Some personal recollections of early experiences on the new frontier of electroacoustics during the late 1920s and early 1930s[a)]

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During this brief presentation, time will be turned back a half-century to permit some personal recollections of early experiences as we explored the new frontiers in electroacoustics. The availability of the vacuum tube for the amplification of weak signals made possible the practical application of a variety of wide-range, low-sensitivity transduction techniques for the generation and reproduction of sound. Our training in electrical engineering provided an understanding of electrical measurements and design techniques that we could adapt for new specialized uses during our early stages of acoustic measurements and electroacoustic research. The demands of the new talking picture industry for improved electrical recording and reproduction of sound helped finance the costs of electroacoustic research, which resulted in rapid progress in the sound reproduction and recording industry during the early 1930s. In less than a decade the reproduction of sound was transformed from the primitive limited frequency range of the mechanical phonograph to the high quality electrical recording and reproduction made possible by the rapid advances in electroacoustic engineering.

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INTRODUCTION

I want to thank the committee for inviting me to take part in this meeting, particularly because it is a memorial to Dr. Harry F. Olson, who was a personal friend since the early 1930s. By coincidence we both started our professional careers in 1928; he joined the RCA Research Laboratories in New York City at about the same time that I went to the Victor Talking Machine Co. in Camden, NJ. At that time, the recording and reproduction of sound was entirely mechanical. The design of the components of the recording and reproducing system was a totally empirical procedure and there was no test equipment available at Victor for making acoustic measurements. It was therefore necessary to develop such equipment to permit quantitative measurements of the performance characteristics of sound reproducing equipment.

I. HISTORY

I first met Harry Olson in late 1928 at the RCA Laboratories when I visited Irving Wolff, who had offered to give me information on a beat frequency oscillator circuit that he had developed. Wolff was involved in the theoretical investigation of the radiation of sound from vibrating diaphragms and Olson had just joined him in this effort.

Using the information received from Dr. Wolff, I successfully built a beat frequency oscillator. I was also able to obtain a condenser microphone developed by Dr. Wente at the Bell Laboratories, which I connected to a primitive vacuum tube amplifier with an improvised low capacity cable, to provide the sound pressure measurement portion of the first frequency-response measurement equipment for use at the Victor laboratories. This early apparatus is shown in Figs. 1 and 2.

During late 1928 and early 1929, the Victor Talking Machine Co. decided to manufacture a combination radio phonograph set; it became my responsibility to design the phonograph pickup. For the design I employed a pivoted electromagnetic armature mounted in an air gap. The armature included a steel chuck with a set screw for holding a conventional steel needle, such as was being widely used with the standard Victor mechanical phonograph.

The radio receiver circuit for the new Victor set used four tuned radio frequency stages which resulted in a noncritical setting of the tuning dial when selecting a radio station.

FIG. 1. Early beat frequency oscillator with logarithmic frequency scale and recording drum attachment for plotting frequency response characteristics of loudspeakers (1929).

[a)] Invited paper presented at the 106th meeting of the Acoustical Society in San Diego, CA, 10 November 1983.

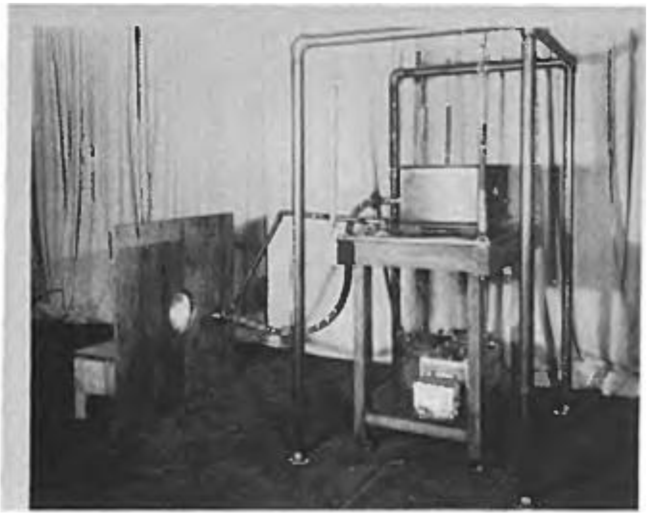

FIG. 2. Condenser microphone with improvised low capacity cable connected to an early vacuum tube amplifier. Note spring suspension to prevent floor vibrations from reaching the amplifier to avoid microphonic tube noise (1929).

