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ENERGY CONVERSION ANYONE? and THE STORY OF MERCURY-STEAM

Chapter 2 — Electricity and Scientific Research

Chapter 3 — The Central Station. A First Look

by

H.A. Liebhafsky
R&D Applications Operation

TECHNICAL INFORMATION SERIES

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SUMMARY

This report, as the successor to 80CRD281, is the second installment of a book intended to acquaint the general reader with large-scale energy conversion generally, and particularly with the story of mercury-steam. It completes the background intended to prepare the reader for the history of the mercury boiler, which W.L.R. Emmet expected would be the crowning achievement of his engineering career.

KEY WORDS

energy conversion, thermodynamics, central station, mercury-steam, electricity, research

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ENERGY CONVERSION ANYONE?
and
THE STORY OF MERCURY-STEAM

PRE-PREFACE 2

To my colleagues, their colleagues, and others:

This report follows 80CRD281, February 1981, as the second in a series eventually to be assembled into a book probably *not* bearing the title above. Present preference: *Energy Conversion: Background and Example* with the two topics named above as subtitles.

I now quote from the earlier Pre-Preface:

What I request from you is help by way of annotations. Never mind respect for old age; just write what you think (good and bad) on the margins of the reports. Then send the annotated copies to

H.A. Liebhafsky
2610 Melba Circle
Bryan, Texas 77801

As of now, interest in the first report was satisfactory if the number of copies distributed is a valid criterion, but I was disappointed in the response to my plea for annotated copies. Perhaps critical interest will be nurtured if I reveal that the second report brings us closer to the present, tells more about the electrical industry, and discloses (not for the first time) why Edison didn't get the Nobel Prize. (The report also implies that electrical research is worthwhile and ought to be continued!)

I apologize for inconveniences you may suffer from such defects as lack of glossary and list of units, but I promise eventual relief when I prepare appendices about which I'm yet uncertain.

H.A. Liebhafsky

Chapter 2

ELECTRICITY AND SCIENTIFIC RESEARCH

In 1698, a century to the year before Rumford's engineering research revealed the probable nature of heat, Thomas Savery patented an "atmospheric" steam engine, primitive but usable. By 1824, when Carnot did his theoretical research on heat engines, steam engines (thanks mainly to inventors led by James Watt) had made England dominant among industrial nations. Heat engines began to change civilization without initial help from scientific research as we know it.

Not so with electricity. By the time Morse introduced his telegraph in 1837, scientific electrical research had in a few decades laid the foundation for today's electrical industry. The main reasons for the difference between the two cases must have been that electricity was far the more exciting, initially seemed more mysterious than heat, and that electrical experiments were better suited to the laboratory. Once a few early discoveries had been made, scientific research on electricity spread like wildfire through much of the Western World. Francis Bacon's "Knowledge is power" suggests "Heat engines, power before knowledge; electricity, power from knowledge."

Scientific research on electricity led inventors and engineers to build a great industry. What on? What is electricity? We have no simple answer because Adamsian multiplicity and complexity here run riot. The latest *Britannica* ("Macropedia," *6*, pp. 537-610) discusses electricity itself in 7 main sections with a total of some 40 subsections; related articles are too numerous to mention. The *Britannica* says that "Electricity is the [hydra-headed] phenomenon associated with positively and negatively charged particles at rest and in motion, individually or in great numbers." That should cover it. "Electricity" is a word Emily Dickinson would have "tipped her hat to," and it fits Humpty Dumpty's "When I make a word do a lot of work like that, I always pay it extra." We shall not be much out of pocket, for we cannot go beyond a cursory introduction that lets the reader judge whether scientific electrical research can, in the future, be expected to match its past record in large-scale energy conversion.

THE BEGINNINGS

Benjamin Franklin (1706-90), who belongs beside Rumford, imagined electricity to be "a subtle fluid diffused through all bodies." It is not.[(1)*] Yet it will pay us to pretend that a subtle electrical "fluid" is generated in a central station and flows as an electric current from there to the consumer, often far away, and returns eventually to the station for "regeneration" to replenish the electrical energy converted en route into other forms.[(2)] In the most common kind of electricity, Franklin's "fluid," if American, changes direction precisely 120 times a second as it "flows."

Moving electricity, the most useful kind, historically had two *static* parents—one electrical, the other magnetic. The marriage of the parents went undiscovered for many centuries.

About 500 B.C., some Greek rubbed amber ("electron" in Greek) with a cloth, and discovered that both materials became "electrified" ("amberized," in literal translation). We know now that all *insulating materials* (i.e., all nonconductors of electricity)[(3)] will respond similarly no matter what their nature; we know the rubbing to be incidental, being needed mainly to improve electrical contact; that electrons ("atoms" of electricity) migrate from one insulator to the other—migrate more readily the better the contact. We have learned that the insulator receiving the electrons becomes negatively charged, while an equal positive charge remains upon the other body; and that the charges on the separated insulators often persist for a very long time—hence the name "electrostatics" for the science that sprang from such experiments. Eventually it was found that like charges repel, and unlike attract. Charles Augustin de Coulomb (1736-1806) proved that, under the simplest conditions, the *mechanical forces* that arise from electrostatic attraction and repulsion vary inversely as the squares of the distances between the charges. Consequently, work must be done to separate charges unlike in

* Notes and references thus indicated appear with other references in Appendix 1.

sign, and work can be gained when charges of like sign move apart.

The Greeks did their bit for magnetism ("magnetostatics") also. Although the Chinese seem to have known magnetic substances for some 4000 years, it was the early Greeks who discovered magnetite (an iron ore, Fe_3O_4) near Magnesia and called it "Magnesia stone," whence "magnetism." About the eleventh century, compasses for navigation began to be made from this iron ore, which was called "lodestone" ("lode" = "lead"—not Pb!) by the Anglo-Saxons. William Gilbert (c. 1540-1603), physician to the first Queen Elizabeth, founded the science of magnetism with the publication of his *De magnete* (1600).

At first sight, the behavior of magnets resembles that of charged insulators. In magnetostatics, *poles* (north N, and south S) seem analogous to charges (+ and −). Like poles repel, unlike attract. A pivoted horizontal needle of Fe_3O_4 is a compass. It will turn so that its "north" pole (a misnomer for "north-seeking" pole) points north, attracted by the earth, itself a magnet. The "inverse square law" found by Coulomb for electric charges holds approximately for magnetic poles, and the forces here are likewise mechanical. However, a crucial and profound difference exists between charged insulators and magnets. Electrical charges on insulators can, as we have seen, be virtually *isolated,* but a magnetic pole cannot. Any permanent bar magnet, no matter of what it is made, will have a "north" pole at one end, and a "south" pole at the other. So will successively smaller bars made from it, no matter how often the parent is divided; and in every offspring, as in the parent, the strength of the "north" pole will equal that of the "south." This fascinating, continuing divisibility suggests that every permanent magnet contains many tiny magnets—magnets perhaps on an atomic or subatomic scale, a conclusion supported by magnetic *induction:* to wit, a bar of iron becomes a magnet when placed *near* a magnet; a bar of copper does not; iron atoms can be *induced* to become magnets; those of copper cannot. "Induction" may well be the word most needed to describe magnetism, electricity, and electromagnetism, without which our daily lives would be changed beyond recognition.[4]

The moving electricity that most concerns us is of two kinds: direct-current (dc) and alternating-current (ac).[5] When dc is steady, the movement is governed by Ohm's Law, commonly written $E = IR$, where E is the potential difference (volts) existing across a circuit of resistance (inverse conductance) R (ohms) through which current I (amperes) is flowing. With ac, E and I vary systematically and periodically with time so that ac is characterized by a *frequency* (units, Hertz, or cycles per second). Ohm's Law holds for ac, but in more complex form.

Georg Simon Ohm (1787-1854) announced his law in 1827. It seems—but only seems—straightforward and easy to understand.[6] By 1827, the curtain had already risen on a scientific drama that would disclose the enduring marriage of electricity and magnetism—that would relate the rubbing of amber to magnetite as compass.

In the winter of 1819-20, during a private lecture to advanced students, Hans Christian Oersted (1777-1851) "by a happy impulse or by design" closed a circuit, causing dc to flow from one pole of a battery, through an external circuit, to the other pole.[7] Near the circuit, *but out of contact with it,* was a compass. When current began to flow, the compass needle moved to a new position. The observation of this motion was *a great discovery.* No such motion had ever been seen before because current had never before flowed through a battery circuit when it was near a magnet being watched. The mechanical force that turned the needle (see Figure 2-1) must have resulted from an interaction that occurred *over the space* separating circuit and compass. *Electromagnetism* had been found. Note that the experiment showed the characteristics (direction, motion, and force acting over distance in the direction of motion) associated with *work.*

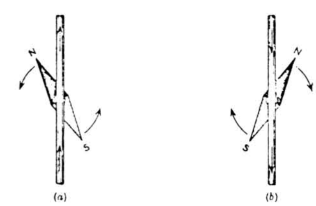


Figure 2-1. Simulation of Oersted's experiment. Movement of needle occurred in one direction (a) when current began to flow through the circuit, and in opposite direction (b) when flow stopped (vertical arrows). The movements showed the presence of transverse forces oppositely directed (curved arrows). In an ideal experiment, the needle would have set itself at right angles to the current-carrying wire. The text explains how the experiment was actually done, and electromagnetism discovered by chance.

MICHAEL FARADAY AND ELECTROMAGNETIC INDUCTION

In emphasizing the importance of early *pure* research to our electrical industries, we shall have to risk distorting history by concentrating on

Michael Faraday (1791-1867), thus not doing justice to other noteworthy men whose life spans overlapped his. A few examples of such: Luigi Galvani (1737-98), who discovered that electricity could cause frogs' legs to twitch; Conte Alessandro Volta (1745-1827), who correctly identified a battery as the source of the electricity required for this twitching; André Marie Ampère (1775-1836), who brilliantly progressed beyond Oersted toward an understanding of electromagnetism;* and others, some of whom (Oersted among them) will later on be briefly mentioned.

Michael Faraday, who through research did more to found the electrical industry than anyone else, had a magnificent scientific career with a most unlikely start.

The son of a poor blacksmith, Faraday had to educate himself. He became a bookbinder's apprentice, eager to learn, and he read what he bound. One day, a distinguished visitor to the bookshop found by chance that Faraday not only knew much about electricity, but also had become "a self-taught chemist of no slender pretensions." The visitor was impressed. Subsequently, a second visitor, likewise impressed, gave Faraday tickets to four lectures by Sir Humphry Davy (1778-1829) at the Royal Institution, then as now on Albemarle Street, London. Faraday bound and presented to Davy the notes he had taken of Davy's lecture. Seldom has bread been cast more fortunately upon the waters. Sir Humphry eventually recommended Michael, then 22, for employment as laboratory assistant in the Institution, citing Faraday as one whose "habits seems [sic] good, disposition active and cheerful, and manner intelligent." Faraday got the job, and during the next 50 years became the proudest ornament to this day of that venerable institution.

Oersted's discovery of electromagnetism struck the scientific world almost as forcefully as Roentgen's discovery of x-rays was to do in 1895. Faraday soon went beyond Oersted. In 1821, he transformed Oersted's displacement of a compass needle into *rotary motion* of two kinds by the ingenious use of a mercury pool to make possible good electrical contact with a moving solid: he demonstrated motion of a slender, pivoted permanent magnet *around* a fixed linear conductor of electric current, and the reciprocal motion of a moving conductor *around* a fixed permanent magnet (see Figure 2-2). Both motions were brought about simultaneously by the same electric current. With this demonstration of *electromagnetic rotation,* Faraday opened the door to the useful conversion of electrical energy into work, a function performed today by electric motors in their millions.

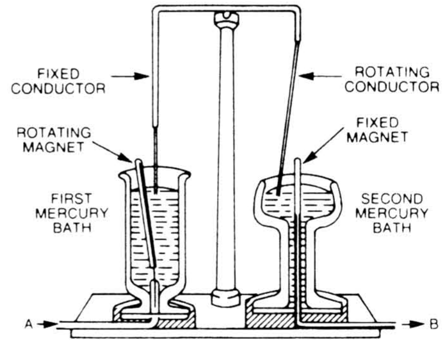


Figure 2-2. Simultaneous demonstration of two kinds of electromagnetic rotation produced by a single electric current. The current enters at A and leaves at B after passing through both mercury baths, and through the two conductors—one fixed, the other rotating—in the upper half of the figure. Both kinds of electromagnetic rotation show that the interaction of a permanent magnet and an electric current produces forces that can do work—in this case, the work performed when a rotating rod is pushed through mercury. Faraday made the fundamental discovery on September 3, 1821, and proved on the following Christmas morning that the earth could serve as the fixed magnet. (Information and figure based on pp. 92-94 of Dunsheath, Ref. (2), Appendix 1.)

Being then occupied mainly with chemistry, Faraday seems to have done no electromagnetic experiments of comparable importance until 1831, when new electrical results came with breathtaking speed, no doubt because electromagnetism had never been far from his mind during the decade preceding. On November 24, 1831, Faraday read to the Royal Society "V. Experimental Researches in Electricity" (38 pages), a paper ranking with Rumford's, and with Carnot's essay. Faraday described the results of experimental work begun on August 29 of that year and continued during some *nine* nonconsecutive days in the laboratory—nonconsecutive because he had to wait for equipment. We shall describe the three most significant of his experiments, and juxtapose them to their modern counterparts for easier understanding and appreciation.

* Ampère realized that a second electric current could replace Oersted's permanent magnet, and that there was no need to speak of "poles" in describing this kind of electromagnetic interaction. His contemporaries were slow to follow suit, and we speak of poles today even when, as in large modern electric generators, permanent magnets are not used. Would Humpty Dumpty approve?

2. Faraday and "Induction via Motion."

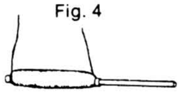
October 17, 1831

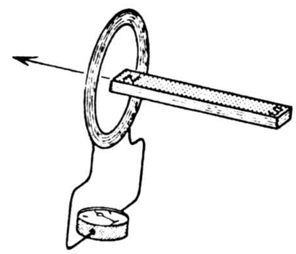
Apparatus

Faraday

Modern

Fig. 4





Experiment

Faraday (his Fig. 4):

A combination of helices ... was constructed upon a hollow cylinder of pasteboard: there were eight lengths of copper wire, containing altogether 220 feet ... . All the similar ends of the compound hollow helix ... were bound together by copper wire [i.e., connected in parallel], forming two general terminations, and these were connected with the galvanometer ... a cylindrical magnet, three quarters of an inch in diameter and eight inches and a half in length [was used as follows]. One end of this magnet was introduced into the axis of the helix ... and then, the galvanometer-needle being stationary, the magnet was suddenly thrust in;

Modern (after Agger, Ref. (3), Appendix 1):

Today, Faraday's painfully constructed helix would be replaced by a coil wound in minutes from magnet wire carried in stock; his earth-shaking experiment could be done (though not understood) by kindergarten pupils. The insulation ("wire enamel") on this wire, so thin and transparent as to escape casual notice, would be tough enough to tolerate violent manhandling. Also, today's permanent magnet could be much stronger than Faraday's.

