. The process then begins anew.[7] In the context of strategic competition, whoever can execute their OODA loop faster to innovate compels their rivals to react to their new capabilities.

THE BOFFINS OF THE TIZARD COMMITTEE

The pivotal element in the OODA loop that led to a strategically transformative innovation for the RAF was the participation of boffins.[8] While the British military received help from countless boffins before and during the war, the development of radar would not have been possible without the direct involvement of the civilian academics of the Committee for the Scientific Survey of Air Defence, also known as the Tizard Committee after its chair, Henry Tizard. This study does not question or diminish the contributions of Air Marshall Sir Hugh Dowding in supporting investment in radar or the practical work of radio engineer Robert Watson-Watt in equipment development. The Tizard Committee played a crucial role in radar's success, advocating to the RAF for resources to support the efforts most likely to bear fruit and providing focus and guidance to the program.[9]

The Air Ministry formed the Tizard Committee in January 1935, tasking it with finding scientific approaches to improving British air defenses under Dowding's supervision. The committee combined impressive academic credentials with practical familiarity with military issues. Tizard, a chemist by training, had a distinguished career as an academic administrator, which parallelled his service as the chair of the Air Ministry's Aeronautical Research Committee. Other members included Harry T. Wimperis, an aeronautical engineer who served as the Air Ministry's director of scientific research; Archibald V. Hill, a Nobel Prize winner in physiology; Patrick Blackett, a future Nobel Prize recipient in physics; and the committee's secretary, Albert P. Rowe. In addition to their academic credentials, all members had seen military service in World War I—Tizard flew in the Royal Flying Corps, Wimperis served in the Royal Navy Air Service, Hill had done work in anti-aircraft artillery, and Blackett had served in the Royal Navy.[10]

The involvement of scientific and technical experts in making science-based recommendations on RAF strategy, operations, and tactics was an innovation in military problem solving. Previously, the RAF limited civilian experts' input to equipment development and design, but not weaponry, operations, or tactics development. In response to public pressure for action, the RAF's need for workable solutions had grown so acute that career military men would consider recommendations from civilian academics. The committee could only make recommendations, and military professionals in the RAF and the Air Ministry could reject proposals that did not adhere to sound military logic or align with military requirements.[11]

OBSERVATION: RECOGNIZING THE AIR DEFENSE PROBLEM

What did senior British civilians and military officers see in January 1935 that compelled them to innovate and found them receptive to civilian scientific input? By the mid-1930s, two trends had created a significant shift in the strategic environment that compelled senior British civilians and military officers to pursue innovations in air defense, since they could no longer expect adequate security from an adversary's direct attack by means of the Royal Navy's protection alone. An opponent with a large bomber force could attack British cities, towns, ports, factories, and military installations with relative impunity. First, advances in aeronautical engineering meant bombers could fly at speeds that would allow them to reach their targets before an RAF response. Second, years of peacetime underinvestment had created a military unprepared for conflict, while its potential foe, Germany, pursued a massive rearmament program.[12]

In 1932, Prime Minister Stanley Baldwin warned in the House of Commons that countries lacked a practical defense against mass bomber attacks with his often-quoted pronouncement, “The bomber will always get through.” The United Kingdom first recognized its vulnerability to attack from the skies during the Great War; London saw its first significant attack in 1917. The tactics of the time called for standing patrols of fighters defending likely target areas. Defenders also benefited from early aircraft models flying slowly enough that once observers on the coast reported their approach, fighters had plenty of time to intercept them. Since 1918, aeronautical engineering advances had allowed leading militaries to develop ever newer models, each able to fly successively higher and faster than its predecessors. The gains in speed and altitude eroded the time available to react once observers saw or heard an attacking formation. Defenders could not keep planes constantly in the air to protect all likely targets. The RAF’s annual air defense exercise in 1934 drew attention to its inability to defend against attacks; fighters could only intercept two out of every five attacking planes, confirming Britain’s air defense impotence.[13]