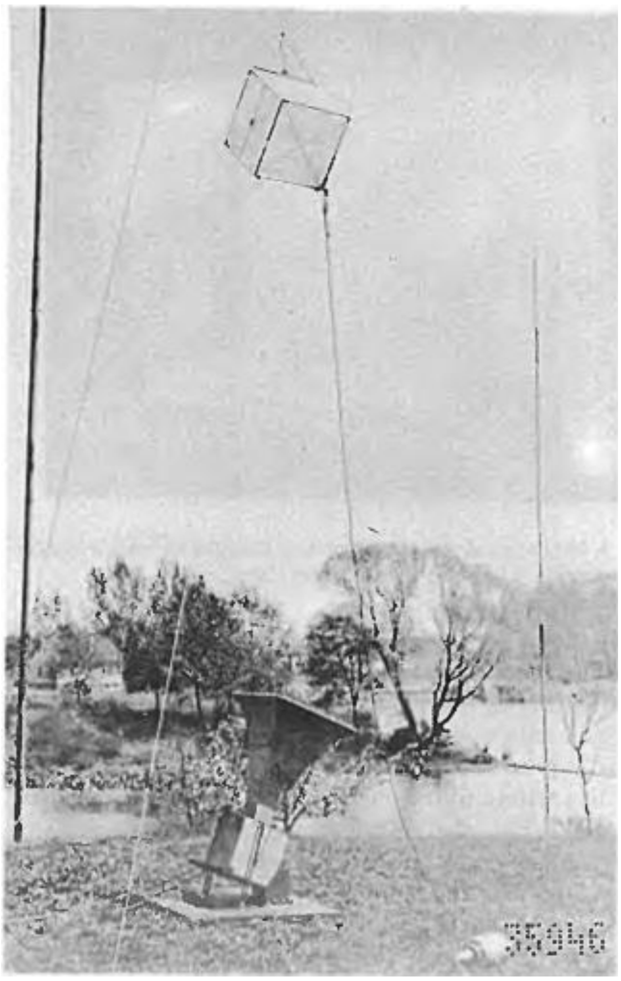

FIG. 4. Outdoor free-field measurement of horn loudspeaker response characteristics (1930).

The superheterodyne receiver being developed by RCA required continual manual adjustment of the tuning knob to correct for frequency drift in the early heterodyne circuits, which made it difficult to keep a station tuned in without the continuous presence of distortion in the reproduced sound.

The great commercial success of the Victor radio-phonograph set attracted the attention of RCA, who acquired Victor in 1929; the merged companies became RCA-Victor. Following the RCA-Victor merger, the radio engineering divisions of General Electric and Westinghouse moved to Camden to become part of the RCA-Victor organization. A few months later the catastrophic stock market crash of 1929 took place; the great depression of the early 1930s quickly followed. As a result, the greatly expanded engineering activities had to be deeply cut. By a fortunate coincidence, the acoustic research department was spared the fate that fell on the majority of the engineering personnel because of an unexpected demand for sound equipment from movie theaters throughout the country who wanted to show the new talking pictures that were just being introduced. To meet this demand, our activity in loudspeaker development was intensified. A portable version of the early Victor sound pressure measurement equipment was built to permit making free-field outdoor measurements on horn-type loudspeakers.