Observations

Faraday:

When the magnet was thrust in, the galvanometer needle was immediately deflected. Being left in, the needle resumed its first position, and then the magnet being withdrawn the needle was deflected in the opposite direction. These effects were not great; but by introducing and withdrawing the magnet, so that the impulse each time should be added to those previously communicated to the needle, the latter could be made to vibrate through an arc of 180° or more.

Modern:

No different, but easier to enlarge and control.

Comparison and Comment

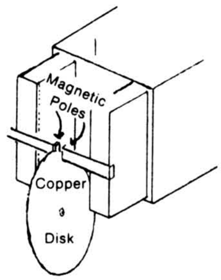
Faraday undoubtedly benefited because he was acquainted with electromagnets, which were unknown in Oersted's time. In a sense, Experiment 2 was an extension of Experiment 1 *by the addition of controllable and directed motion.* This addition was all-important, for it linked *motion* to the *generation* of [transient] electric currents. This linking exists today in all rotating electrical machinery (generators and motors), and in many electrical instruments.

3. Faraday and the Rotary dc Generator.

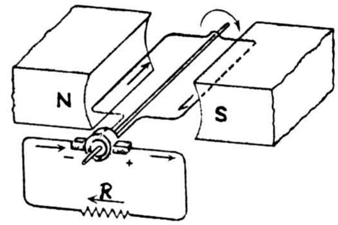
October 28, 1831

Apparatus

Faraday (lettering added)



Modern



Experiment

Faraday (his Fig. 7):

A disc of copper, twelve inches in diameter, and about one fifth of an inch in thickness, fixed upon a brass axis, was mounted in frames so as to be revolved either vertically or horizontally, its edge being at the same time introduced more or less between the magnetic poles .... The edge of the plate was well amalgamated for the purpose of obtaining a good but moveable contact; a part round the axis was also prepared in a similar manner.

Conductors or collectors of copper and lead were constructed so as to come in contact with the edge of the copper disc .... These conductors were about four inches long, one third of an inch wide, and one fifth of an inch thick; one end of each was slightly grooved, to allow of more exact adaptation to the somewhat convex edge of the plates, and then amalgamated. Copper wires, one sixteenth of an inch in thickness, attached, in the ordinary manner, by convolutions to the other ends of these conductors, passed away to the galvanometer.

All these arrangements being made, the copper disc was adjusted ..., the small magnetic poles being about half an inch apart, and the edge of the plate inserted about half their width between them. One of the galvanometer wires was passed twice or thrice loosely round the brass axis of the plate, and the other attached to a conductor ..., which itself was retained by the hand in contact with the amalgamated edge of the disc at the part immediately between the magnetic poles. Under these circumstances all was quiescent, and the galvanometer exhibited no effect.

Modern (after Agger, Ref. (3), Appendix 1):

Rotate the shaft clockwise by any mechanical means available; a motor could be used. Here, N and S are assumed to be the poles of a permanent magnet.

Observations

Faraday:

But the instant the plate moved, the galvanometer was influenced, and by revolving the plate quickly the needle could be deflected 90° or more.

Here therefore was demonstrated the production of a permanent current of electricity by ordinary magnets ....

Experiment 3 is Experiment 2 reduced to practice.

Modern:

In the circuit shown, the "permanent current of electricity" (Faraday) produced with the aid of "ordinary magnets" generates heat, which is rejected to the environment, mainly by the resistor R. The linear arrows show the direction of current flow according to engineering convention. Electrons, of which more later, actually carry the current—and move in the reverse direction.

In the modern device, Faraday's "permanent current of electricity" is still being produced with the aid of "ordinary magnets," but there is a crucial difference in the geometrical arrangement of the conductor and the magnetic poles. Faraday's disk rotated so that every part thereof had the *same* pole as nearest neighbor while it was between the poles. For the modern rotating loop, this is not true. Each long side of the loop will have the *other* pole as nearest neighbor when the shaft has gone one-half revolution (180°) further. Such *alternation* continues while the shaft revolves, and it causes periodic reversal of current and voltage. Currents and voltages are at maxima when the loop is horizontal, zero when the loop is vertical.

In the modern device, the generated current flows through a complete circuit. To accomplish this, the current must be taken from the rotating loop and returned, which can be done by joining each end of the loop to an insulated *slip-ring* mounted on the shaft. On each ring there "rides" a stationary, conducting carbon "brush" that is one terminus of the external circuit. This arrangement (not shown) gives ac, for the current changes direction with each alternation (described above). See Figure 2-3.

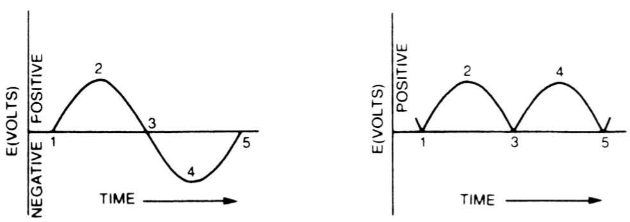


Figure 2-3. Generation of ac (left) and dc (right) by a conducting loop being rotated at constant speed in a uniform magnetic field in modern apparatus analogous to Faraday's dc generator. Between points 1 and 5, the loop completes a cycle; i.e., a complete rotation. At points 2 and 4, the loop is horizontal; at points 1, 3, and 5, it is vertical. At point 5, the succeeding cycle begins.

Faraday's arrangement produced useless "eddy currents" in the copper disk. The modern analogue gives the useful pulsating dc shown on the right of Figure 2-3. To bring about the change from ac to dc, the slip rings (ac) are replaced by a commutator (dc) insulated from the shaft. The simple commutator of the modern analogue is a split ring on each half of which there rides a brush for the collection of current from one terminal of the loop. When the direction of the current in the loop is reversed during rotation, so is the connection of the split ring to the external circuit to provide the dc shown in Figure 2-3. In practical dc generators, the voltage variations are much smaller than those in the figure.

Faraday, Electricity, Magnetism

In the Faraday experiments described, electromagnetic induction, which we shall henceforth use as a general name, was accomplished in three different ways: In Experiment 1, by change of the magnetic field affecting two magnetically coupled coils, the change being accomplished by varying the direct current through one. In Experiment 2, by change of the magnetic field near a coil, the change being accomplished by moving a permanent magnet. In Experiment 3, by changing the magnetic field influencing different portions of a conductor as it moved through the field. *Changing* either a magnetic or an electric field is required for electromagnetic induction. More precisely, electromagnetic induction depends upon a sort of "reciprocal relationship" between electric and magnetic fields, compactly expressed in vector notation by Maxwell. Any change in an electrostatic field (i.e., any movement of electric charge) generates a magnetic field or changes one already present. Conversely, any change in a magnetostatic field (i.e., any change in its strength) generates an electric field or changes one already present: in suitably arranged conductors, induced electric currents will flow in either case. The ancients could not progress beyond electrostatics and magnetostatics because they could not have been expected to appreciate that electromagnetic induction was impossible in such systems if no field was changed.

Faraday, Electrical Energy, and Thermodynamics

Near the beginning of his paper, Faraday mentions his "hope of obtaining electricity from ordinary magnetism," and says that his hopes were fulfilled—presumably first in Experiment 2. Not so. In 1831, a thermodynamic analysis of Experiment 2 was not possible; despite Rumford and Carnot, energy, work, and heat were not yet understood.

We know that Faraday's permanent magnet was unchanged by the experiment. We know that electrical energy is associated with all electric currents, induced or not. Did we get this energy "for free"? Faraday could have moved his magnet horizontally without doing work against gravity. When he thrust it into the coil, he must somehow have done enough non-gravitational work upon his system (magnet and coil) to satisfy the First Law of Thermodynamics. H.F.E. Lenz (1804-1885) explained the mystery when he announced as a law in 1834 that induced currents always exert a force that opposes any motion by which they are generated. Accordingly, Faraday himself, in the act of moving the magnet, did the work that thermodynamics demands. Indeed, Lenz's Law expressed in terms of work, energy, and heat becomes the First Law of Thermodynamics.

In Experiment 2, work by Faraday was thus converted into electrical energy, which was eventually converted to heat as the induced currents flowed through the coil. Electrical energy can also be converted to work, as in the raising of a weight by an electric motor. Must we say that *electrical work* is done in this case, or in any other? Or it is better to use "work" without qualification to mean mechanical work, which after all is the only measurable kind? We shall continue to follow the second course.

We may pretend that utility customers return to the central station a spent, though constant, electron current which must be revitalized (have its energy replenished) by the generator before the customer can use it again. Only a man of genius, as of course Faraday was, could have grasped the relationship of his seemingly casual Experiment 2, concerned with *transients,* to the generator, which is at a *steady state* once it is past start-up, and raises by electromagnetic induction the electromotive force of an electron current.

How can it? Thermodynamics says, by doing work upon the current—ultimately upon the *electrons* that constitute the current. No more than in Experiment 2 can magnets do the work; in the turbine-generator, that is the job of the turbine. Why then have magnets at all?

The answer appears in the legend of Figure 2-4. One of Faraday's laws tells us that the increase in electromotive force (volts) for the current moving between the magnetic poles in Figure 2-4 is equal to the product of the strength of the magnetic field (flux density, B, in teslas), conductor length (l, in meters), and conductor velocity at right angles to the field (v, meters per second). The power needed to move the conductor and the work done upon it during the motion are each proportional to the current (I, amperes)[9] that flows.

In discovering electromagnetic induction, Faraday demonstrated that it would be possible to forge a link between Oersted's electromagnetism and thermodynamics. That link completed, electrical energy rapidly became the most versatile kind available to the world. For most electrical equipment, the First Law of Thermodynamics suffices. Electrical "heat engines," such as thermoelectric and thermionic devices, require the Second Law also.

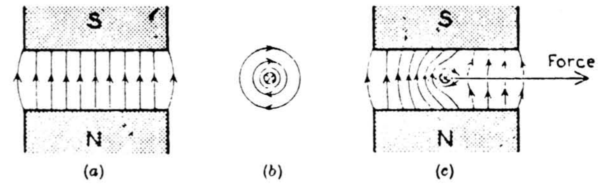


Figure 2-4. After Agger, Ref. (3), p. 202. In the engineering view, for which we must thank Faraday, magnetic lines of force as shown (a) characterize the field between unlike fixed magnetic poles. A conductor in which a constant current is moving away from the observer will have such lines of force concentric about itself (b). Placing the conductor between the magnetic poles distorts both fields, and the distortion (an affront to Nature?) results in a force on the conductor with the direction shown. This force is balanced by another that tries to send both poles to the left. As these poles cannot move, they can do no work. In a turbine-generator, however, the turbine can do work against such a force, moving the current-carrying conductor to the left and increasing the electromotive force associated with the current, thus converting mechanical work into electrical energy, all in accord with the First Law of Thermodynamics.

Electromagnetism inherited a set of units from each parent. There resulted equations that contained fractional exponents, a sure sign of complexity, when the basic units of mass-length-time systems were used. Fortunately, we have today the internationally recognized SI system of units,[9] in which the introduction of the ampere as the *fourth basic unit* has simplified the situation.

THE ELECTRON

The electric currents that flow in copper wire, or other metallic conductors, are streams of negative electrons. These "elementary particles" or "atoms of electricity"—adequate names in simpler times—can therefore claim to be the most important electrical entity even though they cannot exist as close neighbors in large number unless positive charges are also present. The history of the electron illustrates what scientific research, pure and applied, has done *for* and *to* electricity: Henry Adams would regard the growing complexity with detached amusement.

In 1833, just two years after reporting his experiments on electromagnetic induction, Faraday laid the foundation for the modern knowledge of the electron. In electrochemical studies, he found that a fixed amount of electricity, today called the faraday and equal to 96,510 coulombs, always produced unit change of valence (more precisely, oxidation number) in $6.02(10^{23})$ atoms, molecules, or ions reacting at an electrode: thus, 2 faradays will convert 2.016 g H_2 to $2H^+$. The full significance of these results did not become clear until after Faraday's death. In the Faraday Lecture* at the Royal Institution on April 5, 1881, H.V. Helmholtz (1821-94) said: "Now the most startling result of Faraday's law of electrolysis is ... that electricity ..., positive as well as negative, is divided into definite elementary portions, which behave like atoms of electricity." G.J. Stoney (1826-1911) had before this calculated a value of the elementary charge, which we now know to be $96,510/[6.02(10)^{23}]$ coulombs, and he gave the name "electron" to Helmholtz's "atom of electricity." The electron as a recognized elementary particle arrived just before the 20th century.

Today, alas, electrons no longer seem so simple. Further research has shown, to be sure, that all electrons of one kind are alike; but it has also shown that there are two kinds, positive and negative. (Humpty Dumpty will permit us to continue using "electron" for the negative, or garden-variety, kind.) At rest, both sorts have masses about 1/1837 that of a hydrogen atom. Electrons behave like waves; electrons are spinning magnets resembling tiny gyroscopes shaped like spheres or tops; and electrons tunnel through energy barriers too high for them to jump. This is not all, nor is the end in sight, but it does seem clear that the electron must be responsible for tying the knot in the "marriage" of electricity and magnetism.

We may never know what electrons really *are;* what they *seem to be* differs from one kind of experiment to another. Yet, the need for models in science continues undiminished, and the engineers continue to teach us that models—even if false—can lead to correct utility bills.

Certain "fluids," for example, are among the most valuable macroscopic models in classical physics. They are assumed to be continuous, and their "flow" obeys "continuity equations," which describe the flow of any quantity (e.g., mass) that is "conserved and indestructible." We have already spoken of the flow of heat, which, as Rumford surmised, is more nearly a motion, not a fluid: the flow of heat is really the flow of thermal energy. The flow of electromagnetic energy is governed by Maxwell's equations, too complex for discussion here. These equations have been manipulated by Poynting to give a theorem and a vector that bear his name. In simple cases, this vector represents the flow, through unit area, of electrical power in the direction of the vector. For example, if the electric field in charge-free space is directed toward the top of this page, and the magnetic field perpendicularly thereto toward the reader, electrical power will flow to his right with the speed of light. Remember, however, that a copper conductor does not provide charge-free space.

