TECHNOLOGICAL INNOVATION DURING PROTRACTED WAR:

RADAR AND ATOMIC WEAPONS IN WORLD WAR II

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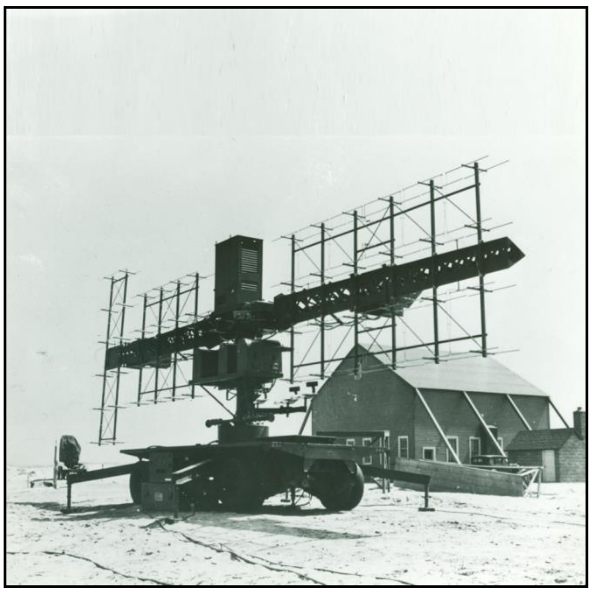
April 2015



Prepared for the Director, Net Assessment

Office of the Secretary of Defense

Contract HQ0034—10-D-0007-0005

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Strategic Analysis & Assessments

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Executive Summary

Over the last two decades, the conventional conflicts in which the U.S. military has participated have been brief and highly successful. Major combat operations in the First Gulf War lasted six weeks and the ground campaign ended after just 100 hours. In the Second Gulf War, Baghdad fell less than a month after Allied forces entered Iraq. Because the wars were so brief, the US military employed the same weapons systems at the end of the conflicts as were available at the beginning. Subsequent wargaming has continued to focus on relatively short conflicts in which changes in military technology play, at most, only limited roles.

The U.S. military's rapid success in recent conventional conflicts may have contributed to a focus on peacetime innovation in the extant literature on military and technological innovation. There is a significant body of work, for example, on military innovation during the interwar era. As a result, historians have concentrated on identifying the sources of peacetime innovation and paid relatively little attention to how to maintain or accelerate innovation during wartime or to the effects of wartime innovation on the conduct of military operations.

Future wars between countries possessing technologies such as reconnaissance-strike complexes, however, may be more protracted than recent conflicts as adversaries struggle to project power and rely more heavily on long-range systems. The Soviets, for one, believed that the Military-Technical Revolution would result in protracted conventional conflicts. Numerous players in Defense Department wargames looking at Asian contingencies set in 2035 have indicated that such conflicts could last a long time as combatants seek to achieve their goals over great distances while managing escalation.

During such protracted conflicts, new technologies may be introduced, resulting in new military capabilities. Radar research and development was underway simultaneously in Great Britain, Germany, the United States, and Japan by the early 1930s. The Germans led in terms of technical innovation but the British were more successful in the operational development of radar by the outbreak of war in 1939. Once the war began, Anglo-American cooperation on radar development accelerated and the Germans fell behind, never to catch up. The Japanese military demonstrated little interest in radar before the outbreak of war in Europe and thus lagged far behind. Similarly, Germany led in atomic research during the 1930s. In 1938, German scientists were the first to successfully split a uranium atom by bombarding it with neutrons. After the United States entered World War II, however, President Roosevelt gave the development of nuclear weapons top priority. German interest in the development of nuclear weapons never fully materialized.

The evidence from the development of radar and atomic weaponry before and during World War II suggests several potential insights regarding technological innovation during protracted conflict.

Large-scale efforts to develop new technologies benefit from centralized, coordinated direction.

The British effort to develop radar, for example, benefited greatly from the direction and funding provided from the Tizard Committee. The German effort, in contrast, was plagued by too many competing agencies and research programs that did not communicate well with one another. The United States lagged behind both Germany and Great Britain in radar research and development during the interwar era due, in part, to the lack any central direction to provide focus for its compartmentalized research effort. The creation of special agencies, such as the NDRC and the OSRD, at the highest levels of government to coordinate scientific research for the military and of laboratories such as the Rad Lab at MIT to perform the research provided a tremendous boost to the American radar program. Japan lacked a centralized effort to address the critical technical problems in the development of radar for virtually the entire war. The Japanese Army and the Japanese Navy conducted their own independent radar research programs. The research efforts were not coordinated within each service, much less between the two services.

The history of atomic research in the United States also demonstrates the importance of centralized direction for technological development. Participants in the Manhattan Project have commented that the United States could never have built the atomic bomb in peacetime given traditional congressional restrictions on federal spending. The outbreak of World War II in Europe and the growing prospect of U.S. entry into the war provided the impetus for the creation of the NDRC and the OSRD. Without the direction provided by those institutions, the development of the bomb may not have been possible, certainly not in as timely a manner.

In contrast, Japan lacked any centralized office to coordinate all its atomic research. Army and Navy research was conducted separately with no real coordination. There was no single military leader in charge in Japan like Groves was in the United States. Technical officers in the military initiated the projects and sought the assistance of civilian scientists when uniformed technicians proved incapable.

In order for such research and development efforts to be successful, they must also have the support of senior leadership.

In Great Britain, Dowding and Tizard provided important direction and significant funding for the development of radar from the start. Churchill was also actively involved in the contribution of science to the war effort, although his assistance was not always beneficial. In Germany, Hitler and Göring were anti-intellectual and scientifically illiterate. Other high-ranking military officers were not much better.

Strong support from senior leaders was also important in the development of atomic weaponry. Roosevelt and Churchill consistently backed development of the atomic bomb, even as they sometimes doubted its feasibility. Hitler, on the other hand, dismissed the German bomb effort and refused to provide it with significant support. The Japanese atomic weapon program also lacked the high-level support necessary to overcome the academic divisions, interservice rivalry, and resource shortages that troubled the program.

Allies can also play an important role in the research and development of new technologies during a protracted conflict.

The British provided valuable radar technology and useful operational experience that facilitated the American development of radar. The British also made an important contribution to the development of the atomic bomb, even if atomic cooperation between Great Britain and the United States did not always proceed smoothly. In contrast, the Germans and the Japanese derived almost no technological benefits from their alliance.

The development of collaborative relationships among the military, academia, private industry contributed significantly to the successful development of new technologies.

Effective collaboration between scientists and military officers was key to American and British success in the development of radar. The British military cooperated closely with scientists U.S. Navy scientists worked closely with the Fleet and private firms to develop radar. Meanwhile, the signals section in the Luftwaffe, which had primary responsibility for conducting research on radar and radio, had little outside contact with civilian researchers.

Similarly, the American atomic research effort depended on extensive collaboration among the military, academia, and private industry. The Army Corps of Engineers, in conjunction with private industry, built the vast facilities necessary to develop the bomb. The Army-directed laboratories at several universities, staffed largely by scientists drawn from academia, conducted much of the research for the bomb project. As noted earlier, the research, assembly, and manufacture facility at Los Alamos was the epitome of a collaborative environment. The work at Los Alamos required intensive collaboration between scientists and engineers.

Applied research and frequent experimentation is more effective than pure research.

British and American researchers would improvise in the laboratory and develop workable devices in advance of a theoretical understanding. Once the British and the Americans developed a new technology, they experimented extensively to understand how to employ it most effectively. In

Germany, the emphasis was on pure research and theory. In some cases, German scientists understood the operational possibilities of their research. However, they often lacked the facilities to experiment or considered experimentation as a less prestigious occupation best left to the engineers of the military staffs.

Interservice rivalry can present a significant obstacle to the development of new technologies.

Interservice rivalry was one of the key factors limiting the advancement of radar in Germany and both radar and atomic weaponry in Japan. In Germany, for example, the Kriegsmarine never told the Luftwaffe about the existence of its highly effective early warning air-search radar. Once the Luftwaffe found out about the radar, the Kriegsmarine worked actively to disrupt the relationship between the Luftwaffe and the private firm that built the radar. In Japan, the Army and the Navy conducted totally separate research program sand produced separate, and sometimes incompatible, radar systems.

Similarly, the Japanese Army and Navy pursued separate atomic programs with little exchange of information or collaboration. On a number of occasions, the services rejected or postponed efforts to improve coordination. Given the limited pool of personnel qualified to conduct nuclear research in Japan, the pursuit of independent atomic research efforts by the services was a significant waste of scarce resources.

Excessive secrecy may also thwart the successful research and development of new technologies.

Although a degree of secrecy is necessary while researching and developing new technologies during wartime, the history of the development of radar and atomic weaponry provides several examples of excessive secrecy slowing down development efforts.

Complacency is dangerous during a protracted conflict.

When World War II began, the Germans were confident that they held a measurable lead over the British in radar. The British, on the other hand, assumed from the start that German science was highly competent and that there were few “safe” areas that the Germans would not explore or where it could be expected that the Allies could maintain a lead without significant effort. Consequently, the British were always looking ahead and planning for the next potential development of radar.

Technical advantage is meaningless without a broader understanding of the operational implications of the new technology.

In 1939, the German and American prototype radar sets were superior to almost all the British radar sets. Chain Home, the heart of the British radar system, was considered obsolete, but it worked. The British recognized the value of radar early and understood that it was not enough to have the information provided by radar, it was necessary to act upon it quickly. Thus, the British began building a system to analyze the information provided by radar and communicate with the fighters rapidly in order to direct them to intercept enemy bombers. By September 1939, the British had a functional air defense system. The Germans and Americans had a few operational sets but no effective organization to use them.

INTRODUCTION

Over the last two decades, the conventional conflicts in which the U.S. military has participated have been brief and highly successful. Major combat operations in the First Gulf War lasted six weeks and the ground campaign ended after just 100 hours. In the Second Gulf War, Baghdad fell less than a month after Allied forces entered Iraq. Because the wars were so brief, the US military employed the same weapons systems at the end of the conflicts as were available at the beginning. Subsequent wargaming has continued to focus on relatively short conflicts in which changes in military technology play, at most, only limited roles.

The U.S. military's rapid success in recent conventional conflicts may have contributed to a focus on peacetime innovation in the extant literature on military and technological innovation. There is a significant body of work, for example, on military innovation during the interwar era. As a result, historians have concentrated on identifying the sources of peacetime innovation and paid relatively little attention to how to maintain or accelerate innovation during wartime or to the effects of wartime innovation on the conduct of military operations.

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During such protracted conflicts, technologies may change significantly, resulting in new military capabilities. The radars in service at the end of World War II, for example, bore little resemblance to those used at the beginning of the war. These technological changes could have important effects on the conduct of military operations. As radars became more capable during World War II, commanders used them in different ways. In some cases, different missions required different operational and organizational concepts. Technological changes can also alter the rules of engagement. Once nuclear weapons were developed during World War II, the United States moved away from the previous aerial bombardment strategy of the gradual accumulation of pressure to one of immediate application of maximum pressure. Thus, the United States provided no warning to Japan before it employed the first atomic bomb.

This case study will examine two historical examples of the introduction of new military technology affecting how a long war was fought: radar and atomic weaponry in World War II.[2] It

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[2] The extant literature on radar development shares the same characteristics as the literature on military aviation and armored warfare. Some works, such as Alan Beyerchen's chapter in *Military Innovation in the Interwar Period*,

will focus on two questions – how did the introduction of these two new technologies affect the conduct of military operations and what were the key factors enabling states to develop and introduce new technologies during wartime. To answer the first question, it will look at how technological changes contributed to the development of new military capabilities and missions and how they altered the speed, scope, and character of military missions. It will also consider how technological changes affected the rules of engagement. To answer the second question, it will examine how the different combatants identified and explored new uses for technology, how they developed new designs and organized military production, and how they trained military members to employ the new technology. It will also consider how important technological superiority was for military success compared to numerical superiority.

The objective of the case study is to improve our understanding of technological innovation during protracted conflict. A look at how military technology and operations changed during past protracted conflicts could improve our understanding of what warfare might be like under a precision-strike regime. More explicitly, focusing on the key doctrinal, organizational, training, personnel, and other factors that enabled states to adapt to technological changes may produce insights, guidelines, and metrics that will be useful for senior Department of Defense leadership in their planning and decision-making regarding future warfare.

RADAR IN WORLD WAR II

The forerunner of radar appeared in 1904 when German named Christian Hülsmeyer developed a device that could transmit radio waves and receive their reflection off of passing objects. Hülsmeyer believed it would be useful to prevent ship collisions at sea or aid navigation. Representatives of shipping lines who attended the demonstrations were impressed but unwilling

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concentrate largely on peacetime development before World War II. Others, such as Robert Buderi's *The Invention that Changed the World,* focus largely on radar development in a single country or are directed at a popular audience and emphasize the people and events associated with radar development rather than the technology. The best work on the subject, Louis Brown's *A Radar History of World War II: Technical and Military Imperatives,* discusses every country's radar development program during World War II and considers both the technological development and combat uses of radar. Even Brown's book, however, emphasizes historical description rather than identification and analysis of the key factors that affected states' abilities to develop and effectively employ radar during the war. Finally, the literature on the development of the atomic bomb also tends to focus on efforts in a single country or small number of countries and to emphasize the broad social and political implications of atomic weaponry rather than the insights relevant to Defense decision-makers interested in future warfare. Geoffrey Herrera's chapter on atomic weaponry in Technology and International Transformation: The Railroad, the Atom Bomb, and the Politics of Technological Change, for example, describes efforts in both Germany and the United States but ignores the small Japanese atomic program. It also focuses largely on the international systemic effects of nuclear weapons. Richard Rhodes's prize-winning The Making of the Atomic Bomb also concentrates on the German and American programs and is heavily biographical.

to purchase the device. Capital was scarce and they could already communicate with other ships using wireless so there was no compelling need.[3]

Over the next several decades, radar passed through three stages of technical development. During the first stage from 1904 through the 1920s, there was a growing recognition that radio waves could be used to detect large objects such as ships (with continuous beams of any wavelength). In the second stage during the mid-1930s, researchers generated focused, pulsed radio beams that could be used as floodlights or searchlights of specific wavelengths to warn of the approach of smaller objects such as aircraft. The third stage began with the introduction of centrimetric (microwave) radar in 1940-41, which radically shortened antenna size and improved the precision of target location.[4]

Radar research and development was underway simultaneously in Germany, Great Britain, the United States, and Japan by the early 1930s. The Germans led in terms of technical innovation but focused more on radio and less on radar because their strategic objectives were fundamentally offensive. The British, in contrast, were on the grand strategic defensive. They saw radar as an important counter to German threats, particularly the changes in mobility and speed of combat made possible by radio-coordination. The Americans demonstrated less interest in radar until 1939. Once the war began, Anglo-American cooperation on radar development accelerated and the Germans fell behind, never to catch up. The Japanese military demonstrated little interest in radar before the outbreak of war in Europe and thus lagged far behind.[5]

The introduction of radar and its application to various domains of warfare dramatically affected the conduct of military operations. At sea, Allied naval radar helped locate German U-boats and was crucial to victory in the Battle of the Atlantic. In the Pacific, radar-directed gunfire enabled U.S. battleships to destroy a Japanese fleet steaming through the Surigao Straits at night in the Battle of Leyte Gulf. In the air, the Allies developed chaff and jammers to foil German radar-aided air defenses and developed sophisticated navigational radars to enable bombing at night or through cloud cover. German night fighters hunted enemy aircraft in the dark relying entirely on radar.

