Weston ENGINEERING NOTES

VOLUME 13 MARCH 1959 NUMBER 1

ADVANCED DESIGN OF A CORMAG® MECHANISM FOR PANEL INSTRUMENTS

General

THE introduction of dispersion-hardening alloys to the electrical instrument industry made available a source of magnetic energy that was many times more powerful than the quench-hardening materials that were in use up to that time. This enabled the designers to utilize smaller and smaller magnets for applications and finally culminated in a size that was small enough to fit within the confines of the movable coil. Thus, the core magnet mechanism, which in the following paragraphs will be designated as the CORMAG, was made a practical reality.

The CORMAG type of electrical instrument has the advantage, as compared with the conventional C-shaped magnet and soft iron core types, of fewer parts, less material, smaller size, lighter weight, and the resultant lower cost, for a given instrument sensitivity. Such instruments are also self-shielded against external magnetic fields since the soft iron yoke or return path for the magnetic flux extends around the permanent magnet core.

These many advantages have led to the expansion of the CORMAG into laboratory, switchboard, portable, and panel instruments.

Construction of the CORMAG

The CORMAG mechanism, as shown in Figure 1, consists of a permanent magnet core structure comprised of a permanent magnet and a pair of soft-iron pole shoes positioned on opposite sides of the magnet, having surfaces mating with the polar surfaces of the magnet. Such parts are secured together without the use of screws, solder or other separate fastening means to provide a rugged, yet functionally accurate, device. The two pole shoes of this design are held firmly to the magnet by the two end caps. The end caps, made of non-magnetic die-cast material, include lugs that serve to locate the system within the soft iron yoke. The end caps are secured to the pole shoes by forcing a portion of the end cap side wall into an undercut portion of the pole shoe. This is done by pressure applied to the edge of the end cap wall by means

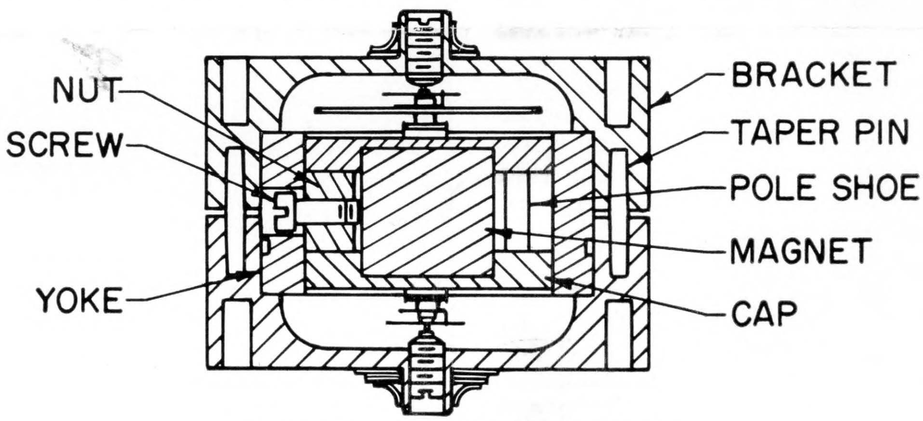

Figure 1—Cross section of CORMAG mechanism.

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John Parker, Editor

W. A. Graham, Technical Editor

WESTON INSTRUMENTS
Division of Daystrom, Incorporated,
614 Frelinghuysen Avenue,
Newark 12, N. J., U. S. A.

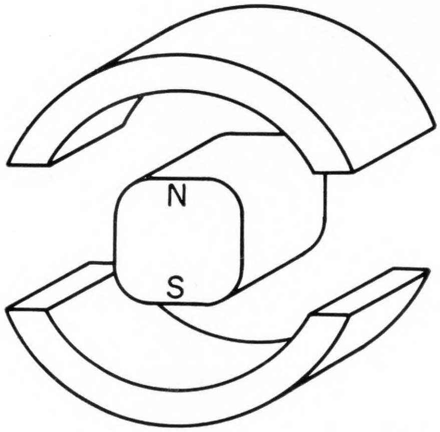


Figure 2—Soft iron pole shoes and magnet.

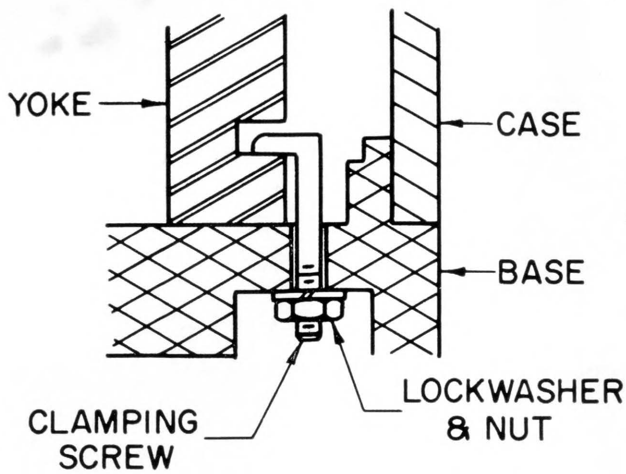


Figure 3—Diagram showing function of cam-headed clamping screw.

of a suitable tool to deform the cap wall. The caps serve to hold the pole shoes in position against the magnet. With this arrangement, the parts form an interlocked assembly, with each part properly positioned relative to the other parts.

The magnetic flux distribution on the surface of the magnet is somewhat non-uniform. This is due mainly to the inevitable variations of the coarse crystal structure of this class of magnet material. The irregularity in flux distribution is compensated by soft iron pole shoes in combination with patented cuts at the magnetic axis of the magnet (Figure 2). The magnetic flux emanating outwardly from the pole shoes is, for all practical purposes, uniform over the surface of the pole shoes.

The yoke, machined from cold drawn steel, provides a return path for the magnetic flux and shields the air gap flux from external fields. A horizontal slot around the circumference of the yoke is used for mounting purposes by providing a seat for cam-headed clamping screws. (See Figure 3.) Top and bottom brackets of die cast metal act as bridges and are positioned in keyways on the outside diameter of the soft iron yoke. The hub section of the bridges are tapped for the jewel screws which engage the pivots of the movable element. The springs of the movable element are soldered to top and bottom abutments that are secured to the bridges with bell grommets. The bell grommet is forced over the O.D. of the hub and provides spring tension against the abutment. The bottom abutment is insulated from the bottom bridge by being sandwiched between two insulating washers. The assembled top and bottom bridges are secured together on the O.D. of the yoke with machined stainless steel tapered pins.

The yoke, core, and bridges, etc., of the CORMAG provide a mechanism of only 29 parts, whereas a similar C-shaped magnet and soft-iron core type mechanism may contain in the order of 68 parts. (See Figure 4.) In this comparison, the