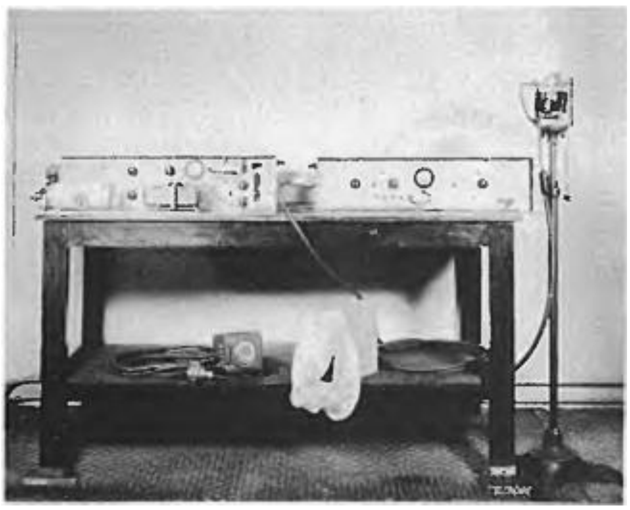

FIG. 3. Photograph of portable version of early frequency response measurement equipment (1930).

Figure 3 is a photograph of the portable equipment showing the condenser microphone mounted on a preamplifier, developed for use in radio broadcasting. An early ribbon microphone which was built for use as an auxiliary measurement microphone is also shown. The open magnetic pole piece construction was designed to improve the high-frequency response of the earlier experimental microphones which used less-open magnetic structures. Figure 4 shows the outdoor free-field acoustic measurement setup for testing horn-type loudspeakers. The cubical frame suspended above the speaker is a silk covered wind shield for reducing wind noise during the measurements.

In addition to the frequency-response test equipment, a Rayleigh disk primary reference standard shown in Fig. 5 was built to permit the absolute free-field calibration of the measurement microphones. The intensity of the sound field is measured by observing the angular deflection of a small

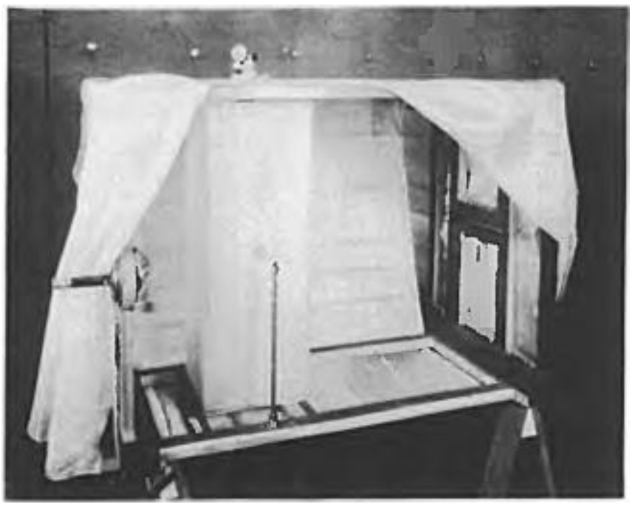

FIG. 5. Rayleigh disk primary calibration standard for making absolute measurements of free-field sound intensity (1931).

round mirror suspended on a very fine quartz filament inside the wind shield. An illuminated scale shown mounted into the right-hand wall of the frame is used to read the deflection of the suspended mirror through the telescope.

In addition to the intensive loudspeaker development program that was going on, we were accumulating experimental data for many months to acquire an understanding of why, whenever early radio sets were extended in frequency range to 8 kHz, the quality of reproduction was generally judged to be very objectionable, whereas an experimental wide range sound reproducing system set up in the laboratory would always result in almost unanimous preference for the widest frequency range being compared during the listening tests. For conducting these subjective tests, we equipped a small studio with a microphone and preamplifier having flat response to 14 kHz. The live sound picked up by the microphone was transmitted by direct wire to the listening room where the power amplifiers and a multichannel loudspeaker system were installed to reproduce the full 14-kHz frequency range of the studio output. A variable cutoff high-frequency filter was included in the reproducing system to permit direct listener preference comparisons to be made between pairs of cutoff frequencies such as 14 vs 12 kHz, 12 vs 10 kHz, 10 vs 8 kHz, etc., to a lower limit of comparison down to 3 kHz. Hundreds of listeners took part in these tests, including Victor recording artists who frequently came to Camden to make their recordings, and many others who were representative of a cross section of the general population.