Great Britain

In the years following the end of World War I, one of the primary strategic threats to Great Britain was the bomber. German Zeppelins and bombers had conducted several raids against British targets during the war. Although the British eventually developed a defensive system that forced

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[3] Alan Beyerchen, "From Radio to Radar: Interwar Military Adaptation to Technological Change in Germany, the United Kingdom, and the United States," in *Military Innovation in the Interwar Period*, eds. Williamson Murray and Allan R. Millett (Cambridge, U.K., Cambridge University Press, 1996), 265.
[4] Beyerchen, "From Radio to Radar," 291.
[5] Beyerchen, "From Radio to Radar," 268-69.

the Germans to abandon daylight raids and limited the impact of the night raids, the psychological effects of the attacks lingered. Finding a way to confront and defeat the challenge posed by enemy bombers was a central occupation of British defense planning during the interwar era.[6]

One of the keys to stopping enemy bombers was obtaining sufficient warning of an impending attack. In 1934, the Directorate of Scientific Research within the British Air Ministry began to investigate ways to provide adequate warning of air attack. The researchers soon concluded that without new ideas, the British situation was hopeless. They recommended formation of a committee of outside experts to explore alternatives. The Committee for the Scientific Survey of Air Defence is better known as the Tizard committee after its head, Henry Tizard, a chemist, rector of Imperial College, London, and civilian adviser to the Air Ministry. It first met on 28 January 1935. The other members of the committee included the Air Ministry's Director of Scientific Research Harry Wimperis, Nobel Prize-winning biologist A. V. Hill (who had been the head of a World War I research group responsible for improving anti-aircraft gunnery), and physicist Patrick Blackett, who later won the Nobel prize in physics.[7]

One of the areas explored was the development of electromagnetic death rays. Robert Watson Watt, superintendent of the Radio Research Laboratory, led the investigation. When it became clear that a death ray would require too much power to be practical, Watson Watt asked his staff for other ideas that might be useful to the Air Ministry. His staff recalled experiments that post office engineers had conducted to test the properties of various radio frequencies. The experiments had produced unexpected results. A beam shot into the ionosphere returned earlier than expected because it reflected off an aircraft. Watt suggested that electromagnetic radiation might be used to provide early warning of incoming aircraft.[8]

Intrigued, the Tizard committee asked for more information. Watson Watt turned to his junior co-worker, Arnold Wilkins, who wrote a paper entitled "Detection and Location of Aircraft by Radio Methods" on 12 February 1935. Wilkins suggested establishing zones of short-wave radio illumination through which aircraft would have to fly. The radio waves would reflect off the aircraft and provide warning of their approach. A double line of these stations emitting radio waves would provide greater precision in location. It would also be useful to have a central control room to plot the data and transponders on friendly aircraft to distinguish friend from foe. The committee approved the report and development of what the British called Radio Direction Finding (RDF) and was eventually called radar soon followed.[9]

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[6] Beyerchen, "From Radio to Radar," 276, 278; John Ferris, "Fighter Defence Before Fighter Command: The Rise of Strategic Air Defence in Great Britain, 1917-1934," *The Journal of Military History* 63 (Oct. 1999): 845-84.
[7] Beyerchen, "From Radio to Radar," 279.
[8] Beyerchen, "From Radio to Radar," 280.
[9] Beyerchen, "From Radio to Radar," 280-81.

Radar research received significant support from the highest levels almost from the start. After Watts and Wilkins conducted a successful test in February 1935, Air Vice-Marshal Hugh Dowding, who oversaw Research and Development for the Air Council, immediately provided £12,300 of funding. When Watson Watt proposed a line of radar stations operating on the 13 m wavelength, the Air Defence Research Committee approved the construction of what became known as the Chain Home system. In December, the Treasury allocated £60,000 for the construction of five stations to protect the Thames Estuary.[10]

In 1936, the Royal Air Force (RAF) created Fighter Command and placed Dowding in charge, at least in part in order to make better use of the information that radar provided. The RAF also began to develop new fighters – the Hawker Hurricane and the Supermarine Spitfire. Dowding and Tizard recognized, however, that the early warning provided by radar and the new fighters would be of little value without a system to analyze the information provided by radar and communicate with the fighters rapidly in order to direct them to intercept enemy bombers. Consequently, they sponsored a series of experiments at Biggin Hill in August and September 1936.[11]

The Biggin Hill experiments incorporated the use of a radar station into RAF exercises. The object was to determine the number of interceptions that could be expected in daytime using radar location and to determine how close to a bomber it was possible to direct a fighter by ground instructions. The experiments, which were supposed to last a few months, showed that the procedures for filtering out contradictory data, funneling reports to operations centers, plotting tracks of enemy bombers, assigning targets to fighter units, and guiding fighters to intercept were inadequate. As a result, the experiments continued for two years, eventually producing a coordinated air warning system, an effective filtering process, and an efficient communications system to alert fighters and guide them to intercept. The basic procedures developed during the Biggin Hill experiments were later used to fight Battle of Britain.[12]

One of the keys to the success of the Biggin Hill experiments was the cooperation between the British military and the scientists who participated. Dowding insisted on military personnel working alongside civilian researchers so the military understood the key technical concepts and civilians understood the military constraints and needs. The traditional military view had been that scientists should develop weapons and gadgets, hand them over to the military, and that was the end of their involvement. The Biggin Hill experience was one of the first times that the British military recognized that the introduction of new technology might create problems that required

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[10] Louis Brown, *A Radar History of World War II: Technical and Military Imperatives* (Bristol, U.K: Institute of Physics Publishing, 1999), 52-53; Beyerchen, "From Radio to Radar," 283.
[11] Beyerchen, "From Radio to Radar," 278.
[12] Stephen Budiansky, *Blackett's War: The Men Who Defeated the Nazi U-Boats and Brought Science to the Art of Warfare* (New York: Knopf, 2013), 85-86; Beyerchen, "From Radio to Radar," 283.

the application of scientific methods to solve. Scientists were intimately involved in what had been the purview of the military: the conduct of operations. According to historian Stephen Budiansky, it marked the beginning of operational research.[13]

Soon after the Biggin Hill experiments began, Tizard recognized that if the Chain Home system was effective in providing early warning, any enemy would likely switch to night-time bombing. Intercepting planes at night would require airborne radar. By late 1937, the airborne radar effort had two objectives – Air Interception (AI) and Air to Surface Vessel (ASV) radar. An early version of the airborne radar stirred comment when it located the carrier *Courageous* through heavy clouds during the September 1937 fleet exercises. ASV radar would prove critical to confronting the submarine threat in World War II since it had greater range than sonar and did not produce the same beaconing effect that allowed submarines to detect surface vessels using active sonar before they were able to detect the submarines. Both ASV and AI were well advanced when war came but far from ready.[14]

In addition to ground-based early warning radar, airborne interception radar, and anti-surface vessel radar, the British also developed sea-based early warning, surface search, and fire control radars. Tizard realized soon after the first radar experiments that radar would be as important to the Royal Navy as to the Royal Air Force; however, his efforts to encourage the Navy to participate in ongoing radar research met with opposition. The Navy wanted its own radar research laboratory to address the special problems of operating and maintaining equipment at sea. The Navy won the argument and the British naval radar program began in October 1935 at the Admiralty Signal School in Portsmouth. Although funding was minimal, air search radar sets operating on 43 Mhz had been developed and installed on *HMS Sheffield* and *HMS Rodney* by September 1938. Tests of the new sets were successful enough that the Navy ordered a large quantity of 100 Mhz sets. Delivery began in February 1941. The British also developed naval radar sets operating at 600 Mhz and higher for surface search and fire-control. [15]

British Army researchers also began exploring other uses for radar soon after Watts's first experiments. They focused on using shorter (1.5 m) wavelengths in order to provide fire control for coastal defense guns. By May 1939, they could determine the range of a 2,000 ton vessel at 15 km and determine direction with an accuracy of .25 degrees at 10 km. Experiments later found that placing the radar on a high tower allowed it to detect low-flying aircraft much more effectively than the longer wavelength Chain Home system. The new system became known as Chain Home Low. The first station began operating on 1 December 1939.[16]

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[13] Budiansky, *Blackett's War,* 86-87.

[14] Brown, *Radar History of World War II,* 61; Beyerchen, "From Radio to Radar," 276-77, 283.

[15] Beyerchen, "From Radio to Radar," 294.

[16] Brown, *Radar History of World War II,* 59.

The scientists and engineers working on radar for the British Army also began working on a radar set to allow anti-aircraft batteries to determine range accurately and put their search lights on attackers. The initial set, Gun Laying I (GL Mark I), was rudimentary. It used a wavelength of 3.5 to 5.5 meters to provide accurate range information but poor horizontal direction and no elevation angle at all. Multiple targets could quickly overwhelm even experienced operators. Its successor, GL Mark II, was only a slight improvement. The primitive character of GL Marks I and II may be attributable, in part, to the low esteem in which anti-aircraft artillery was held in Great Britain. The attitude of the War Office towards scientific research and scientists was likely a more important contributor to the slow development of British gun-laying radar. The War Office, according to historian Louis Brown, "did not wish scientists to initiate projects but to do what they were told; they did not wish scientists to work closely with serving officers to gain understanding of the weaknesses of their inventions; they did not wish to hear the opinions of scientists on how best to employ the new weapons."[17]

The British devoted significant effort to designing and fielding gun-laying radar but not much detailed attention to how to use gun laying data to direct the guns. No one even bothered to figure out how to connect the gun-laying radars to the guns. During the first month of Battle of Britain, the British had to improvise crude links between the radar sets and the guns. Patrick Blackett and a group of scientists eventually developed a method to plot radar data and smooth it out to obtain an average track that could be passed on to the gun battery to direct its fire.[18]

As war approached, radar became an increasingly important component of British defenses. By autumn 1938, five radar stations were on-line with supplementary mobile sets. Fighter Command had already begun discretely intercepting KLM and Lufthansa airliners arriving from continental Europe for practice at the beginning of the year. In October 1938, Fighter Command opened the filter room, the nerve center of the air defense system. The filter room was supposed to reconcile and triangulate all radar data to determine the height, location, direction, and size of incoming raids.[19]

During the 1939 summer air exercises, which were the first complete test of the radar defense system, operational researchers observed the work of the filter rooms. Scientists on the scene could spot bottlenecks, devise procedural changes, and introduce guidelines to help operators eliminate data likely to be erroneous. Other scientific teams were stationed in fighter group operations rooms where the tracks passed on by the filter rooms were plotted and orders were issued to fighter squadrons. Members of the teams focused as much on organization and procedures as on technical matters. One key problem they identified was that tracks were often lost when a raid passed from

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[17] Brown, *Radar History of World War II,* 59-60.
[18] Budiansky, *Blackett's War,* 133-34.
[19] Beyerchen, "From Radio to Radar," 284; Brown, *Radar History of World War II,* 55.

one section to another so they recommended giving one control room officer the sole job of maintaining continuity.[20]

The exercises also highlighted one of the key points of the British approach to radar: its emphasis on communication among the various nodes of the system. Messages passed rapidly between radar stations and fighter controllers, between controllers and fighters in the air, and between radar stations and central Fighter Command. Centralization was intended to accelerate the dissemination of information and thus improve the effectiveness of the system. It appeared to work; radar plots could be fed from radar stations to the central operations room at Fighter Command headquarters and then relayed to Fighter Command Groups and sector stations in as little as four minutes.[21]

By the outbreak of war in September 1939, the British had completed the operational development of radar. Land lines connected 18 Chain Home stations stretching from English Channel to Scottish border to Fighter Command and linked Fighter Command to fighter squadrons throughout Great Britain. All the stations operated on the same frequency so only one system of antenna arrays was needed. Although the individual British radar sets and stations were not as technologically sophisticated as German ones, the connections linking the various elements of the system together and the centralized control enabled the British to contest control of the air effectively. The total cost of the radar contracts placed to date was £10 million.[22]

Radar had relatively little impact during the first year of World War II. After the fall of France in June 1940, however, the British began to anticipate German bombing raids. When the Germans decided in the summer of 1940 that an aerial assault to defeat the Royal Air Force was a necessary prelude to any invasion of Great Britain, the British radar system was ready. The Chain Home network now had 30 stations, almost half of them on the south and east coasts facing the Germans. Several of the most important stations had shadow stations set up a few miles away to act as replacements should the primary stations be attacked. There were also 31 Chain Home Low stations to detect low-flying aircraft in the most vulnerable sections of the country. The plotting rooms and filter centers were fully staffed by well-trained men and women. The British had also developed a method to identify friendly fighters using radio signals emitted by the planes. The method was the forerunner of later Identification Friend or Foe (IFF) systems.[23]

The Germans began their aerial attacks on 13 August 1940. Initially, they focused on air defense targets in southern England and avoided civilian targets. Rapid repairs and the availability of mobile replacement radars convinced the Luftwaffe that the attacks on radar sites were

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[20] Budiansky, *Blackett's War,* 116-17.
[21] R. J. Overy, *The Air War, 1939-1945* (Chelsea, U.K.: Scarborough House, 1980), 15; Richard Overy, *The Bombing War: Europe, 1939-1945* (London: Allan Lane, 2013), 79.
[22] Beyerchen, "From Radio to Radar," 283-87
[23] Overy, *The Bombing War,* 78; Brown, *Radar History of World War II,* 109-10.

unsuccessful and Göring soon suspended them. Radar functioned as expected, providing ample warning of the German attacks and frequent opportunities for ambushes.[24]

Attacks on RAF bases were more successful and might have resulted in the RAF's defeat if the Germans had not switched targets in September. When German bombers mistakenly dropped bombs on London on the night of 25 August due to a navigational error, however, Churchill ordered night attacks on Berlin in retribution. Although the British attacks had little effect on the German war effort, the inability of the Luftwaffe to prevent them embarrassed Hitler and Göring. Beginning on 7 September, the Luftwaffe devoted nearly all of its resources to bombing London at night. The decision allowed the RAF bases the time they needed to recover. It also simplified the task of air controllers by giving them a single target to defend. When an all-out effort against London by the Germans on 15 September was met with unexpectedly strong resistance, the invasion was postponed indefinitely.[25]

Once the Germans switched to night bombing, the British were faced with the problem they had long expected. Defending against night attacks would require airborne radar for night fighters. The AI radar the British were developing was not yet ready, however; the only prototypes available had insufficient range and discrimination to find German bombers at night. During a German raid on Birmingham in mid-November 1940, there were 100 British aircraft airborne but only one German casualty, the result of an accident. In January 1941, the RAF needed 198 sorties for every German aircraft shot down.[26]

As a result, the British had to pursue an interim solution. They built a new radar system based on Chain Home Low that allowed ground controllers to guide the fighters into attack positions based on ground radar signals. Once the fighters were near the bombers, they used the AI radar to close in on their targets. The Ground Controlled Interception (GCI) prototypes were tested in combat during the winter of 1940-41. The first six inland GCI radars for guiding a single fighter to intercept a bomber came online in January 1941. A new version of the British airborne radar, AI-Mark IV, was introduced in April 1941 and further improved the effectiveness of British night defenses. The new GCI and AI radars, combined with new techniques of radar observation and fighter control, reduced the number of sorties required to down a German aircraft to 47. By mid-1941, 17 static and mobile GCI stations were operational and the GCI-AI system was working well enough to bring an end to the Blitz. Of the 435 German night raiders shot down during 1941, 357 of them were downed from April onwards. The British shot down 102 German bombers in May 1941 alone.[27]

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[24] Brown, *Radar History of World War II,* 110-13.
[25] Brown, *Radar History of World War II,* 110-13.
[26] Brown, *Radar History of World War II,* 116-19; Overy, *Bombing War,* 104.
[27] Brown, *Radar History of World War II,* 116-19; Overy, *Bombing War,* 104.

