The Proximity Fuze

Louis Brown
Carnegie Institution of Washington

When men first took to the air other men began to consider how to shoot them down. Technologically this began at Paris in 1871 when the garrison of the city passed messengers in balloons over the Prussian lines, easily eluding the fire directed at them. Before the siege had ended a balloon had been brought down with a specially constructed Balloon-abwehr-kanone, a 36-mm, breech loading gun mounted on a carriage that allowed 360 degree traverse and high angles of elevation. The years between the siege of Paris and 1914 saw the invention of the airplane, even its use in warfare, but no improvement over the Krupp weapon of 1871 other than the normal evolution of firearms. The application of aircraft in the First World War proved to be a struggle between opposing engineers in providing ever-improved designs. The rapid pace was astounding. At the outbreak crossing the English Channel was no small achievement; at the end it was the Atlantic that was spanned. Anti-aircraft ordnance developed in parallel and at an equally fevered pace.

The ballistic accuracy and range of guns in 1914 was adequate for shooting at aircraft, but the method of aiming had not evolved beyond 1871 and was incapable of dealing with the small size, high speed and agility of the airplane. It was quickly realized that one could never expect direct hits by projectiles except by machine gun and automatic cannon, so the high explosive shells of heavier guns would have to be detonated through the time fuzes used for shrapnel. Pointing the gun and cutting the fuze required accurate location of the target and calculation of where it would be when the shell completed its flight. By 1918 these problems had been mastered to the extent that given clear visibility a flier had much to fear from ground fire. Southern England had an elaborate air defense organization that had put an end to raids by airships and greatly deterred the Gothas and Giants that had taken their places. The Germans ended the war with equal anti-aircraft prowess and had already put the 88-mm gun tube into action. Within a few years virtually nothing was left of Britain's air defense system.

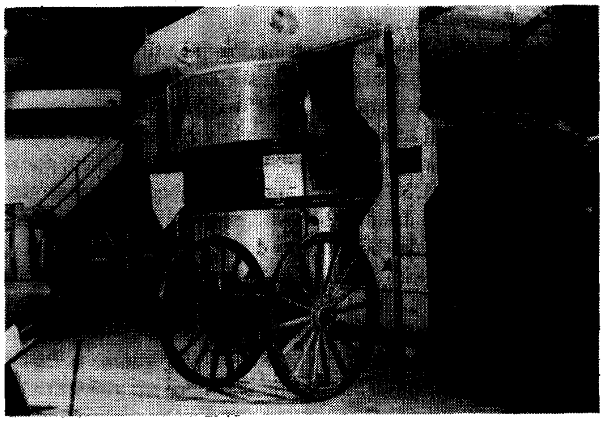

Fig. 1. Artillery and Radio Technology.
The 37-mm gun, Model 1916, is shown here in front of the Carnegie Cyclotron on 14 August 1942, presumably just before its return to the Navy. The gun fired a lower velocity cartridge than the 37's of World War II used in anti-aircraft and anti-tank guns. It was for use against machine guns and was standard in infantry units until about 1940.

The evolution of the airplane during the years between the two world wars continued, but the skills of the gunner atrophied. Of the inaccuracies in causing a shell to explode near an airplane that of the fuze, especially the accurate determination of the flight time, was by far the worst. The solution to this problem seemed to lie in a fuze that felt the influence of the plane in some manner. The idea had been around in Britain for some time. With the coming of war John

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Author's Current Address:
Dept. of Terrestrial Magnetism, 5241 Broad Branch Road, NW, Washington, DC 20015

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Cockcroft and W.S. Butement confronted the problem. They saw three possibilities for sensing the presence of an aircraft: acoustic, photoelectric and radio. All three methods required vacuum tubes for which the ability to withstand the acceleration of firing was essential. Cockcroft ordered a large number of hearing aid tubes from America and began spinning them in a centrifuge to determine their ability to withstand large accelerations. Butement developed an electronic circuit for a continuous wave (CW) radar based on the Doppler effect. The idea, now so popular with traffic police and so hated by speeders, used the low-frequency signal generated by the interference of the reflected with the direct wave, each originating from a source of different velocity.

Unfortunately, the British had too many serious problems to deal with. Cockcroft, who gained everlasting fame in 1932 by first splitting the atomic nucleus, was also engaged on studies of the feasibility of a uranium bomb, and Butement was heavily involved in designing radar for the army. Prototype fuzes were applied to anti-aircraft rockets and bombs—a part of the 'bomb the bombers' scheme—but came to no effective employment. The proximity fuze needed development by forced march but was proceeding at a stroll.