To monitor the level of the reproduced sound during the listening tests, a sound level meter was built using a modified open pole-piece version of an early G.E. ribbon microphone with cobalt steel magnets to eliminate the need for the dc field supply. The meter is shown in Fig. 6. The cylinder shown mounted on top of the microphone contains a piston which can be retracted and allowed to fall under gravity to produce a steady air stream through the tone generator shown projecting from the bottom of the cylinder. The constant repeatable tone served as a calibrator to set the

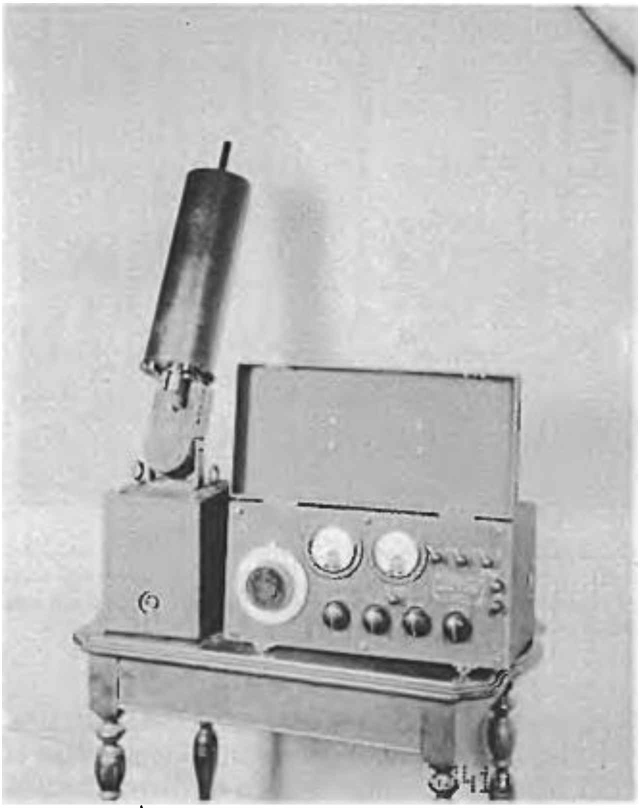

FIG. 6. Sound level meter with selectable 40- and 70-dB ear loudness frequency characteristics (1931).

absolute level of the meter scale. The meter also included a selectable frequency compensation for the 40- or 70-dB ear contour characteristics.

The final analysis of all the subjective data accumulated over a period of about a year from several hundred test participants showed that over 95% of the preferences were always for the higher of the two frequency ranges being compared. However, the preferences changed dramatically when controlled amounts of distortion were introduced in the reproducing system. As distortion was increased, the

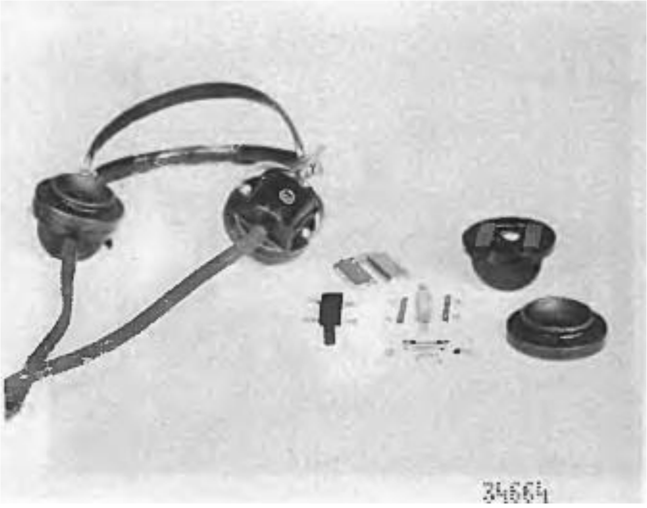

FIG. 7. High fidelity ribbon telephone receiver (1932).

