When to Deploy?
The Proximity Fuse In World War Two

by

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Abstract

I consider the timing of U.S. deployment of proximity fuses for field artillery in World War Two. U.S. military leaders feared widespread deployment of shells with proximity fuses would lead to a dud being obtained by the enemy, who would then reverse-engineer a fuse. A particular fear was the use of shells with proximity fuses against U.S. aircraft---both heavy bombers attacking Germany and Japan, and attack bombers on aircraft carriers. The U.S. may have waited too long to widely deploy proximity fuses because its military leaders were unaware of the time required for the enemy to reverse-engineer proximity fuses.

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1. Introduction

By 1941 the state of the art for fuses for anti-aircraft artillery (henceforth AAA) shells and artillery used against ground forces was a *time fuse* that would detonate the shell at a preset time and location in space (Oldham, 2013). *Contact fuses* that did as the name suggests---detonate on contact---also existed. Time and contact fuses might have been sufficient for use against slow-moving bombers, but they were not effective against dive bombers used against surface vessels. Additionally, properly timed air bursts were much more effective than ground bursts when attacking infantry. Timed fuses worked poorly for airbursts (Holmes, 2020, p. 176).

By 1940 the U.S. had begun researching *proximity fuses* (henceforth PFs). The Germans had begun researching PFs in the 1930s, and had spies in the U.S. who attempted to determine what the U.S. knew about PFs. The Germans never solved the problem of the electronics surviving the blast from artillery (Holmes, 2020, pp. 23-24) .[1] The U.S. successfully tested a PF in August 1942 (Holmes, 2020, pp. 143-146). What ultimately was deployed was a fuse that used a radio signal set for a particular proximity. When the signal bounced back to the fuse, the shell detonated (Holmes, 2020, p. xiii).

The first deployment of PFs in combat was on U.S. surface ships in the Pacific in January 1943 (Holmes, 2020, pp. 156-157). After the Normandy invasion by the Allied Powers in June 1944, PFs were deployed to defend the beaches and harbors there (Holmes, 2020, pp. 220-221). In August 1944, PFs were authorized to be deployed to counter the V-1 drones Germany used to attack England (Holmes, 2020, p. 203).

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[1] The difficulty in development was to produce a fuse that could withstand the gravitational force of an artillery shell. Firing a shell produced 20,000 Gs. Launching the space shuttle only produces 3 Gs (Holmes, 2020, pp. 43-44).

In April 1943, Ralph Baldwin, one of the developers of PFs, was asked if PFs could be developed for field artillery (Holmes, 2020, p. 175). A successful test of PFs in field artillery in that month led to an order of one million PFs for the U.S. Army (Holmes, 2020, p. 176). By October of 1944, the Army had a stockpile of 1.75 million PFs for use in field artillery (Holmes, 2020, p. 262). The U.S. might have deployed PFs in field artillery at some point by fall 1943.[2] However, approval for such deployment did not occur until October 1944 (Holmes, 2020, p. 263), with the first deployment in December 1944 at the Battle of the Bulge.

Why was the deployment of PFs in field artillery delayed for one year or more when these fuses were expected to be far superior (as discussed in Section 2) to what was then in use? The answer is simple. The U.S. feared that a dud shell with a PF would be obtained by the enemy, who would then figure out how PFs worked.[3] Germany, Italy, and Japan were the three major partners in what was known as the Axis Alliance in World War II. Any member of the Axis who reverse-engineered a PF would likely have shared its finding with the other members.

The U.S. Military Joint Chiefs were reluctant to deploy PFs in field artillery after invading Europe at Normandy, France in June 1944 (Holmes, 2020, p. 262). Deployment of PFs in the Pacific was deemed to be prudent because duds would fall into the ocean. Since the Allies controlled territory several miles inland after the Normandy invasion, a dud PF shell fired at a German plane likely would have fallen into the English Channel or on Allied-held territory. Likewise, PF duds fired at V-1 drones would have fallen on England or into the English Channel.

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[2] I believe it is reasonable to assume that deployment in field artillery could have occurred six months after an order for their production was issued since the U.S. already had production facilities for PFs. Also (sub-section 2A), it took six months to produce 500,000 PFs and deliver them to the U.S. fleet. Even allowing some time for training in the setting of the fuses, a significant number of PFs should have been ready to use in Europe by autumn 1943.

