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Development of the

# Proximity Fuze

During WWII
World Class Example
of
Collaborative Innovation
in a
Cross-Industry Multiple Partner Alliance

*By Robert Porter Lynch*[1]

[1] I gratefully acknowledge the great contribution of my neighbor, Ralph Baldwin, who, before he passed away, made sure the tremendous work in developing the Proximity Fuze was not lost to history. I have used his excellent book:
*They Never Knew What Hit Them – The Story of the Best Kept Secret of World War II*, Ralph H. Baldwin, Reynier Press, 1999 as a source for much of the material contained herein.

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# Executive Summary

1. Overview:

Heralded as an "organizational achievement transcending anything of the time … one of the most effective alliances among the military, academia, and industry," the development of the Proximity Fuze during World War II was credited for reducing the duration of the war by at least a year. WWII is singularly distinguished as the only war in history in which the outcome of the war was significantly influenced by scientific breakthroughs that created weapons unknown at the war's commencement.

2. Key Issues:

Development of the Proximity Fuze, used to detonate bombs & Anti-Aircraft shells required:

1. massive breakthrough in technology,
2. rapid innovation and continuous improvements,
3. unification of diverse inputs of thinking,
4. superb organizational coordination within the alliance
5. flawless speed of execution from research to development to commercialization to field proliferation.

3. Critical Measures of Impact:

a. Prior to the war's outbreak, anti-aircraft fire was incredibly inaccurate:
   Typical Rates of accuracy:
   1940: Without Fuze: Thousands of Rounds per airplane destroyed by ground-fire during day, tens of thousands of Rounds per airplane destroyed at night
   1944: With Fuze: 90% kill rates of V-1 Buzz Bombs with 10 rounds of fire, similar impact on Japanese Kamakaze attacks on US Pacific Fleet
   Nearly total elimination of Japanese Aircraft and ships in Pacific Theatre
b. Citations from Eisenhower, Patton, & Churchill for the fuze's impact on war
c. Production of Proximity Fuzes:
   1940: None
   1945: 22,000,000 fuses produced, incorporating miniaturized electronics:
   140,000,000 miniaturized rugged vacuum tubes and numerous impact resistant components totaling over 1 billion components
   Nearly 100% reliability and safety in sub-zero weather and tropical heat
   Employed over 1 million people in production in 110 plants, with such total secrecy as to be unknown to either Japanese or German intelligence
d. Ability to withstand shocks of:
   20,000 G-forces at impact of firing
   5,000 G-forces shell spin during trajectory

4. Essential Learnings:

- Breakthroughs require a powerful *belief* that discovery and commercialization are possible
- Cooperation and Coordination in an alliance will beat fragmented competitive systems
- Saving time is more valuable than saving money
- First to market is more important than perfection
- Exercise of Authority and Responsibility must be vested together
- Moral Responsibility for saving lives in the field was focal point for everyone in project
- Parallel Discovery and Development is essential for rapid innovation
- 80% effectiveness *now* is more valuable in wartime than 100% *later*.

# Case Study Details

1. <u>Prelude to War</u>

In 1940, President Roosevelt created the Office of Scientific Research and Development (OSRD) to bring the best scientific minds to bear on solving critical problems that would give the US and its allies an advantage in an anticipated war. Already Britain was under siege, France and Poland had fallen, and Japan had invaded Manchuria. The sky was filling with the acrid smoke of war, and America was woefully unprepared.

Under the guidance of Vannevar Bush, OSRD organized a Section to be devoted to solving the problem of how effectively to shoot a plane out of the sky when it was attacking a ship at sea. Hitting a moving target was extremely difficult. If a shell could be made to explode when it was simply near the target (within 50 feet), the problem could be solved. Placing a timer device in the shell required calculations that took far too long to make it a combat effective solution.

Accuracy of Anti-Aircraft (AA) fire in 1940 was poor, taking thousands of rounds to gain a hit during the day, and tens of thousands of rounds at night. During the Battle of Britain it typically took 18,500 rounds per aircraft destroyed, and few were destroyed.

The most effective solution was conceived by the British in 1940 – use a radio transmitter in the shell to send a radio wave, which when it came near a plane, would reflect back a signal, which would detonate the shell. However, the problem was extremely difficult when translated to practical application. So perplexing, in fact, that German scientists did not believe the problem could be solved. In 1940, placing a radio transmitter in a shell required technology deemed impossible. Consider these realities: A shell, when fired, suffers G-forces of at least 20,000, and often more. A rotating shell can leave the muzzle of a gun spinning at over 250 rps (revolutions per second), generating 5,000 Gs. No electronics circuits hade ever been designed to withstand such massive destructive force. Car and aircraft radios were the most advanced technologies of this type at the time. Further, the speeding shell could travel only a few feet before sensing the target and detonation, otherwise the firing would occur too late.

