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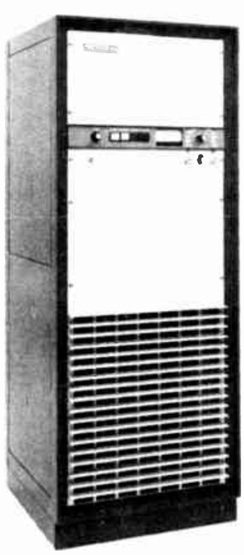

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Sharp Corporation's R-408 microwave oven under test for electromagnetic radiation leakage at the Japan Machinery and Metals Inspection Institute. The radiation may not exceed 5 mW after the door has been opened and closed 100 000 times.

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Microwave ovens: what's cooking?

"Only your roast" say most experts on nonionizing radiation, but consumer advocates and some researchers express doubts

Ours is a society bathed in electromagnetic radiation from commercial broadcasting, radar, portable transmitters, and a host of on-the-job industrial sources. For the past 40 years, researchers have attempted to document the effects of both high- and low-level exposure on human health. Tissue absorption characteristics and heating are among the better understood phenomena, but knowledge is still far from complete in this area.

Meanwhile, a comparatively new kitchen appliance, the microwave oven, has become widely available to consumers. With door seals and interlocks functioning properly, such ovens should have a negligible effect on the level of electromagnetic radiation found in a typical urban environment. However, the method for establishing "safe" exposure levels based on known heating effects involves many interrelated variables—physical condition of the person irradiated, ambient temperature, humidity, radiation frequency, exposure time, etc. And the questions surrounding reported or suspected nonthermal effects have yet to be fully resolved. As a result, many concerned (but not always well informed) people have become alarmed about human exposure to microwave radiation.

In April 1973, Consumers Union announced, through its publication *Consumer Reports*, that it considered microwave ovens "not recommended" for household use unless door seals and other openings permitted no detectable leakage. This position implies that *any* amount of microwave energy is biologically suspect, and has since been publicly denounced by radiation experts, including the IEEE Committee on Man and Radiation (COMAR). Oven manufacturers are particularly incensed at critics' "guilty-until-proven-innocent" attitudes which seek to minimize opportunities for microwave exposure—even at the officially prescribed "safe" levels. And they claim an important victory was achieved in November 1973, when the U.S. Bureau of Radiological Health's (BRH) Technical Electronic Product Radiation Safety Standards Committee (TEPRSSC) failed to back a Consumers Union petition for stricter oven tests.

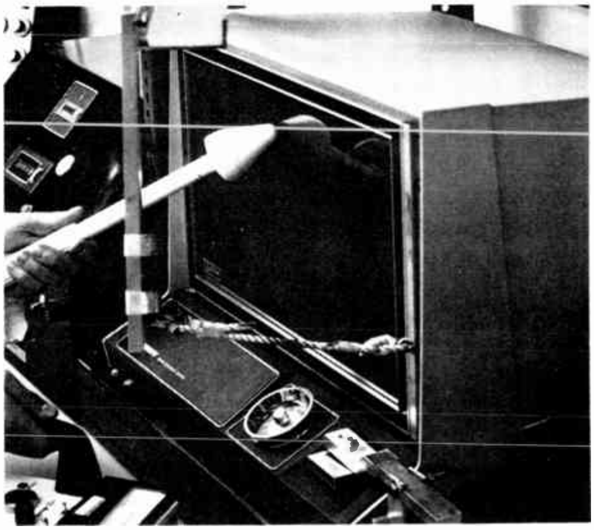
Actually, "detectable" microwave radiation is *produced* by the human body, and this phenomena could prove valuable as a medical tool to detect hidden tumors according to Arthur W. Guy, professor and director, Bioelectromagnetics Research Laboratory, University of Washington, Seattle, Wash. Because of higher temperature, tumors radiate more microwave power than normal tissues.

Nonionizing but not negligible

The term "radiation" was thrust dramatically on the public consciousness 30 years ago with the abrupt end of World War II. The intense emissions produced by atomic reactions and decaying isotopes were termed *ionizing* radiation because of their ability to disrupt the chemical bonds in stable molecules. (Measured in electron volts, the energy needed to eject an electron from a molecule of biological material [ionization potential] ranges from 10 to 25 eV.) The effects of ionizing radiation on man are cumulative, even at low levels of exposure, and generally undesirable. Exceptions would include diagnostic X rays and carefully administered high-level radiation treatments which inhibit certain forms of cancer.

By contrast, a typical quantum of microwave energy is approximately 10^{-5} eV; that cannot cause ionization under standard atmospheric conditions of temperature and pressure. As a consequence, microwaves are termed *nonionizing* radiation, but this is perhaps an oversimplification. Strong microwave transmissions and even the electric field near 100-kV, 60-Hz power lines can light a fluorescent bulb directly—sans

All microwave ovens sold in the U.S. must be examined for radiation leakage during manufacture. The Litton model 201 Minutemaster, shown here, is on a special jig that slams the door, turns the oven on, then opens the door dozens of times per minute. Litton says such ovens have withstood over half a million door slams and still operated well within U.S. safety standards.



Don Mennie Associate Editor

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spectral lines

Disconnecting from The System

In the previous issue, we recognized the growing interest of citizen groups in disconnecting themselves from society at large and its big systems. We noted that such groups seek self-sufficiency, or at least a degree of it, and in so doing expect to exploit "soft" technology. By soft technology is meant that which is not detrimental to the environment. In many cases, this is seen to equate with low or medium technology as opposed to high or advanced technology. In taking note of this trend, one wonders how much the individual citizen rebels at large-scale technology itself, as compared to the increasing limitations its embedment in society often places upon him as a consequence of its associated constraints. In any case, it is clear that the citizen need not be a traditional environmentalist to begin viewing the complicated environment in which he must operate (or merely survive) as unaccommodating or even hostile. He goes so far as to label that total environment "The System," becomes frustrated when it cannot be dealt with in a satisfactory way, and often blames technology for his resulting discontent.

In the February issue, we also addressed specific disadvantages of overconnection or overarticulation within a technically advanced society. For example, we noted that a chain reaction of events that is essentially unpredictable may occur within a system (as in a complex power distribution net) or between or among subsystems of a society (as in the case of a political or economic event triggering a crisis in fuel or electrical energy supplies).

Further elaboration on the characteristics of large complex systems would, in fairness, credit them, generally but not always, with higher efficiencies than a number of smaller systems that would deliver an equivalent output. Another plus is that larger systems may enjoy certain advantages from forced standardization.

On the negative side, large systems generate their own brand of inefficiencies, which may ultimately outweigh the aforementioned "efficiencies of scale." For example, versatility is often lost so that, even if whole chunks of a large system can be temporarily disassociated from the parent, such an isolated segment may be pretty much limited in its mode of operation. By contrast, smaller, locally designed systems that have never been linked to a larger system may feature operating modes tailored to local needs. Also, because of the broad implications of a system-wide failure, large systems may require costly support, maintenance, and backup. Even more important, a large system can be critically vulnerable to exploitation as a political or economic "tool." Consider how a strike can cripple a metropolitan transportation or communication system. Or, recall how bridgetenders threw a monkey wrench into the workings of New York City when they walked off the job, leaving drawbridges in an open position, their operating keys "missing." At a still more frightening level, large systems are vulnerable to human intervention by a *single* individual, either because they almost invariably include sensitive jobs that cannot be automated, or because vandals or political extremists can gain control of or seriously damage such a system. As an example of the former, consider the role of air traffic controllers. As an example of the latter, consider the large amounts of electric power transmitted over long distances without any adequate way of policing the lines. (Recently, a mad bomber dynamited power transmission line towers in the northwestern U.S.)

Finally, a technically advanced society may itself be viewed as a super-complex system. And as it grows, it engenders a plethora of "rules" that seem necessary to make it work, keep it reasonably stable, and maintain its myriad elements in some degree of balance. Such rules usually take the form of constraints or regulations, most of which become part of the "law of the land," or are institutionalized in some other way. As a result, systems and whole societies become "muscle-bound" and, in the extreme, virtually immobilized—unable to react with any serious degree of versatility or appropriateness to changing situations.

Thus, some futurists conjecture that, barring the unthinkable—a nuclear war that would enable the remnants of society to start with a clean slate—it is inevitable that technological development will lead to an oversize, overconnected, and overregulated society, one that grows increasingly inefficient until parts, or the whole, "grind to a screeching halt." Because there is some logic in the reasoning that leads to this unhappy conjecturing, it behooves technologists to examine carefully those aspects of society and systems design that relate to the problem areas cited. This challenge, one must hasten to add, is easy to assign; the doing is something else. In this regard, new systems being designed from scratch may benefit from time-tested rules (e.g., simple is best). One may also take a lesson from the computer field, in which the microcomputer may handle a local task, and still connect into a larger remote computer. The more difficult challenge, of course, rests with the designer who must fix, redesign, or retrofit an existing large system.

Donald Christiansen, Editor

cord or other connections!

Outside extensive communications service, heating is probably the most widespread commercial use of microwave energy. This latter application is dependent on three variables: radiation intensity, frequency, and the molecular characteristics of the irradiated material. Water, for example, absorbs incident microwave energy readily, converting it to heat.

On an atomic scale, water molecules are actually tiny electric dipoles that attempt to align themselves with the rapidly oscillating microwave field. This continuous molecular movement (kinetic energy) produces extensive, increased collisions (friction) between adjacent water molecules and thus general heating of the entire medium.

Other common substances such as glass, ceramics, chinaware, plastic, and paper are essentially transparent to microwaves since their molecules are electrically neutral at all points. Microwave ovens are much more efficient than standard ranges because of this "molecular discrimination." Energy is expended only to heat food (which typically has a high water content), while containers, cookware, and even the oven's reflective metal walls stay cool.

Operating frequency markedly affects the depth of tissue or food penetration at which microwave energy can produce heating. The majority of microwave ovens now being manufactured and used operate at 2450 MHz. The U.S. Federal Communications Commission originally assigned this frequency to diathermy equipment in 1946 based on its allegedly superior therapeutic value.

Recently, this has been criticized by Dr. Guy and others as "a classic example of how the historic lack of engineering in medicine has prolonged ill-conceived practices not only in medicine, but also in non-related industrial applications." (See *Proceedings of the IEEE*, pp. 56–57, Jan. 1974.) For medical treatments, 915 MHz was said to be "therapeutically more effective and safer in terms of leakage radiation than existing 2450-MHz equipment."

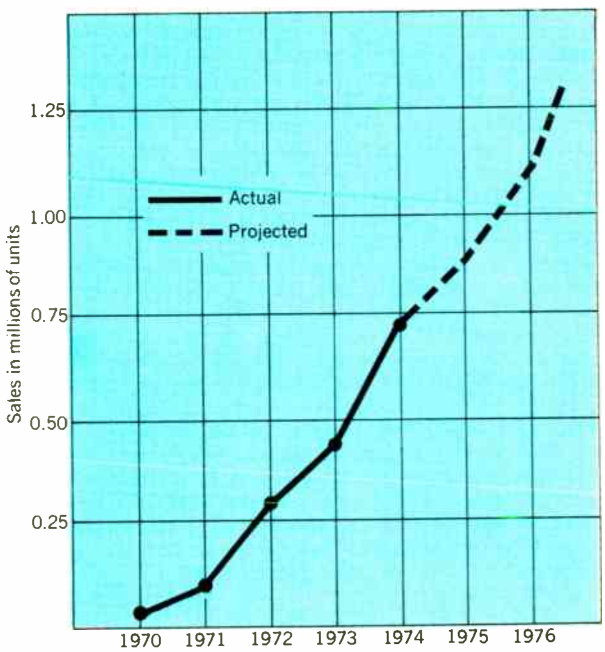
The low-level loophole

Actually, reasonable agreement exists between researchers in reporting the short-term, high-level heating effects of microwave energy, and considerable Government-sponsored research presently continues in this area. Only the most emotional and uninformed consumer advocates confuse the properties of ionizing and nonionizing radiation when discussing nonthermal effects claimed to be hazardous.

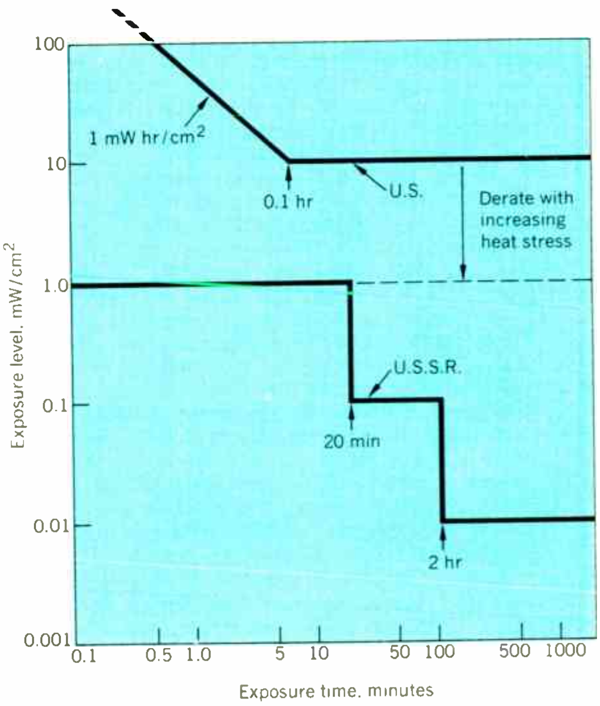
It's the world below 10 mW/cm² (the maximum permissible exposure level for U.S. military personnel and the general public) that provides opportunities for speculation and counterclaims. While many experiments have been performed, and many others continue under present funding, widely accepted, repeatable results are scarce—especially those relating to the long-term biological effects of continuous or intermittent low-level exposure.

Researchers usually don't have 20 or 30 years to pursue a project, and often end up working at levels above 10 mW/cm² simply to find some effects worth reporting. Hopefully, this will be less of a problem with work now being coordinated by the U.S. Office of Telecommunications Policy (OTP) whose objectives (as stated in its second report on the assessment of biological hazards of nonionizing electromagnetic radiation released in May 1974) include "emphasizing the study of exposures at lower power density levels, particularly over extended periods of time." Conclusions about long-term, low-level effects would not then depend on extrapolating downward readily available high-level exposure data.

[1] This projection showing U.S. industry sales of home microwave ovens was prepared by Litton Microwave Cooking Products, and released in January 1975.



[2] A comparison of whole-body exposure standards for nonionizing radiation between Russia and the U.S. illustrates the Soviets' conservative position. The U.S. curve was derived from American National Standards Institute's exposure standard C95.1, recently reaffirmed by U.S. scientists.



Where present legislative trends are concerned, one must also consider the new population now becoming operators of their very own magnetron. After all, microwave sources were long the sole province of engineers and technicians who (it was assumed) understood the dangers and could take any necessary precautions.

The passage of the U.S. Radiation Control for Health and Safety Act of 1968 recognizes the growing popularity of microwave ovens (Fig. 1) with millions of consumers—fascinated with fast cooking but totally ignorant of the accompanying technology. Legally enforceable standards for radiation from all types of consumer electronic products were tightened up considerably compared to the then voluntary 10-mW/cm²-at-5-cm emission standard chosen by the Association of Home Appliance Manufacturers (AHAM) engineers. Considering the average distance most homemakers maintain from kitchen appliances, this permits typical exposures 100–1000 times less than the 10 mW/cm² whole body irradiation allowed by the American National Standards Institute (ANSI) electromagnetic radiation exposure standard C95.1 (see box below).

Set by the U.S. Department of Health, Education, and Welfare, the new oven standards went into effect in 1971. Emissions of new microwave ovens were restricted to 1 mW/cm² measured 5 cm from any point on the oven's surface (i.e., door seals). To allow for wear, aging, and mechanical warpage, a limit of 5 mW/cm² was specified for ovens after purchase. But herein lies the basis of some serious confusion when defining radiation leakage limits: the difference between *emission* and *exposure*. Critics of the U.S. standards often point to those developed in the Soviet Union for industrial workers. On first reading, the Soviets' ceiling on microwave exposure seems much more conservative than comparable U.S. maximums.

How much, how far, how long?

Actually the two nations have exposure limits that best lend themselves to a graphical presentation (Fig. 2). Though ANSI C95.1 allows 10 mW/cm² (for moderate environments) over an unlimited time interval while Russian exposure criteria drop to 0.01 mW/cm² before abandoning time restrictions, consider what this really means in terms of the new U.S. microwave oven emission levels. (Note: C95.1 states, "Under conditions of moderate to severe heat stress the guide number given should be appropriately reduced.")

Since radiation diminishes by the square of the distance from the source, anyone working further than an arm's length from a microwave oven meeting U.S. requirements will be subject to exposure levels well below the U.S.S.R. limits! Even at close range, only a small part of the body could possibly be subject to levels approaching the 5 mW/cm² maximum. *Consumer Reports* failed to explain these details carefully

A level argument

Most experts give a green light to the U.S. radiation standards for consumer products. Responding to *Consumer Reports'* April 1973 microwave oven article, the IEEE Committee on Man and Radiation (COMAR) released a statement that said, "Consumers Union condemned the U.S. microwave emission standard without consulting those in the scientific community who could justify and explain the current standard." The COMAR statement also claimed that the requirement for ovens to emit no detectable leakage "indicates that the author of the article does not understand electromagnetic waves, their sources, or their methods of detection." And although COMAR agrees with the need for an emission standard on all microwave ovens, it concludes, "The vast body of scientific literature in this field shows no evidence of physical damage to humans if exposed to 10 mW/cm², much less 1 mW/cm²."

Indeed, the U.S. Consensus Standard on microwave exposure safety limits prepared by the American National Standards Institute (ANSI C95.1) was reaffirmed in 1973 after two years' deliberation by the scientific community. According to ANSI C95 committee chairman and associate professor of electrophysics at Polytechnic Institute of New York Saul Rosenthal, some modifications were made in the editorial content (i.e., ". . . thermal effects are considered to be the most harmful and therefore have been used as the basis for establishing the levels in this standard") but the "numbers" were unaffected. The latest version of ANSI C95.1 says, "For normal environmental conditions and for incident electromagnetic energy of frequencies from 10 MHz to 100 GHz, the cw radiation protection guide is 10 mW/cm² and the equivalent free-space electric and magnetic field strengths are approximately 200 V/m rms and 0.5 A/m rms, respectively." For modulated fields, the power density and the squares of the field strengths are averaged over any 0.1-h period. . ." (the result should also be under 10 mW/cm²).

Research on low-level nonionizing radiation effects is by no means limited to the United States. Studies of low-level microwaves in the Soviet Union seem to indicate that subjective behavioral factors such as concentration and irritability are the proper barometers, not tissue damage. Some of this work has been criticized by U.S. scientists because the published accounts do not give enough detail for others to repeat the experiments. In one of the few instances where duplication has been attempted (see *IEEE Transactions on Microwave Theory and Techniques*, pp. 168–173, Feb. 1971), negative results were obtained, indicating that some of the effects reported by the Soviets might have been chance variations.

The question of exposure to nonionizing radiation is actually much larger than a single concern for the emissions of microwave ovens (as implied at the beginning of this article). But like it or not, the ovens provide a widely available, tangible example that everyone with an opinion can lay their hands on. Most of the emotion involves disagreement on just exactly what constitutes a "safe" level of exposure.

Those who find complete satisfaction with the present U.S. standards might well consider a short paragraph buried back on page 4 of a technical bulletin released by the Departments of the U.S. Army and Air Force in December 1965. Identified as TB MED 270/AFM 161-7, the booklet lists the biological aspects of electromagnetic radiation. Under the heading "Unexplained response of man to radar," it is mentioned: "Epigastric distress and/or nausea may occasionally occur at as low as 5–10 mW/cm² and are most commonly associated within the frequency range from 8×10^3 to 12×10^3 MHz." Something to think about. Few have as much experience with microwaves as the military.

in its April 1973 microwave oven survey, resulting in the implication that allowable oven leakage in U.S. homes (5 mW/cm^2) would result in "exposures" 500 times higher than the Soviet 0.01-mW/cm^2 limit. This error was noted in a followup item on microwave ovens in the August 1973 *Consumer Reports*.

Assumptions here are that the oven's door seals are not blocked with wax paper or food spatters, and no attempts have been made to defeat the interlocks that prevent oven operation when the door is opened during the cooking cycle.

Definitions but not détente

If these simple misunderstandings were the only issue, microwave oven critics would have soon mellowed to the thought of roasts routed from freezer to table in half an hour. However, several debates still continue—most notably those concerning new warning label requirements, reported biological effects from low-level irradiation in some laboratory experiments (behavior changes and nervous system reactions), and the potential for microwave energy to cause cataracts.

Probably the most outspoken opinions on the long-term effects of high-frequency nonionizing radiation in general and microwave ovens in particular can be attributed to the New York-based ophthalmologist, Milton M. Zaret. He has testified at U.S. Senate hearings and written several articles—including one for the July 1972 *IEEE Transactions on Biomedical Engineering*—which attribute certain types of human eye cataracts to repeated low-level microwave exposure.

Neither the testimony nor the *Transactions* article has gone unchallenged. Senate testimony counter to Dr. Zaret's position has been presented by scientists such as Dr. Guy, University of Washington, and Budd Appleton, chief, ophthalmology service, Walter Reed Army Medical Center, Washington, D.C. In February 1974, Paul E. Tyler, Commander MC, U.S. Navy and head of the electromagnetic radiation project office, Naval Medical R&D Command, Bethesda, Md., gave critical review to Dr. Zaret's *Transactions* material during an opening address of the New York Academy of Science Conference on "Biological Effects of Nonionizing Radiation."

Where microwave-induced cataracts are concerned, the bulk of experimental evidence thus far implicates only high-level exposures—sometimes an hour or more in duration. At exposure levels above 200 mW/cm^2, heating causes eye protein to cloud, much like a cooking egg white (the process is irreversible). However, opacity "threshold" levels of 120–150 mW/cm^2 can cause more subtle effects (lens banding) that take days or weeks to appear. Existing exposure standards have been basically determined from observing animal tissue damage due to temperature rise. It should be noted that the eye lens is poorly cooled by blood circulation and therefore more subject to injury than muscles or skin.