Making a CW radar set small enough to fit into the space available for the fuze of an artillery shell and capable of standing the enormous acceleration of being fired from a high velocity gun was no small achievement. Perhaps even more remarkable was the speed with which the task was accomplished, for on 5 January 1943, USS "Helena," on her way back with two other cruisers and two destroyers from an attack on an airstrip on New Georgia the day before, shot down a Japanese plane with a shell equipped with an industrially-produced fuze, less than 30 months after the first discussions at the newly-formed National Defense Research Committee about the need for such a device. The Chairman of the NDRC was Vannevar Bush, President of the Carnegie Institution, a privately endowed research organization that had physicists in Washington, a few of whom were well-trained in experimental arts. Since 1927, Merle Tuve had worked to build a particle accelerator for nuclear physics and succeeded in adapting the Van de Graaff generator to that end at Carnegie's Department of Terrestrial Magnetism (DTM), a name retained from an earlier, heroic age of wooden sailing ships and expeditions into less than hospitable regions. Bush had taken a quick liking to Tuve and brought him into discussions of defense matters from the start. After discussions with naval ordnance men, Bush formed Section T (for Tuve) to work on an influence fuze at DTM.

Thus in mid-August 1940, Tuve, who had security clearance, asked his as-yet uncleared colleague Richard Roberts, if he thought a vacuum tube could stand an acceleration of 20,000 g, and received a tentative answer of yes the next day. Roberts mounted an obsolete tube, a number 38, on a lead brick that he suspended from the ceiling. He then fired a bullet at the brick, the oft-repeated experiment that demonstrates the conservation of momentum to students in introductory physics. The tube still worked, and calculation showed it had briefly sustained an acceleration of 5,000 g. The next day, Roberts mounted a tube on a hemisphere of lead and dropped it from the roof of a three-story building onto a steel plate. The indentation of the lead allowed an estimate of the acceleration, which was even higher than before, and the tube still worked. The proximity fuze project was under way.

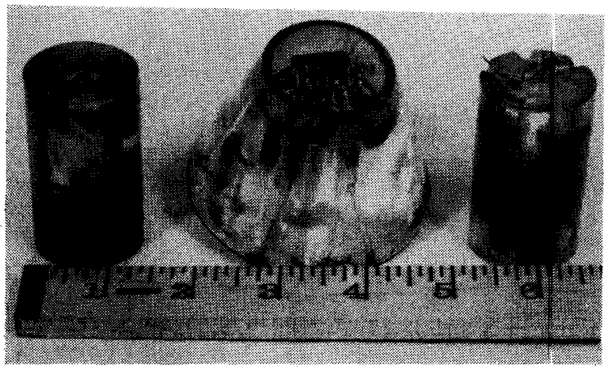

Fig. 2. Test Oscillators. The center one was of the type successfully fired from a 5-inch gun on 8 May 1941. The coil and capacitor of the Hartley oscillator are exposed. The two outside oscillators were probably tested in a centrifuge.

In fact, Tuve and Roberts were already on a war project, for both were on President Roosevelt's Advisory Committee on Uranium. DTM had two Van de Graaff accelerators in operation and was building a 60-inch cyclotron. In January of the year before, Roberts had demonstrated fission in a startlingly simple experiment to Niels Bohr, Enrico Fermi, Edward Teller and Gregory Breit, who were attending a scientific meeting (on low temperature physics!) in Washington at which the knowledge of this new nuclear process had gotten out. Roberts continued to work on fission and subsequently discovered delayed neutrons, which allow fission to be controlled in a reactor. The events during the summer of 1940 disturbed the men at DTM greatly and brought them to the viewpoint that an atomic bomb would come too late to affect the outcome of the war. One of the DTM staff, Norman Heydenburg, continued making measurements for the uranium project until all such work was transferred to Los Alamos and construction of the cyclotron continued, but most of DTM went to work on the fuze. Other thoughts may have been in Tuve's mind. When asked about leaving the bomb project during an interview many years later Tuve said: " . . . and I didn't want to make an atomic bomb."

Tuve and Roberts made interesting contrasts. Tuve was the son of Norwegian immigrant grandparents who had settled in a small town in South Dakota. He and his childhood friend Ernest Lawrence had linked their houses with a telegraph line, replaced with wireless sets when Ernie's family moved. Both went on to build pioneer nuclear physics laboratories, and for a while American nuclear physics was firmly in Scandinavian hands as they were joined by Lauritsen, Hafstad and Dahl. Roberts traced his lineage to colonial roots, had financial independence with origins in Pennsylvania oil, and had gone to the best schools. The two of them guided DTM for four decades with a scientific leadership that kept them active