[3] I do not know the percentage of shells fired in WW II that were duds. Prior to initial deployment on surface vessels in 1943, it was estimated that 15 to 20 percent could be duds (Holmes, 2020, p. 155).

Admiral Ernest King, Chief of Naval Operations for the U.S., knew the effectiveness of PFs against Japanese dive bombers in the Pacific, and did not want U.S. naval aircraft to face AAA with PFs (Holmes, 2020, p. 262). Harold H. (Hap) Arnold, commanding general of the U.S. Army Air Forces,[4] only consented to the use of PFs in England against V-1s if the AAA with PFs fired their shells over water (Holmes, 2020, pp. 261-262). With these two powerful military leaders opposed to the use of PFs in field artillery, more than a year may have passed from when such deployment could have occurred to when actual deployment began.

I discuss the development, deployment, and effectiveness of PFs in Section 2. In Section 3, I consider the expected length of the war, and when the enemy might have deployed PFs. In Section 4, I develop a simple model of the optimal timing of widespread deployment of PFs. In Section 5, I consider whether the actual deployment decision by the U.S. was optimal. Section 6 concludes the paper.

2. The development and deployment of the proximity fuse

A. Development

Germany began work on PFs in the early 1930s, and the British work on PFs began in the late 1930s (Naval History and Heritage Command, 2017). Neither country developed a workable PF, presumably because of the effect of gravitational forces on such fuses (see footnote one). The U.S. began work on PFs in 1940. The first successful use of a PF was against Navy drones in August 1942. To destroy the first drone, eighty rounds were fired. The second drone was destroyed after eight rounds were fired, and the third drone required four rounds for its

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[4] The Air Force did not become an independent branch of the military in the U.S. until 1947.

destruction (Holmes, 2020, pp. 143-146). Production of PFs began at the Crosley Corporation in Cincinnati in September 1942 (Holmes, 2020, p. 149). By March 31, 1943, one half million PFs had been delivered to the U.S. Navy fleet.

B. The Pacific Naval War

Prior to the introduction of PFs, naval gunners set time fuses. The U.S. Navy wanted PFs for AAA on their ships. An example of the problem with AAA without PFs was an attack that occurred in May 1942. The U.S. Lexington aircraft carrier was sunk by fifty-four attacking Japanese planes, only six of which were hit by AAA with time fuses.

Once PFs began to be deployed in the Pacific, their value was clear. In 1943, shells with PFs accounted for twenty-five percent of all shells fired by the U.S., but fifty-one percent of the downed Japanese planes were hit by shells with PFs (Holmes, 2020, p. 243). Apparently, the value of PFs increased over time for naval AAA. During the war, PFs may have increased the effectiveness of U.S. naval AAA by a factor of six (Oldham, 2013, p. 2) or seven (Bush, 1970, p. 109). The first use of PFs in the Pacific (in January 1943) resulted in two Japanese planes shot down, and six Japanese planes fleeing (Holmes, 2020, pp. 156-157).

C. The V-1 drone

The German V-1 drone carried a one ton warhead, and had a top speed of four hundred miles per hour. The effectiveness of PFs in AAA versus V-1s likely increased Hap Arnold's opposition to the widespread deployment of PFs (fearing their use by the enemy against his bombers). To destroy one V-1 required firing between five hundred and six hundred shells with conventional fuses. It took between forty and one hundred shells with PFs to wipe out a V-1 (Holmes, 2020, pp. 256-257). Thus, PF equipped shells were many times more lethal than shells with conventional fuses against a drone, suggesting that PFs could be a real threat to bombers flying in relatively close proximity.

D. Heavy Bombers over Germany

I will focus on the U.S. for brevity and because 1) the U.S. mainly flew in the daytime, and the British primarily flew at night (with the former more dangerous), 2) the U.S. manufactured the PFs and had to decide when and where to deploy them, and 3) the commanding general of the U.S. Army Air Forces, Hap Arnold, had an important role in said decision.

