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IEEE spectrum

features

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THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.

departments

the cover

The heavy and ever-increasing density of air traffic, particularly over large metropolitan areas, is the basis for this month's cover. One approach to the avoidance of collisions between aircraft in flight is the ADSA (air-derived separation assurance) system, described in detail in an article by E. O. Frye and D. E. Killham, starting on page 72.

Spectral lines

On Developing the IEEE's Nonnational Character. Outside the United States, one frequently hears the statement that the IEEE is an "American" professional society—and the term American is here used as meaning only the United States. However, the Institute's basic documents—the Constitution and Bylaws—distinctly state that it is not a national society. Which is it?

There are several observations about the IEEE which would lead one to the first conclusion: its headquarters are in New York; most of its members and officers are from the United States; it publishes its periodicals in English; many of its operating procedures are characteristically American; there are IEEE representatives on national committees in the United States; the published IEEE standards frequently appear to favor U.S. practices. Undoubtedly, other characteristics could be listed that would serve to reinforce this position.

The Board of Directors has recognized that this mistaken idea is very widespread, and at its first meeting in 1965 directed the President to appoint an *ad hoc* committee to investigate those practices and characteristics of the Institute which led to this false impression and to recommend specific steps for its correction. This committee was chaired by Dr. John T. Henderson of the National Research Council of Canada, who recently had served the IEEE as the Director from Region 9—the Region that comprises all the area outside of the United States, Canada, and Europe except for certain portions of the Near East and Northern Africa. The committee included a number of people from outside the U.S. as well as some widely traveled members from inside the United States.

In addition to the committee members, who met on several occasions, many IEEE members acted as corresponding members and contributed their ideas by correspondence. The committee's work culminated in a report to the Board of Directors at its last meeting in 1965, at which the Board unanimously approved the following statements of policy:

1. It is the policy of the IEEE to accept as members technically qualified individuals of any nationality regardless of geographical or political considerations.
2. It is IEEE policy to cooperate and not compete with existing national societies.
3. Since customs and legislation in connection with professional societies differ in various countries, it is the policy of the IEEE that special provision may be made in the Bylaws to provide appropriate technical activities for its members residing in different countries.
4. Appropriate IEEE organizational units may, upon request, appoint representatives to national agencies of a technical nature in any country, subject to approval of the Executive Committee. Appointees will represent IEEE only insofar as its activity in that country is concerned.

As well as accepting these policy statements, the Board directed the Executive Committee to take the necessary action to implement them. The *ad hoc* committee had also indicated some problem areas requiring specific action. These included: (1) a study of the Bylaws to locate provisions which militate against the growth of IEEE activities outside the United States and recommendations for modification to the Board of Directors; (2) a change in procedures that make operation of IEEE organizational units outside the United States difficult; (3) the development within the Headquarters staff of personnel capable of carrying on correspondence in a number of languages; (4) an investigation of the possibility of permitting the payment of dues in local currencies; (5) a study of methods of increasing the number of technical papers submitted to IEEE publications from authors residing outside the U.S.; (6) an investigation of the possibility of facilitating technical communication by expanding the translation of articles into English and the publication of abstracts of articles in languages other than English; (7) a study of methods for improving the process of selecting members (from outside the U.S. and Canada) for promotion to Fellow grade.

Obviously many of these areas will require considerable study before appropriate action can be taken. However, it is clearly the intent of the Board that the IEEE is not an "American" professional society but truly one whose outlook and development are not circumscribed by national boundaries.

F. Karl Willenbrock

Controversy and the growth

Electricity, according to the *Naturphilosophes* at the beginning of the 19th century, was produced by a conflict of forces. Toward the end of the century, theory had altered and practice had developed to the point where it might well have been said that forces of conflict were produced by electricity. Just a casual glance at the history of the electricians' art reveals that the past is studded with some rather vigorous altercations which lend a certain spice and glamour to the field.

Even Benjamin Franklin's celebrated lightning rod was the center of a mild tiff. The debate was over pointed rods, which Franklin advocated, versus blunt ones, which were first proposed on the basis that they were less likely to attract lightning, and later were supported on frankly political grounds. In 1773 a committee of the Royal Society, with Franklin as a member, reported favorably on points; but a dissenting view was picked up by the "colony-phobes," and King George had blunt rods placed on the royal palace—as immortalized in this bit of doggerel:[1]

> While you great George for safety hunt
> And sharp conductors change for blunt
> The nation's out of joint;
> Franklin a wiser course pursues
> And all your thunder fearless views
> By keeping to the point!

Franklin cleverly stayed as clear of this fray as possible and let history take its course. However, other persons, at later dates and on different matters, were unable or unwilling to take a dispassionate view, as we shall see shortly.

Some minor skirmishes

Before analyzing any major battles, let us consider one or two minor skirmishes, which are interesting primarily because of the tactical use made of them. In 1855 David Hughes of Lexington, Ky., invented a printing telegraph described as "very beautiful and very fast," which became a prototype for the future development of automatic telegraphic systems. The United States' rights to this invention were purchased by Cyrus Field, Peter Cooper, and others, who promptly founded the American Telegraph Company and mounted a full-scale attack on the various entrenched users of the Morse system. By giving loud publicity to the increased speed and efficiency promised by the Hughes machine, the American Telegraph Company promoters were highly successful in a series of bitter scuffles within the industry, and before the

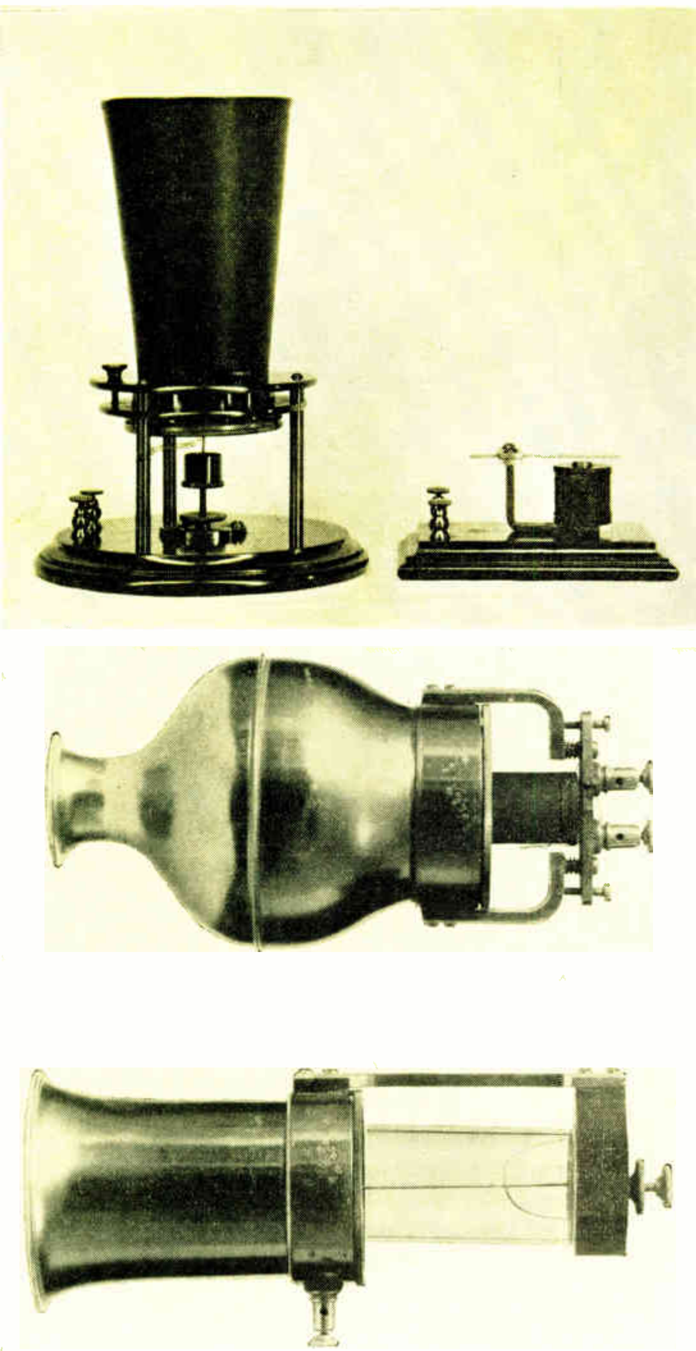

Fig. 1. Variable-resistance (liquid) transmitters and electromagnetic receivers. Top—Bell apparatus (reproductions). Bottom—Gray apparatus (originals). Now in the collections of the Smithsonian Institution.

of the electrical art

Human frailty in an era of rapidly expanding possibilities generated controversies that played an ambivalent role in the development of the electrical art—sometimes sapping and other times fostering the inventive spirit

Bernard S. Finn *Smithsonian Institution*

end of the decade they had taken control of systems covering the entire eastern seaboard. In 1866 a final consolidation was made with Western Union to form a nationwide single network. Meanwhile, the Hughes machine, having performed its services most effectively as a standard bearer, had been speeded into retirement, and telegraphy in this country was carried on almost entirely through reception by the clack of the Morse sounder. Thus an American Telegraph handbook in the 1870s could say of the improved Hughes printer: "The limited extent to which it is employed renders it unnecessary to give a detailed description of its construction and mode of operation."[2] In Europe, on the other hand, there was a stronger tradition of automatic reception, and a modified Hughes instrument quickly became the most widely used receiver on the continent.

In another example, Thomas Edison during his telegraph days invented for both Western Union and Jay Gould's Atlantic and Pacific Telegraph Company, to their respective and alternate dismay and delight. In 1874, for example, Western Union obtained an iniunction against Gould's enterprise for infringing on the Page electromagnetic relay. Edison, who was working on a quadruplex system for Western Union at the time, was called in by Atlantic and Pacific and asked to design a substitute. He shortly came up with the "electromotograph," which consisted of a metallic finger resting on a chalk drum: the friction between them decreased sharply whenever a current flowed through the point of contact. The result was sufficiently effective to save Atlantic and Pacific from extinction and allow it to negotiate an agreement with the opposition.

Gray vs. Bell

Conflicts in which the invention is a promoter's tool and the inventor is a disinterested bystander do not seem as interesting as those in which inventor and invention together have become strongly and directly involved. Furthermore, the latter type of encounter has often produced a melee of considerable dimension.

On February 12, 1876, Elisha Gray, an independent inventor from Chicago working for Western Union, and Alexander Graham Bell, a struggling teacher of the deaf in Boston, both filed proposals at the U.S. Patent Office for instruments that would make voice transmission possible over extensive distances by the use of electricity (see Fig. 1). Some of the crucial factors surrounding the famous dispute that followed were:

1. The credit owing either man is severely limited; certainly it would be unfair to say that either "invented the telephone" without qualifying the statement to recognize the work of several others.
2. Neither man had actually transmitted words over wires at the time of filing.
3. Bell's application was for a patent; Gray's was for a caveat—a formalism, no longer used in the Patent Office, by which an inventor could establish that he had reached a certain point in his work, even if he had not yet produced a practical device. For purposes of establishing priority, the legal standings of caveat and patent applications were identical. Although current practice was to regard patent filing in terms of days, thus making these applications simultaneous, evidence was successfully introduced that gave Bell a priority of about two hours.
4. Both men described electromagnetic receivers in their applications.

Bell described in detail an electromagnetic transmitter—a receiver turned backward—and he made passing reference to other methods (including a variable-resistance device); Gray described in detail a variable-resistance transmitter. Bell's patent was granted on March 7. His first transmission of distinguishable words took place on March 10, through a variable-resistance instrument. By June 1876 Bell had achieved transmission with an electromagnetic transmitter, which he displayed successfully at the Philadelphia Centennial.

5. Bell spent the following year perfecting his electromagnetic transmitter—insofar as it was capable of perfection. Unfortunately it proved of little value, and from 1878 on the American Bell Telephone Company relied for a transmitter on variable-resistance instruments invented by Edison, Hughes, Blake, etc. (The variable-resistance transmitter of Gray and Bell both used a weak acid solution; the later, practical devices used various forms of carbon.) Meanwhile, Gray did practically no work on the telephone, but spent his time on what seemed to him and Western Union to be the much more important problems of multiplex telegraphy.

The Dowd case

Finally, there was a direct clash between the Bell and Gray claims in the Dowd case of 1878–79. In the end,

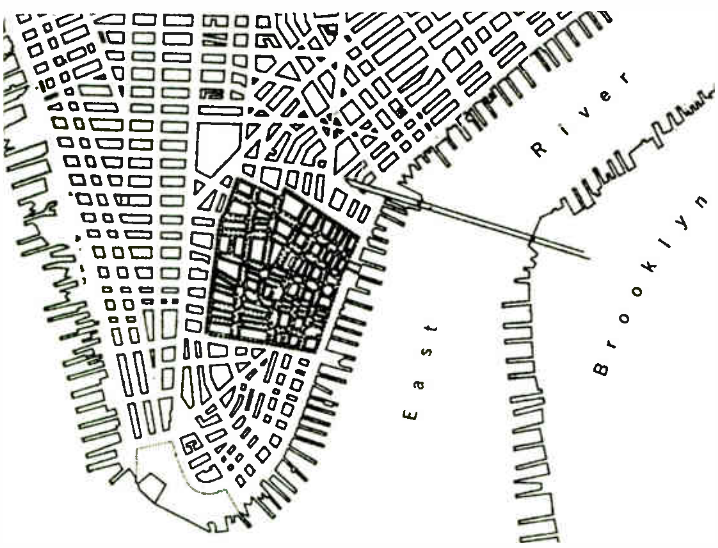

Fig. 2. At 110 volts, Edison could economically service installations within half a mile of a central station. The use of three wires (invented by him in 1883) with 220 volts between the outer two effectively doubled this distance. Map of lower Manhattan shows the area (about 0.2 square mile) initially serviced by the Pearl Street Station.

upon advice of counsel, Western Union capitulated, selling out to the Bell interests for a 20 percent share of the profits from the sale or lease of telephones. As a part of the agreement, the judge was asked to issue a consent decree, by which the contesting party recognized the priority of the Bell position. But, in fact, no actual decision was rendered, making it almost impossible to get one in the future since the Gray rights had become assets of the American Bell Telephone Company. As a net result, Gray was a bit aggrieved, as well he might be, since Bell gained several million dollars for his share in the corporation as well as a great amount of prestige. In later years Gray felt that he had been misled by Bell in correspondence they had carried on during 1876, and there is no doubt but that he was plagued with poor legal advice.

A major characteristic of this controversy was that it was never formally resolved. Rather, it was compromised out of legal existence; the effect of the compromise was to enhance Bell's reputation greatly and to relegate Gray's name to obscurity, at least as far as the telephone was concerned. It should be pointed out, however, that the success of the American Bell company rested only in small part on the strength of the Bell patent. The early achievements of the company would more properly be described as a combination of the electromagnetic receiver (patented by Bell and protected by possession of the Gray claims), the promotional efforts of Bell in 1876 using the receiver and his electromagnetic transmitter, and the timely acquisition of rights to the variable-resistance carbon transmitters. Above all was the good sense or good fortune of Bell interests in understanding the promise of telephony. Bell felt this, as Gray did not; nor did Western Union, which turned down an early opportunity to purchase the Bell patents for $100 000. Perhaps the spoils and the fame were quite out of proportion to the inventive contribution; if so, this could only make things all the more galling to Gray.

Edison and alternating current

In October 1879, at about the same time that the Bell–Gray accord was being reached in court, Thomas A. Edison found that he could burn a carbon-filament lamp continuously for better than a day and a half. We are not concerned with the exploitation of this invention, but with the controversy that sprang up half a dozen years later as other companies began to encroach on Edison's position—particularly those companies that used alternating current for their lighting systems. Starting in 1885, the Edison Electric Light Company began publicizing its intention to prosecute anyone who infringed upon the company's patents. Although Edison never cared much for wasting energy and time in the courts, he greatly favored this vigorous attitude on the part of the company whose financial managers had been a bit cautious since the opening of the Pearl Street Station in New York in 1882 (see Fig. 2).

There were, of course, some pretty clear advantages for the use of high-voltage alternating current in transmission lines. One look at the area covered by Edison's Pearl Street Station is enough to see the major one. But in fairness it must be pointed out that there were also advantages on the other side: dc systems could use batteries for standby or emergency service; they were generally more efficient; and there was no ac motor until 1888–89. Some of the ac deficiencies were still recognized as important when the Niagara Station was being planned in the early 1890s, and many, including William Thomson, counseled against the use of alternators.

Nevertheless, with the development of the power transformer—introduced by Gaulard and Gibbs in England in 1883 and improved in the following year by Déri, Blathy, and Zipernowski in Hungary, and in 1885 by Stanley in this country—ac promoters began to make serious inroads into the electric power business. To counter this, the Edison Company launched an all-out attack emphasizing the dangers of using high-voltage alternating current. Edison himself entered wholeheartedly into this campaign, which included publicizing accidental deaths caused by electricity and describing macabre experiments on dogs; the climax occurred in 1889 when New York State adopted ac for the electrocution of criminals.

This response by Edison was quite uncharacteristic of the man. Throughout the 1870s, in a series of telegraph, phonograph, and telephone inventions, a challenge only served to spur him on to greater competitive effort. The invention of the carbon-filament bulb was itself a magnificent performance, undertaken late in the game with supreme audacity, and leading to supreme success. Furthermore, Edison's position with respect to alternating current was actually quite good. Besides holding general leadership in the electric power field, he even had patent rights to the crucial ac invention through an American option he had taken on the Hungarian transformer.

But Edison in 1885 was in an uncharacteristic position. For the first time he had entered into manufacturing, and as a result he had a great stake in the promotion of a particular system; he was in a position unfavorable to the innovator. Second, and probably less important, he was rich—and enjoying it. He traveled to Europe, built a summer house in Florida, and behaved in a manner befitting the world's most famous inventor. His reaction was, as one might expect, a certain lazy caution and reluctance to change.

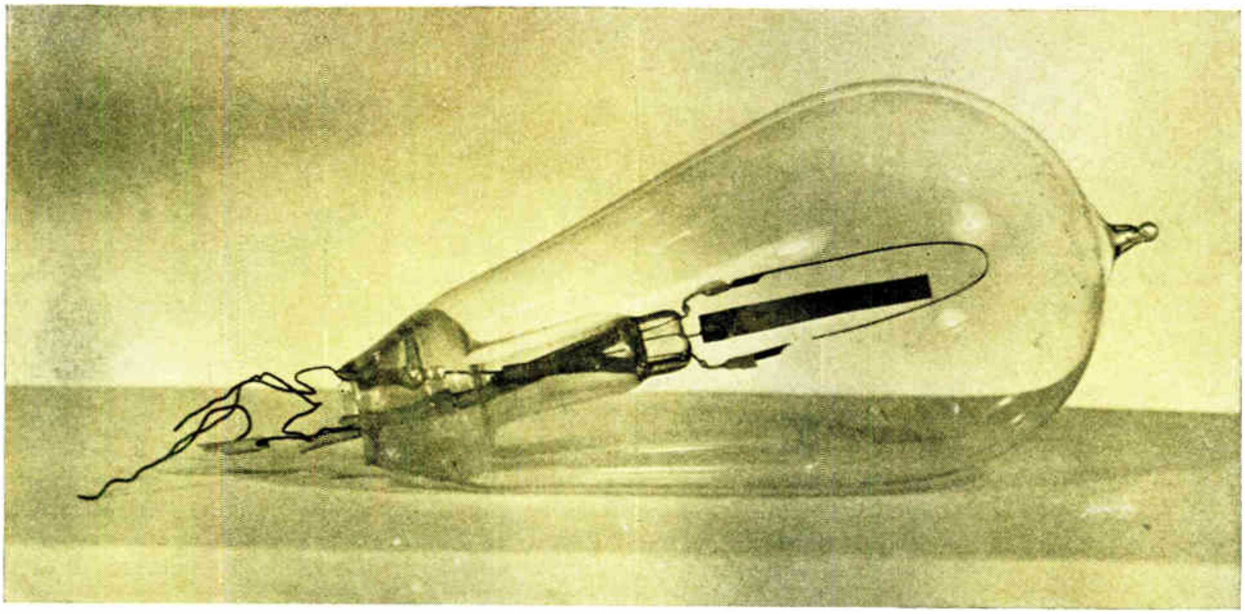

Fig. 3. An Edison effect "diode," 1883, patented by Edison as an indicator or meter.

Within half a dozen years both the company and Edison had extricated themselves from an untenable position. The company joined forces with the ac-oriented firm of Thomson-Houston, and Edison turned his back on manufacture and immersed himself in invention—magnetic ore separation, the movies, and another look at the phonograph.

The rise of radio

While working on the light bulb in 1880 Edison's attention was drawn to a peculiar shadow near the base of the bulb; he investigated this in detail by placing another electrode near the filament, and found that a current could be drawn off through it. He patented this two-element bulb as an indicator, or meter, and promptly forgot about it (see Fig. 3).

John Ambrose Fleming, a London consultant to Edison, did similar experiments on the peculiar effect, and then he too lost interest. Almost two decades later, as consultant to Marconi, Fleming resurrected the Edison bulb as a possible wireless detector. In 1904 he patented it for use as a valve, or rectifier.

On this side of the Atlantic, Lee de Forest, a recent Ph.D. from Yale, always insisted that he came to his concept of the audion independently, through a sequence of experiments with electrodes in gas flames. Fleming felt differently about the originality of de Forest's work, and some bitterness on his part is understandable—especially when one considers that his earlier patent had been automatically assigned to the Marconi Company, and that now even the glory was being taken away. On the other hand, de Forest had made two important additions: one was the use of a voltage between the filament and second electrode; the other was the introduction of a third electrode, or grid. These seemed at first to be trivial alterations, but in the long run, of course, they proved to be crucial. Fleming's feelings are clearly revealed in a variety of his writings on the subject, which attribute to his own diode much more than in good conscience he should have and attribute to de Forest all the qualities of a thief.