While Baldwin spoke to highlight the need to restrict or outlaw bomber attacks, his statement instead called public attention to the country’s vulnerability, which a more hostile international scene only worsened. The rise of a militaristic Nazi Germany in 1933 drew attention to Britain’s underinvestment in its defense since the Great War and the military services’ poor state of readiness. Between 1919 and 1932, the “Ten-Year Rule” mandated the military services to assume for the purposes of their budget plans that the United Kingdom would fight no major wars war for ten years. Combined with drastic peacetime defense spending cuts and its status as the junior military service to the Royal Navy and the British Army, the RAF in 1934 only had about eight hundred planes. In contrast, Nazi Germany had begun rearming itself, first secretly in 1933 and then openly in 1935. That year, the Luftwaffe had almost two thousand planes and was building more each year, reaching about four thousand by July 1940.[14]

Economic depression in the 1930s, however, constrained the Ramsay MacDonald government and Parliament’s ability to make all the investments it needed to modernize. Despite pressure from more hawkish members of Parliament, most prominently Winston Churchill, for a more expansive spending bill, the MacDonald regime chose to prioritize the expansion of the RAF over other expenditures. The MacDonald government based its decision on its assessment that given the time and resource investments necessary to change the military balance at sea and the rapidly advancing level of technology in air warfare, Germany would be most able to directly threaten the United Kingdom from the air in the near term. In July 1934, the MacDonald regime and Parliament agreed to a fifty-million-pound rearmament bill, weighted in favor of funding RAF needs over the other more senior services.[15]

The bill began an RAF expansion that would allow it to field about nine hundred fighters by July 1940, but to use this force, the RAF needed the means to detect attacking bombers and find them in the skies to intercept them before they could attack their targets.[16] While fighters flew faster than bombers, they still needed enough early warning to have the time to launch and intercept any attacks. A Committee of Imperial Defence report in November 1934 estimated that the RAF needed sixteen minutes of warning to intercept aircraft approaching at 250 miles per hour, the equivalent of detecting an incoming plane about seventy miles from the coast.[17]

Meanwhile, British engineers conducting radio experiments found an anomaly that would solve the early warning problem. In 1932, British General Post Office engineers conducting communications experiments reported that aircraft activity from nearby airfields had affected their signal strength during tests the previous year. The report circulated without attracting any real attention and remained forgotten until January 1934. National Physical Laboratory radio engineer Arnold "Skip" Wilkins brought it to the attention of his supervisor Robert Watson-Watt as the two discussed recommendations in response to an inquiry from the Tizard Committee for scientific solutions to improve British air defenses.[18]

ORIENTATION: ASSESS THE SITUATION TO IDENTIFY SOLUTIONS

There was no doubt what was happening: Britain was vulnerable to bomber attacks. The Air Ministry authorized the formation of the Tizard Committee at a time when the military and political leadership faced public pressure to improve air defenses. The boffins brought to the process a scientific perspective that had not been part of efforts to address the problem. Until the committee's creation, there had been no entity in the British defense establishment with the knowledge and the credibility to find and vet potential solutions.[19]

The immediate impetus for the Tizard Committee came from an internal effort by civilian scientists in the Air Ministry's Scientific Research Directorate to consider scientific solutions to the air defense problem. The willingness of the ministry to consider scientific solutions reflected its desperation to find options that would give the RAF a fighting chance compared to the alternative of almost certain military disaster. However, organizations desperate for answers often succumb to wishful thinking, radical options, and poorly vetted equipment and processes.[20] The Tizard Committee mitigated these risks through a rigorous, methodical, and data-driven critical approach to the problem.[21]

