DEVELOPMENT, DESIGN AND CONSTRUCTION OF ELECTRICAL CONDENSERS

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1824

Reprinted from Journal of the Franklin Institute,
Vol. 248, No. 3, September, 1949

Reprinted from JOURNAL OF THE FRANKLIN INSTITUTE,
Vol. 248, No. 3, September, 1949
Printed in U. S. A.

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DEVELOPMENT, DESIGN AND CONSTRUCTION OF ELECTRICAL CONDENSERS *

BY

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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 not much larger than a match head, others as big as a room.

THE COMING OF THE MODERN CONDENSER

The condenser is an old invention but a recent development.

The first electrical condenser, 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.

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 its equivalent, the glass plates.

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* Based on a paper presented before the Seminar of Electrical Engineering, Princeton University, Princeton, N. J., February 28, 1949.

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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 standard, fragile glass jar was then used in the many thousands of high-tension electro-medical machines, in thousands of wireless telegraph installations. Radio communications with ships at sea, and between the ships of all the navies of the world, all depended on the Leyden jars.

Here is an interesting footnote to history. Up to the end of 1911, practically all of the Leyden jars were made in Germany. All commercial and military radio installations used German-made Leyden jars. The German government subsidized the industry and discouraged foreign development.

The British Navy realized that its 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.

THE ROCKY ROAD OF PROGRESS

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 we do today; wave mechanics were nearly two decades in the future.

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 had been developed before the telephone, and then someone had invented a method of making broadcasting secret, by simply guiding the waves along a thin metal wire, he would have received public acclaim.

A little more than a century ago, when trains were first developed, a speed of twelve 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 fifteen 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 twenty-five miles an hour—"without tracks," as an old ordinance put it—was "dangerous." There were local laws to keep automobiles off the roads; and there was broken glass to cut our tires, and stretched wire to cut our necks. The man who first drove an automobile through Central Park in New York was arrested for disorderly conduct.

Long ago, when I was a lad, a bearded German professor named Roentgen 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 as they walked in the streets.

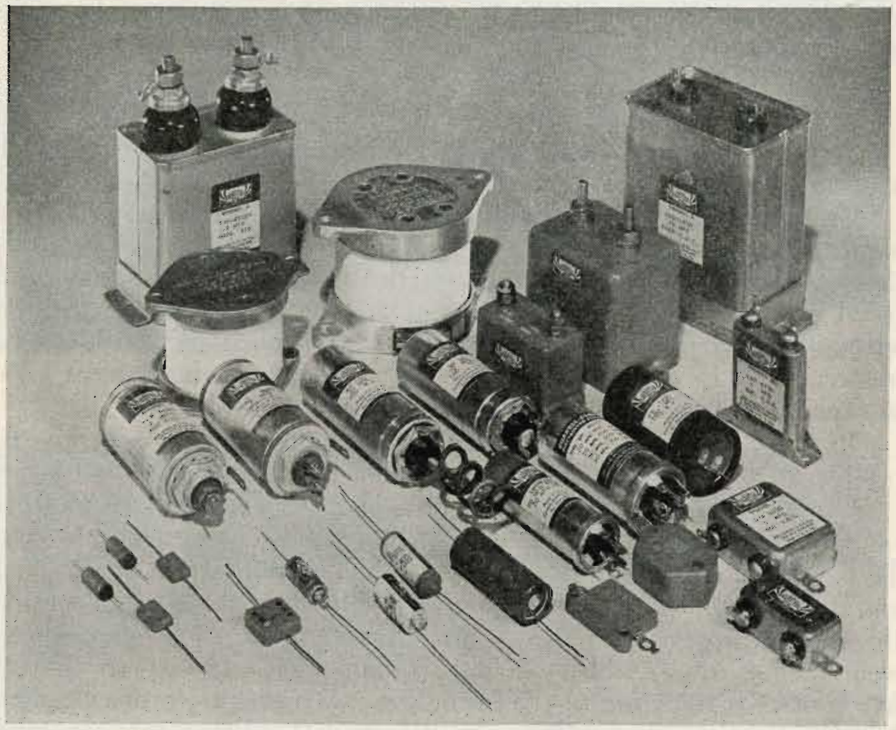

FIG. 1. Representative group of small electrical condensers showing variety of shapes and sizes.

