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Nikola Tesla

Electricity today is generated, transmitted, and converted to mechanical power by means of his inventions.

Kenneth M. Swezey

At the stroke of midnight between the 9th and 10th of July, 1856, a son, Nikola, was born by candlelight to the Rev. Milutin and Djouka Tesla, in the tiny village of Smiljan, Lika, now part of Yugoslavia (Fig. 1). The child's father was pastor of the local Serbian Orthodox church; his mother, though an accomplished needleworker and inventor of household devices, could neither read nor write. From this humble and seemingly unpropitious beginning, Nikola Tesla, driven by some strange, compulsive genius, grew to become a discoverer and inventor whose contributions were, within his lifetime, to change the life and industry of the whole world.

Mention any of today's applications of electricity—and even some not yet fully developed—and the chances are good that Tesla had a hand in their concept and early development. In an incredible flight of achievement, beginning in the early 1880's and racing on for more than two decades, Tesla made basic discoveries and inventions in radio, the wireless control of boats and torpedoes, high-frequency induction heating, electrotherapeutics, gaseous tube and fluorescent lighting, electric clocks, x-ray equipment and techniques, and even rudimentary electric "brains." Before Marconi had flashed his first feeble "S" across the Atlantic, Tesla had already announced plans for a "World Wireless" system which would not only include point-to-point communication but the broadcasting of speech, music, time, and pictures. Tesla's induction motor and related polyphase system for the generation, transmission, and utilization of electric power made possible the first harnessing of Niagara Falls and laid the foundations for the whole modern electric power industry.

Mr. Swezey, a science and engineering writer who resides at 163 Milton Street, Brooklyn, N.Y., was a close personal friend of Tesla.

Tesla Centennial Celebrations

On 10 July 1956—the 100th anniversary of Nikola Tesla's birth—scientists and engineers from all over the world met in Belgrade, Yugoslavia, to pay homage to the memory of this great pathfinder. Convoked under the auspices of the National Yugoslav Tesla Committee, the Society for the Promotion and Advancement of Science and Technology, "Nikola Tesla," and the Nikola Tesla Museum (Fig. 2) of Belgrade, this celebration marked the beginning of a year of commemorative programs in Europe and America.

Niels Bohr of Denmark, Sir Arthur Fleming of England, Fredrik Dahlgren of Sweden, and Carl C. Chambers of the United States were among the more than a hundred distinguished guests. Richard C. Sogge, delegate of the American Institute of Electrical Engineers, presented a citation to the Tesla Committee from that institute. President Dunsheath of the International Electrotechnical Commission brought word that the commission, at its meeting in Munich, 29 June–7 July, had recognized Tesla's fundamental contributions in the field of electricity by adopting the name "Tesla" for the unit of magnetic flux density in the meter-kilogram-second or Giorgi system.

Although Tesla was born a Serb, he came to America in his late twenties and soon became one of our greatest Americans-by-adoption. Among the American celebrations of his centennial, one of the most important was that of the American Institute of Electrical Engineers, which dedicated to Tesla its Fall General Meeting in Chicago, 1–5 Oct. 1956. Apparatus, photographs, and reminiscences were presented at this meeting, and Samuel G. Hibben, past president of the Illuminating Engineering Society, demonstrated how Tesla's gaseous-tube lighting experiments of the 1890's helped blaze the way for some of the latest developments of today in the field of lighting. Hibben repeated this demonstration on 15 May 1957 at a commemoration sponsored by the Franklin Institute of Philadelphia, where Tesla in 1893 had given one of his most famous lectures. Other memorials were arranged by the Institute of Radio Engineers and the Niagara Falls International Section of the American Institute of Electrical Engineers.

One of the chief objectives of these programs was to sift truth from legend and to set down, evaluate, and publicize some of the great concrete contributions Tesla has made to science and engineering.

Tesla's Greatest Contribution

To those who know of Tesla chiefly through association of his name with the "Tesla coil," it may come as a surprise to learn that his greatest contribution was not this popular device for making high-frequency, high-voltage demonstrations but his discovery of the rotating magnetic field and his brilliant adaptation of it to the induction motor and the polyphase system for the generation, transmission, distribution, and use of electric power. It was this motor and system that was instrumental in changing the era of local electric lighting and a steam engine in every factory to the present age of electric light and power everywhere. Today, practically all the electricity in the world—more than 1500 billion kilowatt-hours in 1957—is generated, transmitted, and turned back into mechanical power by means of these inventions.

The story of Tesla's epoch-making motor and system begins in 1878, during his engineering training at the Polytechnic School at Graz, Austria. Although his father and mother wanted him to become a clergyman, Tesla had begun early to lean toward mathematics and physics. Demonstrations of mechanical and electrical apparatus in the elementary schools in Smiljan and Gospić, and in the higher *Real Gymnasium* in Karlovac, fanned his interest. During convalescence from a nearly fatal attack of cholera, Tesla finally prevailed upon his father to send him to the school at Graz, one of the oldest technical institutions in Europe.

One day Professor Poeschl—Tesla's teacher in theoretical and experimental physics—was demonstrating, before his class, a Gramme direct-current dynamo which had just been received from Paris, running it as a motor. Observing a lively sparking at the commutator and brushes, Tesla ventured to remark that somehow a motor might be invented that would not need brushes (*1*). Such heresy was too much for Poeschl. Likening the idea to that of a perpetual-motion machine, he proceeded to entertain the class and embarrass Tesla by explaining in detail why such a motor would be an impossibility!

At first impressed by Poeschl's arguments, Tesla soon fell back on his own intuition. Through the remaining term he struggled with the problem, designing and redesigning all sorts of direct-current and alternating-current machines in his imagination. In 1880, he transferred to the University of Prague, in Bohemia, and the next year he took a position as chief electrician with the newly formed telephone company in Budapest, Hungary. By this time, the problem of designing a brushless, commutatorless motor had become an obsession. Back in the deeper recesses of his mind Tesla felt that a solution was forming, but he could not give it outward expression.

Late one afternoon in February, 1882, the answer came (*1*). Tesla was walking with a friend, Szigety, through the City Park of Budapest, reciting stanzas from Goethe's *Faust,* which he knew by heart. Suddenly the solution he had been seeking flashed through his mind. He saw clearly an iron rotor spinning rapidly in an electric whirlwind—a rotating magnetic field produced by the interaction of two alternating currents out of step with each other. With a stick, Tesla drew diagrams on the sand, explaining in detail to Szigety the principle of the induction motor Tesla was to patent in America six years later!

From early childhood Tesla could visualize so clearly that he often had difficulty in distinguishing real objects from their counterparts in his imagination. This ability, often annoying and even frightening in ordinary life, Tesla used advantageously in inventing. By means of it he could, for instance, assemble and reassemble mechanical parts, alter sizes, weights, and materials entirely in his mind, and end up by building a model that would generally work exactly as he had conceived it (*2*).

Elated by his discovery in the park, Tesla began to picture in his mind actual machines that would make use of the principle. Within two months he had evolved practically all the types of motors and modifications of a system to run them that later became associated with his name.

Finishing his work with the telephone company, Tesla joined the Continental Edison Company in Paris, where he redesigned dynamos, developed automatic regulators, and also acted as general trouble shooter in power stations throughout France and Germany. While in Strassburg, during the summer of 1883, he experienced the joy of building his first actual induction motor and seeing it run. Unable to interest anyone in Europe in promoting this radical device, he finally accepted the offer of an opportunity to work for Thomas Edison in America.

Tesla arrived in New York in June 1884 with four cents in his pocket, a book of poetry, designs for a flying machine, and a headful of ideas. His first job was with the Edison Machine Works, which built dynamos for the Edison Light Company, where he designed 24 direct-current dynamos with short field pole pieces to replace original machines of the long-pole Edison type. The basic salary was $18 a week, but a bonus of $50,000 on the completion of the task, promised him by the manager, stimulated Tesla to work from 10:30 A.M. until 5:00 the next morning, seven days a week. At the end of a year, the work finished, he asked for his pay—only to find that he had been the butt of a practical joke! Tesla quit promptly (*3*).

Tesla's next backers—having no more use for his newfangled motor and the complex alternating-current system needed to run it than had Edison or the European experts—prevailed upon him to form a company to develop a new system of arc lighting, the type of electric illumination then popular for large public buildings and city streets. But at the end of another year, his work again com-

Fig. 1. Nikola Tesla's birthplace at Smiljan, Lika, Croatia. At the time of his birth this province was governed by Austria-Hungary but is now part of Yugoslavia. At the right is the church in which Nikola's father conducted services.

pleted, he found himself richer only by a stock certificate of questionable value.

By April 1887, however, Tesla had secured capital to establish a laboratory in which he could build working models, in practical sizes, of the motors he had previously devised mentally. One by one, he transformed earlier visions into amazing machines of copper and iron—each model working in practice just as he had expected it to.

One of the first eye-witness accounts of the operation of the Tesla motors appeared in a letter from William A. Anthony to Dugald C. Jackson (*4*). Anthony, who had established a course in electrical engineering at Cornell University a few years earlier, had made a series of tests on the Tesla motors as consulting engineer for the Mather Electric Company of Manchester, Connecticut. Jackson was later to become head of the electrical engineering department of Massachusetts Institute of Technology.