Radar came to the committee's attention by happenstance. Watson-Watt and Wilkins had done calculations for the committee confirming the impracticality of a proposal to develop a "death ray" but wanted to offer a more practical alternative. Wilkins recalled the General Post Office memo from 1932 detailing the effects of passing aircraft on radio signals and suggested radio-wave detection to Watson-Watt as a possibility for the committee to explore. Watson-Watt's memorandum contained Wilkin's calculations that showed the scientific feasibility of using radio waves to locate aircraft. The Tizard Committee found the memo convincing enough to recommend to a member of the Air Council for Supply and Research—and future commander in chief of RAF Fighter Command Sir Hugh Dowding—that Watson-Watt receive ten thousand pounds for further research. Dowding, however, only authorized the funds after Watson-Watt demonstrated the concept satisfactorily in February 1934.[22]

While Watson-Watt worked on the prototype under the committee's supervision, the members also methodically studied the RAF's air defense capabilities and explored other possible science-based solutions. Radar may have been considered a favored front-runner because it came to the committee's early attention. Still, the members recognized that their charge would require more than settling on the first plausible one they found out of desperation. Furthermore, the committee's recommendations would ultimately need to stand up to the scrutiny of Dowding and other senior RAF personnel.

The committee consulted with senior RAF officers and familiarized themselves with every aspect of British air defense operations. It also considered proposals for different avenues of research of varying degrees of feasibility. While the committee would continue to explore other options for development, radar had emerged by the summer of 1935 as the best prospect to become a usable capability in the next few years. From the outset, Watson-Watt had proposed building a chain of radar sites along the British coast. All that remained was for the RAF to decide to fund the stations.[23]

DECISION: CHOOSE THE COURSE OF ACTION

Two factors contributed to the quick decision to back radar construction in September 1935. One was Hugh Dowding's support for it; the other was Watson-Watt's progress in developing the basic technology.

Dowding, a believer in unconventional solutions, would fit the description of an "asymmetric thinker" if he lived today. In 1935, he was the most senior officer in the RAF and wielded substantial institutional influence, so any project he supported would receive thoughtful consideration. Furthermore, radar would enable him to make the case that more resources for fighters would not go to waste in the face of competition for funding with strategic bombing advocates in the RAF.[24]

Dowding was a reliable endorser of the Tizard Committee's recommendations for research and development funds. The RAF probably was prepared to commit to radar by the summer of 1935. However, given the costs involved, prudence dictated waiting for a tangible demonstration of progress that Watson-Watt could build equipment with the required capabilities. A satisfactory demonstration of radar equipment that delivered its promised capabilities would provide the necessary evidence to commit to building the radar sites.[25]

In May, Watson-Watt established a research facility at Orfordness, a coastal town about a hundred miles northeast of London. His team had worked through the spring and the summer to turn a scientifically feasible concept on paper into usable equipment that could give the range, bearing, altitude, and numbers of enemy aircraft. The Tizard Committee set the initial goal for equipment that could detect threats at least fifty miles away and within two to three miles of its actual location. By July 1935, Watson-Watt and his team could detect planes forty miles away and distinguish up to three distinct aircraft. By September, he had demonstrated that he could accurately track aircraft flying at seven thousand feet within a margin of error of one thousand feet. The committee had every reason to be optimistic that each iteration would produce further improvement.[26]

While the Tizard Committee would sponsor work in other defensive systems, such as aerial mines and infrared detection, radar effectively cemented its position as the leading option after September's successful demonstration. The Tizard Committee gained the backing of its political supervisors, the Air Defence Sub-Committee of the Committee of Imperial Defence, to construct a system of radar stations along the eastern and southern coasts, known as Chain Home. Parliament approved sixty thousand pounds to build the first five stations in December, to protect the approaches to London.[27] The entire cost to complete all twenty Chain Home stations, which were operational by September 1939, would eventually amount to ten million pounds.[28] This commitment of resources in a time of economic depression—as well as a fundamental redesign of British air defense around a nascent discovery—represented a vote of confidence in radar and in the work of the Tizard Committee.[29]

ACTION: TAKE THE STEPS TO MAKE THE INNOVATION REAL

A timely decision to build Chain Home also gave the RAF as much time as possible to complete four necessary actions to develop a radar-based air defense capability, all conducted with the Tizard Committee's involvement. First, it supervised Watson-Watt and his team's design and construction of the Chain Home stations. Second, the RAF needed a concept for integrating radar into air defense operations as the basis of a new system. Third, the committee worked with the RAF to develop the methods, procedures, and tactics that RAF personnel would need to learn and master for the air defense system to function. Fourth, they had to defend the project against its critics, who questioned the decision to prioritize radar as the centerpiece for air defense.