Development of a radio-transmitter proximity fuse to detonate near a plane would require not just technological breakthroughs involving a variety of fields of expertise, but miniaturization of electronic systems that had never been accomplished, plus near perfect cooperation and coordination of the military forces (specifically the Navy and Army), universities (principally five), diversity of scientists from a variety of fields, industry (engineering laboratories, quality control, and production facilities), amateur radio operators, ordinance experts, testing facilities, along with an unprecedented level of teamwork.[1] Further, the project had to remain top secret during the war, despite ultimately employing about 1 million people in the production effort.

([1]Author's note: today this is often referred to as cross-functional teaming)

2. Organization

Vannevar Bush foresaw the requirement to create an "effective organization for joint functioning of scientific and technical [engineers] on the one hand and military men on the other." According to author Ralph Baldwin, "Prior to WWII war, scientists and [engineers] did not sit on planning councils, and military men, in general, regarded scientists and engineers with either forebearance or contempt."
(Author's Note: In the field of Drug Discovery in the Pharmaceutical Industry, companies like Merck just began to overcome these types of difficulties in the late 1990's when sales & marketing experts were finally allowed to engage in drug discovery and development teams.)

Bush established a variety of key functions at the OSRD, including Patents & Inventions, Radar, Chemistry & Explosives, Communications & Transportation, and Armor & Ordnance. Section T of the Armor & Ordnance division (which held responsibility for the development of fuzes for Rotating Projectiles of the OSRD) was placed under the direction of a bright, but organizationally untested scientist: Merle Tuve. He proved to be not just a bright scientist, but both a brilliant motivator of a breakthrough team and a coordinator of one of the most complex scientific-military-industrial alliances ever created.

Building a team around the Applied Physics Laboratory (APL) at Johns Hopkins University, Tuve began building his alliance of scientists, engineers, military ordnance experts, university science departments, and amateur radio operators who had been experimenting with unique radio gear in the field.

The project received the endorsement of both President Roosevelt and Prime Minister Winston Churchill.

Tuve issued a set of guiding principles for teamwork, results, and speed, which he insisted be followed to make the technical development and the alliance work effectively (see box). Tuve embodied four personal characteristics:

1) moral and intellectual honesty – there was no wishful thinking

**Guiding Principles of Merle Tuve:**

Abridged and Edited

*(Items in parentheses are by RPL)*

1. **I don't want any damn fool in this laboratory to save money. I only want him to save time.**
2. **We don't want the best unit (fuze), we want the first one.**
3. **There are no private wires from God Almighty in the laboratory that I know about – certainly none in my office. (in other words, no "holier than thou" attitude, no "prima donnas")**
4. **The primary duties of any supervisor are initiative and forethought; he is supposed to make his team do the work.**
5. **Any function or area of a total job which can be described and manned should always be assigned. Articulate your work.**
6. **The trouble is always at the top. (Leaders must take responsibility, don't blame subordinates)**
7. **A good short paper in your hand at the right time and place is a marvelous hatchet for cutting through red tape.**
8. **Responsibility and Authority always have the same boundaries. This is axiomatic (a cardinal rule)**
9. **Our moral responsibility goes all the way to the final battle use of this unit (fuze); its failure there is our failure regardless of who is technically responsible for the causes of failure. It is our job to achieve the end result.**
10. **Run your bets in parallel, not in series. This is a war program, not a scientific program.** *( Author's Note: This principle was not reintroduced by engineers until the late 1980's)*
11. **The final result is the only thing that counts, and the only criterion is:** Does it work then?
12. **Shoot at an 80% job, we can't afford perfection.**
13. **The best job in the world is a total failure if it is too late.**

2) work ethic – he worked hard, pushed people hard
3) culture of dedication – he kept everyone focused on how their effort could make a significant impact on winning the war
4) sharp mind – grasping the essence of problems quickly, without getting lost in extraneous details

Vital to this project was a powerful set of *beliefs,* from the outset by all team members, that the problem could be solved. Tuve and his team leaders refused to accept the prevailing opinion of skeptics that the fuze could not be made in time to be of use in the war because of the seemingly insurmountable technical problems. After the war it was determined that the Germans had established over 50 different and fragmented teams to work on the development of the proximity fuze. Yet none of the German teams believed they could really create a viable solution, and eventually their efforts either dwindled or were abandoned.