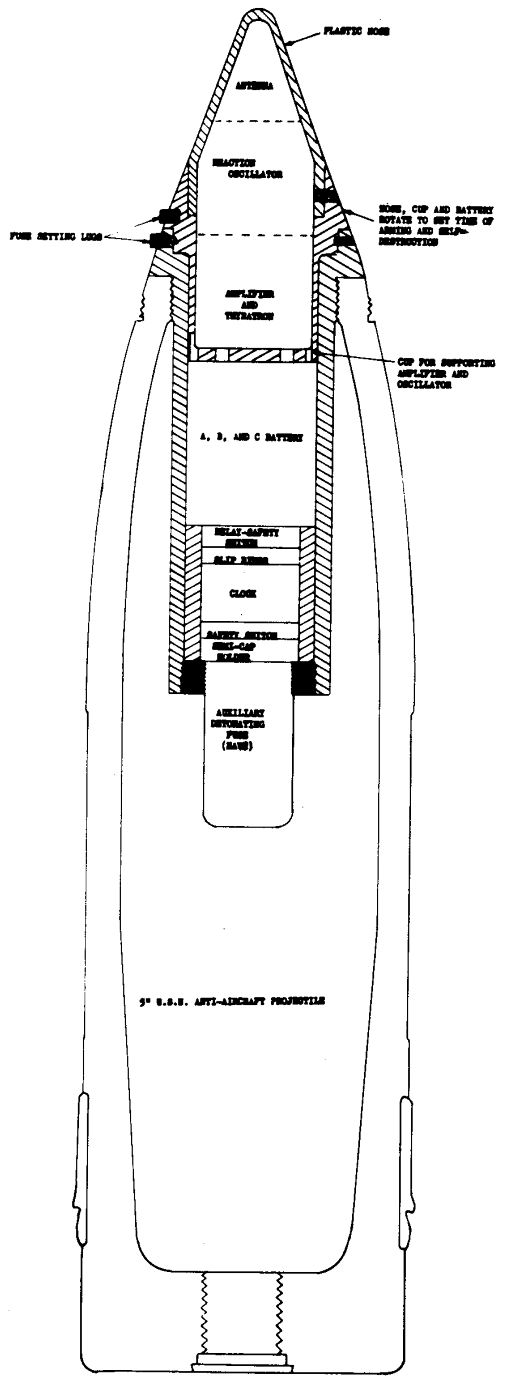

Fig. 3. Section Drawing of a May 1941 Design for the Mounting of a Fuze in a 5-Inch Shell

laboratory partners of their colleagues. They were implacable enemies of big science.

Roberts's first experiments obviously called for shooting vacuum tubes out of a gun, so the workshop made a small muzzle-loading smooth bore, which was taken to a farm owned by a friend of Tuve's in what is now the Virginia suburb of Vienna. The gun was pointed straight up, a projectile with a small tube potted in wax loaded, and the gun fired. And failure! Although the glass envelope had survived, the electrodes collapsed completely. Navy ordnance experts suggested that they try again using smokeless instead of black powder, which explodes instead of burns and gives much higher initial acceleration than smokeless. A 37-mm gun of 1916 vintage was procured, and tubes began to survive. For the next few months projectiles were fired, sometimes hundreds a day, testing tubes and other components. Initial nervousness of the experimenters about where the shots would land was soon replaced by confidence on learning that they could predict the point of impact within less than 100 m.

While the studies to determine whether electronic components could be fired was being settled the Tizard Mission arrived in Washington, and on 14 September, R.H. Fowler and John Cockcroft had dinner at Tuve's home, and open exchanges of information about fuzes soon followed. The Americans had not settled on the method of influence yet and were examining the same methods the British had. Lawrence Hafstad worked on a photoelectric method, and G.K. Green on an acoustic method. An electronic circuit designed by Butement for a radio proximity fuze was extracted from Tizard's famous "black box," and Roberts, who brought the additional skills of a radio enthusiast as well as a reserve officer of Field Artillery to the project, had the circuit working in the lab in a couple of days. The basic circuit remained unchanged throughout the project. The plate resistor of a Hartley oscillator was connected to a two-stage audio amplifier connected to a thyratron, which passed current through a detonator when its grid voltage exceeded a given threshold. Just four tubes!

The laboratory circuit, tuned to 100 MHz, worked beautifully. The thyratron output responded sensitively to the motions of a half-wave dipole anywhere in the room. Roberts' brother, Walter, a radio engineer who had helped design the oscillator for the DTM cyclotron, worked out the theory of the thing and found that if the target came within a few wavelengths of the oscillator, it altered the loading of the antenna, thereby changing the direct component of the plate current, which varied at a rate determined by the relative motion of target and projectile. This signal went to a two-stage audio amplifier through a low pass filter and triggered the thyratron. Doppler was not really involved. It was an elegant design.

With evidence that vacuum tubes could be fired from guns and that a simple electronic circuit could be made to trigger the explosion, it was obvious that a greatly expanded project was needed. Vacuum tube manufacturers had to begin furnishing prototype rugged tubes while preparing for mass production with similar, if less stringent, tasks for less complicated components. Batteries presented particular problems. Circuit and mechanical design had to proceed toward a usable device, and a greatly expanded testing program undertaken. All this required an increased staff, which quickly had over a hundred persons working in a building that had housed only a dozen a few weeks earlier. Tuve put out a set of rules, the first of which was: "I don't want any damn fool in this laboratory to save money. I only want him to save time." For those who had experienced Tuve's frugality, before or after the war, this was a startling rule.

