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A HISTORY OF THE QUARTZ CRYSTAL INDUSTRY IN THE USA

Virgil E. Bottom

3441 High Meadows Dr.
Abilene, Texas
79605

Summary

With the aid of many of the people who were involved, this paper is an attempt to record the history of the quartz crystal industry in the USA. Although crystal units were in use at least a decade earlier, the beginning of the quartz crystal industry in the USA can logically be dated November 1941 when the Quartz Crystal Section was organized in the Office of the Chief Signal Officer.

The history of the industry is traced from its origin with the discovery of Piezoelectricity by the Curie brothers in 1880-81 to the present time. Special emphasis is placed upon the problems which were encountered and overcome in creating an industry capable of meeting the demands of the Armed Services of the United States and their Allies during WW II.

The record of cooperation among the large and small industries, governmental agencies, the armed services, universities and individual citizens inspires confidence that the most critical problem can be solved with cooperation, dedication and effort.

Introduction

The August 23, 1943 issue of LIFE Magazine carried the following letter to the editor:

> Sirs: In proportion to size these little glass like quartz wafers are perhaps the most remarkable of all the tools science has given to war. When the story of the almost incredible progress in research and manufacture of radio crystals can be told, it will prove to be a tale of one of the war's greatest achievements. No less significant will be the fruit of these advancements to a new world at peace where crystals will be the vibrating hearts of most telecommunication equipment. Gerald James Holton, Harvard University, Cambridge, Mass.

The "story" to which Prof. Holton so prophetically referred has not been told and perhaps can never be told in detail. MacLaurin, in the book INVENTION AND INNOVATION IN THE RADIO INDUSTRY, one of the books in the MIT studies of innovation, published in 1949, does not even mention piezoelectricity or the quartz crystal unit. But Prof. Holton's prophecy concerning the peace time uses of "those little glass like wafers" has been fulfilled far beyond anything that he could have foreseen.

The fortieth anniversary of the entrance of the United States into the great war known as World War II provides an appropriate occasion to review the "incredible progress" to which Dr. Holton referred even though quartz crystal units were known and in limited use more than a decade before that date. The 1939 decision of the Armed Services of the United States to convert its radio equipment to crystal control resulted in the creation of an industry which ultimately played an important role in the victory of the Allied Forces over the Axis Powers.

The years 1980-81 are also the centennial of the years in which the Curie brothers discovered the piezoelectric effect; the direct effect in 1880 and the converse effect in 1881.

It is fitting, therefore, that we should at this time look back upon the development of an industry which, in many respects, is unique; an industry staffed for the most part by people who were not trained scientists or engineers. On the contrary they were bartenders, lamp shade manufacturers, wood workers, stone cutters, mechanics and, above all, amateur radio operators or "hams". With a few professionals, most of whom knew little more than they about piezoelectricity and with a totally unsatisfactory basis of scientific information, these entrepreneurs tackled a job which would have taxed the ability of the most advanced and best equipped industrial concern in the nation. And they carried it off. But let us start at the beginning.

Early History of Piezoelectricity

Very soon after its discovery the Curies devised several instruments utilizing the piezoelectric effect. One of these was the piezoelectric voltmeter. Another was the piezoelectrometer which later became the basic instrument used by Pierre and Marie Curie in their work which led to the discovery of Radium. Otherwise, for more than three decades the piezoelectric effect remained little more than a laboratory curiosity. Further developments had to await the invention of the triode vacuum tube.

After the Curies the first application of the piezoelectric effect was made by Prof. P. Langevin in France in 1917. Langevin used X-cut plates of quartz to generate and detect sound waves in water. His object was to provide a means for detecting submarines and his work led to the development of SONAR and to the science of ultrasonics, the results of which are still making headlines (viz., the recent announcement of the successful use of ultrasonic imaging in mammography).

Langevin's work stimulated others to investigate the phenomenon of resonance in piezoelectric crystals. Among those who became interested were A. M. Nicholson of the Bell Telephone Laboratories and Prof. W. G. Cady at Wesleyan University. Both men, working with Rochelle salt, observed the reaction of the resonant piezoid on the driving circuit and both applied for patents based upon their observations. Subsequent litigation resulted in a legal decision in favor of Nicholson who is therefore considered to be the inventor of the piezoelectric oscillator.

In 1919 Cady use a quartz piezoid to control the frequency of an oscillator and in a series of papers during the next three years he described the use of quartz bars and plates as frequency standards and wave filters. It is generally accepted that Cady was the first to use a quartz piezoid to control the frequency of an oscillator circuit.

Both Nicholson and Cady used devices which would today be called monolithic resonators having two sets of electrodes on the same crystal. It remained for Prof. G. W. Pierce of Harvard University to show, in 1923, that a quartz plate with only one set of electrodes could be made to control the frequency of an oscillator circuit using only one vacuum tube. Pierce's circuit has probably been used more than any other quartz crystal oscillator circuit.

Oddly enough, none of the circuits was understood by its inventor until Prof. K. S. Van Dyke, a student and colleague of Cady, showed in 1925 that the two electrode piezoelectric resonator is the electrical equivalent of a series resonant circuit shunted by a capacitor. He was able to relate the electrical parameters of the equivalent circuit to the physical properties of the piezoid. This information in the hands of Vigoreux, Wright, Terry and others led to the understanding of the piezoelectric resonator or piezoid and to its use both as a passive and as an active circuit element.

The importance of the discoveries of Cady, Nicholson and Pierce did not go unnoticed. In 1923 the Bell Telephone Laboratories established a quartz laboratory and the General Electric Company did likewise the following year. One of the individuals who recognized the potential of the quartz crystal unit was August E. Miller. In 1923 Miller left the optical business where he had become an expert in grinding quartz lenses to go into the business of making quartz crystal blanks for amateur radio operators or "hams"; the only market which then existed for the new device. It appears that "Augie" Miller may have been one of the first individuals to go into the business of making quartz crystal units.