3. Design Parameters

Development of the proximity fuze required massive leaps in technology and the interfacing of several complex technologies in order to be successful. The critical factors for the new design had to meet the following specifications:

- Massive G forces: at firing, an AA ammunition shell will suffer 20,000 G's, and possibly 3-5 times more than that. Once airborne, the shell spins at up to 250 rps (revolutions per second), creating 5,000 centrifugal G forces. Electronic Vacuum Tubes (transistors had not yet been invented) must be totally shock resistant.
- Timing: of the fuze must be sufficiently precise to trigger when within 50-75 feet of the target object.
- Safety: must be paramount to prevent premature detonation and injury to our troops
- Quality Standards: had to be higher than ever before. With 300 components in the fuze unit, quality control on each component must reach .9999 to yield a 97% total system quality.
- Miniaturization: entire system (including radio, transmitter, antenna, detonation system, energy source, safety switches) must fit into the size of the length of two cardboard toilet paper tubes. Vacuum tubes must be reduced in size from roughly the size of a pickle to the size of an eraser on a pencil.
- Shelf Life: The power-supply must operate at full power after several years of storage.
- Environmental Conditions: the system must be fully operational in $0^{o}$ cold weather and the heat and humidity of the tropics.

Under any circumstances, these would be difficult design parameters at best. Tuve and his team had multiple breakthroughs required, and the longer the delay, the more the agony of battlefield deaths. To a large degree, the air wars in Europe and the Pacific would be largely influenced by the successful development and deployment of this technology.

4. Creating the team

Beginning in 1941, Tuve began building his team centered around the Applied Physics Laboratory (APL) of Johns Hopkins University in Maryland. By summer 1942, the team had grown at APL to 200 people.

The concept of “team” dominated the organization and its operations with a very fluid hierarchy and assignments. The organization chart was changed quite frequently to prevent anyone from thinking they were frozen into a level or role on the project, especially as the project progressed from stage to stage. Informality was the rule; status was irrelevant; everyone pitched in, regardless of degree or professional standing. No one was exempt. The experience was often described as the most exhilarating and personally satisfying of all their group experiences.

Tuve liked to form teams with a high degree of field/practical experience. Fiftynine members of the scientific team were also amateur radio operators – a fraternity of people who love to experiment with new ideas in the field. A favorite team of Tuve’s was matching a PhD with an amateur radio operator.

Baldwin compared this job assignment with others he had experienced and made the observation in the following table:

| **Most R&D Jobs** | **Proximity Fuze Project** |
|---|---|
| Specific Job | Expected to contribute Ideas and Act on Ideas |
| Written Job Description | Two way flow of ideas |
| Given Specific Role | Accepted as persons, not just workers |
| Job Pre-Planned | No one Fixed on Assignment |
| Specific Performance Expectation | When troubles were encountered, prepared a dozen alternative solutions |

After the war ended in Europe in April, 1945, a team was sent by the U.S. Government to Germany to determine the extent of progress made on a number of technologies to determine how much information had been provided to the Japanese, thus providing a window into the enemy’s forthcoming weaponry. The US team was quite surprised at the poor organization and lack of progress on many technologies, having had quite a different preconception of German technological advancement. Their findings compared the US and German systems of technology development in the following table:

| **US System** | **German System** |
|---|---|
| Coordinative, Team Based, Sharing ideas across many specialties | Government Controlled, Autocratic, Hierarchical, Low Sharing |
| Staffed by the most competent people available loyal to democratic principles | Led by Incompetent, Arrogant Bureaucrats Loyal to Hitler and his political beliefs |
| Used Jewish Talent Extensively | Exterminated Jews or Drove them out of country |
| Put best scientists to use in Laboratories | Many top scientists wasted as soldiers in battlefield |

| | |
|---|---|
| Sense of Urgency and Commitment to the Cause | Little sense of Urgency or Commitment |
| Strong Belief that Technology could be transformed into inventions, such as the atomic bomb, proximity fuze, and radar. High Vision of seeing ideas through to production and deployment | Low belief that certain technologies could be made feasible in time to be of service in the war. Low vision of seeing ideas through to production and deployment. |
| High coordination between scientists, military command, and military in field | Low or no coordination between scientists and military |
| One unified effort per technical project | Many fragmented efforts per technical project |

The proximity fuze investigation team was astounded to find the Germans had scattered 43 separate fuze projects, with most producing less than marginal results. One problem was the project were organized under the Postal Service. Another was the scientists never went to the proving grounds to work with the military ordnance experts, they were simply passed test data, which was often incomplete or inexplicable. The fact that the German scientists thought manufacturing problems were too colossal for production in either Germany or the US was also a significant deterrent to success. (By contrast, the V-1 & V-2 rocket missile programs were successful because they had independence and autonomy from political/bureaucratic constraints.)