De Forest, in his autobiography, which with becoming modesty he called *Father of Radio*, dismissed Fleming curtly: "... still unregenerated at ninety-two... He never yielded in his firm conviction that he was radio's true inventor."[3]

In examining this dispute it is important to note that for the first decade of its life the Fleming–de Forest valve–audion was not considered very interesting or useful. Nobody really understood how it worked, least of all its inventors. As a wireless detector it was not very popular, which is evident from the fact that de Forest allowed his British patent to lapse. In 1913 and 1914 it was Armstrong and others who studied its properties and showed that the triode could be used in an amplifier or oscillation transmitter. Then came World War I and it was only for the last three or four years of the patents' lives (which expired in 1923) that any real conflict between the de Forest and Fleming rights developed in this country.

But the personal controversy never died, and it must have been a source of considerable satisfaction and delight to de Forest when the United States Supreme Court in 1943—two years before Fleming's death—found that the Fleming patent was invalid. One British commentator thought this Supreme Court decision, coming 20 years after the patent had expired, might best be titled "Alice in Patentland."[4]

The controversy was, therefore, primarily personal rather than commercial in character. It was based on the attempts of two men to place themselves in the best possible light among the founding fathers of radio.

The events of 1912–13, especially in regard to the discovery of the oscillating properties of the triode, are rather complex. Armstrong was granted a patent on the regenerative receiver in 1914, which touched off a long battle that ultimately came to a final legal decision in 1934 when the Supreme Court gave credit for the regenerative principle to de Forest. It is worthy of note that by then the radio group (RCA, AT&T, GE, Westinghouse) controlled both patents. Lawrence Lessing, in his biography of Armstrong, suggests that the group was far more interested in seeing de Forest's patent (dated 1924) upheld than the already-expired Armstrong patent of 1914.[5] On the other hand, in May 1934, at the IRE convention in Philadelphia, Armstrong prepared to return the Medal of Honor given him in 1918 for this same discovery, as his final gesture in this prolonged matter. Before he could, the Board of Directors reaffirmed its earlier stand, and the meeting gave Armstrong a standing ovation.

The major aspect of this dispute is that it was between individuals, not corporations. It was Armstrong who pursued the matter to the bitter end. In effect he was seeking a historic judgment from the courts on his position as an inventor. This is a risky business—as Armstrong should have known better than anyone.

More interesting in some respects, however, is the running controversy between Armstrong and RCA over frequency modulation, which in effect began where the regenerative battle left off. On the basis of four patents granted in December 1933, Armstrong almost singlehandedly wrested commerical FM broadcasting into existence. As these events were quite recent and are familiar to many in the profession, they may be stated briefly. Armstrong tried to interest RCA in promoting FM for broadcast purposes, but the negotiations broke down for a number of reasons, including:

1. Investment by RCA in successful amplitude modulation was by this time considerable.
2. There were doubts about the real advantages of frequency modulation.
3. Frequency modulation would need large allocations in a limited radio spectrum.
4. RCA was making heavy financial commitments to television, which seemed a bit closer to commercialization than it actually was.

Armstrong then took on the task himself. He promoted the value of frequency modulation, built his own transmitter at Alpine on the Palisades in New Jersey, licensed others, and battled for frequency space before the Federal Communications Commission. By 1941 there were a dozen or so licensed FM transmitters, about 500 applications before the FCC, and 25 licensed manufacturers. In effect, a considerable miracle had been wrought. RCA approached Armstrong with an offer of a million dollars for a nonexclusive license with no royalties, but Armstrong felt that this would betray his agreements with others, and no compromise was achieved.

After World War II, with the emerging interest in television and with his patents running out, Armstrong was in a considerably weaker position. Still, he pursued RCA for infringement of his FM patents. The case, begun in 1949, effectively ended with Armstrong's suicide in January 1954.

Characteristics of controversy

The examples presented are not typical, for we have, in fact, been considering the giants of electrical invention, and certainly the argument could be made that their reactions were conditioned by special circumstances. Normal and ordinary as these reactions probably were, they were placed in unusually strong focus by the genius of the men and the importance of the events. Conclusions, even though limited to exceptional cases, are still worth forming. Let us consider some threads found common to these disputes.

First, and most important, these controversies were highly personal things—they depended much more on the character of the man than on the character of the invention. The bulldog tenacity of an Armstrong or the incessant quest after fame of a de Forest are such important elements that they overwhelm the technical facts.

Second, the nature of the developing electrical industry has tended to bring some human frailties into sharp relief. By the middle of the 19th century, when possibilities in the field were rapidly expanding, it was not unusual for a man to achieve considerable fame and fortune through his electrical talents. Furthermore, it was not necessary that this talent be very comprehensive. Often a mere smattering of technical knowledge—as in the case of Morse and Bell—could be parlayed into an immense fortune and world renown. With the stakes so high it sometimes was much easier to be stubborn, arrogant, petty, and self-deluding than magnanimous, and therefore ripe for controversy.

Third, the rules of patent law—placing emphasis on certain formal proofs of priority—do not permit the assignment of joint or proportional credit. Because of the need to establish complete uniqueness it is often profitable for an opponent to bring in rather far-fetched claims in order to extend the litigation or force a compromise. In other cases—and Armstrong is a particularly good example of this—a man will seek to establish his fame through the courts; this is unfortunate, since he then commits himself to accepting the rules of the Patent Office as a condition of accomplishment. Either way, the result is controversy. Operating under these rules, the courts are apt to give credit where credit is not due, and frustration is often an additional consequence.

Fourth, the immediate impression that one receives from a study of these famous—or infamous—disputes is that such controversy impedes growth and saps the inventive spirit. Even at second glance there is a good reason to support changes in the patent system that would ease the strain of the inventor and improve the rules for assigning legal credit. At the same time, however, we must realize that the inventive spirit is fostered through challenge. Bell worked feverishly during 1876 to perfect his electromagnetic transmitter. The result was not a truly significant advance in technology, but the promotional effect of his efforts was invaluable. The response of ac promoters to the Edison attacks was probably favorable to the advance of the industry. And it was as a result of experiments Armstrong performed as a part of his defense in the de Forest suit that he came upon the principle of superregeneration—which he promptly and wisely sold to RCA, and which became his most profitable, though not his most important, invention.

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Electrical features of the New Tokaido Line

Japan's new high-speed railroad is currently attracting worldwide attention because of its practical, sensible approach to the problem of moving people both rapidly and safely in a heavily populated area

Toshikazu Kawakami Japanese National Railways

Early in September, while in Tokyo attending the Fourth General Conference of the International Universities Association, I called on Mr. Toshikazu Kawakami to discuss final arrangements for his paper. To my delight, he invited me to bring guests for a ride on "the world's finest railroad."

For a year, I had been hearing about the New Tokaido Line, so it was with an air of excitement that I, accompanied by Mrs. Jones and Dr. and Mrs. Eric Walker, arrived via special escort at Tokyo Station to get our first glimpse of the really new railroad. Our hosts, Mr. Tatsuru Saito and Mr. Yoshikazu Seki of the Foreign Department, Japanese National Railways, took us through the seemingly endless maze of the station, which handles over a million passengers a day. On Track 18 New Tokaido Train Number 9 waited, sleek and clean. As we walked to the front of the train, we found JNR Managing Director Kawakami waiting to see us comfortably aboard, and, true to railroad traditions, to enjoy the satisfaction of seeing split-second on-time departure. Our first impression was one of immaculateness—the crews were white-gloved, and the shiny metalwork and window glass were spotless. We learned later about the automatic washing installations, similar to the auto laundries that one finds in the United States. The acceleration as the train moved out of Tokyo Station was so smooth as to be almost imperceptible, but the train quickly came up to the speed limit for the metropolitan area. At this point we were permitted to visit the control cab, which seemed far too simple for so elegant a train. The answer, of course, lies in the very considerable electronic automation that backs up the indicators and controls.

After we left Yokohama (suburban Tokyo), speed was increased smoothly to 200 km/h (130 mi/h), but was reduced to 160 km/h (99 mi/h) on curves, and to even slower speeds when the train was ahead of schedule! The only real sense of speed came from the indicator, which showed simultaneously actual speed and allowed maximum speed. The engineer was absorbed with two duties: keeping an operating log and adjusting acceleration. He cannot run too fast; electronics sees to that. Very noticeable was the absence of the "clickety-clack" of rail joints. The rails are welded in 1500-meter lengths with electrical insulation in the joints, which are diagonal (for expansion) and some 3 meters long. It was exciting as we met northbound trains, first on an open section of track, and then in a tunnel at 130 mi/h. Our hosts explained that there would be a very measurable rise in pressure in the tunnel (two "pistons" approaching each other at 260 mi/h relative!), but overcame our fears by explaining that the passenger cars are virtually hermetically sealed except for fresh-air intakes, which close automatically at tunnel entrances. As the trains passed, there was only a slightly noticeable change in noise level.

At Odawara we got off and saw decentralized equipment that would permit train control in emergencies. After an interesting and pleasant visit in the community, we caught the northbound express and relaxed leisurely as we talked about the world's finest railroad in the soft conversational tones allowed by the low noise level. The most unforgettable impression was the smoothness of the ride: no lateral sway or jerk. (The air suspension wheel trucks resulted from intensive research on hunting—that is, lateral instability.) We made good-quality tape recordings as we discussed dreams of an expanded high-speed railroad running most of the length of Honshu Island (about 1000 miles), and of fast *trains as frequently as every 15 minutes on some parts of the line.*

We disembarked at Tokyo Station with a much better appreciation of "The New Japan"—a Japan that has earned first place in railroad technology, second in electronic production, and fifth in automobile production, all accomplished in the short space of 20 years!

The New Tokaido Line is an excellent answer to the problem of mass transportation for a megalopolis, and is a magnificent engineering achievement. But its greatest contribution is probably the challenge it makes to transportation people everywhere by presenting operating proof of what can be done through the use of modern technology to improve the comfort, speed, and safety of a passenger railway by at least a factor of two.

Thomas F. Jones
Vice Chairman, Publications Board

The New Tokaido Line, Japan's completely new high-speed railroad, has attracted much attention from all over the world. The railroad was built to meet a critical need for greater transportation capacity, and to stimulate progress in the megalopolis area of Japan covering Tokyo and Osaka.

The original Tokaido Line, opened in 1889, has seen many improvements through the years as traffic has grown. Postwar modernization included complete electrification in 1956, operation of longer and faster trains, and better signals. However, even then it was approaching the limits of track capacity and by 1961 each of the two tracks was carrying slightly more than 200 trains per day on the busiest sections. These included trains of several different types and speeds.

Top—Fleet of trains at carshed. Bottom—Centralized substation control panel and dispatchers.

Several plans for improvement were on the desk for study, including simple additions to tracks of the original line, but the boldest conclusion was recommended as the soundest: to build a completely new, high-speed railroad that would not be restricted by requirements for compatibility with existing railroad tracks or rolling stock. This concept gave design engineers free rein to select tracks, cars, power supply, control systems, and communications, using the best modern technology, and made it possible to plan for high-speed operation. Some of their major recommendations were: the adoption of the standard gauge; an electric traction system of single-phase ac at 25 kV using industrial frequency; and the use of electric multiple-unit trains only.

Many novel engineering designs were incorporated after extensive research and testing. For example, a 40-km test section was constructed, where the record speed of 256 km/h (159 mi/h) was achieved, and the result was a railroad designed for a normal running speed of 200 km/h. Construction of the railroad between Tokyo and Shin-Osaka in Osaka city was completed in five years, utilizing the most modern innovations on a line that links Japan's most populated areas and traverses rugged mountainous terrain.

The line was opened for regular service on October 1, 1964, with two trains every hour in each direction; one makes the 515-km journey in four hours with two intermediate stops, and one, requiring five hours, stops at all ten intermediate stations. These running times were cut by an hour in November 1965. The initial schedule provided 26 through trains and four shorter-distance runs each way every day, with a fleet of 360 multiple-unit electric coaches. Each train consists of 12 coaches with 987 seats. The number of trains has been progressively increased, going to 43 trains per day in October. This figure can be further increased to 80 trains with present facilities by adding more cars to the fleet, and to 160 trains if terminals and servicing facilities are expanded and if all trains continue to run at the same average speed. These capacities are based on day service only, with no trains operating between midnight and 6 A.M.

During 11 months of revenue service, more than 20 million passengers chose to travel on the new line, proving the capability of railroads to provide safe and dependable mass transportation in the new domain of high speed.

Control center

In a modern building at a corner of Tokyo Central Station is the control center, the brain and the heart of the New Tokaido Line. The specialized dispatchers in this center continuously supervise the automatic equipment and control the operation of trains through utilization of many novel supervisory and remote control mechanisms to provide and assure regular, safe, and comfortable high-speed train service for the passengers.

Train dispatchers have their seats at the left half of the control room. In front of the wall is the indication panel for the centralized train control (CTC) system, on which train locations and numbers are indicated on the track layout for the entire line. Train signals are transmitted from the track circuits and wayside electronic coils. In front of the panel are the control desks through which the dispatchers direct, by remote control, the routing of trains starting from stations whereas their entering into the stations is guided by automatic routing. Figure 1 should help toward an understanding of the CTC system. By dialing the train number, the dispatchers can communicate with the engineer of the train. Design characteristics of the system are given elsewhere in this article. Traffic dispatchers in a separate room have a replica of the indication panel and can contact train conductors through the same communication channels.

In the right half of the room are power dispatchers who direct by remote control the switchgear in 25 substations, 22 sectioning posts, and two frequency-converter stations through the centralized substation control (CSC) system. Their automatic tripping as well as any trouble occurring in these substations are indicated on the panel, and energy received at the substations is telemetered and typewritten on a card.

Since the 3800 control and indication codes must be transmitted at high speed, two code-transmission systems at 2000 and 1200 bauds respectively are adopted. For example, the CTC system adopted consists of four groups dividing the entire line, which scan synchronously over track circuits including three or four stations connected in tandem by high-speed code transmission at 2000 bauds. The transmission circuits use a part of the pencil coaxial-carrier cable route, the logic circuits consisting of static digital transistors using 1-kc/s clock pulses. To assure high reliability, a triplex system is employed for the principal parts. The two systems use some 130 000 transistors and 240 000 diodes. No system failures have occurred to date.

Automatic train-control system

A high-speed railroad deserves its name only when a perfect train safety system matched to the speed is properly achieved. The New Tokaido Line has a system called automatic train control (ATC).

The system depends on track circuits as in the conventional automatic block system, but signals received by trains from the rails are indicated on the cab signal indicator, and are simultaneously compared with the running speed. If the speed is higher, braking is automatically

Fig. 2. Principles of ATC system.

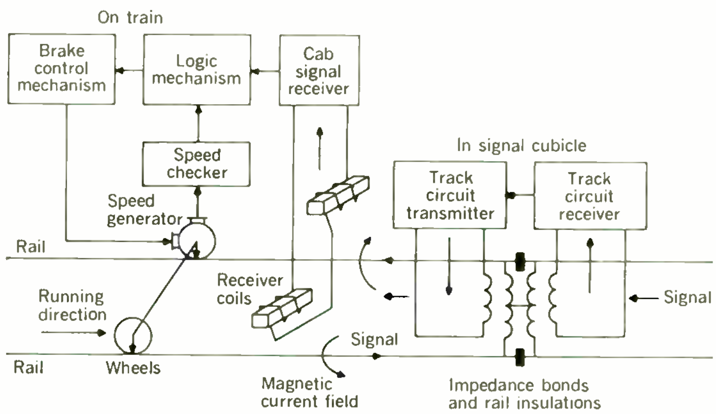
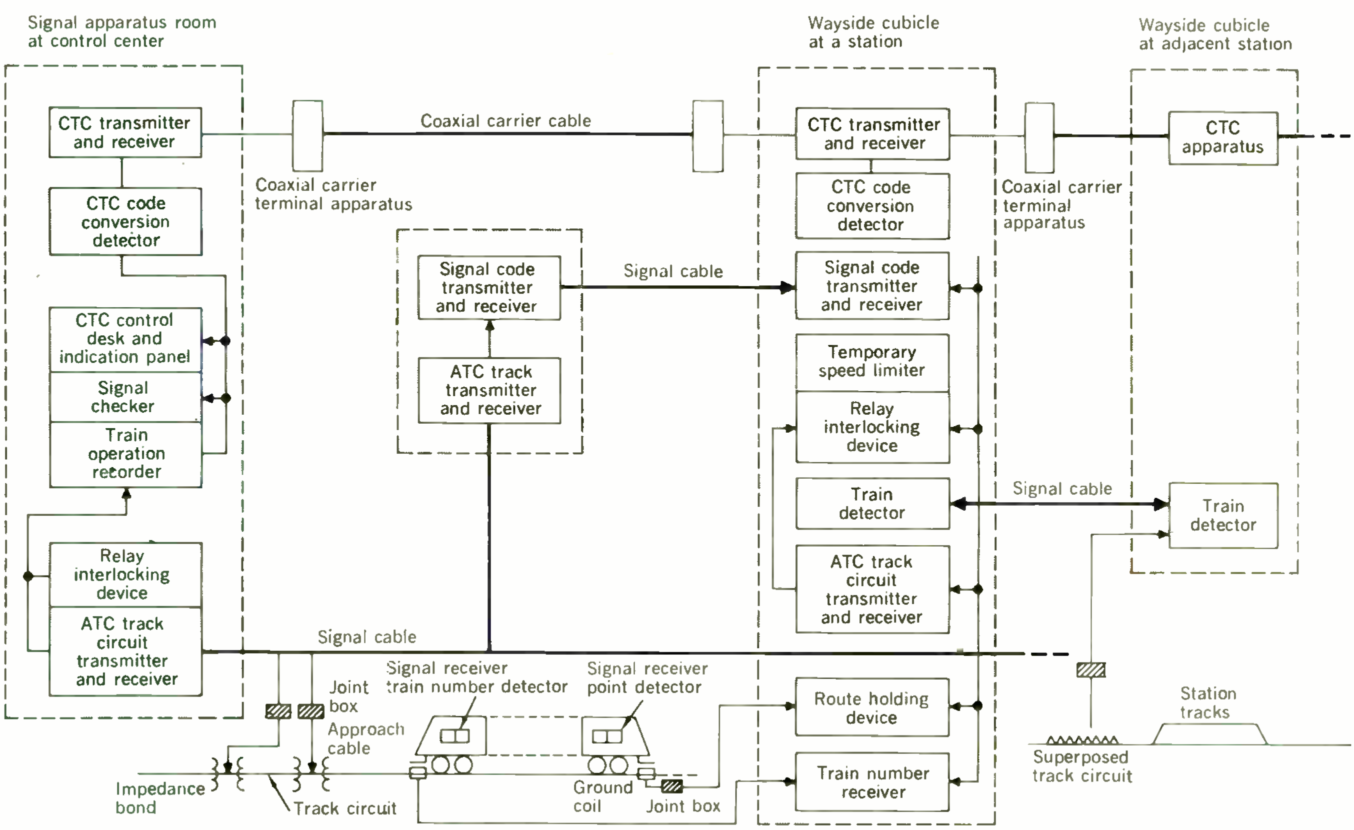


Fig. 1. Block diagram of CTC system.



applied; if lower, the brake remains released. The principles of the system are illustrated in Fig. 2.

During the process of study of the system, extensive research was carried out on the possible employment of traveling block systems using space radio and completely automatic control systems, including acceleration, using electronic computers. Their adoption, however, was not recommended because of the engineering limitations at the time and also the high safety requirements, which always demand first consideration.

Figures 3 and 4 illustrate the process of deceleration of a train under automatic train control at a section between stations when a preceding train occupies one of the track circuits; and at a station when a train is scheduled to stop.

Trains under this system are controlled by six aspects of cab signal indications in six stages. Audio-frequency track circuits were developed, using a single-sideband system, synchronized with the 60 c/s of the contact conductors, to prevent disturbances from similar harmonics of traction current. Speed-control steps and their frequency allocation are given in Table I.

All ATC apparatus are completely transistorized. Transmitters and receivers of track circuits are concentrated at 29 air-conditioned wayside cubicles along the track. They are connected to the rails through aluminum-covered star-quadded polyethylene cables. Insulated expansion joints of a special design are inserted on the long-welded rails at the boundary of the circuits.

The system is designed to be free from faults, and, if one should occur, to be fail safe. These requirements are satisfied by use of reliable components of high quality, carefully located in protected positions, and the utilization of duplex systems for principal parts (and also in two out of three systems in receiver sets) so that the system may have ample redundancy.

Reliability calculations were repeated in the course of design, and data concerning prototypes on the test section were analyzed for possible improvements in system reliability. Some examples of results of such calculations on the improved products are given in Table II.

Service records of the improved equipment installed in 29 signal cubicles along the line and of the apparatus on 30 trains are more than satisfactory: there has been only one system failure since October 1964.