By fall 1935, Watson-Watt's team shifted from basic equipment design to the construction of the prototype radar station. It would provide the basis for the initial five stations that would protect the most direct approaches to London. Watson-Watt directed his team of radio and television engineers on the principle of what he called "the cult of the imperfect"—delivering suitable-enough systems that could be gotten out as soon as possible to prevent the loss of time in trying to perfect designs. When feasible, they used off-the-shelf rather than custom components. By September 1939, the RAF had built twenty operational Chain Home radar stations that could reliably detect aircraft sixty to seventy miles out and, under the most favorable conditions, over one hundred miles out.[30]

Early in its work, the Tizard Committee began thinking through how radar would function together with command-and-control sites and the fighter squadrons as part of a system. Integrating radar with command-and-control processes and fighter tactics made it a practical strategic innovation based on a new paradigm for military operations. While Dowding became synonymous with radar-based air defense—so much so that it remains known as the Dowding System today—the concepts originated from the Tizard Committee's work. Instead of dispersing resources in an unsustainable attempt to defend everywhere, all the time, the RAF would dispatch fighters when and where the need was most urgent. Enabling this new concept for air defense relied on three tactical-level innovations that could only have occurred with the development of radar: first, the location and tracking of enemy aircraft by electronic means; second, the compilation and assessment of enemy locations collected by radar and other means to create an operational picture to guide fighter actions; and third, the use of radar data to direct fighters to enemy locations.[31]

At the urging of the Tizard Committee, and before the construction of the first working radar station prototype, the RAF began training exercises at Biggin Hill in winter 1936 to develop the specific actions needed to execute the three tactical-level innovations. Tizard and other technical experts were actively involved in the Biggin Hill exercises, introducing methodological rigor to evaluate multiple attempts of every anticipated action to identify the most efficient practices. Tizard, a former pilot, developed the

"Tizzy Angle" to help ground controllers determine the most efficient flight path to direct the earliest interception of attackers. By the end of 1936, the tests at Biggin Hill gave the RAF confidence that they could intercept 90 percent of all daylight raids where attackers stayed at a constant altitude.[32]

Equipment, concepts, and procedural developments mutually reinforced one another, resulting in rapid progress toward operationalizing the new air defense system. Well-defined concepts for the roles of planes, radar, and people—and how they would all interact with one another—provided clear direction and underlying logic to equipment and procedural development. Insights from the equipment construction and process development efforts refined the understanding of the entire air defense system's capabilities and limitations and how to best employ it. The lessons acquired from building equipment and developing the methods to operationalize air defense concepts were beneficial to identifying areas where either the equipment or methods could compensate for the shortcomings of the other or inspire new ways of doing things.

A dispute over the direction of the air defense program almost cost the RAF precious time. The program was mired in political infighting with two influential critics, who acted out of genuine concern that the government could do more to improve the nation's defenses: Winston Churchill and his scientific advisor Frederick Lindemann. Both men's patriotic zeal came with ego; they believed that if only the British government followed their advice, then the country would solve its defense problems. Although out of government at that time, Churchill still wielded enough influence to maneuver a position for Lindemann on the Tizard Committee.[33]

By summer 1936, Lindemann's presence on the committee had become a significant distraction that finally came to a head. Lindemann genuinely wanted to improve Britain's defenses, but the radar was not his idea, and worse for him, Tizard backed it. Once close friends, Tizard and Lindemann had a falling-out that added a personal dimension to their disputes over technology. Lindemann's constant demands that the RAF allocate more resources to develop his favored technologies—namely infrared and aerial mines—became a source of frustration and irritation to other committee members. The committee had considered both technologies in its work but assessed that neither could be made workable in the near term. Infrared detection would require more research and development time than the RAF had available. Aerial mines could easily be seen by attackers and avoided.[34]

Lindemann's antics and political maneuvering to gain more resources for his favored projects had generated so much friction that other critical members resigned in protest.