Though subject to change, models are invaluable for the grasping and interpretation of results, and in the planning of experiments. They need not be "true" to be useful: the electrical industry was built upon currents that flow in the wrong direction and upon lines of force in an ether that does not exist. Perhaps Bacon should have said "Knowledge is power even when understanding lags." The history of the electron illustrates that more research generally ushers in greater complexity; but it also shows, as scientists and engineers have long known, that progress in large-scale energy conversion need not wait upon a definitive understanding of Nature.

A TRIO FOR TODAY

In Faraday's time and before, research was usually an adventure, sometimes an avocation, and more like a search for truth with bow and arrow in which the arrow (aided by chance) at times hit an important mark, more often for Faraday than for others less gifted. Today, one had better speak, not of energy research, but of R&D (research and development), which become ever more tightly welded by government and public-utility funding, a process that began long ago. Most research, particularly research related in any way to energy, is now an industry that must accommodate itself to other than academic checks and balances. The bow and arrow are outdated. The modern research arsenal houses weapons so costly, elaborate, and powerful that they sometimes dictate what is done. Where might our "giants" of yesteryear—Rumford, Carnot, Faraday—be were they alive today? Were they truly giants on whose shoulders we as pygmies perch,[10] or were they merely exceptional men lucky to be "present at the creation"? Answers are speculations—but speculations worth making because we may need giants to help us out of our threatening energy situation—exceptional men may not be enough.

To stimulate speculation, let us single out trios. Rumford, Carnot, and Faraday are three who in

* This Faraday Lecture [*J. Chem. Soc., 39,* 277 (1881)] ranks with Helmholtz's paper on the First Law, which was mentioned in a note to Chapter 1, as a great classic of science.

three decades (1798-1831) contributed mightily, by doing research of three kinds (engineering-experimental, theoretical, scientific-experimental), that pointed to the interconvertibility of three quantities (**U**, *Q*, and *W*) that remain with us today. Let us find modern assignments for our trio after considering further information[11–13] about them. This will not be an idle exercise: how research is done, and what may be expected from it, depend more than most people realize upon who does the work. Rumford, for example, seems ill-suited to improving established methods or making them more precise—so, come to think of it, do Carnot and Faraday.

To succeed in the growth industry that modern research has become, our trio would have to make traumatic readjustments. They could work without managers (although Davy did attempt to "manage" Faraday); they had only primitive equipment; and they spent very little money—there were no budgets to confine them. We saw in Chapter 1 that Rumford did not sacrifice even a single cannon in making his epochal experiment; and that Carnot used only writing materials; illustrations in this chapter prove that Faraday, although he did have equipment built, never threatened to bankrupt the Royal Institution. Had our heroes only known how to make "cost-benefit" analyses and compute "cost-effectiveness ratios"! Theirs would have been out of reach today.

Let us name Rumford to head the Department of Energy—if it still exists. For him, survival in Washington would have been assured, especially with Carnot as Chief Scientific Advisor. Carnot, in passing upon research proposals and suggesting his own, would have made certain that the taxpayer got a good run for his money. Faraday, wedded to pure research, could be a problem. What kind of laboratory would be best for one of the world's greatest experimenters if he agreed to do pure research on energy conversion?

Earlier, electricity was described as a hydra-headed phenomenon. Among those heads are whole industries founded on pure research, the semiconductor industry being the most spectacular recent example. Central-station electrical equipment sprang, as we have seen, from pure research by Faraday and others. The introduction of nuclear energy excepted,* central stations have benefited of late, not so much from pure research, as from applied research that led to improved processes and equipment. It is reasonable to suppose that the chance of help from good pure research, though never zero, decreases as an industry matures. Faraday should probably not be assigned to research on existing large-scale methods of energy conversion.

Perhaps Faraday's manager might interest him in the conversion of solar into electrical energy by methods that might ultimately make each home its own central station. Pure research in physics destroyed the simplicity of the electron and is now increasingly concerned with *Alice-in-Wonderland* particles such as the quark, which was named from *Finnegan's Wake*. Still, Faraday, whose "principal aim was to express in his new conceptions only facts, with the least possible use of hypothetical substances and forces,"* might be inspired by what physics has taught us about the solid state, to think of new pure-research experiments on energy conversion. "Might," because he could well be attracted instead to seemingly greener modern pastures—he might well become a "genetic engineer."

The foregoing game of trios was inspired by Henry Adams' "the mind ... would need to jump" to cope with the multiplicity and complexity he saw coming, and which we have brought about. Another source suggests we ask ourselves "Have we men to match our mountains?" a question that faces each new generation. George Bernard Shaw maintains that "Men are what they were." Perhaps, but how much taller are our mountains? The reader must settle this matter for himself. To help him, the book will continue to describe not only energy problems, but the men who faced them.

Chapters 1 and 2 teach that electricity has been a far more fruitful research area than heat: the flicker of Oersted's compass gave scientists a greater diversity of opportunities than did Rumford's horses. Although the electron continues to be as enigmatic as Mona Lisa's smile, electrical research should continue promising, and the taxpayer ought not to complain when asked to support such research into energy problems. How could this money be better spent? But, a word of warning, applicable to research in general, is needed. Much that deserves support is not new; and the better known a field, the less likely therein a major discovery. Fuel cells and fuel batteries, useful and desirable as electrical energy converters, conceptually trace back well into the last century; so does magnetohydrodynamics (MHD), now coming to be called magnetofluid dynamics, which

* Nuclear energy had of course been the object of untold millions of dollars worth of applied research and engineering (pre-1980 dollars) before the first nuclear central-station was built.

* Quotation from Helmholtz's Faraday Address (see above).

Faraday foresaw. Einstein's Nobel Prize for the photoelectric effect, the basis for photovoltaics (electricity from sunlight), came in 1921. The photovoltaic effect was discovered by Hertz in 1887-88, about ten years before electrons were known. Here, a hopeful note. This method of energy conversion will benefit from the virtues of silicon as semiconductor, and these virtues are great enough so that a California valley now takes its name from this element. May solar cells for the home soon be one of its products!

The silicon revolution shows once more that materials (here, the pure element Si) often determine how successful processes will be. Research on materials has helped both electricity and heat, and research of this kind ought to continue even though benefit therefrom is usually gradual and increasingly difficult to come by as materials improve.

A final note. If, as history teaches, heat is less likely a field for advances in energy conversion than electricity, it becomes all the more interesting to follow the story of mercury-steam, in which better utilization of heat was the heart of the matter.

Chapter 3

THE CENTRAL STATION. A FIRST LOOK

Heat engines were fathered by need. Electrical machinery grew out of scientific research. Both profited from invention and engineering. They were united in the steam central-station, an institution that continues to generate most of our electricity, and has therefore formed our civilization to a greater degree than even the far noisier internal combustion engine. Central stations enjoyed benign neglect by the public until the seventies—when our electric bills began going through the roof, nuclear energy began to frighten many, and we were learning that fish could die of "acid rain" from the stacks of some central stations. Today they risk condemnation by that public, which (for its sake and theirs) needs to understand them better: "You never miss the water till the well runs dry."

Chapter 3 completes the background for the story of mercury-steam. It will describe the bare bones of a central station that might have existed when W.L.R. Emmet began his bold, determined, and dramatic attempt to reduce the number of Btu needed to make a kWh of electricity by boiling both mercury and steam in the same central station. Hydroelectric central-stations, truly a godsend although they will never give us all the electricity we use, do not belong in our story: were waterfalls plentiful enough, we might have had no story to tell.

THE STEAM TURBINE-GENERATOR

This marvelous machine is the heart of the modern steam central-station. In such stations, a steam engine—the "prime mover"—drives an electrical generator. In Emmet's time, the source of steam was a steam boiler, which Emmet hoped to displace with one that boiled mercury. Today, steam boilers have become so much more sophisticated than James Watt's teakettle that we must call them steam generators.* Heat for generation of central-station steam need not come from the combustion of fossil fuels (coal, oil, gas), as it does in boilers, but may be supplied by nuclear reactors; and, we hope, will one day come in significant amounts at reasonable cost from the earth and the sun although that is not likely to be an early blessing because "reasonable cost" will certainly delay the day when the wind, the ocean, the sun, or the heat of the earth qualify as competitive sources of steam or electricity. For Chapter 3, we need only to know that there is available from whatever source an adequate supply of *superheated* steam to turn our electrical generators. (Steam is superheated in a central station by raising its temperature out of contact with liquid water without increasing its pressure.) How can we best generate electricity from such steam? Experience gives the answer: Put the steam through successive Rankine cycles using the most suitable prime mover to turn the generators.

* Humpty Dumpty says that anyone liable to confuse a steam generator with an electrical generator ought to visit a steam central-station—not a bad idea in any case!

The Steam Turbine

When the commercial generation of electricity began toward the close of the last century, the most suitable prime mover (i.e., the one giving the best Carnot Trade-off) was the reciprocating steam engine, by then well entrenched. It consequently became the first prime mover for electrical generators.

In retrospect, it is clear that Faraday's Experiment 3 (Chapter 2) made the steam turbine-generator inevitable *provided* safe turbines could be built, for the experiment had shown that effective electrical generators would be rotary machines. This placed reciprocating engines with their linearly moving pistons at a disadvantage. Further, it became clear as central stations demanded more powerful prime movers, that reciprocating engines would no longer serve because they would have to become dinosaurs with unacceptable Carnot Trade-offs. But turbines did not win the battle overnight.

Turbines are rotary machines that derive work from the energy of a steady stream of working fluid such as steam or mercury. The idea is old. The windmill, once as common outside cities as television antennas are now, is a primitive *single-stage impulse turbine* that requires no nozzle because Nature preempts the nozzle's function by giving direction to the wind. The rotary lawn sprinkler, a modern analogue of the steam engine with which Hero(n) of Alexandria amused himself about 125 BC, resembles a *single-stage reaction turbine,* with liquid water (the working fluid) being directed along arms that terminate in nozzles. "Single-stage" needs no explaining, and it suggests that many stages could be built into one machine, as indeed they can—fortunately for us: to approach thermodynamic reversibility, the adiabatic expansion of steam must be gradual—must take place in *many stages.* Also, no material is conceivable out of which a single-stage turbine might be built that could efficiently convert into work the high energy of superheated steam.(1)*

How can this high energy be converted into work? No matter how complex the turbine, and highly complex the best turbines must be, the conversion can always be illustrated by a simple example. Throw a perfectly elastic ball against the perfectly elastic backboard of a truck moving in the direction of the ball. The ball will come back to you but at *reduced velocity* because it did work to accelerate the truck during the time of contact, whilst the ball changed direction. Had the truck been stationary, no work would have been done.

The ball-truck example, though more complicated, does not differ in principle as regards work from the raising of a weight, as in the Galileo *Gedankenexperiment* of Chapter 1. We are still dealing with a *force* (exerted here by the moving ball) that does *work* as it *moves* the truck (during the time of collision) over a *distance* in the *direction* of the force. To be sure, we must now define force as $d(mv)/dt$, the rate of change of *momentum* (mv), which in the simplest case (mass and acceleration $[= dv/dt]$ constant) reduces to the familiar $F = ma$, or $F = mg$, as when Galileo did work against gravity (g assumed constant).

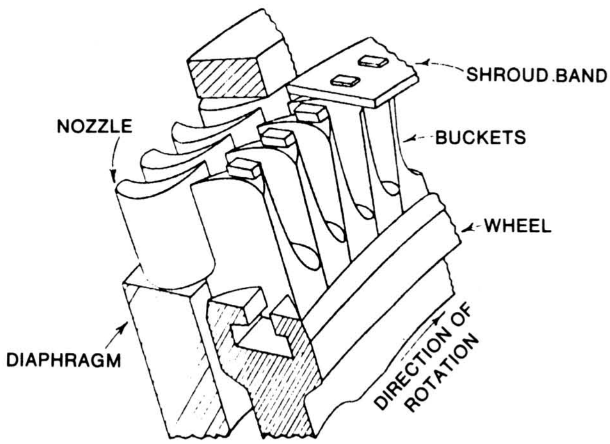
More than a little imagination is needed to jump from the ball-truck example to turbines. To replace the ball, we have jets of steam that have acquired velocities (up to more than a *thousand* miles per hour), and gained direction via adiabatic expansion through fixed passages called *nozzles* located near the periphery of the turbine casing. Such expansion results from a drop in pressure and an increase in steam velocity over what the velocity would have been had no pressure drop occurred. In *impulse* turbines, moving blades called *buckets* replace the moving truck. These are fixed to the turbine shaft,* but located near the turbine periphery, where they can be struck most efficiently by the jets of steam from the nozzles. On impact, the steam changes direction, does work, loses velocity, and the buckets move to turn the shaft. *There is no pressure drop across buckets.* We shall say that *reaction turbines* have no buckets, only nozzles, *fixed* and *movable;* steam pressure drops across both kinds. The movable nozzles do work as they rotate, thus performing the function of buckets in impulse turbines. In the language used here, the windmill has buckets only; and the lawn sprinkler has only nozzles.

We have barely scratched the surface. Actual turbines are diverse and complex. Their design and manufacture demand the utmost in engineering skill. At first sight, their nomenclature is intimidating and confusing.(2) For the general reader, Figures 3-1 to 3-4 supplement this naive introduction to an important subject.

The high efficiency, reliability, safety, and long life of modern turbines are unmatched by other large machines—except, as we shall see, by the generators the turbines turn. Chapter 4 tells us that it was not always thus. Were turbines being developed today, someone would surely condemn them as "unsafe at any speed," and the media would make certain that this verdict reached the public. But, as Governor Al Smith often said, "Let's look at the record." Later on, we shall.

* Notes and references thus indicated appear in Appendix 1.

* In an impulse turbine, the buckets are at the periphery of the *rotor,* through the center of which goes the *shaft* that turns the electrical generator. As the steam pressure decreases on the way through the turbine, this periphery must grow larger, as must the movable turbine blading that delivers work to the shaft. Meanwhile, measures are needed to make certain that *leakage* of steam from higher to lower pressures is minimized. Designing and building good turbines is like designing and building precise, thin, old-fashioned watches—but on a huge scale and for much more demanding operating conditions.



