CHAPTER 2

Organized Wartime Research, Evolution of Microwave Radar and Emergence of New Fields in Science

2.1 Introduction

The Second World War was the most significant conflict of the twentieth century involving great powers of the world of that time. It was the first instance of exploitation of latest advances and new discoveries of science in extensive use in warfare. Innovations that greatly influenced the course of World War II, include microwave radar, sonar and proximity fuses; anti-aircraft and anti-submarine devices; explosives and propellants; rockets and missiles; computerized cryptanalysis and operational research; insecticides, penicillin and blood substitutes; chemical and biological weapons (never used) and finally the atomic bomb. This had happened because of relentless work of thousands of scientists and technologists in both the Allied and the Axis nations. Wartime science mobilization in the United States, the Soviet Union, Great Britain, Germany, Japan and Italy commenced at different time before and during the Second World War. Their approaches to mobilization also differed substantially. However, establishment of organizations for appropriate military research and development; close linkage among defense authorities and civilian scientists; and adequate funding for such work by the government, in the United States, and their exchange of technical know-how and scientific manpower with Great Britain, enabled advent of microwave radar and the atomic bomb that affected the World War II decisively. While atomic bomb ended the war, it was radar that won the war in favor of the Allies.\(^1,2\)


2.2 Organized Wartime Research in the United States

2.2.1 Research and Development Establishments of the First World War

Although the first powered airplane was created by American engineer brothers, Wilber Wright (1867-1912) and Orville Wright (1871-1948), the United States was unable to produce a military aircraft during next ten years. William Howard Taft (1857-1930), the 27th President of the U.S., who was the Secretary of War from 1904 to 1908, in December 1912 planned to form a 'National Aerodynamic Laboratory Commission' with Robert S. Woodward (1849-1924), an American physicist and president of the Carnegie Institution of Washington, as its Chairman. This was the first attempt for organized scientific and technical research for military aviation. The U.S. Congress, however, rejected the proposal in January 1913 when it was put up as legislation.³

2.2.1.1 National Advisory Committee for Aeronautics

On 4th March 1913, Thomas Woodrow Wilson (1856-1924) became the 28th President of the United States of America. The World War I began on 1st August 1914, when Germany declared war on Russia. President Wilson maintained neutrality of the United States in the war for about 32 months, but had to enter into it on 2nd April 1917. During 1915-1916, Wilson was approached by eminent scientists, inventors and engineers, on different occasions with independent proposal, to set up appropriate research and development facilities, where academicians, government officials and

---

military personnel will work together to meet the challenges of developing improved weapons and counter-measures for the army, navy and air force.

In January 1915, Charles D. Walcott (1850-1927), an American invertebrate paleontologist and Secretary of Smithsonian Institution suggested formation of an aeronautical advisory committee as an U.S. federal agency to undertake, promote, and institutionalize aeronautical research. Franklin D. Roosevelt, the then Assistant Secretary of the U.S. Navy (and future President of the United States) endorsed the proposal, based on which legislation was prepared. The legislation was approved by the U.S. Congress and President Woodrow Wilson who created the 'National Advisory Committee for Aeronautics' (NACA) on 3 March, 1915. An annual budget of US $ 5000 was also sanctioned for the NACA. Brig. General George P. Scriven, Chief Signal Officer of the Army was the first Chairman of NACA from 1915 to 1916. William F. Durand (1859-1958) a former Naval Officer and an eminent mechanical engineer at Stanford University was the Chairman of NACA during the remaining years of First World War (1916-1918). In 1917, the NACA established the Langley Memorial Aeronautical Laboratory in Virginia that would become most important aeronautical test and experimentation facility in the World.⁴

### 2.2.1.2 Naval Consulting Board

In one of the darkest act of World War I, the British Luxury ocean-liner RMS Lusitania was torpedoed and sunk by German U-boat on 7 May 1915, during its voyage from New York to Liverpool with over 2000 passengers and crew on board. As a result, 1198 people including 159 American civilians were drowned. The Americans were outraged due to the

---

incidence, as they were officially neutral in the World War at that time.\textsuperscript{5}

In May 1915, Thomas Alva Edison, the great American inventor, in an interview with The New York Times correspondent remarked, “The Government should maintain a great research laboratory .... In this could be developed ..... all the technique of military and naval progression without any vast expense.” \textsuperscript{6}

In 1913, President Wilson had appointed Josephus Daniels (1862-1948) as the Secretary of the Navy. As a response to Edison’s opinion on foundation of research laboratory under the government, Daniels, in 1915, established the ‘Naval Consulting Board’ as organization of the U.S. Navy. While Daniels served as Chairman of the Board, on his request Edison became its President. There were 27 eminent scientists and engineers as members of the board. The physicists included Robert Andrews Millikan and Arthur Compton, who later received Nobel Prize in Physics in 1923 and 1927, respectively. Elmer Sperry, Peter Hewitt, Hudson maxim, Lee de Forest, were some of the eminent engineers. The members made many studies and investigations, and brought out solutions of existing naval technical problems. According to Josephus Daniels, “The president of the board, Mr. Thomas A. Edison, left his laboratory and practically became a naval officer, spending long months in the Navy Department and extended periods of deep-sea cruising ..... Other members of the board gave themselves and their talent as fully”. The U.S. Congress had allocated US$ 1.5 million for the Board in 1916. The Board was in operation until 1920.\textsuperscript{7}

\begin{footnotes}
\end{footnotes}
2.2.1.3 National Research Council

In a separate move soon after the sinking of Lusitania on 7 May 1915, George Ellery Hale (1868-1938), an eminent astrophysicist and a prominent member of the American National Academy of Sciences, suggested to the President of the Academy to offer assistance of the members to the President of the United States in preparation for possible war. With the approval of the Academy Council, Hale led a team of scientist who called upon President Woodrow Wilson to place their suggestion. The President approved the plan. The ‘National Research Council’ (NRC) was formed in June 1916, which would become an important wing for mobilization of science when the United States entered into World War I.⁸

Hale served as the Chairman of NRC from 1916 to 1919. The members of the Council included representatives of scientific, medical and engineering bodies, as also of government scientific and technical agencies of the United States.⁹ The NRC maintained close contact and collaboration with the US Army and Navy, and with research institutions in London and Paris. NRC had organized several committees to cover the fields like aeronautics, agriculture, anatomy, chemistry, zoology, psychology, submarines and engineering. After the war the NRC was decoupled from military.¹⁰

---


2.2.1.4 Council of National Defense

In another independent move, with the approval of the U.S. Congress, a ‘Council of National Defense’ (CND) was established on 29 August 1916, with Secretaries of War, the Navy, Interior, Agriculture, Commerce and Labor, to coordinate resources and industry in support of the war effort, including the coordination of transportation, industrial and farm production, financial support for the war and public morale. The council was to investigate and advise to President and heads of executive departments, on the strategic placement of industrial goods and services for the potential and future use in times of war. On 11 October 1916, President Woodrow Wilson formed an Advisory Commission to be associated with the CND. He nominated seven eminent personalities from different fields as board members of the commission: Daniel Willard, president of the Baltimore and Ohio Railroads, as head of the Advisory Commission; Samuel Gompers, president of the American Federation of Labor; Franklin H. Martin, a distinguished surgeon who founded the American College of Surgeons; Howard E. Coffin, who had experience in coordinating the auto industry in emergencies; Bernard Baruch, a prominent banker; Hollis Godfrey, president of the Drexel Institute; and Julius Rosenwald, president of Sears, Roebuck & Co. Operations of the Council of National Defense were suspended in 1921.