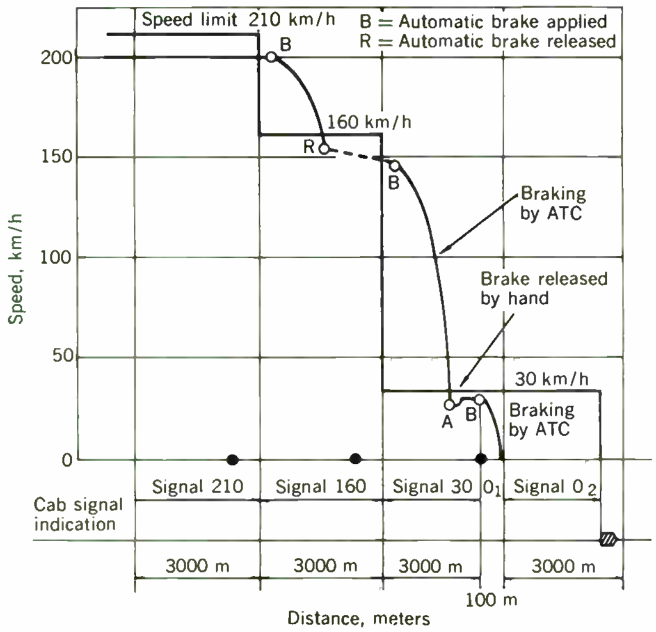
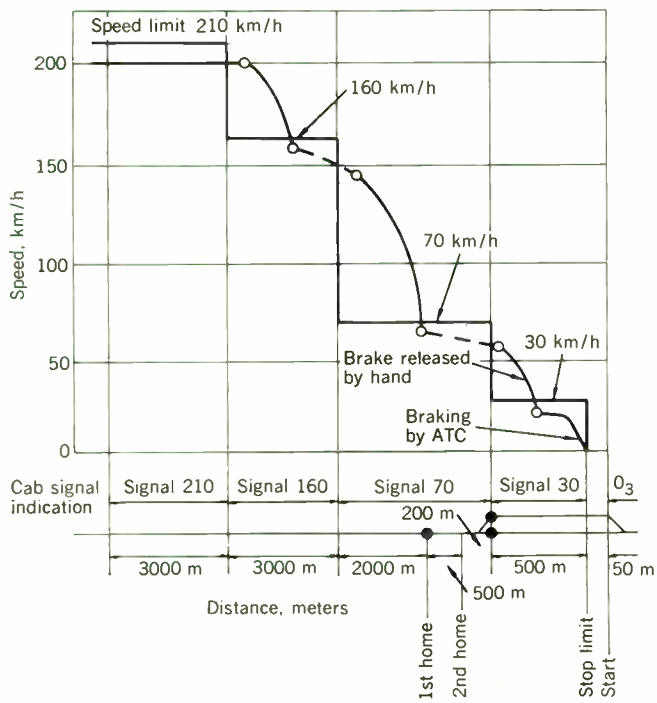


Fig. 3. Speed curve under ATC operation, with train closing up to a preceding train.

Fig. 4. Speed curve under ATC operation, with train entering a station.



Telecommunications

The train radiotelephone system is effectively utilized by the dispatchers, engineers, and conductors on running trains. The system design is based on 11 frequencies in the 400-Mc/s band allocated to the railroad. Communications from 27 fixed stations to any mobile station make use of three frequencies under an eight-channel multiplex system of single-sideband phase modulation. Communications from mobile to fixed stations are accomplished through eight frequencies of a simplex system. Waves from a mobile station are sent only during the course of conversation. The system has four service areas covering the entire route, where tracking devices relay the communications. A number of 400-Mc/s-band tunnel boosters and transistorized amplifiers, and two special parallel cables on the wall enable radio communications to be operational in tunnels.

Orders from dispatchers in the control center to the fixed stations of the train radio system, and codes of indication and control for the CTC and CSC, are all trans-

I. Speed-control steps and frequency allocation of ATC

Signal Aspects of Cab	Permissible Operating Speed, km/h (mi/h)	Modulation Frequency for Signal Control, c/s	Carrier Frequency, c/s	Remarks
210 signal	210 (130)	10	Eastbound track: 720, 900	Maximum permissible speed
160 signal	160 (99)	15	Westbound track: 840, 1020	Speed restriction on curves
110 signal	110 (68)	22	(Two frequencies alternatively used for adjoining track circuits)	Speed restriction on steep curves
70 signal	70 (44)	29		Speed restriction on points
30 signal	30 (19)	36		Final speed traction
Stop signal	0	36	—	P point control, O_1
		No current	—	No block, O_2
		No modulation	Eastbound: 840 Westbound: 900	Absolute stop, O_3

II. Reliability estimates on ATC apparatus

Apparatus	Complexity	Component Failures per Month	System Failures per Month	Mean Trouble Interval of System Failures, hours
Wayside apparatus*:				
Kamonomiya signal cubicle	22 788	2.61	0.25	2900
Hiratsuka signal cubicle	36 143	4.2	0.36	2020
All ATC apparatus between Tokyo and Osaka	1 052 000	136	12	60
Cab apparatus†:				
Receiver	1 107	0.43	0.09	3330

* Component failure is estimated on mechanical correction of 20 percent or more and severity factor of 1.1. System failures are assumed on periodic maintenance each 720 hours (once a month).

† Component failure is estimated on mechanical correction of 20 percent or more and severity factor of 10. System failures are assumed on periodic maintenance each 10 hours (after each round trip).

mitted through ground cables buried near the track. The cables, composed of pencil coaxial cores and star-quadded cores, are armored and sheathed by corrugated aluminum to screen off the induced voltage caused by traction current. The pencil coaxial-core transmission has a 300-channel capacity with carrier bands of 60 to 1300 kc/s and voice bands of 0.3 to 3.4 kc/s. Terminal apparatus, mostly transistorized, are installed at 12 railroad stations. The control center in Tokyo has a central supervisory device for the communication network, where automatic testings of the coaxial carrier system are carried out periodically.

Electric multiple-unit trains

Only electric multiple-unit trains are used, for several reasons:

1. The light uniform axle load of the trains permits light tracks and structures.
2. Shuttle service may lead to simple track layouts in stations.
3. Traction motors on every axle may make use of effective electric brakes at very high speeds.
4. Powerful climbing capability over grade sections may give flexibility in selection of railroad locations.
5. Constant running characteristics may select any consist of a train matched to traffic demand.
6. The tractive force equally shared by each car requires less force to activate the car body and draft gears.
7. The equally distributed motive power over all the train assures constant and reliable operations.

Design of the train was also a result of extensive testing on the test run section. Data from these tests verified that a speed as high as 250 km/h could be achieved in comfort, and provided guidance in choosing between alternative designs. For example, several prototype trucks were tested, and the best one was selected—that is, the one least likely to show the oscillational snake motions that are often observed at very-high-speed operation. This truck is equipped with pneumatic-type bolster springs, which do not need swing bolster hangers because of their lateral rigidity.

Data from these tests also revealed some new problems. As an example, riders on test trains noticed sharp changes in air pressure as they entered tunnels at high speed. These pressure changes were measured, and a decision was made in favor of an airtight design for cars for regular service. Train doors have also been made airtight. Air-conditioning intakes and outlets are closed before trains enter tunnels, with electronic coils along the tracks actuating the closing mechanism.

Two coaches make one unit electrically, a train of 12 cars being composed of six electrically identical units. One of these two cars is equipped with a pantograph, high-tension switchgear with protective relays, a main transformer, a tap changer and other ac high-tension apparatus, with a silicon rectifier set, whereas the other car has apparatus related to the dc main circuit such as a master controller and resistors for dynamic braking. Every axle has a traction motor, making eight in a unit. The apparatus, except for the pantograph, are all installed under the floor so that revenue space can be best utilized. Cars with the heavy electric apparatus are so designed that weight is evenly distributed on all axles within the limitation of 15 tons per axle.

Traction motors rated at 185 kW are driven by pulsating current supplied from the rectifier. Four motors in a unit are permanently connected in series, making two groups in parallel. Speed is controlled by changing applied voltage by use of the tap changer.

In the high-speed range, dynamic brake action decelerates the train, which automatically transits to pneumatic brakes when the speed decreases to 50 km/h. In an emergency, both brakes are applied simultaneously.

The fleet of 30 multiple-unit trains has shown an almost perfect running record. Daily runs for the trains in revenue service have achieved 29 049 train km. Principal dimensions and characteristics are as follows:

Voltage at pantograph: 25 kV standard, 30 kV maximum, 22.5 kV minimum (20 kV for less than 30 seconds)
Tare weight: Approximately 54 tons
Dimensions:
- Length between couplers, 25 000 mm
- Maximum height above rail level, 3975 mm
- Maximum width, 3380 mm
- Floor above rail level, 1300 mm
- Coupler above rail level, 1000 mm

Performance (per unit of two cars coupled):
- Continuous rating output, 1480 kW
- Speed at continuous rating, 167 km/h
- Maximum allowable speed, 250 km/h
- Main transformer, 1650 kW, shell type, oil circulating, forced ventilation
- Silicon rectifier, 1500 kW, bridge connected, forced ventilation
- Traction motor, open type, self-ventilation
- Performance at continuous rating
  - Output, 185 kW
  - Voltage, 415 V
  - Current, 490 A
  - Revolutions, 2200 r/min
- Pulsating factor, 50 percent

Driving and gear reduction system: Paralleled Cardan driving system with flexible gear coupling, one-stage gear reduction
- Gear ratio, 29:63
- Diameter of wheel, 910 mm

Bogie: Two axles, with rolled monobloc wheels having brake disks. Wheel base, 2500 mm
Speed-control system:
- Powering, 25 step tap changers at low tension
- Dynamic braking, 17 steps
- Control, motor-driven cam system
- Control circuit, 100 V dc

Brake system: Dynamic at speeds exceeding 50 km/h, pneumatic at speeds below 50 km/h in normal operations, and applicable over the complete speed range
- Control, by automatic control system or manually
- Mechanical rigging, disk

Auxiliaries:
- Blower motor, cage-type capacitor motor, single-phase ac at 220 V
- Motor–generator, cage-type induction motor, single-phase ac at 220 V
- Air compressor, cage-type induction motor, single-phase ac at 220 V
- Inverter, 100-V dc motor and 60-c/s 100-V single-phase ac motor

Air conditioner: Unit type mounted on the ceiling of passenger room; heat-pump system for heating and cooling

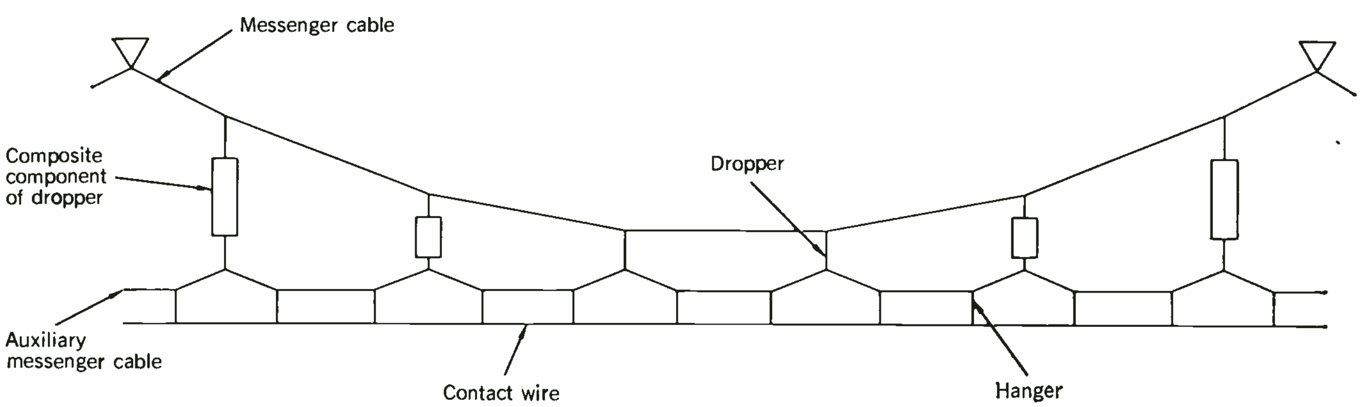
Catenary structure and pantograph

A new approach had to be made in design of catenaries and pantographs for high-speed operations so that they could collect current stably at 200 km/h. The current-collection characteristics are based not only on these factors, but also on movements of cars and track conditions.

After careful study, including wind-tunnel experiments up to 100 m/s (325 ft/s), a compact and light pantograph of high performance was selected from several prototypes.

Extensive research, both theoretical and experimental, was carried out to find an ideal catenary for extra-high-speed trains. Several types of catenaries were subjected to study for possible adoption. They were: normal compound, continuous mesh, modified-Y compound, and

Fig. 5. Composite-type compound catenary structure, designed for high-speed operation.



composite-type compound. After repeated experimentation on the test-run section, as well as on the existing tracks of 1067-mm gauge, data showed superior characteristics on the composite-type compound catenary; see Fig. 5. This catenary has composite components consisting of spring and damper at the droppers. A uniform equivalent mass, proper mechanical resistance, and spring constant of the catenary are obtained by adjusting the spring. Harmful oscillation of the contact wire can be suppressed by adjusting the damper. The catenary displays excellent current-collection capacity with the new pantograph at very high speeds.

Power supply and distribution system

Twenty-five unattended traction substations are installed along the line, at intervals of approximately 20 km. Power is received from two power companies in each area at 60 c/s, except for six substations in Tokyo and to the west, where the 50 c/s of the power companies is converted to 60 c/s by two railroad-owned converter stations and is transmitted to the substations through 77-kV lines built along the track for this exclusive use.

Though power-receiving locations are so selected that the three-phase short-circuit capacity is more than 500 MVA, a Scott-connected transformer of 30 MVA is installed to reduce any unfavorable effects caused by single-phase loading to the supply networks. Load unbalance has been kept within permissible degrees in spite of such maximum train loads as 10 MVA at the point of instantaneous maximum.

Another salient feature of the power supply is the so-called different phase distribution system for eastbound and westbound tracks, which means that two phases of power transformed from three phases by the Scott-connected transformer are fed to the overhead conductors of the eastbound and westbound tracks separately. This system has successfully halved the total number of neutral sections on the line where trains run by coasting.

The other characteristic design of the system is a changeover of supply phases. In place of a neutral section, a section is set at a midpoint between substations, where supply changes from one to the other within several cycles are effected by use of a special switchgear installed at a sectioning post when a train is powering in the section. Therefore, trains can run for 515 km without putting off the notch because of difficulties in the distribution system.

This distribution system permits the possible operation of traction substations in parallel, which would not need any operation of switchgear in the sectioning posts under normal conditions. As is widely known, parallel operation is helpful in reducing the voltage drop. The operation, on the other hand, inevitably produces cross-current flow in the contact system. Cross currents of 56 amperes at the maximum were observed when two substations differing 2 to 3 degrees in phase were operated in parallel. After joint study with the power companies, it was concluded that the operation was feasible if phases differed no more than 6 degrees. At present, 11 out of 24 distribution sections have been put successfully in parallel operation, after addition of some protective relays to compensate for faults peculiar to the system. The paralleling has proved effective in reducing unbalanced loading.

Consumption of energy for traction was about 32 million kWh per month, or 43 kWh per thousand ton·km of carload, according to the monthly record for July 1965.

The data on fixed installations may be summarized as follows:

Electrical system: 60-c/s single-phase ac at 25 kV

Input of trains (12-car consist; average power factor, 85 percent):
- 10 MVA at maximum acceleration
- 7 MVA at balancing speed of 200 km/h (on level)
- 10.5 MVA at balancing speed of 200 km/h (on 10 percent grade)

Short-circuit capacity at receiving busbar of traction substations: More than 500 MVA

Line impedance of distribution circuit:
- $0.21 + j0.79$ ohm/km

Spacing of traction substations: 20 km

Transformer capacity: 15 MVA × 2 (Scott connected)

Booster transformer:
- Spacing, 1.5 km in urban areas, 3 km in other areas
- Capacity, 12 kVA for 1.5-km, 24 kVA for 3-km location

Composition of overhead conductors:
- Messenger cable, 80 mm² of cadmium copper
- Auxiliary messenger cable, 60 mm² of cadmium copper
- Contact wire, 110 mm² of grooved copper
- Feeder cable for return circuit, 300 mm² of hard-drawn aluminum

Conclusion

The speed train, boldly conceived by railroad men six years ago, has been running at 200 km/h (125 mi/h), achieving both technical and commercial acclaim for over a year. The technical success, firmly based on recent engineering developments introduced on trains and at wayside installations, has demonstrated excellent performance results at the initial stage of operation. The commercial success of the high-speed train is demonstrated by the fact that it has attracted more than 20 million passengers within a year of revenue service, all of whom have traveled in complete safety.

This new railroad, though completed within the old framework of two running rails, incorporates the best of modern engineering skills, in which electricity and electronics both play important roles. It has received world recognition in the field of mass transportation. The impact of the success of the new line should give the railroads themselves the challenging opportunity to reappraise their position as an efficient transportation means encompassing speed, safety, and comfort in this age of highway transportation. This mode of ultrahigh-speed transportation by trains traveling at 250 to 300 km/h may have limitations because of conditions relating to reliable adhesion to rails, detrimental motions of rolling stock including snake motion, or severe oscillations of overhead conductors; but it can maintain an unchallenged position for the next ten to twenty years as a predominant means of transportation in megalopolis areas. Planners' predictions may project such future achievements as air cars, linear-motor cars, and aerojet cars, but they are in the future. The New Tokaido Line, a forward-looking achievement for today's world, has proved conclusively that high-speed trains can operate safely and reliably, providing the mass transportation so necessary in today's industrial society.

A 16-mm sound and color film, running approximately 35 minutes, entitled *A New Railway Is Born—the New Tokaido Line*, is available to groups on request from the Japanese National Railways, 45 Rockefeller Plaza, New York, N.Y. 10020.

New applications for nuclear energy

The practical consequences of the nonmilitary applications of nuclear explosives promise to have widespread effects on both the national and the world economy. Although this topic may not be of direct professional interest to most electrical engineers, they will be intimately concerned with some of the technologies that will have to be developed or expanded to meet the needs created by the large-scale use of nuclear explosives. As a typical example, very large radiation and seismic measurement systems will be required to monitor the construction of the new sea-level Isthmian canal, to be described later. Similar monitoring systems will be needed in other applications, such as block caving in mining operations.

Background

The phenomenon of nuclear fission was discovered and identified in 1938.[1] The first self-sustaining nuclear chain reaction was achieved by the late Enrico Fermi and his collaborators only four years later.[2] In the 23 years since that time, the large-scale use of nuclear fission reactions has brought about a number of fundamental and far-reaching changes. The most important of these is probably still the application of nuclear fission to the production of large explosions.

The potential military use of these explosions dominates the political situation in which we find ourselves today. This is likely to remain the case for the foreseeable future until we have been able to develop a system of political control of nuclear weapons that will make it necessary to find other and possibly more effective means of resolving international differences. Controlled fission reactions, as contrasted to the uncontrolled reactions that occur in nuclear explosions, have also found important applications. However, even in this area, perhaps the most novel uses have been those in the military field. The best example is the development of the first truly submersible vessel for which nuclear power was necessary, the *U.S.S. Nautilus*. Nuclear reactors have, of course, also

Some nonmilitary applications of nuclear energy are examined, with particular emphasis on the area of explosives. These uses, in turn, call for the design and development of very large, complex electronic radiation and seismic measurement systems

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been employed to generate electric power for civilian use. The design of power reactors constitutes the more or less conventional part of the field of nuclear engineering. Reactors designed for power production are well developed. They operate at temperatures comparable to conventional power plants and do not present any really major technical problems. The interesting new phase in this field will be the advent of a fuel breeding system that will lower the price of nuclear power below the present figure (5 to 9 mills per kWh) for conventional power. As a matter of fact, the primary effect of the existence of nuclear reactors that could be employed for the generation of electric power has been and will continue to be to force down the price of conventional power production methods rather than to encourage the use of nuclear power. This circumstance is due primarily to the enormous investment we have today in conventional power sources.

Although there are many things—primarily dealing with the question of economics of operation and of fuel cycles—that remain to be done in the field of nuclear reactors, I do not believe that any of these will cause what one might call qualitative changes in the situation as it exists today. It has been shown that it is possible to generate power economically using nuclear reactors, and this type of generation is likely to become even more feasible (and thus attractive) as time goes on. Furthermore, there are certain very special applications of nuclear power reactors for which novel designs might be necessary. An example is the use of nuclear power reactors to supply power for large manned space vehicles. However, none of these applications are likely to bring about changes as spectacular in this field as the ones we have seen in the past 20 years. It is fair to ask whether there exists any application of nuclear fission that may bring about such changes. I believe this question may be answered in the affirmative if attention is focused on new applications of the fission process—that is, if devices understood and known today are employed in novel contexts.

Nonmilitary applications of nuclear explosives

There is one potential application of nuclear power that is likely to cause really qualitative changes in the areas in which the projects will take place. I am, of course, referring to the nonmilitary applications of nuclear explosions, or the so-called Project Plowshare. Project Plowshare was started by the U.S. Atomic Energy Commission in 1957.[3] At that time many of us felt that some of the ideas considered were far out and fantastic. However, in the past eight years, a great many pilot experiments and also a more detailed appraisal of needs and projects have revealed that there are indeed some purposes for which the large-scale use of nuclear explosives is vitally necessary.

It is perhaps not quite accurate to speak of the application of nuclear explosives as an application of fission energy. Although only a fraction of the energy of a nuclear explosion is due to fission rather than fusion reactions, the fission reaction is a vital part of the process. It is thus not too far afield to classify Plowshare projects as new applications of fission energy. In fact it will be shown that the design of nuclear devices to be used for Plowshare purposes is intimately connected with the fraction of the energy which comes from the fission process.

I would like to discuss four major applications of nuclear explosions. In order of apparent feasibility, these are: (1) earth moving on a large scale; (2) the crushing of hard rocks underground; (3) mineral recovery; and (4) the production of power and water purification. There are also a number of interesting scientific experiments that can be conducted using nuclear explosions.

Several questions must be answered regarding each of the proposed applications. These deal with technical possibility, cost, and, above all, safety. In the past eight years many experiments have been performed and have provided the necessary answers to these questions.