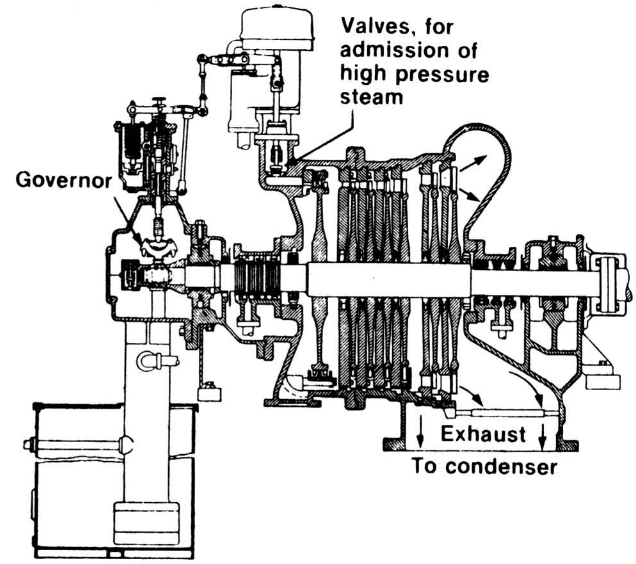


Figure 3-1.* Part of a stage in a General Electric impulse turbine of the thirties. The stationary diaphragms may be regarded as parts of the turbine casing ("stator") that extend radially inward between the wheels attached to the rotating shaft. The nozzles pierce the diaphragm near the casing, and the turbine buckets are mounted opposite them on the periphery of the wheels. Throughout, clearances are minimized to restrict steam flow as completely as possible through the nozzles, in which it expands, and past the buckets, which rotate the shaft as the jets of steam strike them.

Figure 3-3. Section through a small impulse turbine. The governor (the "brain" of the turbine) regulates the flow of steam to keep turbine rotation at constant speed (usually 3600 rpm) when the load on the electrical generator (at right) changes. The curved arrows show the flow of steam to the turbine exhaust. The last two stages show most clearly that larger nozzles and buckets are needed as the specific volume (V') of the steam increases and the pressure drops.

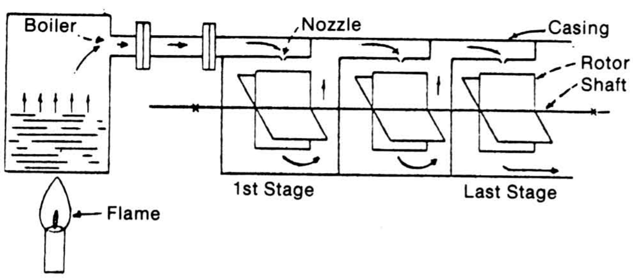


Figure 3-2. Newman visualizes multistaging in an impulse turbine. Three stages are shown. To make a turbine-generator, the electrical generator would be coupled on the right to the shaft.

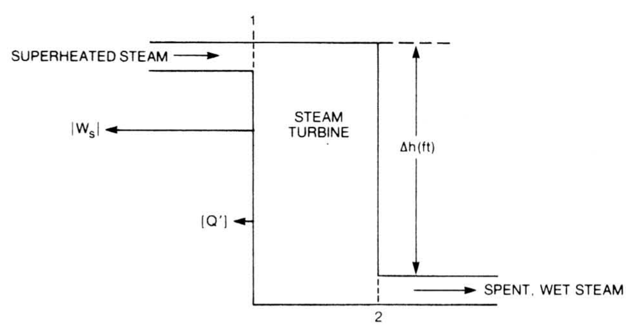


Figure 3-4. Schematic diagram of an open system, which mass enters and leaves at constant rate, consisting in this case of a steam turbine. (The enclosure might contain various open systems such as a single stage of a multistage turbine, a compressor, or even a boiler. Naturally, the flows of mass, of heat, and of work would differ from one case to another.) The boundaries of the system are at 1 (entrance, initial state) and at 2 (exit, final state of the working fluid).

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* This, and the two figures following, are from L.E. Newman, *Power Plant Engineering, 41,* 536 (1937), the first of an excellent series of articles by Newman and others, General Electric Company, Lynn, MA.

Turbine Thermodynamics

The general reader may wish to be assured that the thermodynamics of Chapter 1 applies to the steam turbine. Of course it does—the whole of human experience is not lightly cast aside. But, there are important differences. In Chapter 1, we dealt with *closed* systems—systems whose boundaries were never crossed by mass. In the turbine at steady operation, we have a system that mass (steam) enters and leaves at constant mass-flow rate—a situation wholly different from that in Chapter 1, where we could take a constant (and unspecified) mass of working fluid through complete, successive cycles.

For the steam central-station, those cycles are Rankine cycles, in which different pieces of equipment play different, but comparably essential, roles—that of the turbine being the adiabatic expanding of steam to produce shaft work, W_s. Each individual piece of equipment may itself be regarded as a thermodynamic system—but as an *open* system (see Figure 3-4) through which there is a steady flow of water (gas, or liquid, or both) when the station is generating electricity at constant rate (operating at constant power, once measured in kilowatts—in megawatts today). Naturally, these open systems properly joined make the closed system through which circulates the working fluid—the life blood—of the station.

Closed systems, as we saw in Chapter 1, manage quite well with integrals of the form $\oint_1^1$, which simplifies matters because, for example, **U** has not changed when the system has completed its cycle to return to State 1, the initial state. For open systems, the integrals must take the form $\int_1^2 d\mathbf{F}$, where State 2 is the final state, and the integral gives us

$$\Delta \mathbf{F} = \mathbf{F}_2 - \mathbf{F}_1 \qquad (1)$$

where **F** is any state function.

The crucial difference between open and closed systems is this: In open systems, we must give specific consideration to the rate of mass (working-fluid) flow. To do this, we conveniently base our thermodynamics upon *unit mass* of working fluid. We shall do this by "priming" thermodynamic quantities* as required: e.g., $\mathbf{U}'$ and V', but not P' or T' because these are *intensive* variables independent of mass. (The primed quantities are *extensive*—proportional to mass.)

There is a less important matter that we shall treat in an unconventional way so as not to increase the trinity of **U**, W, and Q beyond necessity. All along, we have included in **U** those components changing during the process under consideration—*and no more.* For example, components related to chemical change, surface effects, electricity, or magnetism have not been included in the **U** of steam in steady flow. On the other hand, $\mathbf{U}'_{\mathrm{PE}}$ and $\mathbf{U}'_{\mathrm{KE}}$ (which were introduced as PE and KE, potential and kinetic energies, in Chapter 1) must now be included because they change in many open systems, as does a new component, $\mathbf{U}'_{PV'}$.

To show why we must add this new component, let us alter Figure 3-4. We replace the turbine by a porous plug, make $h = 0$, insert one piston in the cylinder left of boundary 1, a second to the right of boundary 2, and we provide means for measuring any temperature change across the porous plug, through which dry steam (initially at the same temperature throughout the system) will undergo adiabatic expansion from pressure P_1 on the left to pressure P_2 on the right. With these changes, we have modified Figure 3-4 so that we may now carry out the Joule-Thomson experiment, one of the most celebrated in thermodynamics. To do it, we move the pistons (consider them frictionless and never allowed inside boundaries 1 and 2) so as to expand unit mass of steam through the porous plug, P_1 and P_2 remaining constant. When this is done, there will ordinarily have been a temperature drop across the porous plug even though no shaft work was done and the process was adiabatic.

What happened? Let us concentrate on the steam between the pistons. When the piston on the left moves in, the environment does work $P_1 V'_1$ on this steam, when the piston on the right moves out, this steam does work $P_2 V'_2$ on the environment (V'_2 is larger than V'_1). As the temperature fell during this expansion, we must conclude from the First Law that some of the energy of the steam was converted into work although no shaft work was done; that is

$$P_2 V'_2 - P_1 V'_1 = \Delta \mid W'_{PV'} \mid = \Delta \mid \mathbf{U}'_{PV'} \mid \qquad (2)$$

For the exact description of the behavior of steam in open systems, such as steam turbines, the complete energy equation must therefore contain a $\mathbf{U}_{PV'}$ term.

For such an open system, in accord with what has just been said,

$$\begin{aligned} \Delta \mathbf{U}' &= \mathbf{U}'_2 - \mathbf{U}'_1 \\ &= \Delta \mathbf{U}'_{PV'} + \Delta \mathbf{U}'_T + \Delta \mathbf{U}'_{\mathrm{KE}} \\ &\quad + \Delta \mathbf{U}'_{\mathrm{PE}} \quad \text{(convenient units, Btu)} \end{aligned} \qquad (3)$$

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* Quantities for unit mass may be called *specific:* V' = specific volume, a "primed" quantity. Symbols not defined in Chapter 3 are defined in Chapter 1.

which may be combined with the First Law of Thermodynamics to give a continuity equation* of the form

$$\Delta \mathbf{U}' = \Delta(PV') + \Delta \mathbf{U}'_T + \Delta(v^2/2g) + \Delta h$$

$$= |W'| + |Q'| \quad \text{(convenient units, ft-lb)} \qquad (4)$$

In Equation 4, $|W'|$ and $|Q'|$ are our thermodynamic birds of passage whose flight from (or to) the system changes **U**, and whose algebraic sum measures $\Delta \mathbf{U}'$. During reversible adiabatic operation, which is closely approached in modern central stations with their multistage turbines,[1]

$$|Q'| = 0 \quad \text{and}$$

$$|W'| = |W'_s| \quad \text{(subscript denotes turbine shaft)} \qquad (5)$$

Other comments follow:

1. Both $\Delta \mathbf{U}'_{PV'}$ and $\Delta \mathbf{U}'_T$ for dry steam are functions, but different functions, only of *P*, *V*, and *T*, the three variables in the *equation of state* for unit mass of gas.[3] Detailed discussion would take us too far afield. It must be mentioned, however, that both energy components are decreased when condensation of the vapor (dry steam) forms liquid water. Calculations for wet steam must take this into account.

2. For a steam turbine, Figure 3-4 shows that Δh, the effective height of the system, is small enough to make $\Delta \mathbf{U}'_{PE}$ numerically negligible. Its calculation is of interest because it requires one to distinguish, as did the Galileo *Gxp* in Chapter 1, between pounds force and pounds mass. Here, as there, "*g*," which is 32.1725 ft/s at sea level, is the maximum acceleration that can be given to a mass of 1 lb by a force of 1 lb. Although *g* decreases with *h*, we shall use its sea-level value below.

3. An examination of $\mathbf{U}'_{KE}$ will strengthen our acquaintance with steam turbines. In the impulse turbine, $\mathbf{U}'_{KE}$ is increased only when steam expands by moving through stationary nozzles—the only kind present in the turbine. We might have examined expansion through these nozzles by placing them inside the "box" of Figure 3-4, but that is scarcely necessary because, when $\Delta \mathbf{U}'_{PE}$ is negligible, all that happens in such nozzles is

$$\Delta \mathbf{U}' = \Delta \mathbf{U}'_{PV'} + \Delta \mathbf{U}'_T$$

$$= \Delta(v^2/2g) \quad \text{(units, ft-lb)} \qquad (6)$$

* Continuity equations were mentioned near the end of Chapter 2.

For $\Delta \mathbf{U}' = 1 \text{ Btu} = 777.649$ ft-lb,

$$\Delta v = 778 \times 2 \times 32.17^* = 223.73 \text{ ft/s}$$

$$= 152.55 \text{ mph} \qquad (6a)$$

In 1903, Chicago's Fisk Street Station of the Commonwealth Edison Company supplied steam to its turbines at 170 psig (say 185 psia) and 70 °F superheat (State 1 in Figure 3-4). Let us assume a *single-stage* turbine, operating reversibly and adiabatically, accepted this steam and rejected it at 1 psia and 102 °F. For this turbine, $\Delta \mathbf{U}' = 132$ Btu approximately.[4] By Equation 6a, the Δv is

$$\Delta v = 223.73\sqrt{132} = 2570 \text{ ft/s, or } 1753 \text{ mph.}$$

For tolerable efficiency, the buckets, which are located near the periphery of the turbine wheel, will need to travel at a speed near $\Delta v/2$. Speeds above 1000 ft/s would certainly have been unsafe in Emmet's time because no practical material could then have been relied upon to withstand the stresses in a wheel of best design. The calculation thus shows the need for multistaging to reduce wheel speed in turbines for which $\Delta \mathbf{U}'$ is to approach maximum safe values. It shows further that design (a function of engineering) and better materials (products of scientific research) are both necessary for the improvement of Carnot Tradeoffs in central stations.

Figure 3-5 is a diagrammatic summary for the general reader.

The Electric Generator

In Chapter 2, we risked distorting history by concentrating too much on Faraday in describing the research and discovery that made possible the electrical industry. In describing development, we risked further distortions by confining ourselves largely to the United States—especially by not giving enough attention to Germany and Great Britain. In this development, scientists like Faraday became gradually less important than inventors and engineers, some among the most illustrious in modern technology. The progression, scientist (discoverer) to inventor to engineer, though never clean-cut, is a natural concomitant of growth in knowledge and understanding. The younger the field, the more likely it is for an individual to play more than one of these roles, Faraday having been a notable exception because he concentrated on pure research.

* Rounded values of constants. Longer values quoted in text to illustrate precision of measurements.

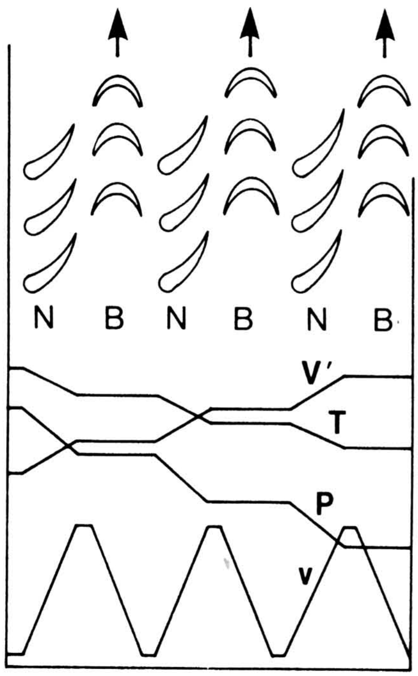

Figure 3-5.* **The fate of steam in three simple stages of an impulse turbine in which the buckets (B) are moved in the direction of the arrows by steam expanded in stationary nozzles (N).**
Properties of steam:
***V′*, specific volume, increases during passage through *N*.**
***T*, temperature, falls as *V′* increases.**
***P*, pressure, falls as *V′* increases.**
***v*, velocity, rises as *V′* increases and falls as steam does work on buckets (B).**
***V′*, *T*, and *P* change only during passage through N.**

The first American central station generated and distributed dc; none do so today. That first station was on Pearl Street, New York City, and it was engineered and built by Edison, who proudly had it go on line at 3:00 PM precisely, on September 4, 1882, while he was in the offices of J.P. Morgan, 23 Wall Street, to watch the incandescent lights respond. (The House of Morgan, vital to the electrical industry then, continues to serve it financially at the same address.) To begin with, Pearl Street had all of 59 customers and lit 400 lights. Though different, Edison's contribution was as important as Faraday's discoveries half a century earlier.