The Air Ministry and the RAF backed the Tizard Committee and reconstituted it without Lindemann. Given Lindemann's friendship with Churchill, the RAF's move might have prompted the latter to exert political pressure for Lindemann's reinstatement. But Lindemann recognized that taking the matter further would open both him and Churchill to criticism that they were impeding progress on Britain's best near-term hope.[35]

THE OUTCOME

The RAF's success in the Battle of Britain from July to October 1940 is a testament to the success of the RAF's adaptation and the role of the Tizard Committee and other boffins in making that adaptation possible. The system was far from perfect. For example, Chain Home stations could only detect from one direction; human observers remained critical to finding attackers who passed beyond the line of radars. Also, Chain Home lacked the accuracy to direct pilots close enough to see and engage enemy bombers at night, increasing the likelihood that bombers could evade interception.[36]

During the Battle of Britain, radar performed as expected. Between July and October 1940, the Germans would lose almost 2,000 planes at the cost of about 1,500 RAF aircraft, an outcome made possible because the RAF could not only find the Germans but also use their scarce resources against the most pressing threats.[37] Radar enabled outnumbered RAF fighters to contest the daytime skies long enough—at such a high price for the Luftwaffe—that the seasonal window for an amphibious invasion closed. The Luftwaffe abandoned its goal of establishing air supremacy for an invasion. Instead, Germany transitioned to a bombing campaign of cities, known as "the Blitz," that killed more than twenty-three thousand individuals but failed to break the will of the British people.[38]

LESSONS

Radar was only one example of how scientific expertise enabled the British to innovate and adapt to national security threats in World War II. These efforts would continue as the RAF adapted to new German capabilities during the Blitz. While the case of British radar occurred nine decades ago, it remains relevant today and can teach the importance of drawing upon the knowledge of scientific and technical experts to meet the strategic challenges created by a rapidly changing technological environment.

DEVELOP WORKABLE SOLUTIONS TO TOMORROW'S PROBLEMS TODAY

Building a new strategic capability takes years, even under the most favorable conditions. The RAF did not know when the next war would come, but they judged that the

United Kingdom would suffer military defeat or major devastation without urgently developing a workable solution to its lack of air defenses. Policymakers should consider "good enough" solutions that could be effective sooner against specific problems and improve with iteration rather than waiting for optimal solutions to solve all issues—solutions that never arrive.

FOCUS ON DEFINED PROBLEMS TO SOLVE

Scientists and engineers are problem solvers by nature, and the Tizard Committee benefited from having a defined problem that, if solved, would give the RAF a way to counter the strategic challenge of large bomber formations. Policymakers should conduct a comprehensive survey of strategic problems rooted in technology-driven challenges to existing capabilities and identify ways that application of current or emergent technologies could provide near-term solutions.

ADOPT A SYSTEMS-BASED APPROACH TO INNOVATION

From the outset, the Tizard Committee recognized that radar's electronic detection and tracking properties would only be useful if they enabled RAF fighters to shoot down bombers before they could attack their targets. For that to happen, the committee needed to consider how to use radar and fighters as part of an organization. Policymakers, in assessing the viability of a proposed technology, should consider how thoroughly its advocates have thought through how it will function as part of a complete system.

REDUCE AND ELIMINATE BOUNDARIES

The RAF took a risk by allowing scientists and engineers to independently recommend solutions to problems professional military men could not solve. The Tizard Committee's involvement in identifying and vetting potential solutions and building the system ensured unity and consistency of effort that reflected technical feasibility and military practicality.

BUILD TIME AND TRUST

The RAF benefited from long-standing relationships with trusted experts like Tizard and Wimperis, who could tap eager and talented scientists and engineers to work on the air defense problem. Today's national security leadership would benefit from similar relationships with trusted experts in the research and development of frontier technologies to find talent versed in current and imminent developments that could solve contemporary strategic challenges.