We, too, had similar obstacles to overcome.

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 electrical 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 eventual adoption of the new compact and efficient power capacitors permitted the development of many branches of the 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 MICA CAPACITOR

The first development that broke the German Leyden-jar monopoly was our *mica condenser.*

Up to 1910, all technical publications and text-books 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 those days 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." We made and tested hundreds of condensers, employing materials of various thicknesses, applying to them different potentials. These condensers were then carefully dissected and examined. Tests showed that, at five times the thickness of the insulating material, the corona began at *less than two times* the previous corona potential. I therefore concluded that the voltage across any two adjacent electrodes must always be less than 1000, irrespective of the total voltage applied to a condenser. This was the origin of the corona-free condenser.

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

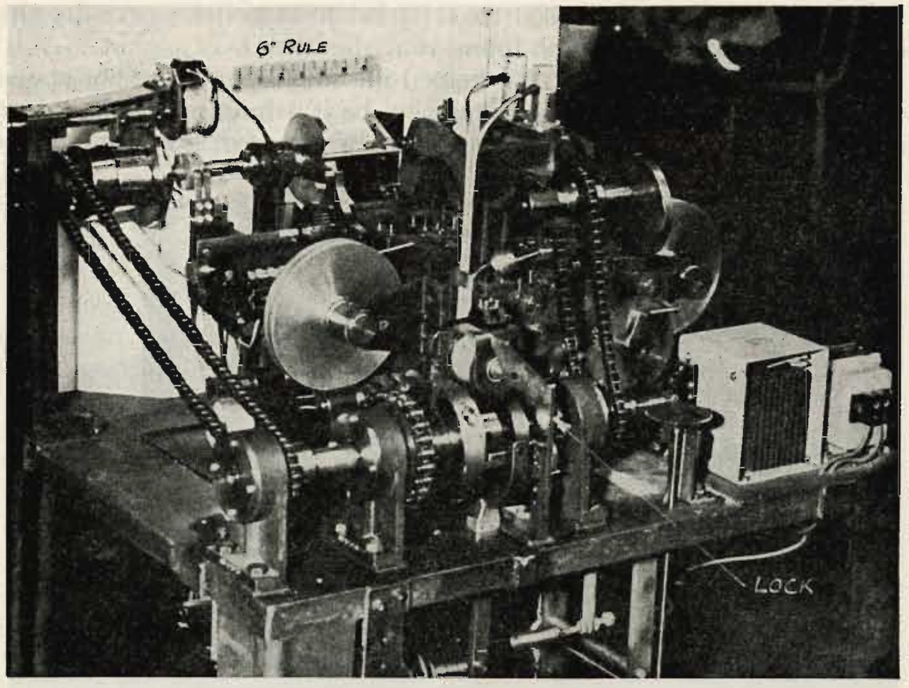

FIG. 2. An automatic machine for making mica condensers.