And yet, ac today has customers in the millions, while the relatively few who use dc do so because they must. Electrolytic processes (such as the manufacture of aluminum) cannot be done with ac, although dc need not be generated for such purposes because "rectified ac" will serve. Edison was the prime champion of the dc central-station, and what we shall later call the Central-Station System was perhaps the greatest among his many inventions. What Edison did for dc, Westinghouse did for ac. In the bitter "dc-ac war" Westinghouse prevailed.(5)

In Chapter 2, we compared Faraday's primitive dc generator with a simple ac analogue. Even the analogue does not accurately represent the modern central-station generator, which has no permanent magnets. In it, the magnetic field is produced by a *rotor,* a huge electromagnet, in which coils carrying direct current fill slots on the surface of the steel of which the rotor is made. The coils in which ac is induced by the rotating field (the *armature* coils so called) are securely positioned around the inner surface of the generator casing or *stator.* Clearance between stator and rotor is minimal. If the rotor has one north and one south "pole," the machine will generate "60-cycle ac"* if the rotor speed is 3600 rpm—or 60 revolutions per second.

Parsons and the Steam Turbine-Generator

Pearl Street had used reciprocating engines as prime movers for dc generators. In 1884, (Sir) Charles Parsons replaced the steam engine with a steam turbine, but the dc generator remained. In his, the first successful, steam turbine-generator, steam at 80 psi entered at the center of a turbine and expanded as it moved in both directions along the shaft, which turned the generator at 18,000 rpm. DC was generated at 75 amperes and 100 volts, which gave the machine a rating of 7.5 kW. After having successfully served a lamp factory, this Parsons turbine-generator was retired to London's South Kensington Museum, where it stands for all to see as the forerunner of the enormously more powerful steam turbine-generators in our modern central stations. The first such installation anywhere was made in 1889 by Parsons at Plymouth, England, and consisted of four machines rotating at 4800 rpm with a rating of 75 kW each.

These were only two highlights of a distinguished career devoted mainly to the replacement of steam engines by steam turbines, a replacement without which our modern central stations could not exist. It was always the prime mover, not the electrical generator, that was the more troublesome, and that limited the sizes of the machines in which they were combined.

* Modeled upon Figure 9, p. 579, of "TURBINE:STEAM," the *Britannica,* v. 22 (1958).

* More precisely, ac of frequency 60 Hz, a Hertz (Hz) being a cycle per second.

THE ANATOMY OF A CENTRAL-STATION SYSTEM

Here we shall present the bare bones of a Central-Station System, in which electricity centrally *generated* is *transmitted* as necessary, and *distributed* to customers for use. We shall deal only with ac, it being clear that this can be rectified (made into dc) on demand.

A Central-Station System is comprised of various systems, as is shown schematically by the example in Figure 3-6. Such systems are active day and night. Why? Because, as A.E. Housman might have said, "Electricity's a rover and a ware that will not keep." It cannot be stored in appreciable amounts.* It cannot be put into a milk bottle and delivered wrapped in the morning paper. It must be on tap when the customer flips his switch. These systems will be needed until the generation of electricity can profitably be localized by replacing the central station and relying instead upon the sun (when it shines), the wind (when it blows), the earth (where heat is accessible), waterfalls (when there's adequate rain), the tides—and so on.

The electrostatic (Coulombic in the simplest case) forces of attraction (between unlike charges) and repulsion (between like charges) make it fundamentally impossible to store electricity on a practical scale. It could be said that Coulombic forces have made modern Central-Station Systems necessary—another triumph of pure research in electricity!

If electrical energy cannot be stored, what happens to the enormous amounts of rotary kinetic energy imparted by the turbine to its shaft? First and foremost, "amounts" is the wrong concept. Instead, we must concentrate upon rates of energy production and transfer because electrical energy must move. The thermodynamics of the turbine was dealt with by considering the energy decrease in unit mass (1 lb) of steam— an *intensity factor.* If this factor is multiplied by a *capacity factor,* namely by the enormous rate (lb/s) at which steam flows through the turbine, we have the basis for computing the *power* of the turbine, this power being the rate at which the turbine can deliver mechanical energy to the generator (ft-lb/s). By the magic of electromagnetic induction, this mechanical energy is converted in the generator to electrical energy so that (in the ideal case of no conversion losses) the *power of the generator* (kW) equals the *power of the turbine.*

* "Storage batteries," such as those used to start automobiles, store, not electrical energy, but chemical energy converted into electrical on demand.

To be specific, electrical power is EI (volts times amperes). Here E (electromotive force) is the intensity factor and I (proportional to the number of electrons flowing per second) is the capacity factor. As we saw in Chapter 2, increases in E are induced as the current I flows through the armature coils of the generator, the increases being governed by the Faraday law that predicts them when a conductor cuts, *or is cut by,* a magnetic flux. (The italicized words apply to generators with stationary armature coils, mentioned above.) Consequently, electrons, on the average, leave the generator at a higher energy than they had on entering.[6]

Transformers make it economical to transmit and distribute ac over much greater distances than are presently conceivable for dc—be it noted, however, that dc transmission is gaining ground. Transformers can indeed qualify as magical black boxes: power EI comes in at one voltage, and goes out at another with very little loss. But what about the transmission line? If EI is transmitted over a line of resistance R ohms, the electrons that make up current I must overcome forces analogous to friction, which means that heat will be generated in the line and rejected by it. The *rate* of rejection at the steady state will be $(\Delta E) I$, this being equal to the rate at which heat is generated by the conversion of electrical energy (First Law of Thermodynamics). How minimize this energy loss? Ohm's Law tells us that $(\Delta E) I$, in which ΔE is the "voltage drop" along the line, equals I^2R. Obviously, by reducing I and proportionately increasing E to keep EI the same. Here the transformer earns its keep. Today's transmission voltages easily exceed 100,000.

Such voltages cannot be generated in a central station, nor can the average consumer use them safely. The following illustration approaches modern practice: let E_g, the generator voltage, be 11,000; the transmission line voltage, 110,000; while the customer demands 110. Then E_g must be stepped up 10 times by a transformer at the central station, and E_t must be stepped down 1000 times by one or more transformers in transformer "substations" so that the consumer may safely and reliably get his morning toast.

In Chapter 2, we pretended that the customer sent his "used" electrons back to the central station for "rejuvenation." Figure 3-6, which represents a simple Central-Station System, shows that what actually happens is more complex even in this simple case. Let us regard the system as containing three closed electrical, magnetically coupled subsystems; namely, a generating, a transmitting,

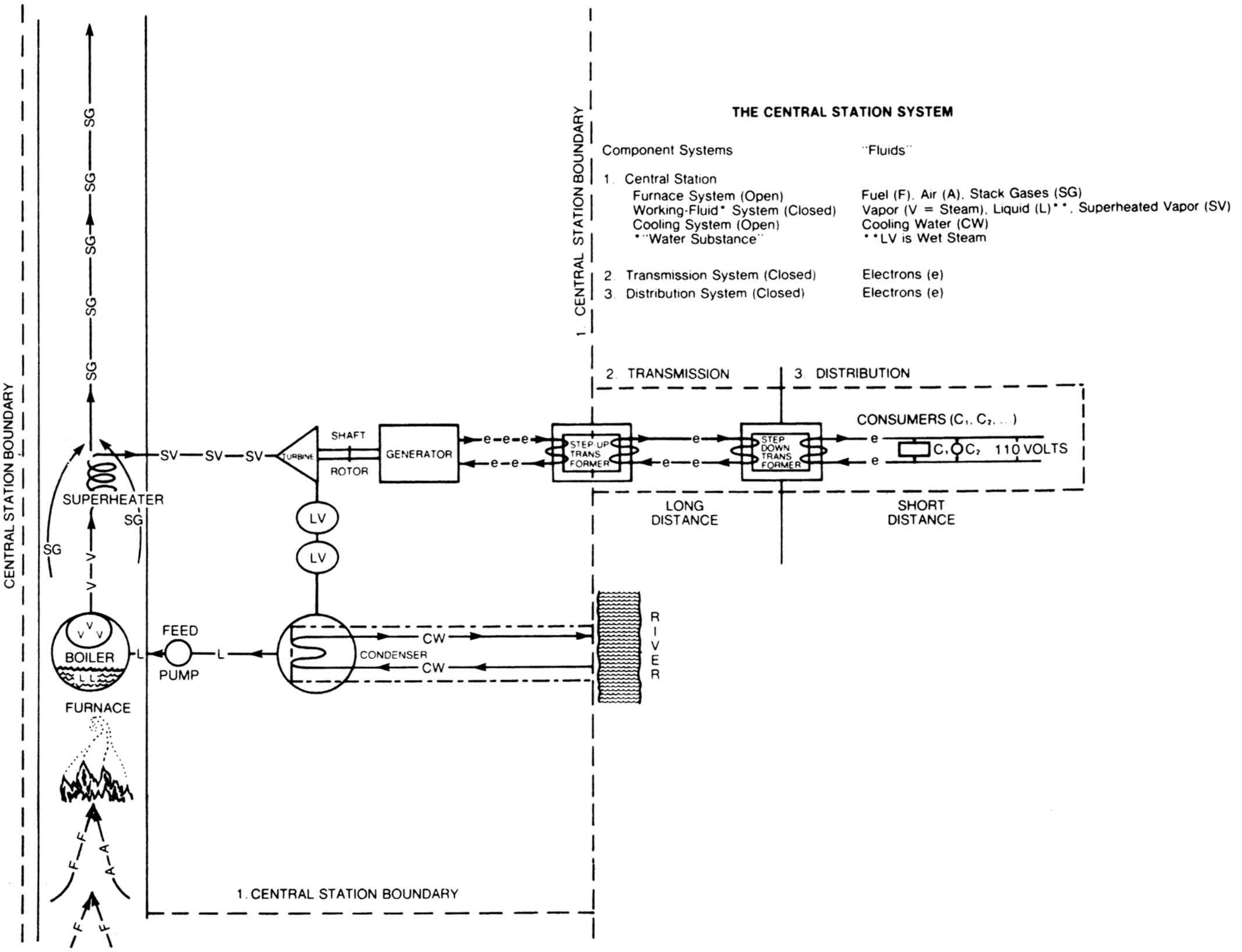

Figure 3-6. The Central-Station System as a flow assembly.

Comment

Figure 3-6 attempts to give the general reader a grasp of the simplest possible Central-Station System by subdividing it into open and closed systems in each of which at least one "fluid" moves. The reader may wish to compare the System with the human body: turbine-generator = heart; electrons leaving generator = arterial blood; returning electrons = venous blood; regulatory and control mechanisms (omitted above) = brain and nervous system; furnace system = digestive system and lungs. The comparison must not be pushed too far: in the body, open systems predominate; matter crosses system boundaries; red blood cells, for example, must get their oxygen from the lungs—they cannot be "regenerated"—as can electrons—through electromagnetic induction. However naive the comparison, it does teach the importance of these Systems to our civilization and emphasizes the complex flow pattern that must adjust itself in response to the flipping of a switch outside the central station.

The turbine is represented above as a triangle to emphasize that, in a multistage turbine, the wheels and the buckets they carry must become larger as expansion increases the specific volume, V', of the steam. Otherwise, representation of equipment is wholly schematic.

What the customer receives is usually "60-cycle ac" at 110 volts. The two wires in the figure deliver "single-phase" ac, which means that waves transmitted reach maximum voltage at the same time. It is possible to send more than one set of waves through the same wire with the timing arranged to make each set reach peak voltage at a different time. Such *polyphase* transmission has advantages over single-phase, but it requires more than two wires. Three-phase transmission with three wires is normal.

Minor matters: In Figure 3-6, all transformer coils have the same number of turns. This error is mitigated by the descriptions "step-up" and "step-down." The generating system (see text) is not named.

and a distributing system. Let the first electrical system include the generator and the primary coil of the station's step-up transformer; the second, the secondary of that transformer and the primary of the distribution transformer; and the third, the secondary of the distribution transformer and the customer's house. The first system is magnetically coupled to the second; and the second to the third. Thanks to our transformers, the "used" electrons can be "rejuvenated" by the central-station generator without ever having to enter the station. On demand, the customer can almost always withdraw electrical energy in his house at 110 volts and at whatever current for however long he desires—"almost always" because, though rarely, customers can distress their central station by demanding energy at a higher rate than the station can comfortably supply. Today, many central stations are interconnected via "grids" so that other stations can relieve those distressed.

The great dc-ac war, which shaped the electrical industry during the last century, soon turned in Westinghouse's favor. Under his auspices, William Stanley[7] in 1885 converted a rubber mill in Great Barrington, MA, into a transformer laboratory. In March 1886, the practicability of ac transmission and distribution was demonstrated there when electric power was transmitted 4000 ft by using one transformer to step up the voltage to 3000 and a second to reduce it from there to 500. On November 30, 1886, in Buffalo, NY, the first U.S. ac central-station went on-line, generating electricity at 133 Hz and 1000 volts. Thereafter, Central-Station Systems resembling that diagrammed in Figure 3-6 became the rule. Edison eventually gave in.

BTUs PER KWH?

This cryptic question goes to the heart of our energy situation, for the more kWh per Btu, the less oil—to name only one fuel—we need, other things equal. To come to grips with it, we must look at working-fluid cycles so that we may understand the thermodynamics of the steam central-station and comprehend Emmet's dream (Chapter 4). To see what the boiler (or other steam source) must supply so that the turbine-generator can deliver a kWh at its terminals, we must become acquainted with the acronym NPHR, which is explained below. Given these starting points, we can glimpse in succeeding chapters the development of the modern central station and follow the fate of Emmet's dream.

Cycles

The reversible Carnot cycle is an unmatched guide to the understanding of thermodynamics, and is a model of efficiency that other cycles can never surpass. But no central station has ever used it, or ever will. Its clumsy *method of heat rejection* doomed it implicitly in 1765 when Watt,[7a] long before Carnot was born, invented the separate condenser for the steam engine.