The letter reads: "My dear Jackson: I wrote you a while ago that I had seen a system of alternating current motors in N.Y. that promised great things. I was called as an expert and was shown the machines under pledge of secrecy as applications were still in the Patent Office. . . . I have seen such an armature weighing 12 pounds running at 3,000, when *one* of the (ac) circuits was suddenly reversed, reverse its rotation so suddenly that I could hardly see what did it. In all this you understand there is *no* commutator. The armatures have no connection with anything outside. . . .

"It was a wonderful result to me. Of course it means two separate circuits to motor from generator and is not applicable to existing systems. But in the form of motor I first described, there is absolutely nothing like a commutator, the two (ac) chasing each other round the field do it all. There is nothing to wear except the two bearings. . . ."

As Anthony's letter suggests, the sum of Tesla's conception was not merely a new motor that could be operated from an existing system; it was a unique system for the generation, transmission, and utilization of electric power, of which his motor formed but a part. The system started with an alternating-current generator having windings which produced two, three, or more separate alternating currents that followed each other, out of step or phase, as the rotor revolved. By leading these "multiphase" or "polyphase" currents, kept always separate, to windings distributed symmetrically around the stator of a motor, a rotating magnetic field was created in the stator which reproduced exactly the magnetic conditions in the generator.

Fig. 2. The Nikola Tesla Museum in Belgrade, where Tesla's personal papers, apparatus, and other belongings are now permanently housed.

Properly designed rotors placed in this field were whirled by it to produce mechanical power. Using an unwound rotor of iron or steel, Tesla obtained a motor which had a low starting torque but which kept in exact step with the rotations of the field, regardless of load; this was the first polyphase synchronous motor. Using a rotor wound with coils of wire closed on themselves, Tesla produced a second type of motor which developed a high torque in starting, built up speed almost to synchronism with the field, and maintained this speed under widely varying loads. As rotation in the latter motor was due to the interaction between the magnetism induced in the rotor coils and the rotating magnetic field which produced it, this motor became known as the polyphase "induction motor."

In October 1887, Tesla began sending applications to the U.S. Patent Office covering a comprehensive system of motors, generators, transformers, and methods—all in an amazing variety of combinations—for the transmission of electric power by the joint use of two or more alternating currents. On 1 May 1888 he was granted his first set of history-making patents.

Fifteen days later, at the urging of Anthony and T. Commerford Martin, Tesla publicly introduced his motors and system in a classic paper, "A new system of alternate current motors and transformers," which he delivered before the American Institute of Electrical Engineers and which was later printed in its *Transactions* (*5*). One of the model motors Tesla demonstrated at this lecture is shown in Fig. 3.

To better appreciate the part these inventions were soon to play in revolutionizing the electrical industry, we must recall the condition of that industry at the time of their introduction. In all the United States there were several thousand central stations operating by means of over twenty different "systems"—combinations of circuits and equipment usually centering around an invention or group of inventions and named after the inventor or manufacturer.

The high-voltage direct-current systems of Charles Brush and others supplied current to arc lamps strung in series for street lighting but could not effectively run lamps or motors. Edison's low-voltage direct-current system lit incandescent lights in densely populated areas in big cities but, because the cost of transmission rose so steeply with distance, could not reach out more than a few blocks from the generating station. By means of transformers which stepped up the voltage for economical transmission and then down again for use, the single-phase alternating-current systems of Westinghouse and Thomson-Houston made incandescent lighting at a distance feasible, but there was no satisfactory alternating-current motor.

In other words, there were many small generating stations, each designed for a specific use, but none able to supply electricity in large amounts for all uses. Also,

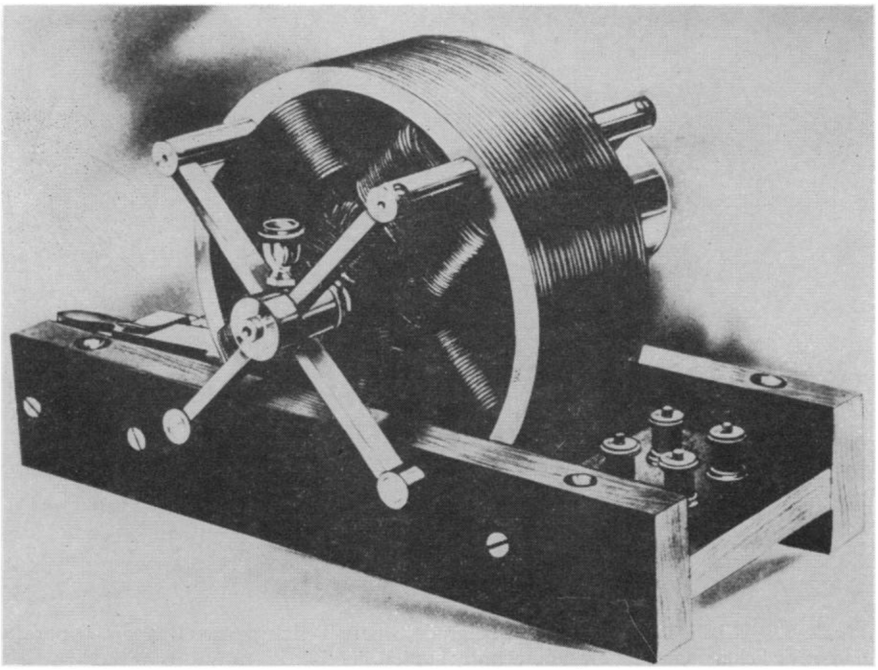

Fig. 3. One of the original induction motors demonstrated by Tesla in his historic lecture before the American Institute of Electrical Engineers at Columbia University, 16 May 1888. This machine developed about ½ horsepower. [Courtesy of the Nikola Tesla Museum, Belgrade]

electricity was used almost exclusively for lighting, difficulties with existing motors and transmission systems making the widespread use of motors impracticable.

George Westinghouse, who had founded his electrical business two years before, largely on the single-phase alternating-current patents of Lucien Gaulard and John Gibbs, pioneer inventors of transformers and alternating-current distribution in Europe, immediately saw in Tesla's motor a means for breaking through this dead end. Within two months after Tesla's lecture before the American Institute of Electrical Engineers, Westinghouse had acquired rights to the Tesla patents and Tesla's personal services to help develop the patents into commercial equipment.

The great hope of Westinghouse was that the Tesla motor could be adapted to existing single-phase circuits, in which most of his company's capital was tied up. At the time, Westinghouse had neither the money nor the interest to try to introduce a radical system which would require completely new generating and transmission equipment.

Tesla helped out by devising several types of "split-phase" motors—induction motors with windings which so divided a single-phase current that it did the work of two. But even these motors—which have since become universally used about the shop and home for performing chores that require fractional horsepower—refused to work efficiently on the 133-cycle current then in use. After several years of failure in trying to adapt the motor to the existing frequency, Westinghouse engineers finally changed the central-station frequency to suit the motor! The frequency they decided on—low enough to run the motor efficiently yet high enough to prevent lights from flickering—was 60 cycles, the frequency which has since become standard for practically all light and power production in America.

Polyphase System Harnesses Niagara Power

The challenge which brought about the widespread introduction of the true polyphase system was the first large-scale harnessing of Niagara Falls. In 1886, a charter had been obtained to utilize about 120,000 horsepower of Niagara's might for purposes of industry. One of the first schemes for accomplishing this involved the formation of an industrial community several hundred yards wide and extending for a mile and a half along the Niagara River. Mills and factories within this area were to be directly connected to 238 water wheels of 500 horsepower each; the water from these would discharge into a tunnel about two and a half miles long, emptying below the falls.

The impracticability of such a scheme soon became evident. For one thing, it would cost too much to build the necessary canals and hydroelectric equipment. For another, how could a city of 5000 population ever hope to attract enough industry to absorb more power than was then used in all the mills and factories in Minneapolis, Holyoke, Lowell, Lawrence, Cohoes, and Lewiston combined? To utilize so much power effectively, a means would have to be found to transmit the power beyond Niagara—possibly even to Buffalo. But by what means?

Hoping to enlist the world's best engineering talent in this quest, the International Niagara Commission, headed by Sir William Thomson (soon to become Lord Kelvin) was established in London in 1890 and authorized to offer $22,000 in prizes for the best ideas for carrying out the undertaking. This commission, which included Coleman Sellers of Philadelphia, E. Mascart of Paris, Theodore Turrettini of Geneva, and W. C. Unwin of London, was probably the first notable international group of scientists organized for industrial purposes. Seventeen projects were submitted by 20 representatives of six countries.

Among these projects were plans for transmitting power from water wheels to mills by means of manila and wire ropes, by water pressure conveyed through pipes to distant turbines, and by compressed air. Of those who advocated transmission by electricity, only two favored use of alternating current. Edison and Kelvin (who were not competing for prizes) advocated the use of direct current, their plan being to connect a number of direct-current dynamos in series to build up a high voltage for transmission and then to distribute this voltage at the receiving end by means of motors also connected in series. Believing that no method of electrical transmission was yet ready for such a great undertaking, George Westinghouse privately recommended that power be generated as compressed air; this would then be piped to Buffalo to run existing steam engines. Having found none of these projects worthy of first prize, the commission was disbanded in February 1891.