Earth moving with nuclear explosives

For projects involving earth moving, the results are summarized in Table I. The question of economy can be readily answered by looking at these figures. The general conclusion is that if the proposed project is sufficiently large, nuclear explosives are by far the most economical way of performing the work. Table I also illustrates the fundamental technical features of nuclear cratering. The volume of earth removed by the explosion is roughly proportional to the yield, and the depth and diameter of the crater are, as expected, roughly proportional to the cube root of the yield. Each of these conclusions is valid if

I. Estimated costs of crater formation in dry desert alluvium

Explosive Power, kilotons	Placement Hole: Diameter, inches	Placement Hole: Depth, feet	Crater Dimensions: Diameter, feet	Crater Dimensions: Depth, feet	Crater Dimensions: Volume, cubic yards	Cost, thousands of dollars: Explosive	Cost, thousands of dollars: Placement	Cost, thousands of dollars: Operations	Cost, thousands of dollars: Total	Cost per Cubic Yard, dollars: 1963	Cost per Cubic Yard, dollars: Revised
1	36	160	400	90	210 000	500	100	500	1100	5.25	...
10	36	325	800	175	1 600 000	500	150	750	1400	0.88	0.78
100	70	620	1600	350	12 000 000	750	300	1000	2050	0.17	0.15
1000	70	1220	3200	690	96 000 000	1000	600	2000	3600	0.04	0.033

Source: "Excavation with Nuclear Explosives" (G. W. Johnson, Report No. UCRL-5917, University of California, Nov. 1, 1969) for all except final column. Since that publication, there has been a further reduction in nuclear explosive costs, and we have added the final column from an AEC press release of May 6, 1964, to show the effect of these price changes.

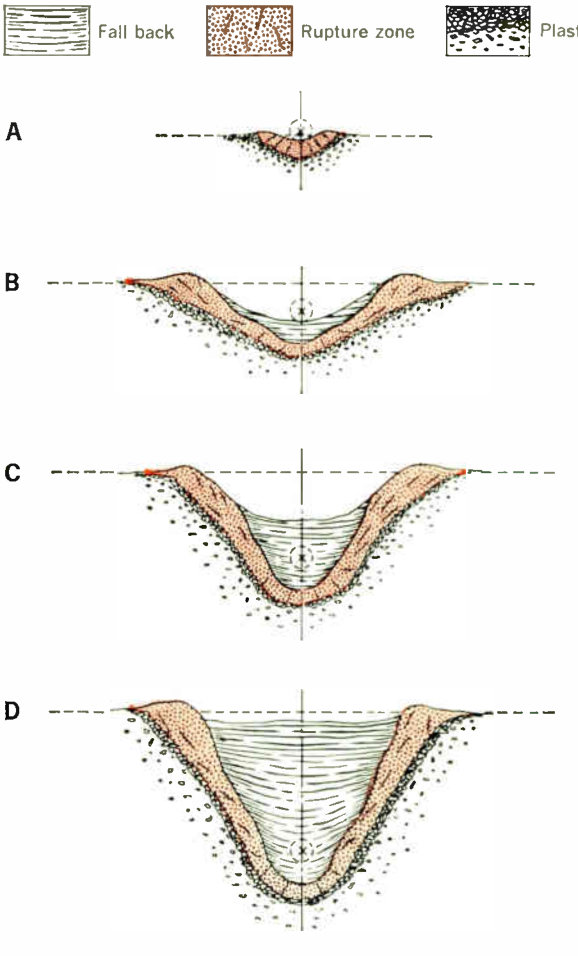
the charge is buried at optimal depth. The effect of depth of burial is shown in Fig. 1. It can be seen that if the charge is not buried deeply enough, most of the energy is dissipated in the air. On the other hand, if the charge is placed too far below the surface, most of the energy is spent crushing rocks, and little goes into throwing earth out of the crater. An additional consideration affecting the depth of burial is the dissipation of radioactive fission products. This point will be considered later when the safety of earth-moving projects is discussed. Much information on cratering theory has been collected in the past eight years. One of the important objectives of this program was to develop scaling laws, which allow one to predict the effects of very large explosions from those of smaller size. These scaling laws have been tested experimentally over a wide range. Figure 2 shows the largest man-made crater ever produced. It was created by a nuclear explosion having the yield of 100 kilotons and detonated 635 feet below the surface of the Nevada desert.

Craters of this type are likely to have limited use even though they do look very impressive. It is important to learn whether holes can be made with specific shapes and specific configurations for specialized purposes. For instance, the creation of large canals using nuclear explosions is likely to be one of the most useful purposes to which they can be put. It is, therefore, important to learn whether a properly placed row of charges can indeed produce a ditch. Experiments have shown that it can.

Another extremely important question that must be asked is: How long is the crater from a nuclear explosion likely to last—that is, how stable is the crater? Fortunately, a number of craters produced by nuclear devices have been around for some time, and thus the appropriate measurements are possible. The title illustration shows the crater produced by a large nuclear device fired on one of the Pacific islands about ten years ago. It is quite obvious from this picture that even though the explosion occurred under water, the crater is still there. The stability of a given crater and also the precise shape and nature of the crater walls depend, of course, on the type of rock in which the explosion occurs. Enough information in this field is now available that reasonably accurate predictions about the results of a proposed explosion, or series of explosions, can be made.

Perhaps the most important limitation on the widespread application or use of nuclear explosions for earth moving is the question of safety. There are two consequences of a nuclear explosion. One is the radioactive contamination of the immediate neighborhood of the explosion, and the other is the production of a large earth shock. If nuclear explosives are to be employed for peaceful purposes, it is quite clear that the release of radioactivity must be appropriately controlled and that the explosion must be carried out in such a way that the earth shock produced causes no great destruction in the neighborhood of the explosion. It has been shown that the radioactivity released in an explosion buried underground is rather less than that which is expected in an atmospheric shot. Many of the radioactive materials

Fig. 1. Craters produced by nuclear explosives buried at various depths. A—Surface burial. B—Shallow burial. C—Optimum burial. D—Deep burial.



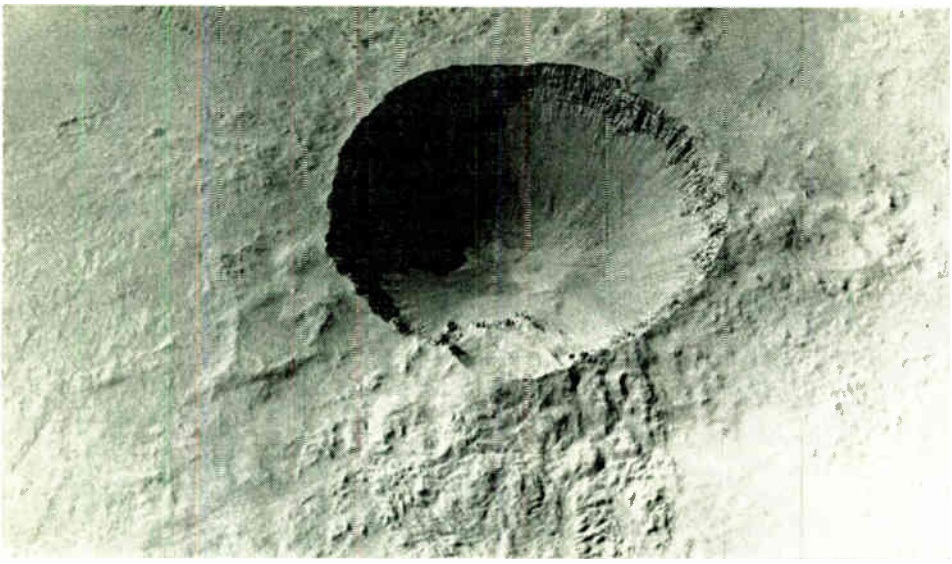


Fig. 2. Crater, about 325 feet deep and 1200 feet in diameter, produced by device of 100-kiloton yield. The explosive was buried originally at a depth of 635 feet.

produced in the underground explosion are trapped in the rock, and those released into the atmosphere tend to be attached to particles, which are quite heavy. Thus, fallout from an underground explosion is limited to an area that is small compared to the area of fallout for an atmospheric shot. Unfortunately, the fallout can never be entirely eliminated. This means that at the time when the excavation is performed, the immediate area of the excavation site must be evacuated.

The existence of the earth shock caused by the explosion also requires evacuation and possibly the permanent destruction of some of the structures in the immediate vicinity of the explosion. If too many people live in the area in which the work is to be performed, then the evacuation is clearly one of the major factors, both economic and political, in determining whether the project is feasible or not. This circumstance has limited the present proposal to parts of the world in which the population is sparse. Moreover, the economics of nuclear explosions dictate that the projects to be considered be large. But fortunately, it is in just those areas of sparse populations that large-scale changes in the environment can be made to yield the greatest benefits. There are three outstanding examples of such programs. The first is the construction of a large harbor in southern Alaska which would make accessible hitherto unusable mineral deposits. The second is a large project of harbor construction and mountain tunnel construction in the northeastern quarter of Australia. The successful completion of this project would make a part of the world inhabitable which at present has almost no population at all. Finally, perhaps the most fascinating of all the proposed excavation projects is the construction of a second canal across the Isthmus of Panama.

That the present Panama Canal is quite inadequate is obvious. There is always a waiting line of ships on either end, and delays of up to a week are not uncommon. Also, the largest ships now being built cannot go through the locks in the present canal at all. Several alternate routes for a new sea-level canal are now being considered; see Fig. 3. The contemplated ditch would be approximately 1000 feet wide and would have a maximum depth of 60 feet—adequate for all ships now in existence.

Population density considerations make only the route through northern Colombia and the route through eastern Panama, the so-called Sasardi–Morti route, feasible. The latter route is the more desirable simply because it is shorter. A canal of the type described here would require the use of several hundred megatons of nuclear explosives. From the numbers given in Table I, it can be seen that 1-megaton charges placed in a line would give approximately the proper size craters to make a canal of the dimensions needed. The radiation patterns that would be established by the detonation of the charges are shown in Fig. 4. The same figure also illustrates the dramatic improvement in the quality of nuclear explosives over the last ten years. The fission yields of thermonuclear bombs have been reduced to the point where it is relatively safe to use very large nuclear explosives for the purposes we are discussing. The numbers given in Fig. 5 show the approximate lifetime doses an individual would receive without any protective or decontamination measures. These figures should be compared with the total lifetime dose received from natural sources alone, which is of the order of 10 roentgens.

The total estimated cost of the Sasardi–Morti Canal constructed using nuclear excavation methods is approximately \$650 million. This number must be compared with the total cost of the cheapest conventional alternative sea-level program, which involves the reconstruction of the existing canal. To eliminate the existing locks and to widen and deepen the present canal by conventional means would cost approximately \$2.3 billion. A somewhat smaller, conventionally constructed canal along the Sasardi–Morti route would cost \$4.5 billion. The cost difference clearly represents the most compelling argument for the use of nuclear methods and large-scale earth moving.

There is little question in my mind that such a canal will actually be built within the next ten years. In 1964 President Johnson requested that Congress authorize an appropriate study for this project. The bill authorizing the study was duly passed and signed by the President on September 22, 1964. Active work is expected to be under way soon. One of the pilot projects in the canal construc-

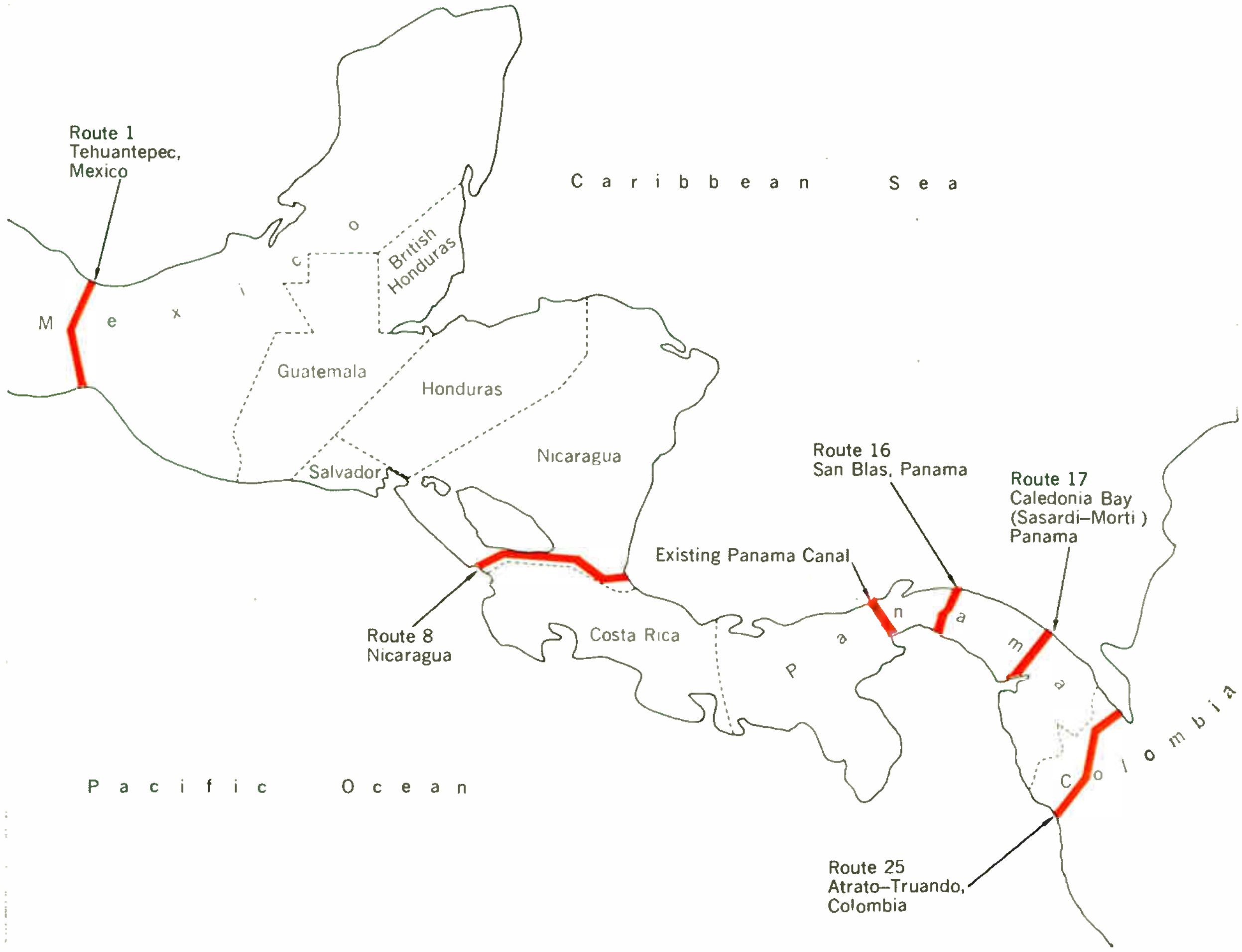
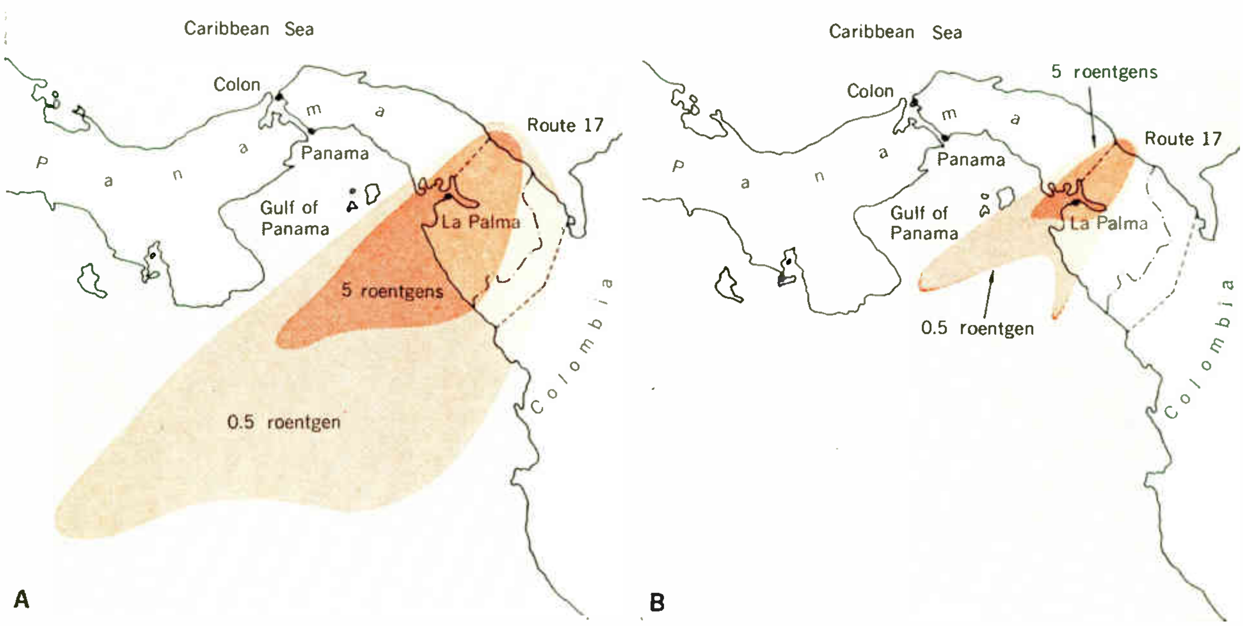


Fig. 3. The alternate sea-level routes for a second canal across Central America. Route 17 (the Sasardi Morti route) is the most likely one to be chosen.

Fig. 4. Radiation dose patterns resulting from the construction of the Sasardi Morti Canal. A comparison is made between (A) explosives available in 1958 and (B) those possible today. The reduction in dose is due to smaller fission yields of present-day devices.



tion study will be the construction of a large railroad cut in the Bristol Mountains of southern California. Approximately 20 explosions, with a total yield of the order of one or two megatons, will be employed.

There is every reason to believe that a number of similar, large-scale excavation projects using nuclear devices will also be carried out in the next ten years. The methods and cost estimation techniques to be employed are similar to those to be used in the Isthmian canal construction project. Rather than discuss these projects in more detail, I would like to describe some of the other ideas now being actively considered by scientists and engineers who are working on Project Plowshare.

Contained nuclear explosions and their applications

The nuclear explosions used in excavation projects are detonated at such a depth that a large fraction of the material crushed by the explosive force is ejected from the crater. If the charge is buried deeply enough, the nuclear explosion will be completely contained and none of the blast effects will be felt above the surface. Also, none of the radioactive products of the nuclear explosion are released into the atmosphere. There are a number of interesting applications of completely contained explosions underground. Although these applications are not as spectacular as those involving the earth-moving projects discussed in the previous section, they may be even more important in their own way. A good many underground nuclear explosions have been conducted; therefore, the phenomenology of such events is well understood. The result of a typical underground nuclear shot is shown in Fig. 5. Immediately after the detonation occurs, a cavity whose walls are made of molten rock is created. High-pressure gases in the cavity sustain the integrity of the walls and prevent the roof from collapsing. As the gas cools, the pressure is no longer high enough to sustain the overburden of the rock above the cavity. The roof of the cavity therefore collapses, and a large, rubble-filled chimney results. The bottom of the chimney is hot and contains most of the molten rock. The radioactivity produced by the nuclear shot is trapped, for the most part, in the molten rock. In very special circumstances it is sometimes possible to prevent the collapse of the roof. This was the case in the Gnome experiment, in which a 5-kiloton nuclear explosion was detonated inside a salt dome. In this event a cavity approximately 60 feet in diameter was created, and the roof, although portions of it collapsed, remained essentially intact. A cavity thus resulted which was probably quite similar to the one that existed immediately after the explosion. However, in most locations the result of an underground nuclear explosion will be the rubble-filled chimney shown in Fig. 5.

What are the possible uses of such a chimney? One obvious application is in the field of mining.[4,5] Underground mining by block caving is a well-established technology. An example of block caving is shown in Fig. 6. The ore is crushed in one way or another at the level at which it is found, and then is fed by a series of channels to the so-called haulage level, from which it is removed from the mine. The use of nuclear explosives to crush the rock will greatly increase the efficiency of such operations by increasing the amount of ore made available and decreasing the cost of the necessary drilling. This occurs because fewer explosions are necessary if nuclear methods, rather than chemical explosives, are used.

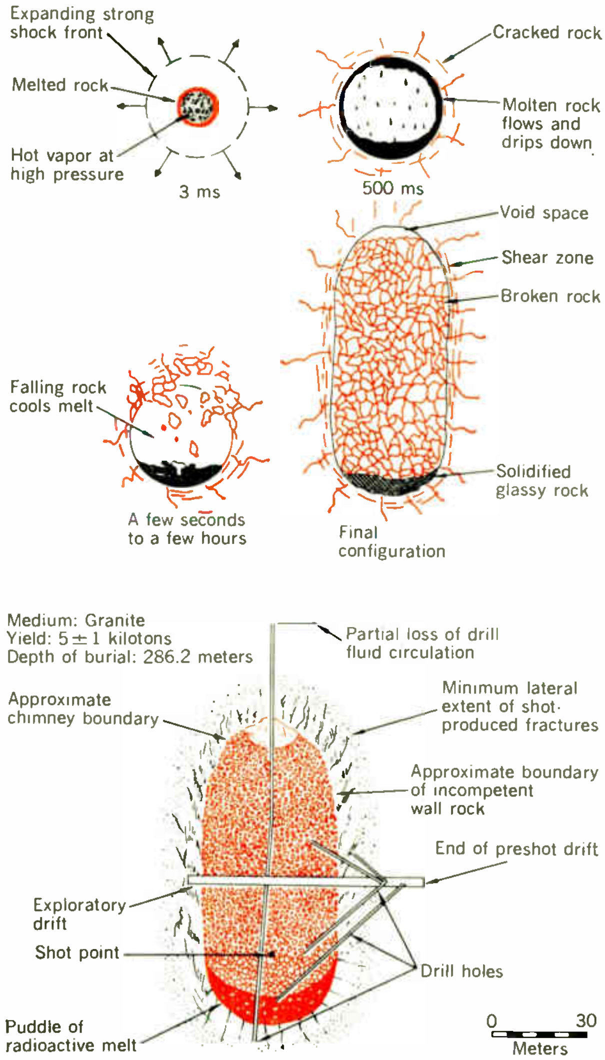
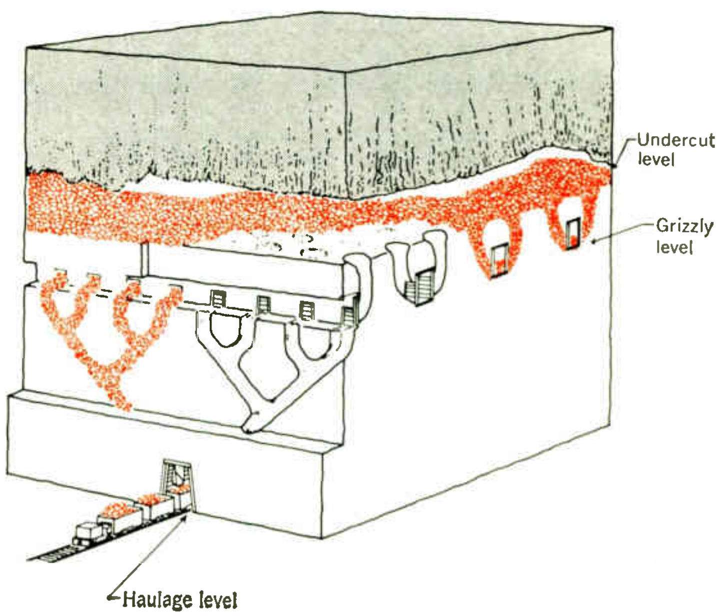


Fig. 5. Way a "chimney" resulting from a completely contained underground explosion is produced.

