DEVELOPMENT, DESIGN AND CONSTRUCTION
OF
ELECTRICAL CONDENSERS

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I came here today to talk to you about electrical condensers.

Any electrical apparatus, however complex, is composed-essentially - of one or more devices employing inductance, resistance, or capacity. They are the building blocks of electrical engineering.

The use of inductances permitted the development of transformers, electromagnets, electric motors, generators and similar appliances.

The use of resistors made possible the development of electric lights, electric heaters, controls, and the like.

But modern electrical engineering would have been impossible without the use of condensers - millions of condensers, of many types and sizes - some of them as tiny as the one I hold in my hand, others as large as a room.

The condenser is an old invention but a recent development. Forty years ago in 1910, we already had a sizable electrical industry - all of it based on electrical devices employing primarily only inductance and resistance. The only practical power condenser then available was the glass Leyden jar, or the equivalent - the glass plates. The telephone and telegraph industry, operating with only minute energies, had a primitive low-voltage low-power paper condenser. For higher voltages and higher powers we used glass plates, or the equally inefficient, cumbersome, fragile Leyden jars.

The Leyden jar was invented in 1746 by Deen Van Kleist. It was referred to by Benjamin Franklin as an "accumulator" of electrical energy. Later, it was used extensively in medical and wireless telegraph equipment. The Leyden jar remained practically unchanged for more than 200 years, retaining essentially the same shape, design and construction.

I brought with me three historic books, published nearly 200 years ago. They describe the electrical knowledge as it existed in those days, and the early condensers - the Leyden jars. I will leave these here as a gift to your library.

As I said, in 1910, there already existed a sizable electrical industry. There were many thousands of high-tension electro-medical machines, thousands of wireless telegraph installations - all using the standard, fragile glass jar. Radio communications with ships at sea, and between the ships of all the navies of the world, all depended on the Leyden jars.

A short history might be of interest. Practically all of the Leyden jars were made in Germany. The German government subsidized the industry and discouraged foreign development. Up to 1912, all commercial and other wireless equipment used Leyden jars made in Germany.

The British Navy realized that their entire communications system was dependent on a foreign power. When I was visiting England, in 1911, the government invited me to assist them in finding a substitute for the Leyden jar. Thus the modern power capacitor was born.

WE BEGAN with crude tools. We were lone workers, shaping the individual bricks of knowledge, Today, the edifice of knowledge is a towering vastness: new bricks are being added daily, raising it ever higher - and I doubt that a single human mind could encompass all the knowledge it contains. We did not know nearly as much about electrons and atomic structure as you do today; wave mechanics were nearly two decades in the future. Today, your universities and research institutions supply you with vast facilities, and with the foremost scientists and teachers. Yours will be the greater progress, and the wider horizons of new knowledge.

In the beginning our progress was slow. We gained new knowledge experimentally, by trial and error. This gave us experience and developed our imagination. Experience and imagination make an ideal marriage.

The rocky road of progress is hard. There are many obstacles to be overcome, and the inertia of public opinion is not the least of these. If radio broadcasting were developed before the telephone, and then someone invented a method of making broadcasting secret, by simply guiding the waves along a thin metal wire, he would receive public acclaim.

This very lack of secrecy is now the very basis of broadcasting. No one back in 1910 dreamed that great orchestras would flood a continent with fine music - that the voice of the President would penetrate millions of homes, or that political fanatics to be called Nazis and Communists would try to influence the populations of neighboring countries with broadcast propaganda.

A little more than a century ago, when trains were first developed, a speed of 12 miles an hour was considered the limit of human endurance. The medical profession, newspapers and others, were quick to point out their terrible menace and danger to humanity. They predicted that a speed of 15 miles an hour would cause nosebleeds, deafness and even death. I recall that in my own boyhood, automobiles were prohibited in many sections - they frightened horses, and a speed of 25 miles an hour - "without tracks" as an old ordnance put it - was "dangerous". There were local laws to keep automobiles off the roads - and there was broken glass to cut our tires, and streched wire to cut our necks. The man who first drove an automobile through Central Park in New York was arrested for disorderly conduct.

When I was a lad, a bearded German professor named Roentgen, had discovered some mysterious X-rays which made it possible to photograph bones in the living body. The now-defunct Pall Mall Gazette of London was horrified. It protested against what it called the "revolting indecency of making pictures of our insides" and hoped something would be done to "thwart the shameless experimenters who were beginning to supply the discovery". This Newspaper stated that it would be possible to see through the clothes of people walking in the streets.