The first hint that the Tesla polyphase system might be the answer to this greatest of engineering problems of the day came from Europe in August of that same year. C. E. L. Brown, electrical director of the Maschinenfabrik Oerlikon in Switzerland, and Michael von Dolivo-Dobrowolsky of the Allgemeine Electrizitäts Gesellschaft in Berlin, had been investigating the capabilities of polyphase generators, motors, and transmission for several years. At the Frankfort Exhibition these engineers demonstrated the results of their labors by lighting 1000 16-candlepower incandescent lamps and running a 100-horsepower motor by means of three-phase alternating current that had been transmitted from a generator in Lauffen, 108 miles away. To do this they sent voltages up to 30,000 and power up to nearly 200 horsepower over three bare copper wires, each only 4 millimeters thick! (*6*).

The second hint came from America. Spurred by the success of the Lauffen-Frankfort transmission, by that of several smaller polyphase installations made by his own engineers, and by the hope of getting the Niagara contract, Westinghouse became enthusiastic about polyphase power and felt that his grand chance to introduce it would be at the 1893 Chicago World's Fair.

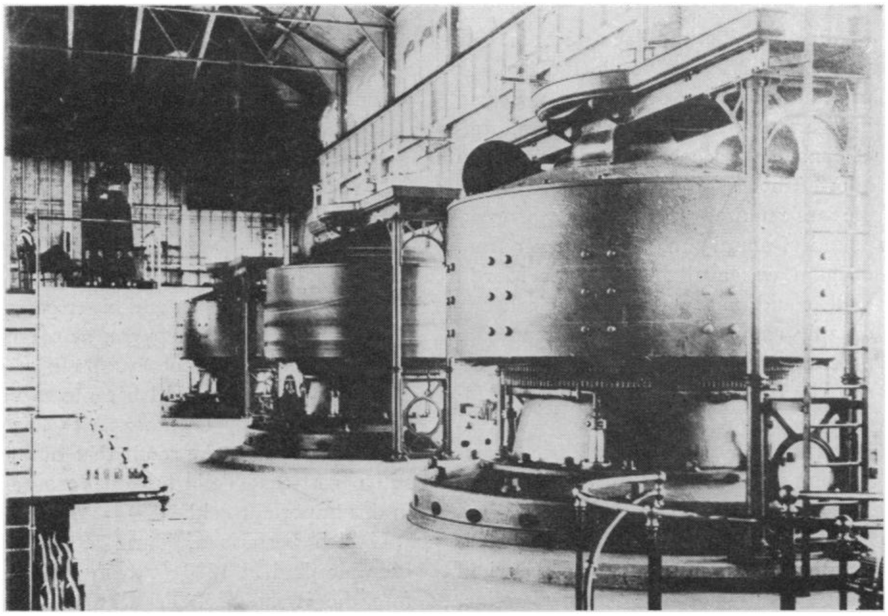

Fig. 4. The first three 5000-horsepower generators of the Tesla polyphase system installed at Niagara Falls in 1895 and 1896. Later rebuilt to operate at higher voltage and as three-phase instead of two-phase generators, they are still in operation and produce the same kind of current as atomic-energy electric plants of today.

By underbidding Edison, Westinghouse won the contract to light this great exposition—the first world's fair to be lit by electricity—and proceeded to do so by means of the Tesla system. Because there were no large polyphase generators yet in existence, he improvised 12 1000-horsepower two-phase generators by coupling 24 500-horsepower single-phase generators in pairs in such a way that their circuits were 90 degrees out of phase. As an extra feature, he also demonstrated the first complete polyphase system ever assembled in units of commercial size. In this, current from a two-phase generator was stepped up by a transformer, sent over a short transmission line, stepped down again by transformers, and used as two-phase current to run induction and synchronous motors and as single-phase current to light lamps and run split-phase motors. To show the complete adaptability of the system, he demonstrated how a rotary converter could change polyphase alternating current to direct current for running a railway motor.

The Lauffen-Frankfort transmission had proved to the scientific advisers of the Niagara project that polyphase power could be sent economically over any distance commercially desirable. The World's Fair exhibit demonstrated further that it could be used to supply all electrical needs. In October 1893—just five years and five months after the issuance of the basic Tesla patents—a contract was signed with the Westinghouse Company to build the first two Niagara generators, of 5000 horsepower each.

In April 1895 the first generator began turning (Fig. 4). In August, electricity was delivered to the first customer—the Pittsburgh Reduction Company, now the Aluminum Company of America. Before the end of 1896, a 22-mile transmission line carried Niagara power to operate the lights and streetcars of Buffalo.

Almost overnight, the Niagara plant became the electrical wonder of the world. Soon, seven more generators were ordered from Westinghouse to complete Power House Number One. Original plans for transmitting power from Power House Number Two by means of compressed air were abandoned, and 11 more generators to complement this station were ordered from the General Electric Company. In 1896, the New York Edison Company began to expand the range and usefulness of its direct-current system by means of polyphase transmission between stations, and several years later it adopted the Tesla system for all new stations. By the time the Niagara plant was completed, in 1903, all new generating stations in the United States were being founded around the Tesla inventions (Fig. 5). The age of modern electric power had begun.

Besides lighting homes and streets, running trolley cars, and replacing steam

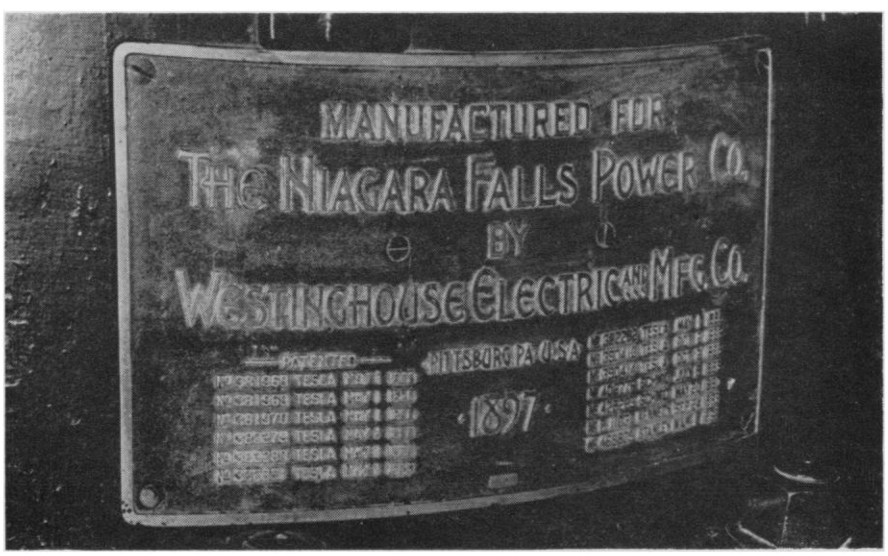

Fig. 5. A recent photograph of the nameplate of one of the earliest generators at the first great Niagara Falls plant. Nine of Tesla's patents are listed. [Courtesy of the Niagara Mohawk Power Corp.]

engines in mills and factories, the new power from Niagara, provided cheaply in previously unheard-of quantities, helped inaugurate great new electrometallurgical and electrochemical industries. Ten kilowatt-hours of electricity, for example, are required in the making of every pound of aluminum. Before power from Niagara was available, Charles Martin Hall could not get enough electricity cheaply enough to make his aluminum process a commercial success. Using an electric furnace operated by a steam-driven generator, E. G. Acheson had failed in his attempt to produce carborundum. As the second customer for Niagara power, he was enabled to found a giant artificial abrasives industry. Willson, the inventor of calcium carbide, had been working at Spray, North Carolina, with a 200-horsepower furnace. Furnaces of 20,000 horsepower each were later set up at Niagara. Within less than a generation, the largest electrochemical community in the world had been built up around Niagara power.

Tesla Patents Sustained by Courts

The moment Tesla's induction motor and polyphase system showed signs of success, the usual costly and bitter patent litigation, cries of anticipation by others, and attempts at patent evasion began. These lasted so long and became so involved that many engineers never knew the outcome, with the result that rumors still persist that Tesla lost out to others in this important field.

Galileo Ferraris of Turin, Italy, for example, had in 1888 (two months before the issuance of Tesla's first polyphase patents, but six months after his application) published a paper entitled "Electrodynamic rotations produced by means of alternate currents." This concerned laboratory experiments he had conducted in 1885 but had not publicly exhibited until three years later. In these, Ferraris had caused a copper cylinder to revolve in a rotating magnetic field produced by two alternating currents out of phase with each other. The two currents were obtained from a single-phase circuit by bringing out two branches and inserting a large inductance in series with one and a noninductive resistance in series with the other.

Although the principle of this device was similar to that of Tesla's split-phase motor, Ferraris had considered his contrivance merely a scientific toy which was too inefficient ever to be practical as a motor. He did not attempt to patent the idea, and later he graciously admitted that Tesla had independently conceived the idea of the rotating magnetic field and had developed from it a motor that far surpassed in usefulness anything he had personally believed possible. He further gave Tesla complete credit for the conception and invention of the polyphase system itself—a system which Ferraris had thought impractical because of the additional wiring required.