With conventional fuses for German AAA, U.S. bombers suffered grievous losses. U.S. bombers flew 718,972 missions in the European Theater of Operations, with 14,200 aircraft shot down (Davis, 2006, p. 568). Thus, about 2% of all sorties resulted in a shoot down. Air crew members shot down were not all killed or captured; some were sheltered by friendly citizens in German occupied territory. However, an allied aircraft shot down over Germany likely meant death or imprisonment for the crew.

Bombers were threatened by both enemy fighter aircraft[5] and flak from AAA. In the European Theater of Operations, the U.S. lost 44% of its bombers to German fighters, and 44% were lost to flak. For the British, 63% of bombers were lost to fighters, and 37% were lost to flak (Werrell, 1986, p. 707, fn. 12). These numbers may understate bomber losses due to AAA. As

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[5] I thank Craig Koerner for alerting me to the importance of German fighters in the loss of Allied bombers.

noted by Nijboer (2021), bombers damaged by flak left their formations, making them easier targets for enemy fighters

Bombers were vulnerable. The British estimated that it was eight times more difficult to shoot down a V-1 drone as it was to shoot down a German bomber flying in a straight line (Baldwin, 1980, p. 258). Bombing accuracy was supposed to have improved with the invention of the Norden bombsight. However, the bombsight's value was limited by several factors.[6] Also, smart weapons did not exist in WW II, so massive numbers of aircraft were used to destroy targets such as factories and refineries. For example, in August 1943, 230 bombers attacked ball bearing plants in Schweinfurt, Germany. These planes dropped approximately 2,000 bombs. Only 80 bombs (4%) hit their target. The U.S. lost 60 planes, and 552 men were killed or captured. The plant was running again in two weeks (Gladwell, 2021, pp. 101 and 104-105).

Bombers tended to fly fairly close together. Escort fighter aircraft would have a more difficult time protecting spread out bombers. Also, a positive externality existed for aircraft in close proximity. Enemy aircraft approaching one plane might not be seen by the crew of that plane, but someone on a friendly plane in the vicinity might see the attacker.

E. Proximity fuses versus ground forces.

The PF had been developed by Section T of the Department of Terrestrial Magnetism, which was part of the Carnegie Institution of Washington DC. In April 1943, Ralph Baldwin of

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[6] The bombsight was a mechanical device that was subject to thickening of its lubricating oil at the low temperatures at high altitude, causing error in the sighting. Also, an operator might be under attack from AAA or enemy interceptor aircraft, causing more error. The bombsight worked only with no cloud cover. In 1945, over Japan, U.S. Army Air Force crews discovered the jet stream, which impacted their ability to calculate their flight speed. The U.S. began to attack Japanese targets by flying below the jet stream at night, since their low altitude made them relatively easy to see in daylight (Gladwell, 2021, pp. 102-104 and 171).

Section T was asked by a member of the Army War College if PFs could be used against personnel, that is, used in field artillery. The army estimated that airbursts were twenty-five times more lethal than ground bursts against personnel, and time fuses worked poorly for airbursts (Holmes, 2020, pp. 175-176). Field artillery were authorized to use PFs as of December 25, 1944. Actual use was moved up to December 18, 1944 due to the German attack known as the Battle of the Bulge (Holmes, 2020, pp. 262 and 266).

The U.S. Army sent high-ranking officers from the Battle of the Bulge to the U.S. to learn how to optimally set PFs.[7] PFs had devastating effects on German troops at that battle. Germans in foxholes and bunkers had no protection. Shells cut through logs on top of bunkers. An airburst from one 155 mm shell could devastate an area 75 yards in diameter. Almost 200,000 shells with PFs were fired by the U.S. Army in the battle. German forces around the U.S. forces besieged at Bastogne, Belgium were slaughtered by PF shells (Atkinson, 2013, p. 460).[8] The value of the PF was so great that, had the Germans possessed such fuses, the Normandy invasion in June 1944 might not have been possible (Collier, 1999, p. 45).