The bulk of Dr. Zaret's clinical evidence is drawn from his experiences with about 50 microwave trouble-shooters working in aerospace-oriented industries. Despite many challenges, he maintains his patients' cataracts are directly related to microwave exposure. A recent chapter of this exchange appears in the October 1974 issue of the *New York State Journal of Medicine*.

What begins as a two-page case history outlining the formation of cataracts in a 51-year-old housewife—cataracts attributed to a microwave oven leaking 1–2 mW/cm^2 when operating and (briefly) up to 90 mW/cm^2 upon opening the door—unfolds into 15 consecutive pages of reviewers' comments (pro and con), plus extensive elaboration and rebuttal by Dr. Zaret, author of the initial report. Even the journal's editor was inspired to include a special half-page editorial on the subject.

Some of the strongest rebuttals of Dr. Zaret's conclusions were submitted by other ophthalmologists. David D. Donaldson, associate professor of opthalmology, Harvard Medical School, Boston, Mass., replied, "After having thoroughly evaluated Dr. Zaret's report my conclusion is that the patient has a presenile type of subcapsular cataract which is commonly seen in individuals exposed to no radiation. Furthermore, there is no evidence that she was exposed to a hazardous amount of microwave radiation. Thus, in my opinion, the cause and effect relationship is totally unfounded and represents an erroneous and dangerous conclusion."

In another sharp response, Dr. Appleton, of the Walter Reed Army Medical Center, said, "The question of whether human cataracts can be caused by chronic exposure to microwaves at low levels has received a great deal of attention in the last five years. The article by Dr. Zaret purporting to cite an example of this occurrence presupposes that the answer to this question is 'yes'. All the clinical survey data and all the experimental data, however, appear to indicate that in fact the answer is really 'no'."

What is COMAR?

Organized in October 1972, the IEEE Committee on Man and Radiation (COMAR) is concerned mainly with the biological effects of electromagnetic radiation, particularly (but not only) on man. Members collect existing information, filter it, and present it in an authoritative manner. The committee does *not* undertake research programs to discover new knowledge or set safety standards. The public in general, and nontechnical people in executive positions in particular, form COMAR's target audience.

Whenever necessary, committee members—or the committee as a whole—attempt to correct false or misleading published information by sending letters of rebuttal (in refuting the *Consumer Reports* microwave oven article, a special press conference was held and an official statement was issued). But COMAR's activities do not stop here.

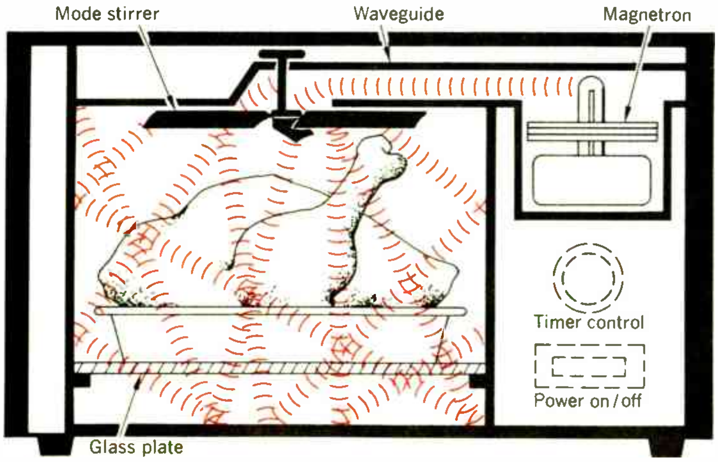
Recently a potato farmer living next to the Grumman Aerospace plant in Calverton, N.Y., claimed he suffered cataracts as a result of exposure to Navy radar at the plant. COMAR offered its services to the individuals involved with the problem. And in Mahwah Township, N.J., local residents protested the installation of a microwave relay tower due to an alleged radiation hazard. COMAR member William Mumford reviewed the pertinent technical data and reported his findings to a Township Board of Adjustment hearing on September 11, 1974.

Supplying his own calculations of exposure levels, Russell L. Carpenter, professor of zoology emeritus and former director, Microwave Radiobiology Research Laboratory, Tufts University, Medford, Mass., concluded that "although we cannot as yet say how much radiation constitutes a cataractogenic exposure . . . , in the case presented here by Dr. Zaret, the low-level radiation and the very brief exposures could not have been harmful to his patient's eyes." George R. Merriam, Jr., of the Institute of Ophthalmology, New York, N.Y., explained that, at his institute, pre- and postoperative microtherm treatments at 2450 MHz are commonly used on human eyes. "The usual dose is about 100 mW/cm^2 for 20 minutes, and treatments are often given twice a day for up to two weeks. No adverse effects have been seen."

Support for Dr. Zaret came from a French ophthalmologist, Joseph A. Bouchat, professeur Agrégé du Val-de-Grace, Paris. Dr. Bouchat outlined his own experiences with a patient where nonionizing radiation was suspected of causing cataracts. He also commented on the problems of observing and identifying cataracts, particularly the "capsular" type thought related to microwave exposure, but concluded "thanks to those very precise observations of Dr. Zaret, the classification of cataracts due to nonionizing radiation will soon be perfectly established."

Oven manufacturers often quote another expert, James A. Van Allen, professor of physics, University of Iowa, whenever the subject of microwave safety crops up. Dr. Van Allen's statement—"In my judgment the [microwave oven] hazard is about the same as the likelihood of getting a skin tan from moonlight"—appears frequently in industry literature. He goes on to claim: "There is not a shred of scientific evidence that microwaves at such low intensities [allowable leakage] have any effect whatever on human health—even for indefinitely prolonged exposure." True enough that such evidence does not exist, but it is also true that research is incomplete in this area.

Unlike conventional cooking, which involves a careful tradeoff between time and temperature, time is the major factor in operating a microwave oven. The magnetron is either "on," delivering full-rated output to the oven cavity, or it is "off." Essentially all the available microwave energy is absorbed by the food load—regardless of size. For example, two potatoes will take about twice as long to cook as one potato. The mode stirrer breaks up the magnetron's output so all parts of the oven cavity (and therefore the food) are evenly irradiated.



It will probably take a well-funded, exhaustive, long-term investigation to resolve the arguments fully. In defending his findings, Dr. Zaret explains, "The vast majority of animal [nonionizing radiation] experiments of necessity are contrived and represent relatively immediate results of acute exposures. On the other hand, most human pathology is the consequence of delayed effects following chronic exposure. In this regard, the ocular radiational burn of the animal experiment, a thermal effect, is seldom seen in man."

Research or rationale?

Nervous system and behavioral reactions are among the biological effects of electromagnetic radiation currently under investigation through the sponsorship of several Federal agencies in the U.S. This work is being coordinated by the U.S. Office of Telecommunications Policy with the assistance of its Electromagnetic Radiation Management Advisory Council (ERMAC), which recommended the need for this research. Besides the commitment to investigate low power density effects mentioned earlier, a stated purpose of this cooperative undertaking is "to ensure the well being of man and his environment without unnecessarily restricting his use of the electromagnetic spectrum and the many benefits it provides." At an informal ERMAC workshop held October 31 and November 1, 1974, in Washington, D.C., researchers gave a brief assessment of their individual projects on nervous system and behavioral effects and answered questions from workshop participants.

Much of the discussion centered on effects observed at energy densities far above the normal leakage from any microwave oven. Several investigators reported studies and observations at relatively low power densities. For example, John Thomas of the Naval Medical Research Institute, Bethesda, Md., did report definite low-level effects on carefully trained laboratory rats. Food was available to them only after performing numerous timed operations of special levers. Dr. Thomas' rats showed considerably less ability to concentrate on the complex task when exposed to only about 10 mW/cm^2 of microwave energy. However, all animals showed complete recovery when the field was removed. Frank S. Barnes, chairman, Department of Electrical Engineering, University of Colorado, indicates that scaling problems prevent a simple extrapolation of such experimental results to man.

Other experimental work (a project that noted brain cell changes in hamsters under 10- to 50-mW/cm^2 exposure) was described by Mark DeSantis from the Department of Anatomy, Georgetown University, Washington, D.C. Dr. DeSantis appeared in place of his colleague and senior research partner, Ernest Albert, of George Washington University, Washington, D.C. These researchers report changes in the cytoplasm of hypothalamus brain tissue as evidenced by the tissue's reaction to standard staining techniques. Positive results have been noted at two frequencies thus far: 1.7 and 2.45 GHz. Irradiations at 3 GHz have yielded negative results, but all experiments at this higher frequency have not yet been completed.

A significant problem for all those engaged in such research is dosimetry. How reliable are the field strength measurements and—more important—how much incident or re-reflected energy is actually being absorbed by the animals under test? Because their physical size approximates certain very short wavelengths, small animals can absorb lethal amounts of energy from microwave fields which would not cause noticeable harm to man. Such was the case with some of the hamsters exposed to about 50 mW/cm^2 by Drs. Albert and DeSantis.

A description of microwave measurement problems was recently provided in *Environmental Health Perspectives*, vol. 8, pp. 133–156, 1974, by Sol M. Michaelson, professor, Department of Radiation and Biophysics, the University of Rochester School of Medicine and Dentistry, Rochester, N.Y. Dr. Michaelson explained,

"It is not always possible to use generally accepted electrophysiological methods in studying the influence of microwave fields on the organism, since the sensors (electrodes, thermocouples, etc.) can act as receiving antennas so that substantial high-frequency voltages are induced in them during irradiation. These voltages may give rise to secondary, but sometimes very strong, stimuli ranging up to thermal coagulation of protein tissues. Unfortunately, investigators have at times overlooked this fact.

"In the performance of experimental studies on animals, it must be remembered that the changes in the organism depend to a major degree on the geometric dimensions of the animals, owing to the depth of penetration of microwave energy which varies with wavelength."

In fact, it is recognized that the presence of a metal probe or any wires in tissues irradiated with microwaves can cause effects that would not have occurred if such sensors were absent. An important development by Dr. Guy which should overcome this problem is an electrolyte probe transparent to microwaves. Instead of wires, a tube filled with conductive fluid approximating the characteristic impedance of animal tissue is used to monitor nervous reactions or body functions during exposure. Probe connections are made with high-resistance plastic leads.

Tome on a tag

Critical assessment of the potential hazards attributed to microwave ovens is not limited to research or scholarly debate. On December 12, 1973, the U.S. Food and Drug Administrations's Bureau of Radiological Health (BRH) held a meeting on the content and physical placement of microwave oven safety instructions. The main issue was a petition proposed by Consumers Union that oven warning labels be mandatory and owners' manuals be amended.

In a prepared statement, Carol A. Cowgill, a Consumers Union attorney, outlined the proposed changes to help consumers avoid "any and all levels of microwave radiation." This approach is basically in disagreement with the concept that instructions to minimize exposure are unnecessary if an oven emits less than 5 mW/cm^2, the BRH maximum. The Consumers Union proposal outlined about a half-dozen desired features for a proposed warning label including: (1) a warning against operating microwave ovens empty; (2) instructions to unplug after use to avoid inadvertent operation; (3) a warning to individuals with pacemakers; (4) specific notes on the importance of clean door seals unhampered by dirt or paper towels; (5) the importance of keeping one's face away from the door while the oven is operating; and (6) a clear statement that children not be permitted to operate a microwave oven. While some of these points are covered in instruction manuals, Consumers Union felt they should be a permanent part of the oven that cannot be overlooked or lost.

Concern for pacemaker wearers is attributed to certain types of older implants that were sensitive to external electromagnetic fields. Newer models are reportedly unaffected by such radiation and have been placed inside operating microwave ovens to illustrate immunity from interference.

Proposed additions to instruction manuals were even more detailed than the warning label petition. Consumers Union wants a summary of suspected long-term low-level microwave effects still under investigation, coupled with an easily understood explanation of the inverse square law phenomenon made available to all oven purchasers.

Manufacturers have some sharply contrasting opinions on this topic, and their position was summarized by Richard V. Prucha, chairman of the Association of Home Appliance Manufacturers (AHAM) technical committee on microwave ovens. He felt one of the first principles ought to be simplicity. Underlining a concern that people will not read or remember involved detail, Mr. Prucha quipped, "I am tempted to remind you of the Ten Commandments if you want an example of how well people remember lists."

Esthetic considerations were also mentioned. "Appliances are considered part of the decor, and not part of the library in our society," claimed Mr. Prucha. "At times, instructions for use appear on the products, but when they do, first priority for available space must go to functional instructions. The best place for precautionary instructions is in the users' manual."

Some ground was given on the subject of printed information. The AHAM speaker did present guidelines that would place important warnings within the first ten pages of the users' manual. In summary, Mr. Prucha claimed that mandatory labeling was not only unnecessary, but potentially misleading. Equally important warnings mentioned only in the owners' manual might be ignored.

A final decision on mandatory labeling and owners' manual revisions is expected very soon from the U.S. Food and Drug Administration. Based on Consumers Union and AHAM inputs, the BRH published its own proposal on the subject in May 1974 and, in the months since, has collected final comments from all concerned parties and has begun the task of evaluating each. The legally binding recommendations evolving from the effort will most likely contain the requirement for a warning label on all microwave ovens. But the text will be tempered considerably from the original Consumers Union proposals. ◆

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Cash crunch dims power prospects

Money doesn't buy what it used to, an inflationary fact that's set back the utilities' expansion programs by years

Hard times have hit the power industry—and the electric utilities are having a difficult time hitting back. Evidence of this is everywhere. Consumer rates are soaring as most utilities and the public service commissions that regulate them engage in a frantic game of leapfrog—new rate-hike requests following hard on the heels of rate-increase approvals . . . sometimes even before the approvals are handed down. Utility issues, once among the bluest of the blue-chip, are today often less attractive than Federal and municipal bonds. And most worrisome of all, a flood of recent utility reports detail massive curtailments of planned capital expansion: according to the most recent data gathered by the National Electric Reliability Council, Princeton, N.J., 72 000 MW have been trimmed from a total of 510 000 MW of new capacity planned in early 1974 by the U.S. utilities for the decade running through 1983.

The consequences of these utility debilities are potentially awesome: beyond skyrocketing rates, the next decade is likely to see a decline, particularly within the territories of the hardest-hit utilities, in power system reliability. Enforced financial austerity may cause certain utilities, for example, to avoid updating existing (and sometimes ancient) transmission, distribution, and switching equipment. Similarly, substation equipment—transformers, circuit breakers, surge arresters, etc.—is likely to be slighted when modernization becomes an added economic burden. And while the average efficient serviceable lifetime of a conventional fossil-fuel generating station is about 30 years, many U.S. generating stations in their "late 40s" are still putting power on the line. (This fact becomes doubly significant in light of the construction cutbacks just mentioned.) It is not surprising then that many utility planners are warning of the possibility of electricity shortages—brownouts and blackouts—by 1980!

The U.S. power industry is in no way monolithic, however. The individual financial pictures of the electric utilities vary widely depending on:

- Their fuel mix—are they primarily dependent on oil, coal, gas, or hydro?
- Their charters—are they investor-owned, Federal, municipal, or Rural Electrification Administration (REA) systems?
- Their particular local requirements—what percentage of their revenues must be devoted to transmission and distribution and what level of load-growth rates can they expect to experience?
- Their management efficiency—obviously, the most difficult of the group to quantify.

Bearing this in mind, *Spectrum* surveyed utilities in every category throughout the U.S.

Ellis Rubinstein Associate Editor
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An American tragedy

Among the investor-owned electric utilities, none is suffering more than New York's Consolidated Edison. Serving not only the largest city in the U.S. but also neighboring Westchester County, Con Ed has had to deal with nearly all of today's utilities' problems in combination. As an oil-dependent utility, it has paid the fourfold price increase following the Arab oil embargo—and when it wanted to switch to coal, it was prevented from doing so by local pollution standards. Further, it must maintain the largest underground cable transmission and distribution system in the U.S. As a New York City and State resident, it must contend with not only the highest inflation rate in the country, but also the steepest tax structure. And, although Con Ed mounted a new generating plant program a decade ago—one that was to replace 90 percent of its 1967 existing capacity—seven years later a combination of adversities have left it to rely on a number of plants that Thomas A. Edison probably visited 50 years ago.

No wonder then that last year the giant utility was reduced to skipping a quarterly dividend for the first time since 1885. Further, two of the three remaining dividend payments were pared by more than 50 percent. And with a "coverage ratio" (see the box on p. 42) of 2.3 or less, there is little or no hope that Con Ed will soon be able to float a successful bond issue, much less issue new stock.

Nevertheless, the future for Consolidated Edison is not *entirely* bleak. Surprisingly, thanks to (1) the $500 million sale of a nuclear and a fossil-fuel plant to the Power Authority of the State of New York (PASNY) and (2) drastic trimming of its capital budget (from $641 million to about $347 million), Con Ed may not need to sell any common stock—even if it could—for two years.

A rather different perspective on utility financial problems can be gained by studying the case of Connecticut's Northeast Utilities. Like Con Ed, Northeast has been hard hit and its price-book ratio (see the box on p. 42) shows it. While unity is considered a prerequisite to raising new capital through bond and stock issues, Northeast's price-book ratio in 1974 had declined to a sickly 0.55. For purposes of comparison, Con Ed's price-book ratio was a disastrous 0.20 (lowest in the nation), and the national average for investor-owned utilities was 0.76—well below unity but well above Northeast's.

Speaking before Senator Henry M. Jackson's (D-Wash.) Senate Committee on Interior and Insular Affairs, Northeast's president, Lelan F. Sillin, Jr., laid a large part of the blame for his utility's weak financial condition on what he termed New England's historical economic position—"the fact that it is at the end of every energy supply line . . ."

Be that as it may, Northeast, like the vast majority of U.S. utilities, faces the near-term need for mammoth expansion, conservation or no. Says President Sillin, "The Northeast Utilities system, at present, represents an investment of about $2 billion. The capital program which we think is required to protect the public interest would aggregate some additional $3 billion during the next five years and potentially $6.25 billion over the next ten years."

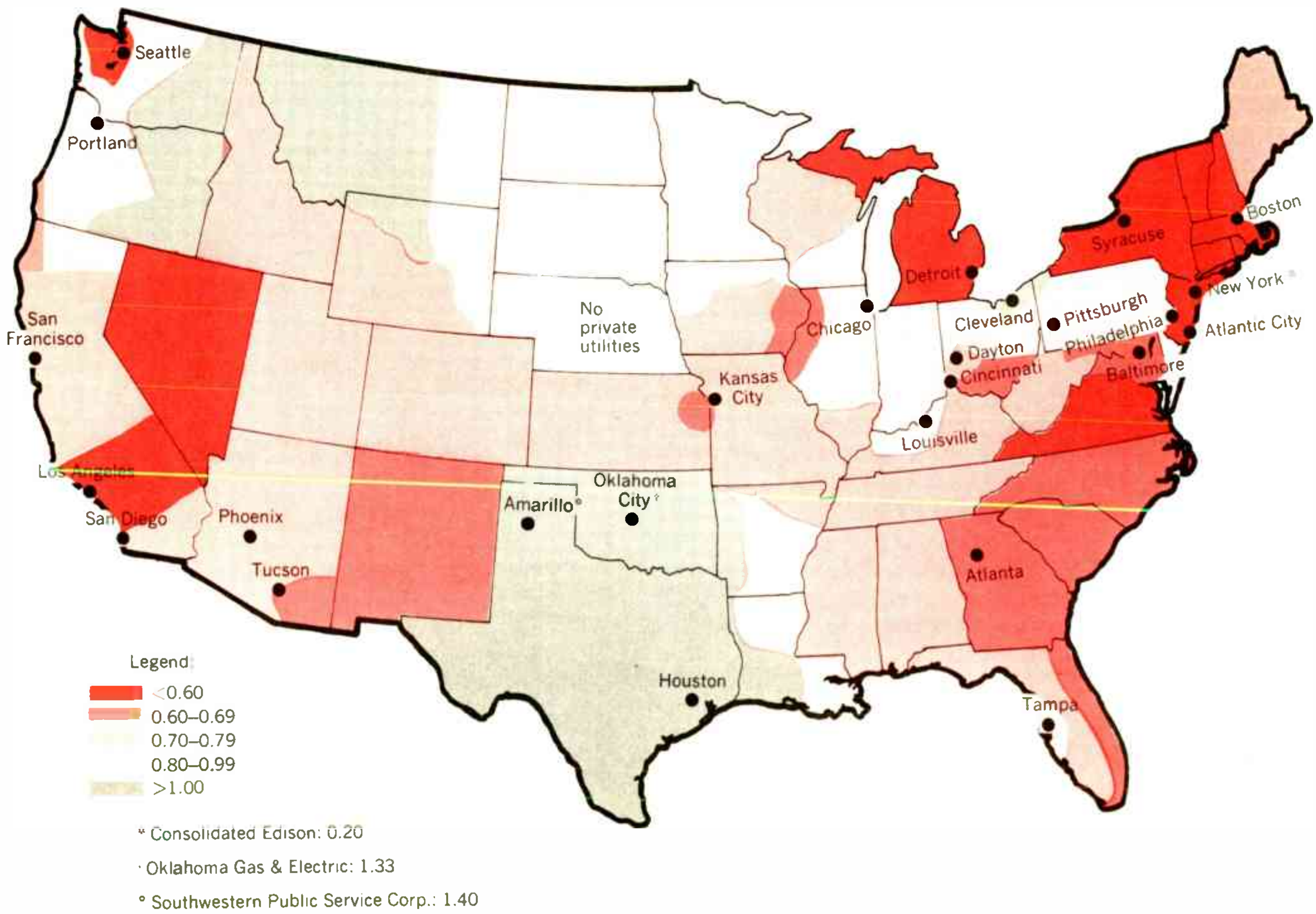
Of these dollars, Mr. Sillin expects 60 percent to be spent on nuclear facilities. He estimates that the completion of such a program would save 58 million barrels of oil (or $250 million) a year.