Fig. 6. Cutaway drawing showing a block-caving operation in which nuclear explosives are used.



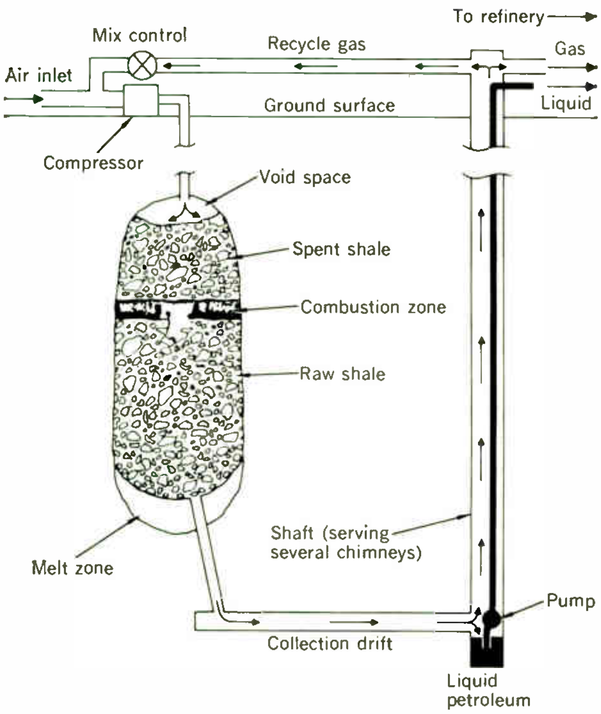


Fig. 7. Underground retorting of volatile products trapped in shale rock crushed by a nuclear explosive.

The radioactive contamination of the ore is not likely to be a major problem. The reason for this circumstance has already been mentioned. Most of the radioactive fission products of the explosion are trapped in the molten rock at the bottom of the chimney. The rubble is almost free of any contaminants. This conclusion has been verified experimentally on a number of occasions. Although nuclear block caving has the obvious advantage of making much larger quantities of ore available, there are, of course, also attendant disadvantages that must be taken into account. Perhaps the most important one is the earth-shock problem. Buildings and the mine head in the vicinity will have to be constructed to withstand considerable ground motion if nuclear block caving is to be used on a large scale. In addition, methods will have to be developed to handle a small amount of contaminated ore, which will be brought to the surface from the multiple chimneys produced in the block-caving operation.

One rather ironic application of block caving is the recovery of oil from shale rocks by the use of nuclear methods to crush the rocks. Here we are contemplating the use of nuclear power to extend the era of fossil fuels by making more efficient recovery of fossil fuels possible. One novel suggestion has been to create the chimney, such as the one shown in Fig. 5, with an underground explosion in oil shale and then to burn the oil-bearing rocks in the chimney itself. A schematic diagram of such a plant is shown in Fig. 7. Combustion would start at the top of the chimney, where the necessary oxygen containing gas to sustain the fire would be pumped in. As the oil is burned out of the rock, the combustion zone would move down the chimney. The hole will be drilled at the bottom of the cavity to collect unburned gas driven out by the pressure created in the combustion zone. Liquid petroleum produced in the same manner would also be collected. Active plans are now under way to try out a similar scheme for the recovery of natural gas trapped in hard rocks. A study of economic feasibility of this proposal by the El Paso Natural Gas Company has led to the belief that such projects will actually be carried out in the near future.[6] Here again several problems remain to be solved. Perhaps the most important is still the contamination of the gas and oil by radioactive materials produced in nuclear explosions. At the present time it is difficult to assess whether this contamination impairs the feasibility of the ideas. All that can be said is that more work on underground nuclear explosions must be done in order to understand in greater detail the actual distribution of the radioactive by-products of the nuclear explosion. A reduction of the fission yield of the explosives used for these purposes would of course also be a great advantage.

The application of nuclear explosions to mining and the recovery of shale oil are relatively unsophisticated. All that the nuclear explosive is really used to do is to crush rock. There have been a number of suggestions of a more complicated nature requiring more stringent control of the conditions under which the explosion is carried out. One of these techniques, recommended by Prof. George Kennedy of U.C.L.A., is to use a combination of geothermal and nuclear energy to desalinate water. His suggestion is simply to create a very large chimney, of the type already discussed, in a zone where there is a large geothermal gradient.[7] A series of 1-megaton explosions set off in a vertical row could produce a chimney as long as 3000 meters. The temperature of the rock at the bottom of this chimney could be as high as 600° or 700°C due to geothermal energy alone. Water would then be introduced at the bottom of the chimney, where it would flash and turn into steam. The steam would rise in the chimney and be recovered through a hole drilled to the chimney's roof. The estimated exit temperature of the steam is approximately 200°C. The water would be pumped through the chimney at the rate of approximately a million gallons per day. The resulting steam would be used for power generation, and the water obtained, when condensed, would of course be fresh. The salt originally contained in the water would be deposited at the bottom of the cavity.

Detailed cost estimates for this scheme have been made, assuming five 1-megaton explosions and an operating time of one year.[8] The numbers obtained are clearly not competitive with other methods for desalinating water contemplated at the present time. It is, however, quite likely that more research in the phenomenological aspects of underground nuclear explosions will reveal important short cuts that could drastically change the cost figures. For the scheme suggested by Prof. Kennedy, approximately half the energy recovered comes from the nuclear explosions, and the other half comes from the geothermal temperature gradient existing in the chimney at the time the explosions are detonated. The major technical problems likely to be encountered are similar to those already mentioned in connection with other possible applications of nuclear explosives. These have to do again with the existence of the ground shock and earth motion resulting from the explosion itself. In this case also, the radioactivity produced by the nuclear explosion is a problem that must be properly understood if the effects are to be adequately controlled. An additional difficulty of Prof. Kennedy's idea is that we do not know enough about the properties of various rocks under the conditions likely to exist in the chimney that we can make the detailed predictions necessary for cost estimates and feasibility studies. For example, it is possible that the rubble produced by the explosion will fuse into solid rock under the conditions of pressure and temperature existing in the chimney. If this occurs, then it is clear that no water can be pumped through the chimney and no steam will emerge from the top. Fissures created in the rock by the explosion of the nuclear devices may also cause difficulties. The steam under pressure at the bottom of the cavity could escape through these fissures and, therefore, render the whole idea impractical. The experimental experience with the Gnome shot seems to indicate that such fissures are in fact created and that it is difficult to trap high-pressure steam in the cavity for generating power.

Scientific applications of nuclear explosions

In the foregoing discussion, I have mentioned most of the ideas and proposals that are now under active consideration dealing with the practical application of nuclear explosives. It would be a mistake in an article of this nature not to say a few words about the purely scientific uses of nuclear explosions. Nuclear explosives can be used both as the means for investigating phenomena in other fields and as a method for studying the phenomena occurring in the explosion itself. A good example of the former are geophysical experiments. Nuclear explosions detonated under the ground create seismic waves, which can be detected thousands of miles away from the site of the explosion. Many experiments on these seismic waves have already been conducted in southern Nevada[9,10] using test explosions. Much has been learned as a consequence about the behavior of the earth's crust and mantel.

Although such experiments are interesting and important, the experiments involving the properties of the nuclear explosions themselves have attracted more attention. Nuclear explosions produce large quantities of neutrons. They also emit large numbers of charged particles, both ions and electrons. Both the neutrons and the charged particles have been employed for a number of scientific experiments. The extremely high neutron flux produced at the instant of the detonation can cause a long chain of multiple neutron capture processes in the vicinity of the explosion. If heavy elements are present in this region, many transuranic species of isotopes can be produced. A good example of this is the discovery of several new transuranic isotopes in the debris of the Mike shot carried out in the Pacific in 1954.[11] The debris was analyzed by scientific groups at the Argonne National Laboratory and the Lawrence Radiation Laboratory, and the existence of the new isotopes was established beyond doubt by these groups. Plans are under way now to continue these experiments with specially designed devices to be detonated underground. Means must be devised to recover the samples rapidly from the immediate region of the explosion, so that the isotopes can be recovered before they decay. Once this is done it should be possible to identify many now-unknown transuranic species.

Neutrons emitted by nuclear explosions have also been employed for neutron cross section measurements.[12] In these experiments the enormously large burst of neutrons emitted by the explosion is used as a source, and velocity selection techniques are employed to determine the neutron energy. Perhaps the most novel application of this method is the work of Dr. R. D. Albert and his associates at the Lawrence Radiation Laboratory. A nuclear explosion detonated at very high altitudes was used in these experiments as the source of neutrons. The detectors and the samples to be investigated were placed aboard sounding rockets. The sounding rockets were then launched from sites roughly 1000 miles away from the point of the explosion. The neutron intensity was then observed as a function of time through appropriate absorbers.

The electrons and other charged particles emitted by nuclear explosions have also been employed for scientific purposes. Nuclear explosions can and have been used to inject charged particles into the geomagnetic field. The behavior of the particles subsequent to the explosion has been determined by means of satellite-borne detectors.[13] Some of the results obtained from these experiments have also led to important insights regarding the nature of the trapped charged particle field that surrounds the earth.

Conclusion

In these few pages I have tried to give an account of the many varied uses of nuclear explosions. Some of the speculations may sound fantastic and improbable, because they deal with large-scale changes in man's environment. Althouth they may sound strange, they are actually characteristic of the technical situation at the present time. We are contemplating similar changes in other areas, such as air pollution control and the control of water resources. There are some people who are even speaking of controlling the weather rather than merely talking about it. Indeed, I have a feeling that large-scale changes in our physical environment are vitally necessary if mankind is to survive on this planet. It would be very surprising indeed if nuclear power did not take its proper place in these enterprises.

Essentially full text of a paper presented at the 1965 Western Electronic Show and Convention (WESCON), San Francisco, Calif., August 24–27.

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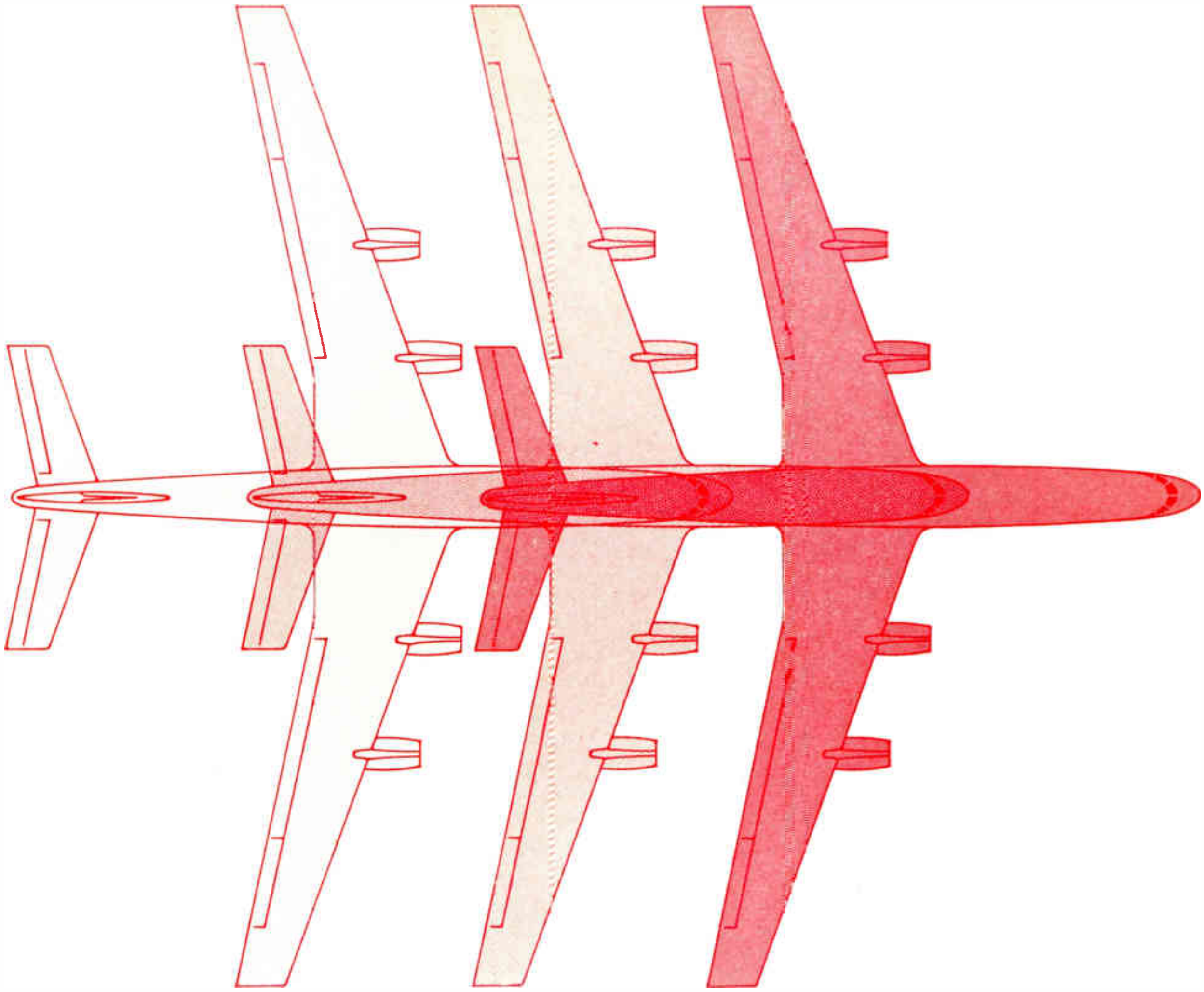

Aircraft collision avoidance systems

Although in-flight aircraft collisions are extremely rare, the recent accident north of New York City underlines the fact that they do occur. However, techniques for their avoidance are constantly being improved and updated. The air-derived separation assurance systems described are designed to supplement the older and better-known ground-operated air traffic control systems

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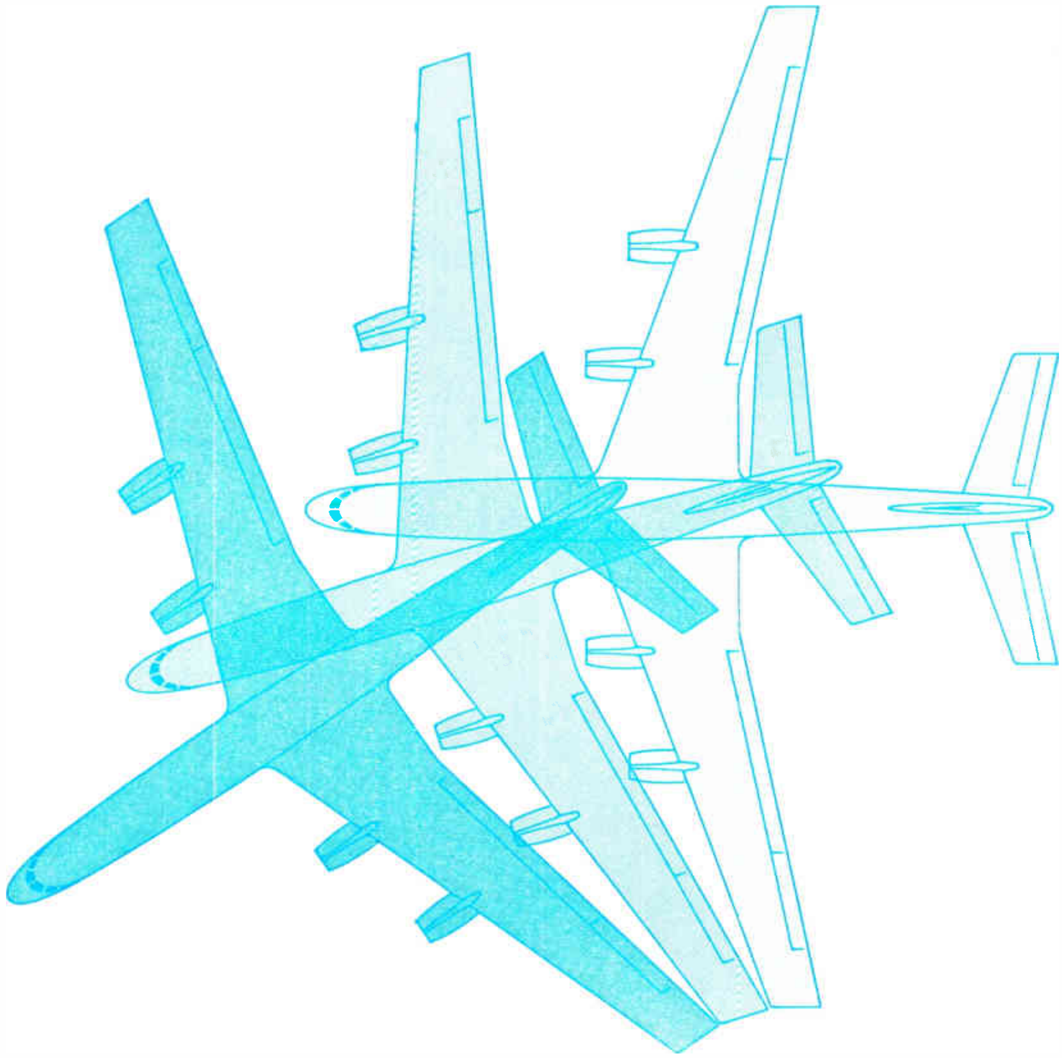
The problem of assuring adequate separation between aircraft in multiple aircraft environments has engaged the attention of workers in the field of aeronautical navigation for many years.

The present ground-operated air traffic control system is an outgrowth of this work, and it performs its mission quite well in most circumstances. The basic aircraft position information necessary for system operation is derived from ground-based radars and/or aircraft position reports with respect to ground navigation facilities. Altitude data are acquired by barometric altimeters in the aircraft and transmitted to the ground by automatic or manual means.

Since safe traffic capacity of the system is proportional to the accuracy with which aircraft positions relative to other aircraft in the area can be determined, dense traffic requires extensive ground navigation facilities, preferably including radar. Moreover, safety requires that the traffic be well-ordered, with every aircraft in the vicinity under some form of air traffic control. Thus, there appears to be



a place for air-derived separation assurance (ADSA) systems in many portions of the air traffic structure to improve safety or increase the safe traffic flow. These systems find appropriate application in areas in which a considerable amount of maneuvering takes place (such as in test areas or military reserves), in the North Atlantic and other areas without well-developed fixed-base navigation facilities, in high-density mixed-traffic terminal areas (where most collisions occur), and as a backup for good air traffic control.

The thinking on ADSA was initiated in the earlier days of aviation, and as far back as 1929 a patent was filed, by Glen Muffly, for an airborne device to provide a separation function (Patent No. 2 066 156). However, the philosophical and technical problems associated with ADSA are formidable, and only recently has it appeared that a practical and reasonably effective system could be constructed for widespread use.

An ADSA system must perform the following basic functions:

1. Detect other aircraft in the vicinity of the protected aircraft.
2. Evaluate the hazards presented by the detected aircraft.
3. Order appropriate escape maneuvers where judged necessary.

Early work on ADSA was conducted from the view that the equipment must not require active cooperation from other aircraft, in order that an aircraft carrying the equipment would be protected from all classes of aircraft in the vicinity. This, in turn, implied that the equipment should not sound an alarm for miss distances in excess of 500 feet, because of the 500-foot altitude separation then allowed by Air Transport Command rules between aircraft in the same plan position. (Current ATC rules allow 500-foot vertical separations only under very limited circumstances, with 1000-foot separations being far more common.) These efforts were stimulated by the occurrence of a collision of two airliners over the Grand Canyon in June 1956.