DEVELOP FUTURE BOFFINS

The RAF in the 1930s benefited from access to a pool of scientific and technical experts who had served during the Great War and the years after to call on as the first boffins. As younger generations today express less interest in public service, finding civilians who can straddle the worlds of science and technology and national security will be increasingly challenging. Policymakers could broaden opportunities for late-career personnel to receive science, technology, engineering, and mathematics education and allow them to repay the costs of that education with continued service, either in uniform or as civilian employees. Alternatively, the government could conduct national security workshops to build interest in public service among STEM students.

NOTES

1. Williamson Murray and Allan R. Millett, eds., *Military Innovation in the Interwar Period* (Cambridge University Press, 1996), especially Alan Beyerchen, "From Radio to Radar: Interwar Military Adaptation to Technological Change in Germany, the United Kingdom, United States," 265–99.

2. The British called it "radio direction finding," but for simplicity's sake, we will use the more common name *radar*.

3. For primary accounts, see A. P. Rowe, *One Story of Radar* (Cambridge University Press, 1948) and Reginald V. Jones, *Most Secret War: British Scientific Intelligence 1939–1945* (Hamish Hamilton, 1978). For secondary accounts, see Louis Brown, *A Radar History of World War II: Technical and Military Imperatives* (Routledge, 1999); Tony Devereux, *Messenger Gods of Battle: Radio, Radar, Sonar—The Story of Electronics in War* (Brassey's, 1991); Austin M. Duncan, "Innovative Determinants of the First Integrated Air Defense System," *The Strategy Bridge*, May 3, 2018, https://thestrategybridge.org/the-bridge/2018/5/3/innovation-determinants-of-the-worlds-first-integrated-air-defense-system; David E. Fisher, *A Race on the Edge of Time: Radar—The Decisive Weapon of World War II* (McGraw Hill, 1988); Justin Roger Lynch, "The Chain Home Early Warning Radar System: A Case Study in Defense Innovation," *Joint Forces Quarterly* 95 (2019): 100–103; and David Zimmerman, *Britain's Shield: Radar and the Defeat of the Luftwaffe* (Sutton Publishing, 2001).

4. See Murray and Millett, *Military Innovation*; Terry Pierce, *Warfighting and Disruptive Technologies* (Routledge, 2004); and Stephen Rosen, *Winning the Next War: Innovation and the Modern Military* (Cornell University Press, 1994).

5. John R. Boyd, "Patterns of Conflict," unpublished briefing version dated December 1986, accessed March 31, 2025, https://ooda.de/media/john_r_boyd_-_patterns_of_conflict.pdf.

6. Ronald W. Clark, *Rise of the Boffins* (Phoenix House, 1962), vii.

7. Boyd, "Patterns of Conflict."

8. For more on the role of boffins in World War II, see Clark, *Rise of the Boffins*.

9. Beyerchen, "From Radio to Radar," 282–84; and Zimmerman, *Britan's Shield*, 60–77.

10. Clark, *Rise of the Boffins*, 31–33; Fisher, *Race on the Edge of Time*, 96–97; and Rowe, *One Story of Radar*, 6.

11. Beyerchen, "From Radio to Radar," 282–84; Clark, *Rise of the Boffins*, 1–13; Rowe, *One Story of Radar*, 1–2; and Zimmerman, *Britain's Shield*, 60–77.

12. Zimmerman, *Britain's Shield*, 35–43.

13. Clark, *Rise of the Boffins*, 23–25; Fisher, *Race on the Edge*, 10–12; and Zimmerman, *Britain's Shield*, 39–43.

14. Stephen Bungay, *The Most Dangerous Enemy: A History of the Battle of Britain* (Aurum Press, 2015), 106; Royal Air Force Museum, "Expansion at Last," accessed April 3, 2025, https://www

.rafmuseum.org.uk/research/online-exhibitions/history-of-the-battle-of-britain/expansion-at-last/#:~:text=In%201934%2C%2042%20squadrons%20existed,new%20air%20and%20ground%20crews; and Derek Wood and Derek Dempster, *The Narrow Margin. The Battle of Britain and the Rise of Airpower, 1930 and 1940* (Pen and Sword Aviation, 1961), 37.