3. Expected length of the war and when the enemy might deploy the proximity fuse

To know whether the timing of U.S. widespread PF deployment was optimal, one must have some idea of when U.S. military policy makers believed the war would end. As of the summer of 1943, Chief of Staff of the U.S. Army George Marshall believed that a cross-channel invasion could result in the war in Europe ending in 1945. However, Marshall feared British

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[7] One young economist who worked on statistical problems, including the timing of PFs, and who met with the officers was Milton Friedman (Olkin, 1980, pp. 322-323).

[8] German POWs did not realize how PFs worked. Some thought that shells detonated due to an igniter set off by the earth's magnetism. Others thought superior training of U.S. artillerymen was responsible for the accuracy of the shells (Holmes, 2020, pp. 266-267).

dallying could put off the invasion until 1945 (Pogue, 1973, pp. 241 and 246). In September 1944, General Dwight Eisenhower, Supreme Commander of the Allied Expeditionary Force in Europe, believed that the war in Europe could be over soon, leaving Japan to conquer (Ferrell, 1981, p. 127). Planners for General Douglas MacArthur, commander of U.S. Army forces in the Pacific, and Admiral Chester Nimitz, commander of U.S. Navy forces in the Pacific, believed (as of August 1943) that Germany would be defeated by the fall of 1944, and final operations against Japan might not end until 1948. However, George Marshall and Admiral Ernest King, Chief of Naval Operations, believed those dates were not serious. Marshall believed Japan would be defeated one year after the defeat of Germany (Pogue, 1973, p. 255).[9]

One month before the June 1944 invasion at Normandy, Marshall did not know if the invasion would succeed, if the atomic bomb would ever be developed, and if the Russians would join the war against Japan (Pogue, 1973, p. 277). By May 1945, Marshall believed that the atomic bomb might shorten the war, but he was not sure if the bomb would work, or, if it did work, if it would be enough to induce Japan to surrender (Pogue, 1973, p. 363). On the island of Saipan in July 1944, 22,000 Japanese civilians committed suicide rather than surrender to U.S. forces (Rhodes, 1988, p. 556). This act affirmed the belief that Japan would not surrender, even with mass casualties.

General Leslie Groves, in charge of the project to build the atomic bomb, said a bomb should be ready by August 1945, but there was no assurance it would work (Pogue, 1973, pp. 354-355). Hans Bethe, perhaps the top U.S. theoretical physicist, declined to work on the atomic bomb project because he believed such a bomb was not feasible (Rhodes, 1988, p. 415). Just

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[9] The planners for MacArthur and Nimitz may have understated the likely end of the war in Europe, and overstated the likely end of the war in the Pacific in order to get more resources for the Pacific theater.

days before the first atomic bomb explosion at Los Alamos, New Mexico, some at the Los Alamos Lab still thought the implosion charge of the bomb would fail (Rhodes, 1988, p. 661). In contrast, in June 1941, a panel of British scientists concluded that an atomic bomb could be ready as early as 1943 (Bhattacharya, 2021, p. 80).[10]

President Franklin Roosevelt met with allied leaders on Malta in February 1945, and stated that the war in Europe would likely end that year, but victory in Japan might not occur until 1947 (Atkinson, 2013, p. 499). From all of the estimates, I conclude that a reasonable range for when the war was expected to end was **mid-1945 to mid-1947**. The earlier date is sensible because of the possibility of Japanese surrender after the massive conventional bombing of Japanese cities. In March 1945, for example, one attack on Tokyo may have killed 100,000 Japanese citizens (Gladwell, 2021, p. 185). The latter date is consistent with the possibility the atomic bomb would not work, and if it did, would not result in Japanese surrender.

Finally, consider how long it would have taken a member of the Axis Powers to reverse engineer and deploy shells with PFs against the U.S. and its allies. Vannevar Bush, head of the U.S. Office of Scientific Research and Development, established in June 1941, convened a panel of experts in 1944 to determined how long it would take to reverse-engineer a PF from a dud shell. The panel estimated it would take at least twenty months to replicate a PF, and seven to ten months to mass produce PFs. Thus, the U.S. could expect widespread deployment of PFs to result in them being used against the U.S. and its allies in **twenty-seven to thirty months** (Holmes, 2020, p. 263).

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[10] Interestingly, U.S. officials apparently did not consider dropping an atomic bomb on Germany because they believed that a dud was more likely to aid the Germans than the Japanese in the development of the bomb (Bhattacharya, 2021, p. 93).