---


2.2.2 Research and Development Establishments of the Second World War

2.2.2.1 National Defense Research Council

By May 10, 1940 when most of the Western European countries were invaded by Germany, it appeared that involvement of the United States in the World War II would be inevitable soon. Vannevar Bush, the President of Carnegie Institute for Science and the Chairman of the 'National Advisory Committee for Aeronautics' of the United States and his colleagues Frank B. Jewett, President of the National Academy of Sciences; James B. Contant, President of Harvard University and Karl T. Compton, President of Massachusetts Institute of Technology, recognized that the existing infrastructure of science and technology of the nation would be inadequate in case United States enters into the war in near future. They felt the urgent need of having a government organization with the authority and means to proceed with the development of new technologies for the war. On 12\textsuperscript{th} June, 1940 Vannevar Bush met President Roosevelt and urged for creation of an agency that would involve civilian scientists; navy and army personnel and industrialists to work together under its supervision to meet the urgent requirements of evolving new methods and technologies for national defense.\textsuperscript{14} President liked the proposal and as a result the National Defense Research Council (NDRC) was established on 27\textsuperscript{th} June, 1940, by his order. Objectives of NDRC were to coordinate, supervise and conduct scientific research on the problems underlying the development, production and use of mechanisms and devices of warfare.\textsuperscript{15}

The terms and conditions for establishing NDRC was worked out by six members of the 'Council of National Defense', namely, Louis Johnson,}


Acting Secretary of War; Lewis Compton, Acting Secretary of Navy; Harold L. Ickes, Secretary of Interior; H.A. Wallace, Secretary of Agriculture; Harry L. Hopkins, Secretary of Commerce; and Frances V. Perkins, Secretary of Labor.\textsuperscript{16}

The order establishing NDRC named Vannevar Bush as its Chairman. It also named five other members and stated that two more members would be nominated by the Secretary of war and Secretary of the Navy. The purpose of this quasi-government organization was to mobilize American Civil Scientists for military research and to enhance the adaptation of science and technology to the war effort during World War II.

The original eight members of the NDRC were: Vannevar Bush, President of the Carnegie Institution (as Chairman); Richard C. Tolman, Professor of Physical Chemistry and Mathematical Physics at California Institute of Technology (as Vice-Chairman); Rear Admiral Harold G. Bowen; Conway P. Coe, Commissioner of Patents; Karl Compton, President of MIT; James B. Conant, President of Harvard University; Frank B. Jewett, President of the National Academy of Sciences and President of Bell Telephone Laboratories; Brigadier General George V. Strong (Strong was succeeded by Major General R.C. Moore on January 17, 1941); and Irvin Steward (as Secretary). The NDRC administered its work through following five divisions:

Division A – Armor and Ordnance.

Division B – Bombs, Fuels, Gases and Chemical Problems.

Division C – Communication and Transportation.

Division D – Detection, Controls and Instruments.

Division E – Patents and Inventions.

Three future Nobel Laureates, I. I. Rabi, N. F. Ramsey and J. H. Van Vleck, about whose contribution in magnetic resonance research will be discussed in Chapter 5 of this thesis, were consultants of the Division D.\textsuperscript{17}

The Divisions were further divided into sections. These sections were served by outstanding American scientists in physics, chemistry and allied subjects, voluntarily without pay, on part time basis. They were however supported by paid technical aides. During the first year of existence of NDRC, research and development in the following important areas had progressed to some extent:

I. Aircraft detection, and its resulting development

II. Gun Control

III. Proximity fuses

IV. Anti-submarine devices

V. Explosives and gases and

VI. Uranium.

An amount of US $ 6.3 million was sanctioned for NDRC project for its first year of operation. NRDC awarded 150 contracts to 41 academic and

research institutions and 52 contracts to 22 industries for research and development work, on no loss – no gain terms.

**Table 2.1 List of Institutions who worked for NRDC on contracts during 1940-1941 in U.S.A.**

<table>
<thead>
<tr>
<th>Academic Contractors</th>
<th>Number of Contracts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brooklyn Polytechnic Institute</td>
<td>1</td>
</tr>
<tr>
<td>Brown University</td>
<td>1</td>
</tr>
<tr>
<td>California Institute of Technology</td>
<td>8</td>
</tr>
<tr>
<td>University of California</td>
<td>10</td>
</tr>
<tr>
<td>Carnegie Institute of Technology</td>
<td>3</td>
</tr>
<tr>
<td>Carnegie Institution of Washington</td>
<td>8</td>
</tr>
<tr>
<td>University of Chicago</td>
<td>9</td>
</tr>
<tr>
<td>College of the City of New York</td>
<td>1</td>
</tr>
<tr>
<td>Columbia University</td>
<td>5</td>
</tr>
<tr>
<td>Cornell University</td>
<td>1</td>
</tr>
<tr>
<td>Cornell University Medical College</td>
<td>1</td>
</tr>
<tr>
<td>University of Delaware</td>
<td>1</td>
</tr>
<tr>
<td>Drexel Institute of Technology</td>
<td>1</td>
</tr>
<tr>
<td>Franklin Institute of the State of Pennsylvania</td>
<td>2</td>
</tr>
<tr>
<td>Harvard University</td>
<td>13</td>
</tr>
<tr>
<td>University of Illinois</td>
<td>6</td>
</tr>
<tr>
<td>Iowa State College</td>
<td>4</td>
</tr>
<tr>
<td>Johns Hopkins University</td>
<td>3</td>
</tr>
<tr>
<td>Massachusetts Institute of Technology</td>
<td>20</td>
</tr>
<tr>
<td>University of Michigan</td>
<td>4</td>
</tr>
<tr>
<td>University of Minnesota</td>
<td>3</td>
</tr>
<tr>
<td>University of Missouri</td>
<td>1</td>
</tr>
<tr>
<td>National Academy of Sciences</td>
<td>3</td>
</tr>
<tr>
<td>University of Nebraska</td>
<td>1</td>
</tr>
<tr>
<td>University of New Mexico</td>
<td>1</td>
</tr>
<tr>
<td>Northwestern University</td>
<td>3</td>
</tr>
<tr>
<td>Ohio State University Research Foundation</td>
<td>3</td>
</tr>
<tr>
<td>Pennsylvania State College</td>
<td>5</td>
</tr>
<tr>
<td>University of Pennsylvania</td>
<td>3</td>
</tr>
<tr>
<td>Princeton University</td>
<td>10</td>
</tr>
<tr>
<td>Purdue Research Foundation</td>
<td>1</td>
</tr>
<tr>
<td>Rensselaer Polytechnic Institution</td>
<td>1</td>
</tr>
<tr>
<td>University of Rochester</td>
<td>2</td>
</tr>
<tr>
<td>Rockefeller Institute for Medical Research</td>
<td>1</td>
</tr>
<tr>
<td>University of Southern California</td>
<td>1</td>
</tr>
<tr>
<td>Stanford University</td>
<td>3</td>
</tr>
<tr>
<td>University of Virginia</td>
<td>2</td>
</tr>
<tr>
<td>Wesleyan University</td>
<td>1</td>
</tr>
</tbody>
</table>
Although, progress made by NDRC in achieving target during the first year of its operation was reasonably good, it was realized by its coordinators that there existed some gaps which needed to be closed as early as possible.
The NDRC did not have the scope to conduct research in the field of military medicine. It was concentrating primarily on research work in the chosen fields, but their innovation required development or manufacture urgently. And finally in addition to the Army and Navy, a close coordination between NDRC scientists and the experts of 'National Advisory Committee of Aeronautics' was absolutely necessary. Meanwhile, Nazi Germany invaded the Soviet Union on 22nd June, 1941, code named as operation ‘Barbarossa’. It was the largest invasion in the history of warfare.