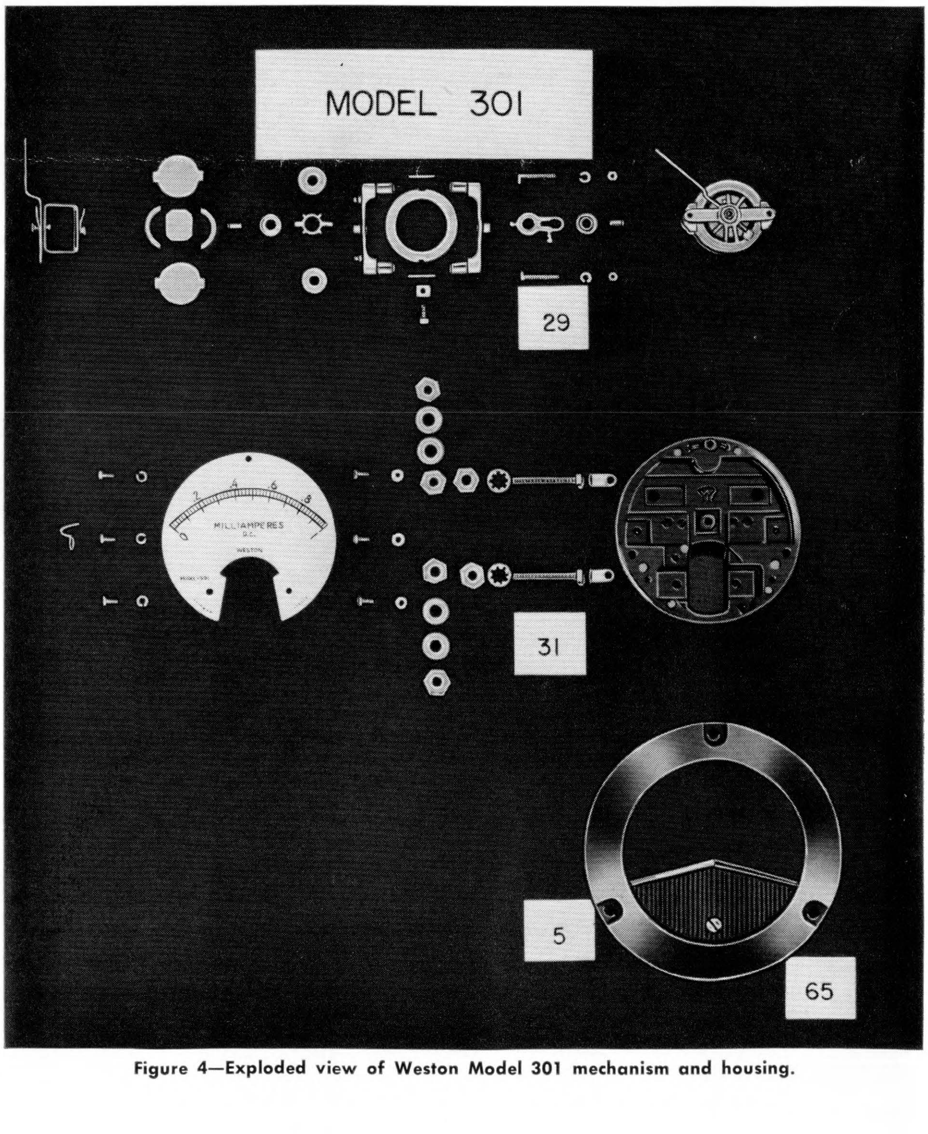


Figure 4—Exploded view of Weston Model 301 mechanism and housing.

movable element proper has been considered as one part. The fewer number of parts means less tooling, fewer parts to stock, less handling time, reduced inspection time, and considerable saving in the assembly of the instrument. The smaller number of parts also results in a weight advantage. The total weight of the CORMAG mechanism used in the Model 301, a 3½″ d-c panel instrument, is 0.1 lb. Efficient utilization of Alnico magnet material is shown in that the Model 301 magnet weighs .015 lbs. and a similar chrome C-shaped magnet producing the same flux may be in the order of 0.13 lbs., or over eight times as much.

The type of construction described provides a mechanism of rigid mechanical design comprised of individual elements which can be made by mass production methods and which are relatively simple to assemble.

Design Consideration for Typical Instrument Application Model 301—3½‴ D-C Panel Instrument

The use of the CORMAG mechanism in a typical d-c panel instrument, the Model 301, offers an instrument that provides adequate space for rectifiers, spools, shunts, thermal elements, and resistors in the base of the instrument.

The Model 301 instrument is a 3½″ flange type d-c panel instrument containing a CORMAG mechanism and designed to meet the dimensional, electrical, and environmental requirements of the military specification for panel instruments, MIL-M-6B, and the American Standard for Electrical Indicating Instruments C39.1-1955. (See Figure 5.)

The housing for this instrument consists of a base and case of molded thermosetting plastic material. A glass window is secured to the case with a pressure-fitted bezel ring. The dial of the instrument is secured by screws to the top bridge of the mechanism. This insures positive positioning of the dial relative to the mechanism. The contour of the dial opening is shaped to act as a pointer stop to limit the travel of the pointer of the movable element. The mechanism is positioned in the base by means of projections on the bottom bridge which engage into molded recesses in the base. The cam-headed clamping screws are used for securing the mechanism to the base. This type of mounting provides positive positioning of the mechanism relative to the base.

The case of the instrument is fastened to the base, utilizing radial holes aligning with threaded inserts forced into radial holes in the base (Figure 6). A washer of deformable but relatively non-compressible material is positioned in each hole in the case; and individual screws pass through the washers and into the threaded inserts in the base. The screws provide sufficient pressure to cause the washer to conform to the contour of the hole and a portion of the washer to extend into the clearance area between the case and the base.

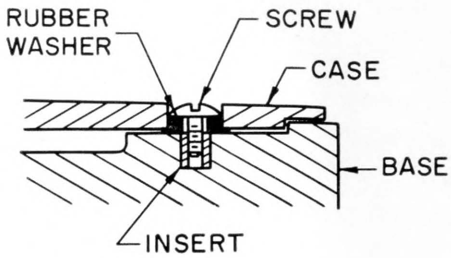


Figure 6—Diagram showing case-to-base mounting.

A zero corrector is provided in the case since it suffices to say that an instrument is no more accurate than the ability with which it can be set to the zero line of the scale.

Solder type terminals are secured to the base of the instrument with push-on type speed nuts. The outer end of this terminal is designed to permit direct soldering. The terminals are suitable for self-contained ammeters both d-c and RF (Model 303) to 10 amperes. By intent, the housing design permits the adaptation of one or more additional modified terminals, should it be necessary.

Figure 5—Typical Weston D-C Panel Instrument using CORMAG mechanism.

Electrical Considerations

The Model 301 instrument offers a wide gamut of performance with ample flux to provide adequate torque under a variety of design conditions. Instruments using this mechanism can be designed for high speed or for low speed; and a wide range of damping is available to the instrument design. The sensitivity range of the instrument not only equals that of conventional C-shaped chrome magnetic systems, but, in addition, gives a considerably improved torque-to-weight ratio for equivalent ranges together with a lower energy consumption.

The shielding properties of the CORMAG mechanism of the Model 301 instrument provides an instrument that can be mounted interchangeably on magnetic and non-magnetic panels. In addition, instruments mounted in close proximity have no effect on each other. The instrument is comparatively unaffected by external magnet fields. For example, with the instrument mounted as close as a foot to a heavy busway carrying 3,000 amperes, the readings of the instrument will not be influenced.

The basic accuracy of the Model 301 instrument is within ±2% of full scale range. When a rectifier is associated with the mechanism to make an a-c rectifier type instrument, it is called a Model 302 instrument and has an accuracy rating of ±3% of full scale range when used on a 60-cycle sine wave at normal room temperature.

The Model 301 and 302 instruments are offered in typical ranges as microammeters, milliammeters, ammeters, and voltmeters.

E. N.—No. 126 —*C. B. Stegner.*

INSTRUMENT BEARINGS— GLASS JEWELS VERSUS SAPPHIRE JEWELS

This article by Mr. A. T. Williams of the Weston Engineering Department, originally entitled "Characteristics of V Bearings," was presented at a Navy Seminar on November 3, 1950, under the sponsorship of the Instrument Jewel Bearings Committee of the American Ordnance Association. It was originally printed as a part of a pamphlet entitled "High-Precision Antifriction Ball Bearings." This article outlines the reason for the development and the salient results of a comprehensive research on the making and characteristics of both pivots and jewels.