In 1926 the A. T. & T. radio station WEAF in New York City became the first radio station in the United States to control its frequency with a quartz crystal unit. Within a few years all radio stations went to crystal control thus providing another small market for quartz crystal units.

Before 1926 all crystal units were X-cut bars or plates. In that year E. D. Tillyer of the American Optical Co. discovered the Y-cut. The temperature-frequency coefficient of the Y-cut is about +100 ppm per C^{o} whereas that of the X-cut is about -20 ppm per C^{o}. This fact naturally suggested the possibility of making piezoids, the frequencies of which would be independent of temperature and so work was started in several places to exploit the idea.

During the year 1927 Prof. Gerald Fox of the University of Iowa spoke to a convention of "hams" on the topic "The Piezoelectric Properties of Quartz". His talk stimulated some of the hams to try to make their own crystal units. One of them was E. L. (Al) Shideler of Manson, Iowa who not only succeeded in doing so but continued to do so until he retired forty years later. Another was Bill Peterson of Council Bluffs, Iowa who founded the Peterson Radio Co. and continued to make crystal units until his recent death. Still another was Herb Hollister of Merriam, Kansas who continued to make crystal units until the end of WWII. This list is doubtless incomplete.

The interest of radio amateurs and radio broadcasters created a mini-market for crystal units and several small businesses were established to satisfy the demand. One of these was the Miller Laboratories started by August Miller in the year 1928.

In January 1930 QST published an article by J. Herbert (Herb) Hollister entitled "Debunking Crystal Control" in which he pointed out "its utter simplicity" and described how a ham could make his own crystal unit. During the same year F. Dawson Bliley founded the Bliley Electric Co. to supply crystal units mainly to the amateur market. Today the Bliley firm is headed by sons of the founder and continues to be one of the most respected companies in the business.

In 1931 Herbert Blazier founded Monitor Piezo Products Co. and began to supply crystal units to hams, radio stations and two-way communication systems on the West Coast. Monitor continues today under the direction of John W. Blazier, son of the founder of the company. Also in 1931, Theodore S. Valpey established the Valpey Crystal Co. which still continues as the Valpey-Fisher Corp. under the direction of the son of the founder, Mr. Ted Valpey, Jr.

In 1931, Dr. W. A. Parlin, Professor of Physics at Dickinson College in Carlisle, PA and three of his students, Ed Minnich, Howard Bair and Charles Fagan decided to try to make crystal units for their ham rigs. They were assisted by Grover C. Hunt, an amateur lapidist who was employed by the college as an engineer. Not only were they successful but in the following year Hunt produced the first commercial units to be made in the Carlisle area. All of the quartz crystal operations in the Carlisle area are direct descendents of Hunt's original efforts.

In 1932 Leon Faber, who had taken up the hobby of amateur radio in 1913, began to make crystal units in Sandwich, IL. His first customers were other hams. When WW II broke out Faber formed a partnership with James Knights who owned and operated a battery shop in Sandwich. Their efforts produced the James Knights Co. which became one of the largest crystal manufacturers in the world. It continues today as the CTS-Knights Co.

The crystal units of the day were either X- or

Y-cut plates mounted loosely between two metal plates which served as electrodes. With suitable temperature control frequency stabilities of a few ppm could be achieved. This was a vast improvement over the free running oscillators of the time but the temperature control equipment was expensive, cumbersome and power consuming. Furthermore, the construction of the units made them susceptible to the effects of vibration and precluded their use in aircraft and other mobile systems.

Meanwhile work had continued to try to find ways of making units which would be less susceptible to the effects of temperature changes. In 1929 W. A. Marrison of the Bell Telephone Laboratories described the first quartz piezoid with a low temperature coefficient. It was made in the form of a doughnut and was later used as the isochronous element of the first crystal clock. It did not, however,prove practical for general use. Efforts to develop a practical unit having a low frequency-temperature coefficient were successful in 1934 when the AT- and BT-cuts were discovered independently by Koga in Japan, by Bechmann and Straubel in Germany and by Lack, Willard and Fair in the United States. Two years later Baldwin and Bokovoy of RCA introduced the V-cut.

Shortly thereafter G. W. Thurston of the Bell Telephone Laboratories discovered that a quartz plate of the rotated Y-cut family could be rigidly supported between two metal plates by clamping it at a few points near the edge and thus providing an air space between the quartz plate and the metal electrode. Although slightly more difficult to produce, the clamped, low temperature coefficient plates were suitable for mobile applications and this increased the market for crystal units.

In response to the new market several new companies were formed. Among them was Standard Piezo Co., the first crystal company in the Carlisle, PA area; organized by Grover Hunt and Linwood Gagne in 1935. In the same year the General Electric Co., which had established a quartz laboratory in 1924, decided that the crystal unit was ready for commercial production and assigned it to the G. E. Laboratories at Schenectady, NY under the direction of C. F. Baldwin. In addition to units produced for internal use, a few were sold on the open market.

One of the most important influences on the development of the crystal industry in the period 1935-40 was the Galvin Mfg. Co. (Motorola). Mr. Dan Noble, ex-professor of Electrical Engineering at the University of Connecticut, was convinced that crystal control was essential to effective two way radio communication. In order to obtain the crystal units which he needed for his new two-way systems he persuaded Mr. Galvin to place orders with and in some cases to subsidize a number of individuals who had some experience with crystal units. Among these were E. L. Shideler of Fort Dodge, IA, Herb Hollister of Wichita, KS and "Ted" Tedford of Cincinnati, OH.