In 1957 it was concluded independently by Collins and others that a practical self-contained equipment could not reliably predict miss distances of about 500 feet or less at ranges great enough to permit adequate time to perform a successful evasive maneuver. This is largely because the usual turbulence-induced random motions of the affected aircraft were of sufficient magnitude to obscure predictions of this order of precision. Since 500-foot miss dis-

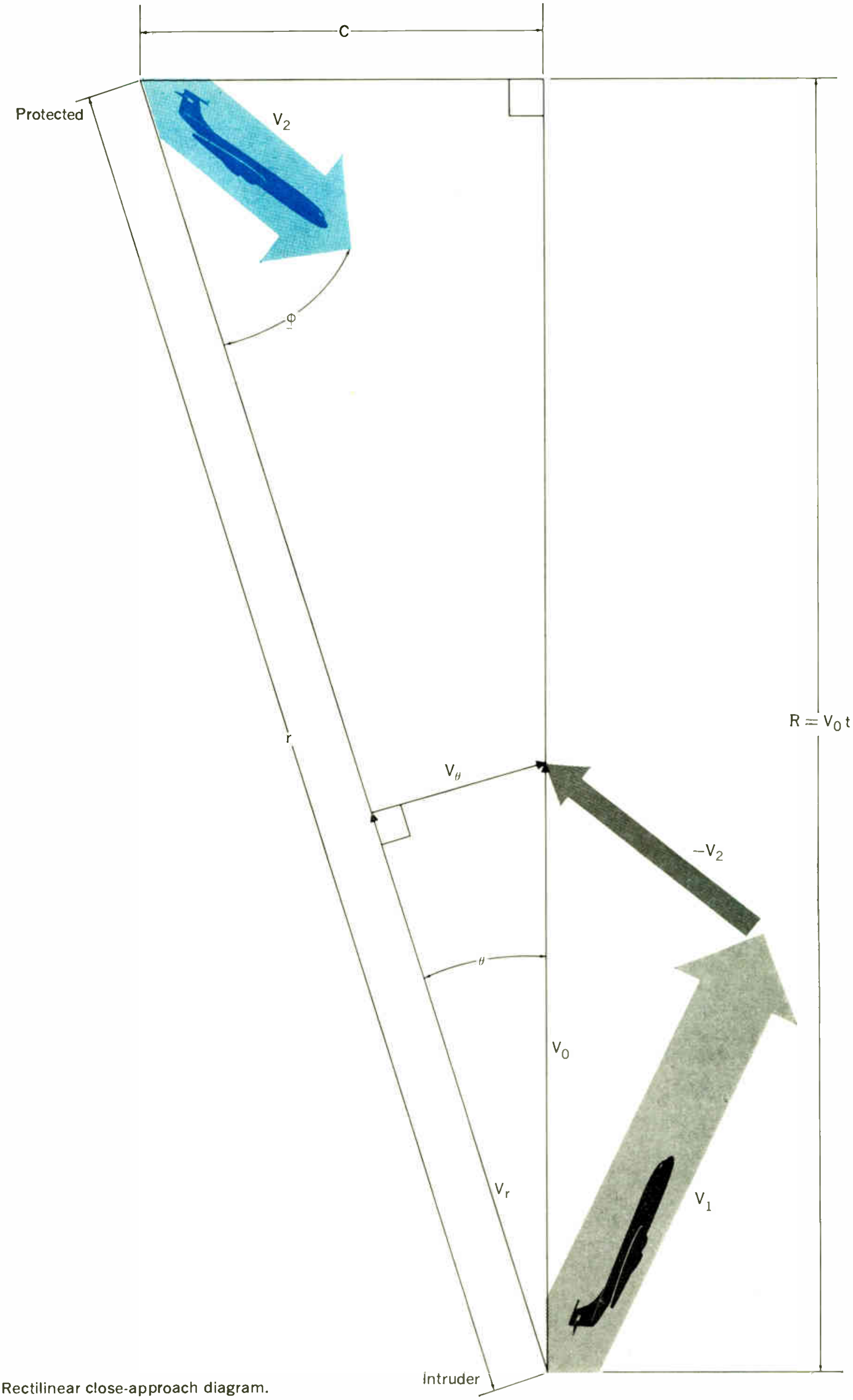


Fig. 1. Rectilinear close-approach diagram.

tances cannot be predicted reliably, at least on a self-contained basis, noncooperative ADSA systems were ruled out. Another significant finding was that reliable miss-distance predictions that converge toward the correct value cannot be made in the face of the usual measurement noises unless a measure of range information is available.

Concurrently, work was being performed by a number of groups on several varieties of proximity warning equipment designed to alert a protected aircraft of the presence of an intruder in the vicinity and to indicate its approximate position. At the same time, the Federal Aviation Agency was performing experiments to determine the utility of pilot warning instrument (PWI) equipment in the environment in which it must operate. The general findings of these programs were that a practical, dependable, all-weather PWI would be extremely difficult to implement, at least in the state of the art as it existed then, and that the value of proximity warning data in resolving conflict situations was marginal.

In view of these results, the present concept of an ADSA system includes the following characteristics:

1. As a minimum, altitude information must be exchanged among aircraft in the vicinity.
2. As a minimum, range must be measured between aircraft at altitudes that are likely to lead to conflicts.
3. The system must operate satisfactorily when large numbers of aircraft are within signaling (radio) range of each other.
4. The system must be capable of resolving reasonable situations in which several conflicting aircraft are involved.
5. The radio spectrum required must not impose excessive demands upon the various frequency allocations.
6. The system must provide a reasonable degree of protection in environments in which a significant number of the aircraft are maneuvering.

Although many ADSA systems have been proposed to FAA and other groups, only a very few of these systems show promise of meeting the requirements that are outlined above.

Some principles of close-approach dynamics

The geometry of a typical close-approach situation involving two aircraft in unaccelerated flight is shown in Fig. 1, which represents the positions and velocities of the two aircraft at some time t seconds before the point of closest approach is reached. Visualization of the situation can be simplified if the coordinate system originates at the location of the protected aircraft and travels with it; thus, positions and velocities are considered relative to the protected aircraft. Note that from this viewpoint, at time t the intruding aircraft is ahead and to the right of the protected aircraft, and proceeds with a velocity vector V_0, relative to it, reaching the point of closest approach at a location ahead and somewhat to the left of the protected aircraft.

Several different quantities may be used to predict the degree of hazard existing in the situation. These include miss distance, time to go (and its approximation, determined from the ratio of the range to the range rate), velocity normal to the line of sight, bearing rate, and range acceleration. Note that if the miss distance is zero, the bearing and range rate are constant.

In this situation, the items that may be measured by the protected aircraft are its own velocity vector and altitude and the bearing and range to the intruder, as well as the range and bearing rates and their higher derivatives. This information is sufficient to solve for the miss distance, time to go, and other geometrical values of the close-approach situation in unaccelerated flight paths; nevertheless, error analyses performed on the hazard predictors obtained on a noncooperative basis show that both the usual measurement errors and the accelerations imposed upon the aircraft as a result of normal air turbulence render the resulting predictions quite undependable.

However, if exchanges of air velocity vector and pressure altitude data between aircraft are allowed, (1) the relative air velocity vector information will improve the accuracy of determination of the miss-distance-based hazard predictors substantially, and (2) the knowledge of relative altitude will relax the necessary precision of the predictors. This latter fact admits the possibility of using hazard predictors that may have a large degree of uncertainty in measuring the miss distance.

Recent ADSA system concepts

One may separate the various promising ADSA techniques into three basic system types, which may be categorized as follows:

1. "Range–altitude" systems, which are minimum systems based on measured range and exchanged altitude information.
2. "Relative position–velocity" systems, which measure and exchange sufficient information that will permit solution of the complete linear close-approach triangle.
3. "Projected hazard predictor" systems, in which sufficient information is measured and exchanged to enable the protected aircraft to "project" its hazard predictors ahead for some distance in turns or other accelerated flight paths in order to increase the precision of predicting the degree of hazard that exists at some particular time in the future for maneuvering situations.

The following paragraphs will describe these system types in somewhat greater detail.

Range–altitude systems

The "range–altitude" systems, which are based on measured range and exchanged altitude information, show a great deal of promise as a minimum system for predicting hazards effectively for aircraft in unaccelerated flight. Comprehensive studies of their behavior have recently been completed.

In these systems, each aircraft broadcasts its own pressure altitude measurements to other aircraft in the vicinity by coding them on a communications carrier along with a signal that can be utilized for range measurement by other aircraft.

With range and altitude as the only information available from intruder aircraft, there are insufficient data to solve for a predicted miss distance, hence other hazard criteria must be used and vertical escape maneuvers must be utilized whenever alarms are given. The ratio of range to range rate, denoted by the Greek letter "tau" (τ), turns out to be a very reasonable and effective means of estimating the hazard.

An expression for tau in unaccelerated flight may be derived with the aid of Fig. 1. Using the notation in this figure, tau is defined as

$$\tau = \frac{r}{\dot{r}} = \frac{r}{V_r} \tag{1}$$

Making use of the fact that the relative velocity and relative position triangles are similar right triangles, the range and range-rate terms can be eliminated from (1), resulting in an expression for tau that is more convenient for visualizing the influences of the geometry of the situation upon its behavior. Thus,

$$\tau = t\left[1 + \frac{1}{t^2}\left(\frac{c}{V_0}\right)^2\right] \tag{2}$$

The behavior of tau for unaccelerated two-aircraft encounters is described in Fig. 2, which shows plots of tau versus the time to point of closest approach for several miss distance to relative velocity ratios. It is important to notice that prior to the point of closest approach, the magnitude of tau reaches a minimum that is twice the value of the time to go at that point.

Figure 3 shows plots of the miss distances that will result in various magnitudes of minimum tau for several velocities. It should be noted that for a fixed-tau warning level, the maximum miss distances that will yield alarms increase with relative velocity, which also means that for very slow closures (as in tail-chase situations), an alarm based on tau only might not be given until the aircraft involved are uncomfortably close. Thus the tau alarm criterion is usually supplemented by a range proximity warning in a range–altitude system. Typical values of warning criteria vary from 30 to 60 seconds for tau and from 500 feet to several miles in range.

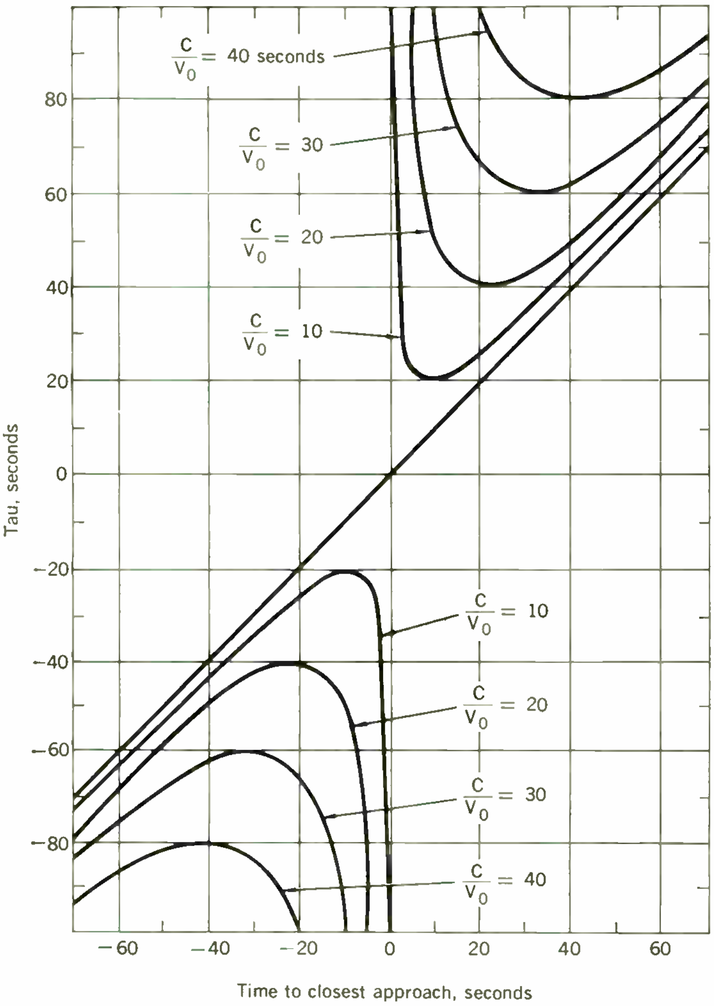
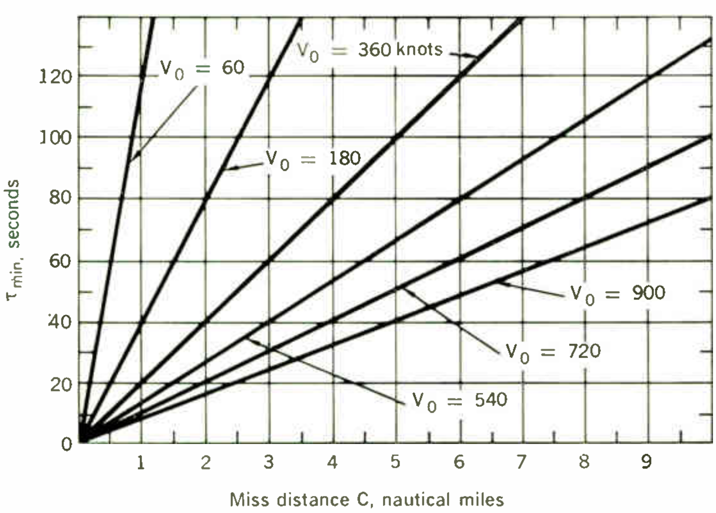


Fig. 2. Relationship between tau and time to closest approach for several values of C/V_0 ratio.

Fig. 3. Minimum tau for unaccelerated flight.



Relative position–velocity systems

ADSA systems based upon relative position–velocity techniques measure or exchange sufficient information to enable the linear close-approach triangle to be solved. In general, the result is a more precise measure of hazard than is given by tau, and the possibility of utilizing horizontal escape maneuvers is introduced. Predictors that can be used include miss distance, velocity normal to the line of sight, and time to go. The parameters to be measured include bearing, range, and range rate, and the exchanged data include velocity vector and altitude. The bearing measurement can be omitted if a single ambiguity in the intruder's position can be tolerated.

It should be recognized that a relative position–velocity system can use the tau criterion and act as a range–altitude system; and, with proper design, a range–altitude system can grow into a relative position–velocity system.

Projected hazard criteria systems

As might be expected, various analyses have shown that hazard predictors based on the assumption of unaccelerated flight do not perform well in certain turning situations. However, if the intentions of each vehicle are known it is possible to project their positions and velocity vectors ahead for some preselected time and to compute the hazard criteria from the projected positions.

Thus, a more reliable estimate of the hazard may be determined.

Several levels of aircraft path prediction can be used, ranging from the assumption that turn rates will remain uniform throughout the projected prediction time to complete knowledge of the future paths of the aircraft involved. It is intuitively obvious that the more accurately the future positions and velocities of the aircraft can be predicted, the more reliable are the hazard estimates. A simple and practical means of improving the near-future path predictions is the use of "turn signals," in which each aircraft broadcasts its maneuvering intent prior to executing any maneuvers.

These remarks about hazard prediction during accelerated flight are applicable both to turning and altitude maneuvers.

Means of implementation

Communications are the key to implementing the ADSA systems described in previous paragraphs, for each aircraft must periodically make a series of measurements and exchange data with all other equipped aircraft in the vicinity. Although many radio techniques exist for performing these measurements or exchanges when no more than several aircraft exist in a vicinity, only a few can meet the requirements when large numbers of equipped aircraft (perhaps in the hundreds) are operating within line-of-sight communications range of each other. The fundamental problem is that in most schemes mutual communication interference becomes so severe that unacceptable errors are introduced into the measured or exchanged quantities. In the more promising systems, the information to be exchanged is coded upon a signal utilized for ranging purposes.

Range-measurement techniques

Obtaining the necessary range measurements without creating excessive communication interference requires the use of special techniques, for in the simple primary or secondary radar means of range measurement, not only does the required communications flow rate increase nearly with the square of the number of aircraft in the vicinity but also the resistance of these systems to mutual interference is quite low. The more recent ADSA schemes utilize interrogator–transponder, ground-bounce, or time–frequency ranging techniques.

Interrogator–transponder ranging

The interrogator–transponder technique employs the principles of secondary radar as the ranging mechanism. In this embodiment, a vehicle desiring to measure range to another vehicle emits an interrogation signal, and the other vehicle replies to the interrogation. By measuring the elapsed time between sending the interrogation and receiving the reply, the interrogator can determine the range to the other vehicle. In these schemes, the interrogation signal has barometric altitude data coded upon it, and the reply contains altitude or altitude-difference information, and perhaps velocity and other data from the transponding aircraft. Although the range data obtained from a system of this type can be quite accurate, the overall scheme results in rather high communication densities in congested areas. Each range measurement requires two radio transmissions, and since each aircraft must know its range from all other aircraft in its area that are likely to be hazards, the rate at which transmissions must be made increases nearly as the square of the number of aircraft in the area.

The high transmission rates possible require very careful coding of the transmitted signal to reduce the effects of mutual interference to tolerable levels for the required traffic densities.

The range rate between affected aircraft can be obtained either by differencing of successive range measurements or by measuring the Doppler shift imposed upon the carrier frequency. The latter technique requires excellent frequency control on the transmitters and receivers involved.

Ground-bounce ranging

In the ground-bounce ranging technique, each aircraft periodically transmits a pulse signal coded with its own altitude data and perhaps other data, and the other aircraft in the system measure the time difference between the arrival of the direct and ground-reflected signals from the transmitting aircraft. Then, with the altitudes of the transmitting and receiving aircraft known, the receiving aircraft have sufficient information to deduce each of their ranges to the transmitting aircraft. Because of variations in terrain height, each aircraft exchanges pressure altitude data, and uses radar altitudes (terrain clearance) to process altitude information for hazard assessment. The roughness and the slope of the terrain between aircraft set an upper limit on the range accuracies obtainable by ground-bounce ranging.

The relatively large range errors associated with this technique require special data-processing methods if reasonably good hazard predictions are to be made. One means of data reduction involves making a least-squares fit of a straight line to several successive data points, which will yield both range and range rate for tau computations.

Since each ranging signal transmitted allows all aircraft within communication distance to determine their range to the transmitting aircraft, the density of the ranging signals increases linearly with the number of aircraft within signaling range of each other.

Time–frequency ranging

The time–frequency ranging technique involves measuring the length of time required for a radio signal to traverse the distance between the affected aircraft. This is accomplished by allowing the transmitting aircraft to transmit only at prearranged instants of time, and by having all receiving aircraft note the time at which the transmitted signal was received. These data permit the range between aircraft to be measured to an accuracy dependent upon the accuracy of the start of the transmission and that of the receiving clock. In practice, each second (or other measure of time) is separated into a number of equal blocks of time, with each aircraft in the system assigned a specific time block. Each aircraft then transmits precisely at the beginning of its assigned block, as the time block recurs; thus each aircraft in the system knows to within a fraction of a microsecond when every other aircraft has transmitted. Each aircraft individually codes its barometric altitude and perhaps other data on its own signal.

The major technical problem with this type of system is the accuracy required by the clocks in each aircraft, for a difference of one microsecond between clock times results in about a fifth of a mile range error. Two basic approaches to time–frequency ranging are feasible. In the first, the aircraft clocks are atomic resonance-frequency standards, which are carefully set prior to takeoff for each flight and are sufficiently accurate to maintain synchronism for the duration of the flight. In the other approach, crystal oscillators are periodically reset with respect to ground stations.

Although a number of practical means of synchronizing ground stations and automatically resetting airborne clocks exist, their description is beyond the scope of this article.

Because of the frequency accuracies available in both transmitters and receivers used with time–frequency methods, range rate is measured most easily by noting the Doppler shift on the carrier frequencies of the transmissions.

The advantages of time–frequency ranging include the following:

1. Ranging signal density is directly proportional to the number of aircraft within communication range of each other.
2. The mutual interference problem is negligible, since only one aircraft transmits at any one time.
3. For navigation purposes, range to selected ground stations can be measured.
4. The intruding aircraft can be catalogued automatically through the use of time-block assignment techniques.

These advantages, which have been recognized for some time, make the time–frequency ranging technique by far the most attractive of those considered. In the past the application of these techniques has been limited by the need for high-precision clocks and synchronizing schemes, but, with recent advances in the state of the art, time–frequency ranging is now practical.

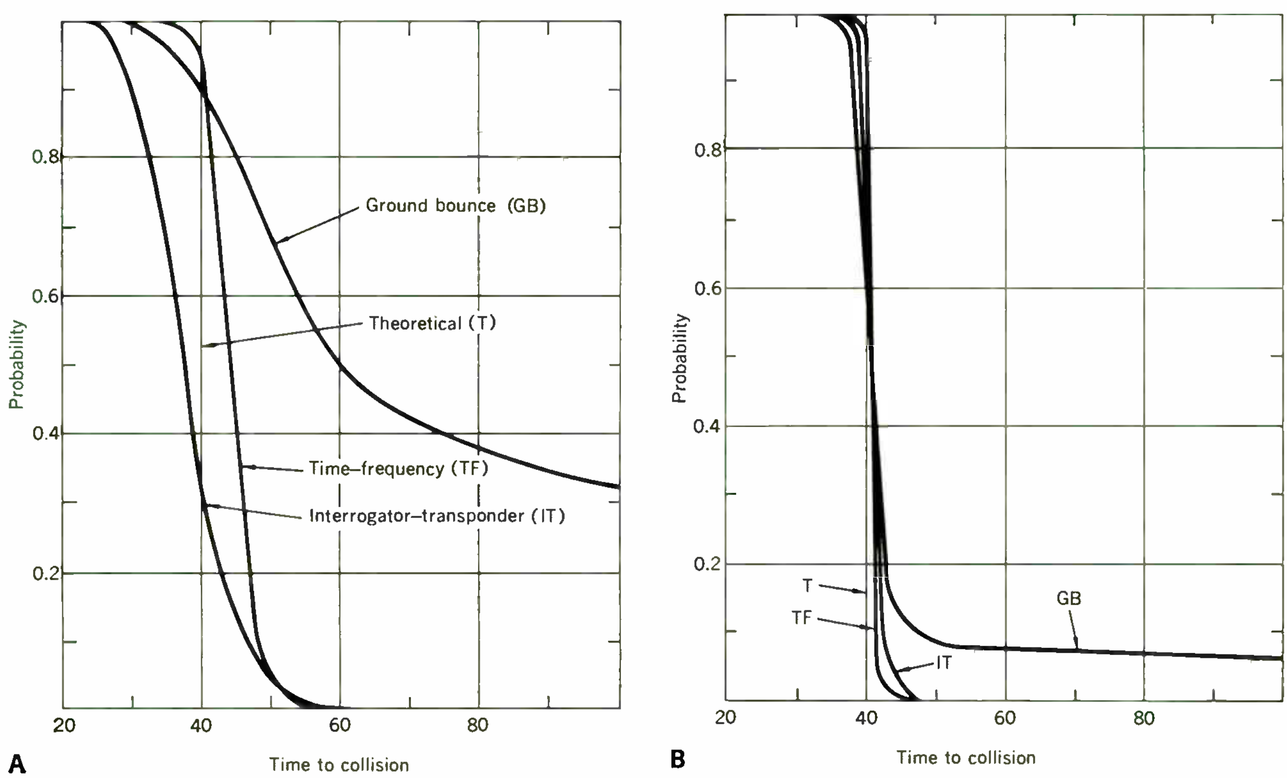
Data-exchange techniques

The amount of data that must be exchanged between aircraft is, of course, dependent upon the type of system under consideration. Thus, in a simple range–altitude system, only altitude data need be exchanged, whereas relative position–velocity or a projected hazard criteria system will require exchange of altitude, air velocity vector, and possibly intent information. Furthermore, the data must be exchanged in such a manner that the exchanged data can always be associated with range, range rate, or bearing measurements to the proper aircraft. This implies that the signal used for making the necessary measurements should also convey the information to be exchanged.