Although the German continued to attack Great Britain with bombers after May 1941, the raids were few in number and almost entirely ineffective. The British continued to improve their air defense system despite the lack of any pressing threat. By spring 1942, Anti-Aircraft Command had new, radar-guided searchlights and radar-directed guns that reduced the number of shells fired per aircraft destroyed to 1,830 from more than 6,000 in autumn 1940 and 3,195 in April 1941. By 1943, the GCI network had expanded to 53 inland stations all across the country. All night-fighters were equipped with the AI-Mark IV radar sets.[28]

Even before the Battle of Britain began, the British were using radar to defend Great Britain against maritime threats. The primary focus of these efforts was detecting German submarines. By January 1940, work on air-to-surface vessel radar was sufficiently advance to install the ASV Mark I radar sets in three squadrons of Coastal Command planes. The new radar could spot a surfaced submarine at a tactically significant range. In operation, its effectiveness against submarines was poor but it proved helpful in locating convoys that were to be guarded and in guiding planes home in bad weather.[29]

The successor to ASV Mark I, ASV Mark II, was far more effective. It could observe a swath 40 km wide. The British ordered 4,000 sets in the spring of 1940 but German bombing and the pressing need for AI sets delayed production. Nevertheless, most Coastal Command aircraft were equipped with ASV Mark II radar sets by the second half of 1941. The transmitter for the radar set sent out such a powerful pulse that it would burn out the circuitry of the sensitive receiver located next to it. The receiver was therefore automatically switched off for a fraction of a second as each pulse went out. While the receiver was switched off, it obviously could not detect anything. Thus, signals that came back quickly because they were bouncing off objects that were very close were not detected. In practice, anything closer than three quarters of a mile was invisible. ASV planes could pick up surfaced U-boats at ranges of 10 to 20 miles but as they approached, they would lose the radar contact before they were within nighttime visual range of the U-boat. They had no way to follow through with the attack. One way to bridge the gap was to equip the planes with powerful search lights. Leigh lights, efficient high-powered carbon arc lamps, could generate powerful beams but weighed less than 600 pounds. The first Leigh Light equipped planes began operating in June 1942 and the number of nighttime attacks increased substantially.[30]

The introduction of ASV Mark II radar, even though it was relatively unsophisticated, dropped the U-boat success ratio from 96 ships sunk and 0 submarines lost to 10 ships sunk per submarine

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[28] Overy, *Bombing War,* 100, 117.
[29] Brown, *Radar History of World War II,* 101-02.
[30] Brown, *Radar History of World War II,* 102; Budiansky, *Blackett's War,* 207-08.

lost. By the spring of 1943, the combination of Allied codebreaking, operations research, ASV radar, and Leigh Lights brought figure down to .8 ships sunk per submarine lost.[31]

The British engagements with the German surface raiders *Bismarck* and *Scharnhorst* were both aided significantly by radar. The cruiser *HMS Suffolk* tracked *Bismarck* in the North Atlantic in 1941 using its gunnery-control radar. The plane that found the German battleship heading for Brest was using its ASV radar. Torpedo planes from *HMS Ark Royal* were using radar to find the target when they conducted the attack that rendered the German battleship's steering gear inoperable. In the engagement with *Scharnhorst* off of the Norwegian coast in December 1943, surface radar determined the battle. Almost all contact was on radar screens. The British salvos were nearly all radar-controlled, while early damage to *Scharnhorst's* gunnery radar left it blind and unable to respond to fire accurately. [32]

Once the initiative shifted to the British in the air, they began to use radar as a navigation aid con conduct night time bombing raids against Germany. The British H2S radar enabled bombers to locate their target in poor visibility conditions. Unfortunately, during the second bombing mission flown with the new device on 2 February 1943, a bomber with an H2S radar set was shot down over Rotterdam. After inspecting the wreckage, the Germans completed a report on the new technology within weeks and work began immediately on countermeasures.[33]

Despite the capture of the H2S set, the British continued to make extensive use of radar in their bomber offensive during spring 1943. They used the H2S as a navigation aid to guide the bombers to their targets. They developed radio countermeasures to block the German Freya radar and to interfere with German ground-control transmissions. New airborne devices warned of German night fighters and radar.[34]

One of the key countermeasures the British developed was Window, small strips of aluminum foil that would create a blur of echoes to confuse German radar operators. It had been developed in late 1941 and initially was planned for use against German radars in May 1942. Introduction was delayed, however, out of fear that the Germans would use the same technique against British radars. Not until late 1942, when new British AI radar for night fighters and GCI radar for ground control that could see through Window were introduced, did the British begin to plan for its use. Even then, the chiefs of staff objected to its use before the invasion of Sicily due to concerns that the Luftwaffe would use it to disrupt Allied air support during the landing. Churchill finally approved use of Window on 15 July 1943. It was first used in the raid on Hamburg on 24 July.

[31] Beyerchen, "From Radio to Radar," 295.
[32] Beyerchen, "From Radio to Radar," 294.
[33] Budiansky, *Blackett's War,* 232-33; Beyerchen, "From Radio to Radar," 296.
[34] Overy, *Bombing War,* 322.

The strips worked perfectly, confusing German night fighters and prompting German defenders to swing their searchlights wildly through the sky and fire their anti-aircraft guns blindly.[35]

Germany

Germany led the way in terms of technical innovation in radar. The Germans produced the broadest range of radar sets, with finer resolution, better capabilities, more rugged construction, and greater versatility than anyone else before the outbreak of the war. They were also the first to explore systematically centimeter wavelengths (microwaves), which turned out to be the most crucial portion of the frequency spectrum during the war. Still, the Germans began World War II at a substantial disadvantage to the British in the operational use of radar. Despite their technical brilliance, they were never able to catch up.[36]

In April 1933, Rudolf Kühnhold of the German Navy Signals Research Division in Kiel suggested that centrimetric waves might provide radiolocation of surface vessels and maybe even aircraft. He conducted experiments at a continuous wavelength of 13.5 centimeters but the transmitted power was too weak to produce results. Efforts to generate more power increased instability. Still, the use of a directional antenna produced results promising enough for Kühnhold to approach Telefunken Company in 1934 to suggest ways to expand the research program.[37]

Kühnhold's efforts to explore the subject further resulted in a split in German radar research. Wilhelm Runge, who ran the radio receiver laboratory at Telefunken, was interested in decimeter waves for relay or point-to-point uses. Runge believed Kühnhold's ideas were utopian and would require advanced technology that would not be available for years. He rejected Kühnhold's proposal to collaborate, citing a shortage of staff and resources. Kühnhold went off and established his own firm, GEMA, to do the research for the Navy.[38]

In 1934, GEMA started doing research for the German Navy. One of the problems the researchers encountered was that transmitter output tended to swamp the echo from the target. By 1935, they had developed a pulsed transmission technique with pauses to listen for the reflected signal that allowed them to place the receiver close enough to the transmitter to make on-board radar sets practical. Demonstrations in 1936 resulted in funding for the research. The amount was significant but far below what was requested and small compared to the money spent on ships.[39]

After receiving initial funding from the Navy, the GEMA researchers sought to extend the range of their radar systems by using longer wavelengths. The GEMA set completed in February 1936 operated on a 1.8 m wavelength. During testing, an improperly aligned antenna meant that the set

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[35] Overy, *Bombing War,* 332-33.
[36] Beyerchen, "From Radio to Radar," 270.
[37] Beyerchen, "From Radio to Radar," 270.
[38] Beyerchen, "From Radio to Radar," 270-71; Brown, *Radar History of World War II,* 73.
[39] Beyerchen, "From Radio to Radar," 271.

failed to find a surface vessel 1 5 km away but detected an aircraft 28 km away. The set was soon reconfigured to use an even longer wavelength (2.4 m) and became the forerunner of the Freya aircraft early warning radar.[40]

Curiously, the German Navy only used the air warning radar developed by GEMA to protect its land installations and never installed it aboard warships. Given their focus on surface raiders and submarines, the Germans may not have fully appreciated the threat posed to ships by aircraft.[41]

The Navy also kept the existence of its excellent air-warning radar secret from the other branches of the German military. When the system was finally demonstrated to Hitler and Göring in July 1938, Göring was furious that the Luftwaffe had not been informed of the device's existence. The Navy responded by telling Göring that it was a Navy weapon; the Luftwaffe could invent its own radar. The Luftwaffe nevertheless ordered some of the sets, which they dubbed Freya, from GEMA. Two sets were deployed for possible use during the invasion of Czechoslovakia. Throughout the rest of the war, the Kriegsmarine actively worked to prevent the Luftwaffe from buying equipment from GEMA and to undermine GEMA's relationship with the Luftwaffe.[42]

Meanwhile, properly aligned antennas and further work produced the Seetakt system. On 18 April 1936, the German Navy decided to equip all cruisers and battleships with the Seetakt surface-search radar – the first operational naval radar. It was capable of detecting capital ships at ranges of 15-20 km with a bearing accuracy of + or – 3 degrees.[43]

Simultaneously, Runge was pursuing his own research. By 1938, he had constructed a parabolic antenna and developed a method for conical scanning that made it possible to automatically track an aerial target. The developments were the beginning steps in the creation of the Würzburg radar system, which used the 50 cm wavelength and was the best gun-laying radar for anti-aircraft artillery until 10 cm equipment was introduced in 1942-43. The Würzburg gave readings of elevation as well as range and bearing at intermediate distances. It could be used for ground control interception in addition to gun-laying.[44]

The number of firms and individuals working on radar in Germany had expanded significantly by 1938. The Navy and the Air Force had both ordered radar sets. Still, production capacity was limited.[45]

Despite all the activity, a number of critical developments undermined German radar efforts. One was the abandonment of research on centrimetric radar in favor of longer waves. German

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[40] Beyerchen, "From Radio to Radar," 272; Brown, *Radar History of World War II,* 76.
[41] Brown, *Radar History of World War II,* 77-78.
[42] Brown, *Radar History of World War II,* 77-78.
[43] Beyerchen, "From Radio to Radar," 272; Brown, *Radar History of World War II,* 76.
[44] Beyerchen, "From Radio to Radar," 272; Brown, *Radar History of World War II,* 80.
[45] Beyerchen, "From Radio to Radar," 273.

researchers conducted research in the region of the electromagnetic spectrum with waves shorter than 50 cm throughout the 1930s and recognized that shorter waves meant smaller antennas and better target resolution. A shortage of technical manpower and the absence of a microwave generator of sufficient power forced Germany to terminate the research. In January 1939, an official decision was promulgated to concentrate on longer wavelengths. Following the decision, the Germans grew complacent. They believed that dramatic improvements were not necessary. All German radar sets until the middle of the war operated on medium to long wavelengths (53 cm to 2.6 m). The great Allied breakthrough was to develop radar with wavelengths shorter than 10 cm.[46]

The second development was the failure to alter operational practices in response to technical advances. In the fall of 1939, a line consisting of eight partially overlapping Freya stations and three naval gunnery radars was under construction to provide warning of approaching Allied aircraft at ranges of 100 km. The radar sets were viewed as enhancements or replacements for the ground observer corps and treated as a way to economize on the use of ground observers. Consequently, the Germans grafted the radar sets on to the existing communications network used by ground observers, which lacked the capacity or speed to make adequate use of radar information.[47]

The third development was the adoption of a more decentralized model for the German radar network than the one used for the British system. Each German air district was responsible for the defense of its own vulnerable targets. Information was not disseminated through a centralized control center. The German lack of a filter room proved problematic. Controllers would send fighters to the anticipated track of British bombers. Ground observers would report airplane noise overhead. The controller would order up more fighters and fratricide would often ensure and German fighters fired at each other in the dark while German Flak batteries fired at their own planes. Not until February 1944 did Germany establish a centralized air defense network with the air warning system, anti-aircraft artillery, and local fighter divisions all under the direct control of Reich Air Fleet headquarters in Berlin.[48]

Despite these difficulties, German radar quickly demonstrated its utility when the war began. On the second day of the war, the British launched a bomber raid on the German port of Wilhelmshaven on the North Sea. German radar picked up the attackers but the defenders did not act quickly enough. The German fighters were only taking off as the British bombers were heading home. When the British returned on 18 December, however, the Germans were ready to

[46] Brown, *Radar History of World War II,* 73; Beyerchen, "From Radio to Radar," 273-74.
[47] Beyerchen, "From Radio to Radar," 274.
[48] Overy, *Bombing War,* 362-63; Beyerchen, "From Radio to Radar," 296-97; Overy, *Air War,* 16.

respond to the warning provided by their Freya sets. Only 10 of 24 British bombers made it home.[49]

The Seetakt surface search radar also proved useful on German surface raiders early in the war. The Germans had built a series of large, fast, and heavily armed ships to disrupt Allied commerce. Despite their size and power, the German commerce raiders had to be wary of encountering significant opposition. Even slight damage could rarely be repaired at sea, forcing the termination of the cruise. Radar allowed German surface raiders to locate their targets at night or in the fog and to distinguish escort ships that might present opposition.[50]

The German pocket battleship *Graf Spee* was the first warship equipped with operational radar. It put to sea in late August 1939 and was well into the South Atlantic when war was declared. The radar set failed on 3 October and proved difficult to fix, due in part to the radar operator's lack of training and the absence of technical manuals and circuit diagrams aboard ship. The captain ordered the chief radio mate to drop everything until the radar was fixed. After a week, the repairs proved successful. The *Graf Spee* sank nine merchantmen before being engaged by one heavy and two light British cruisers off the River Plate in December 1939. The German ship's radar improved the accuracy of its fire, enabling it to inflict substantial damage on its attackers while suffering minimal harm. The *Graf Spee* took refuge in the neutral harbor of Montevideo where its captain, expecting to be confronted by a much larger force should he leave harbor, decided to scuttle the ship.[51]

During later cruises, German commerce raiders used their surface-search radars extensively. They used radar to locate and attack Allied convoys but also to locate and rendezvous with their own tankers and supply ships. The *Scharnhorst* and *Gneisenau* used their radars to run the Denmark Strait at night in foul weather, typically a risky passage but one that proved almost routine with the use of radar. The *Scharnhorst* and *Gneisenau* even used their radars to identify each other when they approached each other at night after separating during the day to improve their chances of finding ships.[52]

By mid-1940, it became clear that the British would retaliate for the German aerial attacks on Great Britain. The Germans sought to improve their defenses against British night bombing raids by improving their early warning radars. Freya was effective but had limited range and poor target resolution so the Germans increased the antenna size but retained the 2.4 m wavelength and circuitry. The results were the Wasserman and Mammut radars, which proved to be the best early warning radars of the war until at least 1944, possibly the entire war. The Wasserman provided

[49] Beyerchen, "From Radio to Radar," 274-75.
[50] Brown, *Radar History of World War II*, 121.
[51] Brown, *Radar History of World War II*, 105.
[52] Brown, *Radar History of World War II*, 122-23.

highly accurate early warning at long range. The Mammut was then used to track multiple formations rapidly and accurately. The two basic designs formed most of Luftwaffe's early warning radar for the rest of the war.[53]

The introduction of the Würzburg radar, which was intended to be a gun-laying radar, in early 1941 also allowed the Germans to conduct ground-controlled interception, even though their night fighters were not yet equipped with airborne interception radar. The Würzburg could determine the three-dimensional coordinates of a target. Supply could not keep up with demand. By spring 1942, only one-third of anti-aircraft guns had the new radar.[54]

Using the Wurzburg to conduct ground-controlled interception was a temporary solution. The Germans recognized that they needed airborne interception radar to combat British night bombing effectively. The head of the German night-fighting command, Lieutenant General Josef Kammhuber, presented the requirements to Runge at Telefunken in early 1941. Runge proposed a 20 cm design but was told that there was not enough time for experimentation. Instead, the company should draw on its accumulated experience with 50 cm radars. By the summer, Runge had a prototype flying. In February 1942, the first German night-fighters equipped with airborne radar, codenamed Liechtenstein, began operating. The set's range proved limited and production was hampered by a shortage of vacuum tubes. Production was also not of high quality. Many sets were returned. Acceptance was also slow. Pilots did not like the appearance of the antennas on their planes or the effect the antennas had on the plane's speed.[55]

When the British strategic bombing campaign began in earnest on 8/9 March 1942 with a raid on Essen, it became apparent that German radar was inferior. The Luftwaffe centralized responsibility for radar development in May and accelerated research and production in an unsuccessful attempt to catch up to the British. The Germans were caught in a position of reacting to Allied moves. Every attempt to combat Allied radar was in response to Allied initiatives. The most successful period of German night-fighting came in the winter of 1943-44 when the Luftwaffe gave up producing its own radio novelties and used the enemy's for accurate interception. [56]

When the British began using Window in raids against Hamburg in July 1943, the German defensive radars were temporarily blinded, but not because the Germans were ignorant of its existence. They had their own chaff, but had been forbidden to research its properties for fear that doing so would lead to its use and then Allied counter-use. Instead, the Germans employed Doppler radars to distinguish faster moving aircraft from falling strips of foil.[57]

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[53] Brown, *Radar History of World War II,* 280-81.
[54] Brown, *Radar History of World War II,* 282;Overy, *Bombing War,* 275.
[55] Brown, *Radar History of World War II,* 286-87; Overy, *Bombing War,* 275.
[56] Overy, *Air War,* 201; Overy, *Bombing War,* 335-36.
[57] Beyerchen, "From Radio to Radar," 296.