Production methods in use at the time were quite primitive. Orientation was done with reference to the natural faces of the crystal and consequently only faced quartz crystals could be used. The usual procedure was to determine the orientation with respect to a rhombehedral face using a protractor to measure the angular position. Sawing was done with a rotating blade in a slurry of silicon carbide and oil or water. The blades were usually of copper although other metals were used and at least one innovator of the day used old 78 rpm phonograph records. The crystal was held at the approximate angle by cementing it to a glass plate with wax or plaster Paris and a test cut was made. The resulting plate was lapped by hand until it would oscillate when placed between metal electrodes, the upper one of which was called a "penny plate" because of its shape and size. Once oscillation was obtained, the temperature was changed by means of a hair dryer or with dry ice and the direction of frequency change noted. Then the saw, which had remained idle during the process, was readjusted and another test plate cut. The process was repeated until a satisfactory angle was found and, if any quartz remained, the crystal was sawed into wafers. Although simple in principle, this method of orientation had two serious disadvantages; it was slow because the saw was idle for long periods of time and the test results were often ambiguous because of the effects of twinning and of coupled modes. Even at best, the accuracy was poor.

In a short time it was discovered that polarized light could be used in determining the angle. By passing a beam of plane polarized light through the blank in the X-direction the angle between the plane of the blank and the Z-axis can be determined with an accuracy of a few tenths of a degree. The use of polarized light greatly increased the productivity of the factory and the quality of the product.

As the market for crystal units expanded in the late thirties, the need for mechanization increased. The first crude saws were improvised from milling machines, surface grinders, and drill presses. Later these were turned on their sides, fitted with diamond blades and equipped with cross-feed compounds from milling machines. Eventually the Delta Mfg. Co., with the encouragement of Elmer Wavering of Motorola, produced 5000 drill press saws. Still later the Felker Corp. (now Felker Operations) produced the Felker Dimet saw, operating on the same principle but incorporating refinements making it a better production machine.

After a slice of quartz, called a wafer, was cut from the crystal it was etched with hydrofluoric acid to reveal the presence of twinning and other defects which were marked out and discarded. The remaining portion of the wafer (if any) was then diced into blanks ranging in size from 1.5 to 3 cm. The typical yield was 20 to 30 blanks per kilogram of quartz costing about thirty dollars. Unfortunately, many beautiful, fully faced crystals proved to be useless because of electrical and optical twinning which could not be detected until the crystal was sawed into wafers.

Blanks were lapped by hand on a rotating cast iron plate called a "stooging wheel" using silicon carbide and water as a slurry. After a few hours of work, the operator of a stooging wheel was usually contributing blood to the slurry from his/her finger tips. Many strange and wonderful devices were used to replace hand lapping. Louis Patla of DX Crystal Co., the first to produce crystal units in the Chicago area, recalls making a lapping machine from an old bread dough mixer. But most of the early laps were made from drill presses. A crank was inserted into the chuck and used to drive a metal carrier between two flat, annular cast iron plates while abrasive slurry was fed in through holes in the top plate. Metal carriers were replaced by plastic ones when it was discovered that, if the two metal plates were insulated from each other, the quartz plates would announce their own frequencies in a radio receiver. Soon the Atlas Machine Co. began producing drill press laps and the Atlas lap became the most commonly used lapping machine in the industry. In 1938 the P. R. Hoffman Co. was organized to produce machinery for the expanding industry. One of its first products was the Hunt-Hoffman planetary lap which is still widely used today without substantial modification.

Frequency measurements were made by determining the difference between the frequency of the test blank and that of some reference frequency such as a secondary frequency standard consisting of a one MHz crystal unit controlling a frequency generator which developed a set of radio frequencies having integral multiples of 10 kHz. Measurement of the difference frequency, detected by a radio receiver, was a major problem which was solved in various ways. One of the early manufacturers, E. L. Shideler, used the family piano as an interpolation oscillator. More affluent manufacturers could procure an excellent analog frequency meter from General Radio Co. and within a short time David Packard and William Hewlett developed the HP-200 audio oscillator which not only met a need in the quartz crystal industry but also launched the Hewlett-Packard Corportaion.

Final adjustment to frequency was done using a piece of plate glass as a lap and silicon carbide or emery as an abrasive. The operator applied force at diagonally opposite corners of the blank while moving it in a figure 8 motion on the glass plate thereby unknowingly reducing the thickness at the edges and creating the contour which is essential in thickness shear plates in which the thickness is not small compared with the lateral dimensions. Finishing to frequency was an exasperating exercise. The frequency of the plate is determined primarily, but not exclusively, by the thickness. But the amplitude or "activity" depends upon the lateral dimensions. Frequently the blank has low activity when adjusted to the nominal frequency and edge grinding is required. But edge grinding has a second order effect on the frequency which often skips to a higher frequency making the blank unuseable for the desired purpose. This phenomenon, which is commonplace and well understood today, was in 1935 variously ascribed to demons or to the perversity of inanimate matter.

Nevertheless, with patience, experience and luck a skilled finisher could sometimes finish to frequency as many as twenty crystal units per day. And so with primitive equipment and methods and little or no understanding of the phenomena involved, the crystal industry in the United States produced an estimated 100,000 crystal units during the year 1939.

It is quite impossible to trace to their origins many of the innovations which were devised during this period. Many techniques, thought to be original by their inventors, were later reported to have been in use elsewhere at an earlier date. This situation was partly due to the desire to keep as a trade secret any innovation which reduced the cost or/and improved the product; and partly to the lack of any effective means of communication between the various entrepreneurs. After the United States became involved in the war patriotism took precedence over industrial secrecy and with only one or two notable exceptions cooperation rather than competition became the rule.

The Quartz Crystal Section

The decision to make large scale use of crystal control in military communication systems was made late in 1939. The Armed Services had considered crystal control before but the idea was always rejected on the bases of (1) lack of flexibility, (2) cost, and (3) unavailability. In the summer of 1939, during field maneuvers in Tennessee, comparative tests were made of FM vehicular radio equipment, with and without crystal control. About the same time some crystal controlled equipment, captured from the German Army by the British, was sent to Wright Field for evaluation. The result of these tests was the decision to convert all military radio equipment to crystal control. This was about two years before Pearl Harbor Day (Dec. 7, 1941) and after the war in Europe was already under way.