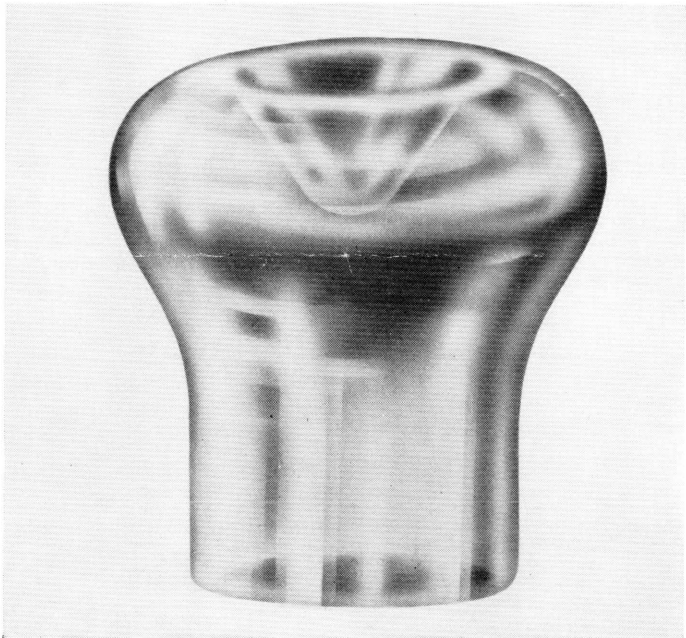


Figure 1—Magnified view of unmounted glass jewel.

PRIOR to 1940, the use of sapphire "V" jewels in electrical measuring instruments was traditional in the industry. The majority of these jewels were made in Switzerland, and, though a parallel American industry was developed, it was not possible to compete pricewise with the Swiss, who operated with lower labor costs and with the traditional skill evolved through generations of watch-jewel manufacturing. As a result, the supply of American-made jewels, using natural American sapphire, was reduced almost to the vanishing point so far as the number of American manufacturers was concerned.

A similar competitive process took place in Great Britain and eventually resulted in the practical extinction of the native British jewel industry. This fact created a crisis in Great Britain because soon after the outbreak of hostilities, the exporting of Swiss jewels to Great Britain ceased and the instrument manufacturers of Great Britain were left without a source of supply. The seriousness of this crisis is plainly apparent when it is remembered that not less than two V jewels are used in every electrical instrument on an airplane—not to mention all the other applications of instruments for war purposes.

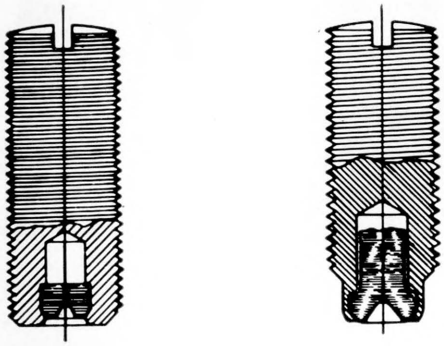
As the crisis developed in Great Britain, our British correspondents cabled, requesting that we organize the American jewel industry, and arrange to ship to Great Britain many thousands of these jewels each week. Unfortunately, it was impossible to organize an increased output in the American jewel industry, as there was no reservoir of trained help, and no prospect of being able to train workers for this tedious, painstaking work within a reasonable time.

Glass Jewels

Fortunately, Weston started some research work on the problem of producing V jewels in 1934. Although no glass jewels were being used in electrical measuring instruments at that time, there had been prior work done in this field and, in fact, a patent had been issued on glass jewels as early as 1899. There was a strong prejudice against the use of softer materials to replace sapphire, based largely on the fact that sapphires had always been used. Despite this prejudice, it was decided to proceed with experimental work on glass jewels in the hope that the shape of the glass could be controlled, and the operation of polishing, with its inherent inaccuracies, eliminated through the use of a glass which would maintain its naturally high surface polish.

Having in mind the fact that from time immemorial most of the ma-

INSTRUMENT JEWELS



SAPPHIRE GLASS

Figure 2—Sapphire and glass jewels mounted into jewel screws.

chinery in the world had been constructed with bearings of material less hard than sapphire, it seemed just a matter of engineering skill to be able to design a properly proportioned instrument jewel in which softer materials could be successfully used.

The problem was not simple, however, because the pressures per square inch of bearing surface involved in instrument service far

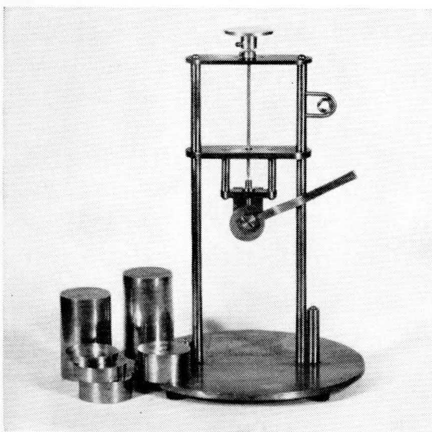


Figure 3—Static load-testing mechanism.

exceed those encountered in normal machine practice, being in the nature of ten tons per square inch and higher. Obviously, pressures such as these preclude the use of any bearing material that could normally be called "soft."

After many months of work and a great many failures, samples of glass jewels were produced having approximately the shape and polish desired. The original production of these jewels, in 1934, was on a purely experimental basis, as a proper technique for controlling the dimensions and surfaces had not then been perfected.

During this development period, laboratory and field tests were carried on simultaneously. As a check on some of the tests conducted in the laboratory, field tests were made by having fifty meters made, twenty-five of the meters containing sapphire jewels and the other twenty-five containing glass jewels.

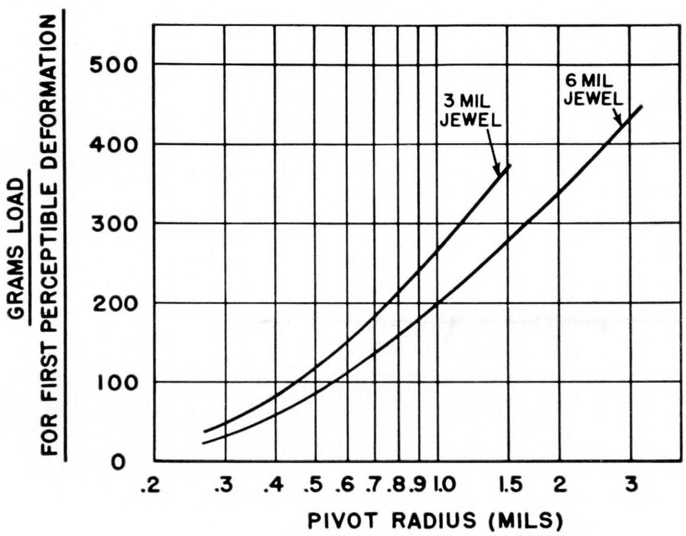


Figure 4—Deformation load curves on glass jewels under static test loads.

These fifty meters were packed in a case, according to our standard packing methods, and shipped back and forth across the country many times, until it was certain that a reasonable transportation test had been made.

On the final return of the instruments, the entire lot was subjected to rigid inspection. It was discovered that less damage had occurred to the instruments with glass jewels than those with sapphire. This, at least, confirmed the theory that if properly proportioned glass jewels could be made, it would be quite possible to use them for instrument bearing applications.

The reason for the success of the glass jewels lay in the fact that both the end shake and the side shake of the pivots had been reduced by proper shaping of both parts of the bearing and an improved surface free of abrasive material, thus reducing the wear caused by vibration during shipment.

Test Was Successful

The success of this test was so encouraging that the experimental work was continued and a small pilot plant was set up to determine if these jewels could be made on a commercial basis. In this pilot plant, the necessary technique for controlling the dimensions, quality of surface, suitable type of available glass, and other factors, were carefully worked out. Eventually the effort resulted in the development of a sound technique which produced glass jewels of high quality without excessive rejections.