Watt was anxious to reduce the appalling rejection of heat by the engines of his time. He reasoned correctly that steam could do more work if it could be expanded to a lower pressure in the engine.* He proved his point, but he did much more. To maintain the exhaust pressure below atmospheric, he had to *change the state* of his working fluid ("water substance") from vapor to liquid. In so doing, he rejected heat as *heat of condensation,* far better than rejecting it after isothermal compression of a gas or vapor as in Figure 1-3. Such compression entails the use of big, costly machinery, much work, and heavy losses owing to friction. A second alternative, compression of vapor mixed with liquid, is even worse. That leaves compression of a liquid, which generates almost no heat whatever. (Liquid water boiling in a teakettle will not become 1 °F hotter when compressed to 1000 psia.) But, if the heat has been rejected in a condenser, it is a simple matter to force the liquid back into the boiler by using a "feed pump" as in Figure 3-6. Before we consider the cycle that is closed in this way, let us become more familiar with water substance in the two forms, liquid and vapor.

Figure 3-7 is a temperature (T)-$\mathbf{S}'$ (entropy per pound) diagram for water substance. For reasons that will appear, let us say the curve in the diagram consists of a *boiling-point curve* (on the left) that rises to a maximum, the *critical point,* and then falls away along a *condensing-point curve.* For every boiling point, there is a condensing point at the same temperature. At the boiling point, $\mathbf{S}'$ has the *minimum* value at which liquid and vapor can coexist: increase $\mathbf{S}'$ by adding heat at constant pressure and temperature, and liquid will begin to disappear. When the condensing-point line is reached in this

* Expanding steam from 15 psia (atmospheric pressure) can yield more work than expanding it from 200 psia to atmospheric pressure, as in a non-condensing reciprocating engine, or turbine. Note: "psia" means "pounds per square inch absolute" (above zero pressure), and "psig" means "pounds per square inch gauge" (shown by a gauge that indicates pressure above atmospheric); 30 psia is approximately 15 psig at sea level.

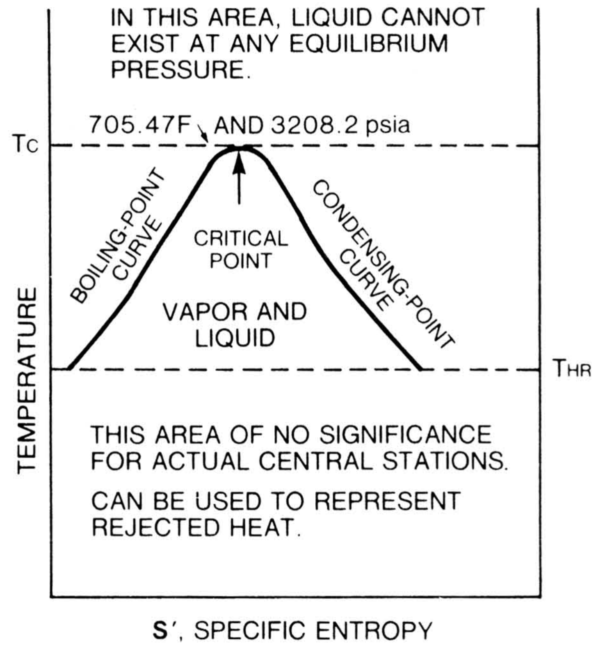

Figure 3-7. Water substance as working fluid for central stations. The lowest temperature significant for operation is T_{HR}, the temperature of heat rejection, which is usually determined by the cooling water available. The critical temperature is T_c, a property of water.

way, S′ will have the *maximum* value at which liquid and vapor can coexist. Normally this line is approached from the vapor side—hence its name; it marks the point at which liquid can first appear when heat is withdrawn at constant temperature and pressure. The curve thus bounds the area in which liquid and vapor exist together in measurable amounts at equilibrium.

As we move up the boiling-point curve, pressure increases until 705.47 °F is reached, when the pressure is 3208.2 psia. At higher temperatures, liquid cannot exist in equilibrium no matter what the pressure because the repulsive forces between water molecules have become so strong that no pressure can force the molecules to form a liquid: hence, there can be no condensing and no boiling. One practical consequence: heat added to steam *confined* above the critical point must increase both pressure and temperature—*superheating* of the steam must result.

Let us now construct in Figure 3-8 a simple, reversible Rankine cycle, something like that at which Rankine and Clausius arrived when they idealized the operation of early steam engines—a cycle which can serve as an idealized model of the working-fluid system of Figure 3-6. Suppose we

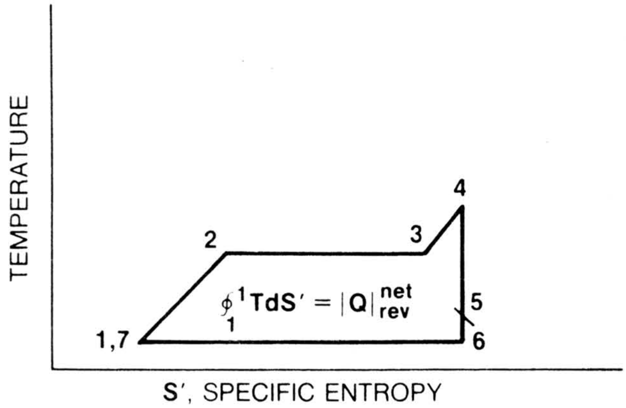

Figure 3-8. Diagram for a Rankine cycle. For explanation of numbers, see text.

are sure of abundant, cheap water from a river or lake so that we can fix [1],* the temperature at which steam leaves the turbine and liquid enters the boiler. Next, choose [2], the temperature at which the liquid is to boil, which also fixes the boiler pressure. At this pressure, move [1→2] along the boiling-point curve. Then, boil [2→3] along the horizontal line until the condensing-point curve is reached. Now, liquid no longer being present with the vapor (the steam is "dry"), superheat along [3→4]. Let the superheated steam enter the turbine and expand isentropically along the vertical line [4→6], which crosses the condensing-point curve at [5], where liquid begins to form, and the steam becomes "wet." Conclude condensation along [6→7] in the condenser. Finally, close the cycle by compressing the liquid isentropically along [7→1], using the feed pump to force the liquid back into (i.e., "feed") the boiler.

With reversible operation, there would be no perceptible pressure gradient along [1→2→3→4] or along [6→7]. There would be no entropy change along [4→6] or [7→1]. For reversible operation, therefore, the Rankine cycle on a plot of P against S′ would be represented by a *rectangle,* though of course a different *kind* of rectangle than that in Figure 1-3. A plot of P against S′ would thus show that the feed pump compensates the pressure drop in the turbine, but that would be its chief value. Because (see above) compression of the liquid causes such a small temperature rise, the vertical [7→1] does not appear in Figure 3-8.

For the Fisk Street Station of 1903,[4,8,9] [1] may be taken as 102 °F and 1 psia, [2] as 375 °F and 185 psia, and [4] as 445 °F. Being the first

* Bracketed numbers are keyed to Figures 3-6 and 3-7.

U.S. central station to rely exclusively on the turbine as prime mover, Fisk Street is a good starting point for the Rankine-cycle race, which continues today in the form of attempts to increase by all means possible the enclosed area in Figure 3-8.

We shall make no detailed comparison of Figures 1-3 and 3-8. The salient point, which visual comparison will show, is that much heat in Figure 3-8 is absorbed below the maximum temperature and some heat is rejected above the minimum temperature, in marked contrast to Figure 1-3, where only two temperatures occur. The former difference is the more important. The best way to increase the enclosed area in the Rankine cycle is by *raising the average temperature* at which the working fluid receives heat. It comes to this: any reversible cycle can be improved by raising the average quality of the heat absorbed, and by lowering the average quality of the heat rejected.

The significance of the enclosed area is this. For all cycles, it will be remembered, from Chapter 1, $\Delta U' = 0$, so that *net* heat absorbed per pound by the working fluid equals *net* work done. For any reversible cycle,

$$\begin{aligned} |Q'|_{rev}^{net} &= \oint_1^1 T dS \\ &= \text{enclosed area } [1\text{-}2\text{-}3\text{-}4\text{-}6\text{-}7\text{-}1] \\ &= |W'|_{rev}^{net} \qquad (1) \end{aligned}$$

For any actual cycle, irreversibility makes it necessary to absorb a greater amount of heat for the same amount of net work. The total heat absorbed from the boiler is $|Q'|_{rev}^{net} + |Q'|_{rev}^{rej}$, the second term being the heat reversibly rejected to the condenser along [6-7] in Figure 3-8. $|Q'|_{rev}^{rej}$ is best taken from the steam tables; at 102 °F and 1 psia, it will be the heat of condensation per pound, or 1036 Btu.

Net-Plant-Heat-Rate (NPHR)[10]

This quantity is the fuel-heat input (Btu) at the furnace door required for a kWh of electrical energy leaving the central station at the transmission line. The lower the NPHR, the better the station as regards saving energy. The values of this quantity and the chances of lowering it are matters of first importance in connection with our national energy situation.

We need not analyze the NPHR in detail. We shall begin with the 1 kWh = 3412 Btu that must be delivered at the central-station boundary, and work our way back to the central-station entrance, adding as we travel the energy increments (in Btu) needed for each step of the way.* Fortunately, the main losses occur in the two *open* systems of Figure 3-6. This is certainly true for the Central-Station Systems of today, and it was probably true at Fisk Street in 1903. Let us use this station as the basis for a guess at the NPHR at the beginning of the turbine-generator era.

At Fisk Street, a *minimum*[4] of 3412/132 lb of steam had to enter the turbine for the 1 kWh to be transmitted. Each pound of this steam would reject 1036 Btu, the heat of condensation, to the cooling water in the condenser. As a consequence,

$$(1036)(3412)/132 = 26{,}779 \text{ Btu} \qquad (2)$$

must appear in the NPHR.

The losses in the other open system depend upon how completely the fuel is burned in the furnace (pulverizing coal helps!), and upon how low a stack temperature one is prepared to risk.[11] Let us take a good round number, 10,000 Btu/kWh, for these losses. Our incomplete NPHR so far is 40,191 Btu/kWh—why not take the complete NPHR to be 50,000 in the same units? Fuel was cheap in 1903!

In 1851, before the days of the turbine-generator, Rankine[12] wrote "... we cannot expect to convert more than about *one-sixth* of the heat expended in evaporation into available power, the remainder escaping into the condenser or the atmosphere. The actual amount so converted is in many ordinary engines less than *one-twenty fourth* part." For a rough comparison with 1903, let us say that the enclosed area in Figure 3-8 represents 6 × 3412 = 20,472 Btu, and that Rankine's NPHR is four times as large, or 81,888 Btu/kWh (no more, no less!).

Evidently a Rankine-cycle race toward lower NPHRs would begin as soon as better materials made it safe to design and build larger and more efficient equipment. In terms of Equation 2, the goal of this race is to increase the denominator (132)—to get more useful work out of a pound of steam—by any means compatible with a satisfactory Carnot Trade-off. This goal can be reached by increasing the enclosed area in Figure 3-8, and by decreasing losses stemming from irreversibility, both of which can be achieved, as we shall see, by making equipment bigger.

* The central-station boundary—the start of the transmission line—in the definition of the NPHR differs a little from that in Figure 3-6, but we may ignore this difference. Among the energy increments are those equivalent to the work required to operate auxiliaries (fuel lift, feed pump, air blower) and to losses owing to friction and electrical resistance.

So long as we use heat engines, we shall have to reject precious heat, but even this inevitability does not warrant unrelieved gloom as the following illustration will show. Suppose a plant, chemical or other, needs live steam for some of its processes, or suppose heat is needed on a large scale near a central station. It might then make sense to run the central station without condensing the steam, which could be expanded in the turbine to whatever temperature and pressure are most favorable for the projected use. That is, the quality of the rejected heat is raised enough to make the heat a valuable product. This old, old idea, long practiced, now bears the new name "co-generation" (of electricity and steam).

CONCLUSION

In concluding this chapter, it is fitting to call once more on Henry Adams. Chapter XXV of his celebrated *Education* is significantly titled "The Dynamo and the Virgin." The order is important. Adams was interested in the great cathedrals of the Middle Ages—notably in that at Chartres—and he regarded the Virgin Mary, to him the Lady of Chartres, as the great unifying force of the era. The title was probably intended to signify that the dynamo, a generator of electrical energy, was to become eventually the dominant force, bringing multiplicity and complexity.

Adams began his electrical education in 1893 at Chicago, where the Westinghouse Electric Company had been retained to light the World's Columbian Exposition.* This education continued at the Paris Exposition of 1900 with Langley† as teacher. The pupil speaks: "To him [Langley] the dynamo itself was but an ingenious channel for conveying somewhere the heat latent in a few tons of poor coal ... but to Adams the dynamo became a symbol of infinity. The planet [earth] itself seemed less impressive in its old-fashioned, deliberate annual or daily revolution, than this huge wheel, revolving within arm's length at some vertiginous speed, and barely murmuring—scarcely humming an audible warning to stand a hair's breadth further for respect of power—while it would not wake the baby lying close against its frame. Before the end, one began to pray to it;‡ ... Among the thousand symbols of ultimate energy [at the exposition], the dynamo was not so human as some, but it was the most expressive." What would Adams have written could he have visited Fisk Street Station in 1903!

Were matters simple, Fisk Street, 1903, with its turbine-generators, should have ended this prologue. But, Emmet, to a greater extent than anyone else, put the new machines into the station, and he is also the principal protagonist in the story of mercury-steam, which follows. Had Fisk Street not strengthened Emmet's position in the General Electric Company, or had he been less forceful a man, there might have been little or no story to tell. The work on Fisk Street turbines will consequently be described as part of the mercury-boiler story, the chronicle of an innovation as bold as that of the turbine-generator.

* Thanks principally to Tesla,[7] the Exposition could boast an ac generator (2-phase) to light lamps and run motors.

† S.P. Langley, professor of astronomy at Harvard, and noted aerodynamicist after whom Langley Field was named.

‡ Adam's veneration of the electrical generator probably was the original inspiration for Eugene O'Neill's *Dynamo* (1929), one of his more extravagant and less successful plays, but interesting here because O'Neill regarded it as a "symbolical and factual biography of a soul sickness" attributable to a "failure of Science and Materialism." See Louis Sheaffer *O'Neill: Son and Artist*, the second volume of a biography published by Little, Brown and Company, Boston, in 1973. On p. 306, Sheaffer has the dynamo becoming "a symbol of infinity" for Adams at the *St. Louis* Exposition of 1900.

Appendix 1

NOTES AND REFERENCES

CHAPTER 2

The many faces of electricity and my casual acquaintance with most of them forced me to examine and compare what various sources had to offer. One consequence was a subjective choice of material for the chapter. Another was the omission of detailed citations, which would have been of little use as the material is by now common property, making exact citation usually impracticable because material from several sources was often blended.

The list below includes the sources to which I am most indebted, and it will serve as a guide to anyone tempted to dig deeper.