The wisdom of this decision was emphasized by Major General Roger B. Colton at the Chicago Conference on July 11-12, 1944 when, despite all of the problems which had by then been encountered, some of which were still unsolved, he could say:

> "Our decision to go into crystal controlled radios for widespread tactical use has been more than justified by the results obtained. The Army had radio before they had crystals. Now the Army has communications. That's the difference. Crystals gave us communications."

Before the United States had seriously started rearming representatives of the British Purchasing Agency came to the United States to obtain equipment for the Armed Services of the U. K. One piece of equipment which they ordered was a VHF transmitter-receiver for aircraft use employing 4 crystal units in the transmitter and 4 in the receiver. The equipment was made by the Bendix Corp. and the crystal units were the DC-11 and the DC-12 types. This set, with a few modifications became the SCR-522, the most important airborne set in the U.S. Air Force and its crystal unit became the CR-1.

As the war in Europe increased in intensity it became apparent that the United States might soon be involved. The pressure on the fledgling crystal industry increased as it was asked to supply crystal units for the Allied Forces as well as our own. It became clear during the latter months of 1941 that a serious bottleneck was developing and that something must be done to expedite the production of crystal units.

If any date can be ascribed to the beginning of the quartz crystal industry in the United States it is probably late October or early November 1941 when the Quartz Crystal Section (QCS) was organized in the Office of the Chief Signal Officer (OCSIGO). It was headed by Lt. Col. James D. O'Connel and house in Bldg. Temporary A at Buzzard's Point near the old Army War College in Washington. The mission of the QCS was to expedite the production of quartz crystal units to meet the requirements of our Armed Services and those of the Allies. The first problem was that of finding personnel who could solve the technical problems and guide the industry which was to be. The original group of civilians in the QCS included:

- Dr. Clifford Frondel of Harvard University
- Dr. Richard Stoiber of Dartmouth College
- Mr. Sam Gordon of the Philadelphia Museum of Natural History, and
- Dr. William Parrish of the Pennsylvania State University, all of whom were mineralogists.
- Dr. Wally Richmond and Mr. Hugh Waesche, both of whom were geologists.
- Dr. Carl Bertsch of Newark College of Engineering, a physicist and Mr. E. K. Woods of the Patent Agency.

Among the Officers initially assigned to the QCS were:

Capt. E. W. Johnson	Capt. Charles Miller
Lt. Les Atlass	Lt. Willie Doxey

The task of this group was to organize an industry, determine what facilities were required and to make them available, obtain the necessary priorities for materials and equipment and to expedite and schedule production. Furthermore it had to be done immediately. Although all three services had small groups working on crystal problems which were peculiar to their particular services, the QCS served as the focal point for the quartz crystal program in the U.S. during the next four years.

In July 1942 the QCS was moved to the unfinished Pentagon Building and Dr. K. S. Van Dyke joined the group as Chief Civilian. His knowledge of the basic theory of piezoelectricity added a much needed dimension to the staff of the QCS which had hitherto been made up largely of mineralogists and geologists. Early in 1943 Virgil E. Bottom joined the group. He was the first member who had actual experience in the manufacture of crystal units. A little later Dr. Allyn Swinnerton, a geologist and Vice President of Antioch College, joined the group.

Work of the Quartz Crystal Section

The first task of the QCS was to publicize the need for quartz crystal units in order to attract potential manufacturers. This was done so successfully that many letters were received from patriotic citizens offering to donate the crystal sets which had reposed in their attics for a decade or two. However the information did reach the desired places and would-be-manufacturers of crystal units whose regular activities had been halted by the War Production Board began to descend upon the QCS asking how they might use their idle facilities to make crystal units. This group which included machinists, blacksmiths, jewelry makers, and amateur radio operators turned in one of the most remarkable records in the annals of American industry. In less than three years Mr. William Halligan, the President of the Hallicrafters Co. was able to say:

> "We had no trained personnel to make crystals. We had no equipment with which to make crystals and out of this has been created what to my mind, is truly a miracle of American incentive and industry."

The information available to these neophyte crystal manufacturers consisted of a few articles in QST, an article or two in the Bell System Technical Journal and the patents which had been issued. A little later the Bell Telephone Laboratories came to the rescue with a collection of articles written by such authorities as W. P. Mason, Walter L. Bond, Roger Sykes, I. E. Fair, G. W. Willard, G. M. Thurston, A. R. d'Heedne, H. G. Weke and R. M. C. Greenidge. These papers were of inestimable value at the time and were later edited in book form by R. A. Heising and published by Van Nostrand in 1946 under the title QUARTZ CRYSTALS FOR ELECTRICAL CIRCUITS. These materials were made available to the new manufacturers who digested them, utilized them and, in many cases, made improvements upon them.

One of the first acts of the QCS was to expedite the development of X-ray diffraction equipment for use in orienting quartz blanks. This became the first commercial application of X-ray diffraction. A few companies had adapted old dental X-ray equipment for making Laue photographs of quartz blanks but the process was slow and the results scarcely better than those which could be obtained with polarized light. At the Western Electric Co. a primitive form of Bragg diffraction equipment was in use by Walter L. Bond but this information had not reached beyond the limits of the Bell Telephone Laboratories. Contracts for the development of X-ray equipment were placed with the General Electric Co. and with the North American Phillips Co. under the surveillance of Dr. William Parrish. Both companies produced equipment in such numbers that most of the crystal companies were equipped with X-ray machines by early 1943. Although the equipment designed and built by the two companies differed in many respects, both were so well designed and constructed that many of the original machines are still in use almost forty years later.