Bush met with Admiral Ernest King, Chief of Naval Operations, in October 1944, and presented King with the estimate for when the enemy could deploy PFs. Bush convinced King to support use of PFs against ground forces, and the U.S. Joint Chiefs approved such deployment on October 25, 1944 (Holmes, 2020, p. 263).

Assume my estimate of when the war was expected to end---mid-1945 to mid-1947---is reasonable. Given that estimate, when is the earliest date when the enemy could deploy PFs? If we use the date when the U.S. deployed PFs (mid-December 1944), and the shortest time for the enemy to deploy, twenty-seven months, the earliest date when the enemy could deploy PFs would be **mid-March 1947**. Using the longest time for the enemy to deploy, thirty months, the earliest date when the enemy could deploy PFs would be **mid-June 1947**. The mid-June 1947 date is troublesome because it implies the U.S. *may* have waited to deploy PFs against ground forces until there was almost no chance the enemy could deploy PFs, because the war would be over, which would likely not be optimal. I consider optimal deployment in the next section.[11]

4. A Model of deployment of proximity fuses

In this section, I consider a simple model of optimal deployment of PFs that could be reverse-engineered and used against the U.S. and its allies. Let ℓ = the uncertain length of time until the war ends (from when the U.S. could widely deploy PFs), $\ell \in [L_0, L_1]$, with ℓ distributed uniformly. For simplicity, let R = the certain length of time after the U.S. deploys PFs on a wide

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[11] Had the U.S. deployed PFs in field artillery in autumn 1943, it is likely only Japan would have been undefeated by the time PFs could have been deployed by the enemy. Twenty-seven months from October 1, 1943 would be January 1, 1946. The actual German surrender was in May 1945.

scale that the enemy would deploy PFs, with R known to the U.S. Let t = the time from when the U.S. is first capable of deploying PFs on a wide scale until PFs are actually widely deployed.

Note, there is no information suggesting what U.S. military leaders believed R was when the U.S. initially could have deployed PFs in field artillery, probably autumn 1943. The model developed in this section assumes the U.S. knew R in autumn 1943. The estimate of R that came from the committee set up by Vannevar Bush was not produced until a year later (in October 1944). I will discuss this point further in the next section.

Two simplifying assumptions are the following. First, I assume $t < L_0$. The U.S. actually deployed PFs on a wide scale in December 1944, and it is possible the actual date was later than the optimal date. Since I have suggested the earliest date the war could end was mid-1945, this is a reasonable assumption. Second, I assume $R > L_0$. With my estimate of when PFs could have been widely deployed---fall 1943---L_0 would then be approximately 1.75. With $2.25 \leq R \leq 2.5$, this assumption is also reasonable. Figure One illustrates the timing of the problem.

There are three per unit time costs to the U.S. to be considered. First, let c_0 equal the cost of the war to the U.S. when it had not widely deployed PFs, that is, when PFs had not been used in field artillery. An important part of cost is the loss of personnel and equipment. Let c_1 equal the cost to the U.S. when it had widely deployed PFs, and the enemy had not deployed PFs. Finally, let c_2 equal the cost to the U.S. when it and the enemy had both widely deployed PFs.[12]

I assume $c_1 < c_0 < c_2$. Clearly $c_1 < c_0$. By using PFs in field artillery, the U.S. could destroy more enemy personnel and equipment, lowering losses of both to the U.S. If $c_0 < c_2$, then the gain to the U.S. from deploying PFs in field artillery is more than offset by the use by the

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[12] Clearly c_2 depends on how many of the Axis countries would still be at war once at least one of them was ready to deploy PFs. As discussed in footnote eleven, it is unlikely the Germans would still be in the war then.

enemy of PFs against U.S. ground forces, naval aircraft attacking enemy ships, and bombers attacking enemy territory. Neither the Germans nor the Japanese had the capability of attacking U.S. forces or territory with bombers. By the time the U.S. could widely deploy PFs, the Germans did not threaten England with aircraft. Only the V-1 drone was then available to the Germans. The V-1 was not much threat as a strategic weapon. It was used to terrorize the population of England, and PFs were already deployed against V-1s. Also, if $c_0 \geq c_2$, the optimal t would be zero. Nothing would be lost from immediately deploying PFs, reducing per unit cost to c_1 until the enemy deployed PFs, and then cost would be no higher than before PFs were widely deployed. Thus, to have a problem to consider, it must be the case that $c_0 < c_2$.