### 2.2.2.2 Office of Scientific Research and Development

The 'National Defense Research Council' did not have authority and funds to carry forward results of their research into development and production. The 'Office of Scientific Research and Development' (OSRD) was, therefore, established by the US President Franklin D. Roosevelt by an executive order on 28 June 1941, “for the purpose of assuring adequate provision for research on scientific and medical problems relating to national defense.” 18 Significantly, the formation of OSRD had happened much before the official entry of the US into the World War II on 8 December 1941.

The President appointed Vannevar Bush as Director of OSRD. Bush discharged and performed his responsibilities and duties under the direction and supervision of the President. OSRD was establish to serve several purposes during the war – most important among them were to function as the center for the mobilization of scientific personnel and the resources of the nation; to coordinate, aid, and supplement the scientific and medical research activities of the Departments of War and Navy as well as other

---

government agencies; to advise the president on matters of scientific and medical research concerning national defense; and to serve as a liaison organization for scientific exchange between Allied nations.\textsuperscript{19,20}

The 'National Defense Research Committee' (NDRC) functioned under OSRD with James Bryant Conant as its new Chairman and had following divisions:

Division 1 (Ballistic Research), 1941-46;
Division 2 (Impact and Explosion), 1941-46;
Division 3 (Special Projectiles and Rocket Ordnance), 1940-46;
Division 4 (Ordnance Accessories), 1940-45;
Division 5 (New Missiles), 1940-46;
Division 6 (Sub-Surface Warfare), 1941-46 (in Washington area) and 1942-45 (in Boston);
Division 7 (Fire Control), 1940-46;
Division 8 (Explosives), 1940-45;
Division 9 (Chemistry), 1940-45;
Division 10 (Absorbents and Aerosols), 1940-45;
Division 11 (Chemical Engineering), 1940-45;
Division 12 (Transportation Development), 1940-45;
Division 13 (Electrical Communication), 1941-46;

\textsuperscript{19} Irving, Stewart. 1948. 36-37.
Division 14 (Radar), 1941-46;

Division 15 (Radio Coordination), consisting of records of field offices in Schenectady, NY, 1942-46; New York, NY, 1943-46 and in Boston, MA, 1943-46;

Division 16 (Optics and Camouflage), 1940-46;

Division 17 (Physics), 1940-46;

Division 18 (War Metallurgy), 1940-46; and

Division 19 (Miscellaneous weapons/sabotage and espionage devices), 1942-46.

A newly constituted “Committee on Medical Research” also functioned under OSRD. The CMR was subdivided into following six divisions.\textsuperscript{21}

Division 1 - Medicine

Division 2 - Surgery

Division 3 - Aviation Medicine

Division 4 - Physiology

Division 5 - Chemistry

Division 6 - Malaria

The OSRD also had an ‘Advisory Council’ consisting of the Director OSRD as Chairman, the Chairman of the NACA, the Chairman of NDRC, the Chairman of CMR, a representative of the Navy designated by the Secretary of Navy and a representative of the Army designated by the

Secretary of War. The council advised and assisted the Director OSRD with respect to the coordination of research activities carried on by private and government research groups and facilitated the interchange of information and data between such groups and agencies.

During the World War II, OSRD did not go for setting up large laboratories, but awarded various project work on contract to universities and industrial laboratories who possessed appropriate infrastructure and research capabilities. OSRD brought together civilian scientists, Army and Navy personnel, government officials and industrialists for the common cause of defense related scientific research. Initially some 6000 physicists, chemists, mathematicians and engineers were involved in OSRD project. The number of scientists serving the OSRD grew up to 30,000 by the end of the year. The scientists were deputed from leading research institutions and universities such as Massachusetts Institute of Technology (MIT), California Institute of Technology (Caltech), Harvard University, Columbia University and many more. Scientists and engineers from industrial research organizations like, Bell Telephone Laboratories, General Motors, Westinghouse Electric Corporation, Philco, Sylvania Electric Products Inc., Standard Oil Company, Dupont and others. These scientists and engineers under OSRD contract undertook a wide range of scientific investigations and produced thousands of reports on their innovations and findings. During the years of its operation the OSRD had spent 450 million USD and provided the US and Allied army, navy and air force with advanced and improved devices, techniques and weapons. Some of the important accomplishments of the OSRD were improved radar equipment, the sonar, amphibious landing vehicles, mine detectors, flamethrowers, rockets, proximity fuse, plasma for transfusion, large-scale production of penicillin and the atomic bomb. Two most significant contribution of the

---


OSRD were microwave radar and atomic bomb. The agency was closed in 1947.²⁴,²⁵

### 2.3 British Scientific and Military Establishments

The British Department of Scientific and Industrial Research (DSIR) was set up in 1915 with objectives to finance worthy research proposals, to award research fellowship and studentships in Universities; and to encourage the development of research associations in private industry and research facilities in university science departments'. From its inception the DSIR also coordinated government aid to university research, which amounted to one million pound in 1915.²⁶ In 1917, the National Physical Laboratory (NPL), the largest applied physics organization in the UK was set up at Teddinton, London. The Radio Research Station (RRS) was founded in Buckinghamshire, England in 1924.²⁷

The British Air Ministry in 1934 instituted the Committee for the Scientific Survey of Air Defence (CSSAD) to explore the possibilities of introduction of new technologies that the Royal Air Force might use to defend British territories against air attacks by enemies. The committee consisted of: Henry Tizard, Govt. research administrator and Rector of Imperial College; Harry Wimperis, Director of Scientific Research, of Air Ministry; Patrick Blackett, a renowned experimental physicist; A.V. Hill, Nobel laureate and

²⁴ Irving, Stewart. 1948.
head of WWI research; Frederick Lindemann, an eminent physicist of Oxford; and A.P. Rowe, Secretary of the Committee. In 1937, another committee dedicated to “Air Offence” was constituted, which was also headed by Tizard. These two committees were joined into an Air Warfare Committee before the beginning of World War II. Besides other contributions, Tizard had propelled development of British indigenous radar before World War II.