Much effort of the QCS went into expediting equipment, supplies and materials for the new industry. Because of the critical nature of the program it was assigned a very high priority which, along with the authority of the OCSIGO, was often invoked to obtain critical materials. At one time a certain piece of equipment was almost within our grasp when it was snatched away by an outfit called the "Manhattan Project" which had a higher priority. Some of us wondered briefly why Manhattan needed a General Radio Primary Frequency Standard. Two of the men who became expert in working with the War Production Board and other agencies were Tom Parrott and Wally Richmond and many crystal manufacturers owed their daily ration of quartz to the efforts of these two men.

Due to the critical nature of the industry the decision was made to locate the production facilities away from the East Coast which was within enemy range. Accordingly manufacturers in the Central Region of the country were encouraged with the result that Kansas City and Chicago became manufacturing centers for the quartz crystal industry and remained so for years.

In May 1942 the QCS organized a training program in Kansas City under the auspices of the University of Kansas. The teacher of the course was John Zeigler, a young engineer, who had learned something about crystal units while working at RCA. The course was taught from copies of patents to a class of about 20 persons including Ernest O. Ruff and Edward Roper, both of whom are still active in the crystal business.

Soon thereafter Zeigler and George (Jack) McGrew organized a company called Crystal Products Co. Except for a small operation called Aerion, owned by the Aircraft Accessories Co., Crystal Products was the first crystal company in the Kansas City Area. All of the other factories in the area sprang from the company organized by McGrew and Zeigler.

By 1943 about 130 manufacturers were engaged in the production of crystal units. Twenty three of these were in the Chicago area, 20 in the New York area, 15 in the Carlisle area and 14 in the Kansas City area. The remainder were scattered over 20 states from Oregon to Florida and California to Massachusetts. The supervision of so many small plants, distributed over such an area was a major problem and the members of the staff of the QCS spent much time on travel duty instructing the new manufacturers, helping them with technical problems, coorelating test equipment and settling arguments between them and the Signal Corps Inspectors.

The Galvin Mfg. Co. (Motorola)

The task of coordinating the activities of 130 companies was clearly beyond the capability of the small staff of the QCS in Washington and so the Galvin Mfg. Co. (later Motorola) was induced to assist in the program. Galvin was heavily engaged in the production of personnel radio equipment known as the"handie-talkie" and "walkie-talkie" sets, all of which used the FT-243 crystal unit. Under the direction of Mr. Elmer Wavering, Galvin Mfg. Co. undertook the Herculean task of expediting and scheduling the production of FT-243 units, testing and assembling them into kits each of which contained 44,000 units on 4400 different frequencies. Mr. Nick Anton, an assistant to Mr. Wavering, prepared and distributed a Crystal News Sheet which supplemented the grapevine and helped contractors to keep abreast of new developments and information related to the production of FT-243 units.

One important contribution of the Galvin Mfg. Co. was the CES-1 Crystal Test Set. The CI-meter had not yet been invented and standardization of crystal units was unknown. It was necessary to provide each manufacturer with a test set consisting of a mock-up of the oscillator circuit of every piece of radio equipment. These test sets were known as "black boxes" from the color and shape of the cabinets which housed them. Each "black box" was periodically returned to the Signal Corps Laboratory at Fort Monmouth for recalibration. The CES-1 consisted of a Pierce oscillator circuit in which the critical parameters were variable. It could therefore be adjusted to simulate a number of different radio sets, thereby reducing the need for so many "black boxes". The CES-1 helped greatly with the correlation problem but did nothing to solve the standardization problem which awaited the invention of the CI-meter.

Growth of the Crystal Industry

Except for the Western Electric Co., all of the crystal unit manufacturers in existence before 1940 were very small. Bliley, one of the largest, had fewer than 15 employees. Monito Piezo had about the same number. It is doubtful if more than 100 persons were engaged in the production of crystal units in the year 1939.

During the period 1941-45 employment at Monitor reached over 2000 and at Bliley over 1400. Scientific Radio Products employed over 750 and a new plant, The Reeves Sound Laboratories in New York City which began production in the summer of 1942, soon employed nearly 1000. In Chicago the Ross Mfg. Co., headed by Ken Ross and the Beaumont Electric Co., operated by the Lieberman brothers, (who formerly manufactured lampshades) each employed over 500. Many smaller companies with fewer than 100 employees also made their contributions. One example was the Good-All Mfg. Co. of Ogallala, Nebraska which employed about 20 people.

In addition to the firms directly engaged in the production of crystal units, many many others were engaged in supporting activities. Diamond saw blades, abrasives, plastic holders, stainless steel electrodes, beryllium copper springs, neoprene gaskets, nickle plated screws and many other items were required to complete the assembly. Coordination of the production and distribution of these items was done by the War Production Board which attempted to match the limited supplies to the almost unlimited requirements.

This motley assemblage of manufacturers, coming from every part of the nation and from almost every type of activity turned in a most remarkable production record. Between 1941 and 1945 they produced an estimated 30 million crystal units.

The FT-241 Program

The radio equipment used by the armored cavalry and the field artillery divisions was designated the BC-608 series. This equipment used frequency modulation and operated in the 30-40 MHz range of frequencies. The crystal unit for the set was the FT-241, developed by the Bell Telephone Laboratories and produced by the Western Electric Co. Each set carried a complement of crystal units ranging in number from 72 to 120 thereby requiring an extremely large number of crystal units.

The crystal units, which operated in the frequency range 350-550 kHz were made with CT-cut quartz plates. They were made at the Hawthorne Plant of the Western Electric Co. in Chicago where more than 10 million such units were produced between 1941 and 1945. The production of this plant was reported to be one million units per month when it was shut down in the summer of 1945. A complete account of the development of the FT-241 unit is given by W. F. Drew and A. E. Swickard in Heising, Chapter XVI.