The pilot plant was in operation at the time the call came from Great Britain for assistance in organizing the American jewel industry. Realizing the seriousness of the situation in Great Britain, it was decided that it would be possible to train operators quickly to produce enough of these jewels to take care of the immediate requirements of our own correspondents in Great Britain. A cablegram was sent explaining the nature of our new development, and guaranteeing proper performance of airplane instruments using these glass jewels. Under the circumstances, the British manufacturer had little choice but to authorize us to proceed—which we did; and within a short time very encouraging deliveries in increasing quantities were made.

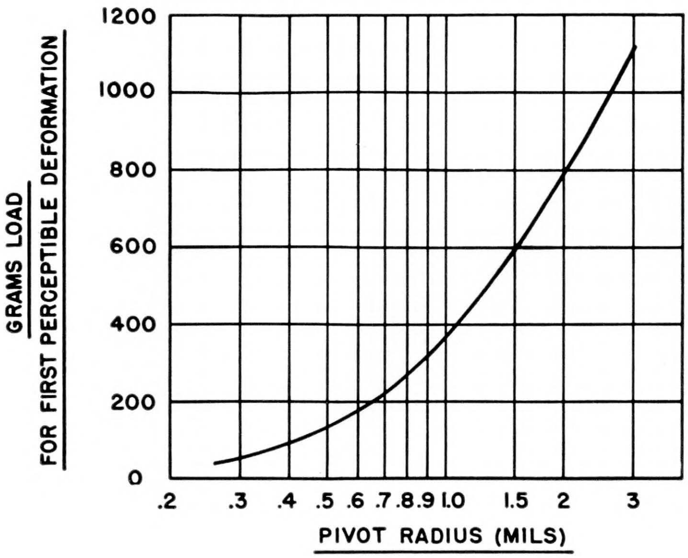


Figure 5—Static load necessary to deform steel pivot.

Curve	Material	Lubricated	Jewel Pit Radius
GD3	Glass	No	3 Mils
GL3	Glass	Yes	3 Mils
GD6	Glass	No	6 Mils
GL6	Glass	Yes	6 Mils
SD6	Sapphire	No	6 Mils

This action helped to tide over the British jewel crisis until such time as they were able to take over the manufacture of glass jewels themselves.

Foreseeing that a similar crisis might easily arise in the United States, if the United States was drawn into the war, it was decided to keep the pilot plant in operation, so that we might have a small force of adequately trained operators to take over in case the American supply of jewels became exhausted. This resulted in what appeared to be a rather unwieldy stock of glass jewels at the time; but our own crisis arrived within a little over a year, and subsequently Weston was in a position to take care of its own jewel requirements without any letdown in production, by using glass rather than sapphire in increasing quantities at a time when sapphire was not available.

In addition to the very practical test of shipping completed meters back and forth across the country, considerable technical and test data have been taken.

Figure 1 shows an unmounted glass jewel. The V is formed by forcing an accurately ground stylus into the heated glass. The contour is accurately held to close tolerances and the hard vitreous surface is completely free of any abrasive material.

Figure 2 shows a glass jewel and a sapphire jewel mounted into jewel screws.

Figure 3 shows the static loading mechanism used during the development work to determine the static load necessary to deform the glass jewel. This deformation is always in the form of a slight splintering of the glass at the point of contact with the pivot. The jewel under test was examined by means of a 40-power microscope although in many cases a sharp needle used as a feeler proved more sensitive in locating a deformation.

Figure 4 shows the static loads necessary to cause deformation of the glass jewels when pivots of various radii are used. It will be noticed that the 3-mil radius jewel will support more load than the 6-mil radius jewel before deforming, the reason being that the contact circle or contact area is greater.

Figure 5 shows the static load necessary to cause deformation of the steel pivot. It is of interest to note that the glass jewel will deform with a static load which is approximately seventy-three per cent of that which will deform the pivot.

Testing Mechanism

Figure 6 shows a mechanism used to test the frictional torque of pivots and jewels. The small motor has a collet on the end of the vertical shaft into which a pivot can be mounted with the sharp end upwards. The jewel mounted in its screw is screwed into the hub of the disc and this entire assembly is then placed on top of the pivot so that the jewel and pivot are in proper contact.

The entire assembly was placed into a vacuum chamber to eliminate air resistance. Power was applied to the motor and the pivot rotated at the same speed as the motor. Because of the friction existing between the pivot and the jewel, the hubbed disc will slowly accelerate. After the hubbed disc has attained a speed of about 0.2 revolution per second, the motor was shut off and the seconds per revolution noted until the disc came to rest. These results were plotted and from these data the deceleration in radians per second was computed. Since the moment of inertia of the disc was also known, the frictional torque could be then calculated.

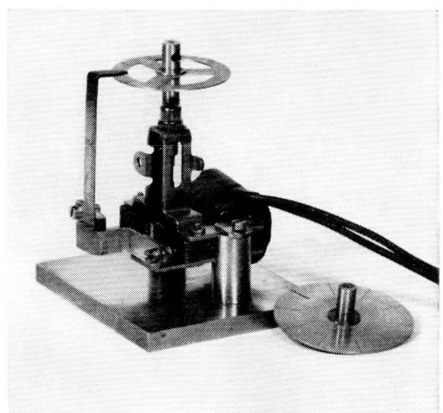


Figure 6—Device to test frictional torque of pivots and jewels.

Figure 7 shows the results of the frictional tests. Note that the frictional torque of the glass and sapphire jewels is about the same. From these curves it is also evident that lubrication is an advantage to a slight degree.

Figure 8 shows a shock testing mechanism. By means of this mechanism, instruments can be subjected to impacts ranging from 0 to 300 "G" units. There is a fair correlation existing between impact test data on this machine and the static load test data previously shown.

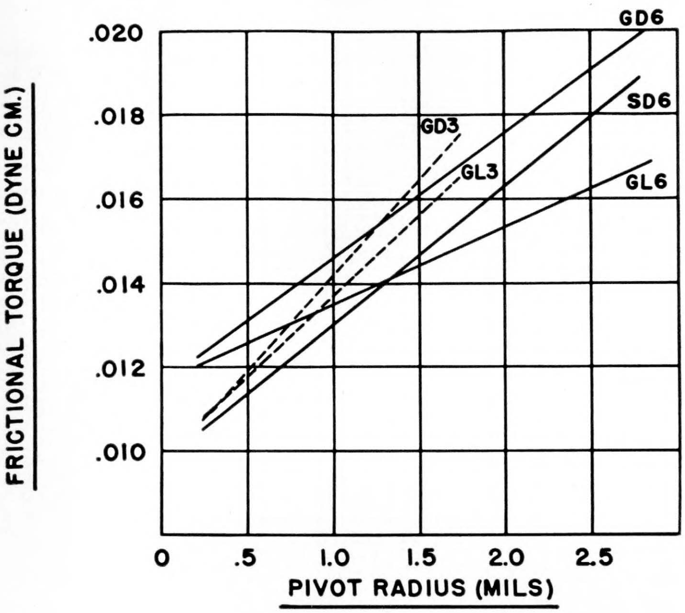


Figure 7—Results of frictional torque tests on glass and sapphire jewels.

Instruments subjected to high impacts will invariably show that when the instrument bearing consists of a sapphire jewel and a steel pivot, the steel pivot will be deformed and when the instrument bearing consists of a glass jewel and a steel pivot, the glass jewel will be deformed.

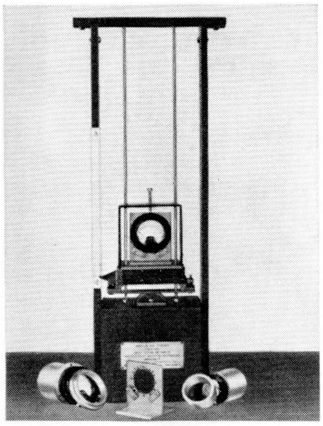


Figure 8—Panel instrument shock tester with dismounted instrument support and accessories.