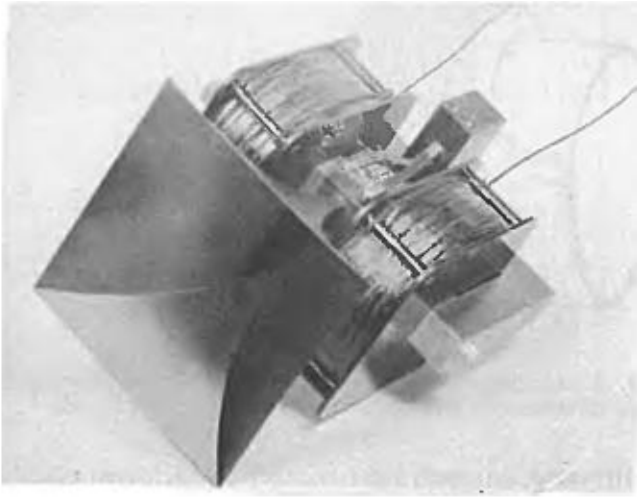

FIG. 8. High-frequency horn-type ribbon loudspeaker (1932).

preference shifted to lower and lower cutoff frequencies. The higher the distortion, the greater was the shift in cutoff frequency preferred by the overwhelming majority of listeners.[1]

II. IMPROVEMENTS

In 1932, Olson moved to Camden accompanied by Julius Weinberger, who became Director of the RCA-Victor Acoustic Research Department. Olson and I became close associates as well as personal friends while jointly concentrating our efforts on the many electroacoustic development projects that were underway. Before coming to Camden, Olson had been doing early work at the RCA Laboratories in the development of the ribbon microphone and the horn-type loudspeaker. This work continued in Camden and we jointly expanded the application of the dynamic ribbon vibrating system. A high fidelity ribbon headset was developed using a cobalt steel magnetic structure, as shown in Fig. 7. A ribbon horn-type loudspeaker, shown in Fig. 8, extended the high-frequency range to 15 kHz. A production design of the ribbon microphone, shown in Fig. 9, became the well-known symbol of NBC during many years of radio broadcasting. We developed a unidirectional ribbon microphone, shown in Fig. 10, that used half the ribbon as a pressure gradient microphone; the other half was terminated in an acoustic resistance to operate as a pressure microphone. The combined response of the two ribbon sections resulted in a cardioid directional pattern.[2]

The most important ongoing development project was the improvement of the horn-type loudspeakers that were in great demand for satisfying the needs of movie theaters, who were installing sound equipment for the projection of talking pictures. In order to generate the high level acoustic power necessary to fill the theater with sound it was necessary to use high efficiency loudspeakers, which in turn indicated the use of exponential horns driven by dynamic speakers. Since we were exploring virgin territory, there was little electroacoustic engineering background experience to serve as a guide. We made use of equivalent electrical circuits to understand and develop the optimum relationships among the basic parameters of a horn loudspeaker system, and to understand how to make the best tradeoffs to achieve good performance at minimum cost.

FIG. 9. Ribbon microphone (production design) with open magnetic structure to improve high-frequency response (1932).

It was determined that two separate loudspeakers would be needed to satisfy the different requirements for low- and high-frequency reproduction.[3,4] We decided that a

FIG. 10. Unidirectional ribbon microphone (1932).

large folded horn with several large dynamic speakers coupled to the throat of the horn would be used to reproduce the low frequencies below approximately 1 kHz and, to reduce distortion, the higher frequencies would be reproduced by a straight axis, relatively small horn driven by a small dynamic speaker.[5,6] It was not difficult to obtain efficiencies of 50% or more at the lower frequencies using conventional dynamic speaker designs, but the efficiency of the high-frequency speaker dropped off appreciably at the upper end of the frequency range. To help increase the high-frequency efficiency, the magnetic circuit was improved to achieve an air gap flux density of 18 000 G. Figure 11 shows an early model of an improved four-post magnetic structure which replaced the conventional U-shaped magnetic yoke and achieved a large reduction in leakage flux, which made possible the higher air gap flux density.