Let the total cost to the U.S. from the war equal C. C has three parts. The first is the cost to the U.S. before it widely deploys PFs. This equals $c_0 t$. The second part of C is the cost to the U.S. when it has widely deployed PFs, and the enemy has yet to deploy them. Thus, first consider the expected length of time the U.S. deploys PFs. The U.S. deploys with certainty from t to L_0, plus the expected length of time the war ends from L_0 to L_1, or:

$$L_0 - t + \frac{L_1 - L_0}{2} = \frac{L_0 + L_1 - 2t}{2}. \tag{1}$$

The enemy's conditional expected length of deployment is $\frac{L_1 - t - R}{2}$, and the probability the war still occurs when the enemy deploys is $\frac{(L_1 - t - R)}{L_1 - L_0}$. Thus, the expected length of time the enemy deploys PFs is:

$$\frac{(L_1-t-R)^2}{2(L_1-L_0)}. \tag{2}$$

Subtracting *eq.*(2) from *eq.*(1), we have the expected length of time the U.S. widely deploys PFs when the enemy does not deploy them. Thus, the total cost to the U.S. is:

$$C = c_0 t + \frac{c_1}{2}\left[L_0 + L_1 - 2t - \frac{(L_1-t-R)^2}{L_1-L_0}\right] + \frac{c_2}{2}\frac{(L_1-t-R)^2}{(L_1-L_0)}\,. \tag{3}$$

In order to solve for the optimal t, t^*, I ignore any effect of t on the end of the war. Had the U.S. deployed PFs in field artillery in fall 1943, it might have shortened the war in Europe by a few months. However, the U.S. and its allies had just invaded Italy in September 1943. They did not invade western Europe and start to march towards Germany until June 1944. Immediately deploying PFs in field artillery in June 1944 might have shortened the war against Germany, which ended in May 1945. However, this would not likely affect my assumption that the earliest the war could end---against *all* the Axis Powers—was mid-1945. An earlier end to the war in Europe would not have resulted in an invasion of Japan by mid-1945.

It is possible that the latest the war could end, L_1, could be affected by t. By ignoring this effect, I understate the gain to widespread deployment of PFs, and thus overtstate t^*.[13]

Minimizing C w.r.t. t:

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[13] Deak Parsons, a naval officer who worked on the development of PFs, estimated that each month the U.S. delayed deploying PFs in the Pacific cost it 1 battleship, 3 cruisers, and 1,350 sailors (Holmes, 2020, p. 119).

$$\frac{\partial C}{\partial t} = c_0 - c_1 - \frac{(c_2-c_1)(L_1-t-R)}{L_1-L_0} = 0, \quad (4)$$

$$\frac{\partial^2 C}{\partial t^2} = \frac{c_2-c_1}{L_1-L_0} > 0. \quad (5)$$

The optimal t is when the lower cost from widespread deployment of PFs, $c_0 - c_1$, equals the probability the war continues multiplied by the higher cost if the enemy deploys PFs, $c_2 - c_1$. Solving the f.o.c. for t^*:

$$t^* = L_1 - R - \frac{(L_1-L_0)(c_0-c_1)}{c_2-c_1}. \quad (6)$$

By inspection of *eq*.(6), clearly $\frac{\partial t*}{\partial c_0} < 0$, $\frac{\partial t*}{\partial c_2} > 0$, $\frac{\partial t*}{\partial L_0} > 0$, and $\frac{\partial t*}{\partial R} < 0$. Also $\frac{\partial t*}{\partial c_1} = \{+\}(c_2 - c_0) > 0$, and $\frac{\partial t*}{\partial L_1} = \{+\}[1 - \frac{(c_0-c_1)}{c_2-c_1}] > 0$.