We had similar obstacles to overcome.

The eventual adoption of the new compact and efficient power capacitors permitted the development of many branches of electrical industry, with its high-frequency equipment and vacuum tube applications. Powerful broadcasting and communications stations, and other high frequency equipment, would have been impractical because of the prohibitive size, cost and inefficiency of the glass jar.

THE CONDENSER appears to be the simplest of all electrical devices -- a pair of conducting sheets separated by insulating layers. Actually, the condenser is probably the most complex of the electrical elements. It has more hidden problems than any other electric device, and is more difficult to produce.

Today, we take our condensers for granted, and expect them to do their job with precision. We can do so only because much ingenuity and many inventions resulting from patient research went into their design and construction.

THE FIRST development that broke the German Leyden-jar monopoly was our mica condenser.

Here is a display showing its elements...

(D E M O N S T R A T E)

Up to 1910, all technical publications and textbooks were in agreement that mica was, theoretically, a more efficient and suitable material than glass. Yet, there was no practical mica condenser, one that could withstand for long periods of time high voltages or high power without deterioration and breakdown. The phenomena of corona, hysteresis, eddy currents, ionization, and above all mechanical losses in capacitors, were either misinterpreted or unknown.

In the design and construction of insulators and insulating materials, whenever higher voltages were involved, it was the customary practice to make the insulating material thicker and larger.

I found that corona, or brush discharge, was particularly destructive, and that it invariably started at potentials of around 1000 volts. To overcome this, I did not "make it thicker and larger". Hundreds of condensers were made and tested, all having units of various thicknesses, to which different potentials were applied. These were carefully disected and examined.

Tests showed that, at 5 times the thickness of the insulating material, the corona began at less than 2 times the previous corona potential. I therefore concluded that, irrespective of the voltage applied to the condenser, the voltage across any two adjacent electrodes must always be less than 1000. This was the origin of the corona-free condenser.

This mica was carefully sealected, eliminating sheets counting air bubbles, stains, metallic particles, and minute pinholes and cracks. To do this efficiently was a difficult task. The normal tendency would be to use a number of multiple sheets with the chance that no two pinholes or cracks would coinside. For an efficient condenser, a solid, single sheet should be used. I had to originate and develop a single fixture whereby each sheet was placed in a rack and a high-

sparking potential was applied across the sheet. The operator could then observe visually if the sparks penetrated through the sheet or around the outside. For this purpose, I used an ordinary ignition spark transformer from an old Ford car. The sheets were tested efficiently, and the fixture had to be arranged to avoid shock to the operator. During this development, we found strange phenomena, A thin sheet of mica, such as you observed of approximately 2 mills thick, was tested with sparks longer than 1/2 inch - many thousands of volts. It would not break down.

Once, many of the same quality mica sheets began to break down. I found that these sheets were handled by an operator on a bench where there were small particles of wax and some minute traces of oil, that adhered to the mica. When the spark struck the spot with a little wax or oil, it immediately broke through. The sheets therefore had to be carefully and cleanly handled.

After the corona was eliminated, some condensers still became hot and broke down. We found that in some cases certain spots in the armatures became discolored because of concentrated heat.

I recalled my school days and the teacher's demonstration of the "talking book" telephone. The "talking book" was a loosely arranged condenser made by placing light metal foils between the pages of a book. When connected to a microphone and a battery, the book "talked". I connected the book across a 60-cycle supply, and it gave a tremendous hum. I recalled that I tried to stop it by pressing the book with my hand, and soon found that the book became hot.

It was this school lesson that helped me eliminate the hot spots. I reasoned that, whatever the frequency, be it a hundred thousand or a half million cycles instead of sixty or a few hundred, a minute movement of the electrodes resulted in heavy power losses. Hence, it was necessary to obtain an intimate contact between the foil electrodes and the mica sheets.

I found that the surface of mica sheets, although it appears perfectly smooth to the eye, is in reality full of microscopic hills and dales. Therefore, a special type of soft metal foil was developed, one that would flow and inbed itself into the fine crevices of the mica sheets, resulting in an intimate contact throughout the condenser. This was the second major improvement which made the mica condenser practical.

With heavy currents, such as are encountered in high-frequency equipment, 1^R2 loss became a serious factor. To reduce this loss to a minimum, changes were made in the shapes, sizes, and assembly. The units were evacuated and impregnated with certain compounds at various temperatures. We were able to reduce the size of the mica condenser to less than 10% of the equivalent Layden jar, and the losses by more than 90%.