To further increase the high-frequency efficiency, aluminum wire was substituted for copper in the voice coil, but this modification resulted surprisingly in a reduction in efficiency. This led to an in-depth analysis of the relationship between efficiency and the magnitudes of the various elements that made up the loudspeaker vibrating system. The result of this intensive investigation raised the average efficiency in the 4- to 8-kHz region from 5% to 20%, which resulted in a spectacular improvement in the quality of the reproduced sound.

Two basic requirements in addition to high flux density were found to be necessary to achieve high efficiency at the high frequencies: aluminum had to replace copper for the voice coil conductor, and most important, the mass of the aluminum coil had to be greater than approximately 1/3 thè total mass of the vibrating system.[7] This latter requirement had not been recognized and therefore the higher efficiency expected with an aluminum voice coil was not originally achieved. Figure 12 shows the ultimate voice coil design developed to maximize the amount of active aluminum conductor that could occupy the available air gap volume. An edgewise wound anodized aluminum ribbon produced a perfectly round, extremely rigid voice coil that achieved a 50% increase in the amount of voice coil conductor over the use of conventional round magnet wire.

FIG. 11. Improved high flux density loudspeaker magnetic structure (1933).

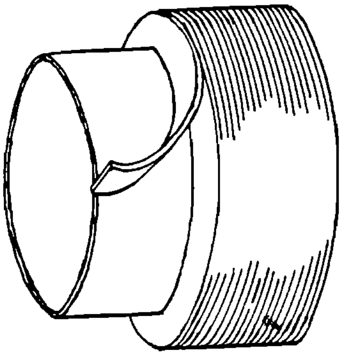

FIG. 12. Edgewise wound aluminum ribbon voice coil to maximize high-frequency efficiency of horn loudspeaker (1933).

The rapid strides in electroacoustic development were made possible by constantly improving our measurement techniques and test equipment to permit the recording of more accurate quantitative data during the progress of our work. At the suggestion of J. Weinberger, Director of our Acoustic Research Laboratory, Olson and I prepared a manuscript describing some of our work and laboratory techniques which was published in 1934 as a textbook.[9]

III. FURTHER DEVELOPMENTS

As we continued to apply our rapidly expanding knowledge in electroacoustics to satisfy the increasing market demands of the sound motion picture industry, a great interest was developing in the Navy Department for improving their methods of communication on battleships. An early development in which I became involved was the design of a lightweight sound powered telephone that would permit the direct transmission of speech without the use of batteries. The telephone unit was also required to withstand several vertical drops from a 6 ft height directly on the steel deck of a battleship. Additionally, the telephone could not change in sensitivity or frequency response when exposed to several rounds of naval gunfire while mounted on the 7-psi-blast pressure contour, which was considered the maximum blast pressure to which a person could be exposed without receiving permanent injury. Figure 13 shows the sound powered

FIG. 13. High efficiency blast-proof sound powered telephone element (1933).

telephone transducer element that satisfied the requirements.

Following the successful sound powered telephone development, a rugged blast-proof loudspeaker system was needed for shipboard installation. The use of conventional paper or aluminum diaphragms could not survive the blast pressure requirements, thus a satisfactory design was developed using a two-layer molded cloth-based diaphragm. Two layers of cotton cloth were first dipped in bakelite resin and dried, after which the two layers were oriented with the threads crossing at 45° and molded into a finished diaphragm including the outer suspension.

By the mid 1930s, the increased government need for electroacoustic transducers to meet very stringent demands for ruggedness and high reliability led RCA-Victor to set up a specialized government sound engineering laboratory; it became my responsibility to develop the new government electroacoustic products and undertake the production engineering function so that complete manufacturing drawings would be ready upon completion of the engineering prototype models. In order to insure the best production design, I had access to the expert advice of a dozen production engineering specialists who discussed the relative merits and cost effectiveness of the several alternate structural possibilities under consideration. From among several acceptable design choices the final selection was decided, based on the total quantities that had to be manufactured and optimizing the total savings versus the alternate increased tooling costs required to realize the anticipated savings.