Although the precise data accuracy needed is dependent upon the specific design requirements on the system, representative allowable communication errors in the exchanged data of the system types under discussion are as follows:

1. *Pressure altitude.* 50 feet up to altitudes of 100 000 feet.
2. *Air velocity vector.* Heading to 2°, one part in 300 for air speed.
3. *Auxiliary data.* Vertical and horizontal maneuver intent: two binary digits each. Altitude rate: one part in 16 plus sign.

Fig. 4. Probability of receiving at least one tau alarm by any given time before collision. Warning tau = 40 seconds. A—Closing velocity = 72 knots. B—Closing velocity = 720 knots.



A narrow pulse signal is probably the easiest and most straightforward means of obtaining range data, and preliminary system calculations indicate that a ranging pulse width of one microsecond would be appropriate. Use of a "double pulse" system (two pulses separated by a fixed time difference that is long compared with the correlation time of the receiver noise) is recommended to reduce the sensitivity of the system to pulse interference.

Measurement of the range rate by means of Doppler shift requires power at the carrier frequency for a time duration that depends upon the received signal-to-noise ratio and the desired accuracy characteristics. A suitable length for this signal would be of the order of two milliseconds. Such a pulse could start with a higher-amplitude double pulse for ranging.

The information to be exchanged can be impressed on the range and range-rate signals in a variety of ways. For example, in systems not measuring Doppler shift, pulse-position techniques can carry the information efficiently, whereas in systems in which a relatively long pulse is used for Doppler measurement, the data can be either amplitude- or phase-modulated in digital form upon the carrier.

Use of air-derived data

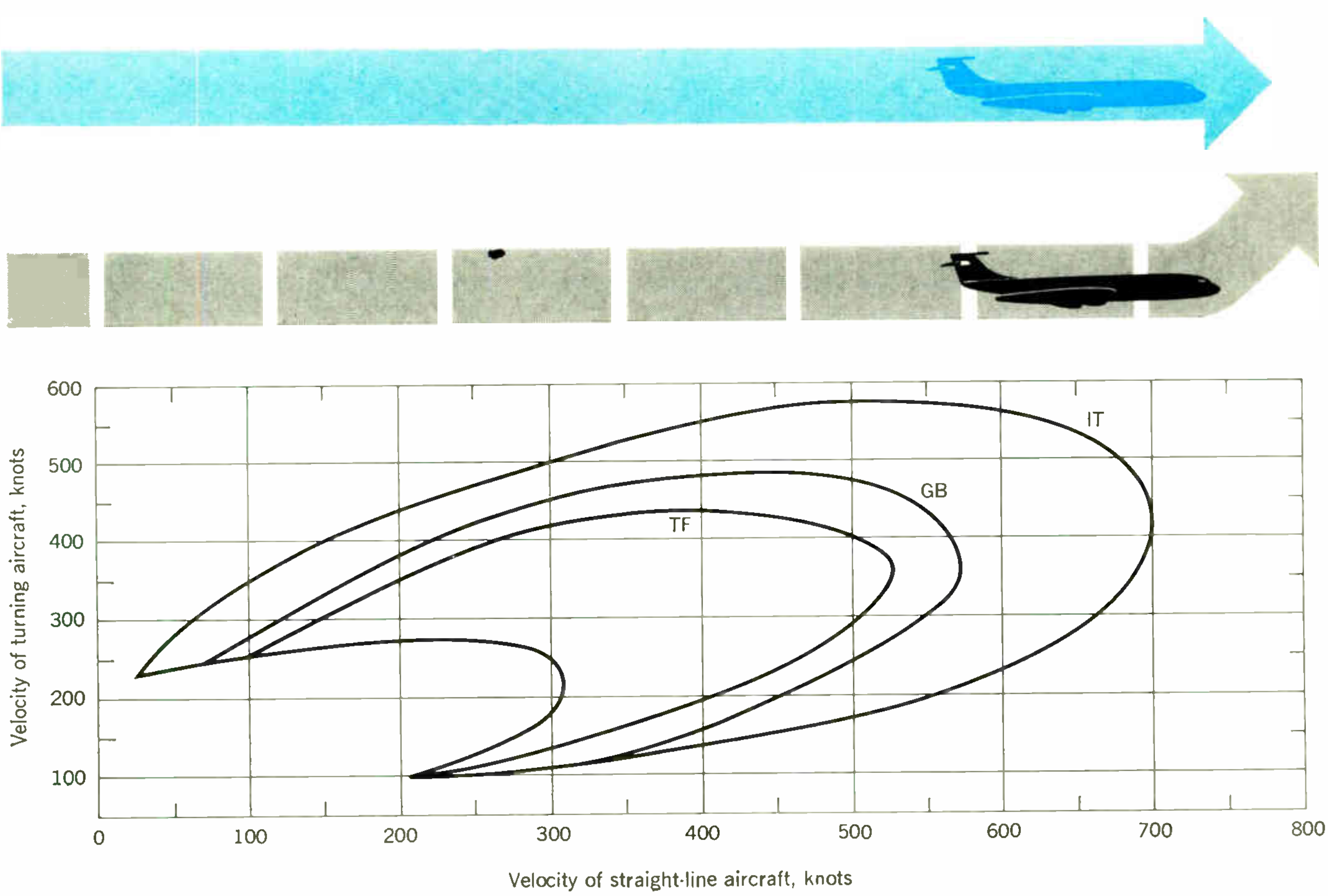
Air-derived data obtained by an ADSA system need not be confined to those aircraft directly affected, for, if a time–frequency ADSA system is used, the synchronous nature of the system will permit reception of these data by ground stations within radio range of the transmitting aircraft. This information can then supplement other data used for air traffic control purposes.

Analysis techniques

The analysis techniques utilized in study of the performance of various ADSA systems included pure analytical methods, primarily applied to the simpler two-aircraft situations, and, for more complex circumstances, simulation techniques utilizing digital computers. Simulation efforts consisted of both special-situation simulation—which involves relatively few flight tracks—and simulation of air traffic that is representative of particular operating areas.

In order to achieve realism in the analysis, development of error models representative of the systems under study was necessary. In developing these error models, block diagrams of the ADSA equipment, including communications mechanisms and hazard predictors, were formulated. The various sources of noises or errors were then identified in the block diagrams, and these were each described statistically in the form of an autocorrelation function where one existed. In those instances where no autocorrelation function existed, as in the case of digitizing errors, the noise or error sources were described by

Fig. 5. Aircraft velocities that do not give an alarm with sufficient maneuver time. Warning values: tau = 45 seconds, proximity = 1.5 nautical miles.



their operational characteristics. Since the relationships of the hazard prediction quantities to the error or noise sources can be determined from the transfer functions of the block diagram, the sensitivity of the predictors to the error sources, and the tradeoffs between them, can be found. This method provides a logical basis from which the desired accuracy of each equipment function can be determined.

The first performance analysis of each system involved studies of various two-aircraft situations, using the hazard prediction errors just described. The probabilities of receiving an alarm in the presence of errors or noises were derived as functions of time to closest approach, miss distances, aircraft velocities, turn rates, and headings. These analyses permitted the determination of the critical aircraft velocity, geometry, and system error characteristics that would not give an alarm with sufficient maneuver time or would give false or early alarms.

To extend the analyses into multiple aircraft environments, a digital computer was used to simulate aircraft flight paths and the logic of the ADSA system under study and to record the reactions of the air traffic to the system. Both special-situation flight tracks and those representative of typical traffic flows at selected locations were simulated. Simulation of the ADSA system included generation of measurement errors or noises from the previously chosen mathematical descriptors, and addition of these quantities to the system measurables. This resulted in quite realistic simulation of the systems under study.

In the simulations performed to date, the aircraft were constrained to follow prerecorded flight paths, except during the execution of evasive maneuvers. The advantages of this type of simulation are that the same geometrical flight conditions can be resimulated with various selected perturbations and that the simulation can be accomplished at a speed limited only by the computer. The primary disadvantage is the lack of real-time air traffic control participation.

A suggested step to be taken in future simulations is to perform real-time simulations at the FAA's National Aviation Facilities Experimental Center at Atlantic City, N.J., in which dynamic air traffic control functions are inserted into the environment and aircraft are "flown" from simulator consoles. In this manner, the "real world" operation of an ADSA system can be tested thoroughly, economically, and safely, and the various means of integrating these systems into the general air traffic control structure can be studied. Note that in this type of simulation, identical situations cannot be reproduced exactly, and the simulations require expenditure of considerably more effort than those performed to date.

The following paragraphs describe a portion of the results of recent analytical and simulation studies of ADSA systems. The complete results of the analysis may be found in Ref. 1 and in a report, to be released shortly by the Federal Aviation Agency, that covers more recent work performed by the authors.

The first step in the analysis was to specify, for study, systems typical of the three types of ranging mechanisms previously mentioned. References 2, 3, and 4 were used as guides in specifying the interrogator–transponder, ground-bounce, and time–frequency systems respectively.

Figure 4 shows the probability in unaccelerated flight of receiving at least one tau alarm by any given time for the three types of systems in the presence of the expected noises or errors. For these curves, the warning value of tau was taken as 40 seconds. It can be seen that system errors exhibit a considerable effect upon the system tau characteristics at very low closure rates. As the closure rates become higher, the effect of errors is less critical and the measured taus approach the theoretical values. These studies indicated that range errors should be limited to several tenths of a mile.

Figure 5 illustrates a typical example of the inadequacy of the tau hazard criterion in curvilinear flight. The flight geometry for this figure is one in which one of two aircraft initially in parallel flight in the same direction subsequently turns into the other. It was determined that at least 30 seconds of warning time must be given to allow the aircraft to take evasive action and build up adequate separation. The area enclosed by the envelope represents the combinations of aircraft velocities that will not produce an alarm by 30 seconds before collision. For this example the turning acceleration was taken as $g/3$, and the tau and proximity warning values as 45 seconds and 1.5 nautical miles respectively. This type of flight geometry represents the most critical flight encounter if only the simplest data exchange is utilized. If more information is exchanged between the aircraft, the predictions of the future relative positions of the aircraft can be improved to overcome these critical flight geometries.

Conclusions

The studies performed to date by the workers in the field have shown that in the present state of the art, range–altitude systems that would provide reasonable protection against suitably equipped intruders in a generally well-ordered and unaccelerated air traffic environment could be constructed.

Recent studies show that with the measurement or exchange of more but still reasonable amounts of data, the performance of hazard predictors can be improved substantially in maneuvering environments. These studies are not yet complete.

It now appears that many of the obstacles that have stood in the way of implementation of an efficient and economical ADSA system are being overcome, and that such a system could be adopted in the foreseeable future.

Much of the material incorporated in this article is a result both of independent studies conducted by Collins Radio Company and studies performed by Collins in conjunction with the Federal Aviation Agency under Contract FA-WA-4598. The views expressed here do not necessarily reflect those of the FAA.

The authors are especially grateful to J. M. Holt, W. J. Jameson, L. K. Belden, and R. D. Joy for their contributions to the studies conducted at Collins.

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(Feature section continues on page 85)

Electrooptics in space operation and research

Large optical systems in space offer several important advantages over conventional ground-based telescopes, including increased resolution, and show great promise for applications in astronomical research and communication

R. M. Scott *The Perkin-Elmer Corporation*

Because of the limitations imposed by the atmosphere and the gravitational effects on mountings and optical components, ground-based telescopes will be limited in their size and usefulness to modern astronomy. These limitations have already begun to restrict the progress of optical astronomical research. The step to large optics in space, where telescopes will not be limited by terrestrial effects, awaits only the availability of large boosters with sufficient payload capability for the injection into orbit of systems with performance exceeding that of present ground-based telescopes.

The Orbiting Astronomical Observatory series of satellites will be of modest aperture (30 to 40 inches) as compared with our largest terrestrial systems, but they are expected to make important observations in regions of the spectrum not available on the earth because of the opacity of the atmosphere to ultraviolet radiation. In addition, these satellite systems could provide resolution of astronomical objects far exceeding that of our best present telescopes, because the atmosphere, being inhomogeneous optically even where it is transparent, limits such resolution. Even though it will take a few years to exploit the capabilities of these systems, which are now under construction, new and larger systems are being planned and are the subject of extensive design study.

Communication

In addition to their applications in astronomical research, large optical systems can be used effectively for communication in space. The optical portion of the radiation spectrum has been an attractive region for the carrier of communication channels because the high frequency, 6×10^{14} c/s for blue-green light having a wavelength of 0.5 micron, permits a very wide bandwidth in communication terms within a narrow percentage range about the carrier. In addition, this very short wavelength provides very high directivity, and thus high antenna gain, for reasonably sized structures. It appears possible to provide a 1-Mc/s bandwidth with a 30-dB signal-to-noise ratio to a distance of 100 million miles with a 40-inch-aperture optical system on the spacecraft. The overall communication system weight would be between 1000 and 1500 pounds. The power radiated would be 0.1 watt, but with the present state of the art an input of about 100 watts would be required.

Mirror design considerations

Before some of the advantages of large space optics can be realized, many difficult problems must be solved. The high resolution of the astronomical systems and the great antenna gains of the optical communication systems require large optics of great surface precision—a precision well beyond that required for large earth-based telescopes. The attainment of the required precision in orbit is by no means a straightforward extension of presently employed optical manufacturing methods. Large, modern terrestrial telescopes depend on large reflecting surfaces for their light-gathering and focusing functions. These surfaces are polished on thick, rigid disks of Pyrex or fused quartz. Such materials are readily brought to a polish of optical quality and to the degree of surface accuracy required for earthbound instruments. The thickness and rigidity of these mirrors are required for two reasons. First, during the manufacturing and finishing process, forces are imposed on the mirror surface. These forces, though very small, are sufficient to distort the surface to an unacceptable degree unless the mirror disk is of great thickness and weight. Second, because telescopes must be pointed to a variety of directions in the sky, direction of the gravitational forces on the optics changes over large angles. Thus, terrestrial telescope mirror disks must be supported by complex mechanical means even though they are quite thick.

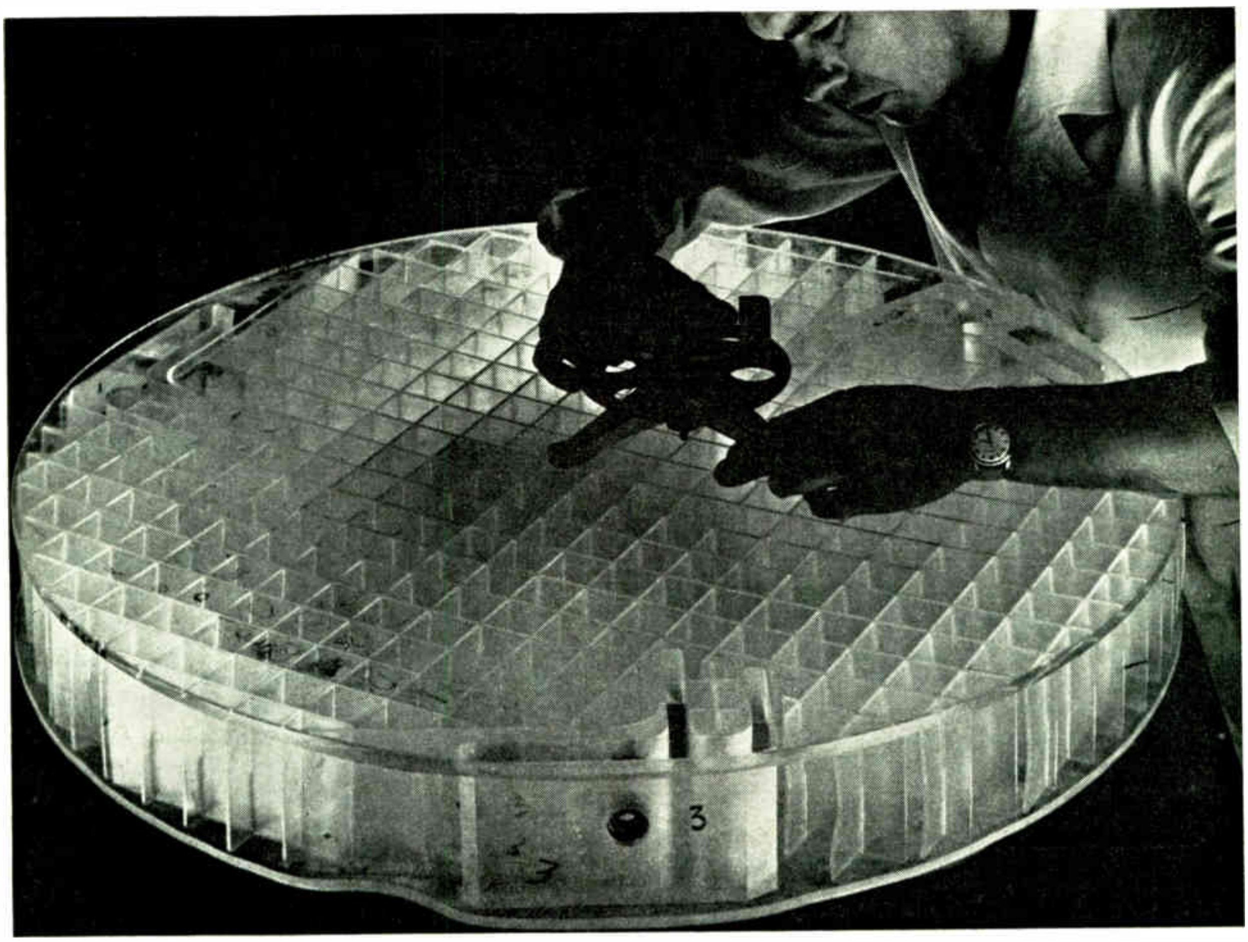
In space the absence of gravity removes the major requirement for sufficient thickness of the mirror so that it will not flex under the influence of its own mass. Thus, we must search for ways of manufacture in the 1 *g* field on the earth that will permit the attainment of a perfect figure when the mirror is used in space. One method of weight reduction of mirrors for space use, an extension of the method used to lighten the 200-inch mirror and now common for most large terrestrial telescopes, is to make them of fabricated structures of fused quartz. The mirror blank shown in Fig. 1 is an example of a fabricated quartz structure. It is interesting to note that this construction has been chosen for several space applications in spite of the fact that such a mirror is quite flexible while being polished as compared to a solid one of the same thickness, and thus its principal advantage would be in an earth-based telescope where it must resist bending forces due to its own weight.

Thermal response

The choice of this structure has been based on an additional consideration—that of thermal response. Although quartz and most other ceramiclike materials have very low thermal expansion coefficients, they also have very low thermal conductivities. Even in the best designs for space there will always be some variation with time of the temperature of the optics; thus, any mirror design using these materials is improved by a reduction of its mass and a reduction in the length of thermal paths so that thermal equilibrium will be obtained quickly. Temperature gradients produce surface distortions because of the differential expansion of the material.

Two other lines of attack on this problem are under investigation. One design involves the use of metal mirrors, with beryllium offering the best combination of characteristics. Since the effect of high conductivity greatly overshadows the large expansion coefficient, equilibrium is achieved quickly and thermal gradients in the structure are reduced to very small values. In addition, the stiffness-to-weight ratio of beryllium offers some advantages over quartz. An alternative design approach employs glasslike materials that are compounded to have almost exactly zero coefficient of expansion; thus, temperature differ-

Fig. 1. Typical example of fabricated structure using fused quartz.



ences are of no consequence. The question yet to be answered in a definitive way concerns the dimensional stability of these metals and pseudo glasses, which are microcrystalline rather than truly amorphous in structure.

A further departure from classical mirror design that is receiving considerable attention is the use of mirrors so thin that they would distort badly under their own weight. Nevertheless, it may be possible to grind and polish and, more important, to test these very thin mirrors so that when they are delivered to their space environment, where they can assume their unstressed shape, they will be of high optical quality. Since prolonged periods of zero gravity are not available on the earth, considerable in-space testing of this concept may be necessary to provide an accurate evaluation.

Another concept, although even more of a divergence from current astronomical practice, offers the possibility of an earlier and more certain solution to the problems of thermal behavior, on-the-ground testing, and the assembly of very large instruments in space. The method involves the assembling of a large mirror from small pieces. These pieces are each small enough to pose no thermal or fabricational problems in themselves. Modern testing techniques provide methods of examining the surface of a mirror, small area by small area, to determine the longitudinal displacement of these areas from their ideal positions. Fortunately, these methods depend only on relatively small devices located at the center of curvature of the mirror. There, they would not be in the way of the normal function of the device for astronomy or optical communication. Figure 2 shows a segmented-mirror system with the error sensing device at the center of curvature and the normal optics to produce a focus back of the main mirror. Each element of the mirror must be provided with three motions: tip about two axes, and translation along the normal to the surface, under servo control from the error sensor. These servos need have only very long time constants (many seconds) and total motion of a few ten-thousandths of an inch to meet the optical requirements. However, the actuators should be capable of much larger total motion so that mechanical deformation of the structure, at launch or with time, may be accommodated. Current developments indicate that the sensor and servo aspects of this approach are quite feasible.