In October, fuzes made of non-rugged components in non-miniature circuits for both the radio and photoelectric fuzes detonated 100-lb bombs dropped at the Naval Proving Ground, Dahlgren, Virginia. The radio fuzes had rod antennae and used camera timers intended for self-portrait photography as arming devices. The entire stock of this kind of device was bought up in Washington and New York; one can only wonder at the puzzles created among photographers. At about this time Tuve decided that fuzes for non-rotating projectiles presented different kinds of developmental problems and turned the work on bombs and rockets over to the Bureau of Standards under the direction of Harry Diamond, who continued to work on the photoelectric method but dropped the acoustic as impractical. The DTM group dropped all methods except the radio fuze.

In February 1941, tubes were fired from 5-inch star shells with the parachute intended to lower the flare being used to bring down the components being tested. On 20 April 1941, an oscillator was shot from the 37-mm and observed to function, and about two weeks later seven oscillators were fired from a 5-inch gun at Dahlgren, four being heard in flight. An oscillator with a modulator to calibrate microphonics generated in flight disclosed no such problem. It was time to make complete fuzes.

The small size of the 37-mm did not allow the firing of complete fuzes, so the vertical firing was transferred to a 57-mm at Dahlgren. This gun had not only a larger shell but a higher muzzle velocity. The Dahlgren firings were enlivened by the caretaker's dog, who raced into the river with each shot, expecting that such a powerful gun would bring down plenty of ducks, and who needed weeks of duckless firing to learn that the hunters were incomparably bad shots. Firing became routine for testing prototype industrial tubes as well as production lots.

Numerous tube manufacturers entered the competition, but Sylvania proved most successful. Its T-3 tube weighed less than three grams. One must remember that small-sized electronic components so common today were not so much admired in 1940. It is also worth noting that the entire U.S. production of vacuum tubes in the last peacetime year was 600,000 per day. By 1945, the production of tubes for proximity fuzes was 400,000 per day with 95% from Sylvania.

The first batteries were specially adapted dry cells furnished by National Carbon, but they soon showed serious shelf-life problems and were replaced by wet batteries that had indefinite life with the added advantage of being activated only at the firing of the gun. A sealed glass ampule containing chromic acid was placed within a stack of annular discs. One side of each disc was zinc, the other carbon. On firing, the glass ampule shattered and the acid was flung into the plates by centrifugal force. If its shelf-life was long, its active life was short, about two minutes, just long enough for the flight of any proximity fuzed shell.

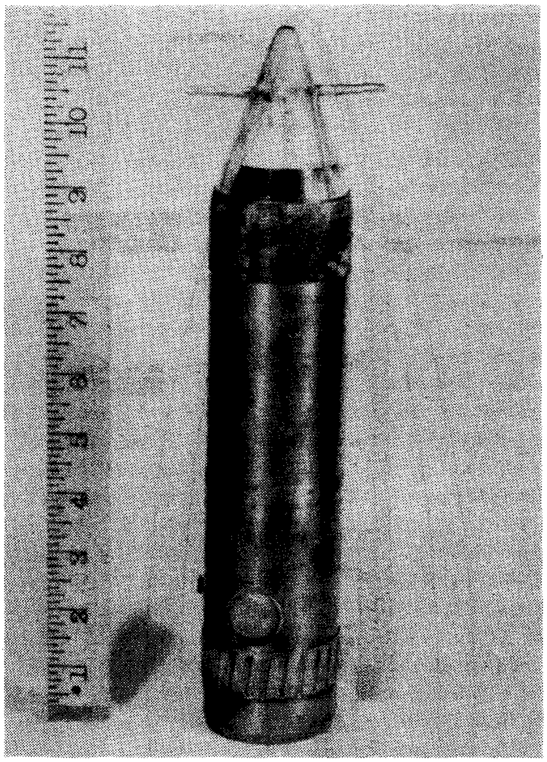

Fig. 4. Radio Sonde Mounted in 1 57-MM Projectile. The two half dipoles snapped into position on firing and produced an amplitude modulated signal that allowed the rotational speed to be monitored throughout flight.

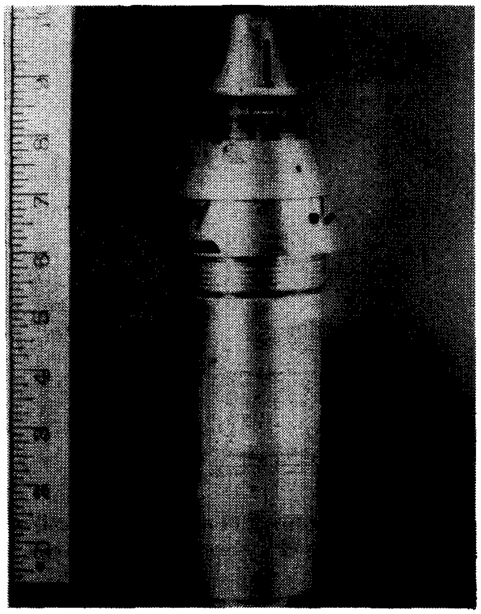

Fig. 5. First Assembled Fuze for a 5-Inch Shell. Voltage from the oscillator was applied between the metal nose cap and the main body of the shell.