First reports to America on the Lauffen-to-Frankfort transmission gave credit for the three-phase system to Dolivo-Dobrowolsky, who had designed the motors used. C. E. L. Brown, originator of the project and designer of the generator, quickly explained, however, that this transmission was not a test of three-phase transmission but of high-voltage transmission; that "the 3-phase current as applied at Frankfort is due to the labors of Mr. Tesla, and will be found clearly specified in his patents" (7).

Walter Baily, Marcel Deprez, and Charles S. Bradley were among other inventors claimed by rival manufacturers to have anticipated Tesla. In an attempt to evade the Tesla patents, Steinmetz helped create for the General Electric Company what was called the "monocyclic" system. For electric lighting, this system supplied single-phase alternating current by means of two wires; where motors were to be run, a third wire carried another alternating current which operated momentarily to give the motors a start. Holding this system to be an infringement, Westinghouse prepared to sue its bigger rival. In 1896, however, General Electric settled the issue of giving Westinghouse rights to valuable Edison, Van Depoele, and other patents in exchange for the use of the Tesla patents.

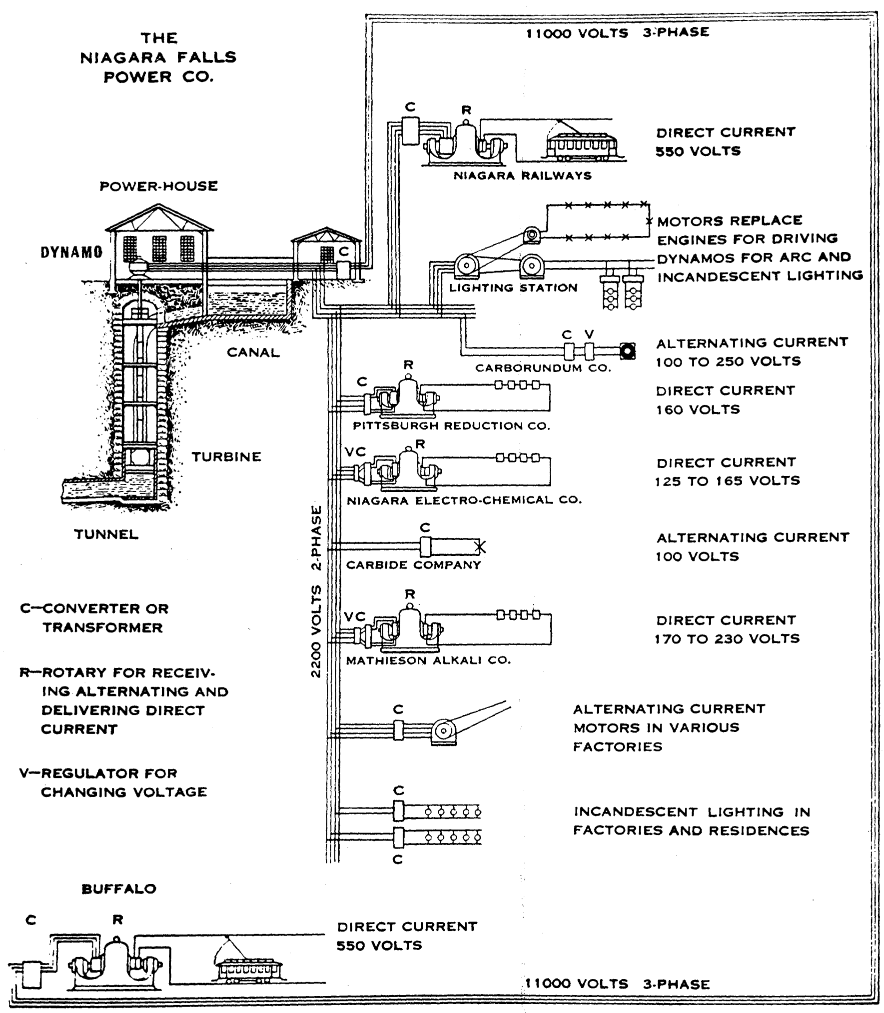

Fig. 6. Diagram of some of the circuits of the first Niagara Falls plant, as of 1897, showing the versatility of the Tesla polyphase system. Originating as two-phase alternating current at 2200 volts, the electricity was easily stepped up or down in voltage and changed to single-phase or three-phase alternating current, or even to direct current, to suit the individual needs of customers. [Charles F. Scott]

The monocyclic system was forthwith abandoned, and so the issue never went to trial.

Had the case been tried, however, the promoters of this unbalanced polyphase system would undoubtedly have lost, as did all the other contenders in a long series of suits which extended over many years. Not only the polyphase induction motor but the split-phase induction motor, the polyphase synchronous motor, and the polyphase system for the transmission and distribution of electric power were all held to be covered by the Tesla patents.

In 1900 Judge Townsend of the U.S. Circuit Court for the District of Connecticut concluded a sweeping decision with these words: "The search lights shed by defendant's exhibits upon the history of this art only serve to illumine the inventive conception of Tesla. . . . It was he who first showed how to transform the toy of Arago (*8*) into an engine of power; the 'laboratory experiment' of Baily into a practically successful motor; the indicator into a driver; he first conceived the idea that the very impediments of reversal in direction, the contradictions of alternations might be transformed into power-producing rotations, a whirling field of force. What others looked upon only as invincible barriers, impassable currents and contradictory forces, he seized, and by harmonizing their directions utilized in practical motors in distant cities the power of Niagara."

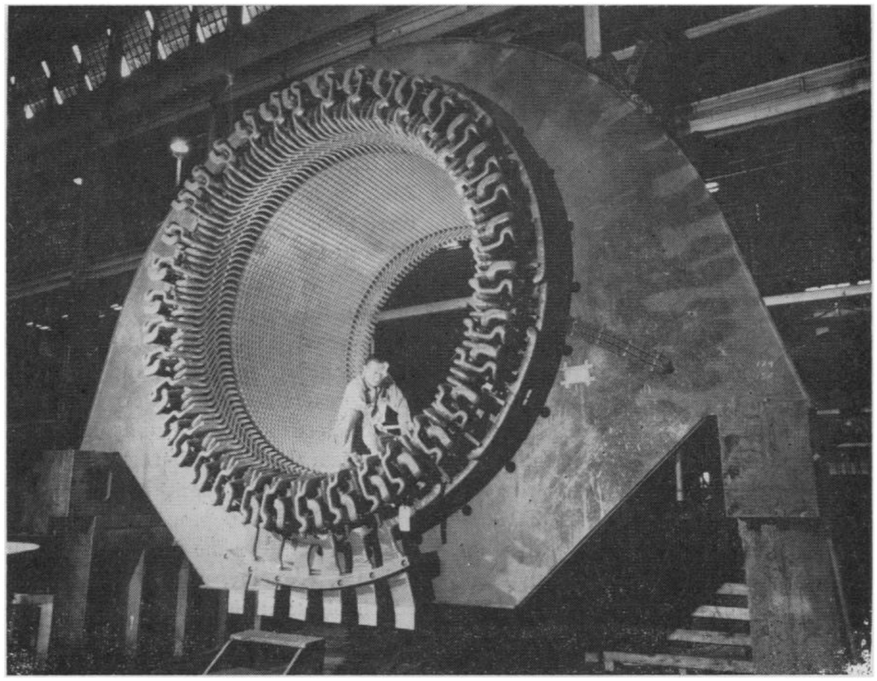

Fig. 7. Today, single and polyphase induction motors and polyphase synchronous motors, all originally covered by Tesla's patents, are built in sizes ranging from fractional horsepower to the 83,000-horsepower giants constructed several years ago to power the wind tunnels of the Arnold Engineering Development Center at Tullahoma, Tennessee. Shown here is the 72-ton stator of one of these machines. [Courtesy of Westinghouse Electric Corp.]

Advantages of Polyphase Power

The polyphase induction motor, so beautiful in its basic principle and so simple in its mechanical construction, early proved itself to be not merely a new type of motor but one superior in all ways to the direct-current motor for any use requiring constant speed and considerable power. Its insulation and windings were simpler; there were no brushes and commutator to wear; and it could be designed for greater efficiency. As a result, the polyphase induction motor was cheaper to build and operate, was more rugged, and could be designed in larger sizes and for much higher voltages. It soon earned the title of the "workhorse of industry."

At first the induction motor was regarded as Tesla's great achievement, and the polyphase system was thought of by many engineers as merely a more complex generating arrangement necessary to run the motor. The Niagara plant helped prove, however, that the Tesla polyphase system itself was even more important than the motor it ran. It constituted the first practical means by which electricity of a single kind could be generated in great blocks in one place, transmitted economically over long distances, and used, for any purpose whatever, at another place. So far it has been the last practical means of accomplishing these results, for no substitute that can even approach it in economy and versatility has ever been found.

Some idea of the versatility of the polyphase system is suggested by a diagram (Fig. 6) made by Charles F. Scott in 1897, which shows a few of the uses of Niagara power only two years after such power first became available (*9*). Electricity was generated as two-phase alternating current at 2200 volts. It was distributed locally in this form to run induction motors and to turn rotary converters which changed the two-phase alternating current into direct current for supplying streetcars and electrochemical processes. Branches of single-phase current were taken off for incandescent lighting. By means of a transformer invented by Scott, the two-phase current was changed to three-phase current at 11,000 volts for economical transmission to Buffalo. According to Harold W. Buck, who was chief electrical engineer of the Niagara Falls Power Company from 1900 to 1907, to have accomplished the same end results with the direct current suggested by Kelvin and Edison would have required "a radiating copper mine running out from Niagara Falls which would have wrecked the enterprise in the first year of its existence" (*10*).