During the first year of operation under my combined responsibilities of product development and production engineering, I thought very seriously of requesting that I be returned to my former research and development activities because I felt that the long hours I spent in production engineering conferences were taking up time that could be more effectively used in developing new products. Fortunately, these thoughts left my mind and during the next several years, I became as much interested and involved in the production engineering problems associated with the manufacture of the product as I was in the research work associated with its development. Many times, I have looked back on this particular period in my life, and I now know that I had the unique privilege of expanding my academic engineering training by becoming knowledgeable in production techniques, including production design, tooling, and assembly procedures. My close working association with a large group of highly competent production specialists exposed me to their individual skills over a period of several years, and in the process I learned much of their different specialized skills, which became a most valuable asset during my entire career.

As the decade of the thirties was drawing to a close, we had a tremendous backlog of Navy work and the government sound division, including manufacturing and engineering, was being moved to a separate plant in western Pennsylvania. Instead of moving to the new location, I accepted an offer to become Director of Acoustic Research for the Brush Development Company in Cleveland to find new applications for piezoelectric Rochelle salt crystals. The company's major income was from the sale of Rochelle salt crystal elements for use in phonograph pickups. Several months after joining Brush, a government ban on the use of critical materials for commercial application put a stop to the manufacture of radio sets, which brought an end to the sale of Rochelle salt phonograph cartridges. At about the same time, a former Camden associate who was called to active naval duty to take charge of expanded activities in naval ordnance, asked me to develop a hydrophone that could be assembled at spaced intervals along a long line that was to be towed along each side of a ship as part of a self-protection system against torpedo attack. The hydrophone was successful and resulted in my becoming totally involved in underwater transducer development and transducer production throughout the entire period of World War II.

IV. UNDERWATER MEASUREMENTS

In 1940, underwater sound pressure measurements were about as inadequate as were air sound pressure measurements before 1930. Also, in 1940, the standard Navy shipboard sonar employed a small Rochelle salt directional piston array operating at 24-kHz mounted back to back with a magnetostriction piston array that could be used as an alternate when the crystal transducer became inoperative. The transducer was rotated manually and was pulsed to echo range at successive bearings to search for submerged submarines in much the same manner as a depth sounder is operated today.

Rochelle salt had very undesirable characteristics, including a very low melting point in the vicinity of 130 °F and a Curie point at 75 °F, which caused enormous variations and nonlinearities in the electroacoustic performance characteristics of the transducer. It was evident that Rochelle salt had to be replaced before real progress in sonar transducer development could be achieved. In reviewing the properties of other piezoelectric crystals, it became evident that ammonium dihydrogen phosphate (ADP) was a superior material. An ADP transducer was built with experimentally grown ADP crystals to replace the standard Navy Rochelle salt transducer. The great increase in power handling capability and its vastly superior performance characteristics resulted in the immediate construction of a Navy sponsored ADP crystal growing plant in Cleveland; Rochelle salt immediately became obsolete for use in new transducer developments.

ADP was successfully used in the development of numerous transducers for operating at frequencies ranging from the subsonic to the high ultrasonic range and for new uses in acoustic mines, acoustic torpedos, passive and active harbor protection, and underwater detection systems. Wide range ADP hydrophones were developed for a variety of broadband receiving applications. The ADP crystal also permitted the development of a very stable underwater sound pressure measurement standard that became widely accepted by the Navy and other underwater acoustic testing facilities.

Numerous ADP transducers were developed for dozens of new sonar applications and many tens of thousands of the new transducers were manufactured in Cleveland during the period of World War II. In 1945, Massa Laboratories was established in Cleveland; its pioneering work in the development and manufacture of electroacoustic products and sonar transducers continues to this day at Massa Products Corporation in Hingham, Massachusetts.

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