Clearly, the objective is worthwhile, but with new nuclear plants far more capital-intensive than conventional plants, how can a utility in Northeast's financial position expect to raise the required funds? The answer, of course, is that it can't, and this accounts for the massive cutbacks already described.

The kinds of problems being faced by New York's Consolidated Edison and Connecticut's Northeast Utilities are common, in greater or lesser degree, to nearly every investor-owned utility in the northeastern U.S. Public Service Electric and Gas (PSE&G) of Newark, N.J., was, in January 1973, one of only two of 93 U.S. utilities (Con Ed was the other) to report a price-book ratio below 1.00. The decline of that ratio continued from 0.98 to 0.53 by June 1974 (currently, about 0.62), and PSE&G, according to John Casazza, vice president in charge of planning, has recently decided to curtail $1 billion of both near- and long-term construction budgeted for the next five years. Similarly, Boston Edison's price-book ratio swiftly dropped from an acceptable 1.19 in January 1973 to 0.50 in June 1974, and Niagara Mohawk Power, the company whose Messina, N.Y., plant is soon to be bought out by its customers in a consumer revolt, reported the third worst return on common equity (see the box on p. 42) for the year 1973 (7.57 percent compared with the national average of 11.16).

But all of these northeastern U.S. utilities share

The financial woes of the U.S. power industry—based on the price-book ratios of 90 electric utilities listed on the New York Stock Exchange in June 1974. Note that when a utility's price-book ratio is less than 1.00 (all red shadings), the utility has a strong financial incentive *not* to invest equity capital. Further, the average price-book ratio of those utilities represented is 0.76 ("deep in the red"). Finally, it should be mentioned that the boundaries on the map are only approximations: the Federal and municipal systems are not included nor are about 180 private utilities (generally small ones) that are not listed on the "Big Board." (The Alaskan utilities fall in the latter category and Hawaiian Electric is doing reasonably well—0.97.)



the unenviable burden of being primarily dependent on oil. What of the coal-burning utilities?

King coal and the investor-owned utility

A sampling of coal-based investor-owned electric utilities shows a mixed picture. In general, these utilities are better off than are the oil-burners in the Northeast—but, like the price of oil, the price of coal also has risen dramatically (from in the neighborhood of $0.17 per million kJ less than a decade ago to as much as $1.23 per million kJ today). There are several reasons for coal's skyrocketing price, according to Donald Cook, head of the coal-based giant holding company, American Electric Power (AEP). Primarily, there was the decision on the part of the Federal government to permit the coal producers to export high-quality coal to Japan to feed its steel industry. In combination with environmental and other government policies that tended to discourage the development of new domestic mines, this exportation increased the ratio of demand to supply and the price of coal quickly doubled. Since then the price of coal has risen exponentially along with, first, the general economic inflation and, most recently, the Arab oil embargo, which led to another leap in demand and resultantly exorbitant spot-shortage prices.

How does all of this apply to AEP's particular financial situation? The acquisition of captive coal mines in West Virginia and ranch land for eventual strip-mining in Montana have made the utility's chairman optimistic about the future. But for the present, AEP has had to cancel 5000 MW of planned capacity while its price–book ratio dropped sharply from 1.60 in January 1963 to 0.89 by mid-1974.

Throughout the rest of the coal-based utility industry, the range of financial solvency is great. At the lower end of the spectrum is Carolina Power and Light (CP&L), a company whose price-book ratio, at 0.63, has fallen well below the already low national average. One consequence to the utility has been the decision to postpone development of two steam-electric generating plants involving two 720-MW coal-burning units that had been scheduled for operation in 1979 and 1980, as well as three 1150-MW nuclear plants planned for the mid-1980s. Said CP&L president, Shearon Harris, the changes were necessary because, with declining utility earnings, investors are unwilling to provide sufficient new capital on reasonable terms. He further noted that CP&L's generating reserves at times of peak load are now expected to fall below 7 percent by 1980. The implications in this forecast are serious: CP&L believes the quality and reliability of its service, particularly in the event of unscheduled outages, could well be adversely affected and the company has further warned its customers that, should loads develop more rapidly than forecast, "restrictions on new loads and other measures may need to be imposed."

Thus, for the customers of at least one coal-using utility (and there are others—Detroit Edison and Consumers Power, both of Michigan, for example), electric shortages by 1980 are as possible as they are in the inflation-wracked Northeast.

Meanwhile, the picture for the customers of several other "coal eaters" seems less bleak. In Chicago, for example, although the consumer is paying more for his electricity, the rate increases have been below the national average. At the same time, the potential investor in Commonwealth Edison, the utility that services Chicago, must be attracted by the company's surprisingly strong coverage ratio—currently above 3.0, permitting the utility to float more bond issues.

Why is Commonwealth Edison doing so well (comparatively)? A company spokesman told *Spectrum* that a major advantage is the company's diversity of

Glossary of fiscal terms

Although few engineers are economists, the present economic crisis is forcing practitioners of our profession to understand some of the financial terminology that is being bandied about not only in *The Wall Street Journal*, but also in engineering trade magazines and professional journals. Here are some that the reader will meet often in the article at hand.

Coverage ratio. This is the ratio of income (before payment of interest and taxes) to interest obligations on outstanding bonds. If the coverage ratio dips to 2.3 or below, the utility is approaching a limitation preventing it from selling additional bonds.

Return on common equity. Common equity is the investment in plant capital made by the utility. The rate of earnings on this invested capital is fixed by regulatory agencies. Usually, the allowed rate of return on common equity is 12 percent.

Price–book ratio. The price–book ratio is the ratio of the current selling price of a company's common stock to its book value. The book value is derived from the common equity (see above), which is simply the total capital investment in plant less accumulated depreciation, divided by the total number of shares of stock that have been issued.

Thus, for example, suppose a utility's stock is selling at $20 per share, the utility's common equity (capital investment) has reached $200 million, and its number of shares outstanding is about 10 million. The ratio of the price of a share ($20) to the book (which is common equity divided by total shares, or $20) is therefore 1.00.

But what is the purpose of computing a utility's price–book ratio? Inasmuch as investment in plant is of major importance to utilities, the resultant figure is a useful, if arbitrary, indicator of a utility's financial health. Specifically, as long as its ratio remains above 1.00, a utility is considered to be in a good position to raise new capital, but once the ratio drops below 1.00, the utility has a greater incentive to cut back on future capitalization than to raise new capital.

This can be seen by considering the hypothetical company already referred to. Suppose it wishes to raise additional capital. If it requires $40 million, it would have to issue 2 million new shares of stock —assuming investors have enough confidence in the company to continue to pay $20 per share. The result of such an action on the company's price–book ratio would be to maintain it at a healthy 20 ÷ (240M ÷ 12M) = 1.00.

However, suppose that for a variety of reasons (a declining stock market, declining corporate profits despite higher rates, etc.), the new investors lacked confidence in the utility and would only pay $10 per share. In that case, the utility would be forced to issue 4 million new shares and the price–book ratio would decline: 10 ÷ (240M ÷ 14M) = 0.59. This, of course, would be an extreme case of investor confidence loss, but it shows how the price–book ratio can change.

customers—city, suburban, farm, commercial, and residential. This diversity permits the utility to hedge its load-forecasting bets. If unanticipated conditions change load requirements in one customer segment (an industrial recession, for example), the load requirements may still remain relatively stable in other segments (residential and farm, for example).

Nevertheless, the company, like so many less fortunate utilities, has decided it must defer construction on a 7700-MW nuclear plant and on two 500-MW coal-fired plants—a decision based not only on high fuel and construction costs, but also on a recession-influenced decreased load-growth forecast.

Similar tales of woe were recently told by Jack K. Busby, president of Pennsylvania Power & Light, and John G. Quayle, president of Wisconsin Electric Power. Speaking before the U.S. Senate Committee on Interior and Insular Affairs, Mr. Busby explained that PP&L has had to "cut back for the 1980s by 4000 MW or about 43 percent" of its planned new capacity. And, at the same forum, Wisconsin Electric's Quayle, while not mentioning any recent construction cutbacks, lamented that the company had recently sold 1½ million shares of common stock at a price of $21⅛, 14 percent below book value of $25.40. "Under any but present-day conditions," Mr. Quayle added, "this sale at below book value would be regarded as an indication of extreme financial weakness." (Interestingly, while Wisconsin Electric Power is primarily a coal user, an unusually high 40 percent of its *present* capacity is nuclear generated.)

But lest the reader think that coal users are all suffering substantial financial difficulties, it should be noted that of the 11 utilities (out of 93) who had managed to stay above unity in their price-book ratios as of June 1974, four are primarily coal-based. These are: Cleveland Electric Illuminating Co., Montana Power Co., Ohio Edison Co., and Public Service of Indiana.

Who's alive and kicking? Gas and hydro . . .

Of the remaining seven utilities above unity in price-book ratio, nearly all are natural-gas users in the Southwest. A good example is Texas Utilities. The company boasts a price-book ratio of 1.14, third highest in the U.S. Its 1973 year-end return on common equity was a healthy 12.99, well over the national average. And with a whopping $1½ billion new construction program to be implemented in the next three years—or 40 percent of its current total capital investment—the utility has not yet announced cutbacks (though it is currently reviewing its projections of load-growth and financing requirements).

Despite all this, Jerome S. Farrington, Texas Utilities vice president, told *Spectrum* that he didn't want to leave the impression that all is rosy in Dallas. Though still below the national average, the utility's rates have been forced up by the inflationary conditions besetting everyone. Furthermore, the era of plentiful and inexpensive natural gas is rapidly coming to an end and so Texas Utilities has determined to decrease its present near-dependence on that resource. (Currently representing only 20 percent of Texas Utilities resource mix, low-sulfur lignite coal from captive coal mines, along with nuclear, is to be the primary fuel of the 1980s.)

But if these are problems, everyone should be as fortunate. There are probably no more than a handful of utilities in the U.S. that can report, as does Texas Utilities, that their capitalization ratio includes only 50 percent debt (along with 35 percent equity and 15 percent preferred). Even the Tennessee Valley Authority has gone over 50-percent debt capitalization! Says Texas Utilities vice president Farrington, the company's conservative financial policies (in dividend payout, normalized accounting procedures, and capitalization ratios) have contributed to the utility's relatively satisfactory financial position. But Texas Utilities has benefited at least as much from the historically favorable conditions in its service area as it has from skilled management. To put it another way, had there been vast reservoirs of natural gas several thousand feet beneath the Empire State Building, even Con Edison might be doing well today.

In much the same way, hydroelectricity has bolstered the finances of the investor-owned utilities in the Pacific Northwest. Take Pacific Power & Light, probably the most successful of the group. Located in Portland, Oreg., and serving 240 communities in the states of Oregon, Wyoming, Washington, California, Montana, and Idaho, PP&L shows a price-book ratio of 1.01 and a return on common equity well above the U.S. average. With a huge percentage of its total energy resource requirements currently met by hydro, PP&L has been effectively insulated from the financial ravages of inflated coal and oil prices, and, thanks to the unique cooperation and coordination among the entire region's public and private utilities, PP&L benefits from coordinated, efficient planning, construction, financing, and transmission.

Nevertheless, despite all of these advantages, PP&L chairman and chief executive Don C. Frisbee has deep concern about the utility's future status. Speaking to the previously mentioned Senate Committee on Interior and Insular affairs, Mr. Frisbee said of the Pacific Northwest in general:

"We are moving from very-low-cost hydropower to high-cost and complex nuclear and fossil-fuel-fired steam plants where the cost of the new power at the new plant's bus bar exceeds the price which the present rates produce at the retail level. And of course the bus-bar power cost is before adding any costs associated with transmission, distribution, customer services and billings, and other general costs. To put it somewhat technically, the marginal costs of power in the Pacific Northwest now exceed marginal revenues, and the gap is widening."

There is one further factor of especial significance to the Pacific Northwest—the influx of new customers. Perhaps no region of the U.S. has a greater immediate potential for growth—both in population and industry—and this means that massive capitalization is necessary precisely when it is most expensive!

Public power

Any survey of the financial state of the power industry would be incomplete without a discussion of the public power systems, which, in 1970, were generating nearly one quarter of the total U.S. electricity. About 12 percent of the U.S. total is generated by five separate Federal agencies that market their power through 40 Federal systems. By far the largest are the

Tennessee Valley Authority (TVA) and the Bonneville Power Administration (BPA). Although it is impossible to utilize investment criteria to determine the health (or lack of it) of Federal power systems such as TVA and BPA, one can discuss costs, rates, and capitalization.

In the case of Bonneville Power, Gene Starr, a consulting engineer for the utility, noted that nothing better evidenced the traumatic change in BPA's financial status than the 27-percent rate hike—the first in ten years!—handed down to customers last year.

Unlike BPA, which is primarily hydro-oriented, TVA is now 75-percent coal-using. Nevertheless, TVA's situation is strikingly similar. Having never required a consistent structure for rate increases, TVA, in 1970, found it necessary to commence a program of quarterly reviews that led to yearly increases starting in 1973. In January 1974, the adjustment deemed necessary was 20 percent, but by August even that had become insufficient. Like most other power systems, TVA has been forced to institute both monthly escalations based on fuel costs and quarterly adjustments based on the price of purchased power. Meanwhile, TVA's rates in 1974 rose by an unprecedented 27 percent wholesale and 19 percent for residential customers, thus causing consternation among many supporters of Federally operated utilities.

A second indicator of TVA's financial problems can be found in a comparison of costs for the fiscal year (F/Y) ending in June 1974 and those projected for F/Y 1975. Fuel costs have risen from $350 million to $579 million; money costs, from $161M to $183M; depreciation, from $97M to $113M; labor, from $126M to $148M; and other costs, from $107M to $125M. TVA's total bill, therefore, is up from $841 million to $1.48 billion—a 36.5-percent leap!

Perhaps the most dramatic statistic demonstrating TVA's new-found problems is its debt ratio. The unique advantage that has historically accrued to a Federal utility is that its initial construction is Federally funded. TVA's Federal funding lasted until about 1956; and, since 1960, when TVA first began to sell bonds to the public, it has benefited hugely from its miniscule debt (compared to that of any private utility). On the other hand, particularly in the last several years, TVA's indebtedness has grown until, as was previously mentioned, it has now passed the 50-percent-of-total-capitalization level. Although, according to Lee Sheppeard of TVA's Office of Information, arrangements are currently being made for new Federal loans at a less-than-market interest rate, TVA has, for the present, joined its investor-owned "competitors" in having to pay today's sky-high money rates.

Last, but not least, the municipal utility

Accounting for about 10 percent of the electricity generated in the U.S., there are today over 2000 publicly owned municipal systems throughout the nation —and their number may be growing. Why? Because, despite having to cope with their individualized brand of problems, municipal systems, by and large, charge lower rates than do investor-owned private utilities.

An excellent example of what may be a trend of the future is the municipal utility of the city of Messina in upstate New York. Angry at having to pay what they considered to be the exorbitant rates charged by the troubled, primarily oil-dependent Niagara Mohawk Power Corp., the residents of Messina decided to ditch Niagara Mohawk and tie into largely hydro-generating PASNY. Negotiations are expected to be completed by the time this article goes to print.

Not all municipal systems are problem-free, however. In Cleveland, Ohio, Municipal Power & Light services some 50 000 city residents while investor-owned Cleveland Electric Illuminating services the rest of the city. Historically, the municipal utility has charged rates from 5 to 12 percent below those of CEI. According to Municipal's Russ Milan, this unfavorable comparison may have been enough to tempt CEI to wish Municipal ill. Whatever its motives, CEI, according to Mr. Milan, has worked hard to "choke Municipal off." As evidence, Mr. Milan cites CEI's refusal to sell Municipal small amounts of electricity for emergency use—that is, until the Federal Power Commission, at Municipal's request, intervened on Municipal's behalf. Further, Mr. Milan told *Spectrum*, when Municipal arranged to buy hydroelectric power from PASNY, CEI refused to "wheel" (transmit) the PASNY electricity through its transmission lines. Municipal has reason to believe that the Justice Department Antitrust Division will be investigating this refusal in the near future, but, in the meantime, says Mr. Milan, "we've been having trouble with our generating equipment." Why? "Because we can't afford the downtime for maintenance. We've even had to convert our peaking units to base load." To Mr. Milan, it's all part of the Cleveland Electric Illuminating plan to run Municipal out of town.

Cleveland Electric Illuminating, on the other hand, has its own, equally interesting, story to tell. CEI vice president Lee L. Howley replied to Municipal's charges by noting that, among other things, Municipal should have had plenty of time for maintenance. According to the CEI source, on a typical day Municipal generates 55 MW (it requires 90 MW and the difference has been coming from CEI for five years) of a 208-MW registered capacity. He says that, of six "down" boilers, Municipal doesn't expect three to be on line before 1976; two others are an open question; and the third has been abandoned altogether. He further points to one of the four Municipal turbines that is out of service, while the others are operating below potential, and says disgustedly, "No wonder they're running peak-load units as base load!"

Why should Municipal try to shift the blame unfairly? Mr. Howley declined to guess at motivations, but a second *Spectrum* source within CEI suggested that, in the near term, Municipal would be getting "cheap" emergency power from CEI [10 percent over cost—the going industry rate]. And in the long term, they can force the "wheeling" of cheap power instead of having to invest in generation ... that is, if they can successfully make CEI the scapegoat.

Meanwhile, CEI vice president Howley laments: "We can't win. Someone has to supply Municipal's customers. We are willing to do it, if necessary, but they've been borrowing a half million dollars a month in power and we haven't been paid since August [1974]! They're completely bankrupt—bankrupt with equipment and with dollars!"

[*Spectrum* plans more on this topic in a future issue.] ◆

The French (train) connection

The railroads of France are seen to be the best in Europe: its "seconds" are exported to AMTRAK

Attendees at the recent Sixth International Conference on Urban Transportation, held in Pittsburgh, Pa., were greeted by some unusually barbed comments regarding the state of the U.S. rail system. Speaker Milton J. Shapp, Governor of Pennsylvania (and a cofounder of Jerrold Electronics Corp.) took note of an announcement by AMTRAK, the National Railroad Passenger Corp., of the acquisition of trains capable of "high" 200-km/h (125-mi/h) speeds. "In each case," Gov. Shapp noted dryly, "America's federally run rail passenger service was forced to buy or lease such trains from France, because no high-speed trains are built anywhere in this country." To make things worse, Gov. Shapp pointed out, "the equipment AMTRAK gets from France is neither new nor novel." According to the Governor, French engineers save their best trains for domestic use.

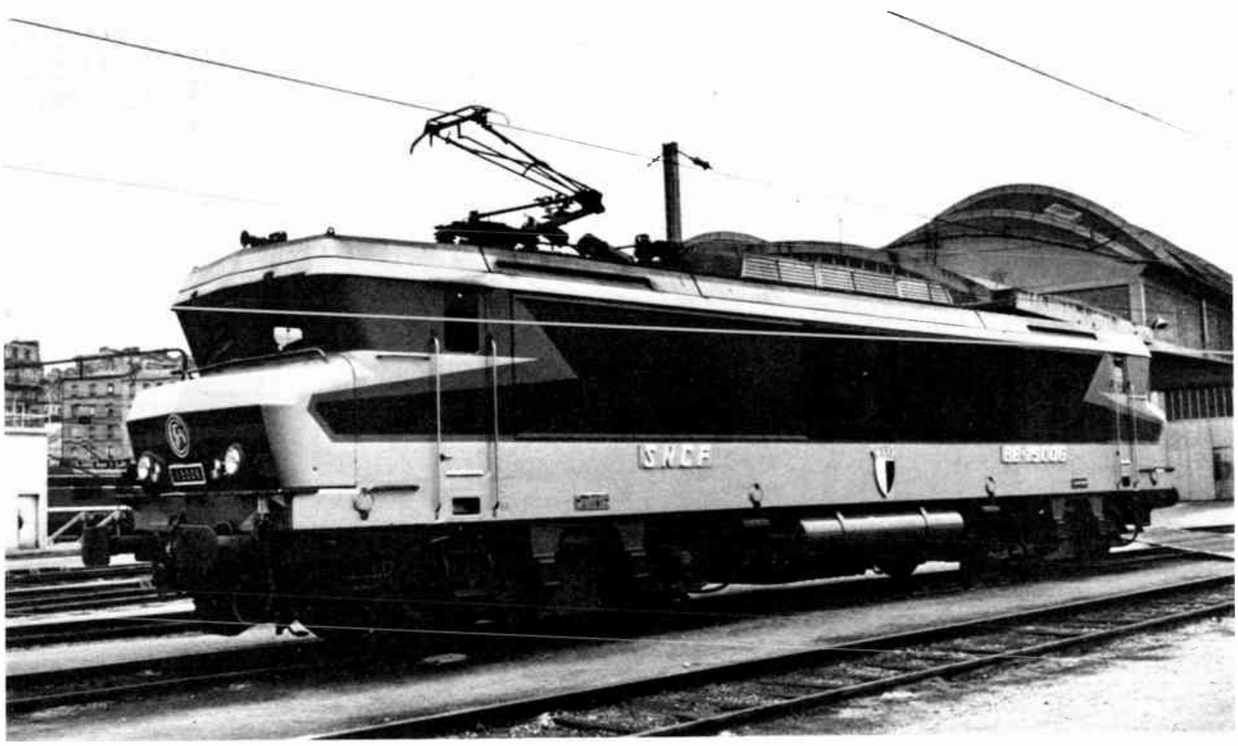
Gov. Shapp is, of course, correct. While selling 200-km/h trains to AMTRAK, the French National Railroads (Société Nationale des Chemins de Fer Français, or "SNCF"), has committed itself to build a very-high-speed rail link between Paris and Lyon.