A fuze was mounted in a 5-inch shell with a hole cut in the side for an ammeter in the plate current circuit. With this, the radiation pattern of the little transmitter driving a necessarily small antenna, a cone shaped electrode at the nose, was measured. The next step was to fire pilot production fuzes in 5-inch guns at Dahlgren, which took place in August 1941. On 29 January 1942, the success rate at Dahlgren exceeded 50%, and full production started while the bugs were still being removed. Unfortunately, removing bugs did not mean they would stay removed. One of the greatest problems in producing fuzes proved to be quality control at all levels. It was a never-ending problem, and there was no letup. The highest rate of duds allowed was 5%, and it was hard to maintain.

The introduction of the high explosive shell at the turn of the century brought an awkward period during which guns exploded on firing from time to time, owing to imperfections in the fuzes. Improvement in design soon made the simple impact and time fuzes both safe, but the proximity fuze obviously had many more ways to fail. Tuve was determined that his race against time was not going to result in dead gunners, so a major effort went into safety devices. The explosion was initiated by a detonator that was activated by some tens of milliamperes, so the first line of safety was to keep it shorted until the projectile was clear of the muzzle. A clockwork located in the base of the fuze and actuated by projectile spin removed a short circuit and a mechanical gate in the powder train half a second after firing. The wet cell battery also helped by taking a tenth of second to come up to voltage. A mercury switch functioned in two ways. Before firing, the mercury resided at the center of a porous cavity where it effected a second short. On firing, centrifugal force spun the mercury through the porous material thereby opening that short and closing a switch that activated the electrical components with a delay determined by the diffusion time through the diaphragm. The thyratron and the last stage of the audio amplifier, which operated in the range from 30 to 300 Hz, were initially biased to cutoff and became active only after a time delay determined by a capacitor charging time. Finally, the presence of the gun tube so loaded the antenna that the oscillator would be quenched while within the gun. Thousands of rounds with only one operable safety and a reduced charge of black powder were fired to evaluate each separately.

Firing at air frames suspended from balloons and from towers at the New Mexico Proving Ground by H.R. Crane measured the burst patterns, which could then be adjusted with the only available parameter, the sensitivity. If the sensitivity were too great, the shell would burst too far from the target; if it were too small, the shell would burst close enough to assure the target's destruction but allow many possibly damaging rounds to pass by. These tests were all made with explosive charges just great enough to permit photography, otherwise target replacement would have become a major waste of time. After these successes it was time for the critical test: firing from a ship at radio-controlled targets, called drones, under routine service conditions. The tests were made on the shake down of the new cruiser USS "Cleveland" in the Chesapeake Bay on 12 August 1942. Roberts was aboard and later recorded the event.

"The next day all was ready off Tangier Island and a drone approached on a torpedo run. At about 5000 yards the ship opened fire with all its 5-inch guns. Immediately there were two hits and the drone plunged into the water. Commander Parsons called for another drone and out it came on a run at about 10,000 ft altitude. Once again it came down promptly. Parsons called for another and then raised hell when the drone people said there were no more ready for use. He enjoyed this very much as he had been on the receiving end of a lot of comments by the drone people in other firing trials. The drone operators had one back-up drone ready in case of troubles but they never expected to have one shot down. In fact the Navy photographic crew who took pictures of all the firing trials of the fleet had never seen a drone shot down before. The ship was ordered to the Pacific with no stops, as the crew had seen too much." [Note: Either Roberts's memory was in error or he was misinformed because the "Cleveland" was soon to take part in the invasion of North Africa.]

As the "Cleveland" was not to dock on her outbound voyage, the technical personnel were loaded into a launch to take them ashore. In a somewhat humorous gesture the skipper of the "Cleveland" gave his evaluation of them when he presented each a life preserver as they descended to the small boat, which naturally had a normal supply of such articles.

It is ironic that this test, which showed that a warship could defend itself very well indeed against air attack, took place less than a hundred miles from the location where, some twenty years before, Billy Mitchell thought he had proved that surface ships were obsolete as a result of air power.

The supreme driving force behind fuze development was its use against aircraft, but once this problem was solved thoughts naturally proceeded to an older problem of the artillerist: air bursts against ground targets. The first explosive artillery shells, which introduced the term "bomb shell" into the language, had used powder train fuzes. If this fuze were cut short, it led to "bombs bursting in air." With better fuzes and more accurate guns this had been refined by General Henry Shrapnel of the British Army into a shell filled with lead balls and that burst in the air with devastating effect on exposed infantry. After World War I, shrapnel had been replaced by the high explosive shell that did its killing with jagged shell fragments instead of lead bullets, but the time fuze remained. Up to fifteen seconds flight time could be obtained with a powder train fuze, twenty-five with a clockwork fuze. With flat trajectory guns at moderate ranges and observed fire these could be effective. At long range, at night or in fog, or unobserved, time fire was almost useless. Use of the proximity fuze was obvious.