There is some advantage in having the jewel fail first as the jewel is more easily replaceable. Also based upon many observations, an instrument with a good pivot in a deformed jewel will have considerably less friction than a deformed pivot in a good jewel.

Figure 9 shows a commercial vibration machine on which instruments can be mounted and vibrated at various amplitudes and frequencies. Instruments subjected to vibration will almost invariably show the following:

When the instrument bearing consists of a steel pivot and a sapphire, jewel vibration will almost invariably wear the pivot and these minute steel particles will oxidize and form iron oxide which in turn will abrase the pivot still further until the jewel is covered with red rouge and result in an unusable instrument. When the bearing consists of a steel pivot and a glass jewel, the formation of iron oxide due to vibration is either entirely missing or the time of vibration necessary to produce iron oxide will be from 25 to 100 times the time required for a comparable amount which will develop in a sapphire jewel.

The foregoing statements are based upon many tests by Weston and also the National Bureau of Standards, Navy Department, Bureau of Ships, Royal Aircraft Establishment, Farnborough, England, and many other laboratories.

The reasons for the superior performance of the glass jewels are not entirely apparent, but it is quite possible that the erosion of the pivot and the resultant rouge are due to: (1) The fact that the contour of the "V" is not as uniform in the sapphire as it is in the glass jewel, hence has more "play"; or (2) The sapphire surface has occluded abrasive materials which are entirely absent in the vitreous surface of the glass jewel.

The glass jewel, which was expedited into commercial use by the necessities of war, has replaced the sapphire jewel in Weston instruments to the extent that eighty-three per cent of the meters being manufactured now contain glass jewels.

The question is often asked whether glass jewels are really superior to sapphire jewels. Sapphire is practically indestructible and, therefore, on a strict comparison basis, the sapphire is both harder and less likely to be damaged. A comparable question would be to ask if babbitt is as good as hardened steel and obviously it is not as good or as hard, and yet the combination of a steel shaft rotating in a babbitt bearing has been used for at least 75 years and automobiles and large motors still use this combination of a hard steel shaft rotating in a material which is substantially softer. In a similar manner, the instrument bearing consists of hard steel pivots rotating in glass jewels and our tests and the tests made in other laboratories have proved the superiority of a steel pivot and a glass jewel to that of a steel pivot and a sapphire jewel.

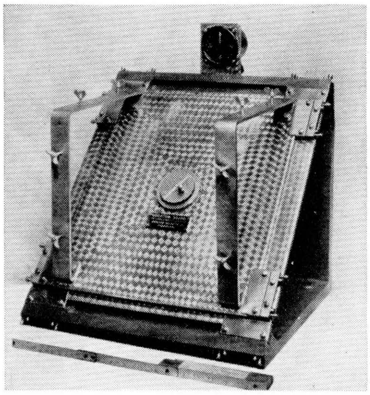


Figure 9—Vibration test stand.

E. N.—No. 127 —*A. T. Williams.*

AMPÈRE AND THE BIRTH OF ELECTRODYNAMICS

Ampère, Volta, Ohm, Watt: who were they and why have we used their names for our fundamental electrical quantities? Mr. Henry Berring of our executive staff, currently Chief Engineer of Daystrom International, has been interested in this matter for many years. His paper on Georg Simon Ohm (Weston Engineering Notes *Vol. 7, No. 2, July, 1952) is well remembered. He has long shared this historical interest with Mr. John H. Miller, Consultant to Weston, retired Vice President and Chief Engineer, to whom he extends his gratitude for much encouragement and advice.*

Mr. Berring tells us that a study of the work of Ampère has been particularly frustrating: although it was largely performed from about 1820 to 1827, there appear to be no published reports of it until 1885. Publication of the great French scientific journal, "Comptes Rendus," was suspended a number of years prior to 1800 in the aftermath of the French Revolution. The "new" series of "Comptes Rendus" which started in 1836 did not in any way attempt to cover prior discussions and reported only on matters current and proposed. Thus, these papers by Ampère on electrodynamic action were not published until 1885 as referred to in Mr. Berring's first footnote. He, in turn, obtained them through the courtesy of Mr. Nathan D. Golden of the Department of Commerce in Washington, D. C., and his friend, the scientist and industrialist, Mr. André Debrie of Paris, France.—The Editor.

THE reaction of a current-carrying conductor upon its twin—the basis of all electric motors—seems axiomatic to us. But the discovery and ensuing discussion of this and associated phenomena opened the gates to a new technological era and sparked a veritable explosion of the electrical science. These years in the second decade of the nineteenth century witnessed many great and important scientific break-throughs in many fields and the establishment of many fundamentals of modern mathematics, physics and chemistry. Perhaps it was the newly won freedom of the mind which was one of the results of the American and French Revolutions; perhaps it was an accumulation of scientific experience which decades of war had repressed and which peace had released; perhaps, also, it was the good fortune by which a number of great scientists appeared simultaneously on the scene; the fact remains that these were years of startling scientific progress.

The French Academy of Sciences

One of the focal points of this activity, particulary in the field of electricity, was the austere assembly of the French Academy of Sciences in Paris. Before that assembly, the most illustrious of French scientists reported their findings and debated their theories. Summaries of their remarks were entered into the minutes and served as reference for further debate. There was much lively communication between scientists inside and outside France and there were numerous scientific publications which printed papers submitted to them and which served as a forum for the public debate of theories and experimental evidence.

It is fortunate that much of the writing of that time has been preserved for posterity and that much of it is now available in compact form through the painstaking care of the French Society of Physics (Société Française de Physique), which collected even the personal correspondence between such men as Ampère and Faraday and others, and published a comprehensive collection of all pertinent material.[1]

Oersted's Discovery

The spark which set off the explosion in the electrical science was not aimed directly at the Academy. It was a Latin language pamphlet on an electrical discovery which was published in the City of Copenhagen, Denmark, under the title "Experimenta Circa Effectum Conflictūs Electrici in Acum Magneticam" (Experiments About the Effect of the Electrical Conflict[2] Upon the Magnetized Needle). Translations of this paper were published in the French magazines "Annales de Chimie et de Physique" and "Journal de Physique." The author was H. C. Oersted, Professor of Physics at the University of Copenhagen and Secretary of the Royal Danish Society of Sciences. The date of publication was July 21, 1820. Less than two months later, on September 18, Mr. André-Marie Ampère reported about it and about his own findings to the Academy and this was the start of one of the significant periods in the history of progress in the field of electricity.

The roster of those who directly or from a distance participated in the ensuing debate on what Oersted and Ampère had discovered, reads like an index to a physics textbook—Arago, Delambre, Humphrey Davy, Fresnel, Biot, Savart, Laplace, De la Rive, Faraday, Gay-Lussac, Pouillet, and others. Hardly had one of them reported on experimental evidence of his own, when others attempted theoretical explanations and suggested additional experimentation which, in turn, led to further reports, debates and criticism by this highly competent group. They corresponded with each other, quoted each other, sometimes politely refuted one another, but generously shared their experiences with the rest.

The stage had been set by Volta, whose electrolytic battery, derived from Galvani's observations on the effects of metals in contact with the limbs of freshly killed frogs, provided a source of electricity better suited to controlled experimentation than the frictional electric charge accumulated in a Leyden jar. Oersted had experimented with a Volta source and discovered that "the magnetized needle is deflected

[1] Collections de Mémoires relatifs à la Physique (Gauthier-Villars, Paris, 1885/87; the volumes dealing particularly with Ampère's work are entitled, "Mémoires sur l'Électrodynamique," Vols. II & III.)

[2] Meaning, "Action" or, more broadly, "Reaction."