Gordon D. Friedlander Senior Staff Writer

To be completed by 1980, the projected $500 million line will be used exclusively by passenger trains running the 425-km (264-mi) distance at an average speed of 265 km/h (165 mi/h), thus bringing Lyon only 1½ hours from Paris. This would be almost twice the speed of AMTRAK's "Metroliners," which run a comparable distance between Washington and New York in three hours. Although considerable thought was first given to the use of a new generation of turbotrains, the recent energy crisis convinced the SNCF to go all-electric on this route.

As reported at the beginning of last year *(IEEE Spectrum*, p. 68, Jan. 1974), the SNCF has been using, since October 1973, an automated, or "cybernetic," centralized traffic-control (CTC) system at Paris' Gare du Nord (North Station), where suburban passenger traffic—about 300 000 commuters daily—is exceptionally heavy along three suburban lines *(lignes banlieues)*. The result is an automated suburban train-operating system, an automated long-distance mainline "fluidizing" system, and a cybernetic train dispatching scheme that utilizes a central computer in association with visual CRT displays in which corrective action can be made in retarding or advancing the speeds of individual trains by means of an "elec-

Four-axle thyristor-controlled SNCF locomotive of the BB 15000 class (1500-volt direct current) has the sleek and restless lines that are indicative of the high-speed for which it was designed.



"Plugging-in" to the national power grid

The primary advantages of 25-kV, 50-Hz single-phase ac on the caternary are that

- Power can be fed from any primary/secondary transmission/distribution line, with or without step-down transformers.
- Wayside converter/rectifier stations are eliminated.
- Greater reliability of service is ensured by the inherent stability of the integrated French national power-supply network.
- Initial capital construction costs of electrified lines are reduced, and concomitant maintenance economies are achieved by a system that utilizes standard commercial frequency.

tronic pen." This system was tested from 1971 to 1973 on an experimental basis before it became operational. In the past year, a 30-percent increase in traffic capacity at the Gare du Nord has been realized. The computer at that location enables the automatic dispatching of trains, and the control of all relay signal boxes and display devices. These capabilities permit the control cabin operator to predetermine, supervise, and make decisions regarding train dispatching and arrivals by means of peripheral subsystems.

A brief historical overview

The first electrified train on the French railways made its debut in 1902. It was placed in service on the line from Paris–Austerlitz to Orsay terminal and Paris–Invalides to Issy. It was similar in design to those used on the New York City and Chicago elevated transit systems. The French wooden-body multiple-unit train consisted of three motor coaches (each of which was equipped with one motor bogie) and six trailer coaches. The nine-car train developed 620 kW, and had a top speed of about 50 km/h (31 mi/h). It collected direct current from third-rail conductors.

Although suburban lines and the Paris Metro (subway) began and expanded their electrified service —both catenary and third rail—from the turn of the century onward, electrification of the French mainlines, in particular, proceeded quite rapidly. Between World Wars I and II, the traditional steam traction dominated freight and passenger routes. By 1940, 3300 km (2050 mi) were electrified. World War II witnessed the systematic destruction of the major portion of the rail lines, traction and rolling stock, in the northern (occupied) third of France as Allied armies and air forces rolled back the German invaders.

During the post-World War II reconstruction period, France, like Germany, had to start from scratch in rebuilding many of its shattered railways. Unlike Switzerland, however, France does not have (except in the French and Maritime Alps) a wealth of ready hydropower for the electrification of a major portion of its mainline rights-of-way. Nevertheless, the construction of catenaries and all-electric locomotives developed at a constant rate in the 1958–68 time frame.

Electrification and traction equipment

The French approach to mainline electrification has been on two levels: first, 1500-volt direct current; and second, 25-kV single-phase alternating current at 50 Hz (the European commercial frequency). The latter—and more recent—effort represents a radical departure from the conventional "gospel" which stipulates that ac railway traction functions most efficiently at about one third of the commercial frequency (16⅔ Hz in Europe, 20–25 Hz in the U.S.).

Today, the SNCF's mainline and suburban catenary electrification consists of about 5000 route kilometers at 1500 volts direct current, and some 4500 route kilometers at 25-kV, 50-Hz single-phase alternating current (Fig. 1). Another 250 route kilometers (ap-

"Le matériel remorqué et la traction"

The rolling stock, traction equipment, and electrified routes of the SNCF mainline and suburban commuter lines are either discussed or mentioned in the main text of this article.

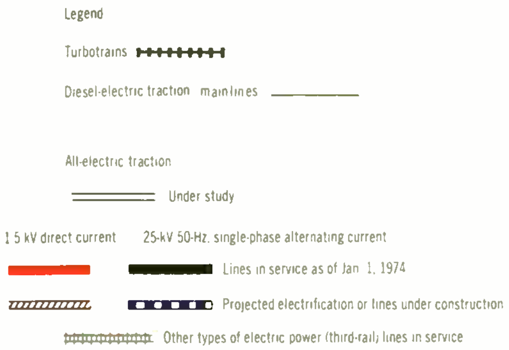
Esthetically, the rakish lines of the SNCF's locomotives—as may be seen in the illustrations—are so restless and sweeping that some of these new machines appear to be traveling 100 km/h even when standing still! Both the all-electrics and diesel-electrics (of the most up-to-date series) are exceptionally striking and dramatic in appearance—and performance. They serve to indicate, in part, at least, why the SNCF rates as the top system in Europe.

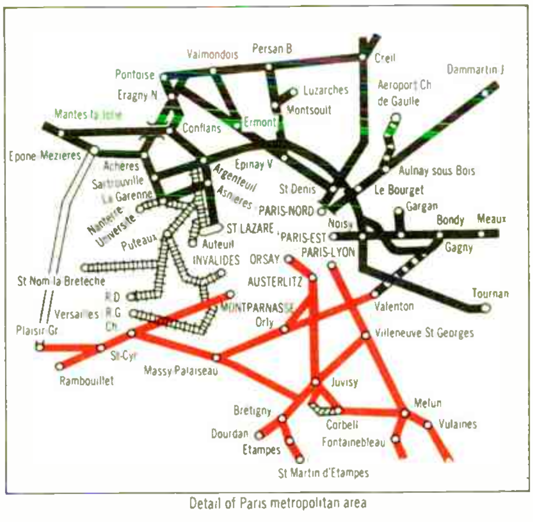
Unlike the all-electrics of any other country, the French locomotives of classes CC 6500 and CC 21000 have the highest maximum speed capability: 220 km/h (135 mi/h). That's really stepping along! Also unlike the locomotives built in Sweden, Germany, and Switzerland, the French machines are mostly equipped with one large traction motor *(monomoteur)* driving, through reduction-gear linkages, each two- or three-axle bogie—instead of the individual traction motors driving each axle, which is the more conventional present-day procedure.

However, either the conventional transformer/tap-changer or silicon rectifiers are employed on the older single-phase ac locomotives; but, the latest models are thyristor- or thyristor/chopper-controlled. Therefore, on the assumption that "if you've seen one thyristor/diode bridge, you've seen them all," the interested reader is referred to a typical thyristor-controlled diagram provided in "Riding Sweden's slick rail system," *IEEE Spectrum*, pp. 53–64, March 1974.

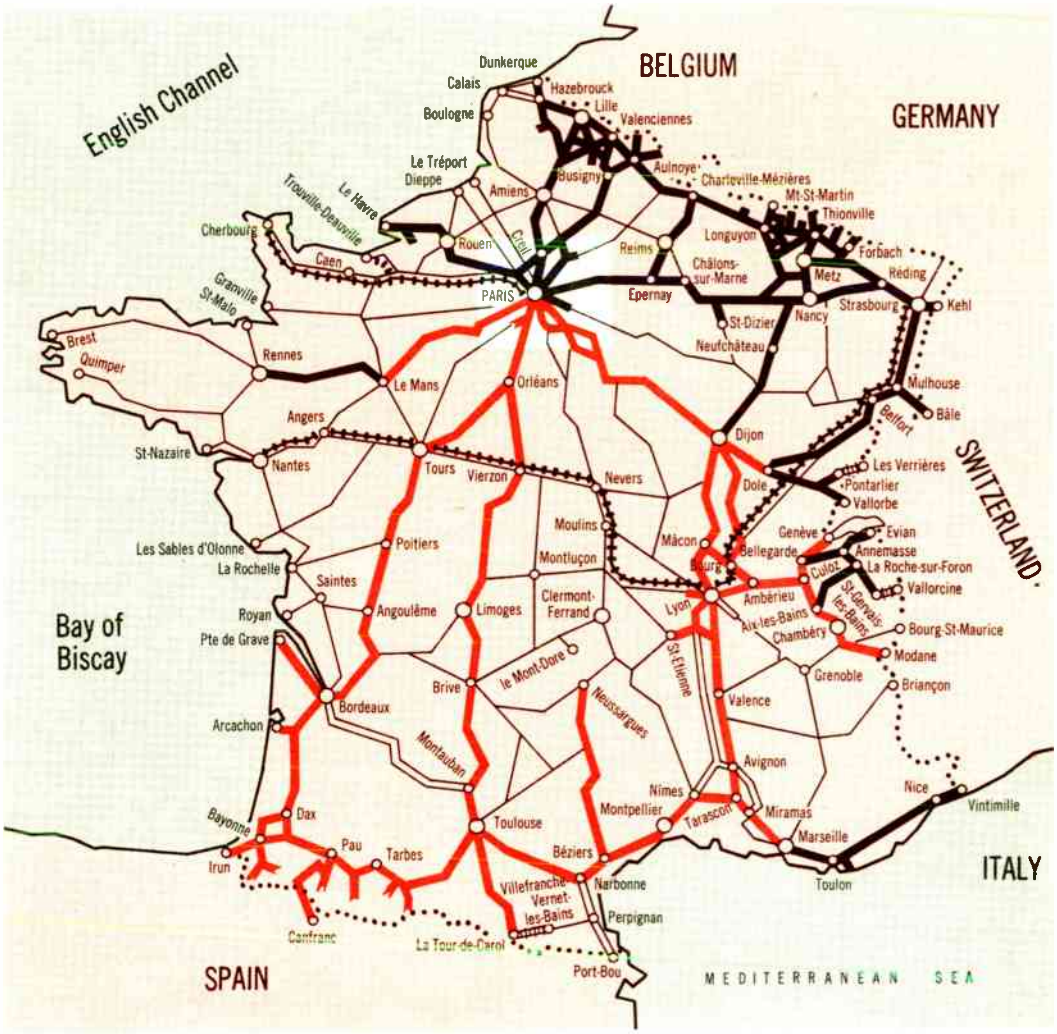
The French have always exhibited an individualistic flair for experimentation and innovation; and, true to this Gallic predilection, the SNCF management has never been constrained to "putting all its *ergs* in one basket." Thus, it is not surprising that electrification has not been a single-minded desideratum; diesel–electric traction, gas-turbine propulsion, and all-electric vehicles have shared more or less coequally in the French quest for high-speed passenger mainline rail service. Therefore, within the SNCF, it would be difficult to find a consensus as to the predominant future direction in traction. For example, F. F. Nouvion (who now holds the emeritus title of "honorary chief engineer" of the SNCF) is an ardent proponent of all-electric traction and scorns diesel-electrics—and turbotrains—as being "costly, wasteful and inefficient, and environmentally polluting." Many of his colleagues, however, respectfully disagree with this eminent railway engineer. Electrification could proceed faster on the SNCF—but it hasn't. This seems to indicate that the French prefer to "keep their options open."

[1] Principal electrified (existing and under construction) and nonelectrified lines of the SNCF in France. The legend indicates the line voltages and the modes of traction used on nonelectrified rights-of-way (diesel and /or turbotrain). The inset map shows the main suburban lines *(grande banlieue)* in the Paris metro area.





Detail of Paris metropolitan area



proximately) comprise 750-volt dc third-rail urban and suburban commuter lines, principally in the Paris metropolitan area (see inset, Fig. 1). About 33 percent of the SNCF's trackage is electrified.

Among the latest electrification projects completed are

- The 32-route-kilometer Paris–suburban line from Noisy-le-Sec to Tournan, energized at 25 kV, 50 Hz, on which revenue service was inaugurated January 15 of this year.
- The 90-km-long 1500-volt dc line between Chambéry and Modane (in southern France, near the Italian border), which was electrified by third-rail conductor in 1930 and is being converted to a catenary system.

At the same time, a modernization program is underway to update some of the older existing catenaries, especially those in southern France (Midi)

I. Performance characteristics of class "CC 6500" all-electric locomotive (two gear-ratio change)

A. With gear ratios of 2.864 to 1
(lower-speed regime: up to 100 km/h)

1. Starting and traction capabilities for trains of
   - 3000 tonnes, on a grade of 0.5 percent, and a curve radius of 1600 meters
   - 2150 tonnes, on a grade of 0.8 percent and a curve radius of 1000 meters
   - 1800 tonnes, on a grade of 1.0 percent, and a curve radius of 1000 meters
   - 600 tonnes, on a grade of 3.0 percent, and a curve radius of 500 meters

B. With gear ratios of 1.314 to 1
(higher-speed regime: up to 220 km/h)

2. Starting and traction capabilities for trains of
   - 350 tonnes, at 220 km/h, on a 0.5 percent grade and 1600-meter curve radius
   - 800 tonnes, at 160 km/h, on a 0.5 percent grade and 1600-meter curve radius
   - 800 tonnes, at 145 km/h, on a 0.8 percent grade and 1000-meter curve radius

—from Bordeaux to Dax, and from Montaubon to Sete—for very-high-speed passenger service.

The six-axle all-electrics

Among the later heavy-duty 1500-volt dc all-electric locomotives of the SNCF is class "CC 6500," built by Societés ALSTHOM and FRANCO-RAIL-MTE. This class is designed for mixed service. The locomotives are equipped with two 3-axle bogies, with one large traction motor *(monomoteur)* per bogie (Fig. 2) that is connected by driving gear trains to each axle. This class of locomotive—in service for about five years—is built in one power, with a two-speed gear change (current collection by pantograph). Twenty have been equipped with third-rail contact shoes until the conversion of the Alps line to catenary is completed. The continuous rating of the class is 5900 kW, with top speeds of either 220 km/h (135 mi/h) or 100 km/h (62 mi/h), determined by reduction-gear ratios for freight or passenger service. (See Table I for some performance characteristics.)

Starting of the locomotive is effected by the progressive elimination of resistance by means of a rheostat. Speed regulation is accomplished by utilizing series/parallel, parallel connections and field shunting of the traction motors. All 6500s have rheostatic braking capabilities.

To date, about 60 locomotives of this class are in service. These fine machines are used to haul the SNCF's crack TEE trains and *rapides* (extra-fare deluxe trains), including the famous *Le Mistral* that runs between Paris and Nice.

Since the SNCF electrification is at two current levels, it was natural that a newer high-speed locomotive, compatible for operation with both the single-phase and dc catenaries, be designed and built. Design dates back to 1967, and the resulting class CC 21000 two-current locomotives (also built by ALSTHOM and MTE) are almost identical in outboard profile appearance to the CC 6500s. The interior electrical equipment, as may be expected, is more complex, since both the CC 6500 equipment *plus* thyristor rectifier equipment must be carried on board.

This class has a continuous rating, like the 6500s, of 5900 kW, and a speed—depending upon whether the locomotive is used for freight or passenger service—of from 100 to 220 km/h. The principal advantage of the 21000s is that they can be used over all electrified routes of the SNCF where a heavy-duty engine is required.

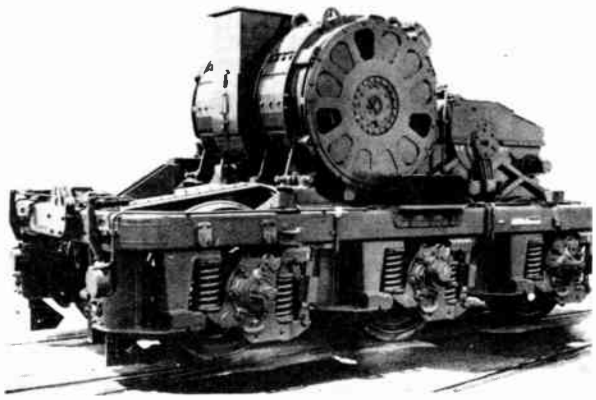
The 21000s are the latest class of heavy two-current thyristor-controlled locomotives (as of January 1972, only two were in service, but more are being built); but a new family of 150 four-axle 90-tonne thyristor-controlled two-current class BB 22200 machines are on order. The 22200s (Fig. 3) have a continuous rating of 4620 kW, with a top speed of 180 km/h (112 mi/h). They will be described in more detail subsequently.

The newer four-axle lightweights

The 110 operational class BB 7200 (1500-volt dc) locomotives, like the BB 22200s, have a continuous rating of 4620 kW and a maximum speed of 180 km/h. The first group of these 85-tonne machines (ordered in 1973) are equipped only with pantographs for overhead current collection. A prototype chopper equipment has been in operation on a BB 9200 class locomotive since 1971. It was the first chopper of such power (4500 kW) to be in commercial operation. This same type will be used on the 110 BB 7200 and the 150 BB 22200 classes on order. The continuous regulation of voltage fed to each traction motor is ensured by an assembly of three primary choppers that function as a network. The operational frequency of each primary chopper is 300 Hz. The control of voltage weakening is attained by $f/27$, $f/9$, and $f/3$. Thyristor bridges permit the continuous regulation of the field current. These locomotives are equipped with dynamic (rheostatic) braking, with separate excitation by each of the three primary choppers.

The four-axle family of locomotives was derived from the class BB 15000, 86-tonne, 25-kV, 50-Hz thyristor-controlled locomotives, with a continuous rating of 4620 kW and a top speed of 180 km/h (112 mi/h). (To date, 15 of this class are in service and 50 more will be delivered in the coming years.) But in outward appearance, the casual observer would be

[2] A large single traction motor *(monomoteur)* is mounted atop each three-axle bogie of the class CC 6500 and CC 21000 locomotives. It drives the axles through reduction gears. The monomotor is typical for a very large number of four-axle (BB) and six-axle (CC) machines of the SNCF.



pressed—unless he could see the alphanumeric class-designation placques attached to the sides and ends of each machine—to differentiate classes BB 7200, BB 15000—and BB 22200—from each other. (This identity problem is also true for classes CC 6500 and CC 21000.) It is the internal electrical equipment that spells the difference.

And that present (and proposed) difference is rather interesting—as may be seen in the Fig. 4 diagrams—in that sufficient experimentation has been completed to build a series of 1500-volt dc chopper/thyristor controlled locomotives similar to subsequent 15000s. Thus, the four-axle classes BB 15000 (ac), 7200 (dc), and 22200 (ac/dc) were created to fill the gap . . . But, we are getting a bit ahead (and behind) in terms of chronological rationale. So, back to the BB 15000, and what makes it go—

In the 15000s, each traction motor is fed by two thyristor bridges—one, all thyristors; the other, mixed thyristors and diodes—connected in series. Field weakening is achieved by shunting thyristors. (The all-thyristor bridge is used in the regenerative braking mode. In braking, the all-thyristor bridges are used as inverters.) The flow of current from the two bridges completely ensures voltage regulation. Field-current control is achieved by one of the mixed thyristors and diode bridges.

With a continuous rating of 4620 kW at a top speed of 180 km/h, the 90-tonne BB 22200 machines are the four-axle counterpart of the larger and heavier CC 21000s.

As might be expected, the on-board electrical equipment of this class of engines is a combination of that of classes 7200 and 15000. The 1500-volt dc chopper/thyristor control system of the 7200s is installed; however, a transformer/rectifier combination is employed in conjunction with the 25-kV, 50-Hz monophase current collection.

The "quadricurrents"

The SNCF, several years ago, built ten heavy four-current six-axle electrics (class 40100) that were compatible not only with the two different catenary voltages, but also with the 15-kV, 16⅔-Hz single-phase ac of the Swiss Federal Railways (SBB) and the German Federal Railway (DB), and the 3000-volt dc of the Italian State Railroads (FS) and the Belgian National Railways (SNCB). These locomotives, like the four-current "électromotrice" TEE trains (described on pp. 52–54 of the August 1974 issue), could cross the international borders of these adjacent countries. The construction of the locomotives, however, was discontinued because of the speed limitations outside France.

At the present time, more than 2200 all-electric road locomotives are in service over the 9500 electrified route kilometers of the SNCF. But that's only one third of the French railway network; the other two thirds (main and secondary lines) are served by:

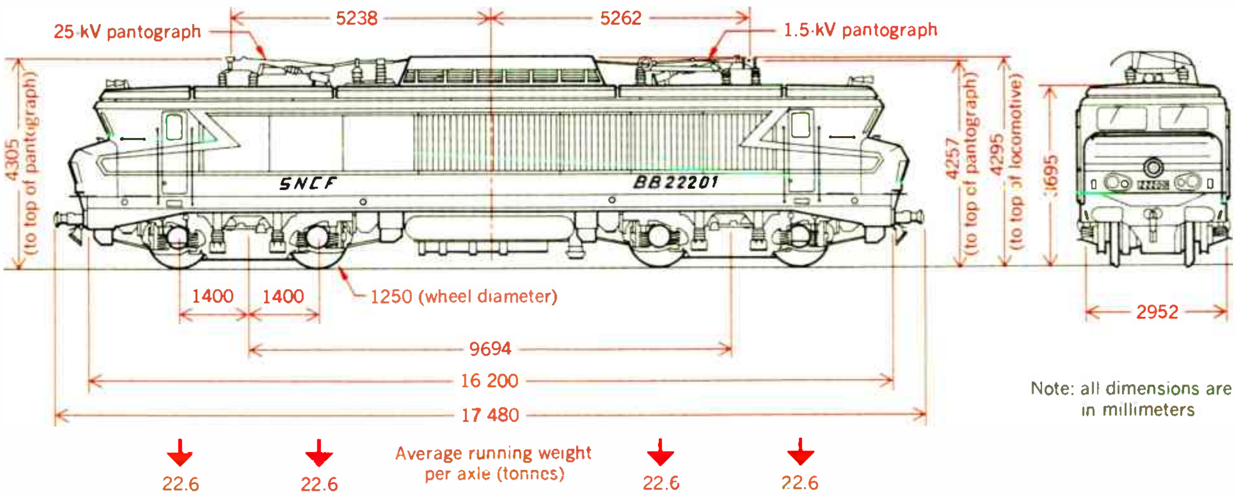
Diesel–electric traction and turbotrains

There are two principal classes of diesel–electric locomotives: the four-axle types BB 67000, BB 67300, and BB 67400; and the six-axle type CC 72000, AlA-AlA 68000 and AlA 68500.