These results are intuitive. A larger c_0 means not deploying PFs widely is more costly, so wide deployment is sooner. Either a larger c_1 or c_2 means a bigger cost once widespread employment occurs, which implies a longer time until wide deployment occurs. A larger L_0 or L_1 means the expected length of the war is longer, so wide deployment optimally occurs later to reduce the time when the enemy could deploy PFs. A larger R means it takes longer to reverse engineer a PF, so wide deployment by the U.S. optimally occurs sooner.

5. Was deployment optimal?

In order to speculate about the optimality of the timing of widespread deployment of PFs, I assume values for the relationship between c_0, c_1, and c_2. Divide the numerator and denominator of the last term in *eq*.(6) by c_0:

$$t^* = = L_1 - R - \frac{(L_1 - L_0)\left(1 - \frac{c_1}{c_0}\right)}{\frac{c_2}{c_0} - \frac{c_1}{c_0}} \qquad (6')$$

Table One contains values for t^* depending on values for $\frac{c_1}{c_0}$ and $\frac{c_2}{c_0}$, assuming that $L_0 = 1.75$, $L_1 = 3.75$, and $R = 2.25$. When the U.S. deployed PFs in field artillery, the use against ground forces added to the use of PFs on ships (against enemy dive bombers), and against German drones.[14] If the Japanese had deployed PFs, they could have used them against U.S. ground forces, against naval dive bombers, and against heavy bombers attacking Japan. Putting aside the military damage from the drones (which was not considerable), the question is this: how costly would the use of PFs against U.S. forces have been relative to the lower cost to the U.S. from using PFs against enemy ground forces?

Suppose the enemy's use of PFs against ground forces raised the cost to the U.S. by the same amount the U.S. deployment of PFs against ground forces lowered cost to the U.S. That alone would imply $c_2 \approx c_0$. Then the use of PFs by the enemy against U.S. heavy bombers and naval dive bombers raises c_2 so that $c_2 > c_0$.

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[14] Over 10.000 V-1s were launched at London. Almost 2,400 were launched against Antwerp after it became an Allied port (Holmes, 2020, p. 268). The faster V-2 rocket was almost impossible to shoot down. About 1,300 V-2s were fired at London, and hundreds were fired at Allied forces in Europe (Hollingham, 2014).

Consider rows three, six, eight, and nine in Table One (shown in bold italics). In those examples, c_2 exeeeds c_0 by more than twice the amount that c_1 is lower than c_0, roughly suggesting that the use of PFs by the enemy against U.S. aircraft was more than twice as important than the U.S. use of of PFs versus ground forces. If that were true, then a value of t^* close to one is plausible.

However, it is not clear that the effect of PFs on the cost of the war was that much larger for airplanes than it was for ground forces. Anecdotal evidence form the Battle of the Bulge suggests PFs were highly effective when used in field artillery. If the impact on the cost of the war was comparable for airplanes and ground forces, we have a situation like that in rows five and seven in Table One. There we have either a 10% or 20% (row seven and row five respectively) reduction in cost when the U.S. widely deploys PFS, and an identical increase in cost (versus no widespread U.S. deployment of PFs) when the enemy deploys PFs. In those cases it would have been optimal to wait six months to widely deploy PFs---about one half ot the time the U.S. actually waited.

Also, the U.S. approved the widespread deployment of PFs immediately after Admiral King was informed of the estimated time for the enemy to deploy PFs. It seems unlikely that this immediate deployment happened to be optimal. It is more likely that the U.S. military realized that they were past the time when they should have deployed PFs versus enemy ground forces.

6. Conclusion

Proximity fuses (PFs) were authorized for use in field artillery against ground forces in October 1944. It was then that Vannevar Bush met with Admiral King, Chief of Naval

Operations, and told him the scientific estimate of how long it would take the enemy to reverse-engineer and deploy shells with PFs. Unfortunately, there is no information about the U.S. military's prior belief about how long it would take for the enemy to field shells with PFs after obtaining a dud U.S. shell. The U.S. approved the widespread deployment of PFs soon after Admiral King was informed of the estimated time for the enemy to deploy PFs.

Might the U.S. have waited too long to widely deploy PFs? It appears that U.S. military leaders had no good information on the time required for the enemy to reverse-engineer PFs until October 1944. These leaders may well have underestimated the time required for the enemy to deploy PFs.