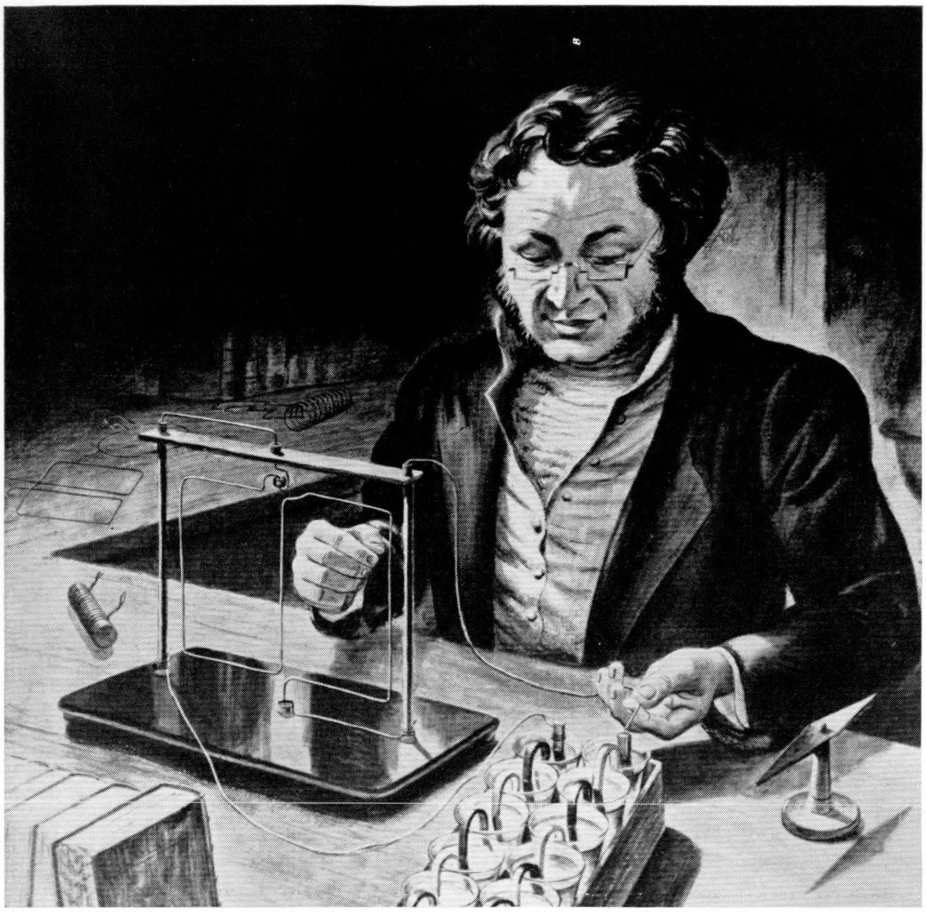


Illustration Courtesy Ohmite Mfg. Co.

Andre-Marie Ampère (1775-1836), brilliant French physicist, inspired by the experiments of Oersted, created a new branch of physics—electrodynamics.

from its position of equilibrium by the action of the galvanic apparatus and that this effect takes place when the circuit is continuous and not when the circuit is interrupted." He had also observed the direction of the motion of the compass needle in relation to the polarity of the source of electricity and had summed up his findings, stating that if a "straight portion of a wire is arranged horizontally above the needle and parallel to its direction, . . . the pole nearest the negative terminal of the galvanic apparatus will deviate toward the west; but when the wire is placed horizontally below the needle, the effects are in the opposite direction." For a wire stretched at right angles to the plane of rotation of the compass needle, Oersted's original text has this to say:

"Quando filum conjungens perpendiculare ponitur a regione polo acūs magneticae, et extremitas superior fili electricitatem a termino negativo apparatūs galvanici accipit, polus orientem versus movetur. Posito autem filo (cujus extremitas superior electricitatem a termino negativo accipit) e regione puncto inter polum et medium acūs situ, occidentem versus agitur."

[If the connecting wire is placed vertically opposite one of the poles of the magnetized needle and the upper portion of the wire accepts electricity from the negative terminal of the galvanic apparatus, the pole is moved toward the east. However, if the wire (whose upper portion accepts electricity from the negative terminal) is placed opposite a point between one of the poles and the center of the needle, it is moved toward the west.]

Ampère Reports to Academy

In a number of meetings of the French Academy of Sciences on September 18-25, October 9-16 and 30, and on November 6, 1820, Ampère took the floor and reported at great length about experiments which he had made in consequence of his occupation with Oersted's discovery. In these sessions he discussed the qualitative aspects and experimental refinements of his work. Later, beginning with a session on December 4, 1820, Ampère began a discussion of the quantitative aspects of his experimental results and provoked two years of heated debate and rebuttal which ended only with Ampère's admission of some early errors.

Nothing, of course, should detract from the profound and fundamental importance of Ampère's discovery and from his contribution to science, even though he was not always right.

Tension and Current

In the sessions of the Academy in September, October and November, 1820, Ampère first defined the differences between those two types of electrical action which we would designate as electrostatics and electrodynamics. Only electrostatic effects were then known and understood by Ampère's contemporaries until Oersted published his findings and demonstrated some of the effects of electricity in motion. These were Ampère's introductory remarks:

"The electromotive action manifests itself in form of two effects which I believe I must distinguish from the beginning by a precise definition. I will call the first of these 'electric tension' and the second 'electric current.'"

He then goes on to explain how electric tension can be observed, for instance, by the attraction of light objects or the action of the electroscope. He contends that electric tension will exist only in a system in which conductors are separated from each other by insulators. He mistakenly holds that this electric tension completely disappears the moment the conductors are connected with each other; but he correctly describes some of the effects which then begin to take place, such as the decomposition of water or, as discovered by Mr. Oersted, the deflection of the compass needle.

Ampère struggles with these new concepts and pictures the "electromotive action" as that of two electric fluids, one positive and one negative, which travel through a circuit in directions opposite to each other, emanating at a point where they are separated electrolytically and ending in another part of the circuit where they recombine with each other and the process terminates.

"In this fashion there results a double current, one of positive, the other one of negative electricity, leaving in opposite directions from the points where the electromotive action

takes place and coming to reunite in the part of the circuit opposite these points. The currents of which I speak continue to accelerate until the inertia of the electric fluids and the resistance which they encounter, in view of the imperfection of even the best conductors, balance the electromotive force; after which they continue indefinitely at a constant speed such that this force preserves the same intensity. However, they stop at the very moment the circuit is interrupted. It is this state of electricity in a series of electromotive and conductive substances which I will briefly call electric current; and as I will continuously be compelled to talk about two opposed directions according to those in which the two electricities move, I propose that each time the subject comes up and in order to avoid repetition, I will describe the direction of the electric current by referring to that of the positive electricity. Talking about [the conditions within] a voltaic pile, the expression 'the direction of electric current in the pile' will mean the direction from the place where hydrogen is liberated in the decomposition of water toward the place where oxygen is obtained. Correspondingly, the direction of the electric current in the [external] conductor . . . will be designated as the one from the terminal where oxygen is generated toward that where hydrogen develops. In order to embrace these two cases in one definition, one may say that the direction of the electric current is that which follows the hydrogen . . ."

Here, apparently, is the source of the difficulty which still confounds students of electricity who must learn that the electronic flow of current is opposite to the direction of the flow of electricity as suggested by the conventional symbols of polarity. Be that as it may, it was necessary in Ampère's day, as it is now, to agree on the direction of current flow in relation to the electrical terms of polarity and the poles of a magnet, so that all concerned can use an identical frame of reference, regardless of whether it be in agreement or disagreement with other theories.

It is fortunate, therefore, that Ampère became bored with the repetitious reference to the two opposing fluids of his electrical theory and decided on a single definition of current direction.

