Crystal Clear

THE STRUGGLE *for* RELIABLE COMMUNICATIONS TECHNOLOGY *in* WORLD WAR II

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Communications Technology
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ALBANY, NY

INTRODUCTION: *"WE WERE HEAVILY ARMED, AND WE HAD CRYSTALS"*

Private First Class Irwin Gottlieb joined his unit in France on June 9, 1944. Trained as a machine gunner, he was assigned to the First Reconnaissance Cavalry Troop of the First Infantry Division. From D+3 till VE Day, Gottlieb and his unit saw almost continuous action, often miles ahead of the rest of the division. It was not uncommon for German troops to avoid contact with the 30-man troop, possibly confusing them for the head of a much larger armored column or, at the very least, hoping to prevent disclosing their position to the recon unit. Firefights did erupt, however; Gottlieb himself was wounded during the last days of the war. In later life, when asked how his unit defended itself against often-times much larger German units, Gottlieb would invariably reply "we were heavily armed, and we had crystals."[1]

Being "heavily armed" is easy to understand: with an assortment of .30- and .50-caliber machine guns, 37-mm cannon, and 60-mm mortars, they could give as good as they got. The meaning of "and we had crystals" is not quite as obvious. What he meant by this was that his unit possessed quartz crystal-controlled radio equipment. The saga of how such equipment came to be regarded by a front-line combat veteran as a weapon as vital to survival as machine guns and mortars is the object of this work.

What made their radio equipment such a powerful weapon were the quartz crystal units that controlled their transmitting and receiving frequencies. Comprised of little more than a fingernail-sized wafer of quartz, these crystal units provided the operating stability that ultimately allowed instant and

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dependable radio communications to be taken for granted by the men in the fields, the tanks, and the airplanes.

Though the outward appearance of the quartz crystal unit suggested a very simple device, their manufacture required methods of exacting standards and extreme precision. So much so that prior to WWII they were produced one at a time, by hand, in a small number of companies across the country. The entire output of the crystal "industry" in 1941 was only 100,000 units. However, by the end of the war, a full-fledged industry numbering nearly 150 manufacturers was turning out over two million units *per month*.

Quartz crystals went from a 19th-century scientific curiosity to the focus of a massive military and industrial program during the Second World War. The largely untold story of this transformation is one of science and technology and the problems of peace-time military planning. It deals with the conflict between the established arms of the military and the rapidly evolving and expanding ones born of the First World War. It involves unprecedented cooperation among and between various government agencies, independent branches of the military, and private industry in order to design, build, supply, and support a wartime mass production industry where none had existed prior to the attack on Pearl Harbor.

In this book, the story of the quartz crystal industry is divided into five sections. The initial section serves as an introduction; covering the history and the science of the piezoelectric effect of quartz, its use in radio electronics, and the ultimate acceptance of this mode of frequency control by the U. S. Army Signal Corps, the branch of the Army with overall responsibility for communications and its corresponding technologies. Sections 2, 3, and 4 address what I refer to as the "Three Crises." The first is the crisis brought on by America's abrupt entry into the Second World War. Suddenly faced with enormous needs for reliable military communication equipment, the country had no mass production industry to produce the crystal units needed for frequency control. Worse still, there existed no mass production techniques or equipment to be utilized even if an industry could somehow have been conjured up immediately from thin air. Being the primary agency involved with the development of new communications technologies, the solution to this problem fell to the U.S. Army's Office of the Chief Signal Officer.

The second crisis involves the problem of supplying the crystal industry with the unprecedented amounts of raw quartz needed for manufacturing the crystal units. The only sources of "radio grade" quartz available during the war were within the interior regions of Brazil. Defined by Congress to be a "strategic and critical" material, the problems of how to increase the production, purchase, and transport of quartz to the United States were faced primarily by the departments of the Executive Branch of the civilian government. The third crisis came about after it appeared that the first two had been overcome by the Signal Corps and the government. It had to do with something known as the "Aging Problem," an inevitable failure of the crystal units

due to the manner in which they were manufactured. Representing a communications research and development challenge, the solution of this problem came primarily from those most experienced in this field, the scientists and engineers of the Signal Corps laboratories.