Years after the war, Tuve commented about the co-creative process used by the team:

*"One of the greatest new developments of the war … was the rediscovery of an old principle, a principle never exercised on so vast a scale as in the wartime technical activities of WWII, both on the home front and in the battle zones ….. the rediscovery of the efficiency of the democratic or collaborative principle in directing the efforts of organized groups of people, which i*s:

- Tell the group what the needs are,
- Make the goals conspicuously clear, and
- Invite them as individuals to contribute in the best way they can.

*"… a boss, using the democratic principle, does not depend on just giving orders from above. He asks his men, his workers, to participate in the efforts. … This means they help him with the whole job; they don't just do what someone else tells them to do. This system of asking people to help with the whole job was what I used in running the proximity fuze development. We were each accepted as persons, not just workers. We were interacting flexibly, but each one had a clear role to play at any one time. Nobody stayed fixed in his or her assignment, and when troubles arose we encouraged each other and proposed a dozen possible solutions. It worked so well, the whole team took hold so vigorously, that during most of the work I had to struggle hard to keep abreast of them. … The web of human ties and shared experiences was so intensive this it was difficult to analyze what was happening at the time.*

*"… The key to democratic or collaborative sharing of control [is enabling] criticism to flow both ways. Criticism and ideas come up from the workers as well as down from the bosses. This gives a tremendous advantage, by the pooling of ideas from everybody who*

*knows the details of the job. This is what the Germans failed to do. With their habitual obedience to authority, they largely denied themselves this two way flow and simply obeyed orders from higher up."*

5. <u>Innovation and Cooperation</u>

As an example of how innovation crossed specialized fields was the redesign of glass vacuum tubes to withstand the intense shock of a shell being fired. The chief designer of the mechanical structures of the new miniaturized rugged tubes was a professor of Mechanical Engineering from Columbia whose specialty was bridge design. He understood stresses, support, and other design factors that could be adapted to the miniaturized elements of vacuum tubes such as filaments, grids, cathodes, and plates. Filaments for the tubes had to be only .00075 inches in diameter, far too fine to assemble without a microscope.

Other components, such as capacitors, needed new technology to be reduced to the size of toothpicks, along with totally new equipment for its manufacture. The scale of the manufacturing required was described by James Cornell, VP of Solar Manufacturing, who stated "more tubes and capacitors were used in this project than all the other electronic projects, including radio and radar, combined."

In the area of batteries, a totally new type of battery had to be designed that was extremely small and powerful. National Carbon was the battery company that created the design breakthrough. The new battery design consisted of about 90 stacked wafers shaped like flat washers, one side being carbon, the other zinc, separated by a spacer capable of distributing electrolyte. In the center of the battery was a glass ampoule filled with electrolyte. The battery was totally inactive until the shell was fired. Upon firing, the shock broke the ampoule, and the spinning rotation spread the electrolyte among the wafers, thus starting the electrical power supply. And thus no battery deterioration while in storage. From April 1943 to January 1945, the batteries were made smaller, with better shelf life, including 6 new advances in design. A.J.Adams of National Carbon remarked about the high degree of cooperation from Eastman Kodak: "How two firms that had not worked together before could combine in a single endeavor is almost unbelievable. It went more smoothly than anybody could have imagined."

One of the essential aspects of the effort was to insure that practical scientists worked closely with both military ordnance experts and industry engineers and manufacturing specialists. Because of the high numbers of fuze units needed for production, early coordination was established between what would normally be considered competitors. Companies like Sylvania, RCA, Crosley, and Kodak where called upon to share information, engineering improvements, and manufacturing process innovations. These companies met monthly to share performance data, new quality control methodologies, reduction of rejects, and production speed improvements.

Herb Trotter of Sylvania later commented how the overall cooperation and sharing from the engineering staffs of each company went a long way to speed up production of the fuzes. Similarly, Lewis Clement of Crosley Radio Corporation, which was one of the largest producers of fuzes, perceived: "This is the greatest example of cooperation between the technical people, the manufacturing people, the suppliers, and the users. Without is cooperation, the job would never be done."