15. Zimmerman, *Britain's Shield*, 35–39.

16. Bungay, *Most Dangerous Enemy*, 106.

17. Zimmerman, *Britain's Shield*, 39–43.

18. Clark, *Rise of the Boffins*, 32–39; Fisher, *Race on the Edge of Time*, 29–31, 44–49.

19. Clark, *Rise of the Boffins*, 1–13; and Rowe, *One Story of Radar*, 1–10.

20. See Kendrick Kuo, "Dangerous Changes: When Military Innovation Harms Combat Effectiveness," *International Security* 47, no. 2 (2022): 48–87.

21. Zimmerman, *Britain's Shield*, xii, 61–64.

22. Clark, *Rise of the Boffins*, 32–39; and Rowe, *One Story of Radar*, 6–8.

23. Beyerchen, "From Radio to Radar," 279–82; Clark, *Rise of the Boffins*, 48–49; Robert Watson-Watt, "Detection and Location of Aircraft by Radio Methods," February 27, 1935, in S. S. Swords, *Technical History of the Beginnings of Radar* (Institute of Engineering and Technology, 1985), 278–85; and Zimmerman, *Britain's Shield*, 61–77.

24. Beyerchen, "From Radio to Radar," 282; Duncan, "Innovative Determinants"; and Zimmerman, *Britain's Shield*, 55–56.

25. Rowe, *One Story of Radar*, 11–19; and Zimmerman, *Britain's Shield*, 81–86

26. Clark, *Rise of the Boffins*, 39–41; Rowe, *One Story of Radar*, 11–19; and Zimmerman, *Britain's Shield*, 81–86.

27. Otto Kreisher, "Radar from World War II Until Today," *Naval Forces* 3 (2007): 71–72.

28. Walter Kaiser, "A Case Study in the Relationship of History of Technology and of General History: British Radar Technology and Neville Chamberlain's Appeasement Policy," *Icon* 2 (1996): 35.

29. Rowe, *One Story of Radar*, 11–19.

30. Beyerchen, "From Radio to Radar," 281; Rowe, *One Story of Radar*, 44; Zimmerman, *Britain's Shield*, 78–81, 117–31.

31. Beyerchen, "From Radio to Radar," 282–84, 286–87; Clark, *Rise of the Boffins*, 49–54; Imperial War Museum, "What Was the 'Dowding System?,'" accessed April 6, 2025, https://www.iwm.org.uk/history/what-was-the-dowding-system; and Zimmerman, *Britain's Shield*, 109–17.

32. Clark, *Rise of the Boffins*, 49–54; Zimmerman, *Britain's Shield*, 109–17.

33. Clark, *Rise of the Boffins*, 43–46; Zimmerman, *Britain's Shield*, 64–77.

34. Clark, *Rise of the Boffins*, 46–47; Zimmerman, *Britain's Shield*, 93–106.

35. Clark, *Rise of the Boffins*, 47–49; Zimmerman, *Britain's Shield*, 106–8.

36. Imperial War Museum, "Dowding System"; and Rowe, *One Story of Radar*, 39–40.

37. John T. Correll, "How the Luftwaffe Lost the Battle of Britain," *Air & Space Forces Magazine*, August 1, 2008, https://www.airandspaceforces.com/article/0808battle/.

38. National World War II Museum, "The Blitz of 1940," August 27, 2025, https://www.nationalww2museum.org/war/articles/blitz-1940.

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Preferred citation: Fidel Cortes, "The Strategy of the Boffins: Lessons from Britain's Radar Innovations for Policymakers Today," Hoover Institution, Working Group on the Role of Military History in Contemporary Conflict, March 2026.

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