2.4 Scientific and Military Research in German Institutes before Second World War

2.4.1 Foundation of Kaiser Wilhelm Society

Germany was one of the few countries in the world that recognized the importance of organized research in science and industry at the beginning of the 20\textsuperscript{th} century. Adolf von Harnack (1851-1930), a German theologian and church historian in 1911 could convince Kaiser Wilhelm II, Frederick William Victor Albert (Friedrich Wilhelm Viktor Albrecht) or William II (1859-1941) the last German Emperor (Kaiser) and king of Prussia that if research facilities, especially in natural sciences, were not provided for, Germany would lose its leadership in research and science. The Emperor founded the Kaiser Wilhelm Society (Kaiser-Wilhelm-Gesellschaft, KWG) for Advancement of Science in 1911. During the first 25 years of its existence the KWG had established a number of institutes to conduct research in pure sciences, applied sciences and also on military technical science.

---


2.4.2 Institutes for Research in Basic Sciences

Kaiser Wilhelm Institute for Chemistry (Kaiser Wilhelm Institute fir Chemic, KWIC) was founded in 1911 by the Kaiser Wilhelm Society and the Society for Promotion of Chemical Research (Verein zur ordering chemischer Forschung) at Berlin-Dahlem. Otto Hahn, an eminent chemist was the first Director of the Institute. Three major divisions of the institute conducted research on pure and applied radio chemistry; nuclear and atomic physics; and on properties of gas.

Kaiser Wilhelm Institute of Physical Chemistry and Electro-chemistry (Kaiser Wilhelm Institute fir Physikalische chemie und Electro-chemie, KWIPC) was founded in 1911 at Berlin-Dahlem by the financial support of Prussian Government and the Koppel Foundation. Fritz Haber, recipient of 1918 Nobel Prize in Chemistry, was the Director of the institute until 1933. He played an important role in development of chemical warfare in World War I. Two future Nobel Laureates, physicists James Franck and chemist Otto Hahn were associates of Haber at the KWIPC for R & D work on chemical weapons.

Kaiser Wilhelm Institute of Biology (Kaiser Wilhelm Institut fur Biologie) was established at Barlin-Dahlem in 1915 by the Kaiser Wilhelm Society and the German Research Society (Deutsche Forschungs-gemeinschaft) with F. von Wettstein as the first Director. The institute conducted research experimental botany and experimental zoology.

Kaiser Wilhelm Institute of Physics (Kaiser Wilhelm Institute fin physic, KWIP) was founded in Berlin by the Kaiser Wilhelm Society in 1917, with Albert Einstein as its first Director. The institute awarded grant in aid to

2011.

scholars to conduct research work in experimental and theoretical physics. Otto Stern, Walther Garlach, Willy Wien, Lise Meitner and Max Born were some of the eminent scientist supported by the Institute for their revolutionary work in physics. When Einstein left directorship of the institute and migrated to the United States in 1933, his Deputy Max Von Laue, became the interim Director of KWIP. In 1936, with a gift of 1.5 million Mark from Rockefeller Foundation a new building of KWIP was constructed at Berlin-Dalhem and Peter Debye was appointed the new Director of the institute. However, in 1940, when the institute was put under the Army Ordnance Department of the Nazi Government, Debye migrated to the United States.

**Kaiser Wilhelm Institute of Medical Research** (Kaiser Wilhelm Institut fur Medizinische Forschung) was founded at Heidelberg in 1930 by Kaiser Wilhelm Society with Ruchiard Kuhn as its first Director. The general purpose of the institute was to promote scientific research in the field of medicine.

### 2.4.3 Institutes for Research in Applied Sciences

**Kaiser Wilhelm Institute for Coal Research** (Kaiser Wilhelm Institute fur Kohlenforschung) was founded in 1912 by the Kaiser Wilhelm Society at Mulheim-Ruhr. The institute was financially supported by the members of three coal syndicates – the Rhinewestfalian Coal Syndicate, the Rhine Brown coal syndicate and the Achener Bituminous Coal Syndicate. The institute conducted research on coal, field fuels and oil. German chemist Franz J.E. Fischer (1877-1947) was its first Director.

**The Kaiser Wilhelm Institute for Iron Research** (Kaiser Wilhelm Institut fur Eisenforschung) was founded at Düsseldorf in 1917 by the German Iron and Steel Industry. The institute had five divisions and seven laboratories
engaged in studies and research in metallurgy of iron and steel.

**The Kaiser Wilhelm Institute for Metal Research** (Das Kaiser Wilhelm Institut für Metallforschung, KWIMF) was founded in 1921 by the Kaiser Wilhelm Society in cooperation with authorities, societies and industrial enterprises at Berlin, with H.C.O. Baner as Director. It was financially supported by the Prussian Government and by interested private industries. However, due to severe economic crisis in Germany, the institute had to be closed in 1933. The institute was reorganized at Stuttgart in 1935 with Werner Koster as the new Director and conducted important research on non-ferrous metals. But the military and the industry were not interested in this field of research at that time.

### 2.4.4 Institutes for research in Military Science and Technology

**Kaiser Wilhelm Foundation for Military Technical Science** (Kaiser Wilhelm Stiftung für Kriegstechnische Wissenschaften or KWKW) was founded in 1917 for mobilization of science for the war effort. The KWKW had six committees comprising forty-four eminent scientists from universities, technical universities and military research institutes. The focus of the foundation was on development of aircrafts, zeppelins, ballistics, telecommunication on war field, replacement materials and alternative explosives. It however, was unable to make significant impact on German military research.\(^{32}\)

**Kaiser Wilhelm Institute for Research in Hydrodynamics and the Aerodynamical Experiment Station** (Kaiser Wilhelm Institute für Strömungsfor schung. Aerodynamischen Versuchanstalt, KWIS) were founded by Kaiser Wilhelm Society in 1925 at Gottingen for conducting studies and research in aeronautics. The institutes were financially supported by the Kaiser Wilhelm

---

Organization Wartime Research, Evolution of Microwave Radar and Emergence of New Fields in Science

Society, the Communications Ministry, the Aviation Ministry and the Society for Promotion of the Aerodynamical Experiment Station. Ludvig Prandtl (1875-1953) was the first director of both the institutes.