The newer classes of diesel–electric bear a remarkable resemblance in lines and general appearance to the later all-electrics (except for the absence of pantographs). To save much time and space in discussing these locomotives, the reader is referred to Table II, which provides an encapsulated description of their salient features. Fig. 5 shows the driver's cab in a late-model diesel–electric.

Like the all-electrics, the French mainline diesel–electric locomotives are used for both passenger-express trains and fast-freight hauling over either level or mountainous terrain. The reduction gear ratios of the traction motors to the wheels determine the tractive effort applied at the wheels—and the maximum service speed. In these machines (except types AlA-AlA 68000 and AlA 68500), the single traction motor is mounted atop each bogie. In the case of AlA-AlA 68000 and AlA 68500, however, two traction motors drive the two outer axles of each three-axle bogie.

[3] A typical four-axle class BB 22200 all-electric two-current (1.5-kV dc, 25-kV, 50-Hz ac) locomotive. That is a common sight on SNCF mainlines.



Average running weight (tonnes) 90.4
Current collection: overhead catenary, and with third-rail contact shoes (on locomotives built since Jan. 1, 1973)

Minimum negotiable curve radius: 100 meters
Maximum service speed: 160 km/h
Continuous rating 4620 kW

The center axle is employed to reduce axle load. (This represents an interesting departure from the conventional *monomoteur* French design philosophy. It is perhaps significant that further construction of classes AlA-AlA 68000 and AlA 68500 has been discontinued.)

During 1973, the SNCF placed 19 two-car diesel-hydraulic units, with a rating of 330 kW per set, in service on nonelectrified suburban lines, and 48 new diesel-electric locomotives, of either 1765- or 2650-kW rating, in mainline operation.

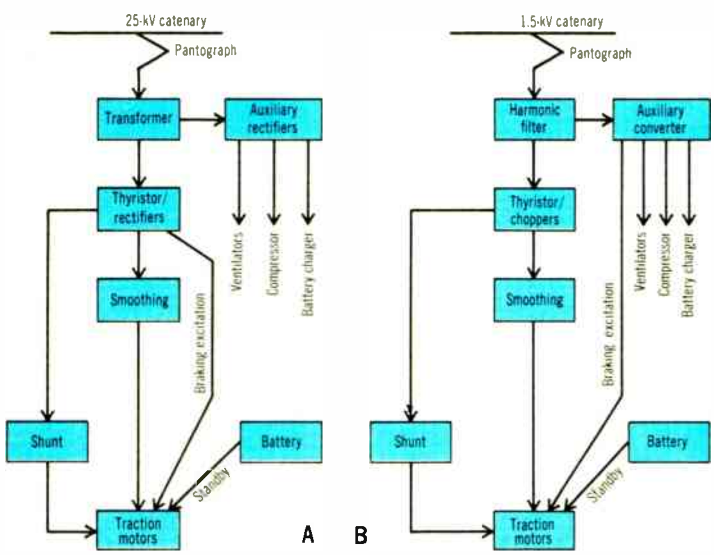
The turbos and TGV-001

In 1972, the SNCF introduced a test program in connection with its "second generation" of turbotrains, with a prototype designated "RTG-01." (This class was originally considered for service on the projected new Paris–Lyon link mentioned at the outset of this article.) Equipped with two gas-turbine engines, it attained a speed of 260 km/h. And 1973 witnessed the placement in revenue service of 15 additional RTG-class turbotrains, modified for a maximum speed of 200 km/h.

A typical RTG consists of three passenger trailer cars interspersed with two propulsion-motor carriages, for a total of five 4-axle vehicles, with an overall length of 129 meters and a total weight of 237 tonnes. The train is double-ended and has an operator's cab at front and rear. The two turbo engines each have a rating of 820 kW; fuel tanks have a capacity of 7200 liters, and the train has an operational range—without refueling—of 960 km (595 mi). Auxiliary turbines drive alternators for lighting, air conditioning, and the compression of air for braking.

An experimental "Très Grande Vitesse" (very high speed) turbotrain, designated TGV-001, was ready for testing in 1973, and has, since that time, been used in long-distance trial runs. By mid-1974, TGV-001 had run a distance of 145 000 km (90 000 mi), of which 10 000 km (6200 mi) were covered at speeds over 270

[4] A—Electrical equipment on board a standard class BB 15000 locomotive. B—Electrical equipment necessary to convert a standard BB 15000 to 1.5-kV dc thyristor/chopper control.



One SNCF philosophy—and its implementation

Back in 1970, F. F. Nouvion (then chief engineer and head of the Traction Studies Department of the SNCF) enunciated a unique philosophy for the French design of traction equipment, multiple units, current collection, and rolling-stock suspension systems: then—as now—the French design criteria for high-speed systems were the opposite of those that are generally applied in the U.S. The SNCF's locomotives and rolling stock are designed for adaptation to existing rights-of-way. Thus, the rights-of-way are *not* modified to accommodate the high-speed equipment that attains speeds of up to 220 km/h (135 mi/h). For instance, short-radius curves are not eased, extensive welded-rail track sections are not installed to replace standard track lengths and bolted splices, catenaries are neither structurally reinforced nor redesigned, superelevations on curves are not increased, and the roadbed elements (crossties, ballast, etc.) remain unchanged.

When a train enters a curve at very high speed, the standard maximum track superelevation (usually limited to 6°) is insufficient to cancel out the effect of centrifugal force, and hence discomfort (if not hazard) to passengers is the result. To compensate for such conditions of undercant, the SNCF, 14 years ago, developed a pendular-suspended vehicle that banked the locomotive or passenger carriage naturally into the curve to a degree that is proportional to the resultant of the vehicle's weight and the centrifugal force. (For details of the general approach to this technique, see the article "Riding Sweden's slick rail system," *IEEE Spectrum*, pp. 53–64, March 1974.)

In addition, small-diameter wheels are used to lower the center of gravity of the rolling stock. This tends to increase resistance to overturning forces and reduce the vertical load and horizontal thrust on the outer rail when negotiating curves.

Furthermore, the SNCF employs a small-size (one-meter-high) Faively-type pantograph for twofold application: as the main current-collector installed on locomotives or multiple units operating on newly electrified lines whose catenary height is constant, and also as a "piggyback" collector riding atop either a conventional parallelogram or standard Faively pantograph. (The latter use is applied along lines in which the catenary height drops appreciably below normal at overpasses and in tunnels. In this application, the "knee-action," or vertical motion caused by the varying height of the conductor, is absorbed by the small pantograph, with very little flexing of the main pantograph.) The principal advantages of this technique are

1. The piggyback collector, because of its weaker compression springs, places less pressure on the conductor, and thus reduces the frictional wear.

2. At high speeds, there will be less vertical deflection (and less amplitude in the horizontal and vertical oscillations) introduced to a catenary conductor that is built to standard construction specifications.

In France, trains are being operated at speeds of 220 km/h under catenaries built more than 50 years ago (which are, in turn, fed by substations just as old). Electric locomotives placed in service almost 40 years ago perform their duties with high efficiency; they run, on the average, more than 190 000 km/year. In 1955, one of the class CC 7100 (six-axle) locomotives attained a speed of 328 km/h (203 mi/h); and today it is still averaging 200 000 km/yr in revenue service.

II. SNCF diesel-electric performance and statistics

Class	First Year of Construction	Weight (tonnes)	Continuous Rating (kW)	Max. Speed (km/h)	No. of Traction Motors	No. of Locomotives Built	Constructors (body, frame, diesel and/or electric motors, and equipment)
BB 67000	1963	80.0	1470	90/140	2	123	BRISSONEAU, S.A.; LOTZ, S.A.; Société des Forges et Ateliers du CREUSOT, Société des Forges et Ateliers de Constructions Electriques de JEUMONT; Société OERLIKON; Chantiers de l'ATLANTIQUE
BB 67300	1967	80.6	1765	90/140	2	70	BRISSONEAU; LOTZ; Société M.T.E. (Schneider Creusot—Jeumont Schneider); Société OERLIKON; Chantiers de l'ATLANTIQUE
BB 67400	1969	83.0	1765	140	2	232 (on order)	BRISSONEAU; LOTZ; Société M.T.E.; Société OERLIKON; Chantiers de l'ATLANTIQUE
CC 72000	1967	114.0	2650	85/140 85/160	2	92	Société ALSTHOM; Société Alsacienne de Constructions Mécaniques de Mulhouse
AIA-AIA 68000	1963	106.0	1985	130	4	81	Compagnie des Ateliers et Forges de la Loire (jointly with Société FIVES LILLE-CAIL); Compagnie Electro-Mécanique; Compagnie de Construction Mécanique (SULZER)
AIA-AIA 68500	1963	105.0	1985	130	4	28	(Same as Class AIA-AIA 68000, except for diesel engine.) Société Alsacienne de Construction Mécaniques (AGO)

km/h (170 mi/h)—and 500 km (300 mi) at speeds of more than 300 km/h (up to 200 mi/h). The trials are still underway.

During the 1973 tests, the aerodynamic qualities, stability, passenger comfort, and noise insulation of the TGV were determined, and the information was used as a valuable data-bank input for the better understanding of very-high-speed rail travel; it should be extremely useful in the design of future sophisticated vehicles.

Unfortunately, however, the TGV-001's energy consumption per passenger seat is 40 percent higher than that of an all-electric train. With energy costs running about 15 percent of total operating costs, the French reason that electrification (which requires initially heavy capital investment) will prove cheaper in the long run. Nevertheless, the ultrahigh-speed electric trains that will eventually run between Paris and Lyon will be similar in design concept to the most recent turbotrains.

"Carriages and wagons"

The French have a general category for trailing rolling stock—*le matériel remorqué*—that covers both passenger and freight cars hauled by locomotives. However, since few of our readers will have any interest in "hopping a freight,"* we will limit our discussion to passenger carriages rather than freight wagons. The SNCF is engaged in an ongoing program of scrapping a large number of old and obsolescent passenger carriages and replacing them with fewer—and far more up-to-date—vehicles. Also, many of the older third-class carriages are being rebuilt and modernized. Thus, for example, in 1973, 509 units, of a total of 12 302 units, were taken out of service and replaced by 392 new or modernized carriages. Among the brand-new rolling stock are

- 212 first- and second-class carriages (including 25 sleeping cars and 11 dining cars).
- 57 suburban-commuter multiple-unit cars, with thyristor/chopper controls.
- A prototype extra-long first-class carriage (26.4 meters in length), all air-conditioned, and with nine six-passenger compartments capable of nighttime conversion to "couchette" sleepers.
- The first 35 units of a large order of type "T2" sleeping cars, containing 18 double bedrooms; they are equipped with self-contained heating/air-conditioning systems and a combination of disk/shoe brakes. (These cars can be hauled at speeds of 160 km/h without discomfort to sleeping passengers.)

At this point, it might be well to mention that, today, almost all European railways (both mainline and suburban) carry first- and second-class carriages that correspond somewhat to the "first-class" sleepers and parlor cars—and less expensive coaches—carried on railroads in the U.S. Generally, the European cars are subdivided into compartments, with a full-length side passageway. In daytime travel, each first-class compartment carries six passengers in individual facing seats of three each. Individual armrests are provided, and the seats can generally be adjusted to a semireclining position. Second-class carriages carry similar compartments, but eight passengers can be seated in each. (New second-class vehicles will seat six per compartment.) Although usually quite comfortable, the second-class carriages do not have the

* Some old-timers may remember the "40 and 8" cars *(quarante et huit)*—40 men, 8 horses—of World War I. These four-axle wooden relics were used to transport American troops to the fighting front.

[5] Driver's cabin in a class CC 72000 diesel-electric. Directly in front of the operator (whose position is in the left center of the cab) is a massive console, containing from top to bottom: two ammeters for each of the two electric traction motors; one motor per bogie and two voltmeters; a signaling board for auxiliary devices and wheel slippage. The large circular dials to the left are the diesel tachometers; the white dial on the right is the speedometer/odometer. In all, the dials are very well positioned.

deluxe ambience and amenities of the first-class accommodations. Similarly, there are first- and second-class sleepers and "couchette cars" (the latter notably a feature of the SNCF). First-class sleeping compartments carry a maximum of two persons in an upper and lower berth; second-class, or "tourist" sleepers carry three persons, in triple-tiered berths in each compartment. The couchette cars, similar to American sleepers, are convertible from daytime seating to two- or three-tiered narrow "bunks" (depending on whether they are first or second class). Couchette-car passengers are provided only with a pillow, sheet, and a blanket.

"Rapides" and TEEs—and "locals," too

With Paris as its hub, the SNCF probably runs the largest number of *rapides* (passenger express trains) and/or international TEE trains of any European country. During 1973, five new rapides were placed in service on the Paris–Bordeaux run, for a total of 11 express trains (in addition to the TEE-trains *l'Aquitaine* and *l'Étendard*) on this 579-km run during weekdays. Also, improved service was begun last September on ac lines between Paris and Strasbourg, and Le Havre and Paris. And, for the first time, RTG turbotrains were placed in service between Lyon and Strasbourg. In addition, international express-train schedules (Paris–Vienna, Paris–Basel, Paris–Lisbon, Lyon–Geneva, etc.) were significantly improved by more frequent service and reduced running times.

Local trains running off mainline rights of way have benefitted by the construction of 545 route kilometers of trackage (since 1966) along spurs to smaller towns and villages.

TEE-ing off to Paris

Our second recent experience with the fabulous Trans-Europ-Express (TEE) trains began with our departure from Bern's Hauptbahnhof, en route to Paris (for appointments with the SNCF management). We boarded the *Rheingold*, an all-electric locomotive-hauled (Re 4/4 of the SBB) TEE that runs daily from Hook of Holland to Geneva, at 1702, scheduled to arrive in Lausanne at 1807 for the very tight connection with the TEE "électromotrice" *Le Cisalpin*—a four-current six-car train set (see *IEEE Spectrum*, pp. 52–54, Aug. 1974)—whose indicated timetable departure was 1809 for Paris. Our anxiety at transferring, with bag and baggage, in two minutes flat (assuming adherence to schedules) was allayed when we arrived at Lausanne Central; *Le Cisalpin* was on the adjacent track of the platform at which the *Rheingold* came to a stop, *precisely* on time.

A platform conductor and railway personnel expertly guided us to our seat reservations on the connecting train, while a porter simultaneously scooped up our bags and deposited them in the end-of-car luggage space of *voiture cinq* (carriage five) as we plopped into our overstuffed reserved seats. *Le Cisalpin* glided quietly out of the station at exactly 1809, for the $4\frac{3}{4}$-hour, 450-km run to Paris.

At the Swiss–French border (Vallorbe), the *électromotrice* had to transfer from the Swiss catenary voltage of 15 kV, $16\frac{2}{3}$ Hz to the French 25 kV, 50 Hz for the 100-km-long leg to Dole. From Dole to Paris, the catenary is energized at 1.5 kV direct current—no problem for *Le Cisalpin*. All the driver had to do was to depress buttons in his cab console to raise and lower pantographs that were compatible with the prevailing electric currents on the overhead conductor.

We arrived at Gare de Lyon, Paris, at the exact time shown in the *horaire* (timetable)—2258. The worst part of the up-to-then comfortable journey was the detrainment: the rush of too many passengers for the too-few luggage carts, and the mad, unorganized scramble for a taxi that is the unfortunate scenario at journey's end for passengers of almost all long-distance trains terminating in the French capital.—*G.F.*

The French have a word for it . . .

Magnifique is the word most generally used by Parisians to describe the new Réseau Express Régional (regional express network—or "RER"). This grid of fast suburban commuter mainlines interfaces with the Paris Metro (subway) at interchange stations. The RER is part of the larger Régie Autonome des Transports Parisiens (self-governing transportation administration of Paris—or "RATP") that is responsible for operating all metropolitan rail, bus, and tram lines. In Paris itself, the RER's existing sections—as well as those being built—are underground; the suburban routes will be either at grade or elevated. ◆

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Ferrofluids: liquid magnetics

A space-age research spin-off finds its way out of the laboratory and into a host of lubricating and damping applications

Spun-off from space technology and refined after several years of down-to-earth development, ferrofluids consist of magnetic particles suspended colloidally in a carrier fluid. Developed in the early 1960s at the National Aeronautics and Space Administration as a means of controlling fuel flow under the weightless conditions of space, ferrofluids became commercially available in a variety of reliable formulations only about five years ago. At first limited to carrier liquids of kerosene and water, ferrofluids can now be manufactured with virtually any carrier liquid, including natural and synthetic lubricants.

Exciting a ferrofluid is as simple as applying a magnetic field from an electromagnet or permanent magnet. The fluid almost instantaneously responds by flowing, repositioning, or altering its internal pressure distribution. Removal of the applied field around the ferrofluid restores the ferrofluid to its unmagnetized condition. This behaviour is very analogous to the paramagnetism exhibited by oxygen gas—i.e., no hysteresis or remanence effects, but orders-of-magnitude higher magnetic moments.

The development of proprietary methods for colloidally suspending ultramicroscopic magnetic particles in any number of carrier liquids has meant the availability of numerous ferrofluids whose carrier-liquids' physical, chemical, and electrical characteristics could be tailored for specific applications.

Most current applications for ferrofluids exploit the ability to position and control the ferrous materials magnetically. Thus, with ferrofluidic materials such as lubricants and damping liquids, permanent magnets or electromagnets can remotely position and hold the liquids in position, exactly when and where needed. In ferrofluidic components like rotary shaft seals, magnetically confined ferrofluids withstand pressure differentials, for each axial centimeter of shaft length, of more than 3 kg/cm^2.

Applications under development are tapping ferrofluid properties for other than magnetic positioning. For example, a metals-reclamation scheme, described in the box on p. 54, relies on a ferrofluid's variation in apparent specific gravity, as the strength of an applied magnetic field changes. Proposed heat pipes and magnetocaloric generators rely on unbalanced magnetic body forces, created when a ferrofluid is heated at one end of a closed system and the liquid loses magnetization as it approaches its Curie point.

Complete characterization of ferrofluids can be found in the literature (see Bibliography, p. 57) and is beyond the scope of this article. Some properties are described in the box on p. 55. The following discussion of some typical applications can provide further insight into the nature of ferrofluids, their capabilities and limitations.

Ronald Moskowitz Ferrofluidics Corporation

Zero-leakage seals

Rotary shaft seals built with ferrofluids as the sealing elements can function equally well in either inclusion or exclusion applications. Operating as inclusion seals in vacuum systems, for example, ferrofluidic seals prevent any leakage and permit high speeds (over 100 000 revolutions per minute) and high torques (as much as a shaft can handle). In exclusion applications, ferrofluid seals prevent dust and moisture contamination in, for example, disk drives, potentiometers, encoders, and motors.

In a ferrofluidic seal, a magnetic field forces the ferrofluid into the gap between the surfaces of rotating and stationary elements. Completely filling the gap as though it were a liquid O-ring or liquid lip seal, the ferrofluid sets up a positive hermetic barrier in vacuum and high-differential-pressure systems.

Depending on the choice of carrier liquid, the ferrofluid can contribute negligible torque or high viscous drag. In addition, the liquid makes the seal self-lubricating while forgiving such undesirable features as runout, the shaft's slight wobble or displacement, surface finish, and eccentricity.

A typical ferrofluidic seal is built with a number of stages, each capable of holding a pressure in excess of several kg per square centimeter. As the burst pressure of a stage is reached, a pinhole leak at a point in the circumference automatically pressurizes the interstage volume for the next stage. Stage failure is not catastrophic, and liquid is not sprayed out of the seal. Indeed, when the overpressure condition abates, the leaking stage heals itself because the magnetic field forces the ferrofluid to refill the gap.

Because a ferrofluid retains its liquid properties even when magnetized, the seal shaft is free to rotate without sticking friction and with only the drag that arises from viscous shear. Viscosity decreases as temperature rises with shaft velocity. This temperature rise, which increases fluid evaporation, appears to be the sole limitation on seal speed. Liquid cooling extends the surface velocity range.

Fluid evaporation also limits seal life. But evaporation has been a negligible factor inasmuch as it takes place only from the outermost stages—and seals contain many stages. Seal life can be prolonged indefinitely, with a very low vapor-pressure liquid, or with periodic in-situ replenishment of the ferrofluid. Figure 1 shows replenishment and liquid cooling facilities for ferrofluidic seals.

Sealing potentiometers and motors

An inert atmosphere can reduce arcing in a potentiometer. But no conventional seals can maintain this

The junkman cometh

Whether you call it garbage or, as the comedian Jonathan Winters puts it, "gar-*bahge*," it's junk to be gotten rid of or reclaimed. For junk containing nonferrous metals, Avco Systems Division in Lowell, Mass. and the U.S. Bureau of Mines* are proposing to separate nonferrous from ferrous metals by immersing the two types of trash in a ferrofluid.

With pressure constant everywhere and motion absent, the ferrofluid must rise when a magnetic field is applied. There can also be a jet flowing freely and horizontally. The jet's velocity increases the moment the jet encounters a magnetic field, when elevation and pressure terms are the same everywhere along the streamline. To maintain a constant flow rate, the jet cross section gets smaller as its velocity increases.

Pressure distribution in a ferrofluid can be affected strongly by an applied magnetic field. When a solid or liquid of whatever shape (immiscible with the carrier liquid) is immersed in the ferrofluid, the solid or liquid experiences a net force, given by the product of the pressure times the area, summed over the entire surface. A substance whose density is greater than that of the ferrofluid's will normally sink, but can be buoyed to the surface when a strong magnet is brought to the bottom of the container. The magnetic field interacts with the ferrofluid so as to augment the pressure within it, by an amount sufficient to overcome the force of gravity. In effect, the ferrofluid's specific gravity changes by an amount controlled by the fluid's magnetic saturation and the strength of the magnet.