Ralph Baldwin guided this adaptation quickly to completion. The Field Artillery had gone over to howitzers to a large degree, and they presented a few problems. They never had the high muzzle velocities of the AA guns and even had a variety of velocities from which to choose, determined by the amount of propelling charge loaded. Varying muzzle velocities meant varying spins, and spin operated the safeties. Thus high acceleration, that horrible problem in the summer of 1940, became a necessity. It was soon decided that only the top three powder charges for howitzers would be considered. Fuzes were soon ready.

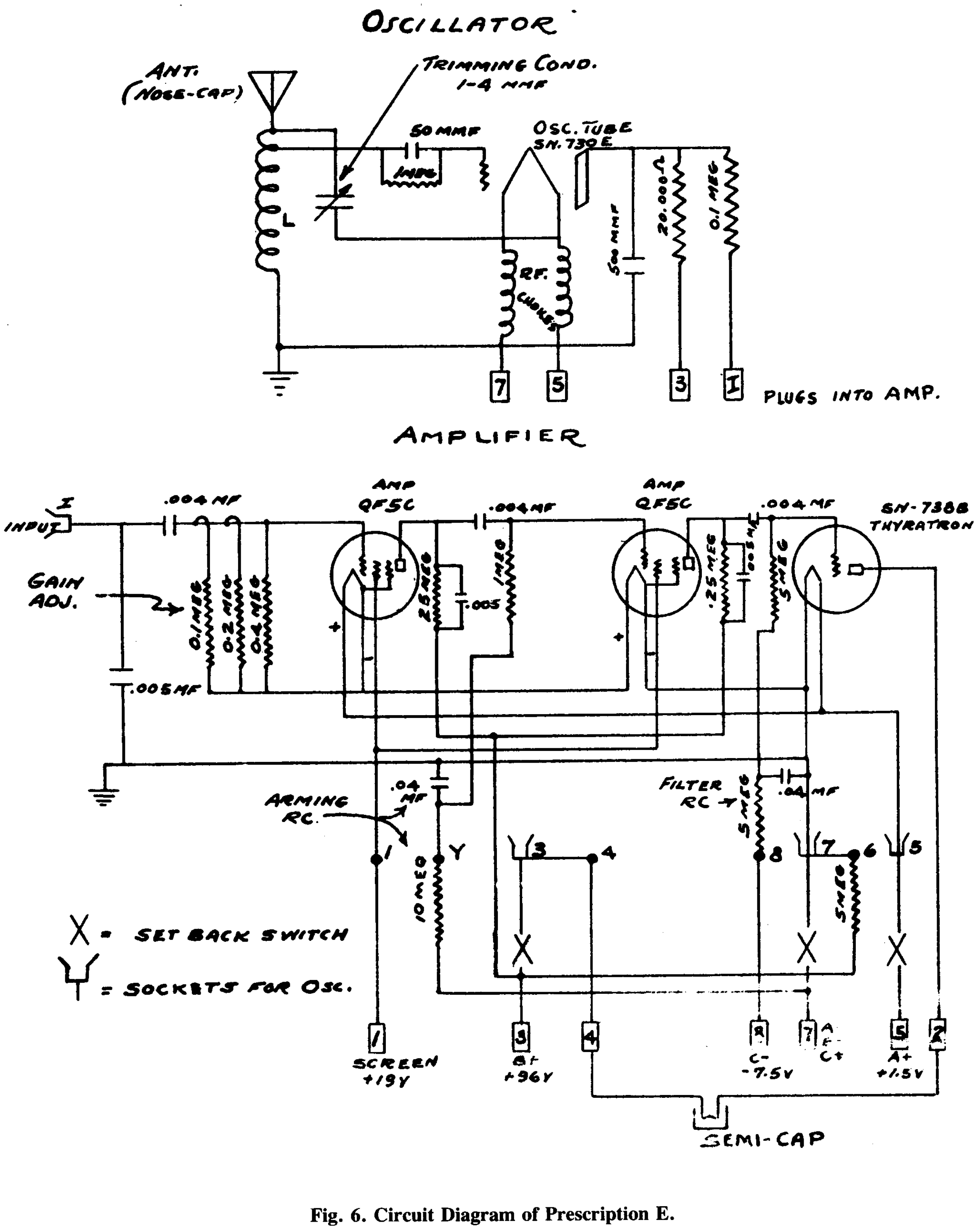

Fig. 6. Circuit Diagram of Prescription E.

This is a slight modification of the design of W.S. Butement. The free running Hartley osciullator has the direct component of the place current altered by a change in radiation resistance when a conducting object comes within a few wavelengths. This signal passes through a low pass filter into a two stage audio amplifier. When the output of the amplifier exceeds a fixed level the thyratron conducts, discharging the semi-cap.