The successful British use of radar and radar countermeasures prompted the Germans to increase their emphasis on radar. A new office for high-frequency research was established. Some 3,000 scientific personnel tried to learn what they could from the remains of crashed British bombers, such as the one carrying anH2S radar that was downed over Rotterdam in early February 1943.[58] Within six months, a prototype copy of the H2S was ready for testing. The Germans quickly accelerated technology development programs and improved coordination of technical and operational advances. [59]

By late 1943, the Germans had developed two devices, Würzlaus and Nürnberg, that allowed skilled radar operators to distinguish between the echoes produced by Window and those produced by an airplane. Some 1,500 Würzberg radars were modified with the devices by the end of the year. German researchers from Telefunken also developed an airborne radar that was not affected by Window interference and launched a crash program to produce the sets.[60]

The Germans also figured out how to track the Allied H2S radar navigation signals by the end of 1943. A homing device called Naxos-Z enabled German night fighters to track planes using the navigation device. Allied bombers not carrying H2S could still be located using their IFF mechanism. When the Americans introduced a Würzberg jammer in December 1943, the Germans found a partial solution by introducing a modification that allowed the radar to switch frequencies and avoid the jamming.[61]

By late 1944, the gap between German and Allied radar technology had largely been erased, but it was too late. The Germans did not have enough aircraft to mount advanced radars. Allied air superiority had been achieved.[62]

United States

The United States lagged behind both Germany and Great Britain in radar research and development during the interwar era. Small groups of researchers achieved some notable technical advances that gradually filtered upward but the American effort remained compartmentalized. There was no sense of urgency to develop radar and no central direction or focus to the research efforts until after. Once the outbreak of war in Europe heightened the sense of urgency, however, it did not take long before the United States was at the forefront of radar innovation.[63]

Experiments using radio waves to detect objects over long distances conducted by radio engineers A. Hoyt Taylor and Leo C. Young of the Naval Research Laboratory (NRL) produced intriguing

[58] Overy, *Bombing War,* 335-36.
[59] Beyerchen, "From Radio to Radar," 296.
[60] Overy, *Bombing War,* 363.
[61] Overy, *Bombing War,* 363.
[62] Beyerchen, "From Radio to Radar," 296.
[63] Beyerchen, "From Radio to Radar," 287, 291.

results as early as 1922, although the Navy Department paid little attention due to doubts that radio detection would work on moving vessels. In 1930, however, Taylor and Young requested funding from the Navy's Bureau of Engineering to explore a phenomenon that they had discovered in which airplanes reflected enough high-frequency radiation to create a noticeable interference pattern in a distant receiver. Taylor and Young made little progress until they switched from continuous wave to pulsed equipment in 1933. The shift soon produced more promising results. One of Taylor and Young's assistants, Robert M. Page, built and demonstrated a pulsed radar prototype in late 1934, detecting a moving aircraft at a range of one mile. [64]

Over the next several years, the NRL engineers continued to refine the design of the radar receiver. In a test in April 1936, the radar set was able to detect planes up to nine miles away. Engineers quickly doubled that range with small adjustments. The tested set operated at a frequency of 28.6 Mhz, however, which required an antenna nearly 250 feet long. To make radar workable at sea, NRL had to shift to a higher frequency. The NRL engineers focused on construction of a set that would operate at 200 Mhz, which they believed to be the maximum frequency practicable with existing vacuum tube technology. To minimize the space the radar set would occupy, the engineers also sought to create a system that would work with only a single antenna. They developed the duplexer, an electronic switch that protected the receiver from high-voltage transmissions without limiting its capacity to detect reflected, low-energy radio waves. Tests of the new design later in 1936 produced mixed results; the primary finding was that more power would be needed in order for the range at sea to match or surpass the range achieved earlier on land.[65]

By late 1938, the Navy's Bureau of Engineering was eager to finalize the specifications of the radar set so it could begin supplying the Fleet with the new tool as soon as possible. Although the engineers and scientists at NRL were working on a 500 Mhz system to extend the detection range even farther, the Bureau ordered them to freeze the design of the 200 Mhz radar set and construct a prototype as quickly as possible for shipboard trials. Unbeknownst to the NRL team, the Bureau of Engineering had covered its bets by secretly contracting with RCA in 1938 to build a separate 385 Mhz pulsed radio detection set. Both prototypes were ready for testing in January 1939. The NRL set outperformed the RCA set in all aspects; it operated nearly continuously under all weather conditions, was not bothered by the shock of gunfire, and generated ranges accurate to within three hundred yards, while the RCA set could not withstand the moisture or heavy gunfire aboard ship and produced weak and inconsistent returns. The NRL set detected ships at 10 miles and planes up to 48 miles away. It even detected a partially submerged submarine and tracked 14-inch shells in flight. The RCA set struggled to detect anything farther than 5 miles out. After the trials concluded, Admiral A.W. Johnson, Commander of the Atlantic Squadron, wrote to the

[64] Beyerchen, "From Radio to Radar," 288-89; Timothy S. Wolters, *Information at Sea: Shipboard Command and Control in the U.S. Navy, from Mobile Bay to Okinawa* (Baltimore, Md.: Johns Hopkins University Press, 2013), 176.
[65] Ivan Amato, *Pushing the Horizon: Seventy-Five Years of High Stakes Science and Technology at the Naval Research Laboratory* (Washington, D.C.: Naval Research Library, 1998), 86-87; Wolters, *Information at Sea,* 176-80.

Bureau of Engineering, "…the equipment is one of the most important military developments since the advent of radio itself. Its value as a defensive instrument of war and as an instrument for avoidance of collisions at sea justifies the Navy's unlimited development of the equipment."[66]

Following the successful tests, the Navy decided to procure six of the NRL-designed radars, which were designated as CXAM. RCA would build them while NRL worked to improve radar performance at sea. Shortly thereafter, the Navy ordered an additional fourteen slightly sets, designated as CXAM-1. The first of the twenty sets was delivered in May 1940. By December 1941, all the U.S. carriers as well as six battleships, six heavy cruisers, two light cruisers, and a seaplane tender had the new air warning radar sets installed.[67]

As the new radar sets were being installed, the Navy encouraged fleet personnel to experiment and formulate recommendations on how to improve the radar sets and how to improve the exchange of radar information. To handle all of the incoming suggestions, the Navy established a single individual to coordinate its radar program. One of the more important improvements was the development of a radar plot room where information could be recorded. Some officers recommended taking that development further by building appropriate facilities on ships to process and evaluate radar information. On 21 August 1941, the CNO authorized installation of radar plots on all carriers. The radar plot would be the brain of the organization to protect the fleet and individual ships from air attack.[68]

Using radar effectively proved to be more art than science and heavily dependent on the skills of radar operators and the officers receiving the information. Consequently, the Navy added radar instruction to the Radio Material School at NRL in January 1941. The curriculum incorporated valuable information on British radar operations provided by the Tizard mission. Still, the Navy faced the problem of how to train enough radar experts. In September 1941, the Navy estimated that the fleet would need two thousand maintenance technicians and more than ten thousand operators by the end of the fiscal year. The Navy sent men to the Royal Canadian Air Force radar school but less than half the personnel needed would be available by mid-1942. Finally, in November 1941, the Navy initiated the establishment of a radar school in Hawaii. At roughly the same time, the Navy also established fighter director schools on each coast. The curriculum incorporated many successful British practices, such as using a designated symbol and numbering system for incoming raids and employing a standard vocabulary for fighter direction. [69]

While the Navy was exploring the use of radar at sea, the Army was working on its own set of radio detection projects. The Army Signal Corps began investigating radio detection methods in the

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[66] Wolters, *Information at Sea,* 179-81; Amato, *Pushing the Horizon,* 87-91.
[67] Wolters, *Information at Sea,* 182-83; Beyerchen, "From Radio to Radar," 289; Brown, *Radar History of World War II,* 237; Amato, *Pushing the Horizon*, 91.
[68] Wolters, *Information at Sea,* 188.
[69] Brown, *Radar History of World War II,* 237; Wolters, *Information at Sea,* 190-93

early 1930s, although the resources devoted to the effort were limited. In December 1936, Signal Corps Engineers conducted the first field test of their radar equipment at the Newark, New Jersey, airport where it detected an airplane at a distance of seven miles. In May 1937, the Signal Corps successfully demonstrated the concept in the field to the secretary of war, senior generals, and several congressmen. The crude radar set guided a searchlight so that nearly every time the light turned on, the aircraft was already in the beam. A modified version of the set that used improved vacuum tubes to achieve higher frequencies and greater accuracy went into production in December 1940 as the SCR-268, a short-range radar set to control searchlights and anti-aircraft guns. By December 1941, the operating forces had more than 350 sets. With periodic updates, the SCR-268 would constitute the mainstay of Army and Marine Corps anti-aircraft batteries through 1944.[70]

The successful demonstration of short-range aircraft detection radar in 1937 prompted the Air Corps to urge the development of a long-range version for use as an early warning device. By June 1938, the Signal Corps had a working prototype that consistently detected aircraft at a range of 85 miles. Field tests in late 1939 that achieved detection ranges exceeding 130 miles resulted in production approval for the SCR-270 mobile long-range aircraft early warning radar and its fixed counterpart, the SCR-271. The first sets were in active use guarding the Panama Canal by October 1940.[71]

Thus, both the Navy and the Army had aircraft detection radar sets in operation in 1940. The sets were quite large, however, and operated at frequencies of 200 Mhz or below with wavelengths in the two to three meter range. There was no American radar set small enough to be carried on a plane or even on small escort ships. The Americans were working on centimeter-wave radar but were finding it difficult to generate sufficient power using vacuum tubes.[72]

Fortunately for the Americans, the British, hoping to improve relations with the United States, proposed an exchange of secret technical information in July 1940. One of the devices the British Technical and Scientific Mission to the United States, better known as the Tizard Mission after its leader, Henry Tizard, brought to the United States in September 1940 was the resonant cavity magnetron. Developed by two British scientists at the University of Birmingham, the small device was capable of generating high-powered, centimeter-wavelength pulses of radio waves, also known as microwaves. Its greater power and shorter wavelengths increased detection range, improved accuracy, and enhanced resolution while its small size made the installation of radar sets on

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[70] Rebecca Robbins Raines, *Getting the Message Through: A Branch History of the U.S. Army Signal Corps* (Washington, D.C.: U.S. Army Center of Military History, 1996), 233; Wendy Rejan, "Radar," in *A History of Innovation: U.S. Army Adaptation in War and Peace,* ed. Jon T. Hoffman (Washington, D.C.: U.S. Army Center of Military History, 2009), 21-24.

[71] Raines, *Getting the Message Through,* 233; Rejan, "Radar," 25.

[72] Budiansky, *Blackett's War,* 127.

aircraft and smaller ships possible. The value of the cavity magnetron was immediately apparent and it was quickly put into production at Bell Laboratories.[73]

The magnetron had been unveiled at an informal dinner party hosted by Alfred Loomis, chair of the Microwave Committee of the National Defense Research Committee (NDRC). The NDRC had been formed only a few months earlier at the urging of Vannevar Bush, president of the Carnegie Institution, who had been frustrated by the failure to bring scientific research to bear on military problems during World War I. Bush developed an idea for a government agency of civilian scientists to serve military needs and foster the exploration of new technologies. He summarized his ideas on a single page, presented them to President Roosevelt on 12 June 1940, and received immediate approval to implement them. The creation of the NDRC was an important change in the role of science in the development of American military technology. During the 19th century, American scientists had focused on evaluating proffered inventions for the military; the establishment of the NDRC shifted that focus to conducting large-scale research projects to meet military needs and blurred the line between scientific research and engineering development.[74]

Within a month of the Tizard Mission's visit, a revised American radar research and development program emerged. The members of the Tizard Mission urged the NDRC to employ the cavity magnetron to concentrate on microwave radar and to follow the British model of creating a large, central laboratory staffed primarily by civilian scientists and engineers from academia and industry for the purpose. The Microwave Committee agreed and recommended the establishment of what was soon called the Radiation Laboratory, or Rad Lab, at the Massachusetts Institute of Technology. The Rad Lab produced 150 radar systems during the war for a variety of missions, including airborne interception radars for night fighters, high-precision fire-control radars for anti-aircraft guns, airborne surface-search radars to locate surfaced submarines, long-range navigational aids, ship-borne air control radars to conduct nighttime air operations, and high-power warning radars, among others. The success of the Rad Lab rested on, according to historian James Phinney Baxter, "a highly flexible and effective administration, extensive research in fundamentals, steady improvement of components, and close liaison with the Army and the Navy, and the British."[75]

Although the United States had developed several functional radars, initiated some radar training, and launched a centrally-directed effort to develop new radar technology, the country was not yet prepared to use radar effectively in combat when Japan attacked Pearl Harbor in 1941. The

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[73] James Phinney Baxter 3rd, *Scientists Against Time* (Boston: Little, Brown, 1946), 143-44; Paul Kennedy, "History from the Middle: The Case of the Second World War," *The Journal of Military History* 74 (Jan. 2010), 40-41.
[74] Christopher Alan Eldridge, "Electronic Eyes for the Allies: Anglo-American Cooperation on Radar Development during World War II" (Lehigh University: Ph.D. diss., 2001), 91; Barton C. Hacker, *American Military Technology: The Life Story of a Technology* (Baltimore: Johns Hopkins University Press, 2006), 89.
[75] Baxter, *Scientists Against Time,* 144-57; Beyerchen, "From Radio to Radar," 293; Hacker, *American Military Technology,* 94.

incoming Japanese aircraft were detected by one of the six SCR-270 mobile, long-wave, air-search radar sets positioned on the island of Oahu's perimeter. Operators picked up the Japanese planes at very near the set's maximum range of 150 miles, reported the contact to an information center at Fort Shafter, four miles east of Pearl Harbor, and continued to track the raid for almost 30 minutes, until it was within twenty miles of Oahu. The information center was supposed to plot information from radar sites and direct fighters to intercept the attackers, but it was inadequately manned. There were no fighter control or liaison officers in the information center. In fact, only two people were on duty that morning and the senior officer present had stood only one previous watch. The technology necessary to identify the incoming tracks as friend or foe was not yet available and the Army had not established either aircraft approach lanes or a movement reporting system. Consequently, the senior officer dismissed the report as an incoming flight of B-17 bombers and did not telephone the operations officer at the fighter wing on Oahu. Even if the information center had called the fighter wing, the Army's existing alert condition precluded a rapid sortie of defending aircraft. Without a well-prepared, complex organization that had fully integrated radar into its operations and could use the information that radar provides in a timely fashion, the system was, in the words of historian Tim Wolters, "almost predestined for failure."[76]

The Navy sought to strike back quickly against Japan and relied on its nascent radar capabilities to do it. Early carrier operations in the Pacific, including Vice Admiral William Halsey's raid on the Marshall Islands with *USS Enterprise* and Rear Admiral Jack Fletcher's raid on the Gilbert Islands with *USS Yorktown* in February 1942, used the long-range warning radars developed before the war to detect Japanese reconnaissance aircraft early enough so the task force commander could decide what to do. When Vice Admiral Wilson Brown aboard *USS Lexington* raided Rabaul a few days later, radar again allowed the carrier to detect prowling Japanese reconnaissance planes. It also provided a timely alert of incoming Japanese raids, enabling American fighters to intercept and destroy the Japanese bombers well before they reached the task force. At the end of February, *Enterprise* used the YE homing radio to guide its planes to their targets during an attack on Wake Island and its air-search radar to locate a plane that became lost during the raid and guide it back to the carrier.[77]

The utility of radar became even more clear when the Navy encountered its first major operational problem in 1942. To offset an anticipated U.S. superiority in battleships, the Japanese Navy before the Second World War adopted tactics emphasizing night combat and the use of large, powerful oxygen-propelled torpedoes. The Japanese demonstrated their night fighting prowess during the Guadalcanal campaign. Although the U.S. Navy had more advanced radar and a larger proportion of its ships equipped with radar than the Japanese Navy, it suffered significant losses in five major night battles from August through November 1942. Meanwhile, the Japanese were also keeping

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[76] Wolters, *Information at Sea,* 172-74; Brown, *Radar History of World War II*, 215-18.
[77] Brown, *Radar History of World War II,* 238-39.

exhausted U.S. Marines on Guadalcanal awake with "Washing Machine Charlie" raids conducted by night-flying aircraft with intentionally unsynchronized engines that produced an annoying, throbbing sound. The Army Air Forces achieved limited success against the Japanese night raids by using Lockheed P-38s in conjunction with ground-based searchlights and anti-aircraft artillery. The Navy, however, lacked any equipment to contribute to the effort.[78]

Even before it encountered difficulties during the Guadalcanal campaign, the U.S. Navy had already launched a program to improve its ability to fight at night. Project Affirm began in April 1942 to develop, experiment with, and evaluate aerial night fighting equipment and tactics. The Massachusetts Institute of Technology provided custom-built radar sets and pilots experimented extensively to determine the capabilities of their new equipment and devise appropriate tactics. Less than a year later, the Navy commissioned its first night fighter squadron. The squadron was deployed to the Solomons in August 1943 and, working with a Marine Corps night fighter squadron, quickly reduced the Japanese nighttime harassment raids.