(1) The two latest *Encyclopedias Britannica* under "Electricity" and related headings.

(2) P. Dunsheath, *A History of Electrical Power Engineering,* The MIT Press, Cambridge, MA, 1962. An excellent source of information about Faraday, from which quotations about him in the text were taken.

(3) L.T. Agger, *Introduction to Electricity,* Oxford University Press, New York, 1971.

(4) C.S. Siskind, *Electricity,* McGraw-Hill, New York, 1955.

(5) C. Schaefer, *Einführung in die Theoretische Physik,* in three volumes, De Gruyter & Co., Berlin, 1929.

(6) M.L. McGlashan, *Physicochemical Quantities and Units,* the Royal Institute of Chemistry, London, 1968.

1. Franklin's definition of electricity is quoted from the Oxford English Dictionary (OED), which ought to be consulted as the many meanings of the many words deriving from "electron" are themselves an illuminating introduction to electricity.

   Rumford, as we saw in Chapter 1, showed that heat, being "imponderable," cannot be a fluid, yet we speak of its flow. Analogous usage for electricity has at least the justification that in an electric current something ponderable does move: moving electric charges, positive or negative, are always carried by mass.

2. This scanty introduction of a central station and its distribution system is closer to reality than something the press reports* as having been described on Sun Day, June 1978, by President Jimmy Carter: "It is not exactly logical to have a nuclear core developing millions of degrees of heat and temperature, heating a cooling agent to thousands of degrees to be transported hundreds of miles to heat a house to 68 degrees." Whatever happened to electricity? Is this an elaboration of the "thermodynamic overkill" mentioned in Chapter 1?

3. Conductors of electricity (metals; e.g., copper) cannot be electrified by rubbing with a cloth unless they are carefully insulated so as to prevent "leakage" of charge, which can occur through the human body to the earth (to "ground"). If an adequately insulated bar of metal is brought near a charged insulator, the end nearest the insulator will become oppositely charged by electrostatic *induction,* and the other end will show an equal charge of the same sign as that on the insulator. Note that induction[4] occurs *without contact* between the charged insulator and the initially neutral metal.

4. To most who are not physicists or electrical engineers, "induction" is a confusing, enigmatic miracle. Let Faraday speak:

   > The power which electricity of tension [electrostatic potential] possesses of causing an opposite electrical state in its vicinity has been expressed by the general term Induction; which, as it has been received into scientific language, may also, with propriety, be used in the same general sense to express the power which electrical currents may possess of inducing any particular state upon matter in their immediate neighborhood, otherwise indifferent. ... ["Power" here means "capability" and not the rate of doing work.]

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* The Schenectady Gazette, June 19, 1978, p. 28, and several days before.

Now, the OED on "induction" as restricted to electricity and magnetism:

> The action of induction or bringing about an electric or magnetic state in a body by the proximity (without actual contact) of an electrical or magnetized body. ...
>
> *Electrodynamic* or *voltaic induction*, the production of an electric current (induced current) by the influence of another independent electric current. *Electromagnetic induction*, the production of a state of magnetic polarity in a body near or round which an electric ... current passes, or the generation of an electric current by the action of a magnet (the latter called by Faraday, more properly, *magneto-electric induction*). *Electrostatic induction*, the production of an electrical charge upon a body by the influence of a neighboring body charged with statical electricity. ... *Magnetic induction*, the production of magnetic properties in iron or other substances when placed in a magnetic field, as when a bar of soft iron is magnetized by a neighboring magnet. *Mutual induction*, the reaction of two electric circuits upon each other; *self-induction*, the reaction of different parts of a circuit upon one another.

5. Often dc and ac describe the flow of electrons in copper. Such electronic currents will flow more or less easily through any metal(6) when a potential difference (E) exists: the greater the *electronic conductivity* of the metal, the easier (other things equal) the flow.

   Electrical conductivity (there are other kinds!) varies widely (perhaps 10^{30} times, other things again equal)—more widely than any other property of solid matter. It decreases in the order *metals, semiconductors, insulators.* Consider a sheet, 0.1 millimeter (10^{-7} kilometers) thick, of the best possible insulator. Other things once more equal, this sheet would have about the same *electrical resistance* as a column $10^{30} \times 10^{-7} = 10^{23}$ kilometers high of the best conductor. This height is $7(10^{14})$ times as great as the distance from earth to sun. It becomes infinite if *superconductors* operating near absolute zero were placed ahead of metals in the series above, a fact of growing importance for the future.

6. We have seen that some of the best scientific minds in England failed to understand the First Law of Thermodynamics on first exposure. Ohm's Law also proved difficult: certainly Joseph Henry, if anyone, should have understood its consequences. But—educators especially—please note what Dunsheath[(2)] has to say:

> The improvement of Sturgeon's electro-magnet was taken up by Professor Joseph Henry (1797-1878), of New York, who during the next few years made valuable suggestions which brought this important fundamental component of all electrical engineering to a point of great practical value. ...

It is very interesting today to see how intelligent men like Henry groped in the dark over such simple ideas as the Ohm's Law relationship in a circuit.

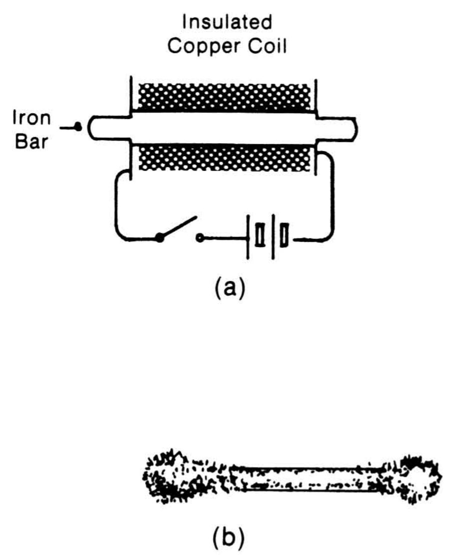
If we think of electricity as a fluid, we can make a hydraulic picture of Ohm's Law. Consider a closed system in which a mechanically driven centrifugal water pump forces water through piping to drive a hydraulic motor that does external work. Owing to friction, the pressure drops as water flows through the piping, and heat is rejected. Replace the pump with an electrical generator that drives an electrical motor, and the piping with copper wire. The electric current I is then analogous to the flow rate of water, and the potential difference E to the pressure. There is, of course, an important microscopic difference: E has its source in the Coulombic forces between electrical charges. Thermodynamics applies in both cases. The hydraulic picture makes central stations easier to understand (see Chapter 3).

But, the flow of electricity is not really as simple as opening a valve to irrigate a field. Consider electron flow. Coulomb's Law tells us that the repulsion of like charges makes rapid, tidy flow of negative electrons impossible unless there are positive charges, moving or stationary, in the neighborhood to neutralize the negative charges: not quite, but well enough so that electrons can be near neighbors.

In good metallic conductors (such as copper), each atom contributes about one electron to carry current, which gives us about 10^{23} current carriers available in a cubic centimeter. How fast can such a current move under ordinary conditions? Electric fields travel at speeds approaching that of light, but steady electric currents in metals are far, far more sluggish. When we try to visualize this journey, we become frustrated because we know so much about the electron that we can no longer consider it a simple particle, negatively charged. In matters such as this, we are well advised to favor the engineer over the physicist (e.g., Figure 2-4).

*Con*duction and the lack thereof in insulators rank alongside *in*duction in making electricity useful.

7. Oersted was not alone in experimenting with electricity and magnetism in conjunction. In 1820, (D.-) F. (-J.) Arago (1786-1853) found that an iron bar becomes magnetized upon being placed inside a coil carrying an electric current; and that most of the magnetization disappears when the bar is removed or the current interrupted. Although there has been electrical induction of magnetism, the iron has *not* become a useful permanent magnet. About 1821, William Sturgeon (1783-1850) built the first *electromagnet*, a modern form of which is shown in Figure N-1.



igure N-1. After Agger, Ref. (3), p. 185. An electromagnet (a), and a permanent bar magnet (b) to which iron filings have been attracted at the ends (poles). When the battery circuit is closed and an electric current flows through the insulated copper coil (magnet-wire coil) in (a), that iron bar will attract iron filings as has the permanent magnet in (b).

The modern electromagnet owes much to Joseph Henry, an American, who in 1828 built one having three features that make electromagnets indispensable in modern electrical machinery: the iron (or steel) core, the current-carrying coil, and the insulation of the coil. The first two features, not due to Henry, strengthened the electromagnet. The third—the use of insulation to prevent the escaping of electrons from one turn to a close neighbor—was a most important step in the same direction, for it enabled Henry to wind the "magnet wire," as it is now called, upon itself. Today, "wire enamels," made of polymeric materials, are used to insulate magnet wire. Thin, strong, temperature-resistant, coherent (hole-free), and adherent (to the copper), wire enamels are perhaps the most important among modern insulating materials.

Faraday won the subsequent controversy over credit and priority for the electromagnet largely because his discovery, like all his work, was superbly described and documented, as Henry's was not.

8. Faraday invented "fields of force" ("fields" for short) and "lines" therein, to serve as *models* to explain the interaction ("marriage") of electricity and magnetism. James Clerk Maxwell (1831-1879) brilliantly worked out the quantitative implications of Faraday's model. Many, notably Einstein, have failed in heroic attempts at a unified field theory that would include gravitational forces. The Faraday-Maxwell model called for an ether, the existence of which Michelson and Morley disproved in experiments described in Chapter 1.

Fields are "spheres of influence" within which bodies can attract or repel each other. The forces acting depend upon the distances between the bodies (e.g., Coulomb's Law), and the forces can be mechanically measured. Consequently, in terms of the First Law of Thermodynamics, we can regard the two bodies as a system that can do work or have work done upon it. In simple systems, no heat need be generated or absorbed when the work change occurs. Under these conditions, $dU = w$.

An alternative description emphasizes the field. *Field strength* is the force acting upon a *unit test body* at any point in the field. This force changes as the position of the body changes. The work and the energy difference associated with the change are then equal to a *difference of* (field) *potential* between the initial and final positions of the test body.

To bring this discussion down to earth, let us return to Oersted's experiment and envision a linear current-carrying conductor poked perpendicularly through a large square of cardboard. Let us move a test compass on the cardboard so that it occupies positions around the conductor at various distances from it. The compass needle will tend to align itself perpendicularly to the axis of the conductor in every position; the pole nearest the conductor will change with the direction of the electric current. The movement of the compass in this way permits mapping the magnetic field, and shows that it is concentric with the conductor. Mapping by the use of iron filings, which when tapped will align themselves owing to electromagnetic induction, gives similar results. Quantitative measurements prove that the magnetic field strength decreases with increasing distance from the conductor.

9. The following incomplete table of SI electrical units is taken from McGlashan (see above), p. 24 (s = second, kg = kilogram, m = meter):

Physical Quantity	SI Unit	Symbol	Definition
frequency	Hertz	Hz	s^{-1}
energy	joule	J	$kg\ m\ s^{-2} = Jm^{-1}$
power	watt	W	$kg\ m^2s^{-3} = Js^{-1}$
current	ampere	A	(see below)
charge	coulomb	C	As
potential difference	volt	V	$JA^{-1}s^{-1}$
resistance	ohm	Ω	VA^{-1}

Making the ampere into the only basic SI electrical unit calls attention to the importance of electricity *in motion*. Its definition takes us back to Oersted. From p. 18, *op. cit.:*

> AMPERE. The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in a vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.

Because magnetic fields tend to merge, the force between the conductors will be attractive when they carry currents flowing in the same direction; repulsive otherwise.

Humpty Dumpty commands that SI units be used, but scientists and engineers are still in the position of the housewife struggling with the metric system in the supermarket. Our electrical bills show kilowatt hours, and we shall use this unit. We have written Ohm's Law, $E = IR$, with E representing potential difference; I, current; and R, resistance. The table above gives the names and symbols for the units in which these quantities are expressed. We shall favor the names.

10. Robert K. Merton in *On the Shoulders of Giants,* Harcourt Brace & World, New York, 1965, has given an exhaustive, scholarly, amusing, historical account of the celebrated "pygmies standing on the shoulders of giants" quotation. Of interest here is that Newton used it (perhaps with tongue in cheek) in modified form when he wrote Robert Hooke (1635-1703) on February 5, 1675/6 about their controversy over what credit each deserved for the discovery of Newton's celestial mechanics. Newton mentioned no pygmy. Whether a scientist making a discovery is to be judged a pygmy or a giant depends upon many things, among which are what he knew at the time, how lucky he was, what others were doing, and how important the discovery (which is governed by how reliably and completely his field was known). Today, we cannot simply put Faraday on Oersted's shoulders, omitting Ampère among others, and (for example) Edison on Faraday's—poor Oersted would truly have to support a massive inverted pyramid of scientists and engineers!

11. A more interesting scientist-engineer than Rumford (Sir Benjamin Thompson, Count of the Holy Roman Empire) would be hard to find. Consider that he (1) at age 19, married a wealthy widow in Rumford, New Hampshire; (2) soon thereafter became a spy for George III, by whom he was knighted in 1781; (3) fled from Rumford to London, England, in 1776, leaving wife and daughter behind; (4) returned soon to command a British regiment in New York; (5) back in Britain, did significant experiments on gunpowder, promoted potatoes as a dietary staple, and improved methods for heating and cooking; (6) and in becoming Count of a questionable empire long since gone, preserved for posterity the name of his wife's home, which now calls itself Concord.

Rumford was co-founder of the Royal Institution, later Faraday's scientific home. He also

Electrical Events By Years

(see page 29)

			1 Entry				
1269	1712	1762	1785	1812	1830	1855	1930
1492	1720	1764	1786	1813	1831	1862	1938
1544	1745	1765	1787	1816	1834	1864	1940
1576	1747	1768	1794	1818	1846	1865	1944
1600	1750	1769	1797	1821	1847	1871	1945
1660	1752	1772	1806	1824	1848	1907	1946
1665	1753	1774	1809	1825	1852	1915	1955
1687	1761	1775	1811	1826	1854	1916	1961
			2 Entries				
1800	1833	1857	1904	1921	1928	1937	1947
1801	1835	1866	1909	1922	1931	1941	1948
1808	1850	1876	1914	1923	1933	1942	1949
1828	1851	1885	1917	1927	1934	1943	1953
							1959
			3 Entries				
	1820	1842	1867	1884	1910	1952	
	1839	1843	1870	1890	1932	1956	
	1840	1844	1872	1893	1939		
	1841	1863	1880	1901	1950		
			4 Entries				
		1832	1859	1874	1912		
		1838	1860	1895	1918		
		1845	1861	1899			
		1856	1868	1911			
			5 Entries				
		1858	1896	1903	1913		
		1873	1898	1905	1924		
		1875	1902	1908	1925		
			6 Entries				
			1836	1919			
			1878	1926			
			1894	1929			
			1906	1936			
			7 Entries				
			1837				
			1888				
			1892				
			8 Entries				
			1887				
			1897				
			1920				
9 Entries		10 Entries		11 Entries		12 Entries	
1877		1879		1889		1900	
1886							
13 Entries		15 Entries		16 Entries		17 Entries	
1883		1891		1881		1882	

impulse turbines? The answer to both these rhetorical questions is obviously "Of course not!"