Great effort and much repetitive argumentation are used by Ampère to drive home to his listeners the difference between tension and current and the experimental evidence which then existed in support of these concepts. In all this discussion, however, Ampère still contends that the electroscope will cease to deflect once current is allowed to flow, just as the compass needle is not deflected by "electric tension" alone. This was still seven years before Ohm correctly described the relationships between current and tension and admitted the simultaneous existence of both in the same circuit. The causal relationship between the two was certainly not clear to Ampère.

Current Measurement

While still on the subject of Oersted's discovery, Ampère mentions the value which the interaction of current and the compass needle would have for the purpose of electrical measurement. "The ordinary electrometer indicates the presence of a tension and the intensity of that tension. What has been missing is an instrument which makes known the presence of the electric current in a pile[3] or a conductor, and which indicates its strength and direction. That instrument now exists."

He goes to great length describing how to use the compass needle as what we might call a polarized iron vane type ammeter. However, in this he was not original. He did not know that a man named Schweigger had given a lecture on September 13, 1820,[4] (thus five days before Ampère's first talk before the Academy), in which he had described the compass needle as a current indicator and where he had even pointed out that one could wind the wire which connects the positive with the negative pole of the galvanic apparatus, so that it encircled the compass needle, whereupon "the needle became as sensitive to the action of a simple pile as the muscle of a frog." This came to be known as Schweigger's "multiplier" and appears to have been the first use of a coil or winding for the purpose of producing an increased or "multiplied" electromagnetic effect.

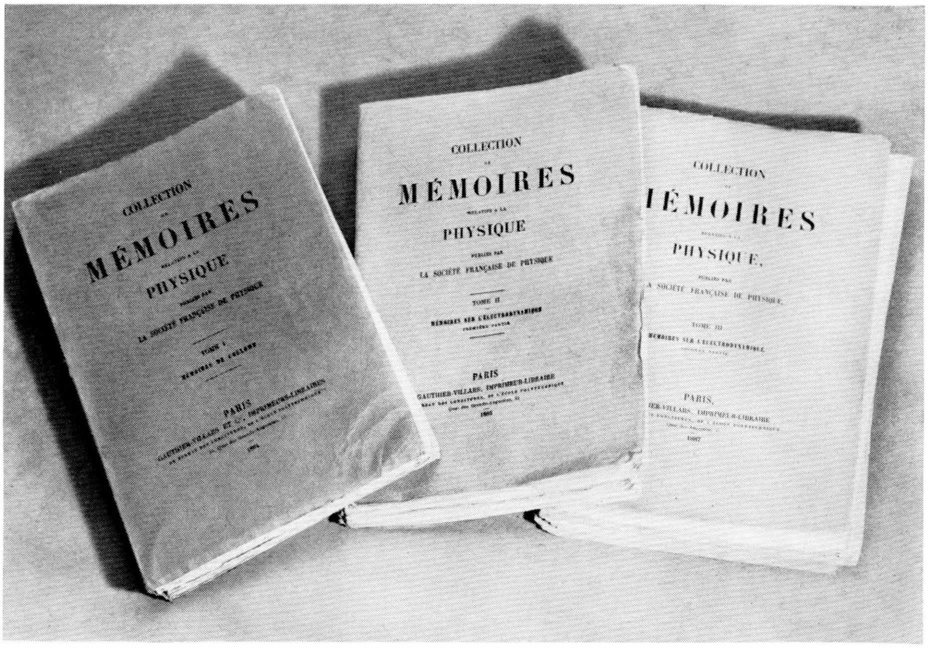
Ampère's Discovery

It is only after his elaborate description of the differences between tension and current that Ampère makes the statement that "the differences of which I have spoken are not the only ones which distinguish these two states of electricity." This, then, brings him to his own discovery:

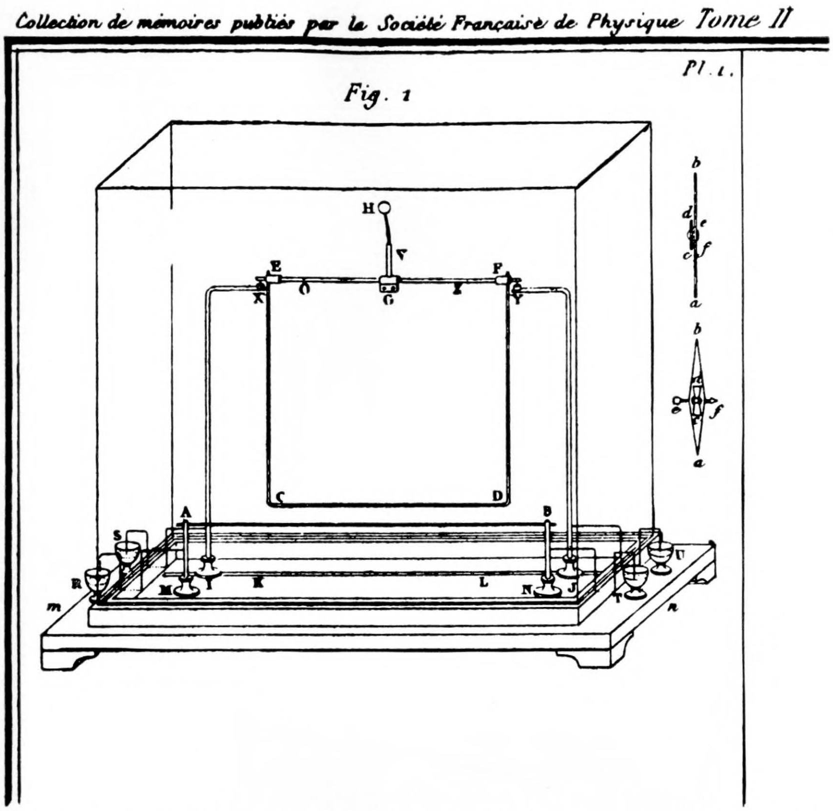
"I have discovered even more remarkable differences by arranging in parallel directions, two straight portions of two conductors which connect the terminals of two piles. One was fixed and the other was suspended on pivots and was made very mobile by a counterweight and the two could approach each other or move apart and yet preserve their parallelism. I have observed that when simultaneously an electric current was passed through each of these, they mutually attracted

[3] Pile is the term frequently used by Ampère and his contemporaries for the electrolytic current source devised by Volta, which we call a battery.

[4] Allgemeine Litteraturzeitung, No. 296, November, 1820. This report probably remained unknown in France until Oersted reported about Schweigger's work in Annales de Chimie et de Physique, Vol. XXII, 1823, pp. 358-380.



Books in which the work of Ampère and his contemporaries is preserved.



Ampère's sketch of apparatus with which he demonstrated his discovery. Taken from the collection of Ampère's papers by the French Society of Physics.

each other when the two currents were in the same direction and that they repelled each other when the currents flowed in opposite directions.

"Now these attractions and repulsions of electric currents differ basically from those which the electricity produces in the state of rest. First of all, they cease, just like the chemical decomposition, the moment the circuit of conductive substances is interrupted. Secondly, in the ordinary electric attractions and repulsions, it is electricities of opposite kind which attract each other while those of the same kind repel each other. In the attractions and repulsions of electric currents, the exact opposite takes place. When the two conducting wires are placed parallel to each other, so that the ends of the same name find themselves on the same side and very close to one another, there is attraction; yet there is repulsion when the same conductors, still parallel, carry currents in opposite directions so that the ends of the same name find themselves at the greatest possible distance from each other. Thirdly, in the case where there is attraction so strong as to cause the movable conductor to come in contact with the fixed conductor, the two remain attached to one another like two magnets, and will not immediately separate from each other as it happens when two conducting objects touch each other after attracting each other because they are electrified, the one positively and the other one negatively."