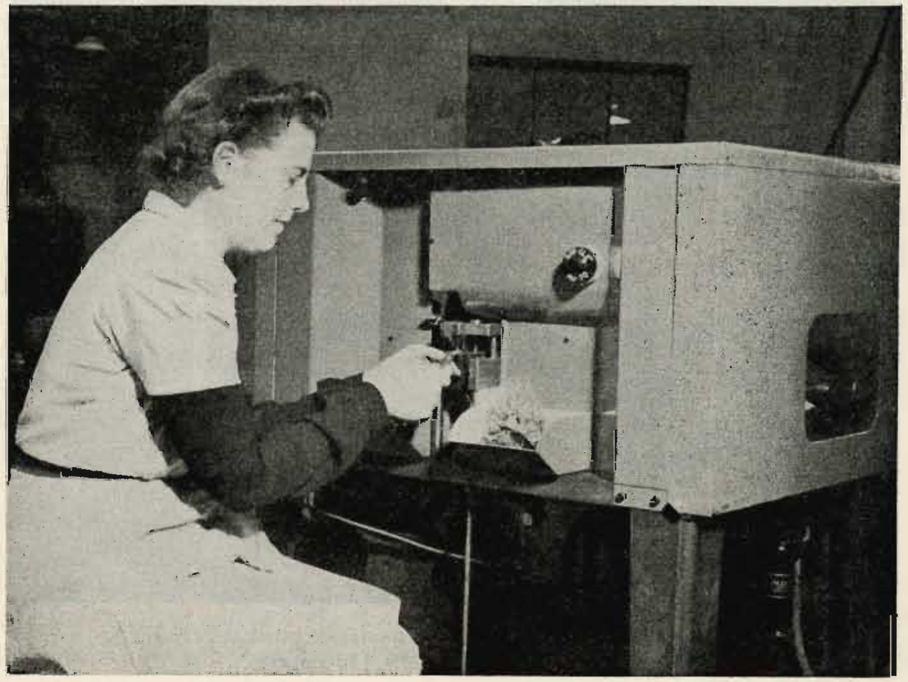

FIG. 3. Finished condensers being ejected from the machine shown in Fig. 2.

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 to eliminate the hot spots. I reasoned that, whatever the frequency, be it a hundred thousand or half a 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.