The final section of the book attempts to put the story of the quartz crystal unit into context with much better-known industrial and scientific contributions to the war effort. In terms of rapid industrial growth and dramatic increases in output, this story is not unique. A great many industries (such as aircraft and ship manufacturers) grew in size during the war. A great many other sectors of industry (such as the automotive industry) retooled their plants for the production of war materiel. Completely new industries (particularly the synthetic rubber industry) were created in this country by scientists, engineers, and industrialists where none had existed before. What is truly unique about the crystal industry is that it was *invented from scratch*. There was no mass production industry to expand. To enter the crystal business took much more than a simple "retooling" of manufacturing plants; in early 1942, no one really knew *how* to mass produce crystal units. Even the synthetic rubber industry, essentially a new entity in the United States, was built along the lines of existing programs in other countries. No such blueprints existed for the quartz crystal industry.

The complete story of this wartime effort has never been told in any unified way. Though a handful of reports and conference presentations have been produced that recount the history of particular groups involved with the quartz crystal industry, this book, based on hundreds of primary documents, correspondence, and interviews, is the first to attempt to portray the entire enterprise.

This story more than anything else is one of invention. At its heart, this book is about the quartz crystal oscillator, a product of pure research that was almost instantaneously embraced by the amateur radio community. However, the invention theme encompasses much more of the story. It also involves the inventiveness of the early pioneers of the crystal industry, developing the tools and techniques needed to manufacture the crystal units. It includes the work of the Signal Corps and the U.S. government to invent a mass production industry for an item whose crucial importance to the military was never fully realized until the war began. The new methods of business cooperation and the ways of confronting the age-old problems of supply and demand that were developed with respect to the crystal industry can also be considered inventions. Overall, this is a story of an interconnected web of inventors (scientists, industrialists, basement hobbyists, and military administrators) and inventions (material objects, techniques, and ideas). The overall success of this wartime program can quite possibly be linked directly to the fact that it essentially had no history; no previous modes of thought and action that could inhibit the free-thinking and inventiveness on the part of the participants.

This book aims to show that the crystal program played just as important a role as radar or the atomic bomb in terms of its scientific and engineering

contributions to the war effort and as any other sector of industry in terms of its rapid response to the challenges brought on by the war. Furthermore, the development of a mass production industry for quartz oscillators during WWII had far-reaching effects on late 20th-century technology and society. Today, nearly everything that requires some type of timing or frequency control depends on a quartz oscillator. This includes cell phones, color television, computers, watches and clocks, wire-based multisignal telephone technology, and many other items upon which our modern society depends. In fact, it can be argued that the move toward crystal control, with its reliance on a truly 20th-century, solid-state technology, presaged society's coming dependence upon the transistor and the integrated circuit and marks the very beginning of the evolution from an analog to a digital world.

"Pass not the shapeless lump of crystal by,
Nor view the icy mass with careless eye:
All royal pomp its value far exceeds.

And all the pearls the Red Sea's bosom breeds,
This rough and uniform'd stone, without a grace,
Midst rarest treasure holds the chiefest place."
                                        Claudius, 14 AD[2]

"We have faith that future generations will know that here, in the middle of the twentieth century, there came a time when men of good will found a way to unite, and produce, and fight to destroy the forces of ignorance, and intolerance, and slavery, and war."
                                        Franklin Delano Roosevelt

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FROM WIRE TO WIRELESS: THE DEVELOPMENT—AND ACCEPTANCE—OF TACTICAL RADIO

Ultimately, the argument came down to one inescapable fact: you just couldn't run a telephone line to a tank or an airplane and have them do what they were designed to do. Like it or not, by 1940, tactical radio was a military necessity. This change in communications doctrine took place very slowly during the interwar years of the 1920s and 1930s and paralleled the development of two military branches spawned by the previous war: the Air Corps and the Armored Forces. As the usefulness and importance of these two branches increased in the eyes of the nation's military leaders, so did the attention to their needs. Primary among these needs was dependable, *mobile*, communications technology—radio.