2.4.5 The effect of German Wartime Research

Germans technologists developed many war weapons such as high-speed jet airplanes, high-speed long distance submarines, remote controlled flying bombs, nerve gas etc. German scientists were able to produce synthetic substitutes of scarce essential raw materials like mineral oil, metals, leather, rubber, etc. During the war years, Germany could increase production of coal, aluminum and steel to a great extent.33

Germany, however, failed to create any decisive weapon that could help them win the Second World War. Although German scientists were pioneer in inventing radar (1904) and early magnetron (1924), they could not produce any advanced radar system or a microwave radar, like Great Britain and the United States, during the War. German physicists discovered 'nuclear fission' in 1939, but the ultimate destructive weapon, the atomic bomb, was produced in 1945, as a result of joint collaboration of British and American physicists.

The German military hardly collaborated with the German scientists for wartime research. The military problems were generally subdivided to individual scientists to resolve. The scientists worked on the problems in their own institutions or laboratories and had no interaction with the end users. The overall outcome of wartime research in Germany thus remained ineffective in winning the Second World War.34

2.5 Invention of Klystron

The Klystron was the first practical source of microwaves. It is a special type of vacuum tube used as an amplifier and/or oscillator for electromagnetic waves of 8-12 GHz. In case of pulsed signals the peak power may rise to over 150 MW at 2-4 GHz. A Klystron is characterized by high power, high stability, high voltage, high gain vacuum tube, wherein electrons are formed into a velocity modulated beam by the input waveform to produce microwave energy.

In 1932, D.A. Rozhansky, a professor of physics at Leningrad Polytechnic Institute proposed a method to produce electron beams of 'varying density', an important requirement to develop a klystron tube.35 In 1935, Agnessa Arsenjewa-Heil (1901-1991) and Oskar Heil (1908-1994) in Germany published an important paper on 'velocity modulation theory of electron beam' titled "A New Method for Producing Short, Undamped Electromagnetic Waves of High Intensity." 36 Oskar Heil was a German physicist, who earned his doctorate from the University of Gottingen in 1933. His wife Agnessa Arsenyeva, was a Russian physicist. Together they moved to England to work with Lord Rutherford at the Cavendish Laboratory in Cambridge. Subsequently, Agnessa joined the Leningrad Physico-Chemical Institute in Soviet Union and Oskar worked at Standard Telephone and Cables in England on 'coaxial-line oscillators'. Oskar returned to Germany just before commencement of World War II. While working with Standrad-Lorentz in Berlin, he a developed a microwave


oscillator tube and it was used by the Germans during the war.\textsuperscript{37}

W.W. Hansen (1909-1949) an Associate Professor of Physics at Stanford University, in 1937, invented ‘microwave cavity’, a type of electrical resonator.\textsuperscript{38} During that time, Russel H. Varian (1898-1959) and Sigurd F. Varian (1901-1961) joined at Stanford Physics Department as Research Associates and worked with Hansen on development of a new source of ultra-high frequency oscillator, which they believed would be used for air-defense. They soon developed a Klystron tube, which was published as a paper in 1939.\textsuperscript{39} Further improvement of Klystron tube commenced both in the United States and Great Britain, as they were found useful for development of microwave radar. With the outbreak of war in 1939, physicists of Oxford University were engaged by Admiralty to develop microwave radar technology. The research led to development of reflex Klystrons at X-band (3 cm) and K-band (1.25 cm), which were subsequently manufactured by Raytheon of Waltham in USA on a large scale.\textsuperscript{40}

\subsection*{2.6 Evolution of Microwave Radar}

Nine countries of the world had independently and secretly developed early radar for military use – Germany, Italy, France, the Netherlands, Great Britain, and the United States before World War II, and the Soviet Union, Japan and Hungary after commencement of the war. These radar operated mostly in ‘Very High Frequency’ (VHF) range i.e.,


\textsuperscript{38} Hansen, W.W. “A Type of Electrical Resonator”, J. Appl. Phys. 9 (1938) 654.


from 30 MHz to 300 MHz frequency band. Attempts were on to increase the operating frequency of radar to microwave range, in order to get greater accuracy and better resolution.

### 2.6.1 The British Multi-Cavity Magnetron for Microwave Radar

At the outbreak of World War II, the British Royal Air Force felt an urgent need for having superior radar systems that would be more powerful, but smaller in size than the existing radar like the Chain Home radar. Two eminent professors of Physics, John D. Cockroft of Cambridge University and Mark L. Oliphant of University of Birmingham were immediately brought into British radar development program, by the British Admiralty. Oliphant recommended development of high power microwave generators at 10 cm wavelength as an essential component for the desired performance of the radar for operation on land, at sea and from air.\(^\text{41}\) The Committee on Valve Development of the British Admiralty was given responsibility in 1939 to coordinate the research and development work to urgently produce high power (about 1 KW) magnetron to operate at centimeter (10 cm or less) wavelength, which in turn would make development of advanced radar for the three services – Army, Navy and Air force. Mark Oliphant at Birmingham University constructed a klystron tube by December 1939 that could produce microwave of 400 W at a wavelength of 10 cm (3 GHz). The output however, was not sufficient to be used in airborne radar.

As a parallel action, Oliphant advised two young physicists John Randall (1905-1984) and Harry A.H. Boot (1917-1983) at Birmingham University to develop a microwave generator of high-power which would be suitable for use in airborne radar. After working for about two months, by the end of February 1940, Randall and Boot developed a multi-cavity resonant

---

magnetron that produced about 400 W continuous power at a wavelength of 9.8 cm. Industrialized prototype of the magnetron, marked as E 1188, was assembled soon by GEC. They were, however, unaware of similar work done by A.L. Samuel in the US, Alekseev and Miliarov in Russia, and Ito and his colleagues in Japan. Eric Stanley Megaw (1908-1956) at General Electric Company in Wembley modified the Randall-Boot design and by June 1940, his magnetron (E 1189) produced 10 KW pulsed power output at a wavelength of 10 cm. Both the prototypes E 1188 and E 1189 had six cavities. In August 1940 the design of E 1189 was modified with 8 resonating cavity. One of these 8 cavity prototype of E 1189, the sample No. 12, was taken to the United States by the Tizard Mission in September 1940 and its design details were transferred to Western Electric, Raytheon RCA, Westinghouse and to MIT Radiation Laboratory in USA and to Research Enterprises Ltd. in Canada. By the end of the war more than a million magnetrons were manufactured collectively by British, American and Canadian Companies.