Although the Hawthorne plant was in a secure location militarily, it was early recognized that at least one more source for these units should be available. The technology involved in making the FT-241 was clearly beyond the capability of most of the small plants which were successfully making the FT-243 and CR-1 types. Accordingly a contract was awarded to the Federal Telephone and Telegraph Co. of Newark, a subsidiary of ITT, to set up a second source for the FT-241 unit. However, despite the expenditure of a large sum of money and much precious quartz and with the experience of the Western Electric Co. available, the war ended before any units of the FT-241 type were produced outside the Hawthorne plant in Chicago.

The Quartz Shortage

One of the most critical problems faced by the QCS was the shortage of raw quartz. Although quartz is found in a few other places including the United States, practically the only source of natural quartz of electronic grade is Brazil. At the beginning of 1939 the United States had a stockpile of about 10,000 pounds of quartz suitable for processing into crystal units. During 1939 about 30,500 kg (67,000 pounds) of quartz was imported from Brazil. The amount imported in 1940 was 57,500 kg. Approximately 10% of this quartz was considered to be of electronic grade. Dr. Richard Stoiber was assigned the problem of expediting the supply of quartz.

Before the end of 1942 the supply of faced quartz which could be processed without the use of X-rays was nearly exhausted and the industry was forced to begin to learn to process unfaced quartz of which a considerable quantity was still available. Various techniques and devices were developed to enable manufacturers to use this material. These are adequately described by G. W. Willard in Heising, Chap. IV.

By the end of 1942 X-ray diffraction equipment began to become available to the manufacturers enabling them to effectively utilize unfaced quartz crystals. This relieved the shortage somewhat but the supply was still inadequate and steps were considered to increase the supply. The quartz mining regions of Brazil are not in the "hot, steamy jungles" but rather in the highlands in the central states of Minas Gerais and Goias near the capital city of Brazilia (which, of course, did not exist at that time). The mining of quartz was not then, nor is it now, an organized activity. The 'garimpeiro' (diamond hunter) would dig or hunt until he found a crystal which he could trade to a local merchant for supplies. The merchant, in turn, exchanged it for goods and eventually the stone reached Rio de Janiero where it was finally sold to the purchasing agent of the Metals Reserve Corp. or some other purchaser.

This ad hoc system was incapable of meeting the needs of the growing crystal industry and the quartz shortage continued to become more acute. As an example, on Easter Sunday 1942 an executive order was obtained from the White House releasing 200 pounds of quartz which was needed for a special order for crystal units.

Various steps were considered for alleviating the shortage which was partly due to inadequate grading facilities in Rio. Consequently inspection teams were trained and sent to Brazil to inspect the quartz prior to shipment. Eventually several thousands of pounds of quartz were loaded on a ship bound for the Port of Newark. The ship was hardly out of the harbor before it was sunk by a German submarine. After that incident all quartz was flown to the United States in DC-3 cargo planes at a cost of $2.00/pd. (1941 dollars).

In an effort to encourage the mining of quartz the purchasing agents in Brazil were authorized to double the price of quartz. However the authors of this strategy had failed to take into account the economic system of the 'garimpeiro' who was not interested in building up a savings account and who only dug or hunted quartz when he needed to replenish his supplies of rice, beans and pinga. Consequently the result of the program was less, not more, quartz and the program was abandoned.

It was then proposed that mining machinery be sent to Brazil. Accordingly a cargo ship was loaded with bulldozers and other earth moving equipment and dispatched to Rio. It was sunk enroute. Another ship was loaded with similar equipment. It arrived safely but most of the machinery never reached the mining areas because of lack of roads and that which did reach the quartz mining area proved unsuitable because of lack of fuel and because the nature of the operation made mechanical mining impractical.

At this time it was considered uneconomical to process stones below about 200 grams in size. One day in 1943 Mr. Morris Hanauer, owner of American Gem and Pearl Co., a quartz importer, was trying to convince Lou Patla of DX Crystal Co. that he should use these small stones. "Lou", he said, "God made lots of small crystals but very few large ones. So why don't you go along with God and use the small ones ". Soon ways were found to process the small stones with satisfactory results. This information spread quickly throughout the industry and for a time alleviated the quartz shortage.

Nevertheless, through the entire war period the quartz crystal industry lived on a hand to mouth basis and the shortage problem was eventually met, not so much by increasing the supply as by conservation. The yields were increased by making the blanks smaller and stones formerly considered unuseable were processed. Production records were maintained and with one or two notable exceptions, quartz was allocated only to the producers who could show that they were able to utilize it efficiently.

The lesson learned from the shortage of a critical raw material for which we were totally dependent on an offshore supply was not wasted.

Efforts were made to find a substitute for quartz. These were unsuccessful but at the end of the war it was learned that Germany, faced with a similar quartz shortage, had made some progress toward making man-made quartz. Consequently a major effort was mounted to make cultured quartz with such success that we are now almost completely independent of the natural material.

The Ageing Problem

By the middle of 1943 the task of setting up an industry was complete and crystal units were being produced in numbers adequate to meet the demand. It was then that the second, and even more serious crisis confronted the crystal program Reports began to filter in of extensive crystal failures both in service and in depot storage. The first responses to these reports ranged between indifference and disbelief. However the reports became more persistent and the Signal Corps Engineering Laboratories (SCEL) at Fort Monmouth were requested to investigate the situation. The progress was slow because the problem was treated as an academic question rather than a matter of the utmost urgency. Late in 1943 a telegram was received at OCSIGO which changed the situation. It read as follows:

COMMUNICATIONS EIGHTH AIR FORCE BASED
IN BRITAIN BROKEN DOWN LACK OF CRYSTALS
FIND CAUSE CURE SAME EAKER

Reception of this communique caused a flurry of activity at both the QCS and at SCEL. A test facility euphemistically named "The Swamp" was constructed at Camp Coles Signal Laboratory. It subjected crystal units to temperatures of 100 F° in an ambient relative humidity of 100 % simulating the conditions reported from the Burma theatre. The tests quickly confirmed the field reports. All crystal units failed within a few days or at most a week or two. Some of the failures were due to the phenomenon of corrosion fatigue in which the ammonia released by the phenolic holders attacked the brass connectors at points of stress causing them to break. This problem was corrected by eliminating brass from the assembly. A much more serious problem was the ageing syndrome characterized by loss of activity and increased frequency. Many theories were advanced to explain the phenomenon and these had to be checked out experimentally. Meanwhile the manufacturers were producing crystal units at the rate of a million per month; nearly all of which were destined to be useless.