Radio saw very little use in World War I; wire, both telephone and telegraph, was the primary medium of communication, supplemented by runners, motorcycle messengers, and carrier pigeons. This arrangement still dominated Signal Corps planning on the eve of the Second World War. It is sometimes said that the military always prepares to fight the *previous war*, never the next one. In terms of the Signal Corps during the years between the World Wars, this seems very true. It is difficult, however, to really blame them. The primary charge of the Signal Corps was to develop the communications equipment needed for the next conflict and have it ready and available whenever that conflict should break out. Essentially, they were expected to predict the future, and such predictions are usually based on the past. In the previous war, the ground forces fought on nearly stationary fronts. *Mobility*, if it could

be claimed at all, usually meant movements parallel to the front lines, not across. Thus, wire and cable were the perfect technology upon which to build a communications system stretching from the rear areas "all the way to the barbed wire."[1]

With a nod toward a possible increase in mobility, the Signal Corps of the 1920s and 1930s concentrated on ways of laying wires faster, on the development of cable and amplification methods for longer distance transmission, and on improved field telephones and switchboard equipment for front-line units. Radio, if it were to play any tactical role, would be seen as a "stand by" or emergency piece of equipment.[2] Again, it is hard to fault the Signal Corps for this mind set due to the many benefits of wire: it had a long established history, it had proven its usefulness in battle, there had been time for the Signal Corps to work out the problems that had surfaced during the previous war, and it was familiar—it did not take a lot of training for someone to be able to pick up a conventional telephone and talk into it. The U.S. military was by no means the only one to view radio in this manner. The 1935 edition of the British Army's *Field Service Regulations* included no mention of radio whatsoever and the 1934 declaration of Germany's chief tank tactician, Heinz Guderian, of his desire to lead his tank divisions "from the front, by wireless" was regarded as "nonsense!" by his superiors. Guderian's ideas were vindicated, however, in both the invasions of France (where only one in five French tanks was supplied with radios) and of Russia (where only battalion commanders' tanks were so equipped).[3]

The communications picture for the Air Corps was a lot clearer; as wire obviously was not an option, radio had to be utilized. Much of the early Signal Corps research and development work carried out with regards to radio was geared toward airborne sets. Evidence of the importance of this work is the creation in 1927 of the Signal Corps' Aircraft Radio Laboratory (ARL) at Wright Field in Dayton, Ohio, placed in charge of development and testing of new airborne radio equipment.[4] In some ways, even this was seen as a compromise on the part of the Signal Corps. While still considering radio of secondary interest, it did not want to lose complete control of its development to the rapidly expanding Air Corps. Though the Signal Corps prevailed in its dominance over radio research and development, its association with the Air Corps was less than comfortable (with the Air Corps accusing the Signal Corps of "slow and unimaginative" research and development, and the Signal Corps constantly on the lookout for challenges to its turf from the Air Corps).[5] The work continued in spite of these difficulties until, by 1936, it could be claimed that all Army war planes were fully equipped with radio technology.[6] In fact, a large proportion of the Signal Corps' 1937 appropriation of $5.6 million went toward the needs of airborne radio.[7]

The struggle for improved communications was much harder for the ground forces. As discussed above, wire-based communications were a proven concept for ground warfare and, in the opinion of the Signal Corps, only needed to be strengthened; radio did not figure prominently in the Signal Corps' plans

for the next war.[8] Opposition to this point of view came primarily from the newest ground arm, the Mechanized Cavalry (later to be known as the Armored Forces). Armored tanks had been developed in the last years of the previous war for the express purpose of reintroducing cross-front mobility. Some way had to be found to break out of the trenches and move toward *and beyond* the enemy's positions; the tank had held this promise. During the 1930s, a new doctrine began to emerge that placed a greater emphasis on both mechanization and mobility, with the armored forces serving as spearheads of rapidly moving campaigns. This new doctrine could not be expressed within the Signal Corps communications model. Along with needing constant communications among the armored units and their support troops, a rapidly advancing column would surely outrun its wire-based communications (examples of this will be discussed in Chapter 3).[9]