So far, Ampère's observations are completely correct and confirmed by all that has been learned since. However, at this point, and occasionally at other points, Ampère draws conclusions beyond experimental proof and gets to be carried away by his imagination. This is what he says: "Finally, the two electric currents attract or repel each other in a void just as in air which is . . . contrary to what is observed of the mutual action of two conducting objects which are electrified in the ordinary manner." Apparently, Mr. Ampère believed that electrostatic attraction did not occur in a vacuum.

Starting from his basic discovery of the attraction and repulsion of two current-carrying conductors, Ampère then pushes forward into this new and fascinating field.

"I had originally thought that it would be necessary to establish the electric currents in the two conductors by means of two different piles. However, this is not necessary. It is sufficient if the conductors form part of the same circuit . . . One must conclude from this observation that the electric tensions of the two terminals of the pile do not enter into these phenomena because there certainly is no tension in the rest of the circuit. This is further confirmed by the possibility of causing the magnetized needle to deflect at a considerable distance from the pile by the use of a very long conductor which is bent back at its mid-point and placed in the direction of the magnetic meridian and so that it passes above or below the needle. This effect was suggested to me by the illustrious scientist, Mr. de Laplace . . ."

It is obvious that Ampère wants to guard himself against any possible suspicion that the new effect which he had discovered might be no more than a different form of electrostatic attraction or repulsion. It is largely for this reason that he repeatedly denies the existence of "tension" as soon as current flows in a circuit.

Ampère's Telegraph

Despite his preoccupation with purely theoretical matters, Ampère shows good practical sense when talking about possible uses for what he has discovered.

"With as many wires and magnetized needles as there are letters, and by placing each letter on a different needle one could, with the aid of a pile placed at a distance from the needles, . . . create a sort of telegraph with which to write all the details which one might wish to transmit, across whatever obstacles there might be, to a person instructed to observe the letters placed on the needles. By setting up on the pile a keyboard whose keys carry the same letters and would make the connections when depressed, this means of communication would function with great facility and the time to operate it would be merely the time necessary to touch a letter on one side and to read it on the other."

Some twenty years later, Gauss and Weber actually developed an electromagnetic telegraph.

Controversy About Magnetism

As a result of these preliminary observations, Ampère then engages in extremely involved speculations on the nature of magnetism. His experiments prove that the behavior of a current-carrying conductor of appropriate shape will duplicate that of a bar magnet. For instance, Ampère suspends a glass rod so that it can rotate in the manner of a compass needle, but places upon it a wire wound in the shape of a helix. Very elaborate and clever means are used to conduct current into and out of the helix via mercury cups arranged in such a manner that the rotation of the rod is not impeded. The action of this device with respect to another magnet or another current-carrying conductor, or even with respect to the magnetic field of the earth, is found to be exactly like that of a magnetized needle. Consequently, Ampère advances the theory that ferromagnetism is brought about by minute circular currents which, no matter how created, continuously flow within the molecules of iron and which, in the process of magnetization, are so oriented as to bring about the magnetic behavior of the material.

In this, Ampère differs from Biot and others who regard magnetism, no matter what might be its nature, as the total effect of innumerable small "elementary" magnet bars. Ampère makes great efforts to show that the magnetic forces which stem from his assumed elementary currents are numerically and geometrically identical to the forces ascribed to Biot's elementary magnets. To prove his point, Ampère sets out to compute the force between an infinitely small current element in one conductor and a neighboring current in a conductor of infinite length. The purpose of this approach is to derive, by integration over a finite length of the first of these conductors, the force between any two conductors of finite length. In this derivation, Ampère takes recourse to some simplifying assumptions only to find that the resultant theory is not in agreement with experimental evidence. A great debate ensues until 1822, while Biot and others are suggesting more complete mathematical solutions. Even in the end, there still remained the difficulty of proving the identity of Ampère's and Biot's laws with those pronounced by Coulomb.[5] Not until about 20 years later did Gauss and Weber furnish proof of the compatibility of these various theories and offered precise constants for the relationship between current and force.

Electromagnetic Induction

In 1822, Ampère visited Geneva where there was an excellent physics institute and where he hoped to refine some of his previous experiments. He was accorded great courtesy and was permitted to use the facilities of the institute to any extent he wished. It is interesting to note that in the ensuing experimentation, Ampère came close to demonstrating the principle of electrical induction. He suspended a closed circular loop of wire on pivots within a fixed winding and placed magnets on fixed supports so that poles of opposite signs faced the movable winding at points of greatest distance from the axis of rotation. In his report we read:

"... the experiment had as its objective to determine whether it is possible to produce an electric current through the influence of another current. ... I have succeeded with [the] apparatus by employing the excellent horseshoe magnet of the museum in Geneva which Professor Pictet had procured for me."

Ampère had indeed succeeded in causing the electrically isolated movable coil to deflect under the "influence" of current in the fixed coil. But, strange as it may seem, —he did not pursue the matter. He never discovered that the "influence" he had witnessed was not continuous. There is no mention of this experiment in Ampère's correspondence with Faraday; but it was Faraday, rather than Ampère, who described and proved the correct derivative relationship between primary current and induced voltage. Ampère seemed to have been blinded by the fixation that his task was exclusively that of explaining the nature of magnetism.

Magnificent Failure

This was the great tragedy of Ampère's work: He wished to reconcile his theory of magnetism with those of Coulomb and Biot and the basic gravitational laws of Newton in search of the one all-embracing law of an electromagnetic universe which, he believed, existed. This was a magnificent vision but it winged its way up into the realm of speculation and Ampère did not succeed in bringing it down to earth. In seeking the unattainable, he failed to see the practical significance of his discovery.

In a monumental résumé of his papers to the Academy from 1820 to 1825, Ampère finally reiterated his entire electrodynamic creed. This paper, entitled "Report on the Mathematical Theory of Electrodynamic Phenomena, Exclusively Deduced From Experience", fills nearly 200 printed pages. Yet, despite its tremendous mathematical detail, it fails completely to reduce the laws of electromagnetism to practical form.

In substantiation of his original discoveries and subsequent theories, Ampère devised a profusion of extremely clever apparatus, yet he never measured the forces between current-carrying conductors against known, independent standards. He set up a great number of situations where the forces between conductors balanced each other and from these observations he drew ingenious geometric and trigonometric conclusions. Many times he admitted the absence of results as positive proof and yet, by a series of such negative observations, he arrived logically at perfectly sound conclusions. But these were all unrelated to any existing system of absolute measurement.

No one described these failings better than the man who later brought Ampère's work to fruition and who constructed one of the first electrodynamometer type instruments with which he made precise measurements of the forces of attraction or repulsion which had eluded Ampère. This man was Wilhelm Weber. In his famous paper, "Electrodynamic Measurements" (Elektrodynamische Massbestimmungen, Weidmann'sche Buchhandlung, Leipzig, 1846), Weber has this to say:

"Ampère's classical paper is only in a minor part devoted to the phenomena and the laws of the reciprocal effects of conducting wires; the greatest part is devoted to the development of his ideas on magnetism ... The fact of the mutual attraction of two conductors was verified [by him] time and time again and is beyond any doubt; but the verifications have always been made under such conditions and by such means that no quantitative measurement was possible ... More than once, Ampère drew conclusions from the absence of electrodynamic action as if a measurement had given him a result equal to zero; ... but these negative experiments ... do not have ... the full value ... of the latter ..."

So it happened that Ampère's crucial discovery and the ingenuity of his experimental and mathematical demonstrations were to have their decisive effects upon the electrical age only through the work of others. Nevertheless, his findings of the motor reaction of one electric current upon another have been given their deserved recognition: his name has been immortalized by its use for the unit of electric current.

[5] Coulomb described the force between magnets, Biot (after Ampère's fundamental discovery) that between magnet and current-carrying conductor, and Ampère that between two current-carrying conductors.

E. N.—No. 128 —*H. Berring.*