The importance of developing microwave radar was understood earlier or almost at the same time by other countries and they independently invented magnetrons to generate microwave. But those were not efficient as that developed by the British scientists in 1940.

2.6.2 Invention of other Early Magnetrons

Magnetron is an electronic valve that generates high-power electromagnetic signals in the microwave range due to combined action of electric field between its electrodes and a magnetic field applied externally. Pulsed microwave radiation from a magnetron is used in radar

---

Microwaves are electromagnetic waves with wavelengths ranging from one meter to one millimeter, or equivalently having frequencies between 0.3 GHZ and 300 GHZ. The ability of microwaves to penetrate rain, snow, clouds, haze and smoke make it most suitable for transmission of information from one place to another. Microwaves of a few centimeter wavelengths are used for radar.

Early magnetrons used various configurations of anodes as single anode, split anode, split anode with internal resonator, four segment anode etc.

2.6.2.1 United States of America

The first ‘magnetron’, a microwave generator, was invented in 1920 by American physicist Albert Wallace Hull (1880-1966) at the Research Laboratory of General Electric (GE) at Schenectady in New York. Hull’s magnetron was a diode electron tube, comprised of a coaxial cylindrical anode and a filament, operated in an axial magnetic field. With F.R. Elder, his colleague at GE, he further developed high-power magnetron oscillators and multistage high-gain magnetron amplifiers. Hull served at GE from 1914 to 1949 and was also a professor of physics at the Worcester Polytechnic Institute for many years. In 1925, F.R. Elder at GE was able to produced magnetron output of 8 KW at 30 GHZ. By the end of 1925 magnetron produced by Hull and Elder at General Electric could generate a power of 15 KW at a frequency of 20 GHZ. Hull at that time considered magnetron
as a power converter, and not for communication applications. In 1934, American physicist Neal Hooker Williams (1870-1956) and his student Clan Ewin Cleeton (1907-1997) at University of Michigan had conducted very first spectroscopic measurements at microwave frequencies, by using their split anode magnetron which produced microwave of 47 GHz.47

Several other magnetron development work took place in the United States before the World War II. Westinghouse Research Laboratories, by 1934, produced internal-circuit magnetron to generate 1W microwave at 9 cm. Radio Corporation of America on the other hand could generate 100W radio wave at 60 cm wavelength in 1938.48 G.R. Kilgore at the General Electric Research Laboratory developed a magnetron in 1936 that could produce radio-waves between 300 MHz and 600 MHz of 25 W power output.49 Large number of publication appeared worldwide on this subject during 1924-1940. Most of these magnetrons, however, suffered from low efficiency.50

2.6.2.2 Germany

In 1924, Erich Habann (1892-1968) developed a magnetron having split anodes, as a project of his doctoral research work at University of Jena in Germany. His magnetron produced oscillations in the frequency range of 100 MHz to 1 GHz, like the magnetron of Zacek, but delivered fairly stable


output.\textsuperscript{51} Hans Erich Hollmann (1899-1960) in 1935 prepared a detailed design of a cavity magnetron and filed a patent application in Germany.\textsuperscript{52}

\subsection{2.6.2.3 Czechoslovakia}

August Žáček (1886-1961), a Czech physicist at Charles University in Prague developed a magnetron in 1924. The device produced electromagnetic waves of decimeter wavelength range ($\leq 29$ cm). Žáček received patent of his magnetron in 1926.\textsuperscript{53, 54}

\subsection{2.6.2.4 The Soviet Union}

Russian physicists, Abram A. Slutskin (1881-1950) and Dmitry S. Shteinberg developed magnetrons while working at University of Kharkiv in Ukraine of Soviet Union during 1926-1929.\textsuperscript{55, 56, 57} N. F. Alekseev and D. D. Malairov, two Russian engineers at Scientific Research Institute 9 (NI9)

\begin{flushleft}

\textsuperscript{52} “Hollmann Magnetrons.” Radarworld.org. Web. 16 March 2011.


\end{flushleft}
produced a series of cavity magnetrons between 1936 and 1937.\cite{58}

### 2.6.2.5 Japan

Hidetsugu Yagi (1886-1976), a Japanese physicist and his student colleagues made significant contributions in the field of radio research at Tohoku University for almost two decades before World War II. In 1926, Yagi and Shintaro Uda (1896-1976) developed a directional antenna, known as Yagi-Uda antenna, which was subsequently adopted worldwide for radio communication. In 1927, Kinjiro Okabe (1896-1984), an electrical engineer and a doctoral student of Yagi at Tohoku University, developed a split anode magnetron that ultimately generated 20 GHz (or 1.5 cm) microwaves. In 1936, Yoji Ito (1901-1950) and Tsuneo Ito, at Tohoku University development an 8-split-anode magnetron that produced 10W output of 3 GHz (or 10 cm).\cite{59, 60, 61}

### 2.6.2.6 The Netherlands

In 1934, Klass Posthumus at Philips in the Netherlands developed a four segment split anode magnetron. He further gave a theoretical treatment of the rotating electron clouds, in a magnetron tube.\cite{62, 63}

\begin{itemize}
  \item \cite{58} “Radar -- The Soviet Union WWII (Part I).” Soviet Hammer. Web. 12 March 2011.
  \item \cite{60} Okabe, Kinjiro. “On the short-wave limit of magnetron oscillations.” Proceedings of the Institute of Radio Engineers 17 (1929): 652-659.
  \item \cite{62} Posthumous, K. “Oscillators in a Split Anode Magnetron.” Wireless Engineer 12 (1935): 126.
  \item \cite{63} Posthumous, K., “Magnetron Oscillations of a New Type.” Nature 134 (1934): 179.
\end{itemize}
2.6.3 **Invention of other Multi-cavity Magnetrons**

2.6.3.1 **Germany**

Hans Erich Hollmann S (1899-1960), a German electrical engineer designed and built the first microwave communication link in Germany. During 1933-36, he wrote the first comprehensive book on microwaves titled “Physik und Technik dev ulttrakurzen Wellen” (Physics and Technique of Ultrashort Waves, Springer (1938). He also developed a multi-cavity magnetron that was patented in Germany (1935) and in USA (1938).  

2.6.3.2 **United States of America**

The first multi-cavity magnetron was developed by A.L. Samuel at the Bell Telephone Laboratory in 1934 and was patented in the United States in 1936. In Samuel’s four-cavity magnetron, the anode was inserted into a thin-walled copper tube, a thoriated tungsten filament was supported axially by tungsten rods sealed into glass domes which were then sealed to the ends of the copper tube. The magnetic field was provided by a solenoid.