A third military entity to play a role in the development of a tactical radio doctrine was that of the anti-aircraft batteries and the Air Warning System. With the increased speed of aircraft, it became essential that a method of early detection and warning of approaching aircraft be developed. In this regard, the Signal Corps played perhaps its most famous role: that of the development of radar. However, radar only answered the need of early detection; word still needed to get out to the defensive batteries and pursuit plane airfields, and that word would travel by wire. At work in all of the military planning of the interwar period was the isolationist sentiment strongly entrenched in the country. Any future war, it was said, would surely be a war for the defense of the American homeland. The nation was through with foreign wars, especially those started by the Europeans. Thus, plans for aircraft warning and defense only dealt with the coastal regions of North and Central America; a very extended region, but one that held the benefit of well-established communications systems. In any future war, it was believed by war planners, the military would be able to take advantage of the nation-wide system of wire-based communications.[10] In fact, in terms of an aircraft warning system, the public telephone and telegraph utilities were expected to play a prominent role. Throughout the 1930s, exercises were held in which these utilities and their employees took part. Though the response times for aircraft warnings were not as good as had been hoped for (up to five minutes from detection to alert in some cases), the utilities saw them as a success and called for government assistance in increasing the sizes of their companies in the name of national defense.[11]

Though of dubious success, these exercises only demonstrated the effectiveness of the communications systems in those areas (the East Coast and coastal Southern California) where the population density called for extensive networks. Maneuvers carried out by ground forces during the 1930s in such underpopulated parts of the country as Texas and Louisiana pointed out the potential problems of operating in areas without extensive commercial resources. Early in the decade, these maneuvers only seemed to prove the point being made by the Signal Corps: research and development work needed

to be concentrated on ways to improve the means of a ground force for setting up its own wire-based system when operating in territory lacking sufficient resources. However, as the decade wore on, and the armored forces began to steer military thinking toward the twin goals of mechanization and mobility, the roles of radio and wire, in the minds of the ground forces, began to reverse. By 1940, things had pretty much come to a head due to two primary factors: the failures of wire technology and the successes of radio in the 1940 summer maneuvers in Louisiana, and the advent of FM radio technology.

By 1940, the picture of what the next war would be like had become much clearer. The German air force, utilizing the Spanish Civil War as a training exercise, had demonstrated the close cooperation possible between air forces and mobile ground forces. Hitler's rapid conquest of continental Europe during 1939 and 1940 laid to rest any remaining doubts as to the importance of mobile forces interconnected through radio. In May 1940, 60,000 U.S. troops were assembled along the Sabine River of Louisiana for maneuvers that, more than any other, would focus on the mobility needed in modern warfare and also, more than any other, would point out the serious shortcomings of wire-based communications.[12] Even though the area did possess commercial resources, communication between units was hampered. Field wire failures were many; some due to the amount of vehicle traffic rolling over the wires, some due to rainy conditions, and some due to the preference shown by farm animals for their apparently tasty insulation. It appears that some types of insulation were preferred by cows and others by pigs; a Signal Corps lieutenant jokingly suggested that the type of wire used in a particular area be dictated by the type of farm animals present.[13]

Still, there were those in the Signal Corps who held to the wire-over-radio status quo, if for no other reason than in the interest of military secrecy. Wire-based communication, many Signal Corps officers believed, was secret (see Chapter 3 for counterexamples of this). Radio, however, was out in the open for anyone to receive. Radios in the hands of the common soldier, especially those capable of sending voice transmission, were quite possibly "more dangerous than useful."[14] Be that as it may, in the minds of those whose job it would be to use the radios in combat, it was high time for a change. And, ultimately, the Signal Corps was forced to make this change, in large part due to its own developments in the areas of frequency control and FM radio.

Perhaps the most important detail in radio technology, whether for transmitters or receivers, is frequency control, i.e., how the radio is constrained to transmit on, or receive, the particular frequency of interest. Distilled to its most basic concepts, a radio works because the electrical current within a particular part of its circuitry is oscillating. The frequency at which it is oscillating determines the transmitting or receiving frequency. All things in nature that are able to oscillate (i.e., vibrate) possess what is known as a *natural* or *resonant* frequency. Left to its own devices, this is the frequency at which an oscillating system will vibrate; a violin string, for instance, will vibrate at its natural frequency when plucked and will therefore give off its

characteristic musical tone. Just what the natural frequency of the system is depends on its physical characteristics. For an object oscillating at the end of a spring, it depends on the stiffness of the spring and the mass of the object. For a simple pendulum (or, approximately, a child on a playground swing), it depends on the length of the pendulum. For a violin string (or that of any other stringed instrument), it depends on the thickness and the length of the string.