While the Navy was working to enhance its nighttime aerial combat capabilities, it was also examining how to improve its nighttime surface combat capabilities. It concluded that its ships needed a central location that could receive, assimilate, and evaluate information from all available sources, not just radar, with minimal delay. In January 1943, the Navy designated this new facility the Combat Information Center (CIC); six months later, it published its first comprehensive statement of CIC doctrine. The CIC proved its value during the night surface action in the Surigao Strait in October 1944, when the situational awareness it provided to U.S. commanders helped them decisively defeat their Japanese counterparts, who possessed primitive radars and excellent lookouts but lacked a mechanism to translate the information into a comprehensive battle picture.[79]

The Navy also began equipping its submarines with radar in large numbers in 1942. The SD was a low-frequency, long-wave air warning radar that was used infrequently; the SJ was a microwave surface-search radar that was used extensively. Commanders used the SJ to track enemy merchants at night or in storms and to detect enemy escorts at ranges up to 6 miles. The *USS Raton* used its SJ radar to orchestrate a night-time attack on a nine-ship Japanese convoy on 18 October 1944. The Raton sank two freighters and damaged another two before withdrawing to reload its torpedo tubes.[80]

By late 1944, the outcome of the Pacific War was no longer in doubt. Nevertheless, Japan refused to surrender and the United States began preparations for the invasion of Japan by seizing a base

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[78] Trent Hone, "'Give Them Hell!': The US Navy's Night Combat Doctrine and the Campaign for Guadalcanal," *War in History* 13.2 (2006), 171-72.
[79] Wolters, *Information at Sea,* 204-06; Trent Hone, "Triumph of U.S. Navy Night Fighting," *Naval History* 20.5 (Oct. 2006), 52-59.
[80] Brown, *Radar History of World War II,* 361-63.

in the Ryukus, Okinawa. To protect the Allied fleet against air attack, a ring of radar pickets consisting of destroyers and other light vessels was established 60 to 80 km from the main fleet. The pickets bore the brunt of the Japanese kamikaze and bomber attacks. From the first American landing on Okinawa on 1 April 1945 until the end of Japanese resistance on 19 June, 23 U.S. ships were sunk by kamikazes, including 10 destroyers. Despite the terrible losses, the U.S. invasion succeeded. The next step would have been the invasion of Japan if the use of atomic weapons, which were detonated by radar fuses, had not ended the war in August 1945.[81]

Japan

Electronics, especially radar, was the naval technology most vital to the relative performances of the Japanese and U.S. navies in the war. For Japan, radar development was a case of too little and too late. Japanese researchers began exploring field almost as early as counterparts in Great Britain and United States but official indifference, haphazard mobilization of scientific talent, and lack of interservice cooperation delayed practical military application of radar in Japan. [82]

Early radio and radar research in Japan was led by civilian scientists and engineers. One of the leading figures was Yagi Hidetsugu, professor of Electrical Engineering at Tōhoku Imperial University in Sendai and later dean of science at Osaka Imperial University. In 1926, Yagi invented the dipole array antenna, which became known as the Yagi antenna. The British and the Americans both adopted the Yagi antenna for their long-wave airborne search systems early in the war.[83]

The Japanese military, in contrast, demonstrated only limited interest in radar during the 1930s. Early in the decade, the armed services joined with the Communications Ministry to explore electromagnetic radiation. By 1936, the Japanese Army had discovered how to detect passing aircraft using radio waves and development of a viable prototype radar apparatus had begun. In 1939, the Army achieved moderate success detecting passing aircraft with experimental continuous wave radar sets using 20-centimeter wavelength and 4-meter wavelengths. Meanwhile, the Japanese Navy began experimenting with frequency-modulated continuous-wave radio signals in 1937. During a 1939 naval review in Tokyo Bay, ships were detected at ranges of up to 5 kilometers using a 10 cm wave radar set. The Army and the Navy did not pursue such efforts vigorously, however, and neither service made a serious commitment to radar development until after the outbreak of the war in Europe. As a result, Japanese radar development lagged far behind Allied efforts. For

[81] Brown, *Radar History of World War II,* 418-19, 424-25.
[82] David C. Evans and Mark R. Peattie, *Kaigun: Strategy, Tactics, and Technology in the Imperial Japanese Navy, 1887-1941* (Annapolis, Md.: Naval Institute Press, 1997), 411.
[83] Walter E. Grunden, *Secret Weapons and World War II: Japan in the Shadow of Big Science* (Lawrence, Kan.: University Press of Kansas, 2005), 98.

example, the Japanese were unaware of the utility of the Yagi antenna for radar until the capture of a British searchlight control apparatus in Singapore in July 1942.[84]

The outbreak of war in Europe heightened interest in radar in Japan. Seeking to improve its maneuvering and combat capabilities at night and prevent collisions, the Navy funded research on a 3-centimeter wave transmitter and small radar sets to be used on torpedo boats in 1939. The results were unsatisfactory; the equipment was not accurate at ranges greater than 100 meters. Meanwhile, the Army ordered a 3-watt radar set, designated the Type A, into production in March 1940. In 1941, the Army began operating a network of 120 Type A sets along the coast of the Sea of Japan to defend against a potential air assault from the Soviet Union. The sets proved inaccurate at range, however, and continued development on the type was discontinued.[85]

Seeking to learn more about European military developments, including radar, the Japanese military sent several missions to Germany in late 1940 and early 1941. The Japanese Army's mission, dispatched to Germany in December 1940, returned with reports on the British use of pulsed radar that prompted the Army to shift its development efforts away from the Type A continuous wave radar set to the Type B pulsed radar set. The Navy's mission in January 1941 inspected German radars and returned with German technical reports as well as additional information on the use of pulsed radar by the combatants in Europe.[86]

The missions to Europe, combined with reports on combat in Europe, contributed to a growing recognition of the importance of radar in the Japanese military. The Navy had initially believed that the danger of ships revealing their locations by using radar outweighed the potential ability to detect threats. Reports of the British victory over the Italian Navy in the Battle of Cape Matapan in March 1941 changed the minds of Japanese naval leaders. British codebreakers had reported the sailing of an Italian battle fleet intended to attack Allied convoys in the Mediterranean. The British Mediterranean fleet sailed to intercept the Italians. During the battle, British ships equipped with radar detected an Italian squadron at night, closed to within 3,500 meters, and opened fire. The Italian ships, which were not equipped with radar, were caught completely by surprise. The Italians lost two heavy cruisers and two destroyers in five minutes. The Japanese Navy, unaware of Allied codebreaking efforts, attributed the victory solely to the British advantage in radar and subsequently became more supportive of radar and its use in combat. On 2 August 1941, the Navy ministry ordered a crash program of radar development.[87]

By late 1941, Japanese radar development efforts had made some progress. The Navy tested meter-wavelength, land-based, air-search sets along the coast and the first production model were ready in

[84] Grunden, *Secret Weapons and World War II,* 98-102; Evans and Peattie, *Kaigun,* 411.
[85] Evans and Peattie, *Kaigun,* 413; Grunden, *Secret Weapons and World War II,* 100-02.
[86] Grunden, *Secret Weapons and World War II,* 102-03; Evans and Peattie, *Kaigun,* 413.
[87] Grunden, *Secret Weapons and World War II,* 104-05; Evans and Peattie, *Kaigun,* 413.

late November 1941. The sets were electrically and mechanically crude by Western standards, however, and their range was only 35 miles. They were also subject to frequent breakdown early in the war because they had not been designed for use in humid tropic environments. Improvements later in the war reduced malfunctions and improved range but the sets were never equal to Allied radar sets. More importantly, the Japanese Navy had no shipborne surface search or fire-control radar or any radar that could be installed in an aircraft when it attacked Pearl Harbor.[88]

It was not until mid-1942 that the Japanese Navy began testing ship-borne radar. The first shipborne radar sets were installed aboard the battleships *Ise* and *Hyūga* for use in the attack on the Aleutians that preceded the Battle of Midway in June 1942. None of the Japanese ships at Midway, including the aircraft carriers, had radar.[89]

Without radar, Japanese early warning and fighter direction proved deficient at Midway. The Japanese carrier task force had to rely on picket ships and float planes to provide early warning. American planes were able to use cloud cover to get within a few miles of the carrier group. As a result, the fighters in the Japanese combat air patrol (CAP) were often engaging American torpedo planes in dangerously close proximity to the carriers. American dive bombers were not spotted until they were almost directly overhead. Once the American planes were spotted, it proved difficult to direct the CAP fighters to intercept. Without any ability to anticipate future attacks, the CAP fighters tended to bunch up to respond to incoming raids, leaving other sectors uncovered and the carriers vulnerable to subsequent attacks from different directions. [90]

The Japanese defeat at Midway provided an even greater impetus for change since Japanese naval leaders were convinced that radar played a significant role in the outcome. The results of the Battle of Cape Esperance on 11 October 1942 confirmed their beliefs and ended the Japanese Navy's indifference to radar. Just before midnight, a U.S. force of four cruisers and five destroyers intercepted a Japanese flotilla of three heavy cruisers and two destroyers as the Japanese force approached Savo Island near Guadalcanal. The American ships, which were equipped with radar, closed to within 4,600 meters of the Japanese ships, which did not have radar, before opening fire. The Japanese were taken almost completely by surprise. American shells slammed into the Japanese ships, sinking a cruiser and a destroyer, inflicting heavy damage on another cruiser, and mortally wounding the commander of the flotilla. The Americans lost a destroyer; a second destroyer and a cruiser were heavily damaged. [91]

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[88] Evans and Peattie, *Kaigun,* 413-14.

[89] Grunden, *Secret Weapons and World War II,* 104; Jonathan B. Parshall and Anthony P. Tully, *Shattered Sword: The Untold Story of the Battle of Midway* (Washington, D.C.: Potomac Books, 2005), 136, 497-98.

[90] Parshall and Tully, *Shattered Sword,* 136-37, 186-88; 215, 226; Mark R. Peattie, *Sunburst: The Rise of Japanese Naval Air Power, 1909-1941* (Annapolis, Md.: Naval Institute Press, 2001), 156.

[91] Evans and Peattie, *Kaigun,* 595, n. 70; Grunden, *Secret Weapons and World War II,* 104-05. Parshall and Tully note that simply possessing ship-borne radar might not have helped the Japanese since using it effectively for air defense

By late autumn of 1942, the Japanese Navy understood the advantage that radar gave to the Americans and began to take steps to address the gap in capabilities. The Navy began to set up radar stations to protect its land-based air groups at its larger bases in the Pacific. The radar sets were not as technically advanced as Allied radar sets, however. Their range was only 100 km and they could not provide accurate information on the altitude or speed of approaching aircraft. They were also unreliable. The Navy General Staff issued urgent demands to accelerate development of radar technology but their stringent specifications were impossible to satisfy in the time available.[92]

In the spring of 1943, the Japanese Navy decided to equip all types of warships with radar sets when possible. The Navy also focused on simplifying the technology so the sets could be used by less technically qualified personnel.[93] The action in the Kula Gulf on the nights of 5 and 6 July 1943 appeared to validate the Navy's efforts. On both nights, a Japanese destroyer task force carrying reinforcements to Japanese garrisons in the Solomon Islands used the surface search radar on board its flagship, *Niizuki,* to gain the tactical advantage against a larger American force. On the first night, the Japanese flotilla detected the Americans first, fired a salvo of torpedoes at long range, and then turned away. The torpedoes sank a U.S. destroyer; the American commander attributed the loss to a submarine and never even realized he had been involved in a surface engagement. On the second night, the Americans, incorrectly believing that the Japanese ships lacked radar and they thus had the advantage of surprise, closed to within 7,000 yards of the Japanese escort group before opening fire. The American barrage sunk the *Niizuki* but the delay in firing enabled the other two destroyers in the escort group, which had detected the Americans first and were therefore prepared for combat, to fire numerous torpedoes before retreating. At least three torpedoes hit the *USS Helena*, severing its bow and causing it to sink rapidly. Once the only radar-equipped Japanese ship was lost, the Americans were able to inflict significant damage on the nearby Japanese transport groups, sinking another destroyer and damaging three more.[94]

Although the Japanese military now recognized the value of radar, it struggled to expand radar research and development. The limited Japanese industrial and scientific-technical resource base and the mounting combat losses made it difficult for Japanese manufacturers to produce sufficient numbers of existing designs, much less to design, develop, test, and then produce new weapons and equipment. Consequently, Japanese radar at the end of the war was at the technical level of British radar during the Battle of Britain in 1940 or U.S. radar in 1942. Japanese radar sets were more poorly designed and constructed than British and American sets. Japan had no ground-

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required the coordination of air defense assets in a single location, such as the American Combat Information Center. The Japanese never made such a conceptual leap, even after the introduction of ship-based radar. It also required effective communications with the individual CAP elements, which the Japanese did not have due to inadequate radios in their fighters and the use of a single radio frequency for all aircraft operations. Parshall and Tully, *Shattered Sword,* 188.

[92] Grunden, *Secret Weapons and World War II,* 110; Peattie, *Sunburst,* 198; Evans and Peattie, *Kaigun,* 414.

[93] Grunden, *Secret Weapons and World War II,* 104-05.

[94] Evans and Peattie, *Kaigun,* 596 n. 75.

control intercept equipment, anti-aircraft fire control systems, or radar-equipped submarines at the end of the war. Japan did not develop airborne radar until 1944, too late to field any night-fighters before the end of the war. An IFF system debuted the same year, but the equipment was rudimentary and there was no standardization of IFF frequencies between the services.[95]

The inadequacy of Japanese radar systems contributed to the military's inability to solve one of Japan's greatest problems – how to defend against U.S. long-range bombers. Japan lacked accurate radar for ground-control intercept and fire control and an integrated system to maximize the effectiveness of their radar sets. By May 1945, Allied radar jamming technology was so effective that in most cases, Japanese anti-aircraft batteries had to make visual contact before opening fire.[96]

There were several reasons for Japan's low level of radar development during the war. The most important, according to U.S. post-war assessments, was the "fundamental failure of the Japanese High Command to realize the operational importance of radar" early in the war. Japan's lack of appreciation for the value of radar was attributable, at least in part, to its strategic culture. The Japanese military, like the Germany military, was focused on the offensive so it was less interested in weapons considered to be defensive, such as radar. Once the utility of radar for offensive purposes was demonstrated in naval engagements and in the Battle of the Atlantic, Japan's interest increased.[97]

The Japanese Navy's leisurely approach to radar was motivated, at least in part, by its initial conception of radar as a defensive system. Radar, the Navy believed, might be useful as a means to protect ships from incoming aircraft but would remain only an auxiliary device for targeting the enemy. The Navy planned to rely on its optics, perhaps the best in the world when the war began, and its night battle tactics in combat. Early in the war, when American commanders and crews were insufficiently trained in the use of radar, the effective use of optics by the more experienced Japanese made a significant difference in night combat. During several night engagements, Japanese lookouts using optics spotted US ships before their own ships were identified by American radar. Still, a year into the war the Japanese Navy increasingly found itself fighting blindfolded.[98]

The lack of interest in radar within the Japanese high command meant that there was no large-scale, nationwide effort to mobilize the scientific and technical expertise in academe, industry, and the military to attack the critical technical problems. Japanese radar research and development was, according to at least one post-war U.S. assessment, poorly coordinated. It was also highly

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[95] Grunden, *Secret Weapons and World War II,* 117; Evans and Peattie, *Kaigun,* 508, 595 n. 69.
[96] Grunden, *Secret Weapons and World War II,* 122-23.
[97] Grunden, *Secret Weapons and World War II,* 83-84, 117-18. Evans and Peattie describe the claim that the Japanese military's preference for the offensive contributed to its lack of interest in radar as possible but not demonstrable. Evans and Peattie, *Kaigun,* 414-15.
[98] Grunden, *Secret Weapons and World War II,* 104; Evans and Peattie, *Kaigun,* 414-15; 507.

decentralized. In the Army, for example, separate sections of different General Staff bureaus were responsible for various aspects of radar research, including specifications, research oversight, research procurement, and operational use. Most of the research was performed by civilian institutions and private firms according to specifications provided by the General Staff. The Army Air Service had its own laboratories, separate from the Army. It was not until 17 June 1943 that the Army established the Tama Technical Institute to coordinate radar research. The Navy waited until early 1945 to consolidate its electronics research projects at one facility and provide a central office for their administration.[99]

Japan's decentralized approach produced excessive compartmentalization and a lack of communication between the military and civilian scientists. Radar research and production were carried out on a component basis rather than a complete equipment basis. The research group and company producing a radar component had little insight into the design and manufacture of other components or into how the equipment would be used. Civilian engineers and technicians were not informed of how the equipment performed in combat and were not allowed to visit radar installations in the field. Civilian scientists could not go aboard warships on which radar sets had been installed, making it more difficult to understand how the sets functioned at sea.[100]

The lack of central direction, coordination, and communication were particularly problematic given the smaller, less experienced pool of technological expertise in Japan. A shortage of technical personnel remained a significant problem for Japanese radar development throughout the war. By one estimate, Japan had only 5 to 10 percent of the research personnel the U.S. found necessary to staff a "full-fledged radar program." Without any central direction, the already small pool of technical talent was poorly utilized. Researchers were assigned arbitrarily to labs and projects with little regard to their specialties. There was no systematic effort to ensure that scientists in key fields and electrical engineers were assigned to radar research.[101]

It was not only personnel that were in short supply. The Japanese electronics industry was small when the war began. A lack of equipment and parts, such as high-quality vacuum tubes, also hindered Japanese radar development and production. The destruction of facilities from bombing exacerbated the problem. About 80 percent of the productive capacity for microwave equipment was destroyed or was forced to relocate by the end of 1944.[102]

Japanese radar training also lagged behind the West. The Navy began radar training in March 1942 at the Navy Communications School in Yokusuka and established a more extensive training facility in September 1944. The Army did not establish a radar training facility until April 1943.