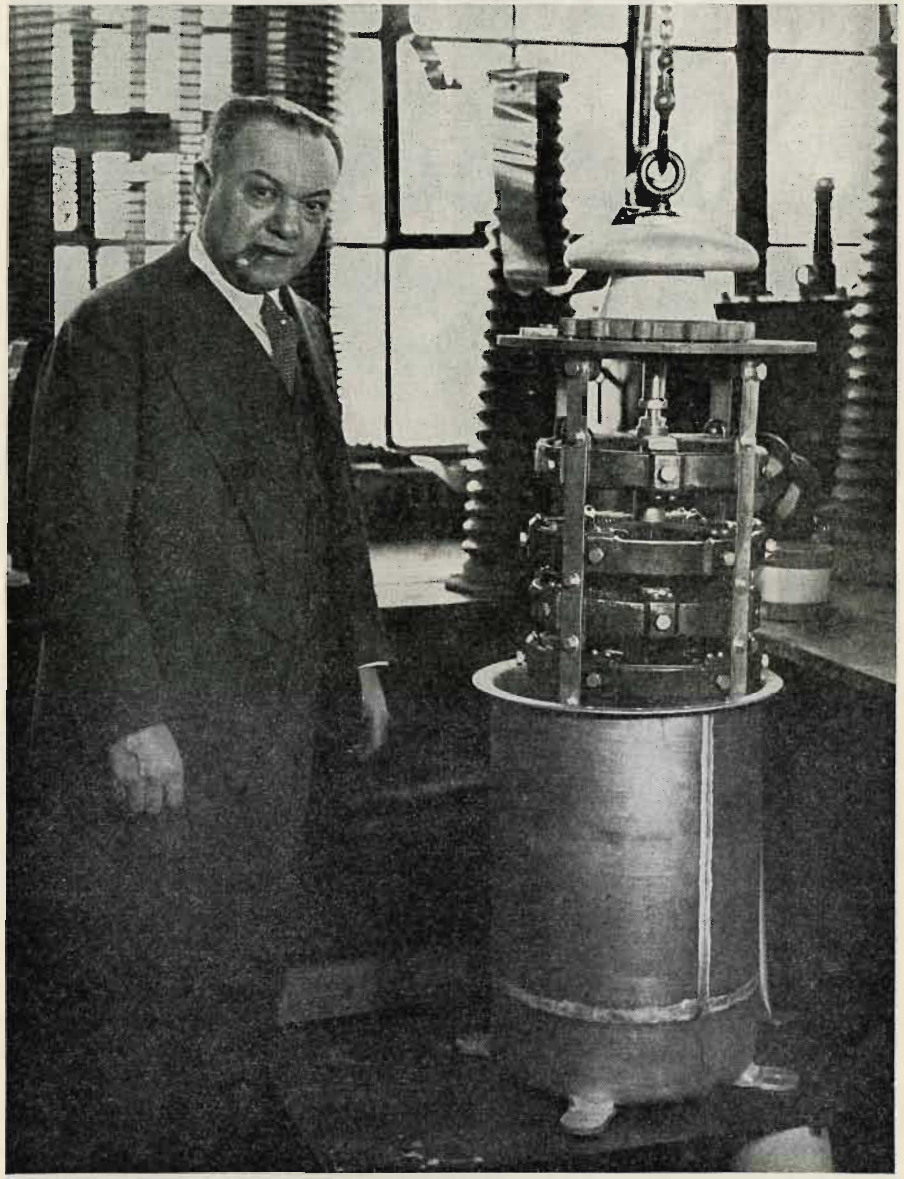

FIG. 4. The author, with a large mica condenser rated at 2250 KVA. for operation at 15,000 volts, 150 amperes.

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 imbed itself into the fine crevices of the mica sheets, ensuring 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, X^2R 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 per cent of the equivalent Leyden jar, and the losses by more than 90 per cent.

Ours being a new development, we were subjected to most rigid specifications. Although the size (and therefore the radiating surface) was considerably reduced, and consequently heat generation due to losses was also reduced, instead of allowing us a temperature rise equivalent to that allowed in Leyden jars, we were limited to 10° C., in places where the equivalent Leyden 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 per cent of the equipment space.

For a while, the government distrusted our 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.

Today, it is a source of some satisfaction to us that every radio broadcasting station, every radio transmitting station on land, at sea or in the air, and other high-frequency electrical equipment use mica condensers as originated by us forty years ago.

PAPER CONDENSERS

Paper condensers employ impregnated paper as the dielectric. Paper condensers look quite simple, but their appearance is deceiving. They are 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 pinpoint, will cause the entire condenser to fail. In a modern condenser factory, the materials controls which apply to the paper begin 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 paper-making machines find their way into the paper, impairing its dielectric efficiency. Paper thickness is exceedingly important, as the cost and the bulk of condensers increase as the square of the thickness.