No matter what the physical system, if it can oscillate, something about it determines its natural frequency. Electronic circuits are no exception. Perhaps the simplest type of oscillating electronic circuit can be constructed from a capacitor, an inductor, and a resistor (available for pennies at any electronics store). A capacitor is an energy storage device. By "condensing" positive and negative charges on opposing metal plates separated by an insulator, energy is stored in the electric field existing between the plates. Capacitors only allow current to flow when they are either charging (collecting charges) or discharging (releasing charges). Thus, a completely charged or a completely discharged capacitor will stop the flow of current. Under alternating currents of high frequency, a capacitor is never allowed to charge or discharge very much, thus offering little "resistance" to the current flow. An inductor is little more than a coil of conducting wire. However, it has the ability to store energy within a magnetic field generated by rapidly alternating currents. In opposition to a capacitor, it only allows alternating current to flow easily when the frequency of the current is low. A resistor is a component that dissipates energy from the circuit as current passes through it, regardless of which direction or at what frequency that current is traveling. How easily current flows through a circuit containing all three of these components depends upon their mutual interaction. It turns out that current flows best through such a combination of components at one particular frequency: the resonant frequency. Thus, in this respect, alternating electric circuits behave exactly like all other physical oscillators.

Used within a radio circuit, this simple combination of electronic devices determines the natural oscillating frequency of the radio, and therefore controls its transmitting and receiving frequency. Should the physical conditions of an oscillating system change, its frequency of oscillation will change (a fact learned by most children around the age of three years old when they learn to swing by themselves by "pumping" their legs). The electrical characteristics of the capacitors, inductors, and resistors in a simple radio circuit depend on such things as temperature and humidity. Thus, a radio based on this type of simple circuit will change its frequency as it heats up or cools down, or as the weather conditions change. Throughout the first third of the 20th century, efforts at *stabilizing* the frequencies of radio were carried out. By the late 1930s, two primary frequency control options existed: the master oscillator concept (based on the previously described combinations of electrical components) and a radically different technique known as quartz crystal control.

A great deal of progress was made in oscillator technology in the years approaching the Second World War. Primary among the goals of radio engineers was a method of eliminating, or at least compensating for, the drift in frequency due to changes in temperature. Special circuits were developed to compensate for this "thermal drift" in the tuning circuits. In other cases, the tuning components were manufactured from materials found to be relatively unaffected by temperature changes. One other option was to enclose the entire oscillating portion of the circuit within a constant-temperature oven. Furthermore, the oscillating portions could be isolated or buffered from the effects of the surrounding circuit by use of amplifiers. These "master oscillator power amplifier," or MOPA, sets were admirably stable, provided they were given a nominal 20 minutes to warm up and come to thermal equilibrium. They also offered the benefit of an almost unlimited number of frequencies at which they could function; tuning being accomplished by adjusting the variable components within the tuning circuit. They were far from perfect, however, as will be discussed in detail in the following chapter (for instance, they could be nearly impossible to tune while in a moving tank, jeep, or armored vehicle).

The other primary option for frequency control during the pre-war years was the use of quartz crystal oscillators, also known as quartz crystal units (QCUs). The QCUs were composed of thin wafers of quartz crystal placed between metal plates (which served as electrodes). By virtue of the piezoelectric (pronounced *pie—ezo—electric*) effect, quartz behaves as a natural oscillator when placed within an electric circuit, with the natural frequency of the quartz wafer governing the oscillating frequency of the circuit. The generation of electrical "polarization," or voltage, through mechanical deformation is known as the direct piezoelectric effect and was discovered by Jacques and Pierre Curie in 1880. A household application of this effect can be found in some types of lighters used to start fires in grills or fireplaces. When the trigger of the lighter is pulled, pressure is placed on a small piezoelectric crystal, producing the needed voltage (sans batteries) to power the starter. Piezoelectric crystals, particularly quartz, are also used in pressure-sensing devices. Changes in pressure lead to changes in the induced voltage across the crystal, which is monitored electronically. Such devices prove to be extremely sensitive and physically robust instruments. The converse piezoelectric effect, predicted by G. Lippmann in 1881 and later observed by the Curies,[15] is physical deformation due to the application of a voltage across the crystal (such as by placing it in an electric field or within an electronic circuit). This physical deformation can take the form of a bending, shearing, or torsion (twisting).