Ours being a new development, we were subjected to most rigid specifications. Although the size and therefore the radiating surface were considerably reduced, and consequently heat generation due to losses was also reduced, instead of allowing us a temperature rise equivalent to that allowed in Layden jars, we were limited to 10°C., in places where the equivalent Layden jar became so hot that many times the glass melted, and cooling fans were therefore necessary.

Not only did we reduce the overall dimensions of the capacitor, but we also eliminated a great deal of such associate equipment. The importance of this can be realized when we recall that in a radio installation on board a battleship, Leyden jars usually occupied more than 50% of the equipment space.

In all capacitors, we have a vicious cycle. Increased heat results in increased losses -- which in turn causes more heat, and that causes more losses -- and so the temperature rises until the unit breaks down. That is why heat rise control is so important .

For a while, our government distrusted this new and revolutionary condenser, as lives and ships depended on its continued safe operation. To meet the exacting government specifications, we produced units where the heat radiation was equal to the heat generation, and thermal stability was reached within less than 10°C.

Now every broadcasting station, radio communication and other high frequency equipment use condensers as originated by us.

PAPER CONDENSERS

These employ impregnated paper as the dielectric. Here we have a display showing their construction.

The paper condenser, as you see, looks quite simple. But it is extremely difficult to engineer and produce.

Consider the paper that serves as the dielectric. Many of our capacitors contain enough paper to cover the walls of a room. A single microscopic defect, a mere pinhole, will cause the entire condenser to fail.

In modern condenser factory, the material controls which apply to the paper being with the manufacturer of the paper itself. He must carefully control the chemical content of the water used for washing the pulp from which the paper will be made. He must control, within close limits, the ash content, the acidity, the alkalinity, the porosity, and the residual moisture in the finished product, Minute metal particles from the paper-making machines find their way into the paper. Uniformity of paper thickness is exceedingly important, as the cost and the bulk of condensers increase as the square of the thickness.

The design of metal electrodes, and the composition of the metal foil, are equally important, Under certain operating conditions, metal particles detach themselves from the foil and penetrate the paper, resulting in disintegration and breakdown of the condenser, Aluminum foil has been found to minimize such ionic effects.

Paper condensers are impregnated with various insulating materials, such as waxes, oils, chlorinated diphenyl preparations, and others. These must be constantly tested before using, and must be free from contamination. Blending some of the impregnants results in improvements; other blends produce poor results.

Condensers are impregnated under vacuum, and the production cycle sometimes takes more than 150 hours. The vacuum is as low as 100 microns, and the temperatures are about 250°F.

The manufacture of paper condensers is a controlled precision operation from start to finish. Materials must be kept free from contamination. We must even guard ourselves against the effects of perspiration of the assembly workers.

The fibrous paper and the impregnants alike have a great affinity for moisture. Unless thoroughly sealed, they can absorb a great deal of moisture from the atmosphere. on an ordinary humid day, in a few hours the units may become unfit to use.

To guard against moisture absorption, paper condensers are assembled and impregnated under carefully controlled conditions, and then hermetically sealed. The seal itself must withstand the internal expansion and contraction over a wide temperature range.

There are many other, unseen dangers. The condenser may operate satisfactorily for a length of time, with some slight defects. Under power strains, internal heat is generated due to the various losses. Unless proper precautions are taken, fatty acids may be formed inside the unit. In many instances, inhibitors must be added to the impregnants. As the impregnants are forced into the units under vacuum at elevated temperatures, it eliminates one of the possibilities of deterioration during operation.

The completed unit is tested at approximately twice its normal operating voltage, and its terminals at five times. It is then passed through long heated ovens for detection of minute flaws. Finally, the unit is given an accelerated heat test under power overload.

These are some of the problems in condenser manufacture. Many special unforeseen problems arise, which must be solved. Here in an interesting puzzle that gave us many a sleepless night.

We made a large number of paper condensers, rated at 660 volts, for a new high-voltage anode supply source, which operated over long continuous periods. Before shipment, they were all tested at 6000 volts. The breakdown tests showed more than 10,000 volts. Under normal conditions, they should have lasted almost indefinitely.

A few months later, many of these condensers failed in service and were returned to us. We were mystified. Investigation showed that dark streaks and spots had developed on the paper inside the condensers.