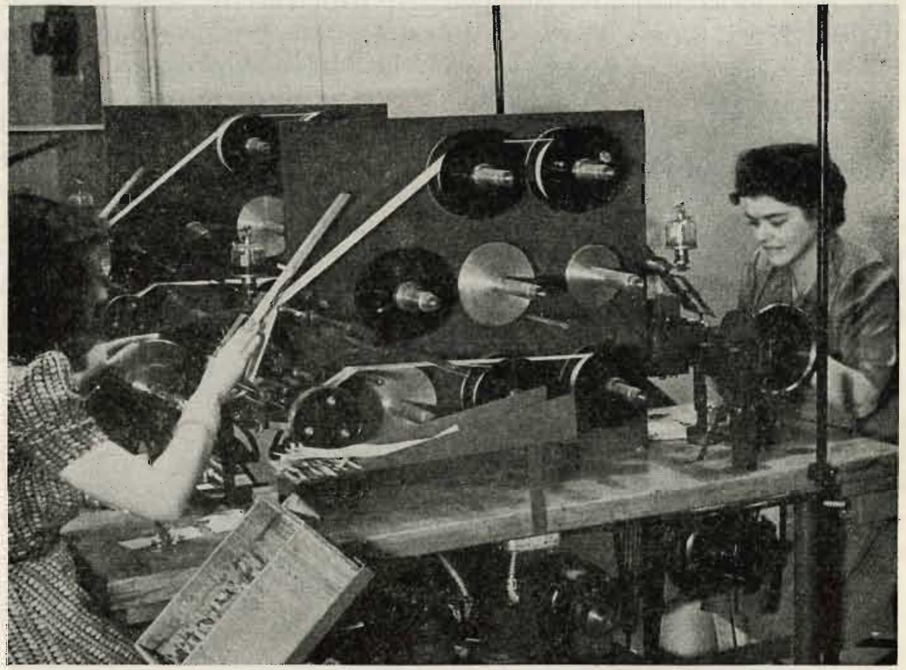

FIG. 5. Winding paper condensers.

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 hr. 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 effect 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 for 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. A slightly defective condenser may operate satisfactorily for a length of time, but 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.

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 only some of the problems in paper condenser manufacture. Many other, unforeseen problems arise, which must be solved.

Here is an interesting puzzle that gave us many a sleepless night. We made a large number of paper condensers, rated at 600 volts, for a new high-voltage anode supply source operating over long continuous periods. Before shipment, our condensers were all tested at 6000 volts. The breakdown tests showed more than 10,000 volts. The condensers were impregnated with a refined paraffin wax, as we had practiced successfully for many years, and under normal conditions would 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.

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 center retained its heat for a much longer period, keeping the wax soft and fluid. As the center 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. In addition, the uneven contraction of the wax also imposed severe mechanical strains and distortion along the insulating layers. Thus, condensers made to operate reliably at thousands of volts may break down at a potential of a few hundred volts, unless precautions are taken to prevent ionic discharges within the unit.

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 three to five 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

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 a-c. motors, and in filtering circuits.

Although the electrolytic condenser seems to the eye to be much more complex, the problems of its manufacture are nowhere near as great as those of mica and paper condensers.

CERAMIC CONDENSERS

During the First World War, the Germans purchased, through Holland, a small number of our transmitting condensers, and copied them, Japanese fashion. Those 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. The best mica came mostly from England and India. Therefore, Germany 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. 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.

The development of low-loss ceramic insulators, particularly those with high-capacitance possibilities, soon affected the electric power industry.

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 possessing 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 per cent. (The K of mica is about 7; that of 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 per cent. Recent developments in low-loss ceramics show most encouraging results.

WHAT OF THE FUTURE?

The future progress in electricity and radio is inseparable from progress in condenser design.

Inductances and resistances have never presented serious design or manufacturing problems: they are not likely to present them in the future. But the third of the building blocks of electrical engineering—the condenser—remains a limiting factor in applied electrical and radio engineering.

Forty years ago, our horizons limited by the old Leyden jar, we could not foresee the variety, the complexity, the utility of modern electrical apparatus. New and better condensers were a major factor in making the modern electrical and radio industry possible. Today, forty years later, our eyes can see farther, and our vision is clearer. With our mind's eye we can see the magnificent vistas which the development of newer and better condensers may bring about comparatively few years from now.

There always is something newer and better waiting to be developed. Forty years ago, the new compact mica capacitor replaced the Leyden jar. Today, its supremacy is already threatened by the newer types, such as for instance the ceramic capacitor, and the yet-newer vacuum-tube type. And yet, such is the excellence of the modern mica condenser that it will never be eliminated or supplanted by others; rather, the newer capacitors will open new fields, will make possible new apparatus as yet in the dream stage.

It is a thankless task to prophesy; but, given capacitors smaller and more efficient than the best we have today, such obvious new devices as vest pocket telephone transmitters, capable of reaching a relay station a few miles away, would be a practical possibility. Those same condensers would also permit us not merely to bounce a few radar pulses against the surface of the moon, as was done some two years ago, but to maintain communications with the space ships which will inevitably venture forth in a few years, ranging farther afield than the moon, into the solar system, perhaps beyond.

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