Piezoelectric crystals are quite common; of the 32 known classes of crystals found in nature, 20 of them exhibit piezoelectric properties.[16] Of these 20 classes, quartz is by far the most suited for electrical oscillator use, having the best combination of piezoelectric along with electrical, mechanical, and thermal properties. Extreme hardness, for example, is just one physical prop-

erty required of piezoelectric oscillators; oscillating at 100 MHz (i.e., 100 million oscillations per second), a point on the surface of a crystal oscillator is undergoing accelerations several million times that of the acceleration of gravity (several million "g's" in fighter plane parlance).[17] Substances of lesser internal strength might very well fly apart under such conditions.

The piezoelectric effect results primarily from the disturbing of the precisely ordered planes of atoms within a crystal. Electrically neutral when in an undisturbed state, the displacement of the atomic planes leads to polarization of electrical charge within the crystal (i.e., a separation of the more positively charged atoms from the more negatively charged ones) and the production of an electrical "potential difference" or voltage between opposite faces of the crystal. In the converse effect, the atoms within the crystal physically move to realign themselves with an externally imposed electric field. The particular movement of the atoms depends on the characteristics of the electrical field. Reversing the polarization of the field (i.e., making the positive direction negative and the negative direction positive) results in a similar reversing of the internal structure of the crystal. An electric field that continuously switches its positive and negative orientation will result in the crystal constantly realigning its internal structure (a physical oscillation of the crystal).

As discussed above, all physical oscillators display preferences for particular manners and frequencies of vibration. Oscillators vibrate most efficiently and with the greatest amplitude when in these "resonant modes." Consider a quartz wafer placed between two electrodes and incorporated into an electric circuit (such a configuration would be referred to as a quartz resonator). The presence of an alternating voltage will cause physical oscillations to occur within the wafer (through the converse piezoelectric effect). These physical oscillations, however, will lead to the generation of an alternating voltage across the wafer (through the direct piezoelectric effect). Thus, the wafer can act as a conduit for the voltage signal propagating through the circuit. However, the efficiency of this transmission depends greatly on the frequency of the imposed voltage. If the frequency of the alternating voltage is far removed from the natural or "resonant" frequency of the crystal, the oscillations of the wafer are extremely weak and the quartz acts much more like an insulator, impeding the transmission of the signal. When the frequency of the signal is at or very close to the resonant frequency of the crystal, the wafer's oscillations are at a maximum and the signal is transmitted very effectively. Thus, the crystal serves to control the frequency of the oscillator, only permitting it to oscillate efficiently at the resonant frequency of the crystal.

Academic research involving quartz crystals as frequency control devices had been carried out for some years before World War II. As a student at Wesleyan University during the 1920s, Karl Van Dyke was involved in research on crystal oscillators. Due to the manner in which quartz oscillators reacted to alternating voltages and currents and how they stored and dissipated energy, Van Dyke concluded that their electronic characteristics could be

described in terms of an "equivalent circuit" composed of two capacitors, an inductor, and a resistor. This equivalent circuit (the diagram of which is shown in Figure 1.1) allowed electrical engineers to easily determine the effects of placing various oscillators into radio circuits and enabled them to design oscillators to have just the types of characteristics needed.

The resonant frequency of a quartz wafer depends primarily on its physical dimensions. In the case of the shear mode of vibration, the most important dimension is the thickness. The thicker the wafer, the more mass and inertia the wafer possesses. Thus, a thicker wafer will vibrate more slowly, or with a lower frequency, than a thinner wafer. To produce a crystal oscillator of a particular frequency, the wafer must be ground to a very precise thickness. In order to create a resonator, slabs of quartz are initially cut from a "mother crystal" and then sliced into relatively thick wafers (millimeters thick), usually with diamond-tipped saws. "Blanks" are then diced from these irregularly edged wafers using a trim saw and then squared using a diamond-impregnated grinding wheel.[18] Blanks are then "rough ground" (or "lapped") to near the final thickness (often within 0.4% of the desired frequency).[19] Ultimately, it was determined that a three-stage lapping procedure, each stage utilizing a finer grade of abrasive than the one before, worked best.[20]

The final lapping steps needed to bring the blank to the desired frequency are referred to as "final finishing." Though the rough grinding can be done by machine, the final lapping is done by hand, moving the blank around a grit-coated glass plate with a fingertip.[21] As the frequency response of the crystal blank is extremely sensitive to its mass, only a tiny amount of surface quartz may be needed to be removed during the final finishing step to bring the blank to the proper frequency. If too much quartz is removed, the frequency of the blank will be too high (and may now be worthless to the manufacturer). Once a blank is finished to final frequency, great care has to be taken to maintain the cleanliness of the blank. Any foreign material (including oil from the finisher's skin) would add mass back to the blank and lower the oscillating frequency. The production of crystal oscillators was an activity requiring a high degree of precision, accuracy, and attention to detail.