Making the magnet an electromagnet allows one to vary the ferrofluid's specific gravity by varying the current through the electromagnet. One can change apparent specific gravity sufficiently to separate such metals as magnesium, aluminum, zinc, tin, brass, copper, lead, gold, platinum, and even osmium.

* For more details, see S. E. Khalafalla's and G. W. Reimers' article "Separating Nonferrous Metals in Incinerator Residue Using Magnetic Fluids," in *Separation Science*, vol. 8, pp. 166–178, 1973.

atmosphere over the many years of a potentiometer's expected life. With a small ferrofluidic seal on a potentiometer's shaft, an inert atmosphere can be maintained indefinitely while contaminants are excluded.

This sealed-in-atmosphere condition permits designing compact motors for explosive environments and for vacuum or space systems, in which a sealed atmosphere prevents the vacuum-asperity welding and wear associated with brush-type motors. Such sealed motors can be self-contained because no air or other gas supply is needed. Furthermore, the engineer can specify atmospheres that enhance motor performance—hydrogen, for example, to reduce windage losses. As with potentiometers, a ferrofluidic seal can prevent the entrance of contaminants.

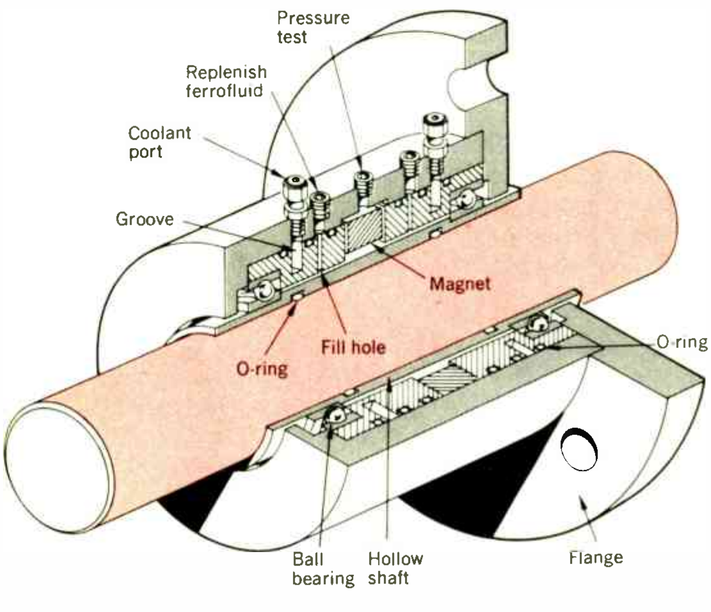
All ferrofluidic seals can act as exclusion as well as inclusion seals. Figure 2 shows the simplest exclusion seal, a small ring magnet attached to metal washers. Under the influence of a magnetic field, the ferrofluid seals against vapors or droplet sprays, traps magnetic particles, and spews out nonmagnetic particles, at high differential-pressure levels.

Like inclusion seals, exclusion seals also prevent gas leakage and permit high-speed operation with low-drag torque and friction. They have been adopted for computer disk drives to prevent catastrophic failure from oil-drop and dust contamination, in the sensitive head-to-disk gap.

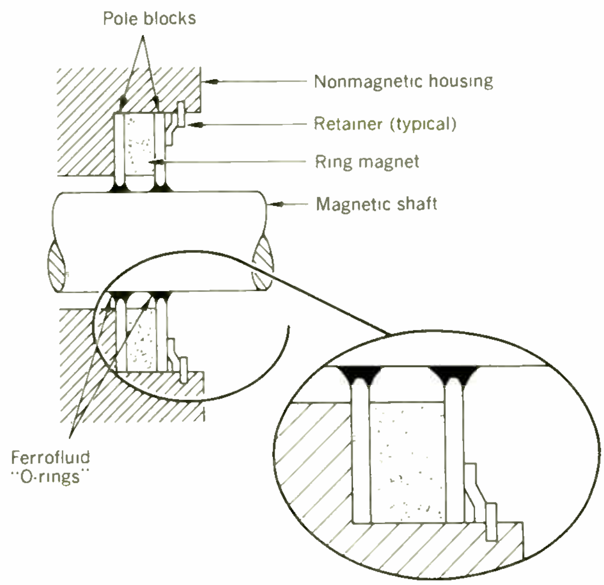
A laser face seal

Heretofore, ferrofluidic seals were built in only axial rotary-shaft configurations. Recently, a fer-

[1] Provision for in-situ replenishment of a fluid prolongs the seal life indefinitely. Liquid cooling extends seal speed range. Highest surface velocity attained to date is 12 000 revolutions per minute for an 8.89-cm shaft.



[2] The simplest of exclusion seals can withstand differential pressures up to 34.5 kPa (5 lb/in²).



rofluidic face was incorporated in a gas laser. To extend the life of the laser's window, manufacturers have tried various schemes for periodically rotating the window. These attempts have been less than satisfactory because of some loss of vacuum each time the window was turned. With the installation of a ferrofluidic face seal, vacuum integrity is maintained throughout many incremental rotations of the window.

Ferrofluids themselves may be useful as windows or shutters for high-power lasers. A simple electromagnet could control opening and closing of the shutter. However, optical transmission and absorption characteristics of ferrofluids, and the effects of intense laser radiation on them, have not been extensively measured or fully analyzed.

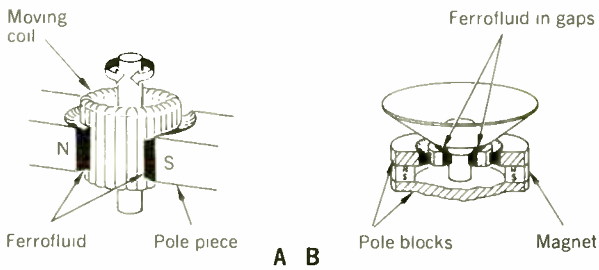
Damping

Viscous-damping advantages of liquids could not be exploited simply until ferrofluids provided the opportunity to position a small amount of liquid exactly where needed, and where its effects were predictable. Sensitive instruments are underdamped to eliminate friction from moving parts. In D'Arsonval meter movements and similar instruments with magnetic fields, damping to reduce needle oscillation is achieved with a small amount of ferrofluid in the gap that separates moving from stationary members. Because the magnetic field is usually highest in the gaps, the magnetic liquid clings to the surfaces. As an example, a flowmeter manufacturer damps an instrument readout ferrofluidically with the use of two permanent magnets that follow each other across a solid barrier.

In stepper motors with permanent magnets, ferrofluidic damping reduces settling time by a factor of three or four. The magnetic liquid is trapped magnetically between the stator and rotor. In force motors, a ferrofluid around the moving coil supplies the desired damping. The same technique, shown in Fig. 3, has been applied in loudspeakers and tweeters where the addition of ferrofluid decreases gap reluctance, seals the speaker assembly, provides self-centering positioning force on the coil, and gives controlled velocity-proportional damping.

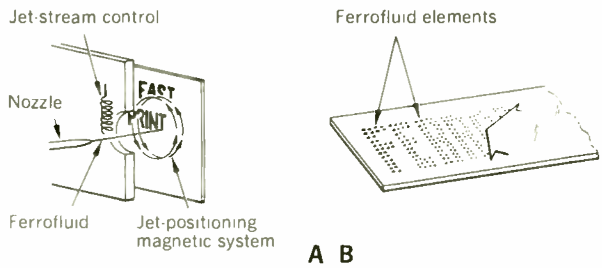
Permanent printing and erasable displays

Because ferrofluids respond readily to magnetic fields, a simple positioning set-up can control a special ferrofluidic ink for printing alphanumerics. As shown in Fig. 4, X–Y and on–off slave controls command a magnetic-ink-droplet jet for writing alphanumerics or drawing curves and pictures. Also shown in Fig. 4 is an erasable display in which a ball of ferrofluid is sealed within a capillary tube. Controlled magnetically, the ball rises to produce a dot image and falls to erase the image.

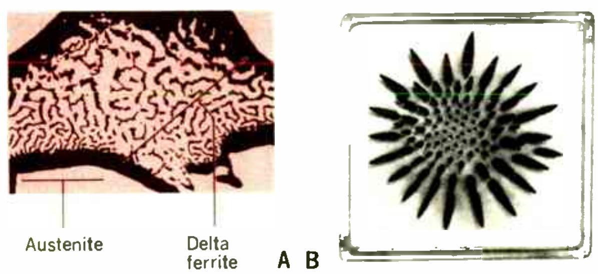


[3] A technique for damping an instrument coil (A) is also adapted to a loudspeaker (B).

[4] Printing of hard copy (A) requires a ferrofluid with exceptionally uniform colloidal particles. In display (B), capillary tubes sealed at both ends are aligned with the axes perpendicular to the plane of the surface. A ball of ferrofluid within each tube rises or falls in response to the "magnetic-pencil" sweeping across the top of the surface, and erasing the magnetic field on the reverse side.



[5] A ferrofluid highlights the delta phase within austenite and sigma granular structures of stainless-steel weldments (A). Spikes generated due to mutual self-repulsion of induced poles on the surface of the ferrofluid make up one example of how magnetic liquids can be used for educational purposes (B).



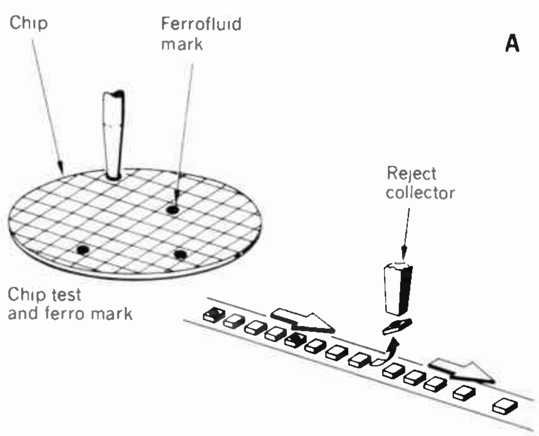
On the nature of ferrofluids

In making ferrofluids, 100-angstrom particles of a magnetic solid, such as magnetite, are colloidally stabilized in a carrier fluid. Monomolecular coatings help prevent particle flocculation—in effect, particles magnetically attracted to each other are repelled by the elastic coatings. In addition, the particles collide randomly with the carrier-liquid's molecules and these thermo-molecular collisions (Brownian motion) keep the particles suspended indefinitely.

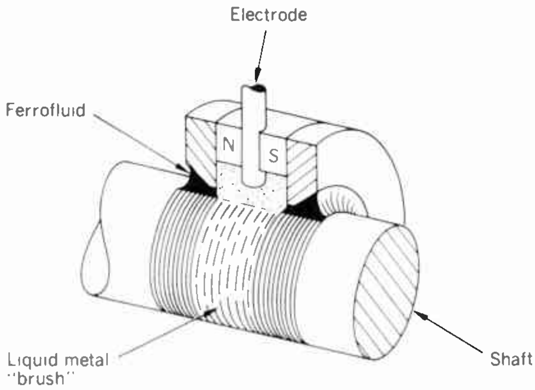
Because a ferrofluid is perfectly soft, magnetically, it shows a negligible hysteretic effect when an applied magnetic field is reduced to zero. When a magnetic field is applied, the magnetic particles become oriented almost instantly; when the field is removed, the particles demagnetize in aggregate. Electrically, commercial ferrofluids are nonconductive in such carrier liquids as diesters, fluorocarbons, hydrocarbons, and water. Electrically conductive ferrofluids, in metal carriers like mercury or gallium alloys, may be possible.

Mechanically and chemically, the magnetic fluid shares the characteristics of the carrier liquid in which the particles are colloidally suspended. Because the fluids are ultracentrifuged during their manufacture, they can withstand enormous acceleration forces without becoming unstable.

An applications sampler

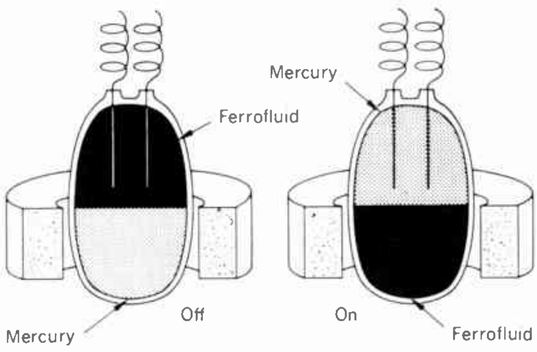


A

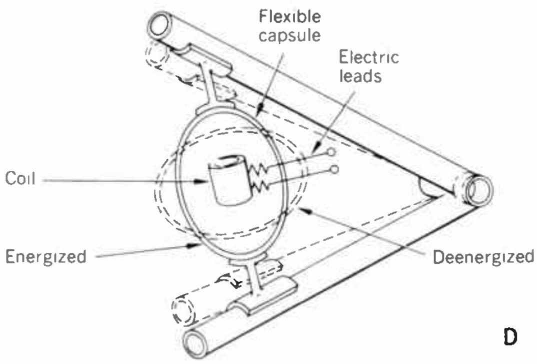


B

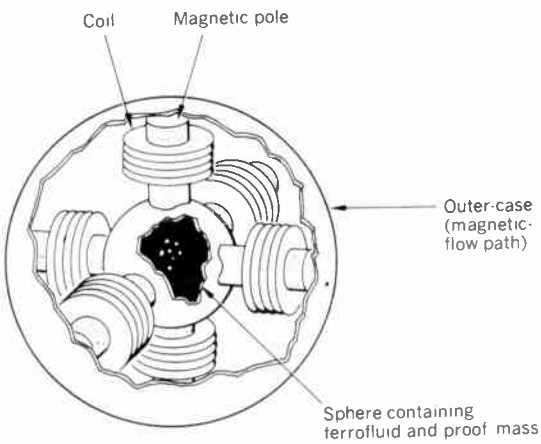
Semiconductor chip sorting (Fig. A). During acceptance tests, chips are marked with a ferrofluidic ink before slicing and dicing operations. Chips are then sorted either by magnetic pick-up or by reading the number or intensity of magnetic dots.
Liquid brush (Fig. B). Insulating ferrofluids seal-in conducting liquids such as mercury, gallium alloys, sodium, or potassium, to create nonwearing, no--noise electric brushes or slip rings.
Nonwearing switch (Fig. C). Mercury and a ferrofluid are encapsulated in a nonconducting container. Current applied to an electric coil causes the ferrofluid to displace the mercury into a pair of electric contacts. With current off, the switch opens.
Actuator (Fig. D). Developed originally as an artificial muscle, an actuator or transducer without sliding mechanical parts is created by filling a flexible container with a ferrofluid. Electric energy applied to a surrounding coil is then converted to mechanical displacement of the ferrofluid.



C



D



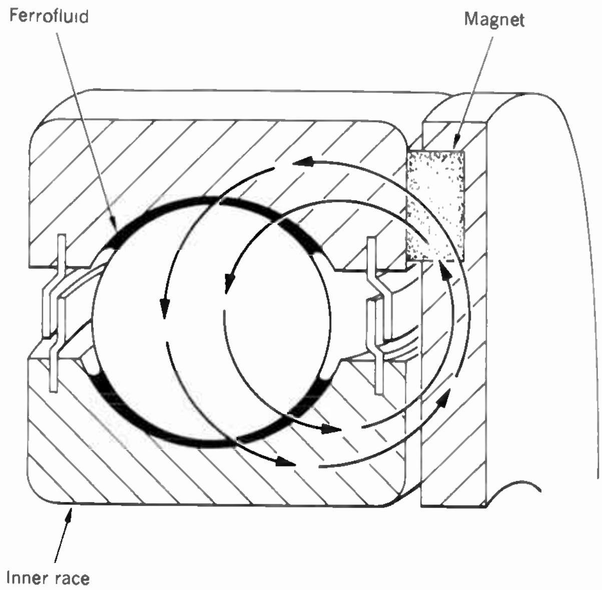
E

Triaxial accelerometer (Fig. E). A container is filled with a ferrofluid and has a nonmagnetic spherical proof mass. Deflection of the proof mass is monitored with electrostatic probes. Zero starting friction makes the unit sensitive to extremely low acceleration.

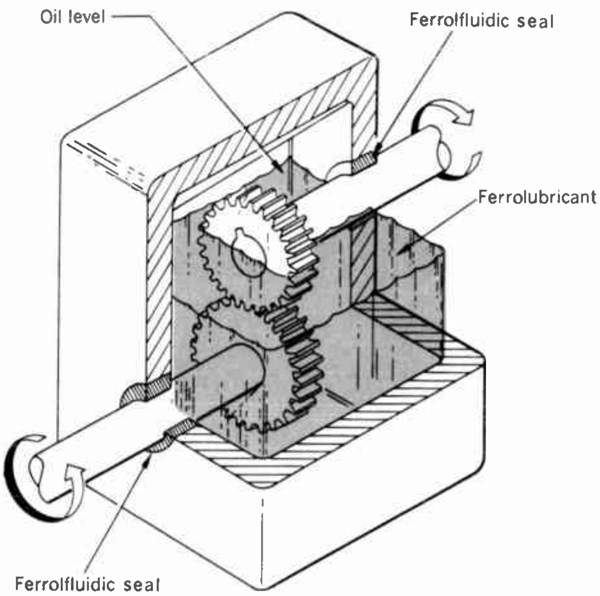
Test and measurement applications generally utilize the free-flowing nature of ferrofluids. As an example, ferrofluid on a motor stator with permanent magnets will become concentrated over the stator's poles. Ferrofluid spikes rise above each pole such that a spike's height is a measure of the relative magnitude of a pole's magnetic strength.

At one time, magnetic slurries encased in plastic were used for "visualizing" the energized sites on magnetic recording tape. In theory, the iron filings should have lined up with these sites. But the slurry dried out rapidly and the filings were too large to display the recorded signals accurately. Stable ferrofluids, with their magnetic subdomain particles, can be put directly onto the tape. The fluid lines up with energized sites to allow inspection or splicing.

In a similar application in basic research, the ferrofluid outlines magnetic domains so that the magnetic-domain structure of a bubble memory is observed through a microscope; at IBM, ferrofluid was used to simulate behavior of bubble memories mechanically. Ferrofluids can highlight strain-induced changes in



[6] A magnetized bearing retains a ferrolubricant to counteract film-starvation influences at the contact points of the rolling element and the races.



[7] Leakage is totally prevented in a gearbox with a magnetized lubricant and a ferrofluidic seal.

the magnetic microstructure of stainless steel, possibly providing a method for discovering weaknesses in metals before catastrophic failure of structures. Alternatively, a ferrofluid's free-flowing nature and responsiveness to applied magnetic fields can demonstrate magnetic phenomena more visually, and more accurately, than can the traditional iron filings. Figure 5 illustrates how ferrofluids highlight metal strain and magnetic phenomena.

Silencing a solenoid

Sometimes the need, or immediate applicability, of a ferrofluid is not readily apparent. A maker of high-fidelity turntables, for example, had made design modifications to improve the performance of his product. Every component worked as designed except for a solenoid which contributed a loud and unacceptable "thunk" every time it operated. A dab of ferrofluid to damp the solenoid eliminated the "thunk" and enabled the manufacturer to move into production with his new more-quiet turntable design.

Also designed for turntables was a sealed bearing in which magnetically trapped ferrofluid supports radial loads, and a gas, hermetically sealed at the bottom of the bearing, supports axial loads. Although not adopted for turntables, the bearing has been evaluated for other applications, such as supporting a disk, on which a laser writes data, where acoustical, electrical, and mechanical vibration isolation is a necessary requirement.

The development of this ferrofluidic bearing led to the concept of lubricating conventional bearings with a magnetic lubricant. Figure 6 shows how a permanent magnet can concentrate the ferrolubricant on only those areas where wear occurs. Many synthetic and natural lubricants can be made magnetic, with very little effect on their lubricating properties. Recently, a ferrofluid concentrate has been developed that can be added to existing lubricant reservoirs such that the lubricant becomes magnetic. With the addition of a ferrofluidic seal, as shown in Fig. 7, no lubricant leakage can occur.

An interdisciplinary challenge

Ferrofluids challenge the traditional discipline of electrical and electronics engineering. They combine electromagnetic phenomena with the physical and chemical phenomena of a fluid. They challenge the engineer to conceive of a material that acts as a magnetic solid at the same time it acts as a liquid. ◆

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Ronald Moskowitz (M) is the president and cofounder of the Ferrofluidics Corp. of Burlington, Mass. From 1961 to 1967, he was the principal investigator in the development of the magnetostatic method of spacecraft magnetic-dipole-moment measurement at RCA Laboratories and Astroelectronics Division. In 1967, he held a professorial appointment in electrical engineering at the University of Mississippi. He received the B.E.E. degree from the City University of New York in 1961, and the M.Sc. and Ph.D. degrees from Rutgers University in 1966. Dr. Moskowitz has published several papers on magnetic phenomena.

Equations for managers

Management "by the numbers" has been denigrated, yet the author, with tongue only partially in cheek, raises provocative possibilities

We engineers are inclined to try to reduce *all* problems to their essentials. This includes, wherever possible, putting our observations in the form of equations, inequalities, differential calculus, and sets. But will this technique work as we don our management hats? I'm inclined to think that, in some important cases, it will, and that, furthermore, it helps us to understand some normally hidden corollaries. So bear with me! You'll find no Fourier analysis, and you may question the rigorousness of my manipulations, but hang in there! We'll probe responsibility, authority, decision-making, and organization.

Risk: a linear equation

One of the most troublesome management problems I've encountered is one faced by the project manager—how can that guy ever accomplish his job when he has so little control over many of the variables? His sponsor keeps changing the budget. His boss keeps changing the objectives. His subcontractors fail to deliver on time or on cost . . . and yet, he is held responsible.