2.6.3.3 **The Soviet Union**

Soviet engineers N.F. Alekseev and D.E. Maliarov develop a multi-cavity magnetron in 1937 that could generate up to 300 watt microwave at a wavelength of 9 cm. (3.3 GHz). This information remained unknown for

---


many years outside Russia.\textsuperscript{66}

2.6.3.4 Japan

In 1939, under the leadership of Yogi Ito (1901-1950), an electrical engineer, a group of engineers from Naval Technical Research Institute (NTRI) and Japan Radio Company (JRC), built a 10 cm (3 GHz) stable frequency multi-cavity magnetron that could produce 500 Watt power.\textsuperscript{67}

2.7 British Technical and Scientific Mission to the United States

In mid-1940, Great Britain had essentially no allies in her war efforts. Germany by that time was on the way to invading large part of Europe. Britain was approaching towards the limit of producing electronic components and devices that essentially was guiding development of weapons to a great extent. Henry Tizard, Chairman of CSSAD and a key person in deciding Britain’s scientific war efforts, made a unique suggestion to disclose British scientific and technical secrets on military matters to the United States and Canada in exchange for desperately needed assistance in research and production.\textsuperscript{68} Winston Churchill, after becoming Prime Minister of Great Britain in May 1940, considered the proposal of Tizard with great interest and approached Franklin Roosevelt, the American President for a joint Anglo-American venture. As a result of a proposal approved by


\textsuperscript{67} Watson, R.C. Jr. 2009. 315-316.

both governments in July 1940, an official British Delegation, known as 'British Technical and Scientific Mission', visited the United States and Canada during August-September 1940 and interacted with their counterparts there. The British Mission is also known as Tizard Mission, after its team leader Henry Tizard. It consisted of six more members, three of whom were Brigadier F.C. Wallace, Captain H.W. Faulkner and Group Captain F.L. Pearce, representing the British Army, Royal Navy and Royal Air Force, respectively. Other three members, specialists in the new technologies of war, were Prof. John D. Cockcroft, a nuclear physicist and Assistant Director of Scientific Research at the Ministry of Supply, Dr. Edward G. Bowen, a radar specialist and Arthur E. Woodward Nutt, an Air Ministry Official. During the first week of August 1940, members of the mission collected documents available on recent wartime developments such as on RDF technology, rockets, explosives, superchargers, gyroscopic gun sights, submarine detection devices, self-sealing fuel tanks, basics of jet engines, estimation of critical mass for proposed atomic bomb etc. They also collected an eight-cavity resonant microwave magnetron (E1189), capable of producing peak microwave power output of 100 KW at 10 cm wavelength, produced by the General Electric Company Ltd. These were carried to Washington in a black box by E.G. Bowen and four other members of the mission on 28 August 1940.

Tizard and Pearce, two members of the mission, arrived in Ottawa on 15 August 1940. They met C.J. Mackenzie, acting President of National Research Council (NRC) of Canada, as also many important Canadians in politics, the armed forces and scientific research. The first meeting of the Tizard Mission with the Americans started in Washington on 12th September 1940, at the Army and Navy Headquarters. Subsequent meetings were held in different places till the end of September, 1940. The American side was represented by Alfred Loomis, a scientist and radar expert; Karl Compton, a professor of MIT; Vice-Admiral Harold G. Bowen, Director of the office of

Naval Research; and Major General Joseph C. Manborgne, Chief Signal Officer of American Army.  

There were Canadian representatives too who attended most of the joint meetings – C.J. Mackenzie, acting President of NRC; J.T. Henderson, radar expert from NRC, Senior Officials of Canadian Army. Tizard returned to England on 2nd October 1940, but other members of his mission remained in the United States for some more time and interacted with their counter parts on exploring the possibilities of joint collaboration in research and development on war efforts.

Such a unique collaborative Anglo-American effort helped the Allies in many ways in their war against the Axis nations. The most significant contribution of the British was the disclosure of the cavity magnetron to the US and Canada. The use of this device made possible development of different microwave radar during the World War II in Great Britain, in the United States and also in Canada. The allied radars were superior to any of the German radar. List of some notable radar developed by Germany, Great Britain and the United States during World War II is presented in Chapter 1, Section 1.7.2 of this thesis.

---

70 Watson, R.C. Jr. 2009. p156.
2.8 Organized Research and Development of Radar in the United States

2.8.1 MIT Radiation Laboratory

The Radiation laboratory (Rad Lab) at Massachusetts Institute of Technology, Cambridge had operated between 1940 and 1945 as a project of National Defense Research Committee to design and develop microwave radar systems. Rad Lab invented over 100 different radar systems, which was about half of the radar used by the United States in World War II. The Rad Lab at its peak, in 1945, had around 3500 employees and had spent US$ 4 million a month. The Research focus of Rad Lab during those five years was on physical electronics, microwave physics, electromagnetic properties of matter, and microwave communication principles. By the end of the war, it transpired that the Rad Lab had made significant contribution to microwave theory and technology, operational radar, system engineering, long-range navigation, and control equipment.75

Many reputed physicists, including Isidor I. Rabi, Norman Ramsey, Polykarp Kush, Willis E. Lamb Jr., Charles H Townes, Arno A. Penzias and Arthur L. Schawlow, who received the Nobel Prize at some stage of their illustrious career, served the Rad Lab project.

Lee Alvin DuBridge (1901-1994), an American physicist, was Director of MIT Rad Lab from 1940 to 1945. He received PhD in physics from University of Wisconsin in 1926. He spent next two years at Caltech as National Research Council Fellow and then six years at Dept. of Physics of Washington University. During 1935-1940, he served at University of Rochester, initially as a Professor and subsequently as the Chairman of the Dept of Physics. He was President of Caltech from 1946-1969.

2.8.2 Harvard Radio Research Laboratory

The Radio Research laboratory (RRL), at Harvard University operated during 1942-1945 under directorship of Frederick E. Terman, as a subsidiary unit of the Radiation Laboratory of MIT. It had a staff strength of around 800, who contributed for development of tunable receivers to detect radar signals, Jammers to block enemy radar and developed techniques to countermeasure enemy radar electronically.\textsuperscript{76}

Terman received BS in chemistry (1920) and MS in Electrical Engineering (1922) from Stanford University. In 1924 he was awarded Sc.D. degree in Electrical Engineering by MIT, where he worked under Vannevar Bush. During 1925-1941 he was a teacher at Stanford. In 1942, Bush appointed him as the Director of Radio Research Laboratory at Harvad University.\textsuperscript{77}

2.8.3 Columbia Radiation Laboratory

A Radiation Laboratory at Columbia University was set up in early 1942 under the aegis of MIT Radiation Lab to develop pulsed transmitting tubes for radar in the wavelength region of 1 cm and 3 cm. The result was the invention and development of tunable magnetrons, which could emit microwave at various frequencies. Isidor I. Rabi, who received the 1944 Nobel Prize in Physics, was the Director of Columbia Radiation laboratory from 1942 to 1945.\textsuperscript{78}