Progress in electric power development since the adoption of the Tesla inventions has been a matter chiefly of technical refinement and enormous expansion. As late as 1902, the 80,000 kilowatts turned out by the 21 5000-horsepower generators at Niagara equaled the electrical output of 31 states and the territories of Arizona and Oklahoma combined. Today, electric utilities of the United States have a capacity for generating more than 128 million kilowatts, with industry turning out some 17 million kilowatts more. Each of the giant generators whirled by water power at the Grand Coulee Dam now produces more electricity than the entire original Niagara plant (which, incidentally, is still running strong!), and steam-driven generators with a rating of 450,000 kilowatts are now being planned. Because three-phase motors and generators can be designed for about 50-percent greater output than two-phase machines, on a given frame, and because three-phase current can be sent over three wires with a saving of about 25 percent in copper for a given power, this type of polyphase current is now almost universally used.

Polyphase induction and synchronous motors have been stepped up in size from the ½-horsepower model shown by Tesla in 1888 to 83,000-horsepower mammoths (Fig. 7) used to speed air through the great wind tunnel of the Arnold Engineering Development Center near Tullahoma, Tennessee—the most powerful wind tunnel in the world. Transmission voltages have risen from the 11,000 volts of the original Niagara–Buffalo line to as much as 330,000 volts, and experiments are now being conducted with 500,000-volt lines. "Electric service," which before the introduction of the polyphase system meant arc lights in streets and incandescent lamps in homes and business establishments in thickly populated areas of big cities, now means electric light and power for all purposes in 98 percent of all buildings of America. In addition to lighting, electricity now runs 97 million radios, 39 million television sets, and 100 million miscellaneous appliances, ranging from toasters and percolators to washing machines and air conditioners. Within 25 years, the demand for electricity in the United States is expected to quadruple.

One new use for electricity, completely unforeseen at the turn of the century, is in the separating and making of materials for atomic- and nuclear-energy programs. Plants of the Atomic Energy Commission at Oak Ridge, Tennessee, and Paducah, Kentucky, now require a total of twice as much electricity (generated and transmitted as polyphase current by plants of the Tennessee Valley Authority) as the city of New York. Our Atomic Energy Commission program uses, altogether, more than 60 billion kilowatt-hours of electricity a year, or about 10 percent of all the electricity used in this country.

However, the total contribution of Tesla's induction motor and his polyphase system for the universal distribution of electric power, encompasses much more than the tremendous growth of the electrical industry which these inventions made possible. To properly evaluate it, we must consider the vast revolution in industry, economy, and everyday living which plentiful electric power, available everywhere, has been instrumental in bringing about.

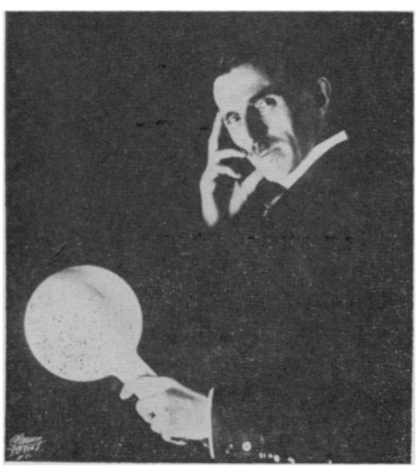

Fig. 8. Nikola Tesla holding a gas-filled, phosphor-coated, wireless light-bulb which he developed in the 1890's to replace the incandescent lamp, which he considered inefficient. This light-bulb, made nearly half a century before fluorescent lights became commercially available, may still provide some ideas for those who will devise the lighting methods of the future.

Tesla Explores High Frequencies

Tesla, elated by his success in creating the induction motor and the first system by which large quantities of electricity could be sent over long distances, found it hard to settle down to a job of working out mere technical improvements on these discoveries, even though he had been given a huge salary by Westinghouse Electric Company and a part interest in the company as an inducement. A year's experience at Westinghouse's East Pittsburgh plant convinced him that his inspiration worked best when he worked untrammeled and alone. In 1889, Tesla returned to his own laboratory in New York to begin investigations on several completely new frontiers of electricity and mechanics.

Most spectacular of these were his researches in high-frequency phenomena; these brought him world fame and contributed enormously to such fields as radio, diathermy, induction heating, gaseous tube lighting, and radio-guided weapons.

Tesla's first interest in currents of high frequency was the result of his ambition to develop an electric light which would be more efficient and adaptable than the newly developed incandescent lamp of Edison, Swan, and others. Hertz had recently demonstrated that high-frequency oscillations could be produced by a condenser discharge. Crookes had produced fascinating glow effects by passing high voltages from a spark coil through glass tubes filled with various gases at low pressure. Tesla had an idea that the light of the future might well be a suitably designed gas-filled tube energized by high-frequency currents (Fig. 8).

Because the Hertz apparatus was too feeble and inefficient and the spark coil was too impractical and dangerous for purposes of everyday lighting, Tesla first had to devise entirely new means for producing electricity of high frequency. His earliest attempts resulted in a series of ingenious high-frequency alternators which could deliver frequencies up to about 33,000 cycles a second. Besides serving his own early researches, these machines became the inspiration for the great high-frequency alternators developed by others for continuous-wave radio communication several decades later.

Tesla's next and better-known apparatus for producing currents of high voltage and high frequency was the oscillation transformer or "Tesla coil," an air-core transformer having the primary and secondary tuned to resonance. With this device, Tesla was able to convert the weak, highly damped oscillations of the original Hertz circuit to remarkably sustained currents of almost any magnitude desired. Starting with transformers which produced sparks only several inches long, Tesla, in 1899, built a Tesla coil at Colorado Springs which hurled a bolt of artificial lightning across a gap of 135 feet (Fig. 9). With characteristic thoroughness, he designed more than fifty types of oscillation transformer during a period of ten years—coils with cylindrical, conical, and flat windings, coils with oil insulation and with air insulation, coils with the primary encircling the middle of the secondary, and coils with the primary at one end, as in the "Oudin coil."

To increase the efficiency of these coils, Tesla developed rotary and series spark gaps, oil-insulated transformers and condensers, choke coils, and mica condensers impregnated with wax under a vacuum. Realizing that high-frequency currents travel near the surface of conductors, he cut down resistance in his coils by using stranded conductors having the strands separately insulated, a type of conductor that appeared commercially some years later as *Litzendraht*.

By the turn of the century, a Tesla coil for demonstrating high-voltage and high-frequency phenomena had become part of the equipment of probably every college science laboratory in America and Europe. In 1929—before E. O. Lawrence had introduced his cyclotron—Gregory Breit and his associates of the Carnegie

Institution of Washington were using a 5-million-volt Tesla coil, which they had designed and built, in pioneer attempts to smash the atom.

The fame of the Tesla experiments and apparatus was spread rapidly and widely by a series of remarkable lecture-demonstrations which Tesla gave before leading scientific societies; these lectures were published and discussed in technical journals, and they were reprinted in 1894 in Thomas Commerford Martin's book, *Inventions, Researches, and Writings of Nikola Tesla* (*11*).

In the first of these, "Experiments with alternate currents of very high frequency and their application to methods of artificial illumination," given before the American Institute of Electrical Engineers at Columbia University, New York, on 20 May 1891, Tesla noted that the earlier laws of electricity held good only when currents were of a steady character; that when currents rapidly changed in direction and strength, different laws applied; and that enough knowledge had been obtained to put these laws to practical use. By means of his high-frequency alternators and Tesla coil, he then demonstrated some of the novel effects produced by these new "Tesla currents."

One effect concerned the rapid heating of iron cores and conductors when brought within an intense high-frequency field—pioneer observations which were to lead Tesla and others to the application of high-frequency currents in melting metals and heating body tissues. In another demonstration, illustrating the importance of capacitance in a high-frequency circuit, he showed how motors could be run and lights lit with only a single terminal connected to the generator, the other being connected to an insulated metal plate. In a third demonstration he showed how gas-filled tubes, some coated with phosphors to increase their brilliance (forerunners of modern fluorescent lights, which were not to make their appearance until nearly half a century later), could be lit without any wire connection at all, merely by bringing them within a high-frequency field. The demonstration which caused the greatest wonder and consternation, however, was that in which Tesla lit lamps, held in his hands "like flaming swords," by several hundred thousands of volts of high-frequency electricity passing through his own body! Thus Tesla dramatized his answer to the accusation then circulating that alternating current was more deadly than direct current: provided the frequency were high enough, alternating current of enormous voltage could be completely harmless.