Years ago, an idea that remains prevalent even today was conceived—that responsibility and authority must match. We have all heard the assertion that one should be given enough authority to accomplish the job for which responsibility has been assigned. And, indeed, that may be true at the first level of management and for situations where the work output is largely one's own. But it is manifestly *not* true if the job involves very complex management tasks. Most obviously, responsibility and authority do not, and cannot, match in *project* management jobs.

Spacecraft and tracking network projects are good cases in point. The managers in such projects cannot conceivably be given control over all the elements necessary for success. Spacecraft managers have little or no control over the launch vehicle and, I would guess, sometimes wonder whether they have much say in other supporting systems such as tracking networks. But managers of the latter have to depend upon other countries, other communications networks, and sudden changes in their spacecraft customers' plans. And yet these managers are held responsible for "the whole show." The situation is much the same in defense projects and in contractor plants. (However, it is also true that project managers are usually given more than the average credit—or blame—for the performance of the whole show. On the one hand, the project manager may get national recognition—or he may get fired!)

But let's not agonize over the lack of a good match between authority and responsibility; instead, let me propose that this situation is reasonable and necessary. It is definable as follows:

$$\text{responsibility} - \text{authority} = \text{personal risk}$$

In other words, the greater the difference between responsibility and authority, the greater the personal risk. And if we assume that risk is rewarded by appropriate compensations, this situation is not something bad or regrettable. There are lots of high-risk jobs besides that of project managers—test pilots, astronauts, combat soldiers, Congressmen, quarterbacks, and coaches, too.

Fortunately, people who can and like to take risks have a psychological makeup essential for it. Yet they also must train, or be trained, to take risks by starting with small ones, taking on bigger ones as they learn how, often through mistakes. Too sudden an assumption of too much risk can be disastrous. (Not as frequently recognized is that, conversely, too sudden a shift from high-risk to low-risk work can be psychologically traumatic.)

In short, people in positions of higher responsibility than authority should be "trained volunteers." We should no more expect success from making project management the directed assignment of a previously untrained specialist than from asking a typical motorist to perform well as a test pilot, particularly when things go haywire.

Because of the potential trauma associated with risk-filled management positions, we may wonder if it is really necessary? I think an argument can be made that personal risk-taking is unavoidable for the success of projects. In most projects, decisions must be made with far less information than is needed for a zero-risk decision. A man unused to risk-taking would want to delay until all the facts were in—a decision in itself and almost certainly wrong. Such delay is no more realistic in project management, with its tight schedules, than in a game of chess or poker.

The linear relationship between responsibility, authority, and personal risk is only a first approximation, of course. It probably needs modification for situations where risk is negative and where responsibility so far exceeds authority that personal risk gets out of hand. In the latter situation, the project manager either quits or adopts a devil-may-care attitude, feeling in either case that he cannot be faulted if the project fails—as well it may.

The greatest difference between responsibility and authority, and hence the riskiest management positions, can be at middle-management, rather than top-management, levels. There, responsibilities tend to be for single large efforts; at the top the responsibilities usually cover a broader range and the risks tend to be averaged. Recognition of this situation is sometimes implied in compensation curves. Some bend

Eberhardt Rechtin Hewlett-Packard

over rather than rise linearly with increasing management rank. In any case, we should not begrudge project managers their due recognition—nor should they apologize for getting it. After all, we have little compunction about assignment of blame! On the other hand, if the risks and tensions of a particular middle manager's job are seen by top management as being excessive, then it is in the interest of the job and the organization to do something about it. Top management can take on more of the burden of responsibility and make more of its authority available to help the project manager. For example, it's surprising what so simple a thing as a phone call to the right guy at the right time can do when it comes from top authority. And it's amazing how much of a burden can be lifted from a middle manager's shoulders by a public statement from his boss that the boss fully agrees with what is being done by the manager.

A nonrandom series

A rule that was painful for me to learn as an enthusiast (if not evangelist!) for my projects some years back is that decisions must be made in the right order. Regardless of how urgent a particular decision may seem, if it isn't preceded by the necessary prior decisions, it won't work out. Perhaps this is self-evident to those of you who work with PERT charts every day. But it wasn't obvious to me for some years that management decisions had to be ordered and scheduled and not "just made" in whatever order seemed convenient or satisfied the noisiest claimants for attention. Let's look at an example.

The table lists several top management decisions that need to be made in order to begin a project. These decisions, if made as shown under "successful sequence" are reasonably likely to avoid trouble. The "disastrous sequence," on the other hand, can almost be guaranteed to produce overruns, missed schedules, and a frustrated if not embittered project staff. Among other things, the project manager arrives on the scene late, only to find the commitment has been made to produce something without the resources or technical developments to back it up. Furthermore, he inherits a staff which he hasn't had a hand in selecting. Now, there's real personal risk!

The placing of decisions in the right sequence and at the right time takes courage—it is almost the opposite of the idea that "the squeaking wheel gets the grease." By the same token, when the time for the decision does come, it *must* be made or later decisions will be fouled up.

On responsibility
'Responsibility and authority do not and cannot match in project management jobs'

A variation of this rule is that some possible decisions should simply be avoided—they either lead nowhere, or else subsequent events may make them obsolete. This conscious avoidance of decision is not the same as hoping a decision will go away—it is based on having reason to believe it will be unnecessary.

I. Project decision sequences and consequences

Decision	Successful Sequence	Disastrous Sequence
Determine in-house resources	1	7
Select interesting project type	2	1
Choose project manager	3	6
Draft proposal	4	2
Find sponsor	5	3
Begin critical developments	6	9
Specify performance, time, and cost	7	8
Obtain funding commitment to complete	8	4
Organize for the long haul	9	5

The application of this rule is seen not only in the PERT chart, but it is also applicable in the budget cycle and in questions of reorganization, where its misapplication can have great impact. In the latter, as in a game of chess, making moves in the wrong order is a prescription for disaster or for a hopeless stalemate. And, as in chess, too, managing a reorganization takes concentration, patience, and the risk-taking ability of a master.

Some Boolean thoughts

Good sets of objectives to assure project success, or good corporative objectives for company success are hardly arguable. I submit that those same sets of objectives may also determine what the organization should *not* do. The postulate is:

In other words, a set of objectives which, if met, assures success in area A does not automatically guarantee success in area B, and may lead to failure. In many technically talented organizations there is a belief that the organization could do anything it might choose to do. For such organizations, the hardest but wisest decisions may be to stay *out* of some appealing technical areas, because the organization is unlikely to do well there.

A few examples:

- A large aerospace organization whose forte is large projects will seldom do well in small jobs—the overhead essential for the large projects may easily sink the small ones.
- A high-technology organization devoted to high-quality and high-performance products will seldom do well in a highly cost-competitive market—it doesn't know how to make a cheap product (and might think it slightly immoral to do so!).
- A large industry whose livelihood depends upon a particular product, such as oil or automobiles or wool or electric power, will usually succeed in R&D devoted to product improvement but seldom in R&D aimed at product replacement—in the latter, it has too much to lose! (As a case-in-point, none of the three leading semiconductor manufacturers ever made vacuum tubes.)

The reasons usually given for less-than-successful performance in such cases often range from "personality conflicts" to poor planning. But I suspect that most really stem from people not doing what comes naturally, or unknowingly working at cross purposes. In short, the company objectives don't match what is needed for success in the particular project.

On decisions
'When things really begin to look up, a fundamental decision has probably been made'

Another variation of this postulate is seen in the deliberate designing of objectives to deny success in undesirable areas. One good example is the U.S. solution to the age-old problem of preventing an internal takeover of the Government by the military. The mechanism was to set, by law, objectives which are inherently conflicting. There are inherent conflicts between security and keeping the populace informed, between being a professional military force and reporting to political appointees with little military experience, and between keeping a technological edge against our more numerous opposition and holding costs to tight limits. A wise observer of the Washington scene took note of the situation saying, "The Constitution and the Congress in their wisdom made sure that the Department of Defense could never do its job too well!"

A first derivative

How does one deal with those risky decisions where complete information is not available? How can we tell, *early*, whether the decision is probably right or probably wrong?

For a good decision,

$$\frac{d}{dt}\text{(new solutions} - \text{new problems)} > 0.$$

In other words, if, after a decision, new solutions arise faster than new problems, we are probably on the right track. Things, in other words, are looking up. On the other hand, if the project runs into more and more problems with fewer and fewer solutions, the decision may well have been wrong, and steps should be taken to rectify it.

This relationship, being an inequality, suggests the imprecision associated with judging decisions. It also tends to suggest that the more positive the left hand side, the better—but without saying by how much. And the time derivative reflects the old truism that "time will tell" in judging decisions.

A particular decision that had the above characteristic was the U.S. choice of using continuously operating, stabilized spacecraft for exploration of deep space, rather than intermittently operating spacecraft. The U.S.S.R. took the latter approach, and lost. On the negative side, an early U.S. decision to take over the Vietnam fighting from the South Vietnamese led to an escalation of problems; when the decision was reversed, the situation began to clear.

In my own experience, I've found this relationship helpful in maintaining confidence in what is going on during the course of a project. It also makes me feel, when things really begin to look up, that a fundamental decision has been made, not just another of the many "routine" detail decisions that are necessary. To elaborate, we all know that project objectives are fundamental, and that a good amount of effort must be expended at the outset to define the objectives correctly *and* completely. Yet, it often happens that the initial list is incomplete, with a consequent risk to success. Clearly, the sooner a necessary objective is recognized, the better. One of the quickest ways I've found to spot a previously unrecognized, fundamental objective is to observe when a particular decision clears up a lot of arguments very quickly. It is quite likely that the particular decision dealt with, *de facto,* a missing objective; explicit recognition of that objective can enhance the probability of success. An example is the delayed recognition by the Apollo project managers of the importance of real-time television from the moon. Not stated as an original objective, it later proved central to complete success.

A corollary to the foregoing relationship is that fundamental decisions that are sound tend to make a project or organization self-managing. Later, subordinate decisions can be made at lower management levels almost automatically—they "fit." Hence, recognition of a good decision can help pinpoint those fundamentals that underly a smooth running operation.

In my experience, the number of fundamentals that control success or failure in a major project is remarkably small—a handful at most. Hence, the importance of searching them out if they aren't apparent.

A topological exercise

Popular organizational topologies are the line/staff and the matrix, and, of course, there are hybrid formats, too. Yet, regardless of which topology is embraced, there has never been an organization without serious problems. There are just different organizations having different problem sets. These problems are unavoidable—they are inherent in the topology of the organization chart. And it does no good to avoid making an organization chart—that only results in the emergence of an informal or phantom organization that has its own problem sets. The problem set for a line/staff topology usually includes inter-element friction, inflexibility and difficulty in changing direction, and a high level of status consciousness. The problem set for a matrix-type format, on the other hand, usually includes excessive paperwork, multiple bosses, and, perhaps, undue mismatch of responsibility and authority.

On organization
'There's never an organization without serious problems—there are just different organizations having different problem sets'

The urge to reorganize often arises when the problem set associated with an existing organization, say set *A*, becomes so irritating that managers begin sketching out an alternate organization, *B*, designed to get rid of problem set *A*. The known demerits of *A* are then compared to the presumed merits of organization *B*. Since many of the proponents of the reorganization haven't lived through the problem set of organization *B*, they either don't recognize it or believe it soluble. Should the reorganization take place, then its members may revel in the lack of problem set *A*—but only until problem set *B* rears its ugly head.

In light of this situation, a more realistic approach to reorganization would be as follows:

1. List the problems of the present organization, *A*.
2. Suggest organizations (*B*, *C*, etc.) which eliminate or alleviate the worst of problem set *A*.
3. Assume the role of devil's advocate, listing, as objectively as possible, problem sets *B*, *C*, etc.
4. Determine how the effects of the problems in each set might be minimized, or show that the effects are of little importance in the kinds of jobs that have to be done by the organization.
5. Then compare the proposed organizations/problems/effects and determine which organization *and associated problem set* you wish to enjoy/endure.

Exponential delay

Having presented some observations in the abstract forms of equations, inequalities, calculus, and sets, I shall conclude with an equation on bureaucracy. Having been a bureaucrat (hopefully in a constructive way!), I nonetheless propose the following frightening relationship between the time it takes to get full approval and the number of signatures required to do it:

$$T = 2^{n-2}$$

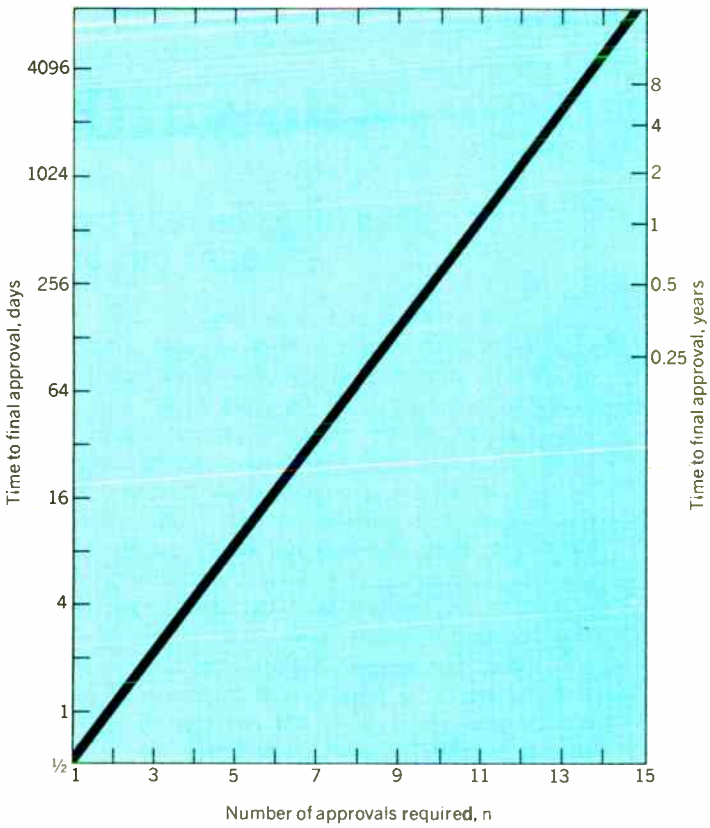
where T is in days and n is the number of signatures.

For reference, approval typically takes ½ day if only one signature is needed. On the other hand, if a dozen signatures are required, approval will take about three years. Those of you who live with projects requiring full-scale Governmental approval, including Congressional appropriation of funds, will sympathize. This exponential relationship seems to hold from n = 1 to at least n = 15. (See curve above.)

The relationship is best confirmed experimentally, but it can be derived. Assume a project is proposed to a superior. He seldom approves immediately but asks for a revision. The proposer starts again, proposes again, gets his first signature, and the project goes to the next level. There it is seldom approved but is instead sent back, not just to the next level down but to the beginning.

There are important corollaries. Every time an additional signature is required by the establishment of a new organizational level of "coordination," the approval time *doubles*. Fair warning to reorganizers! At JPL we could all look back fondly to the early space days when the signatures were few and the final approval times short, even for some very complicated projects. Or, look at what it now takes to get approval for a computer, or a freeway subject to environmental impact statements!

As a constructive recommendation, if the number of signatures required cannot be reduced, one should try to get as many signatures *in parallel* as possible. A particular example of trying to do this arose in the problem of rapid command and control of the military strategic forces. The command chain has many levels, and almost all are necessary depending on the circumstances. But it took too long to take action. So a concept is being worked on which is, essentially, operating the chain in parallel—all levels informed simultaneously and commenting on a kind of management-by-exception basis. Such a scheme will not work for the routine, massive jobs for which the chain of command was originally designed, but it may well handle the special case of expedited action.



The delay time to final project approval increases exponentially as a function of the number of signatures required in sequence. Twelve approvals take about three years.

Many engineers to whom I have presented the foregoing "management math" have reacted by saying, "*Now* I understand!" Then they've suggested "theorems" of their own; the reader is invited to do likewise. ◆

Eberhardt Rechtin (F) joined Hewlett-Packard Company in 1973 as manager of telecommmunications and, in 1974, was named chief engineer, responsible for coordinating corporate-wide engineering activities and managing the company's telecommunications affairs. Before joining H-P, Dr. Rechtin was the U.S. Assistant Secretary of Defense (Telecommunications), Principal Deputy Director of Defense Research and Engineering, and Director of the Defense Advanced Research Projects Agency. At the Jet Propulsion Laboratory, California Institute of Technology, he directed the Deep Space Network of the National Aeronautics and Space Administration (NASA) and JPL. Dr. Rechtin, a Fellow of the American Institute of Aeronautics and Astronautics, and a member of the National Academy of Engineering, received his B.S. and Ph.D. degrees from the California Institute of Technology.

Kilowatthours vs. liters

Gas buggies may be on the ropes by the Eighties if "super batteries" arrive on schedule

Long known only as golf carts and "go" carts, electric vehicles in increasing numbers are appearing in specialized intraurban applications—from industrial delivery to people-moving (both in buses and private automobiles). When operating at low speeds (under 60 km/h) and within a low acceleration range (to 50 km/h in at least 10 seconds), these lead-acid-battery-powered electric vehicles are significantly more efficient than their conventional gasoline-powered counterparts, but so far, they have been limited, in speed and range, by the lead-acid batteries presently available. This limitation may well be passé by the mid-1980s, assuming availability, in large quantities, of batteries with high power and energy densities by that time. As a result, the electric vehicle, with its already formidable assets, could well play an important role in vehicular transportation in the future.

But what of today's electrics? How good are they? The currently available limited-performance electric vehicle can reach typical cruising speeds of 65–80 km/h and is capable of accelerating from 0–50 km/h in 10–15 seconds. Its driving range, at maximum cruising speed, is typically 65–80 km, a figure that increases at reduced speeds. But determining precisely how today's electric vehicle compares to its gasoline-powered competitor is a somewhat more difficult task.

This author examined published test results of two different models of limited performance (lead-acid-battery-powered) electric automobile prototypes—a 2100-kg model and a smaller "urban" car weighing 750 kg.

The overall specific energy consumption (see box on p. 63 for a precise definition of this term) for the two electric vehicles was calculated by considering each vehicle as part of an overall system including the electric power plant and transmission and distribution network (Fig. 1). Current nationwide efficiencies—35 percent in power generation and 91 percent in its transmission and distribution—were assumed. The calculation was based on published measured values of ac energy, fed to battery charger, multiplied by the above efficiencies of power generation and distribution. Overall specific energy consumption in the limited-performance electric vehicles, at different speeds, was plotted (Fig. 2). In the same figure, similar overall specific energy consumption curves for two gasoline-powered vehicles were plotted for comparison.

Gasoline car—fuel and energy consumed

Obviously, the energy consumption of conventional gasoline-powered cars can be used as a baseline, but the energy consumption for these cars varies widely, even in two identical model cars from the same manufacturer. Therefore, the baseline data must be derived by averaging measurements on a large number of cars. Results of such measurements have been available in terms of "fuel economy," expressed in km/liter, during the Federal Driving Cycle or at "constant cruise speed" (see box on p. 63). The data used were all for 1968–69 model cars.

Figures 3 and 4, plotted from the fuel economy data, show that, at low speeds and over the Federal Driving Cycle, specific fuel consumption (see box on p. 63) in 1/(km × kg) varies only slightly with vehicle weight. The variations are relatively higher at higher speeds, due, primarily, to the nonlinear variations in aerodynamic resistance with weight. The data of Figs. 3 and 4 are used as baseline for comparison of electric to gasoline vehicles. But a question immediately poses itself, and that is: how can a comparison be made between such different data—overall specific energy consumption, of electric vehicles against specific fuel consumption of their gasoline-powered counterparts? This can be done by considering the energy content of the burned fuel and converting the fuel consumption information to overall specific energy consumption.

Two actual gasoline vehicles—a 2100-kg conventional car, and a 610-kg, special purpose, "urban" car—were selected for comparison with their previously mentioned electric-powered counterparts. Similar to procedures carried out with the electric vehicles, overall specific energy consumption for the two gasoline cars was calculated by considering each vehicle as part of an overall system, including the refinery and gasoline transportation and distribution network (Fig. 5). The overall specific energy consumption is thus expressed in kWh/(km × kg) of crude oil fed to the refinery. For the 2100-kg car, this was obtained from the curves of Fig. 4, assuming 10-percent deterioration in fuel consumption associated with pollution devices of more recent, conventional gasoline cars, and a combined efficiency of 85 percent for refining, transporting, and distributing gasoline. Energy consumption values for the special-purpose urban car were obtained from published fuel economy data for the car, and by assuming the above efficiency for refining and distributing gasoline. It was further assumed that about 9.3 kWh of energy are contained in one liter of gasoline.

Comparing energy consumptions

In Fig. 2, overall specific energy consumption curves for two gasoline vehicles traveling at different speeds are included, in addition to electric vehicles curves. From the figure, it is clear that, at all speeds, the overall specific energy consumption of each gaso-

Jalal T. Salihi Otis Elevator Co.

Useful terminology

Fuel economy, a key term in evaluating energy consumption in cars, is normally expressed in kilometers/liter. Another convenient way of expressing fuel economy is in terms of *specific fuel consumption* defined as liters consumed per kilometer per one kilogram of the car's weight. Such a criterion, almost independent of vehicle weight (see Figs. 3 and 4 in the main text), gives a true measure of energy-conversion efficiency.

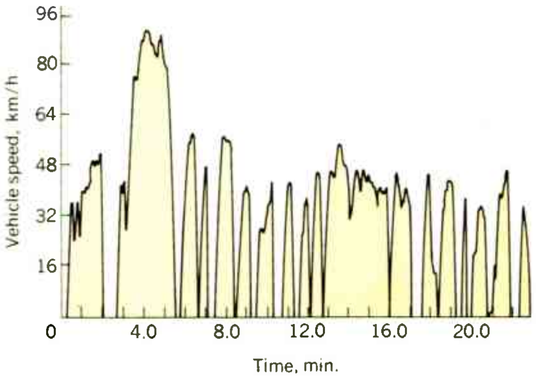
Another useful criterion in analyzing vehicle efficiency is energy consumption—the energy consumed per unit distance (kWh/km), under specified conditions. From this term, *specific energy consumption* is derived—the energy consumed per unit distance per unit weight of the vehicle, expressed in kWh/(km × kg).