*(Author's note: This may be origin of cooperation in the electronics industry that has continued to this day and has given this industry a tremendous lead as the electronics industry evolved into the computer industry. Alliances in this industry have a long heritage, whereas in other industries, collaboration has been less intense and taken longer to develop.)*

Ultimately, almost 80% of the production of final fuze units was spread nearly evenly between Crosley, RCA, and Sylvania, with the remaindering 20% given to Kodak and McQuay-Norris.

The magnitude of the manufacturing ramp-up is noteworthy. 22 million fuze units, composed of over 300 components, were produced between 1942 and 1945. During this time the cost per unit dropped from $742 to $18. Overall, 110 plants were involved in production of the fuzes and their components without a single breach of security, resulting in neither German nor Japanese intelligence having knowledge of the technology nor its deployment.

6. <u>Technological Effectiveness</u>

Once deployed in the battlefield, the proximity fuze's effectiveness, when coupled with new radar-reliant gun directors using computers, was nothing less than astounding. Between December 1944 and April 1945, the end of the European war, the fuze was credited with shooting down 1,000 German planes. The combination of proximity fuzes, radar, and computer directors, deployed against the 400 mph V-1 Buzz Bombs in the second Battle of Britain (June-August of 1944) and later in the defense of Antwerp (December 1944), were credited for up to 90% hit rates with less than 40 rounds per hit. (Compare this to 18,500 rounds needed for far lower hit rates only 4 years earlier.)

In the Pacific theatre the proximity fuze was used defensively in Anti Aircraft fire and offensively in rockets and dive-bombers against enemy aircraft carriers, cruisers, and battleships, resulting in nearly the entire Japanese air force and naval fleet being destroyed.

The total cost of R&D and production was about $1billion (about three days of war expenditures), while reducing the length of the war by perhaps a year, according to Chief of Naval Operations, Arleigh Burke.

7. <u>Epilogue</u>

World War II was the only war in history where the outcome was largely decided by technologies that did not exist when the war broke out – atom bomb, radar, sonar, proximity fuze, computers, cryptic code breaking, etc. The war was won, not just on the basis of the production capacity of the US, but also on the Allies technological leapfrogging. The Allies simply innovated more and faster than the Axis forces.

However, the outcome could have been considerably different had the Axis powers been slightly faster in their technological innovation. Before the war ended in Europe, German jet engine technology had been transferred to the Japanese, and the first production jet fighters were just being introduced into the Pacific theatre as the Pacific war came to a close. Had the Germans continued to refine the V-2 rockets (which reached altitudes of 50 miles and speeds of 1 mile per second), the Allies had no effective means of stopping them, despite radar and proximity fuzes.

Shortly after Germany's surrender, a U-boat laden with a very large shipment of uranium bound for Japan turned itself over to US authorities. Clearly the Japanese had plans for nuclear weaponry, but we did not know the extent of their abilities.

The Japanese were also introducing their own proximity fuzes in bombs and rockets (a more stable platform than cannons). In June, 1944, the Japanese bombed an airbase on recently captured Saipan, with a single1700 pound proximity bomb, which exploded 35 feet above the airfield, destroying or damaging scores of parked B-29s, (the most advanced bomber of the time), which were to be used to begin bombing raids on Japan. Proximity fuzes were scheduled to be used by Japan in a fleet of kamikaze bombers to be launched from submarines at US cities on the west coast and the Panama Canal just a month after the atom bomb was dropped on Nagasaki. As the Pacific war ended, Japan had perfected and produced over 12,000 proximity fuzes for use in AA artillery. Fortunately there was not an opportunity to use them.

In many ways WWII was a race of technologies against technologies.

Interesting, unverified anecdote:

A General Electric executive committed an unforgiveable "goof" by leaving a top secret prototype on the table after a meeting. Recognizing the transgression, the executive raced back to the meeting room into another meeting to recover the prototype.

He was aghast to find it in the hands of another GE engineer/designer who knew how to cut the costs from $50-$60 each to a few pennies and how to mass produce them. Who was this marvel?

He was in the GE Christmas tree lights section before the war and saw how to use that know-how to build these. --Chris

## 8. Key Learnings & Principles

This is a superb example of how strategic alliances with multiple partners built a strong level of commitment and trust to underpin a massive collaborative innovation program.

- **Principle #1: People Support What They Help Create!**
- **Principle #2: Trust is the Foundation of all Collaborative Enterprise**
- **Principle #3: Sharing Expands, Hoarding Contracts.**
- **Principles 1,2,&3 enable Principle #4:Differentials in Thinking are the Greatest Source of Innovation**