Before the end of 1943 it had become apparent that the most important factor in the ageing process was the surface of the quartz which was damaged in the process of lapping to frequency. Particles of quartz, partially loosened by abrasion, were further loosened by the effects of water vapor, eventually breaking away completely. The presence of these loose fragments on the surface of the blank reduced the activity by damping and their loss caused an increase in frequency because of the reduction of mass.

The problem of ageing was especially severe in the CR-1 unit used by the Air Force because these units operated at higher frequencies and required closer tolerances. As a temporary measure orders were issued by Wright Field that all quartz plates must be able to withstand the test of scrubbing with soap and water and a toothbrush. Soon each Signal Corps Inspector and each crystal finisher was equipped with a toothbrush and a dish of soapy water. The directive was a boon to the toothbrush industry but contributed little to the solution of the ageing problem.

By the end of 1943 it had been shown that quartz blanks which had been etched to frequency exhibited very small changes of frequency and activity even when subjected to tropical conditions. However considerable opposition existed to the idea of etching and much valuable time was lost in investigating other approaches before the decision was made to require etching. This was due to a reluctance to specify a manufacturing process which might require rewriting of the specifications and renegotiating of contracts and to a wise policy of specifying test results instead of manufacturing procedures. Yet it was impossible to depend upon inspection procedures to insure that crystal units would remain useable and a vast amount of work had failed to reveal any other manufacturing procedure which would do so.

Consequently a Conference of all Crystal Manufacturers was called on July 11-12, 1944 in the old Stevens Hotel in Chicago. The problem was explained in detail and the proposed remedy was presented. There was no time to rewrite the specifications or to renegotiate contracts so the manufacturers were asked to convert their production processes from hand lapping to etching. It was expected that units made by the etching process might be more expensive. Again the industry rose to meet a challenge. The manufacturers went back to their plants and converted to the new process with such success that they produced satisfactory units at a lower cost. As one example, Ken Ross, who had converted his coil winding plant in Chicago to a facility for making FT-243 crystal units, designed and built a continuous etching system which, with four operators, turned out as many finished crystal units as 20 operators finishing by hand lapping. The Ross system was soon widely copied throughout the industry.

Ironically, the ageing problem might have been avoided had better communication existed. The phenomenon of ageing had been noted as early as October 1940 at RCA. The work of H. E. LeRoy and V. E. Trouant led to a Company Confidential memorandum dated April 14, 1941 in which they said:

"Etching... reduced the number of failures" and that "Etching will be incorporated in the processing as soon as details can be worked out and operators trained."

Unfortunately this work was unknown outside the RCA Laboratories until after the war and even there it does not appear to have been exploited.

To provide crystal units for special purposes in the field, twelve three-man crystal grinding teams were given a three months crash course in finishing crystal units. They were trained by Dr. D. G. McAA, a retired physician, at Camp Coles Signal Laboratory. These teams were provided with the necessary equipment and supplies and shipped to various theatres of the war. Upon arrival they found that many of the crystal units in depot stocks were useless and much of their time was spent in opening, cleaning and grinding thousands of crystal units to new frequencies. Mr. H. J. Benedikter, who is today associated with the General Electric Crystal Manufacturing Facility, was a member of one of the original crystal grinding teams.

At home teams of GI's and civilians were trained to examine depot stocks of crystal units and to select out useable units which were often flown immediately to a war theatre. Later some attempts were made to salvage the defective units and at least one company, The Hudson American Co., was commissioned to do so. However most of the units were enclosed in phenolic plastic holders and many others contained brass contacts, both of which were considered unsatisfactory, leaving little besides the quartz blank to be salvaged. It soon proved to be uneconomical to salvage the units and ultimately millions of the unetched units were destroyed.

It may be worthwhile to examine the ageing episode; not to assess blame or responsibility but to see if, by doing so, we might avoid a similar debacle in the future. It appears that the ageing problem resulted from three basic mistakes; each understandable and perhaps forgivable. The first was to depend so heavily on an immature technology, the second was to disperse an industry so widely that it could not be properly supervised, and the third was failure to follow up with an adequate reliability test program. The recall programs of the United States automobile industry indicates that some of these lessons may not even yet have been learned.

Post War History of the Industry

It is difficult, if not impossible, to trace the histories of all of the firms which have been engaged in the business of manufacturing quartz crystal units. Only a few firms, notably Bliley, Monitor and Valpey still operate under their original (or similar) names and can show continuity of management. Most of the companies have either disappeared or have changed names and locations so many times that to trace their records is virtually impossible. It may be of some interest to trace the history of one company; noting that it is typical of the industry.

When Grover Hunt discovered that people were willing to pay for crystal units he formed a partnership with Linwood Gagne and they began to make crystal units in a small building adjacent to Gagne's home in Carlisle. In 1935 they formed Standard Piezo Co., the first crystal company in the Carlisle area. One of their employees was Wally Samuelson. In 1940 Hunt left to form his own company, the Hunt Corp. which is today Erie Frequency Control. At the end of the war Gagne sold Standard Piezo to a group of local business people headed by John Fowler. Later it was sold to Brown Oil Co. and Luther McCoy was made Sales Manager. In 1952 McCoy left to form his own company and Standard Piezo was sold to the Hupp Corp. which, in turn, sold it in 1958 to Herman Schall and Wally Samuelson who renamed it Piezo Crystal Co. In 1963 Schall and Samuelson sold out to the Renwell Corp. who sold it to the Sunshine Mining Co. The plant was subsequently sold to a holding company, Anchor Operating, Inc., which operates it today under the direction of Charles Jansik.