Once ground to final frequency, the crystal blank would be cleaned, dried, tested for activity (a measure of its ability to vibrate), have its frequency double-checked, and then be placed within the "holder." The holder was designed to both protect the crystal blank and allow it to be incorporated into
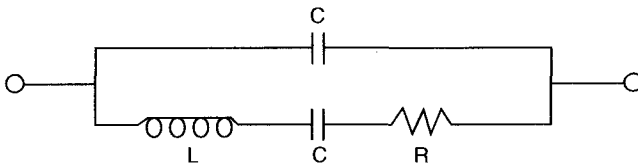
Figure 1.1. The equivalent circuit of the quartz oscillator

the radio for which it was designed. Most World War II–era holders were molded of material such as Bakelite and included two plugs or pins that allowed them to be connected to the electric circuit within the radio set. Though quartz crystal units came in a wide variety of sizes and shapes, two of the most common ones will be described here. The first, the FT-243 used in most vehicular radio sets, was small; approximately 2 cm wide, 3 cm long, and 1 cm thick (see Figure 1.2). The metal face plate of the unit carried the essential information of the oscillator: the unit type, the frequency in kHz (kilocycles during the World War II era), the manufacturer, and the unit's serial number. Most face plates also contained a space for the noting of a channel number, but, as this applied to the particular operating scheme of the military unit utilizing the QCU, this information was not always included.

The face plate of the FT-243 was held on by three small screws passing completely through the unit from front to back. Under the face plate, a small gasket served to protect the interior region from water and other foreign
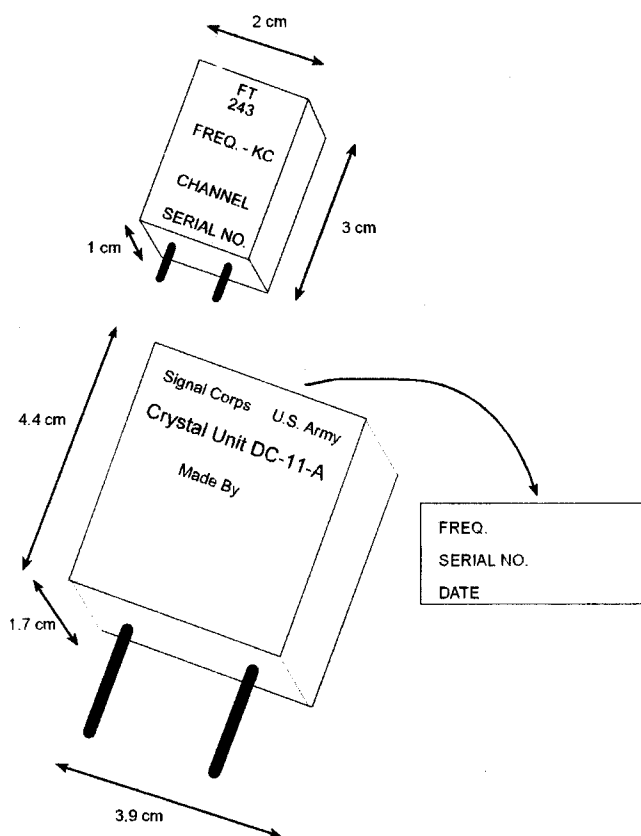
Figure 1.2. Crystal holders FT243 (*top*) and DC-11-A (*bottom*)

material. Beneath the gasket was a spring-like mechanism that also served as an electrode (connected to one of the holder's pins with copper wire). A similar mechanism, connected to the other pin, was soldered to the back of the holder. Between the two spring electrodes was the quartz blank or "plate," sandwiched between two metal plates. One of the metal plates was machined so that it only contacted the plate at its center and corners (thus leaving the remainder of the plate free to vibrate). The quartz plate itself was a rectangle 1.5 cm by 1.2 cm and 0.33 mm thick.