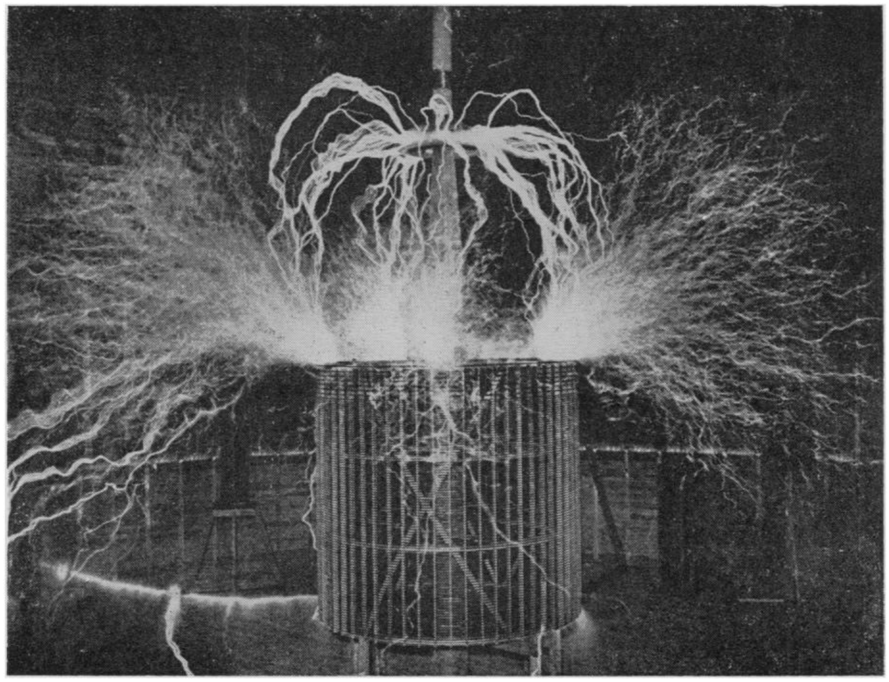

Fig. 9. A flamelike discharge, 65 feet across, from a tuned helix coupled to the primary of a giant oscillator built by Tesla at Colorado Springs in 1899 in his attempt to send power without wires by changing the electric charge of the earth. This oscillator was the largest Tesla coil ever built. Its true secondary, which could produce sparks 135 feet long, can be seen in the background, surrounding the helix.

In 1892 Tesla delivered his second lecture, before the Institution of Electrical Engineers and the Royal Institution of Great Britain, in London, and the Société Internationale Française des Electriciens and the Société Française de Physique, in Paris, and in 1893 he delivered his third, before the Franklin Institute in Philadelphia and the National Electric Light Association in St. Louis. In these later lectures, Tesla not only discussed the lighting, heating, and resonance effects of high-frequency currents but suggested that communication could be made by means of them; he demonstrated (in his lecture of 1893) actual circuits and apparatus remarkably similar to those which were adopted subsequently by other inventors and which became standard for all wireless transmission until the introduction of the transmitting electron tube, several decades later (see Fig. 10).

First Radio-Controlled Weapon

Soon after beginning his researches on high-frequency currents, Tesla became interested in a new field of science which he named "telautomatics" and which we now call "automation"—the design and operation of electromechanical devices which could "think for themselves" and also the control of such devices from a distance without intervening wires. The idea had struck him after study of his own reactions to external influences, and he had come to regard himself as a sort of mechanism of flesh and blood. Why could he not construct an automaton possessed of sense organs, nerves, reflexes, and muscles which would respond much as he did to stimuli from outside? Using intricate combinations of commutators, gears, ratchets, electromagnets, tuning devices, and coherers of his own invention, Tesla set out to achieve this end.

By 1895 he had already exhibited contrivances which performed simple movements under wireless control and had perfected plans for constructing several complete telautomata. In 1897 he built and operated two model boats which could be started, stopped, steered, and made to flash lights and fire explosives by means of radio impulses from a distance (Fig. 11) and the following year Tesla was granted a patent on this invention.

According to the patent's broad specifications, Tesla's device could be used to control "boat, balloon, or carriage"; it could be operated by direct conduction through earth and water or by any form of electromagnetic radiation through the air; it could be used "for killing whales and for other scientific, engineering, or commercial purposes. But its greatest value is in its effect on warfare and armaments for by reason of its certain and unlimited destructiveness it will tend to bring about and maintain permanent peace among nations."

In an article in the New York *Sun* of 21 Nov. 1898, "Torpedo to revolutionize warfare," Tesla explains further: "We shall be able, availing ourselves of this advance, to send a projectile at a much greater distance; it will not be limited in any way by weight or amount of explosive charge; we shall be able to submerge it at command, to arrest it in its flight and call it back, and to send it out again and explode it at will; and more than this, it will never make a miss. . . ."

While newspapers gave banner headlines to Tesla's radical contrivance as the doom of navies and the end of all war, more conservative technical men raised their eyebrows. "When we are expected to accept in silence such an utterance as that quoted above . . ." wrote the editor of the *Electrical Engineer,* "we refuse point blank, and we are willing to face the consequences." In another issue of the same magazine, C. F. Brackett of Princeton gave in detail his opinion of why a radio-controlled torpedo would not work: "What Tesla has done is merely to make theoretical application of inventions which had already been discovered . . . the theory is perfect, but the application absurd. . . . Do you suppose that in the din of battle it would be possible to put into execution those minute and carefully adjusted mechanical experiments all of which are presupposed by this theory, which require the uninterrupted quiet of a laboratory to work successfully?"

That Tesla not only conceived the idea and built working models of the first noninterferable, radio-controlled guided weapons but also, more than half a century ago, clearly foresaw the type of development necessary to lead to the marvelous missiles of today is strongly suggested in his article "The problem of increasing human energy," which appeared in the *Century Magazine* of June 1900: "The automatons so far constructed had 'borrowed minds,' so to speak, as each merely formed part of the distant operator who conveyed to it his intelligent orders; but this art is only the beginning. I propose to show that, however impossible it may now seem, an automaton may be contrived which will have its 'own mind,' and by this I mean that it will be able, independently of any operator, left entirely to itself, to perform, in response to external influences affecting its sensitive organs, a great variety of acts and operations as if it had intelligence. It will be able to follow a course laid out or to obey orders given far in advance; it will be capable of distinguishing between what it ought and what it ought not to do, and of making experiences or, otherwise stated, of recording impressions which will definitely affect its subsequent actions. In fact, I have already conceived such a plan."

Tesla went on to say that the principle was applicable "to any kind of machine that moves on land or in the water or in the air," that the art he had evolved would not bring about "merely the change of direction of a moving vessel; it affords a means of absolute controlling . . . all the innumerable translatory movements, as well as the operation of all the internal organs, no matter how many, of an individualized automaton."

One of Tesla's original model boats did utilize far more intricate control apparatus than was indicated by his patent No. 613,809. To protect inventions he was not yet ready to disclose, he outlined only the basic idea in his specifications; besides, at the time his application was filed, utilization of the invention was seriously being considered by the United States Navy for help in our war with Spain. One of the features not revealed was a system to prevent interference by means of coordinated tuning devices responsive only to a combination of several radio waves of completely different frequencies. Another was a loop antenna which could be completely enclosed by the copper hull of the vessel; the antenna would thus be invisible and the vessal could operate completely submerged.

Turbines and World Wireless

Among other achievements, Tesla invented a turbine having smooth parallel blades and no buckets. The principle, which involved the surface drag of air, steam, or gas, was used in a device to couple the elements of a speedometer made for years by Waltham and used on many of our best cars. Tesla demonstrated synchronous electric clocks and hoped some day to power as well as synchronize them by radio. Although the means for producing sufficient power was not yet available, Tesla wrote in 1917 of plans for detecting ships and other distant objects by training on them a powerful ray of short-wave electrical impulses and then picking up the reflection of the ray on a fluorescent screen—a clear prophesy of the radar that was to come.

Tesla's great dream at the turn of the century was to send electric power without wires by making the whole earth

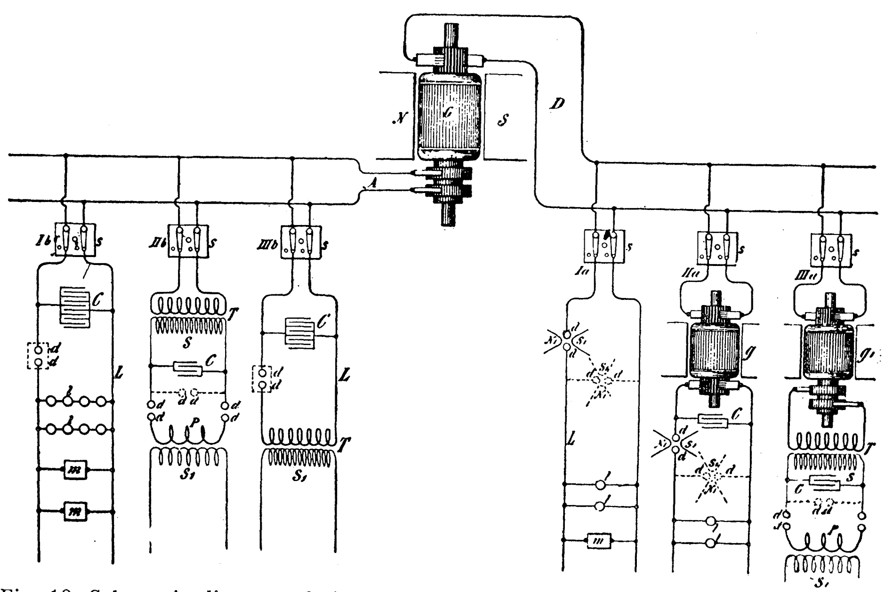

Fig. 10. Schematic diagram of circuits for producing high-frequency electrical oscillations, as described by Tesla in his lectures before the Franklin Institute and the National Electric Light Association in 1893. Circuits III*a* and II*b* contain all the basic elements of spark radio transmitters introduced a number of years later by Marconi and others; these remained standard for several decades. [T. C. Martin, *Inventions, Researches and Writings of Nikola Tesla* (1894).]

part of a gigantic oscillator. Convinced that this was possible by the results of his experiments at Colorado Springs in 1899 and 1900, he began construction of his first demonstration plant at Shoreham, Long Island, a few years later. Although Tesla ran out of funds before he could complete this plant, he outlined a "World Wireless" plan which was to be a subsidiary project; this anticipated not only the radio broadcasting of 20 years later but many of the special services that have been added since, and even a few that are still in the future.