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[99] Evans and Peattie, *Kaigun*, 414-15; Grunden, *Secret Weapons and World War II*, 105-07, 117-18.
[100] Evans and Peattie, *Kaigun*, 415; Grunden, *Secret Weapons and World War II*, 120
[101] Grunden, *Secret Weapons and World War II*, 118.
[102] Grunden, *Secret Weapons and World War II*, 121; Evans and Peattie, *Kaigun*, 415.

Before then, Army officers were sent to the factories that manufactured the radar sets to receive training. A centralized administration for military radar training was not established until May 1945.[103]

Japan might have overcome some of these deficiencies had it received more substantial assistance in radar research and development from its putative ally, Germany. The Germans, however, believed that Japan was a weak ally and were concerned that any advanced technology they provided to the Japanese would fall into Allied hands if Japan was defeated. Consequently, they provided little information on radar or aid in radar development to Japan. German policy began to change somewhat in late 1943, but even then, the Germans only supplied the Japanese with information that they believed the Allies already possessed. The Germans showed Japanese emissaries all of the radar sets in production in 1943 but did not share any technology then under development. Germany provided complete specifications for the Würzburg-type radar and Japan arranged to duplicate it but only three sets were built and only one was put into operation on an experimental basis by the end of the war.[104]

The most significant factor impeding Japanese radar development during the war was interservice rivalry. The Army and the Navy conducted totally separate research programs, wasting resources and duplicating effort. Japanese manufacturers had to maintain separate development and production sections for Army and Navy radar projects until late in the war. Permission was required before information concerning Navy sets could be passed on to the Army, and vice versa.[105]

Separate radar research efforts produced separate, and sometimes incompatible, radar systems. The Japanese Army established an air defense system for the home islands. The Navy established its own network to protect its bases. The two networks were completely independent of each other; poor liaison between the Army and the Navy meant that it was difficult to coordinate the two separate systems. Similarly, the Army was initially responsible for the development of an IFF system in aircraft but the Navy was so dissatisfied with the pace of the Army's progress that it launched its own development program. As a result, the Army and the Navy had different IFF systems operating on different frequencies. When they tried to standardize, they lost the capability to distinguish friend from foe. No substantive effort to standardize radar equipment between the Army and Navy until January 1944.[106]

Evans and Peattie call radar "the single most important technological advantage held by the U.S. Navy in the Pacific War." It stripped protection of darkness away from Japanese torpedo tactics

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[103] Grunden, *Secret Weapons and World War II,* 110.
[104] Grunden, *Secret Weapons and World War II,* 121-22.
[105] Grunden, *Secret Weapons and World War II,* 119; Evans and Peattie, *Kaigun,* 415.
[106] Grunden, *Secret Weapons and World War II,* 110, 119.

and made irrelevant superior quality of Japanese optics. In combination with combat information center, improved air defenses tremendously, especially in vectoring combat air patrols to intercept incoming Japanese air strikes. SJ radar aboard American submarines enabled them to make attacks independent of weather and daylight.[107]

ATOMIC WEAPONS IN WORLD WAR II

The nuclear age began in December 1938 when Otto Hahn and Fritz Strassmann, German scientists working at the Kaiser Wilhelm Institute for Chemistry in Dahlem, Germany, split uranium nuclei by bombarding the uranium with slow neutrons. Although Hahn and Strassman published their results in early January 1939, they were uncertain about the outcome and the significance of their experiments. At the Washington Conference on Theoretical Physics later that month, however, eminent Danish physicist Niels Bohr announced that Hahn and Strassman had discovered nuclear fission.[108]

In a paper published in the summer of 1939, Bohr claimed that the isotope responsible for the slow-neutron fission was uranium-235 (U-235). Nuclear weapons would require large amounts of U-235, which would have to be separated from uranium-238 (U-238). Identifying the best method for isotope separation and employing it successfully to create large quantities of U-235 became one of the focal points of nuclear research.[109]

The discovery of nuclear fission sparked intense interest in the world scientific community. By the end of 1939, over one hundred papers had been published on the subject. Many scientists were optimistic that nuclear energy would provide a new source of power to meet the world's growing energy demands. Others were concerned that the discovery would be used to make powerful weapons.[110]

United States and Great Britain

In the United States, Leo Szilard, a Jewish physicist who had fled Germany in 1933, was worried that the Germans would try to use the discovery of fission to build a new weapon. Szilard, who had moved to the United States from England in 1937, met with Enrico Fermi, a Nobel Prize-winning physicist who had just fled Italy to escape persecution, in New York shortly after Bohr's announcement.[111]

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[107] Evans and Peattie, *Kaigun,* 508.
[108] Grunden, *Secret Weapons and World War II,* 50-51; Geoffrey Herrera, *Technology and International Transformation: The Railroad, the Atom Bomb, and the Politics of Technological Change* (Albany, N.Y.: State University of New York Press, 2006), 130-31.
[109] Grunden, *Secret Weapons and World War II,* 54.
[110] Grunden, *Secret Weapons and World War II,* 48.
[111] Grunden, *Secret Weapons and World War II,* 51.

After Szilard convinced him that it was possible to build an atomic weapon in the next few years, Fermi met with representatives from the U.S. Navy and the Naval Research Laboratory (NRL). The NRL scientists were interested in the possibility of using a controlled nuclear chain reaction to power submarines while the Navy representatives were interested in creating a bomb. Three days after meeting with Fermi, the NRL provided $1,500 to begin research.[112]

Meanwhile, Szilard continued to work to increase government support for nuclear fission research. On 16 July 1939, he met with Albert Einstein and convinced him that a nuclear chain reaction was possible. Szilard and Einstein agreed to write a letter to President Roosevelt. The letter explained that it may be possible to build an atomic bomb, and that the Nazis may be working on such a project.[113]

On 11 October 1939, Alexander Sachs, an economic consultant to the president, delivered the Szilard-Einstein letter to Roosevelt. The letter urged Roosevelt to establish a mechanism that would enable the government to work closely with the nation's scientists to study the potential of nuclear fission. Sachs added his own note warning Roosevelt of the potential threat posed by German nuclear research and emphasizing the importance of securing access to uranium for the United States and denying access to Germany. The next day, Roosevelt established the President's Advisory Committee on Uranium, more commonly known as the Uranium Committee. [114]

The Uranium Committee, led by the head of the National Bureau of Standards, Lyman Briggs, submitted its first report on 1 November 1939. The report highlighted the potential of using a controlled, nuclear chain reaction as a source of motive power for submarines. It also mentioned the possibility of employing the chain reaction to create a weapon. The committee recommended funding fission research but the Army provided only $6,000 to fund Fermi and Szilard's experiments.[115]

With a small budget and a conservative director, the Uranium Committee accomplished little. Consequently, it was subsumed by the recently formed National Defense Research Committee (NDRC) led by Vannevar Bush in June 1940. The Uranium Committee reported directly to Bush. The action assured greater direct support from the government while reducing dependence upon the military. It also facilitated closer cooperation with civilian scientists. Bush soon reorganized the committee and added more scientists.[116]

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[112] Grunden, *Secret Weapons and World War II,* 51.
[113] Graham Farmelo, *Churchill's Bomb: How the United States Overtook Britain in the First Nuclear Arms Race* (New York: Basic, 2013), 129; Grunden, *Secret Weapons and World War II,* 53.
[114] Farmelo, *Churchill's Bomb,* 129; Grunden, *Secret Weapons and World War II,* 54.
[115] Grunden, *Secret Weapons and World War II,* 54.
[116] Herrera, *Technology and International Transformation,* 178-79; Grunden, *Secret Weapons and World War II,* 55; Baxter, *Scientists Against Time*, 423; Farmelo, *Churchill's Bomb,* 134.

As Bush began to mobilize the scientific community in the United States, significant nuclear fission research was also underway in Great Britain. When World War II began in September 1939, the leading centers for research in Great Britain were the Cavendish Laboratory at Cambridge University and the University of Birmingham. At Birmingham, German-born physicist Rudolf Peierls and Austrian-born physicist Otto Frisch, both of whom had fled to Britain to escape religious persecution on the Continent, were leading the research effort. They had been excluded from working on radar because they were deemed a security risk.[117]

In February 1940, Frisch and Peierls discovered that the amount of uranium needed to create an atomic bomb was much smaller than conventional wisdom assumed. It was thus possible, at least in theory, to build an atomic weapon of moderate size within a reasonable length of time, perhaps even before the conclusion of the war. The memo recounting their findings eventually reached Henry Tizard, chair of the Committee on the Scientific Survey of Air Defence. Tizard ordered the formation of a special committee, later designated the MAUD Committee, to consider the implications of the Frisch-Peierls report. .[118]

The MAUD Committee, chaired by physicist George Paget Thomson, first met on 10 April 1940. The members of the group were skeptical that an atomic bomb could be built, but they agreed that further investigation of isotope separation and fast fission was warranted. The committee members' skepticism may have been the product, at least in part, of xenophobia. Frisch and Peierls were not included on the committee because they were foreigners. When British physicist James Chadwick provided evidence from his own research confirming Frisch's and Peierls's findings at a later meeting, the committee was, in the words of one of its members, "electrified." The committee decided to redouble its research efforts.[119]

By December 1940, the research on isotope separation initiated by the MAUD committee was complete. The report issued by the committee recommended gaseous diffusion of U-235 on a massive scale and provided cost estimates and technical specifications for a large uranium enrichment plant. The report concluded that production of a bomb in time to affect the outcome of the war was possible. On 15 July 1941, the MAUD Committee approved its final two reports and disbanded. The first report examined the use of uranium for a bomb. It concluded that a bomb was feasible and described it in detail, providing specific proposals and including cost estimates. It warned that the Germans could also be working on a bomb and urged the British government, in cooperation with the United States, to build one as a matter of the "highest priority." The second report concluded that controlled fission of uranium could be used to generate energy and provide large quantities of radioisotopes for medical research. The

[117] Grunden, *Secret Weapons and World War II,* 53; Farmelo, *Churchill's Bomb,* 155.
[118] Farmelo, *Churchill's Bomb,* 141, 144.
[119] Farmelo, *Churchill's Bomb*, 159, 161; Richard Rhodes, *The Making of the Atomic Bomb* (New York: Simon & Schuster, 1986), 329-331.

construction of a "uranium boiler," or nuclear reactor, held great promise for the future but was not worth considering during the present war. [120]

The reports of the MAUD Committee and the minutes of all the committee meetings were forwarded to the Americans but the British received no response. Curious why the United States was ignoring the Committee's reports, one of the members of the Committee, physicist Mark Oliphant, called on Briggs during an August 1941 trip to the United States to work with his NDRC counterparts on radar. He found that Briggs had locked the reports in his safe and had not shown them to anyone. Oliphant was "amazed and distressed." Soon thereafter, Oliphant met with the Uranium Committee and stressed that the immediate focus of nuclear research should be on developing an atomic bomb rather than finding new power plants for submarines. Oliphant conveyed the same message to Bush and several prominent American scientists in later meetings.[121]

Oliphant's visit could not have come at a more propitious time. In June 1941, the United States formed the Office of Scientific Research and Development (OSRD). The NDRC had served as a useful mechanism to encourage research but it did not have the authority to pursue engineering development. The OSRD would have broad authority over all government science in the service of war. The OSRD director – Vannevar Bush – would report directly to the president. Responsibility for nuclear research was transferred from the NDRC to the Uranium Section of the OSRD.[122]

The United States thus had the resources and the organizational structure necessary to pursue a large-scale atomic bomb project but it still lacked the will. The MAUD report and Oliphant's visit tipped the scales. On 9 October 1941, Bush met with Roosevelt to discuss the implications of the MAUD report. He explained that construction of an atomic bomb was possible before the war ended. The bomb would be far more powerful than existing weapons but would require a vast industrial effort to build. Bush also urged complete cooperation with Great Britain on all technical matters. Roosevelt concurred; he sent a letter to Churchill a few days later offering to collaborate closely in atomic bomb development and approved a thorough exploration of the feasibility of constructing a bomb.[123]

Roosevelt's offer to collaborate was initially ignored by the British. Although some British scientists, such as Oliphant, were eager to enlist American assistance, Churchill and his science advisor, Lord Cherwell, were concerned that sharing information with the Americans would endanger the secrecy of the effort and would disproportionately benefit the Americans, who they believed were behind the British in their research. Most of all, however, Churchill and Cherwell recognized that whoever possessed the means to construct an atomic weapon would be able to

[120] Farmelo, *Churchill's Bomb,* 184.
[121] Rhodes, *Making of the Atomic Bomb,* 374-75.
[122] Grunden, *Secret Weapons and World War II,* 58.
[123] Farmelo, *Churchill's Bomb,* 195; Herrera, *Technology and International Transformation,* 179.

dictate terms to the rest of the world. They were unwilling to put themselves at the mercy of the Americans.[124]

The report on the feasibility of constructing a bomb that Roosevelt ordered bore more immediate fruit. The report, conducted under the auspices of the National Academy of Sciences (NAS), concluded, "A fission bomb of superlative destructive power will result from bringing quickly together a sufficient mass of element U235." The required mass of U-235 was between 2 and 100 kg. The report also predicted that atomic weapons might be available in significant quantities within three or four years.[125]

On the basis of the MAUD report and the NAS report, Bush was ready to move the atomic bomb program from research to development. He met with the members of the Uranium Committee on 6 December 1941 to reorganize their work. The members would pursue multiple avenues to separate sufficient U-235 to build a weapon while simultaneously beginning to design the bomb. Over $1 million was allocated to the effort. Nuclear weapons development had become a government priority. The Japanese attack on Pearl Harbor the following day reinforced the decision to move the bomb project into the industrial production phase and strengthened the conviction that OSRD should move as quickly as possible.[126]

In early 1942, a new department, designated the Manhattan Engineering District, was established within the Army Corps of Engineers. The objective of the district was to construct large-scale industrial sites for the separation and enrichment of U-235 as part of the effort to build an atomic bomb. There would be plenty of work for the Army engineers. In May 1942, James B. Conant, who had taken over the NDRC after Bush became head of the OSRD, decided that it would be prudent to pursue all five known methods for making a bomb – centrifuge, gaseous diffusion, electromagnetic separation, plutonium, and heavy water – simultaneously. Pilot plants would be needed for all five methods and production plants would be built for the most successful methods. Adapting the separation methods to large-scale, mass-production levels would require advanced engineering and vast technological and industrial resources.[127]

When administrative delays from the Corps of Engineers slowed progress, Bush sought out a dynamic military officer to take charge of the Manhattan Engineering District Program. He chose Colonel Leslie Groves, who had supervised the building of the Pentagon as deputy chief of construction for the Army. Groves was promoted to Brigadier General and placed in charge of the

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[124] Barton J. Bernstein, "The Uneasy Alliance: Roosevelt, Churchill, and the Atomic Bomb, 1940-1945," *The Western Political Quarterly,* vol. 29, no. 2 (Jun. 1976), 206-07; Rhodes, *Making of the Atomic Bomb,* 372.
[125] Baxter, *Scientists Against Time,* 427..
[126] Grunden, *Secret Weapons and World War II,* 58; Baxter, *Scientists Against Time,* 428; Herrera, *Technology and International Transformation,* 138.
[127] Grunden, *Secret Weapons and World War II,* 58; Baxter, *Scientists Against Time,* 434-35; Herrera, *Technology and International Transformation,* 180; Rhodes, *Making of the Atomic Bomb,* 406-07..