The Radiation Laboratory and its subsidiary units worked closely with


\textsuperscript{78} “Columbia Radiation Laboratory, Lab History – General Overview.” Columbia Center for Integrated Science & Engineering. Web. 30 March 2011.
leading American laboratories or industries like Bell Telephone Laboratories, Radio Corporation of America, Westinghouse Electric Corporation and Sperry Corporation, for radar development during the war years.\textsuperscript{79}

\section{2.9 British and American Microwave Radar of Second World War}

Early warning (EW) radar is used to detect its target from a long distance. Some of the notable EW radars developed during the early part of the Second World War were the British Chain Home, the German Freya, and the American CXAM (Navy) and SCR-270 (Army). These radar operated at meter waves and could detect targets at distances up to 200 Km. In 1944, the Radiation Laboratory developed a microwave early warning (MEW) radar system AN/CPS-1 that could overcome such shortcoming of previously produced EW radar. It was able to detect the presence of enemy fighter aircrafts located at a distance of 380 Km and at an altitude of 4900 m.\textsuperscript{80}

In 1941, the first British operational microwave radar, Type 271, a naval surface warning system, was introduced. More than 300 sets of this radar were produced during the war years. They were installed on escort ships to detect enemy ships and surfaced U-boats.

The first American microwave (10 cm) airborne radar for interception, designated as SCR-520, was designed and developed jointly by the Radiation Laboratory and the Bell Telephone Laboratories in 1941. Western Electric Company, Inc. manufactured 108 units of this radar and they were installed in 'Lockheed P-38 Lightning' fighter aircrafts, 'Northrop P-61 Black


\textsuperscript{80} Watson, R.C. Jr. 2003. p216.
In 1942, Bell Telephone Laboratories designed SCR-720, an improved version of SCR-520 that was lighter in weight and equipped for identification of friend or foe (IFF). These radar, were also manufactured by Western Electric and installed in P-38, P-61 and P-70 aircrafts. By adopting the design of SCR-720, Great Britain subsequently produced their air intercept radar AI Mk X and installed them in Royal Air Force multi-role combat aircraft 'de Havillard DH.98 Mosquito'.

In 1943, the Radiation Laboratory and Westinghouse Electric and Mfg. Co. Inc. designed and developed a light-weight search and intercept microwave (3 cm) radar AN/APS-6, suitable for a single seat aircraft, that enabled the pilot to use the equipment personally during the flight. Westinghouse Electric produced 2161 units of this radar for installation in American fighter bombers, 'Grumman F6F Hellcat' and 'Grumman F7F Tigercat', introduced in the war in 1943 and 1944, respectively.

The AI Mk VII was the first British airborne interception microwave radar produced in 1940. It was installed on night fighters to detect and intercept enemy aircrafts. AVS Mk III, the first successful British air to surface vessel (ASV) microwave radar was introduced in 1943. This high resolution centimeter radar could easily detect periscope of a submerged submarine. It was installed on torpedo bomber aircrafts 'Swordfish' and 'Barracuda'.

British H2S was the first airborne ground mapping microwave (10 cm) radar.

---

81 Watson, R.C. Jr. 2003. p177
82 Watson, R.C. Jr. 2003. p210
84 Watson, R.C. Jr. 2003. p176
85 Watson, R.C. Jr. 2003. p190-191
It was developed by Telecommunications Research Establishment in 1942 to see target at night and through cloud cover. Royal Air Force bombers were equipped with H2S radar from 1943 onwards. The Radiation Laboratory subsequently adopted the H2S design and produced H2X (called the AN/APS-15, when manufactured) radar which operated at a shorter wave length of 3 cm to get sharper image of the target. H2X was used by both British and American fighter aircrafts during the war.\textsuperscript{86}

US Army's first radar system SCR-268 for tracking aircraft for the purpose of directing searchlights against the aircraft and also for laying guns was introduced in 1938. It was, however, replaced by much smaller and more accurate microwave radar SCR-584 that was produced as a collaborative effort of the British and American scientists in 1943.\textsuperscript{87}

The radars developed under the Rad Lab project were superior to any of the German or Axis radar deployed during the war. It can be said that the Allied radar won the Second World War.

\section*{2.10 Battles won by use of Microwave Radar}

Battle of Britain was fought primarily between Great Britain and Germany from 10 July 1940 to 31 October 1940, entirely by involving air forces. Chain Home, the British early warning radar, played an important role in decisive British victory in the battle. With the advent of microwave radar, an outcome of British and American collaborative research and development projects, the Allied forces were victorious in three major battles of the Second World War, namely, the Battle of the Atlantic\textsuperscript{88}, the Battle of

\begin{thebibliography}{99}
\bibitem{86} Watson, R.C. Jr. 2003. p210
\bibitem{87} Watson, R.C. Jr. 2003. p166, 211
\bibitem{88} Brown, Louis. \textit{A Radar History of World War II: Technical and Military Imperatives.}
\end{thebibliography}
the Mediterranean\textsuperscript{89} and the Battle of the Pacific.\textsuperscript{90}

\subsection*{2.11 Emergence of New Fields of Science as Spin Off of Radar Research}

In early 1946, after closure of the Rad Lab project, Lee Alvin DuBridge had remarked in an article -- “Nearly 1000 physicists and engineers, who, in the past three to five years, have been through the equivalent of ten to fifteen years’ normal development experience, are now returning to their old jobs or to new ones. They will take to university laboratories new methods of working and new electronic techniques which can have similar effects on university research.”\textsuperscript{91} His expectation came true. Radar pioneers of Great Britain and the United States, based on their wartime radar research experience, made several inventions and innovations in the fields of radio astronomy, microwave communication, microwave spectroscopy, magnetic resonance and quantum electronics, during three decades after the end of the Second World War.\textsuperscript{92} We shall discuss on the development various branches of magnetic resonance, that evolved after the world war II, in the chapters 4, 5 and 6 of this thesis.

\subsection*{2.12 Conclusion}

Prior to commencement of the Second World War, the belligerents -- Germany, Great Britain, France, Italy, the Soviet Union, Japan and the


\textsuperscript{89} Brown, Louis. 1999. p353-358.


\textsuperscript{92} Buderi, Robert. 1996. 13-17.
United States, had emerged as prominent nations with strong scientific and industrial infrastructure. All of them had independently invented and developed some kind of radar before the war. But it was Great Britain to use radar decisively in war against Germany.

Laying the foundation of most effective wartime research in Great Britain and the United States was possible due to farsightedness of a few eminent scientists and the respective political supremo. Their dream to evolve the ultimate weapon for the war came true as a result of untiring research and development work of thousands of civilian scientists in collaboration with military personnel and industrialists during the war years.

The advancement of science and technology in various fields during the war, and the knowledge and experience gained by the scientists of these two countries, had resulted in emergence of new areas of science that benefited mankind immensely. Magnetic Resonance is one such field, which is being studied under the purview of this thesis.