Besides proposing to run and sychronize the clocks of the world by radio, Tesla included in this plan "the interconnection and operation of all the telephone exchanges on the Globe; the world transmission of typed or hand-written characters, letters, checks, etc.; the inauguration of a system of world printing; the world reproduction of photographic pictures and all kinds of drawings or records." Outlining his idea of broadcasting, Tesla continued: "I have no doubt that it will prove very efficient in enlightening the masses, particularly in still uncivilized countries and less accessible regions, and that it will add materially to general safety, comfort and convenience, and maintenance of peaceful relations. It involves the employment of a number of plants, all of which are capable of transmitting individualized signals to the uttermost confines of the earth. Each of them will be flashed to all points of the globe. A cheap and simple device, which might be carried in one's pocket, may then be set up somewhere on sea or land, and it will record the world's news or such special messages as may be intended for it."

His Work an Inspiration to Others

Beyond demonstrating his own achievements as a discoverer and inventor, Tesla's lectures and writings of the 1890's aroused wide admiration among older contemporaries and inspired untold numbers of younger men to enter the new fields of radio and electrical science. In some cases this influence has already been acknowledged in print. It is even more apparent in personal letters from more than seventy pioneers in science and engineering which I collected on the occasion of Tesla's 75th birthday, in 1931. These were mounted and presented to Tesla in the form of a testimonial volume, now on permanent display in the Nikola Tesla Museum in Belgrade.

Among those who expressed indebtedness and appreciation were Robert A. Millikan, Lee DeForest, William H. Bragg, E. N. daC. Andrade, E. V. Appleton, Arthur H. Compton, J. B. Whitehead, B. A. Behrend, André Blondel, Count George von Arco, Jonathan Zenneck, L. W. Austin, Addams S. McAllister, and W. F. G. Swann.

During his long life, Tesla accepted many conventional honors and turned down others. In 1894 he was given honorary doctoral degrees by Columbia and Yale Universities and the Elliott Cresson medal by the Franklin Institute. In 1917 the American Institute of Electrical Engineers awarded Tesla the Edison medal, and in 1934 the city of Philadelphia awarded him the John Scott medal, for his polyphase power system. He had many engineering and scientific society affiliations—was an honorary member of the National Electric Light Association and a fellow of the American Association for the Advancement of Science. In May 1938, as a foreign-born citizen "whose influence is national and international in scope, constructive in character, and purposeful in objective," Tesla, along with Giovanni Martinelli and Justice Felix Frankfurter, was awarded a scroll of honor by the National Institute of Immigrant Welfare.

Hypersensitive, aloof from other scientists of his day, driven by inner forces which made sheer creation the most important thing in his life (Fig. 12), Tesla was little impressed by degrees, scrolls, and decorations. He claimed that although he kept his American citizenship papers in a safe, he stored his honors and decorations in a dresser drawer. On one occasion he turned down an invitation from Kaiser Wilhelm II to come to Germany to demonstrate his experiments and to receive a high decoration, and on another he missed getting an honorary degree from a western American university because he was unwilling to take time from his work to attend the ceremony.

Like many another dedicated artist and scientist, Tesla had no regard for money except as a means to further his inventive work. He also naively believed that money would automatically flow to him in proportion to his needs. To help his friend George Westinghouse out of a financial scrape—and incidentally to provide himself with immediate cash for new ambitious experiments—Tesla let millions of dollars slip through his hands by scrapping a lucrative royalty contract for his polyphase inventions for an outright payment. According to legend, this payment was a flat $1 million, made personally to Tesla; cold business reports, however, place it nearer $200,000, paid to the Tesla Electric Company, of which Tesla owned only a one-third interest.

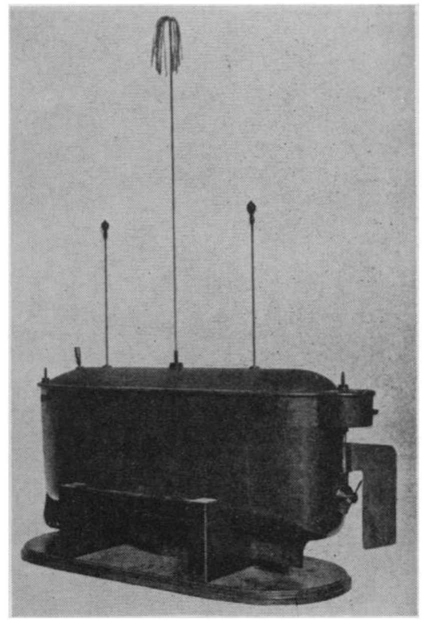

Fig. 11. Model of Tesla' first automaton, built in 1897, the year Marconi took out his first U.S. patent for wireless telegraphy. The boat model shown in the photograph is controlled, without the use of wires, by transmission from a distance of electrical oscillations to a circuit carried by the boat and adjusted to respond only to those oscillations. This and other "telautomatic" devices developed by Tesla between 1892 and the early 1900's provided the concept which led finally to the development of today's guided weapons. [Illustration from N. Tesla, "The problem of increasing human energy," *Century Magazine* (June 1900).]

Although the experiments, apparatus, and prophecies of Tesla's lectures in 1891–1893 were admittedly the inspiration for many of the prominent pioneers of radio communication who came later, and earned for Tesla the title of "father" of wireless, or radio, from such authorities as Adolph Slaby, the "Marconi of Germany" (*12*), and L. W. Austin, long head of radio research of our National Bureau of Standards (*13*), Tesla got little or no money from his wireless inventions.

Believing that mere point-to-point communication by means of Hertzian waves was an obvious application of Hertz's own experiments of 1887, Tesla

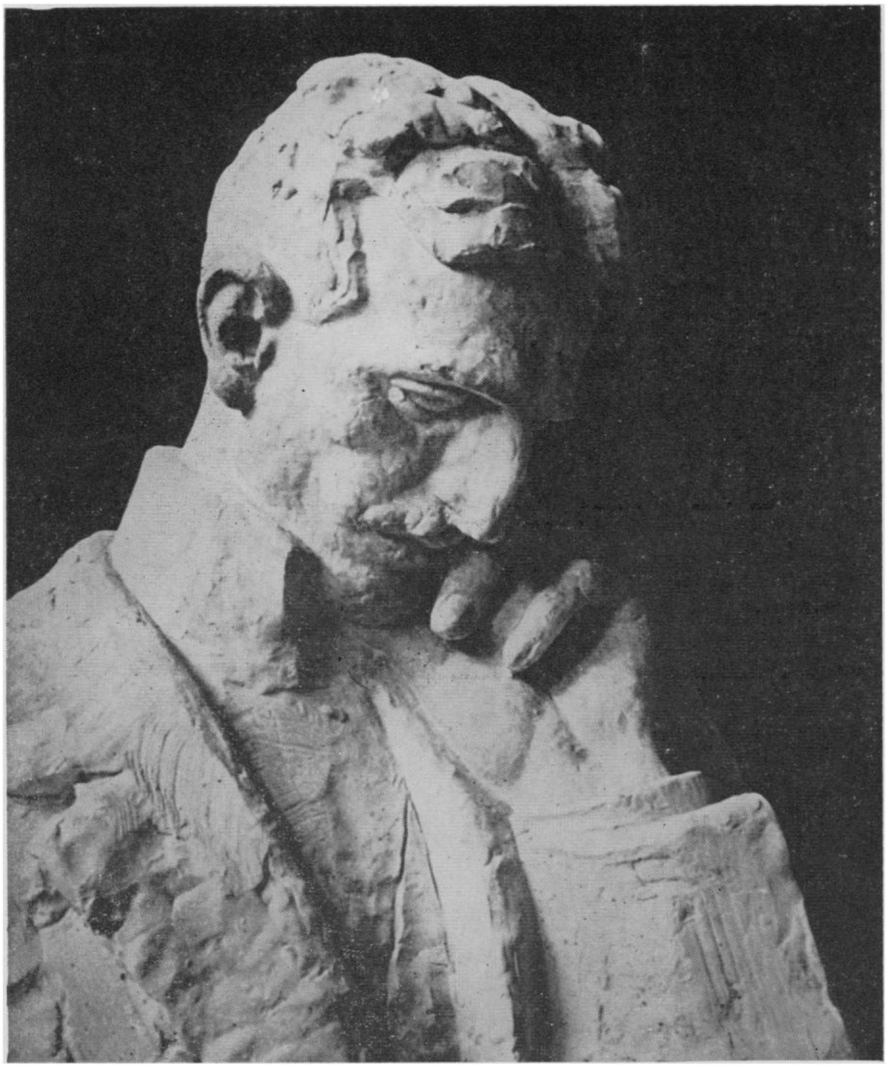

Fig. 12. A bust of Nikola Tesla made after his death by the internationally renowned sculptor Ivan Mestrović. The original plaster model is on exhibition at the Yugoslav Academy of Art and Science in Zagreb, Yugoslavia, and bronze replicas are displayed in the Technical Museum in Vienna and the Tesla Museum in Belgrade.

made no attempt to apply and patent his early apparatus for this purpose. Instead, he flung his imagination into trying to devise a new and more efficient system of wireless wave transmission which could convey not only messages but also power for light and motors. He never completely succeeded, but in his efforts Tesla incidentally—and ironically—produced some of the most advanced Hertzian apparatus of the day, apparatus which was eagerly adapted by others for less ambitious but more profitable and immediately productive purposes.