The other commonly used crystal unit during World War II, the DC-11-A used in most crystal-controlled aircraft radios, was of similar design. It was larger than the FT-243; 4.4 cm long, 3.9 cm wide, and 1.7 cm thick (see Figure 1.2). The unit also differed in that the unit type and manufacturer information were printed on the front, but the frequency and serial number of the unit were stamped into a metal plate at the top. Below the metal plate (held on by two screws) were two more screws that allowed the top of the unit to be opened. A spring-like piece of folded metal held the metal-quartz sandwich tight against the front of the holder. The front and back of the holders consisted of smooth metal plates serving as electrodes, connected to the holder's pins. The quartz plate of the DC-11-A was square, 1.8 cm on a side and 0.31 mm thick. (See plates for images of assembled and disassembled units, including the FT-243 and the DC-11-A.) Deceptively simple in their design and construction, nevertheless, quartz crystal units presented some of the most difficult manufacturing challenges of any wartime commodity.

The ability of a system to maintain its oscillations is oftentimes a very important characteristic. Oscillating systems are often described in terms of their energy losses utilizing a term known as the "Q factor" (defined as the total energy stored in the oscillator divided by the energy lost during each oscillation cycle). An efficiently oscillating system (one possessing a high Q value) is one that suffers little energy loss. On the other hand, the oscillations of an inefficient, or low Q, system damp out fairly quickly. It is not unusual for quartz crystal oscillators to have Q values ranging from hundreds of thousands to millions (compared with, say, a piano string, which might possess a Q value of only a few thousand).[22] In practice, this means that the frequency of a radio utilizing a crystal oscillator for frequency control suffers almost no drift in its operating frequency. This characteristic alone made quartz crystal units immediately popular with amateur radio enthusiasts when they arrived on the commercial scene during the mid-1920s.

Quartz crystal units had serious drawbacks, however. First, the raw quartz from which radio oscillators could be produced was rare; the primary source of radio-grade quartz was the remote Minas Gerais region of interior Brazil. Whether sufficient quantities of raw quartz could be obtained in time of war to supply the military with the oscillators it would need was the single-most problematic issue facing the Signal Corps in its pre-war frequency control deliberations (it is also the topic of Chapters 6–8). Secondly, though crystal

control offered unparalleled frequency stability, it restricted a radio to a single frequency; to change to a different frequency, a different crystal unit had to be plugged into the radio.

For the Signal Corps in the last years before WWII, the question was this: whether to accept the master oscillator method of frequency control or to gamble everything on the greater stability and ease of operation provided by quartz. One offered a "known" and easily manufactured technology but did not allow for the mobility the ground forces desperately needed. The other gave impressive stability and "push-button" tuning yet might be impossible to mass produce in time of war. The decision of which technology to use would have great implications for the entire war effort.

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CRYSTAL CONTROL—THE GREAT GAMBLE

The use of quartz for radio frequency control had a long and established history. Though other types of piezoelectric substances had been shown to be useful for controlling the frequencies of electronic oscillators, Walter G. Cady, of Wesleyan University, first demonstrated in 1923 that quartz resonators could be used very effectively to control the transmitting and receiving frequencies of radio sets.[1] From this discovery until its grudging acceptance by the Signal Corps in late 1940, quartz crystal control existed primarily in the world of the amateur radio enthusiast. It was the "ham" radio operator who first seized upon crystal units as a useful means of frequency control. Early hams, by their very nature, were experimenters, many finding no more joy than in building and constantly improving their homemade "rigs." Many amateurs carried this enthusiasm for the homemade into the field of crystal control—designing, building, and, in some cases, ultimately manufacturing and selling their crystal units to other hams.[2]

Most early hams adopted crystal control as a means of stabilizing their transmitters. In the earliest transmitter designs, the antenna was a part of the tuning circuit. If, for instance, the antenna moved in the wind, the frequency of the transmitter would change. These radio sets were also very susceptible to temperature changes. In order to maintain their assigned positions in the increasingly crowded radio spectrum of the early 1920s, hams bought or made crystal units.[3] The ham radio operator was helped in this endeavor by the radio publications of the day. The primary publication, *QST*, carried

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