The PF was viewed by some as the greatest scientific achievement of World War Two, except for the atomic bomb (Atkinson, 2013, p. 459). The development and deployment of PFs have received little attention. An exception is the recent book by Holmes (2020). Holmes exhaustively covers the development of PFs. However his discussion of PF deployment is almost entirely focused on PF use versus German V-1 drones. More attention should be given to the use of PFs against enemy forces, which I have considered in this paper.

Figure One.

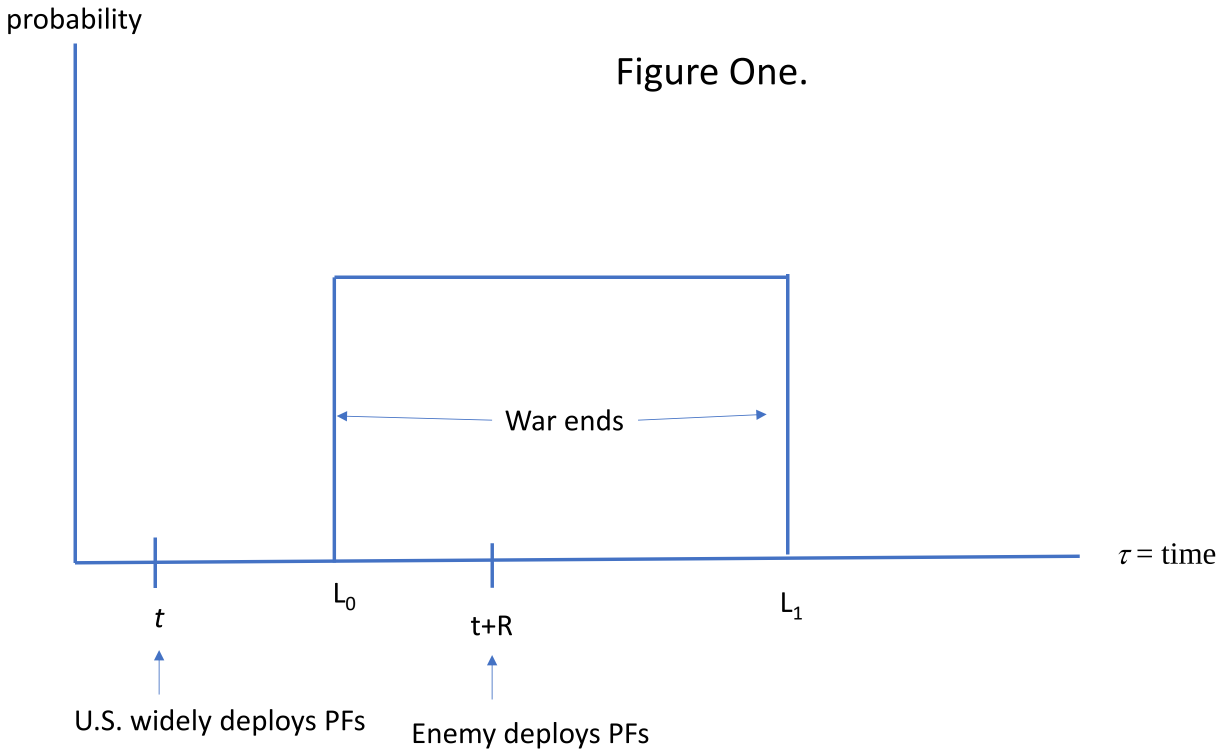
probability
War ends
τ = time
t
L0
t+R
L1
U.S. widely deploys PFs
Enemy deploys PFs

Table One. Optimal time, *t**, to wait until wide deployment of PFs by the U.S.

c_1/c_0	c_2/c_0	t^*
.75	1.1	.071
.75	1.2	.389
.75	***1.5***	***.833***
.8	1.1	.167
.8	1.2	.5
.8	***1.5***	***.929***
.9	1.1	.5
.9	***1.2***	***.833***
.9	***1.5***	***1.167***

Note. For the table it is assumed that $L_0 = 1.75$, $L_1 = 3.75$, and $R = 2.25$.

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