The army equivalent to the "Cleveland" firings was a demonstration to the Field Artillery Board at Ft. Bragg on 24 and 25 September 1943, with Lt. Gen. Leslie McNair, Chief of Army Ground Forces in attendance. It was fouled up, yet a stunning success. The fuzes for different caliber weapons were mixed up at the gun positions causing up to 30% duds and bursts at the wrong heights. The Section T men were frantic, and it showed. The Board was so startled to see air bursts at extreme ranges, air bursts unobserved, air bursts with high angle fire (shells descending almost vertically), air bursts at night, that its enthusiasm was almost uncontrolled. When Baldwin went on about the poor performance, McNair answered: "Gentlemen, you want all this and the moon too?"

The account of the story at this point does not convey a proper picture of what had been going on. Tuve's objective was a weapon to be placed in the hands of the warriors—and soon! This meant that production had to be brought in early, well before designs were final, and the entire project grew at an incredible pace. The early fuze work had more than 40 industrial and academic contractors, and Canadians helped with battery design. The year 1940 was a good time to place orders because industrial mobilization had just started and there was plenty of slack yet to be taken up. In April 1942, Section T had outgrown the space at DTM and moved to a large building on Georgia Avenue in nearby Silver Spring, Maryland. At that time the Carnegie Institution transferred administrative control to Johns Hopkins University, and the newly established unit was named the Applied Physics Laboratory. By the time of the "Cleveland" firings production of fuzes was already great. Needless to say, this gamble brought on no small number of emergencies. Strange infirmities would appear, in a product that had a built-in bias against diagnosis, yet diagnosis was demanded immediately. U.S. and British forces had between them 40 different kinds of shells for which the fuze, now called VT, meaning variable time, was required, and each had to be individually fitted. As the magnitude of the project spread, curious ways were found to conceal the true function of various components. The plastic noses were ordered through Johns Hopkins Medical School under the name of "rectal spreaders."

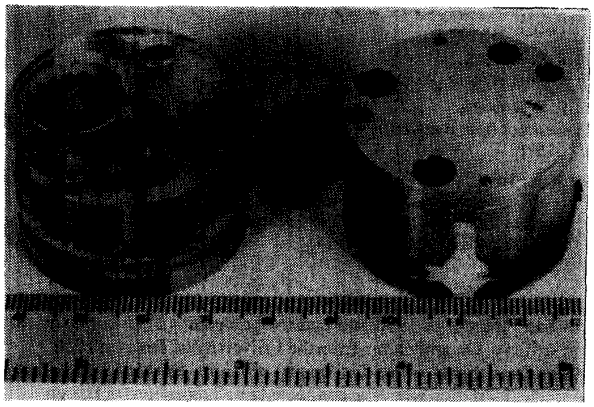

Fig. 7. Centrifugal Clock. This timing safety uses an escapement driven by a small load attached to the rim of the wheel. Delay is accomplished by the time required to pull the wheel around to the point where the load is farthest from the center of the spin.

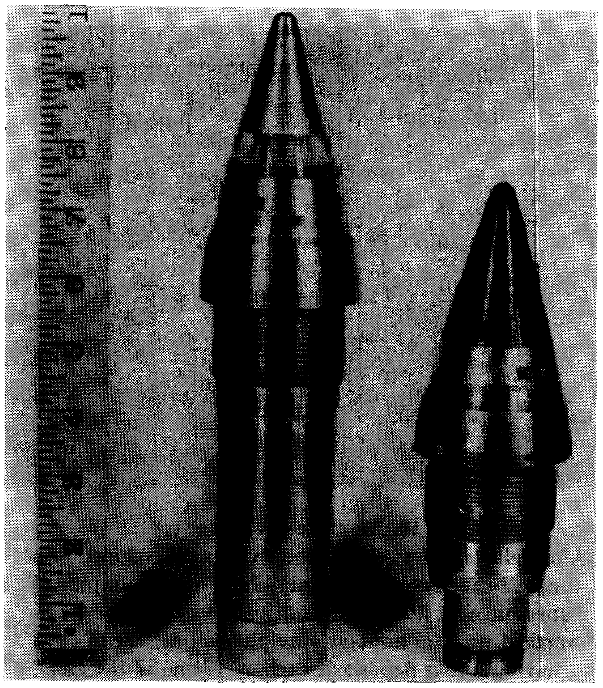

Fig. 8. A Proximity Fuze Compared with a Standard British Clock Fuze at the Right