Tesla understood well the nature of Hertzian waves and constantly used them. His obstinacy in refusing to admit that these waves played a significant part in the operation of his wireless power equipment—which they undoubtedly did—merely helped confuse judges and lose cases for him throughout his lifetime. It was not until several months after Tesla's death that the United States Supreme Court, in continuing a suit held over from World War I, declared Marconi's four-circuit wireless patent—his most important—invalid because the four-circuit wireless had been anticipated by Tesla, John Stone Stone, and Oliver Lodge (*14*). Stone and Lodge, incidentally, had found inspiration for the inventions cited in this case in the earlier lectures of Tesla.

Tesla's wireless power experiments at Colorado Springs were financed largely by his friend John Jacob Astor; his turbine was financed by John Hays Hammond, and his experimental wireless power station at Shoreham, Long Island, by J. P. Morgan. Because Tesla could not get enough additional capital to finish the latter, it finally had to be abandoned, untried.

Unwilling, and actually unable by temperament, to work with the commercial experimental organizations that had gradually taken the place of the individual self-supported inventor, Tesla spent his later years, alone and without funds, feverishly working over in his mind the dreams which he could no longer afford to translate into physical actuality. No one could really have helped him. Tesla accepted pain and hardship philosophically, as essential to all great creative work. If someone gave him a modest amount of money he would either be offended or, on impulse, give it to someone he thought needed it more. Once, when he had nothing, he laughingly confided to me that "I will never have any money unless I get it in amounts so large that I cannot get rid of it except by throwing it out the window!"

In 1937, while taking one of his daily long walks about New York, Tesla was hit by a taxi. With his usual obstinacy he refused medical attention and continued walking, on the theory that this would keep his blood from clotting. Tesla never fully recovered from this accident. During the following years he kept himself shut up more and more in his room in the Hotel New Yorker. He was seldom willing to see old friends, and his voice over the telephone became feebler and his thoughts less coherent. On the morning of 8 January 1943, a maid knocking on the door of his room got no response. Nikola Tesla was dead. Hidden from the flashing neon signs, rumbling subways, blaring radios, and light and power in a million homes of the city which had become the symbol, for the world, of the modern age of electricity which he had so largely helped to create, Tesla had died in the night, as quietly as he had been born.

References and Notes

1. N. Tesla, "Some personal recollections," *Sci. American* (5 June 1915).
2. Personal communication.
3. N. Tesla, "My inventions," *Elec. Experimenter* (May 1919).
4. W. A. Anthony, in letter dated 11 Mar. 1888. This was introduced in patent litigation: *Westinghouse Electric & Manufacturing Co. vs. Mutual Life Insurance Co., Defendant's Records and Briefs* (1902), p. 1255.
5. *Trans. Am. Inst. Elec. Engrs.* **1888**, 305 (1888).
6. For a complete description of the conception and construction of the first great Niagara plant, and for mention of the Lauffen-Frankfort transmission, see E. D. Adams, *Niagara Power* (Niagara Falls Power Co., 1927), vols. 1, 2. See also *Cassier's Magazine* (July 1895); the issue is entirely devoted to this project.
7. C. E. L. Brown, in letter from Baden, Switz-

erland, dated 12 Oct. 1891, published in *Elec. World* (*N.Y.*) 1891, 346 (7 Nov. 1891).
8. Arago had merely arranged a disk of copper below a compass needle with a sheet of paper or glass between them to shield the needle from air currents. When the disk was turned, the needle would tend to revolve in the same direction, pulled by the interaction of its own magnetism and that set up in the rotating disk. Arago could not correctly explain the working of his device and did nothing further with it.
9. Diagram from a paper, "The installation of the Niagara Falls Power Company," given by C. F. Scott before the Engineers' Club of Philadelphia, 17 Apr. 1897; the diagram was reprinted in E. D. Adams, *Niagara Power* (Niagara Falls Power Co., 1927). Scott later became professor of electrical engineering of the Sheffield Scientific School of Yale University.
10. From minutes of the meeting of the American Institute of Electrical Enigneers of 18 May 1917, at which Tesla was awarded the Edison Medal. Buck was then president of the institute.
11. These lectures, together with Tesla's lecture on polyphase motors, most of his patent specifications (complete with drawings), and 25 of his most important articles have been reprinted in a memorial volume, *Nikola Tesla—Lectures, Patents, Articles* (Nikola Tesla Museum, Belgrade, 1956).
12. A. Slaby, in a personal letter to Tesla, now in the Tesla Museum.
13. L. W. Austin, in a personal letter to me, dated 14 June 1927: "The 1891 lectures, published in 'Inventions, etc. of Nikola Tesla' in 1894, I am sure, furnished the material for at least some of the inventors who developed the coupled tuned circuits which came into use about 1900 and constitute Mr. Tesla's right to be called the 'father of radio.' "
14. *United States Reports: Marconi Wireless Co. vs. U.S.*, vol. 320, pp. 1–80.

A Theory of Ice Ages II

The theory that certain local terrestrial conditions caused Pleistocene glaciation is discussed further.

Maurice Ewing and William L. Donn

In a recently proposed theory of ice ages (*1*) we formulated the thesis that (i) the Pleistocene Ice Age was initiated when the North and South poles migrated into the thermally isolated locations of the Arctic Ocean and Antarctica, respectively, and that (ii) fluctuations of glacial with interglacial climate during the Pleistocene epoch were controlled primarily by alternations from an ice-free to an ice-covered state of the surface waters of the Arctic Ocean. According to this theory, the local terrestrial conditions of thermal isolation and adequate precipitation, rather than broad, world-wide changes of terrestrial or extraterrestrial origin, should be emphasized as the causes of Pleistocene glaciation.

Further Notes on the Northern Hemisphere

Despite the feeling of some authorities that the effects of an open Arctic Ocean would be quantitively insufficient to cause the amount of glaciation that existed, the validity of the theory seems to be illustrated by present conditions in the Arctic and Antarctic regions.

Thus, the unexplained glacial conditions which have continued in Greenland since the Pleistocene contrast very sharply with the present ice-free condition of northern Canada at the same latitudes. The significant geographic difference between Greenland and northern Canada is their location with respect to the North Atlantic Ocean. As a result of the location of Greenland, there is enough moisture in its atmosphere to cause sufficiently heavy precipitation of snow for the maintenance of glacial conditions, whereas the very scanty precipitation at the same latitudes in Canada results in the present lack of glaciers there. Also, the precipitation in the southern part of Greenland is much heavier than that in the northern part. Hence, an open Arctic Ocean during the Pleistocene seems to be the only geographic condition which could have produced glacial conditions in northern Canada equivalent to those in Greenland today. Further, the effects of the combination of thermal isolation and adequate precipitation can be seen from a comparison of present conditions in the Arctic and Antarctic areas. The thick Antarctic icecap contrasts sharply with conditions in the Arctic Ocean area, with the exception of those in Greeland. This can be explained by (i) the more complete thermal isolation of Antarctica than of the Arctic (the condition in the Arctic is the result of the small interchange of water between the Arctic and Atlantic oceans, without which interchange the Arctic Ocean would have a permanently thick frozen cover); and (ii) the availability of moisture from the surrounding open oceans for snow precipitation on Antarctica. Such precipitation is very slight over the nearly completely landlocked Arctic.

Greenland is similar to Antarctica in being thermally isolated, in being bounded largely by open water, and in having an icecap equivalent in thickness to that of the icecap in Antarctica. Greenland is also similar to Antarctica in that its icecap was probably maintained with little change during the Pleistocene interglacial stages. The following observation recorded by Charlesworth (*2*, vol. 1, p. 94) certainly supports this: "The Pleistocene ice sheets had a maximum thickness . . . which significantly enough is roughly that of the modern ice sheets of Greenland and Antarctica." In view of these conditions, we may expect the Greenland and Antarctic icecaps to be preserved, with minor fluctuations, as long as the Poles are located in their present positions.

Thus, the present contrast between Greenland and northern Canada and that between the Arctic and Antarctic regions, which result from local conditions, are comparable to contrasts between glacial and interglacial stages and make it a plausible conclusion that the latter are also the results of restricted terrestrial changes rather than of global or extraterrestrial causes.

Further evidence that there was formerly a source of precipitation in the Arctic region lies in the position of the glacial divide, as determined from indicators of ice movement and glacial re-

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