Manhattan Engineering District on 23 September 1942. By the end of 1942, Groves had chosen the sites for building the industrial and laboratory facilities needed to develop the atomic bomb. The Manhattan Engineering District became the military headquarters of the Manhattan Project.[128]

In December 1942, Roosevelt approved the expenditure of $400 million for uranium separation plants and a plutonium-producing pile. As the Manhattan Project entered its industrial phase, Groves worked closely with a number of private companies to design, build, and operate the large industrial facilities necessary to produce the enriched uranium and plutonium for an atomic bomb. There were Army-directed research laboratories at the University of Chicago, Columbia University, and the University of California, Berkeley; plutonium and uranium manufacturing facilities at Oak Ridge, Tennessee, and Hanford, Washington, and a bomb research, assembly, and manufacture facility at Los Alamos, New Mexico.[129]

Research, development, and construction was carried out by several different companies and groups – M. W. Kellogg's subsidiary, the Kellex Corporation, designed the gaseous diffusion plant, which was built by the J. A. Jones Construction Company. The electromagnetic plant was constructed by the Stone and Webster Engineering Corporation. Du Pont also contributed extensively to the effort, without profit and without patent rights. Du Pont engineers worked closely with scientists from the University of Chicago.[130]

As the United States was scaling up its atomic weapon development efforts dramatically, the British struggled to keep up. Throughout 1942, British and American scientists exchanged information freely. British scientists visiting the United States were amazed at the scale of the effort and the progress the Americans had made in just a short time. As the British confronted dwindling resources and scarce manpower, they concluded that they would have to depend heavily on American assistance to pursue the bomb project. Sir John Anderson, the Lord Chancellor and cabinet minister in charge of Britain's atomic energy project, known as Tube Alloys, argued on 30 July 1942 that the British should pursue a closer partnership with the Americans and move their work the United States. "We now have a real contribution to make to a 'merger,' Anderson noted. "Soon we shall have little to none." [131]

The leaders of the Manhattan Project, however, were increasingly wary of working closely with the British. They believed that they no longer needed British assistance to solve the major scientific problems. They also worried that the British would use American research to gain industrial advantages after the war. Most significantly, they recognized that atomic weapons would bestow

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[128] Grunden, *Secret Weapons and World War II,* 59.
[129] Herrera, *Technology and International Transformation,* 165, 179.
[130] Baxter, *Scientists Against Time,* 441-42.
[131] Bernstein, "The Uneasy Alliance," 208; Farmelo, *Churchill's Bomb,* 213, 215.

tremendous advantages on whichever country possessed them after the war. They were unwilling to share those advantages with the British.[132]

With the concurrence of Roosevelt, the Americans began limiting the exchange of information with the British in December 1942. The British retaliated by no longer sending their scientists to the United States. Finally, in early August, the two sides reached an agreement. At the highest level, information would be exchanged through a Combined Policy Committee, composed of representatives from the United States, Great Britain, and Canada. At lower levels, full interchange in scientific research and development on common problems would resume but the British would receive only limited information on the design, construction, and operation of large-scale plants. The new policy was ratified when Roosevelt and Churchill signed the Quebec Agreement on 19 August 1943.[133]

After the Quebec agreement was signed, the British immediately sent scientists to the United States to join the Manhattan project. Professor James Chadwick, discoverer of the neutron, became head of the British group participating in the Manhattan Project. He and a number of other British scientists went to Los Alamos, where they had access to all of the research and development taking place there. Although the British were now the junior partners in the Manhattan Project, the British and American scientists worked agreeably and equally together.[134]

The atmosphere at Los Alamos was highly collaborative, carefully planned, precisely timed and executed, yet haphazard and unpredictable. It was representative of some of the keys to American success. Scientists had to determine the properties and behavior of the fissile material (uranium 235 and plutonium 239 and figure out how to bring the material to its critical (fissioning) state fast enough to create an explosion. The most complex problem was the design of an explosive device to bring the fissile material to critical mass. The work required intensive collaboration of scientists and engineers. Sufficient progress had been made by 5 March 1945 that research was frozen so that all attention could be focused on bomb assembly and test firing. The test, conducted on 16 July 1945, was successful. Less than a month later, the first atomic bomb was dropped on Hiroshima, Japan.[135]

To ensure the successful delivery of the first atomic bomb, the U.S. Army Air Forces made an important operational change. To both disguise and protect the single plane carrying the atomic bomb, Groves had planned to hide it inside a massive wave of bombers. Groves' plan would have been consistent with established practice, which relied on massive fleets of bombers carrying incendiary weapons and flying at low altitude to avoid the high winds of the jet stream and

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[132] Bernstein, "The Uneasy Alliance," 209; Farmelo, *Churchill's Bomb,* 218, 226.
[133] Bernstein, "The Uneasy Alliance," 217; Farmelo, *Churchill's Bomb,* 240.
[134] Barnstein, "The Uneasy Alliance," 220-22; Farmelo, *Churchill's Bomb,* 276, 279.
[135] Herrera, *Technology and International Transformation,* 181-82.

Japanese anti-aircraft fire. However, General Ernest LeMay, who had developed the concept of low-level incendiary bombing, advised Groves that a lone bomber flying at high altitude would be safer, because single weather planes and photo observers regularly flew untouched over Japan. On its mission over Hiroshima on 6 August 1945, the *Enola Gay* flew virtually alone, accompanied by only an instrumentation aircraft and a photo aircraft, at 32,000 feet.[136]

Coming as it did so close to the end of the war (indeed, arguably hastening the end of the war), most of the organizational and operational adaptation resulting from the development of the atomic bomb occurred during the next war – the Cold War. The creation of the Strategic Air Command (SAC) in 1946 was an attempt to adapt organizational structure to technological change. In this case, the restructuring was designed to facilitate exploitation of atomic weaponry. The establishment of SAC was intended to improve the U.S. Army Air Forces' ability to employ strategic bombers and nuclear weapons to conduct long-range offensive operations in any part of the world, either independently or in cooperation with land and naval forces. When the U.S. Air Force was established as an independent service the following year, the SAC became the largest command within the service.[137]

Over the next decade, SAC adapted its operations and organization in order to carry out its mission more effectively. In 1948, the purchase of aerial refueling equipment gave SAC global reach. Aerial refueling entered the SAC training syllabus in 1950. The dispersal of the bomber force became official policy in 1954. No more than 45 B-47s or 15 B-52s were permitted to be permanently stationed at any one base. The objective was not only to protect the bombers from a devastating surprise attack but also to enable more of them to get into the air faster by making more runways available. The culmination of this first stage of operational and organizational changes wrought by the development of nuclear weapons came in 1955 when the concept of ground alert was approved. SAC was ordered to develop the skills necessary to ensure that one-third of its bombers and tankers could be in the air within fifteen minutes.[138]

Germany

Germany was where nuclear fission was first discovered. It was also the first country to establish an office devoted to the military applications of nuclear energy. Yet Germany failed to develop an atomic weapon during World War II. The primary difficulties were a dearth of resources and industrial capacity and a lack of support from senior leadership.

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[136] Warren Kozak, *LeMay: The Life and Wars of General Curtis LeMay* (Washington: Regnery, 2009), 196-97, 213-14, 247-48; L. Douglas Keeney, *15 Minutes: General LeMay and the Countdown to Nuclear Annihilation* (New York: St. Martin's, 2011), 15.
[137] Keeney, *15 Minutes,* 31.
[138] Keeney, *15 Minutes,* 43, 114, 148-49.

Following the announcement in early 1939 of Hahn and Strassman's discovery of nuclear fission, a number of German scientists attempted to bring the idea of nuclear power to the attention of the German leadership. Nikolaus Riehl, an industrial physicist and head of a research department at the Auer Company, encouraged the Army to explore nuclear energy. He even offered the services of the Auer Company for uranium production, but the Army displayed little interest.[139]

Others had better luck. Physicists Wilhelm Hanle and Georg Joos were researching the use of uranium fission in an energy-producing reactor. They informed the Ministry of Culture of their research. The Ministry of Culture forwarded the information to the Ministry of Education, which assigned Professor Abraham Esau, president of the Reich Bureau of Standards and head of the physics section of the Reich Research Council, to organize a conference on the subject. The organizational meeting was held on 29 April 1939. It led to agreement on a few issues. Radium would be supplied from mines in Czechoslovakia to conduct further research, the export of uranium would be banned, and a formal atomic research program was established.[140]

Just four days earlier, n 24 April 1939, Professor Paul Harteck, a physical chemist, and his assistant, Wilhelm Groth, wrote a letter to the German War Office outlining recent research in nuclear physics and emphasizing the potential of uranium fission for use in a weapon. Harteck's letter attracted little notice and proceeded slowly through the German bureaucracy for months. In August 1939, however, Harteck's letter reached the office of Kurt Diebner in the Army's Ordnance Department. Diebner recognized the import of the letter but lacked the influence to act independently. He passed the letter on to Professor Hans Geiger, co-inventor of the Geiger counter, who then encouraged the War Office to proceed with nuclear fission research. As a result of Geiger's suggestion, a laboratory was established at Gottow within a section of the Army's rocket-projectiles and explosives research division. The Army's Ordnance Department later established an independent nuclear research office and placed Diebner in charge. When World War II began in Europe, Germany was thus the only country with an office devoted exclusively to research on the military applications of nuclear energy.[141]

In January 1940, the German War Office took over the Kaiser Wilhelm Institute of Physics in Dahlem. Scientists there soon began constructing a nuclear reactor. As a moderator, they chose to use deuterium oxide, or heavy water, because they considered graphite too expensive and time-consuming. Germany secured a steady supply of heavy water when the German Army captured the production facilities of the Norwegian Hydroelectric Company during the invasion of Norway in April 1940. The company was the largest producer of heavy water in the world.[142]

[139] Grunden, *Secret Weapons and World War II,* 52.
[140] Grunden, *Secret Weapons and World War II,* 52.
[141] Grunden, *Secret Weapons and World War II,* 52-53.
[142] Grunden, *Secret Weapons and World War II,* 55.

During the summer of 1940, a new facility for nuclear research was established in Berlin near the Kaiser Wilhelm Institute. To hide its true purpose, it was built on the grounds of the Institute of Biology and Virus Research and given the name Virus House. Germany had also acquired thousands of tons of high-grade uranium ore for its research program. By the end of the year, construction of a uranium pile at the Virus House had begun.[143]

The American and German bomb efforts were very similar in the winter of 1941-1942. The amount of money spent was nearly equal and the scientific results were similar. Yet over the next year, Germany fell irretrievably behind. By the end of the war, Germany was nowhere near attaining a bomb and had not even achieved a chain reaction. The German atomic weapon development effort failed, in part, due to chance. In the spring and summer of 1942, the German research effort experienced a number of setbacks. Prototypes using several different methods to separate U-235 proved unsuccessful. The uranium pile with which eminent physicist Werner Heisenberg was experimenting in Leipzig overheated and exploded, destroying the laboratory and wasting the resources in the reactor.[144]

More important than mere chance as an explanation for the failure of the German atomic program was the lack of interest demonstrated by Germany's top leaders. When Hitler met with Reichsminister Albert Speer on 23 June 1942, he labeled the research effort "Jewish physics" and refused to provide any additional support. Although the Reich Research Council took over supervision of nuclear fission research earlier in the year, there was no extensive government commitment or large-scale funding of nuclear research efforts in Germany at the end of June 1942.[145]

The most significant reason of all for the failure was the German inability to muster the enormous resources required to build an atomic bomb in the midst of a bitter, protracted war. By 1942, the war had changed from one that seemed likely to end quickly in Germany's favor into one that seemed likely to continue for some time. Based on the pessimistic reports from German atomic scientists German Army officials concluded that production of a bomb during the war was unlikely. With economic hardships mounting rapidly, every German scientific resource was needed on programs with obvious and clear benefit to the war effort. Consequently, they decided to scale the program back and keep it in the lab rather than move it to industrial production. [146]

Japan

Japanese scientists closely followed the progress of international nuclear research in the 1930s and contributed to the growing body of knowledge. Japan was the first country outside the United

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[143] Grunden, *Secret Weapons and World War II*, 55.
[144] Grunden, *Secret Weapons and World War II*, 59.
[145] Grunden, *Secret Weapons and World War II*, 59.
[146] Herrera, *Technology and International Transformation*, 137-38.

States to build and successfully operate a cyclotron, which produced powerful neutron sources that could be used to make a variety of new artificial radioisotopes. During World War II, the Japanese military sponsored several nuclear research efforts. Nevertheless, when General Leslie Groves, head of the Manhattan Project, asked scientists from the University of California at Berkeley who had helped train some of Japan's scientists and knew them personally to evaluate Japan's potential to build an atomic bomb, they concluded that due to a lack of "uranium supplies, industrial capacity and scientific resources," Japan would not be able to build a bomb. For the remainder of the war, the Allies had no fears of a Japanese nuclear effort and did not seek to gather any information about it. The scientists' assessment proved accurate. Japanese atomic research made little progress during the war. The scale of the research effort was small and its accomplishments were miniscule. [147]

Japan was a latecomer to modern science but had caught up to the level of most western countries by the 1930s. Serious quantum research in Japan began around 1931-32. Nishina Yoshio, who studied under Ernest Rutherford at the Cavendish Laboratory and conducted research with Niels Bohr, was a key figure in the research effort. In 1931, he founded the Nuclear Research Laboratory at the Riken Institute, Japan's national scientific research institute. Nishina's laboratory included over 110 scientists on the research staff and was the center of Japanese nuclear physics research. It was Nishina's laboratory that built and operated Japan's cyclotron in 1937. The physicists in the lab stayed abreast of nuclear research in other countries by reading western periodicals and corresponding with colleagues abroad. In 1939, two Japanese physicists published an article calculating the number of neutrons released as the result of atomic fission and suggesting that a chain reaction was possible. [148]

Despite its pre-war achievements, Japan's scientific community lacked sufficient size, unity, and motivation to successfully build an atomic weapon. There were not enough scientists in Japan to conduct a large-scale research effort focused on nuclear fission. The military research efforts never involved more than 20 to 30 research scientists and technicians at any one time. Civilian research labs expanded the personnel and equipment available somewhat but the Japanese development effort was still resource constrained.[149]

The scientific community in Japan was also riven by institutional rivalry and elitism. Academic cliques, known as *gakubatsu*, made it difficult for scientists from different educational institutions to work together. Similarly, the feudalistic *Koza* system, which gave a single senior professor all the

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[147] Grunden, *Secret Weapons and World War II,* 48, 82; John W. Dower, "Science, Society, and the Japanese Atomic-Bomb Project During World War Two," *Bulletin of Concerned Asian Scholars,* vol. 10, no. 2 (Apr.-Jun. 1978), 42, 51; Charles Weiner, "Retroactive saber rattling?" *Bulletin of the Atomic Scientists*, vol. 34, no. 4 (Apr1978), 11.
[148] Grunden, *Secret Weapons and World War II,* 50, 56-57; Dower, "Science, Society, and the Japanese Atomic-Bomb," 43; Weiner, "Retroactive saber rattling?" 10.
[149] Grunden, *Secret Weapons and World War II,* 80-81.

power over funding and research at a university, limited constructive criticism and academic debate.[150]

Moreover, many Japanese scientists did not believe development of an atomic bomb was possible. They saw the effort as hopeless, not only for Japan, but for all countries, including the United States. They calculated that a serious atomic bomb project would take 1/10 of the electricity and ½ of the copper in Japan. Consequently, they approached the endeavor as *gakumon*, or a "purely scholarly exercise." Enlisting young scientists in the research effort would protect them from conscription and thus help to ensure the future of science and physics in Japan. The additional funding associated with the effort would also provide the funds the Japanese scientific community needed to become world class. There was not, however, any sense of urgency like there was in the Anglo-American effort.[151]

In any case, the deficiencies of the scientific community were less important since the initiative for nuclear research in Japan came from the military services rather than civilian scientists, as was the case in the United States, Great Britain, and Germany. The Japanese military followed international developments in nuclear physics by reading foreign science journals, although much of the responsibility was delegated to low-ranking technical officers. The first serious inquiry into the prospects of a Japanese atomic bomb began in April 1940 under the auspices of Lieutenant General Yasuda Takeo of the Army Aeronautical Technology Research Institute. The report ordered by Yasuda concluded in October 1940 that an atomic bomb might be possible and Japan may have enough uranium ore to produce one. Yasuda next asked for a feasibility study on the construction of a weapon using nuclear fission. Responsibility for the study was eventually assigned to Nishina, who was unenthusiastic because the study would interfere with his efforts to complete the assembly of his laboratory's new cyclotron [152]