A related term is *overall specific energy consumption*—the energy that has to be fed into a system per unit distance per unit weight of vehicle, in kWh/(km × kg). In the case of electric vehicles, this relates to energy of coal, or other fuels, fed to the power plant. In gasoline vehicles, it relates to energy of crude oil fed to the refinery.

In the calculations, *road energy* is used to refer to the total energy supplied to the wheels to overcome air drag and rolling resistances, as well as vehicle inertia during acceleration.

Again, the *average efficiency of electric car* is defined as the ratio of road energy per unit distance to ac energy supplied to battery charger, per unit distance. *Average overall system efficiency of an electric car* is defined as the ratio of road energy per unit distance to corresponding energy of coal of other fuel, per unit distance, fed into the electric power plant. Similarly, the *average efficiency of a gasoline car* is the ratio of road energy per unit distance to the corresponding energy in gasoline, consumed in the fuel tank per unit distance. And *average overall system efficiency of a gasoline car* is the ratio of road energy per unit distance to corresponding energy of crude oil fed to the refinery.

A fundamental measure in the evaluation of cars is their performance in specified driving cycles—the *Federal Driving Cycle* (FDC), for example. Currently used in emission measurements, FDC is derived from actual driving patterns encountered by Los Angeles suburbanites. The 'cycle' (see figure) has a precisely specified pattern of speed vs. time, including accelerations, decelerations, and stops, and it covers a total driving distance of approximately 12 km during a period of 1370 seconds. The aerage FDC speed is about 31.4 km/h. One other gage for assessment of car operation is its performance at *constant cruise* speed—namely, when the car is moving at a fixed speed (say, 80 km/h), experiencing no acceleration or deceleration.



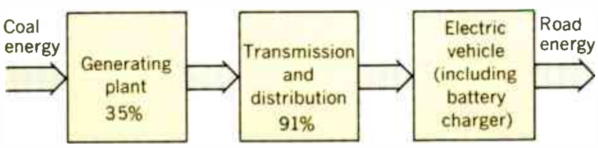
This precisely specified "Federal Driving Cycle" (FDC) includes accelerations, decelerations, and stops, over nearly 23 minutes. The cycle is currently used mostly in emission measurements, and it was derived from actual driving patterns encountered by Los Angeles suburbanites.

line vehicle is considerably higher than that of its electric counterpart. For example, at 64 km/h, a ratio of 1.5:1 exists between the consumptions of the 2100-kg gasoline and electric vehicles.

From Fig. 2, it is also noted that the urban gasoline-powered car attains an optimum fuel economy of 31 km/l at 48 km/h. However, this car is only about half as efficient as an electric car of equal test weight moving at the same speed. It is further noted that the efficiency of the electric car increases as the speed decreases, while the efficiency of the gasoline-powered car deteriorates appreciably with declining speed.

In the previous analysis, overall specific energy consumption of gasoline-powered vehicles was derived from fuel economy data. A reverse process, related to electric vehicles, can also be very useful. That is, at a given overall specific energy consumption of an electric vehicle, what fuel economy is needed from a gasoline car of similar weight, to get the same consumption? To answer this question, data on energy consumption of two electric vehicles were compiled over "average" city and residential driving cycles (not the Federal Driving Cycle) and were computed in a manner similar to that used to obtain the electric vehicle consumption curves in Fig. 2. The results (Fig. 6) show that the overall specific energy consumption of limited-performance electric vehicles is almost independent of vehicle weight. The overall energy consumption is, therefore, nearly proportional to weight. In addition, it was concluded from Fig. 6 that a fuel economy of nearly 19 km/liter would be needed in a 906-kg gasoline vehicle to achieve the efficiency of an electric vehicle of similar weight, under the mentioned conditions.

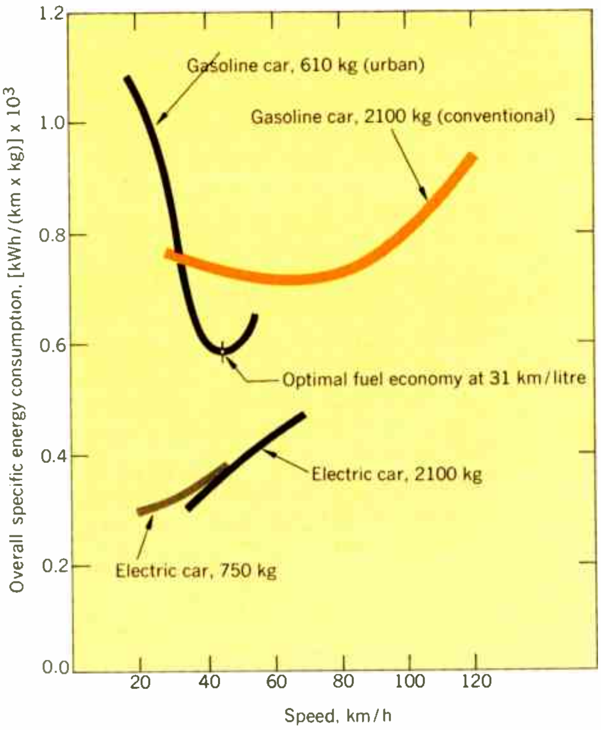
[1] Overall system representation of battery-powered electric vehicles, assuming current nationwide efficiencies—35 percent in power generation and 91 percent in its transmission and distribution in the U.S. Vehicle efficiency has not been included as it varies with driving mode for a specified vehicle.



These data indicate that available electric vehicles are significantly more efficient than conventional gasoline-powered vehicles during both city driving and driving cycles involving low speeds and frequent stops.

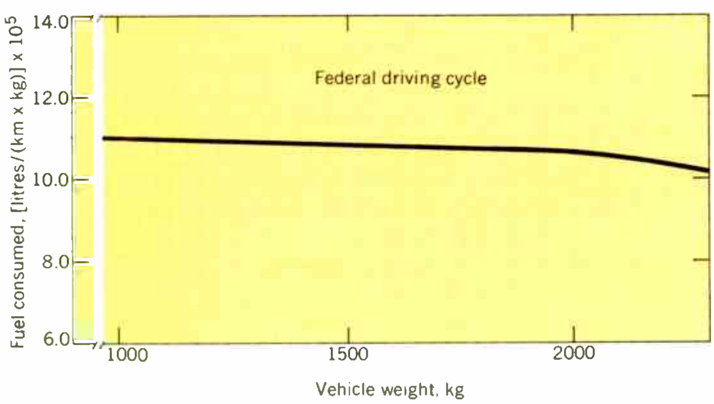
Future electric cars

The primary factors limiting the performance and range of the available electric vehicle are the low

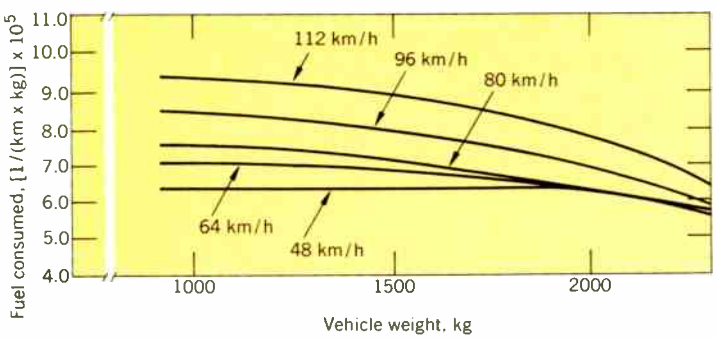


[2] Comparison of overall specific energy consumptions of lead-acid-battery-powered electric vehicles with those of gasoline-powered vehicles at constant cruise speeds. The weights shown are the vehicles' "test weights," a term that generally includes passenger and instrumentation weights, in addition to the vehicle's own "curb weight."

[3] Specific fuel consumption of conventional gasoline-powered cars, over the Federal Driving Cycle (see box on p. 63). The curve represents an average of data taken from over 170 cars, all 1968–69 models.



[4] Specific fuel consumption of conventional gasoline-powered cars at constant cruise speed (see box on p. 63). Average data from a large number of 1968 and 1969 model cars were used.



power and energy densities of current lead-acid batteries. These terms are usually defined as power (energy) per unit weight (not volume) of battery. Research has been underway to make batteries with improved characteristics. Energy density of 212 Wh/kg, about 6–7 times the values of present-day lead-acid batteries, and power density of 212 W/kg will be needed to provide, in future electric cars, the range, performance, and comfort (heating and air-conditioning, for example) available in present-day gasoline cars. Assuming the future availability of such batteries, energy consumptions and efficiencies of a high-performance electric car and a conventional gasoline-powered car can be compared.

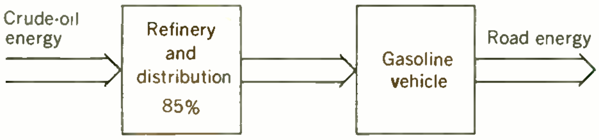
An exact analysis of the energy requirements for the future electric car over a given duty cycle requires knowledge of both the characteristics of each component in the vehicle's "power train" (for example, efficiency at different vehicle loads and speeds) and the values that will determine the maximum efficiency of the entire vehicle. The same is true for the conventional gasoline-powered car. However, such information for electric cars is not available, and, despite the long history and large population of gasoline-powered cars on the road, there is negligible data in the open literature regarding the full characterization of their components and their simulation on practical duty cycles. Therefore, it becomes necessary to assemble the widely scattered established data available on electric vehicles as well as conventional gasoline-powered cars, and then to interpolate those data, all the while eliminating unnecessary variables.

Heeding these guidelines, this author has posited a hypothetical electric car of the future that would weigh 1430 kg and would have body design and road losses similar to those of a conventional car of equal weight. Energy and power densities of 220 Wh and 220 W per kg and a combined charge–discharge efficiency of 72 percent are assumed for the battery of this reference car. The efficiency values assumed for the rest of the power-train components are achievable with current technology. The motor, it is assumed, would provide smoothly variable transmission without gear shifting and would power the rear wheels through a conventional differential including a fixed gear reduction to match the motor speed to the wheels.

To compute energy consumption, assume that maximum battery weight is limited to less than 25 percent of the total car weight. In the calculations, 113 kg, representing average additional passenger and luggage weight, must be added to the car weight.

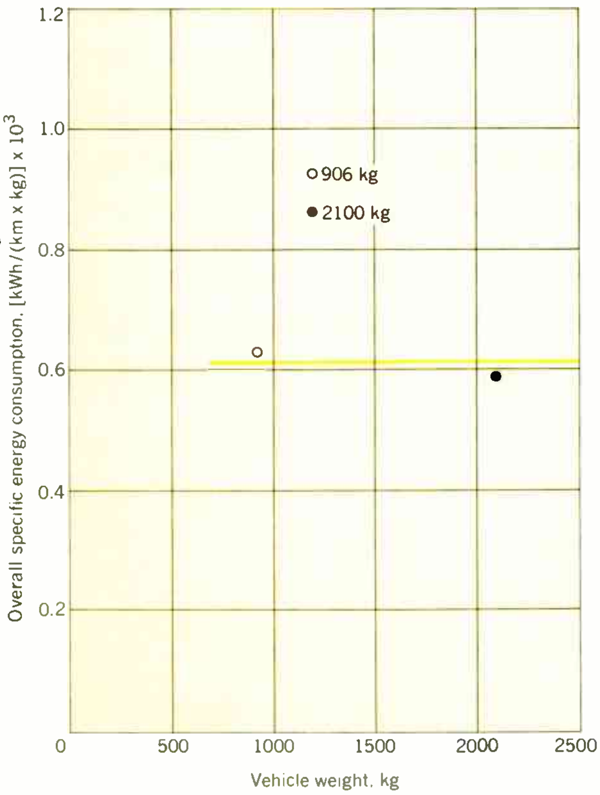
In Fig. 7, overall energy consumptions and efficiencies of the hypothetical electric car are depicted, along with comparable values for the baseline gasoline-powered car of the same weight and road energy (see box on p. 63). Since the operation of a passenger car is a mixture of the two driving modes used in Fig. 7 (that is, the Federal Driving Cycle and a constant speed of 112 km/h), the average of the two modes is employed as a basis for comparing energy consumptions and efficiencies. Using these average values (see the table that summarizes Fig. 7), we note that the hypothetical electric car of the future will consume about 72 percent of the energy required by its gasoline-using counterpart—1.32 kWh of coal fed to the power plant against 1.84 kWh of crude oil fed to the refinery for each kilometer of driving. And these results also indicate that the projected electric car will be more efficient than its gasoline competitor.

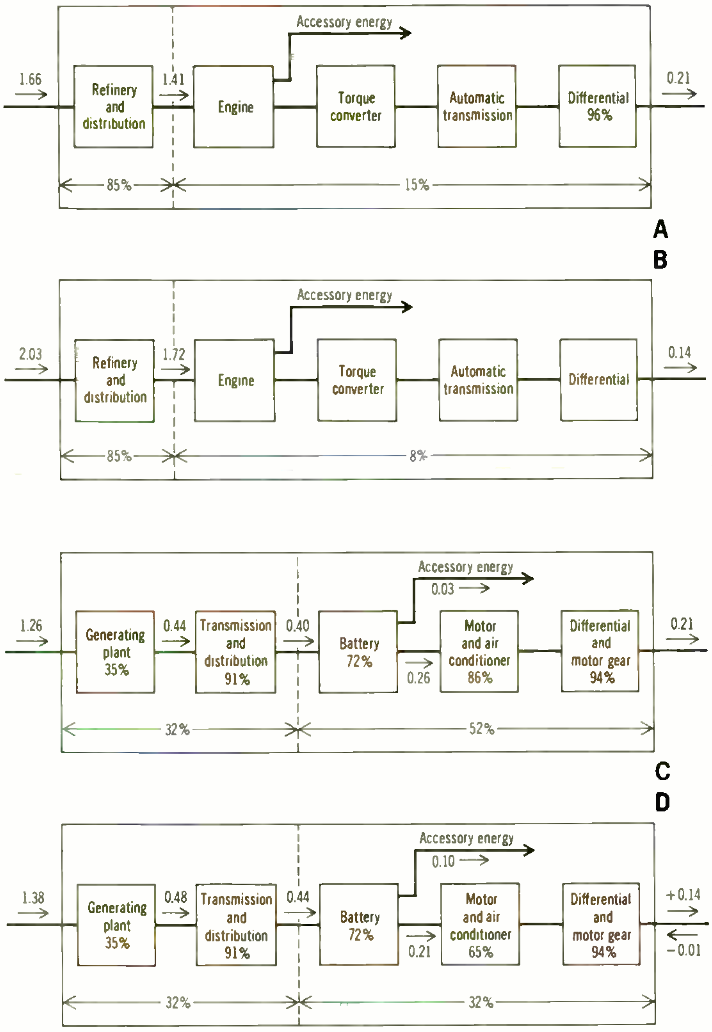
Despite the foregoing analysis, the final word has not yet been said about the efficiency of future electric cars. I have shown (see, the first reference in the "For further reading" box, p. 66) that by improving the aerodynamic design of the body, using more efficient tires, and better matching of power-train components, the energy consumption of the hypothetical electric car could be improved by 30 percent. Furthermore, I believe that a lighter-weight, optimized 906-kg electric car is the most likely type of future electric car, in view of energy and fuel saving requirements. In addition to its projected lower energy consumption (0.20 kWh against 0.42 in the 1430-kg hypothetical electric car, in ac-energy fed to battery charger, per km) this smaller, future electric car will also be more appropriate for residential charging, in



[5] Overall system representation of gasoline-powered vehicles, assuming 85 percent efficiency for refining, transportation, and distribution of gasoline. Vehicle efficiency has not been included as it varies with driving mode for a specified vehicle.

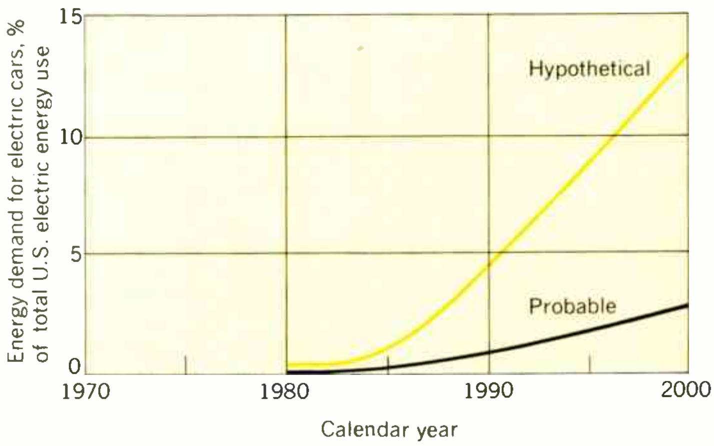
[6] Overall specific energy consumption of lead-acid-battery-powered electric vehicles during average city and residential driving cycles (not the Federal Driving Cycle). The weights shown are the vehicles' test weights (see Fig. 2 caption for an explanation of this term).





[7] Energy flow diagrams in a conventional, baseline, 1430-kg gasoline-powered car, and in a hypothetical, reference electric car of similar weight, body design, and road losses. All energy consumption levels per unit distance are expressed in kWh/km. Partial efficiencies of system components, indicated in percent, represent the ratio of average output to input energy per unit distance, in each component. A—Gasoline car at 112 km/h; B—Gasoline car at Federal Driving Cycle; C—Electric car at 112 km/h; D—Electric car at Federal Driving Cycle. The effect of energy regeneration during parts of the cycle is represented by 0.01-kWh/km reduction in road energy.

[8] Impact of widespread use of electric cars on total usage of electrical energy in the U.S.



view of charging limitations in residential electrical wiring systems.

Electrics' impact on energy demand

What impact will electric cars of the future have on energy demand from power generating plants? The answer depends on several factors beyond the energy consumption of electric cars themselves. These are: the growth in electric car population, the average yearly mileage per car, and the increase in power generating capacity. I assume electrics will replace gasoline-powered cars gradually, and the rate will be mostly determined by the availability of practical high-energy-density batteries, that are not likely to be developed before 1980. Even if the technology for manufacturing such batteries is developed by then, an additional five years would be needed to produce these batteries in large quantities. Consequently, about five million electric cars are projected to be on the roads in the U.S. by 1985. In a hypothetical case, an extremely fast growth rate of the electric car population beyond that year will lead to about 180 million electrics by the year 2000. A more probable growth rate leads to about 72 million electric cars by the year 2000.

Assuming a yearly average driving distance of 16 000 km per car, and a gradual increase in energy usage leading to over 9000 billion kWh per year in the U.S. in the year 2000, the impact of electric cars on energy usage in the U.S. was plotted in two cases (Fig. 8). According to the probable assessment, 72 million electrics in the year 2000 (40 percent of the total estimated car population), with an energy consumption of 0.20 kWh/km per car (ac energy fed to battery charger), would consume 2.5 percent of the total electric energy generated. However, even in a hypothetical worst case (180 million electrics consuming 0.42 kWh/km each), the impact will only be 14 percent. ◆

I. Energy requirements and overall system efficiencies for a hypothetical electric car and a baseline conventional gasoline-powered car, of identical weight (1430 kg) and structure, and having similar road loads

	Constant Cruise Speed (112 km/h)	Federal Driving Cycle	Average
Energy consumption and efficiency of cars			
Ac energy per unit distance, fed to battery charger of electric car, kWh/km	0.40	0.44	0.42
Heat energy per unit distance, of fuel in tank of gasoline, kWh/km	1.41	1.72	1.56
Efficiency of electric car, (%)	52.4	32.4	42.4
Efficiency of heat engine car, (%)	15	8.3	11.6
Overall system energy consumption and efficiency			
Heat energy per unit distance, in coal fed into electric power plant for the electric car, kWh/km	1.26	1.38	1.32
Heat energy per unit distance, in crude oil fed into refineries for gasoline car, kWh/km	1.66	2.03	1.84
Electric car system efficiency, (%)	16.7	10.3	13.5
Heat engine car system efficiency, (%)	12.7	7.1	9.9

For further reading:

Energy consumption data of a high-performance electric car and its impact on electric power generation and distribution systems were derived mainly from the paper, "Energy requirements for electric cars and their impact on electric power generation and distribution system," *IEEE Trans. on Industry Applications*, vol. IA-9, no. 5, pp. 516–531, Sept./Oct. 1973, by the author. Specific fuel consumption data over the Federal Driving Cycle, shown in Fig. 3, were derived from the Environmental Protection Agency's (EPA's) Technical Report of the Office of Air and Water Programs, Nov. 1972—"Fuel economy and emission control." The constant-speed specific fuel-consumption data, of Fig. 4, were derived from *Consumer Reports* (pp. 33, 93, 153, 329, 359, and 549 in the 1968 edition; and pp. 29, 87, 159, and 325 in the 1969 edition). The overall specific energy consumptions of lead-acid battery-powered electric vehicles (Fig. 2 and 6) were computed from measured data on ac energy fed to the battery charger. The data for the 2100-kg electric car were derived from Report No. JV-2623-K-1 of Cornell Aeronautical Laboratory—"Technical Report on Mars II Electric Automobiles." The data for the 750-kg electric car in Fig. 2 were derived from SAE's paper No. 690461 of May 1969—"Special-purpose urban cars," by Gumbleton *et al.* The data for the 906-kg electric car in Fig. 6 were derived from SAE's paper No. 720188 of Jan. 1972—"Sandancer, a test-bed electric vehicle," by R. S. McKee *et al.* (More can be learned on this topic from p. 528 of the previously cited IEEE paper by the author.) The overall specific energy consumptions of gasoline cars (Fig. 2) were derived from published data on fuel economy. The data for the urban, 610-kg gasoline car come from SAE's paper No. 690461 of May 1969, "Special purpose urban cars," by Gumbleton *et al*: and for the 2100-kg, conventional gasoline car, from the specific fuel consumption data of Fig. 4.

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