Newton's Laws of motion apply to all collisions. When the colliding bodies are perfectly elastic, momentum (mv)—called by Newton "the quantity of motion"—is *conserved.* Ideally, momentum lost by the steam is gained by the turbine. Turbines are more easily understood if this fact is kept in mind.

3. Our treating $\mathbf{U}'_{PV'}$ as a component of **U**, though sensible enough, will not please the thermodynamic establishment, engineering and scientific, which uses $\mathbf{H}' = \mathbf{U}'_T + \mathbf{U}'_{PV'}$ instead. The road taken here has the advantage of not enlarging the trinity ($\Delta\mathbf{U}$, $|W|$, $|Q|$) in the First Law, and it should for this reason be an easier thermodynamic road for the general reader. Whether **H**′ (or **H**) earns its keep by making thermodynamics more convenient for the scientist and engineer is a thorny question beyond the scope of this book.

   One thing is certain. Thermodynamic functions have been unfortunately named, as the general reader will learn if he digs into their history. The OED tells us that *energy* in a thermodynamic sense was first used by T.F. Young in 1807, but that by it he meant mv^2; and that Clausius, assuming in 1865 that energy meant the "work-contents" *(Werk-inhalt)* coined *entropy* to represent the "transformation-contents" (*Verwandlungsinhalt*—capacity for conversion?) of a system. From there, it was an easy step to *Wärmeinhalt* (heat content—"s" omitted) for **H**, which is an *energy,* as heat—being a bird of passage in the modern view—cannot be *contained* in a body. Presumably to correct this embarrassing situation, *enthalpy* was coined. How successful the coinage? Well, the word has wide circulation. Probably most who use it do not realize that *thalpein* (Greek) means "to warm": from "heat" to "warmth"—once again "the Greeks had a word for it."

   That is only the beginning. $\mathbf{H} - T\mathbf{S} = \mathbf{G}$ is, according to the First and Second Laws, reversible *work;* we call it the Gibbs *energy.* $\mathbf{G}-PV$, a related function, may here be ignored. Neglecting work, Gertrude Stein might well have said "An energy is a heat is a warmth."

   The groping and the confusion show that thermodynamics is not easy, and that engineers and scientists are human. We might do well to return to Gibbs, who (with the exception of "energy" and "entropy") left the principal thermodynamic functions nameless, representing them (of course) by Greek letters.

4. The information about Fisk Street is in *Steam,* p. 5. The energy data for the calculation are from the 1967 ASTM *Steam Tables,* which every steam engineer should carry graven on his heart as they contain information indispensable to the intelligent operation of any steam engine.

   To the nearest Btu by linear interpolation of the tables:

(1) State 1 (turbine entrance)
185 psia, 375 °F (boiling point); steam superheated to 445 °F: $\mathbf{U}' =$ 1238 Btu

(2) State 2 (turbine exit)
1 psia, 102 °F (boiling point): $\mathbf{U}' =$ 1106 Btu

(3) Hence, $\Delta\mathbf{U}' = 1238 - 1106 =$ 132 Btu (used in text)

(4) Heat rejected in condenser at 102 °F = $\mathbf{U}' - \mathbf{U}'_{liquid} = 1106 - 70 = 1036$ Btu (Dry steam is assumed.)

(5) At 375 °F, $\mathbf{U}'$ for dry steam at 185 psia is 1197 Btu

Three comments:

First, Items (3) and (4) show that almost 8 times as much heat was *rejected* during condensation as was used to produce work during expansion—truly a pitiful situation, which shows why the importance of rejected heat was stressed in Chapter 1. Obviously, two things (not mutually exclusive) can be done: reduce the *relative* amount of heat rejected and/or put it to use. Both have been accomplished, the former with a greater effect on the lowering of our electricity bills.

Second, Item (5) shows the great value of superheating steam. By raising its temperature a mere 70 °F above the boiling point, *without increasing pressure* (an important consideration when operation is near the safe limit for the materials available), the $\Delta\mathbf{U}'$ is increased from 1197−1106 = 91 Btu to the 132 Btu of Item (3). Not often can a Carnot Trade-off be improved so easily.

Third, how much will the speed at which steam enters the turbine contribute to v at the nozzle exit? The answer, very little. Suppose steam in the supply line moves at 100 ft/s. Then,

$$v = (100)^2 + (2570)^2 = 2572 \text{ ft/s.}$$

We must add energies, not velocities!

Finally, all the calculations are illustrative and are not quantitative indicators of central-station performance around 1910, although they correctly imply that opportunities for marked improvements in performance then existed.

5. In the dc-ac war, Edison and Westinghouse were the opposing generals. Westinghouse won.

Thomas A. Edison (1847-1931), probably the greatest American inventor, is so well known that little need be said about him here. Among many pertinent books, R.W. Clark's *Edison,* G.P. Putnam's Sons, New York, 1977, is particularly interesting. Its subtitle, *The Man Who Made the Future,* is a little extravagant. Edison is probably overrated by the general public and underrated by those scientists to whom the "Edisonian method" represents blind empiricism—it was usually far more than that. Edison admired Faraday; diligently acquired from anywhere any knowledge he could use; was ingenious, prolific, shrewd, and tenacious; more interested in getting from, than in contributing to, science; prized patents above rubies. He was more generous than is indicated by the few incidents for which we have room.

George Westinghouse (1846-1914), inventor and manufacturer, is less well-known than Edison. Yet, Westinghouse's role in the dc-ac war was important enough to legitimize the slogan "Every house needs Westinghouse," used in our time by the Westinghouse Electric Company, which he founded in 1886 to help win this war. In 1885 he had imported European transformers and ac generators to set up an electrical system in Pittsburgh. He and his colleagues improved the transformer and modified the generator to operate at constant voltage. He bought the patents on the only satisfactory ac motor then known, which had been invented by Nicola Tesla, of whom more later. In the panic of 1907, Westinghouse lost control of his electric company. Fifteen years before, on April 15, 1892, the Edison General Electric Company had been merged with the Thomson-Houston Company to form the General Electric Company. In our words, Edison founded the Central-Station System in this country, and Westinghouse changed it so that it could grow.

The dc-ac war became less civilized as the conviction grew that ac had technology and economics on its side. In desperation, the dc (Edison) party tried to have potential differences above 800 volts made illegal, which—as the text will explain—would have been a death blow to ac. They further suggested that ac was a menace to human life—as if a lightning stroke (dc) could not kill! Clark (see above) says on p. 160:

> The alternating current interests eventually triumphed, but only after a dramatic coup by their opponents. The direct current party first carried out a gruesome promotional campaign, conceived by Insull, Johnson, and Edison and carried out by Harold P. Brown, a former Edison laboratory assistant, for the use of the electric chair as a method of executing criminals. As part of a complex plot, Brown had in 1889 bought three of Westinghouse's alternating current motors [generators] without giving Westinghouse any idea that they were to be resold to the prison authorities. A year later it was announced that future executions in Auburn State prison, Sing Sing, and Clinton would be carried out by electrocution and on 6 August 1890 William Kemmler was electrocuted for murder in Auburn. He died by alternating current and in the minds of large numbers this became synonymous with death.

Many would today transfer that distinction to nuclear energy used in central stations!

6. It is a relief to learn that it has proved possible to set up continuity equations for transformers and for rotating ac machinery by using Poynting's vector to represent the flow of power. See Chapter 2 near its end and the *Britannica, 8,* 3050, 1958.

7. William Stanley (1858-1916) and Nicola Tesla (1856-1943) contributed mightily to help Westinghouse win the dc-ac war. They may not belong in a pantheon of "giants," but they can serve as surrogates for the many other able men who helped found the modern electrical industry, and who will pass quickly into oblivion even for the well-informed general reader.

   For further examples, see the first literature cited above under Chapter 2.

   Only by comparing a workable transformer with Faraday's "motionless induction," which we have not the space to do, can one assess Stanley's (and Westinghouse's) great contribution to ac transmission and distribution: Stanley had a long way to travel. He eventually left Westinghouse to form the Stanley Electric Manufacturing Company, Pittsfield, MA, which made ac (polyphase) motors. His company eventually became the Pittsfield Works of General Electric, where the Works Laboratory bears his name today. One might say that Stanley jumped from Westinghouse to Edison.

   Tesla, Croatian born, temperamental, theoretically inclined, and with more than a touch of genius, reversed Stanley's jump. According to Clark (pp. 158-59), Tesla had been working less than a year for Edison when he left because he felt that Edison had bilked him of fifty thousand dollars promised him by Edison for improvements made by Tesla in an ac generator. Tesla "gained the support" of Westinghouse, and twenty-odd years later refused the 1912 Nobel Prize for physics although he loved acclaim and could have used the money. Why? It was to be an award joint with Edison!

8. James Watt (1736-1819), an instrument maker gifted with insight, understanding, and ingenuity, belongs in any pantheon of "giants" who gave us practical energy conversion. When he returned in 1756 from London to his native Scotland, he found that the Glasgow guilds refused to let him practice his trade because he had not yet completed his apprenticeship. Fortunately, he could (and did) become mathematical-instrument maker to the university there. Even more fortunately, when he was called upon in 1764 to repair a model of Newcomen's steam-engine, he had already been discussing with two able, intimate friends (Joseph Black, the discoverer of latent heat, and the less well-known John Robison, later professor of natural philosophy at Edinburgh) the possibility of improving such engines. He repaired the model and became determined to discover why engines of this primitive type needed so much steam to do so little work.

   Watt eventually did something amazing for his times. He began an experimental study of steam that led him to these two conclusions about good steam engines: (1) "the cylinder should always be as hot as the steam which entered it" (his words); and (2) the temperature of the spent steam should be as low as possible, 100 °F or lower, so that the steam before becoming spent would have expanded into the best possible "vacuum" and done the greatest amount of PdV work. In 1765, some thirty years before Rumford surmised the nature of heat, Watt concluded that these two conditions could be made by adding to the steam engine a condenser separated from the cylinder in which the steam was doing its work by expanding against a piston. In January 1769, Watt obtained his first steam-engine patent, which disclosed several inventions in addition to the separate condenser, one of the most important inventions ever patented. Had prime movers, not thermodynamics, been the principal concern in Chapter 1, Watt could have been our first giant. As it is, we might regard a boiling teakettle as the origin of the ASTM Steam Tables—if such a kettle did really initiate Watt into the mystery of liquid water and its vapor.

9. The Fisk Street Station, important in Chapter 4, contained 96 Babcock and Wilcox boilers rated at 508 hp (horsepower) each. Why not fewer, larger boilers? Because the safety required by the Carnot Trade-off would not permit realizing the saving larger boilers would have brought. At the same pressure, small vessels are safer than large.

   The history of the horsepower is a history of energy conversion—almost. In 1782, after experimenting with strong dray horses, James Watt concluded that a standard horse ought to pull with a force of 175 lb on a crank 12 ft in radius while walking round and round 2.5 times per minute to pump water, a task then being taken over by steam engines. Although the average horse could not hope to do this for a complete working day, Watt (was he cruel to animals?) defined 1 horsepower as doing work at the rate of 33,000 ft-lb per minute because $2.5 \times 2 \times 12 \times \pi \times 175$ has almost that value. In Btu/min, the horsepower is 42.44.

   Rumford (Chapter 1 and p. 93 of his article) reported in 1798 that his calorimeter and its contents had a "water equivalent" of 26.58 lb, which means that the heat captured over 250 min could have raised the temperature of this amount of water by 180 °F, or at an average rate of 31.89 Btu/min. Rumford's two horses were therefore working at only 31.89/42.44 times the rate Watt expected from a standard horse. Of course, Rumford sternly reminds us that "no estimate was made of the heat accumulated in the [wood of the] box, nor of that dispersed during the experiment." Nevertheless, it does appear that Rumford was kinder to horses than Watt.

   As units are wont to do, the horsepower grew fruitful and multiplied. To the Watt original, now called the mechanical, were added the electric, the metric, and another that is slipping into oblivion, though not rapidly enough; namely, the *boiler* horsepower, which was based upon the heating surface thought necessary to supply standard steam at the rate required by an engine of 1 (mechanical) hp rating. As defined, 1 boiler hp = 13.548 mechanical hp precisely!

   Calculations indicate that Babcock and Wilcox used mechanical hp in rating the 96 boilers of the Fisk Street Station. Even then, these boilers were rated as equal to 48,768 of Watt's horses wearily plodding their circular paths 2.5 times a minute.

10. What we have called the Carnot Trade-off no doubt dictated that the boiling point be no higher than 375 °F, the pressure no greater than 185 psia, and the superheat temperature (which concerns the turbine as well as the boiler) not above 445 °F—all for the "state of the art" in 1903. The "degree of wetness" of the steam is another factor in the Trade-off: wet steam erodes turbine buckets and reduces efficiency. The condensing conditions, 102 °F and 1 psia, seem reasonable for 1903: cooling water (perhaps from a river or lake) below 102 °F was surely available. The Trade-off once more: the lower the turbine exhaust pressure (here, 1 psia), the greater the risk of damaging air leakage.

11. In NPHR, the "rate" is taken with respect to unit energy, not unit time. The NPHR helps determine the allowable charge for electricity, and its determination and calculation therefore must follow exact rules that do not concern us. All we need know is this: If the amount of fuel required burned in t hours to deliver EIt kWh at the transmission line yields x Btu upon complete combustion, then NPHR = x/EIt.

12. If combustion is satisfactory, cooling stack gases by transferring heat to the working fluid is an obvious way of lowering the NPHR. Alas, this simple-sounding remedy is inordinately complex, for it involves consideration of matters such as the kind of fuel, corrosion and deposits in the boiler, "fly ash," nitrogen oxides, and SO_2 ("acid rain"). No aspect of the Carnot Trade-off is a better illustration of the "seed of the poppy" (Chapter 1).

   I do not know what measures, if any, were taken to reduce stack losses in the 1903 Fisk Street Station.

13. W.J.M. Rankine, *Phil. Mag.*, ser. 4, v. 2, 61 (1851).