It is interesting to note that the 1980 edition of the QUARTZ CRYSTAL INDUSTRY GUIDE AND DIRECTORY states that Piezo Crystal Company was established in 1938. In a sense this is true, but it is in the same sense that an antique axe which has had several new handles and a few new heads is still the same axe.

A list of manufacturers of quartz crystal units dated 1 May 1945 includes the names of some 130 companies. One year later the number had dropped to fewer than half this number. After revival of the industry during the Korean War approximately 50 companies were engaged in the business of making crystal units. The number deceased again when the Korean War ended but has increased again in recent years.

Today the industry includes between 50 and 60 companies employing about 6500 people. It is impossible to say how many are engaged solely in the manufacture of crystal units since many of the companies also produce items such as crystal filters, TCXO's and VCXO's and in addition some of them produce only blanks while others only finish blanks.

The typical company, if it existed, would have about 100 employees including two engineers but the size of the companies varies by two orders of magnitude. The largest companies, CTS-Knights and Piezo Technology employ 580 and 515, respectively. The two smallest, American Crystal Co. and Defco employ 6 and 3 persons, respectively. Several companies have fewer than 10 employees.

The foregoing figures do not include the firms which support the crystal industry. These are more numerous than the actual crystal manufacturers and employ more people. Among the products supplied by these firms are cultured quartz, holders and bases, abrasives, chemicals, silver and gold, electronic instruments and machine tools, and supplies in an almost endless variety.

Problems of the Crystal Industry

The wartime expansion of the crystal industry came to an abrupt halt with the end of the war. Contracts were cancelled, plants were converted back to civilian production and equipment was dispersed. The number of producers dropped from 130 to below 50 in a few months. When the Korean War came in 1950, bringing with it a new requirement for crystal units it was necessary to subsidize the companies to obtain the crystal units needed by the Armed Services.

For its entire forty years the quartz crystal industry has been plagued by the feast/famine cycle. In times of military rearmament the demand has escalated only to be followed by abrupt deescalation when the crisis was over. Until only recently the civilian requirements for quartz crystal units have been small compared with military requirements in times of crisis making continuous production impossible.

One problem in the quartz crystal business has been lack of research and development. It is true that in the decade following WW II the Armed Services did support an R & D program which yielded some useful results. A notable example is the program which led to the development of a cultured quartz industry. But for the most part the results have not been effectively utilized; partly due to the fluid nature of the industry. Outside a few large companies, notably the Hewlett Packard Corp., very little work in quartz crystal technology has been supported with industrial funds.

The field of piezolectricity has always been, and continues to be ignored by the Schools of Electrical Engineering. Quartz crystal technology has been treated as an art, or even worse, as black magic. With the exception of the students who have received formal training at Northern Illinois University under Dr. W. E. Newell and at Colorado State University and McMurry College under Dr. Virgil E. Bottom, most of the people in the industry have learned from one another going back to the handful of men who started the industry who had, themselves, learned in the School of Experience.

Academic neglect of the field is also shown by the dearth of literature available to the newcomer. The classic work of Cady, the books of W. P. Mason and the compliation of 1942 papers by Heising include practically everthing which has been published in this country. The book publishers naturally have been reluctant to make the necessary expenditures to publish books for a nonexistent clientele.

The industry has had its share of "get rich quick" entrepreneurs who jumped at the opportunity to make a quick profit during times of emergency but these have been a very small minority. Most of the men who entered the crystal industry, particularly during the war, were motivated by the challenge of a difficult job and by the desire to make a patriotic contribution as much as by the profit motive. Many continued in the business as long as they were financially able to do so; often bidding on production contracts at prices below the cost of production in order to hang on a little bit longer. They have done so at great financial sacrifice to themselves and to the detriment of the industry.

The industry has always been too small to be of interest to Wall Street and the large corporations and technically too difficult for the small entrepreneur without adequate financial backing and scientific capability. In those instances where large corporations have taken over small crystal companies the results have been almost uniformly disastrous. Generally speaking, the management of the large companies have attempted to apply the same production management techniques which work successfully in the production of most standard components; failing to recognize the great complexity of the apparently simple crystal unit. When they have found out, they have been unable or unwilling to make the capital investments needed to put the production of crystal units on a firm financial and technical basis.

The crystal industry has experienced four bursts of activity during the past decade. These involved crystal units for color television sets, citizen band radio, watches and clocks, and lastly microprocessors. Each of these products has resulted in a temporary expansion of the industry followed by a collapse when prices fell below the cost of production in the United States. In order to compete successfully for these mass markets it appears that the crystal industry needs more capital and more trained people. Unfortunately both seem to be in short supply.

Consequently the quartz crystal industry which produces the device that W. P. Mason has called "The cornerstone of the communication art", has remained, like the North American Indian, a ward of the government, dependent upon it for financial and technical support, and struggling to stay alive to be in position to meet the challenge of the next military crisis.

EPILOGUE

The author wishes to thank each of the persons who contributed material for this account. Without their help it could not have been prepared. He is fully aware of the deficiencies of the paper. Many important topics have been omitted and numerous persons who made important contributions have not been mentioned. Despite every effort to make the report factual, it is almost certain that errors have been made. The author accepts full responsibility for these and solicits corrections. He also asks forgiveness of those who have been omitted and of those who may have been unfairly represented.

Those having further information and/or corrections are urged to communicate with the author. Perhaps at a later date the story can be told in greater detail and more precisely.