Meanwhile, Captain Ito Yoji, the same Navy scientist who had traveled to Germany in early 1941 to learn about radar, raised the possibility of developing an atomic bomb in late 1941. In late November, the Navy decided to begin research on nuclear fission at the Navy Technical Research Institute (NTRI). On Ito's recommendation, the Navy also created the Committee on Research in the Application of Nuclear Physics to oversee research in nuclear fission. The Navy provided funds to initiate committee meetings and brought in Nishina to head the committee. [153]

Nishina was in a difficult position since he had been conducting the Army's feasibility study on nuclear weapons since April 1941. Shortly after being appointed to head the Navy committee, he

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[150] Dower, "Science, Society, and the Japanese Atomic-Bomb," 44-45.
[151] Dower, "Science, Society, and the Japanese Atomic-Bomb," 42-45, 53; Grunden, *Secret Weapons and World War II,* 65.
[152] Dower, "Science, Society, and the Japanese Atomic-Bomb," 42, 47; Grunden, *Secret Weapons and World War II,* 53, 56-57.
[153] Dower, "Science, Society, and the Japanese Atomic-Bomb," 47; Grunden, *Secret Weapons and World War II,* 60-61..

proposed a unification of the military nuclear efforts under the aegis of the Army Aeronautics Department. The Navy would have had to surrender its infant nuclear program, which it was unwilling to do. As a result, nuclear research continued to be conducted separately in each service with no practical efforts to encourage collaboration.[154]

The first meeting of the Navy "Physics Committee," as Nishina called it, was held in July 1942 and the last meeting was in March 1943. The committee concluded that an atomic bomb was possible but would be very difficult for even the United States to develop during the war. The chief difficulty would be acquiring sufficient materials, especially for Japan, which lacked a domestic supply of uranium. No one knew exactly how much U-235 was necessary to induce a chain reaction but the expectation was that it would require an enormous amount of uranium ore to obtain the U-235 necessary for even a few bombs. Even if sufficient uranium was available, no one in Japan had ever successfully separated uranium isotopes. The lackluster prospects that the committee described led the Navy to concentrate its efforts in other areas, such as the development of radar.[155]

By August 1942, the Japanese Army was ready to expand its efforts to develop an atomic weapon. As part of the NI Project (*Ni-go kenkyu),* the Army approached Nishina and asked him to assume responsibility for continued nuclear research at Riken. The Army gave Nishina a year to conduct fundamental research and a second year to conduct a feasibility study on the construction of a nuclear weapon. They also allowed him to select ten young scientists who would receive draft deferrals to work on the project. The first formal meeting of the research group did not occur until January 1943. Although there was general agreement that the purpose of the project was to determine how best to use nuclear fission to meet the needs of the Army, there was also widespread recognition that sufficient amounts of enriched uranium would be necessary to pursue further development. It was therefore necessary to develop a method to isolate U235. On 17 March 1943, Nishina decided to pursue thermal diffusion exclusively. Other potential separation methods were excluded for time, technology, and financial reasons.[156]

The NI Project was the largest Japanese atomic bomb effort of the war. The personnel roster listed 32 individuals, but the contribution of most of the people listed is in doubt. Until March 1944, the project was conducted largely by just two scientists. After March 1944, they were joined by ten recent university graduates. By early 1945, the project's full-time work force was less than fifteen persons –all young, none distinguished, and none a recognized expert in nuclear physics."[157]

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[154] Grunden, *Secret Weapons and World War II,* 61.
[155] Dower, "Science, Society, and the Japanese Atomic-Bomb," 47.
[156] Grunden, *Secret Weapons and World War II,* 67-68.
[157] Dower, "Science, Society, and the Japanese Atomic-Bomb," 48.

The NI Project produced few useful results. Project scientists successfully developed an isotope separator and began producing small amounts of uranium hexafluoride by early 1944. Starting in July 1944, they ran the uranium through the separator. When they used their cyclotron to analyze their results in February 1945, however, they found that they had failed to separate U-235. Since they never solved the problem of separating U-235, they did not even move on to bomb design or manufacture. The building housing the project was razed by bombs in April 1945 and the project ended.[158]

One of the critical weaknesses of the project was a lack of uranium. Nishina had just over 2 pounds of uranium oxide for experiments in spring 1943. The Japanese searched for uranium in Korean mines but did not find sufficient quantities to extract it efficiently. Some previously-mined, uranium-bearing ores were found in Manchuria but logistical difficulties prevented their shipment to Japan. The only other possible source was Germany. Japan asked Germany to provide it with pitchblende; Germany promised two tons of ore which were never delivered. One of the U-boats carrying the ore was sunk en route. The other surrendered to the Americans in the Atlantic after the German surrender in May 1945.[159]

The F-gō Project (F for fission) was the Japanese final attempt to develop nuclear weapons. Seven senior scientists and a few research assistants from Kyoto Imperial University began working on the project in May 1943. The F-Project attempted to separate isotopes via the centrifugal method. Since centrifuges fast enough to separate uranium did not exist in Japan at the time, much of the Kyoto effort was devoted to designing an ultracentrifuge. It eventually became clear, however, that Japan lacked the technology and the resources to build a centrifuge even half as fast as was required. The last formal meeting of the project was on 21 July 1945 (25 days before the Japanese surrender). At that meeting, the members agreed that while an atomic bomb was theoretically possible, it was not likely to be produced in time for the war effort. The F-gōproject was terminated. Unbeknownst to the scientists at the meeting, the United States had successfully tested a nuclear device just days before.[160]

The slow progress of both the Army's NI project and the Navy's F-gō project prompted discussion of greater coordination between the two projects in summer 1944. Both services were focused on isotope separation, albeit using different methods. Nevertheless, it took nearly a year of negotiations before a tentative agreement on nuclear research was reached. In was not until 1945 that scientific research was coordinated under one agency – the Japan Scientific Research Council.[161]

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[158] Dower, "Science, Society, and the Japanese Atomic-Bomb," 49.
[159] Dower, "Science, Society, and the Japanese Atomic-Bomb," 49; Grunden, *Secret Weapons and World War II,* 76-78.
[160] Dower, "Science, Society, and the Japanese Atomic-Bomb," 50; Grunden, *Secret Weapons and World War II,* 65-67.
[161] Dower, "Science, Society, and the Japanese Atomic-Bomb," 45, 50; Grunden, *Secret Weapons and World War II,* 66.

INSIGHTS ON TECHNOLOGICAL INNOVATION DURING PROTRACTED CONFLICT

The evidence from the development of radar and atomic weaponry during World War II suggests several potential insights regarding technological innovation during protracted conflict. The first is that **large-scale efforts to develop new technologies benefit from centralized, coordinated direction.** The British effort to develop radar, for example, benefited greatly from the direction and funding provided from the Tizard Committee. The German effort, in contrast, was plagued by too many competing agencies and research programs that did not communicate well with one another.[162]

The United States lagged behind both Germany and Great Britain in radar research and development during the interwar era due, in part, to the lack any central direction to provide focus for its compartmentalized research effort. The creation of special agencies, such as the NDRC and the OSRD, at the highest levels of government to coordinate scientific research for the military and of laboratories such as the Rad Lab at MIT to perform the research provided a tremendous boost to the American radar program.

Japan lacked a centralized effort to address the critical technical problems in the development of radar for virtually the entire war. The Japanese Army and the Japanese Navy conducted their own independent radar research programs. The research efforts were not coordinated within each service, much less between the two services.

The history of atomic research in the United States also demonstrates the importance of centralized direction for technological development. Participants in the Manhattan Project have commented that the United States could never have built the atomic bomb in peacetime given traditional congressional restrictions on federal spending. The outbreak of World War II in Europe and the growing prospect of U.S. entry into the war provided the impetus for the creation of the NDRC and the OSRD. Without the direction provided by those institutions, the development of the bomb may not have been possible, certainly not in as timely a manner.

In contrast, Japan lacked any centralized office to coordinate all its atomic research. Army and Navy research was conducted separately with no real coordination. There was no single military leader in charge in Japan like Groves was in the United States. Technical officers in the military initiated the projects and sought the assistance of civilian scientists when uniformed technicians proved not up to the task.[163]

In order for such research and development efforts to be successful, they must also have the support of senior leadership. In Great Britain, Dowding and Tizard provided important direction

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[162] Brown, *Radar History of World War II,* 83; Beyerchen, "From Radio to Radar," 270.
[163] Grunden, *Secret Weapons and World War II,* 79-80.

and significant funding for the development of radar from the start. Churchill was also actively involved in the contribution of science to the war effort, although his assistance was not always beneficial.

In Germany, Hitler and Göring were anti-intellectual and scientifically illiterate. Other high-ranking military officers were not much better. When Runge explained to Luftwaffe General Ernst Udet's that radar could locate an airplane in a fifty km area at night or through fog, Udet reportedly replied, "If you introduce that thing you'll take all the fun out of flying." The German Navy left the position of Chief of Development for Signals vacant from November 1939 until April 1943.[164]

Strong support from senior leaders was also important in the development of atomic weaponry. Roosevelt and Churchill consistently backed development of the atomic bomb, even as they sometimes doubted its feasibility. Hitler, on the other hand, dismissed the German bomb effort and refused to provide it with significant support. The Japanese atomic weapon program also lacked the high-level support necessary to overcome the academic divisions, interservice rivalry, and resource shortages that troubled the program.

Allies can also play an important role in the research and development of new technologies during a protracted conflict. A comparison of the cooperation between Great Britain and the United States and the lack of cooperation between Germany and Japan on the development of radar and atomic weaponry underlines the importance of allies. The British provided valuable radar technology and useful operational experience that facilitated the American development of radar. The British also made an important contribution to the development of the atomic bomb, even if atomic cooperation between Great Britain and the United States did not always proceed smoothly.

In contrast, the Germans and the Japanese derived almost no technological benefits from their alliance. The Germans provided little information on radar and none on nuclear weapons to the Japanese. They also failed to deliver desperately needed radioactive ore to Japan. The Japanese, for their part, had little technical knowledge worth sharing with the Germans.

The development of collaborative relationships among the military, academia, private industry contributed significantly to the successful development of new technologies. Effective collaboration between scientists and military officers was key to American and British success in the development of radar. The British military cooperated closely with scientists during the Biggin Hill experiments in 1936. Similarly, scientists from NRL worked closely with the U.S. Navy's operating forces and private firms such as RCA, Western Electric, and General Electric to develop

[164] Beyerchen, "From Radio to Radar," 272-73.

radar. Meanwhile, the signals section in the Luftwaffe, which had primary responsibility for conducting research on radar and radio, had little outside contact with civilian researchers.[165]

Similarly, the American atomic research effort depended on extensive collaboration among the military, academia, and private industry. The Army Corps of Engineers, in conjunction with private industry, built the vast facilities necessary to develop the bomb. The Army-directed laboratories at several universities, staffed largely by scientists drawn from academia, conducted much of the research for the bomb project. As noted earlier, the research, assembly, and manufacture facility at Los Alamos was the epitome of a collaborative environment. The work at Los Alamos required intensive collaboration between scientists and engineers.

Applied research and frequent experimentation is more effective than pure research. The tradition of applied research and experimentation was important in Great Britain and the United States. Researchers would improvise in the laboratory and develop workable devices in advance of a theoretical understanding. When British researchers developed the cavity magnetron, for example, they did not really understand how it worked. They recognized, however, that it could generate high-power microwaves that would greatly improve the resolution of radars while also making much smaller radar sets possible.

Once the British and the Americans developed a new technology, they experimented extensively to understand how to employ it most effectively. The British continued the Biggin Hill experiments for two year in order to gather as much information on the operational potential of radar. Similarly, the U.S. Navy encouraged operational officers to experiment with radar and other shipboard systems and submit their recommendations on how to improve operational effectiveness.

In Germany, the emphasis was on pure research and theory. In some cases, German scientists understood the operational possibilities of their research. However, they often lacked the facilities to experiment or considered experimentation as a less prestigious occupation best left to the engineers of the military staffs.[166]

Interservice rivalry can present a significant obstacle to the development of new technologies. Interservice rivalry was one of the key factors limiting the advancement of radar in both Germany and Japan. In Germany, for example, the Kriegsmarine never told the Luftwaffe about the existence of its highly effective early warning air-search radar. Once the Luftwaffe found out about the radar, the Kriegsmarine worked actively to disrupt the relationship between the Luftwaffe and the private firm that built the radar. In Japan, the Army and the Navy conducted totally separate research program sand produced separate, and sometimes incompatible, radar systems.

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[165] Beyerchen, "From Radio to Radar," 298; Wolters, *Information at Sea,* 174, 183, 193-94; Overy, *Air War,* 201.
[166] Overy, *Air War,* 191-92.

Similarly, the Japanese Army and Navy pursued separate atomic programs with little exchange of information or collaboration. On a number of occasions, the services rejected or postponed efforts to improve coordination. Given the limited pool of personnel qualified to conduct nuclear research in Japan, the pursuit of independent atomic research efforts by the services was a significant waste of scarce resources.

Excessive secrecy may also thwart the successful research and development of new technologies. Although a degree of secrecy is necessary while researching and developing new technologies during wartime, the history of the development of radar and atomic weaponry provides several examples of excessive secrecy slowing down development efforts. Some of the first German ships equipped with surface-search radar, for example, could not repair their radar sets because the Kriegsmarine refused to put instruction manuals and circuit diagrams on board in order to maintain secrecy. Similarly, Japanese civilian scientists found it difficult to understand how the radar sets they designed functioned at sea because they could not go aboard warships equipped with radar due to secrecy concerns.

The case of chaff is particularly interesting. Both the British and the Germans had developed small strips of metal designed to temporarily blind radars when dropped from a plane. However, both sides worried that using the technology would reveal its existence and lead to its use by the opponent. The Germans were not even allowed to research its properties for fear that increased knowledge of the technology's capabilities would lead to German use, which would be followed by Allied counter-use.

Excessive secrecy also slowed the pace of the Allied atomic bomb effort. The British distrusted foreign scientists such as Frisch and Peierls and refused to let them join the MAUD Committee. During the period from October 1941 until early 1942, Churchill and Cherwell were reluctant to exchange information on atomic research with the Americans, in part, because they did not want to endanger the secrecy of the effort. The Americans, for their part, kept the reports of the MAUD Committee locked in a safe for months and thus failed to benefit as much as they could have from British research efforts.

Complacency is dangerous during a protracted conflict. When World War II began, the Germans were confident that they held a measurable lead over the British in radar. The successful detection of a British bomber raid on the second day of the war confirmed the efficacy of German radars in the minds of the military leadership. Dramatic improvements were unnecessary and research and development areas could be shifted to more pressing areas. The British, on the other hand, assumed from the start that German science was highly competent and that there were few "safe" areas that the Germans would not explore or where it could be expected that the Allies could maintain a lead without significant effort. Consequently, the British were always looking ahead and planning for the next potential development of radar. Tizard's recognition that the successful deployment of long-wave early warning radar would lead to the adoption of nighttime bombing and create a new requirement for airborne radar is an example of British forward thinking.

Technical advantage is meaningless without a broader understanding of the operational implications of the new technology. In 1939, the German and American prototype radar sets were superior to almost all the British radar sets. Chain Home, the heart of the British radar system, was considered obsolete, but it worked. The British recognized the value of radar early and understood that it was not enough to have the information provided by radar, it was necessary to act upon it quickly. Thus, the British began building a system to analyze the information provided by radar and communicate with the fighters rapidly in order to direct them to intercept enemy bombers. By September 1939, the British had a functional air defense system. The Germans and Americans had a few operational sets but no effective organization to use them.[167]

The U.S. Navy's experience with radar and combat at night also suggests that a single technical advantage alone may not be sufficient to prevail in future conflicts. The U.S. Navy's surface ships had a distinct radar advantage and often used it to fire effective first salvos but still suffered significant losses in their nighttime engagements with Japanese ships in late 1942. It was not until they developed the ability to combine radar data with other information into a complete operational picture that U.S. surface forces were able to defeat their Japanese counterparts decisively at night. Similarly, Navy pilots learned that successful aerial combat at night required more than just effective radar. It demanded constant practice and special techniques. Pilots had to learn how to change altitude abruptly, turn quickly, and change speeds suddenly using only instruments in order to follow instructions from ground control and intercept an unseen enemy target. Future decision-makers need to be sensitive to the possibilities of such technological integration in order to fully exploit the military capabilities of new technologies.

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[167] Brown, *Radar History of World War II,* 82-83.