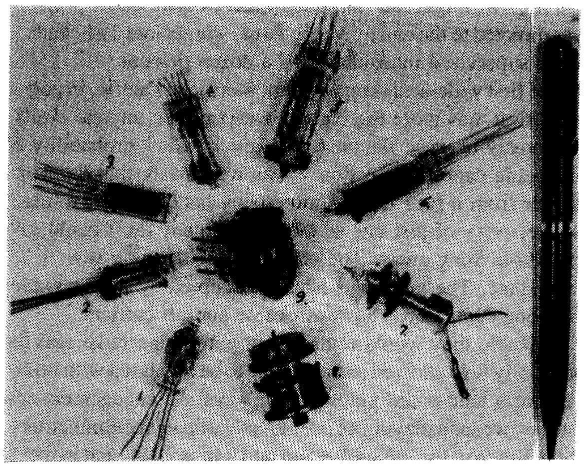

Fig. 9. Early Rugged Tubes. 1) Second Bell Labs Thryatron; 2) Hytron Triode Electrode Structure; 3) Hytron Pentode Electrode Structure; 4) Raytheon Pentode; 5) Hytron Triode; 6) Hytron Pentode; 7) First Bell Labs Thyratron; 8) General Electric Thyratron; 9) Bell Labs Pentode

By the end of the war, 112 companies were engaged in production work on fuzes and more than 22,000,000 had been manufactured with the price eventually falling to $18. As a wartime project it was exceeded in magnitude only by the bomb

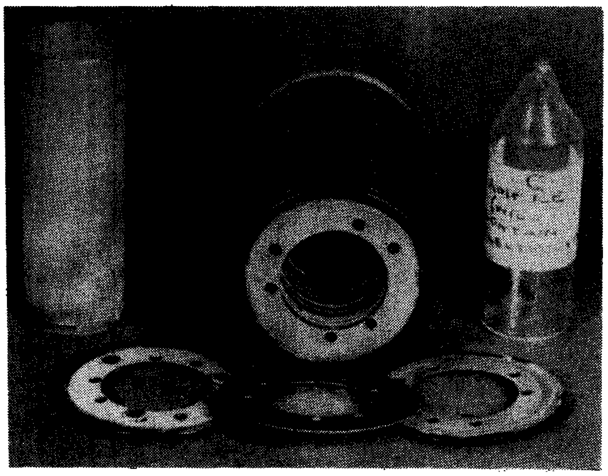

Fig. 10. The "Reserve" Battery. After failure of dry cells National Carbon developed what it called the "reserve" battery. In it a glass ampule of chromic acid fits in a cylindrical space defined by a vertical stack of annular zinc plates, one side of each having a thin deposit of carbon. Firing of the gun shatters the ampule, and the acid spins out to produce the required voltages.

and what we might call "large set" radar. Yet the entire project was directed to the end by Merle Tuve, who before 1940 had never supervised more than half a dozen persons.

The first wide-scale employment was in the Pacific, in part because it was more the Navy's weapon than anyone else's but mostly because fleet use gave the smallest probability of one being captured. Section T was well aware that the first danger from a fuze falling into enemy hands was jamming, and recovery of just one of the all-too-many duds could give the whole thing away. The effect on naval action was immediate. The numerous islands occupied by the Japanese had long been feared as "unsinkable aircraft carriers." Unsinkable they would remain, but gun-laying radar and the proximity fuze allowed strong points to be bypassed with little fear from land-based planes. Each naval air engagement saw the new weapon playing an ever greater role with culminations at the Battle of the Philippine Sea on 19 June 1944, and in the defense against the suicide pilots, principally at Okinawa. The first use in the European theater was again naval, during the invasion of Sicily.

The most spectacular triumph of the fuze was in the defense against the flying bombs, but it was a triumph shared with the gun-laying radar SCR-584 and the electronic director M-9. It was crucial in the Battle of the Bulge, where it was used to devastating effect against infantry advancing in fog.

After the war the newly-founded Applied Physics Laboratory continued in military and quasi-military development, but Tuve and Roberts returned to DTM, which went back to its pre-war budgets and staff size. Tuve became Director and moved the Department from the study of the nucleus into radio astronomy and geophysics. "I left nuclear physics when it changed from a sport into a business" is how he often expressed it. This from the man who, perhaps more than any other allied scientist, became a business man for the duration of the war. Roberts joined with Philip Ableson, who returned to DTM from the Manhattan Project, to form a bio-physics group at DTM. Hafstad left to become Director of Reactors at Oak Ridge and later a vice president of General Motors. Vannevar Bush remained President of the Carnegie Institution.

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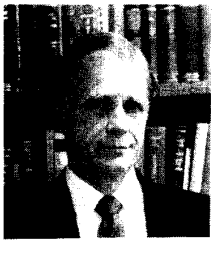

Louis Brown graduated from St. Mary's University in San Antonio in 1950 and entered graduate school in physics at Austin after having served two years as a battery officer in artillery. On graduating from the University of Texas in 1958 with a Ph.D. degree he worked three years at the Physics Department of the University of Basle, Switzerland. In 1961 he came to the Department of Terrestrial Magnetism, Carnegie Institution where he conducted a collaboration for fifteen years with the Basle group in experiments with nuclear reactions initiated by polarized protons. Subsequently he has applied physics methods to the problems of geochemistry with both conventional and accelerator mass spectrometry. He received the Amerbach Prize from the University of Basle and is a Fellow of the American Physical Society.