It took much time and work to analyze and solve this riddle. The condensers were impregnated with a refined paraffin wax, as we had practiced successfully for many years.

We discovered that when the condenser units were removed from the impregnating tanks, the outside of the units cooled rapidly and formed a hard solid shell. But the centre retained its heat for a much longer period, keeping the wax soft and fluid. As the centre finally cooled and contracted, minute spaces were formed internally, sealed by the solid outer crust. Gases filled these spaces, and the gases glowed at potentials of 200 volts or less. Our condensers, in effect, contained miniature glow lamps.

When subjected to long continued periods of operation, enough heat was generated to destroy the insulation, causing breakdowns. Thus, condensers made to operate reliably at thousands of volts may break down at a potential of a few 100 volts, unless precautions are taken to prevent ionic discharges within the unit.

In addition, the uneven contraction of the wax also imposed severe mechanical strains and distortion along the insulating layers.

This was a serious problem, and one that we had to overcome at once. Finally, one of my assistants suggested cooling the condensers under oil. This allowed the entire impregnated mass to cool without the hard shell.

This cooling process increased the life of the condenser tenfold, and its rated safe operating voltage from 3 to 5 times. This simple manufacturing improvement proved to be one of the most important and revolutionary developments in wax-impregnated condensers, and now is universally used in the manufacture of high voltage capacitors.

ELECTROLYTIC CONDENSERS...Here we have a display showing how they are made.

(DEMONSTRATE)

Up to 1925, one of the basic precautions taught to every condenser worker was to be always on guard against any risk of contamination of condenser materials by outside chemicals-alkalis or acids.

We knew, from our own sad experiences, that a single drop of water or acid in a gallon of impregnating oil or wax would make the entire batch of material unfit for use.

We were so thoroughly trained in strict precautions against chemical contamination of our condenser materials, that the very idea of making a chemical condenser seemed at first frightening.

Although we knew that metallic oxides were good insulators, we also knew that strong acids are needed for the formation of such oxides on aluminum foil--and strong acids could never be tolerated in or near a condenser plant.

These were the mental roadblocks that the new electrolytic condenser had to overcome. Yes, we were slow and cautious in accepting the electrolytic condenser. But today, it has found its rightful place in industry, especially for starting small AC motors, and in filtering circuits.

I have with me today one of our plant managers, Doctor Deeley, who had considerable experience in their development and manufacture, and is the author of a well-known book on this subject. He will answer any questions and discuss details with you.

I WILL CONCLUDE my talk by showing you some examples of recent developments in ceramic condensers. Mr. William Bailey, our chief engineer, and Dr. Paul Deeley will gladly answer any question and give you further details.

(DEMONSTRATE)

During the First World War, the Germans purchased, through Holland, a number of our transmitting condensers, and copied them, Japanese fashion. These were shipped by us in 1916, and I knew that they were destined for Germany. After the War, in 1920, I visited Berlin. The Telefunken Company, which was then the largest radio organization in the world, showed me thousands of units made exactly like ours. Most of them failed after a few weeks service. I knew they would fail-- another proof that experience is necessary for success.

Ceramic condensers originated in England, about a quarter of a century ago. However, they received their highest development in Germany, after the First World War -- again with the aid of financial subsidies from the German government.

At the end of the First World War, the new mica condensers were used extensively, in transmitters and other electrical equipment. Germany had no mica supply of her own, they heavily subsidized and encouraged the development of ceramics to replace mica.

The resultant ceramics were much stronger and had lower losses than the old wet-process porcelains. The development of low-loss ceramic insulators, particularly those with high capacitance possibilities, may affect the electric power industry.

Units were made of many materials, such as magnesium, and later the titanates. Their production required higher firing temperatures and closer manufacturing tolerances and controls.

Ceramic condensers were gradually improved until the overall efficiency of the best German-made condensers during the last War was about equal to mica condensers of similar dimensions.

Since then, American manufacturers concentrated on the development of titanates, mostly for use in low-voltage applications. Titanate compounds have the advantage of posessing a large capacity, and occupy but a small space.

We have made some ceramic condensers with a K as high as 500,000. The losses, however, were more than 30 percent. (The K of mica is about 7; that of the paper, around 4; of paraffin around 2.

Improvement in ceramic condensers has been rapid. At present, large quantities of ceramic condensers are being made, with a K of between 3000 and 5000, with losses as low as 2 percent. Recent developments in low loss ceramics shows most encouraging results.