Pointing systems

We have discussed so far only those aspects of the subject that deal with the image-forming systems. If the capabilities of these large, very high quality optical systems are to be utilized, the images must be kept very still in the case of astronomical telescopes or the optics must be pointed at the receiver with great precision for the communication system. In fact, the pointing of the transmitter optics in a communication system must be so exact that the receiving system must be led with high accuracy to provide for the earth's motion during the transmit time of the signal. It is proposed that the pointing system track an optical beacon near the receiver and provide variable offset for the transmitting source, since this offset is a function of distance and the angle between the line of sight to the receiver and the receiver's velocity vector.

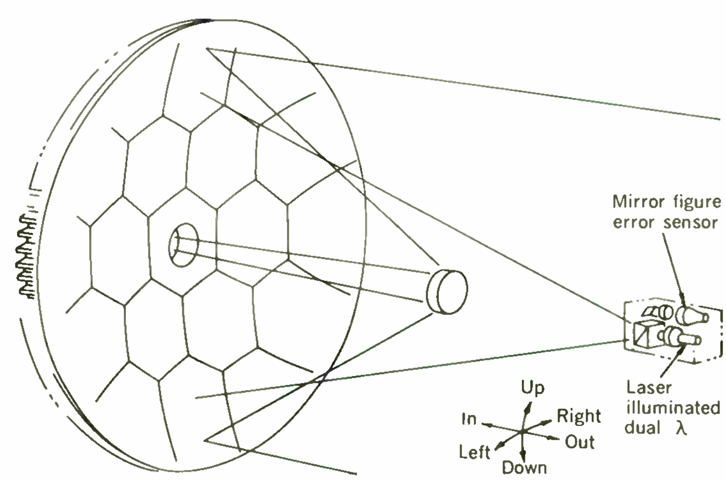
Some experience is being gained with high-accuracy automatic pointing or tracking systems from the astronomical balloon flights. These flights are for the purpose of carrying high-resolution telescopes to sufficiently high altitudes that they will be beyond the resolution-reducing effects of the atmosphere. Additional high-accuracy guidance systems have been developed for the Orbiting Astronomical Observatory program; however, the requirements for systems of the type discussed here are even more demanding, and extensions of the present techniques for vehicle stability control and independent telescope pointing will be needed.

It might be well to inquire here about the potential role of a man in these affairs. Although there are many aspects of alignment and adjustment, of acquisition and identification, where the use of human intelligence greatly simplifies the problem, the functions of pointing control and guidance to the accuracy required can be done much more accurately over long periods of time by automatic systems. It has been traditional in astronomy to "guide" large telescopes for long photographic exposures or spectrographic observations by the direct visual and manual activities of an "observer." This activity requires his full attention over long periods of time. Even for these terrestrial systems, the guiding process is being automated on large telescopes. Thus, it seems obvious that the astronaut should not be asked to perform this function, even if he could be assisted by optical and electronic aids that would enable him to do the job satisfactorily.

Even with large optics of great perfection, the transmitted energy is spread over a considerable area at the receiver and as much of this energy should be collected as is possible. Large receiving optics are thus indicated. These receiving optics are in reality light collectors rather than high-resolution telescopes. The segmented concept discussed earlier for space optics could greatly reduce the cost of these large receivers as well; Fig. 3 shows one concept for the receiver. The system from spacecraft to earth is shown in Fig. 4. Four to six receivers would be required, distributed in longitude, to provide continuous coverage and independence from weather. Thus, their cost is an important consideration.

The utilization of light beams (radiation in the wavelength range from 0.3 to 1.5 microns) for communications purposes poses many new problems to the communication engineer. This wavelength range is picked because the

Fig. 2. Large spaceborne optical system.



atmosphere of the earth is transparent to these waves. For either all-space systems (both receiver and transmitter in space) or for evacuated, piped systems on the earth, other wavelengths are of course available as well.

Lasers

Coherent light sources, such as lasers, are now quite extensively developed so that they may be used as transmitter generators. The technology of frequency control and frequency modulation of these sources is also well developed. Amplitude modulation is perhaps not quite so well along, particularly with regard to the efficient use of input power. The same may be said of the laser itself, where great development emphasis is being placed not only on higher continuous power output but also on greater overall efficiency. In the past year we have moved from a few milliwatts to continuous output levels of 10 to 100 watts.

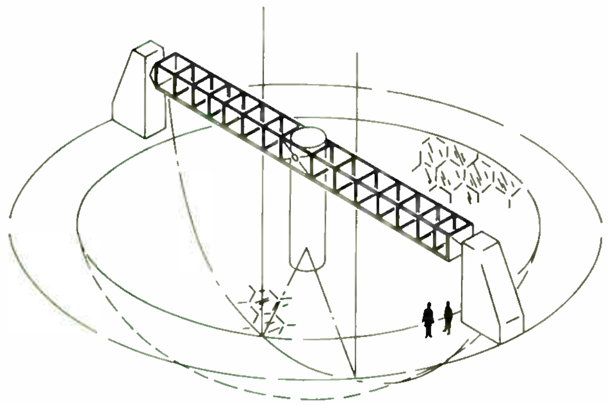
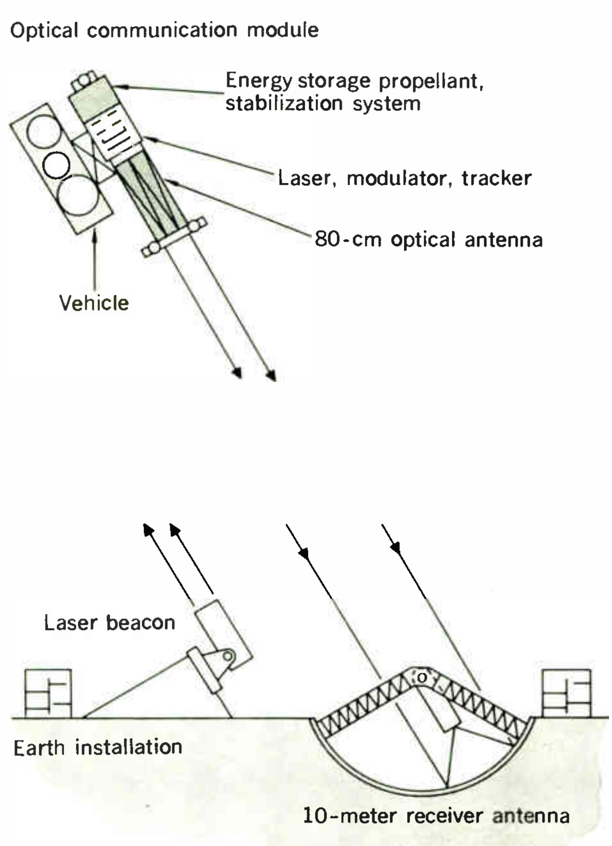


Fig. 3. Segmented primary-optics concept.

Fig. 4. Spacecraft-to-earth optical communication system.



One area of laser communication systems development that is receiving considerable attention is polarization modulation. Both frequency modulation and amplitude modulation have been extensively explored and exploited in electronic systems, and the conversion to the higher optical carrier frequencies, at least in concept, is straightforward. Although the advantages and limitations of polarization modulation are not very well understood, extensive studies and hardware development efforts on polarization modulators and converters are being made. These are, of course, optical devices which make use of the polarizing properties of certain types of crystals. Passive optical systems are now commonly used for converting back and forth between the three types of modulation.

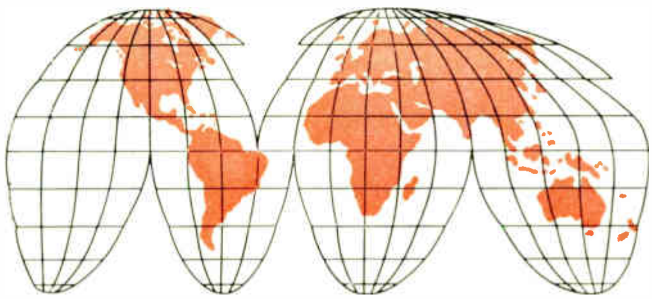
Optical equivalents of electronic components, filters, heterodyne detectors or converters, mixers, send–receive switches, and so on, are under development for application in the communication field in general and will be investigated for space applications. As an example, we have suggested earlier that a communication telescope in a spacecraft could be pointed by a beacon on the ground. This technique implies an isolation between the beacon receiver and the transmitted communication signal power of something like 10^{14}. The methods of isolation and filtering, which must be optical, present a great challenge to the optical systems designer.

A sample problem in this area concerns the predetection filter at the receiver or, alternately, the method of heterodyning the incoming light signal. It is not yet certain that the phase disturbances introduced in the beam by the atmosphere will permit the use of the latter method, so the first is being investigated thoroughly. Here appears a problem that, though common to optical components, is not faced by the electronic analog. Whereas the electronic signal is one-dimensional, the optical signal is two-dimensional; hence, the characteristics of a filter or converter may be and are dependent on the direction of arrival of the optical beam. The beam will almost always have some angular extent, and therefore the filter characteristics will be different for different parts of the beam. Optimization of the design requires consideration of these variations.

Conclusion

In review, we have discussed the opportunity for considerable contribution to the knowledge of astronomy by large optics in space. It has been pointed out that although there are many problems associated with these optics, methods of manufacture and assembly now being developed are likely to provide satisfactory optical components. The advent of lasers and large optics makes the utilization of optical frequencies for deep-space communication most attractive. These systems require the development of a large family of optical analogs of electronic devices. Progress made so far in this area is most encouraging.

Essentially full text of a paper presented at the IEEE Conference on Military Electronics (MIL-E-CON 9), Washington, D.C., Sept. 22–24, 1965.



International comparison of measurements at high frequencies

Measurements of dc and some low-frequency electrical quantities have long been coordinated internationally. Cogent arguments are set forth for intensifying emerging efforts to achieve this same status for high-frequency (30 kHz to 40 GHz) quantities

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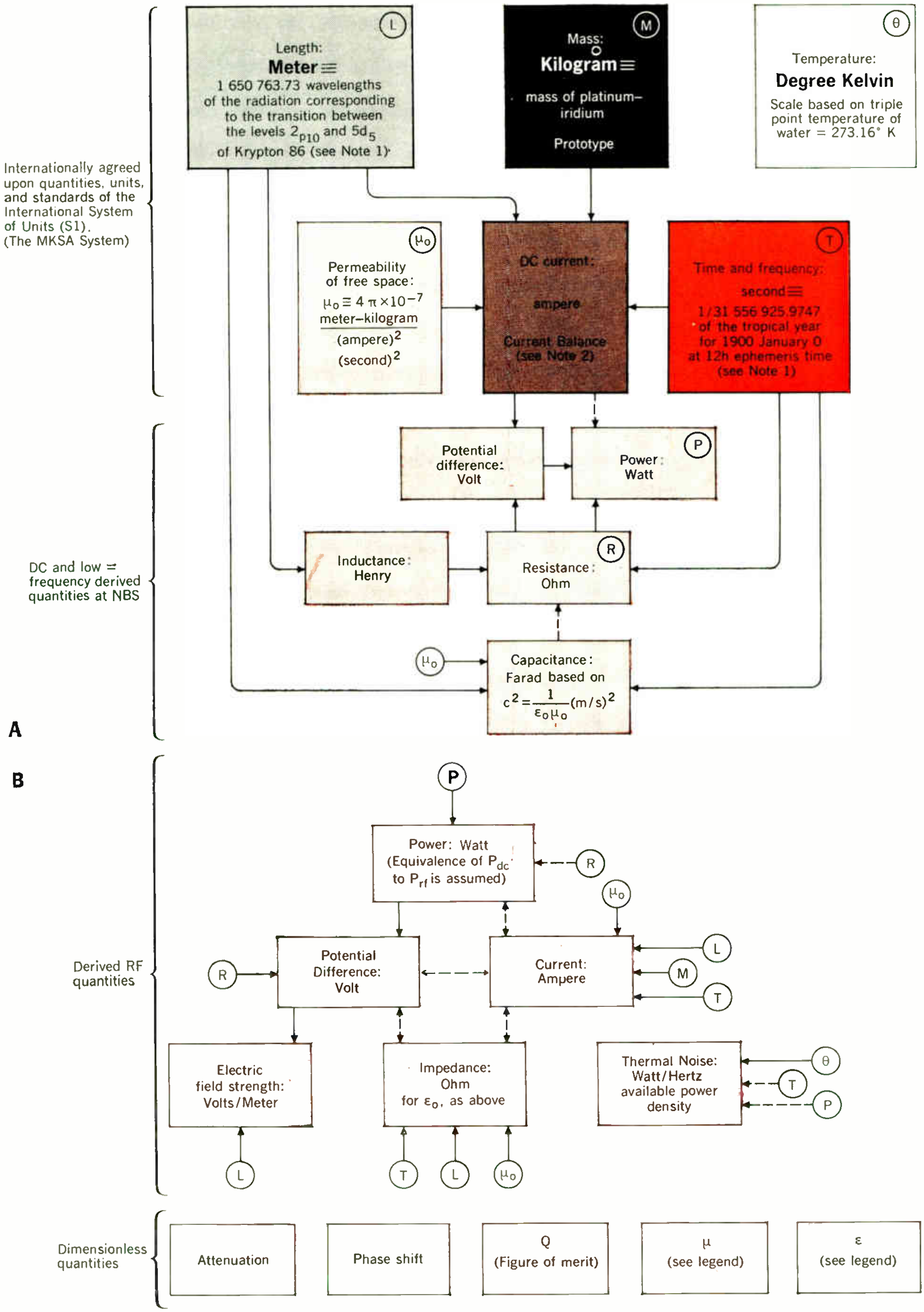
At a recent discussion of the status of international coordination of high-frequency electromagnetic measurements, the Director of the International Bureau of Weights and Measures (BIPM), in Paris, was asked why that Bureau has not yet entered this important area and whether the lack of financial resources is the reason for the delay. He replied that economics is only one of the reasons; another reason is that some authoritative scientists see no need to establish agreement, say, on measuring a milliwatt of power at 10 GHz when agreement already exists on the "basic" electric dc watt via the international intercomparison of the units of mass, length, and time.

Other typical arguments against wide standardization efforts are: Why intercompare presumably valid results obtained by leading experts of highly developed countries? Why worry about quantities derived from basic standards? Why trace measurements to standards when failures will show up in the product and may better be corrected then? Why is it necessary to have agreement on a picowatt of thermal noise, for example, when there already is agreement on temperature? Why strive for extreme accuracies like 0.005 percent in a power ratio of ten to one when commercial ratio-measuring devices have accuracies of only one percent? We have survived so far without international intercomparison, so why worry about it now? Some may still question even the very need of any measurement when, after all, it is "performance that counts." True, the last argument is raised with rapidly diminishing frequency for the simple reason that the person raising it is risking his reputation as a "civilized person"[1]; nevertheless, one too frequently hears references to skeptical or indifferent attitudes on the part of "management" toward their measurement and standardization departments.

The preceding arguments were first effectively refuted in the far past by Francis Bacon, who introduced, philosophically, the concept of the scientific method; Galileo applied it in practice. It was amply shown then and underscored numerous times since that experimental observation and measurement are one of the three foundations of the scientific method (along with hypothesis and mathematical analysis). A number of the preceding arguments were also discussed at length in recent publications.[2-4] It is now assumed to be common knowledge that (1) measurement is an indispensable part of the scientific method; and (2) the measurement of a phenomenon or of a quantity to a given accuracy is valid only if the same result can be reproduced to the same accuracy at will in any place, at any time, and by any sufficiently qualified worker. To prove this second point, intercomparison is necessary.

The objective here is not to try to improve on previous voluminous dissertations but to implement these when necessary, as applicable to the international aspect of measuring high-frequency electrical quantities. An attempt is made to point out by examples the role of international agreement and to acquaint the reader with the status of past and present efforts toward international intercomparison in this area.

Figure 1 shows a chart of the high-frequency quantities we are concerned with and the "basic" physical quantities from which these are "derived." The frequency range in mind starts at approximately 30 kHz (top audio frequencies) and extends roughly to 30 or 40 GHz, the highest frequency at which considerable development work for practical applications is presently in various progressive stages. The terms "high frequency" and "radio frequency" (RF) are used here interchangeably. Though many of the specific justifications indicated in



Legend:
c = Speed of light in vacuo
$\varepsilon_0 \equiv$ Complex permittivity of free space
$\varepsilon \equiv$ Relative complex permittivity
$\mu_0 \equiv$ Complex permeability of free space
$\mu \equiv$ Relative complex permeability

$$Q \equiv 2\pi\left(\frac{\text{Energy stored in the circuit}}{\text{Energy dissipated in the circuit during one cycle}}\right)$$

the following may be applied to higher coherent frequency ranges (e.g., to the laser range), this article will be limited to the ranges for which international cooperation is more likely to develop within the foreseeable future. However, the likelihood of early international standardization in some specific range, such as the laser range, cannot be ruled out; spectacular applications of lasers to medical electronics, for example, may furnish an impetus in this area prior to standardization at some lower frequency ranges.

Figure 1(A) illustrates how dc and low-frequency electrical quantities of the International MKSA System were developed from the "basic" physical quantities of mass, length, and time (see bibliography for Fig. 1 at end of list of references). The basic quantities and temperatures have been coordinated internationally via the BIPM. Figure 1(B) shows the development or "derivation" of high-frequency quantities from those in Fig. 1(A). It also shows several dimensionless high-frequency quantities. None of the quantities in Fig 1(B) have as yet been officially coordinated internationally. The total of 11 high-frequency quantities shown is somewhat arbitrary. For example, some may prefer to split impedance into its components (resistive, inductive, capactive). Others might prefer "field intensity" (in watts per square meter) instead of "field strength." But, for purposes of this discussion, the quantities given seem adequate.

It is important to acquaint the reader with the term "measurand," which more and more is being introduced for convenience into discussions of measurements: "The measurand is a physical quantity, property, or condition which is to be measured."[5] Thus a measurand, such as voltage, can be used in a very general sense, without regard to its magnitude, frequency, or waveform. In practice, however, one is nearly always concerned with a "specific measurand" as restricted to a specific range of parameters, generally requiring individual measuring techniques or instruments. For example, there are unbalanced and balanced voltages; sine-wave, pulsed, or otherwise modulated waveforms; peaks or average values; voltages at different ranges of frequency and magnitude. The techniques or instruments for measuring kilovolts at frequencies of 30 to 300 kHz are different from those employed for microvolts at 30 to 300 MHz. The term "measurand" is used here in this more restricted sense, as a synonym of "specific measurand," for the sake of brevity.

Fig. 1. Electromagnetic quantities of the International System of Units (SI). A—Derivation of dc and low-frequency electrical quantities from the "basic" physical quantities of mass, length, and time (see bibliography). B—High-frequency quantities derived from those of A. The symbols in the circles refer to the corresponding symbols in A, and indicate the quantities in A from which the corresponding quantities in B are derived. Dashed lines trace derivation of a quantity in one way while the solid lines indicate a different derivation. [The unit of luminous intensity (candela), sixth basic quantity of the SI, is not pertinent to this discussion.]

Note 1. In 1960, the General Conference of Weights and Measures defined the meter (as above), and ratified the definition of the second (as above) made in 1956 by CIPM. In 1964, the CIPM declared that the standard to be used temporarily for the physical measurement of time is a specified transition of the cesium-133 atom having an assigned frequency of 9 192 631 770 Hz.

Note 2. The basic correlation between the ampere, on one hand, and mass, length, time, and M_0, on the other, is given in the 1948 CIPM definition: "The ampere is the constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular sections, and placed one meter apart in a vacuum, will produce between these conductors a force equal to 2×10^{-7} MKS units of force per meter of length. The ampere is a derived measurement unit but independent as a symbolic unit for dimensional analysis."

Why international agreement

The answer to this question seems evident if we realize that (1) the "world" within the confines of our globe is rapidly growing smaller as a result of the spectacular strides in international communication, transportation, and economic interdependence; and (2) electromagnetic phenomena, e.g., propagation, interference, radio calls in case of emergency, etc., do not obey international boundary regulations. It is necessary to agree internationally for essentially the same reasons that we must agree nationally.

Establishment of international agreement on measurement of electromagnetic quantities is, in the long run, just as important and justifiable throughout the practicable frequency spectrum as it is at direct current. Among the well-known benefits of international agreement on values of dc quantities or, for that matter, on measurements of any physical quantity, are:

1. *Accuracy benefits*

a. Elimination of some or all systematic errors. Different techniques are frequently used in different countries for the same measurand; hence, agreement between results suggests the absence of systematic errors.

b. Reduction of random errors.

c. Availability of a very wide range of diversification in operational and environmental conditions, as well as in the character and attitude of personnel, for those participating in the international comparisons. This is of great help in error reduction and in improvement of techniques. The element of skill and details of procedure cannot always be spelled out in publications.

2. *Economic benefits*

a. Elimination of wasteful efforts, personnel, funds, and time as a result of faulty design.

b. Elimination of duplication through a limited number of regional international standardization centers, since many small nations can hardly afford standardization laboratories on a par with large nations.

c. Enhancement of reliability and uniformity of product when measurements agree, thus avoiding failure or waste of materials and products, trade barriers, and possibly even hazard to property or life.

3. *Psychological benefits*

a. Development of confidence in one's own results.

b. Mutual trust and cooperation between individual citizens of different countries.

c. International recognition of the areas of excellence in the participating countries.

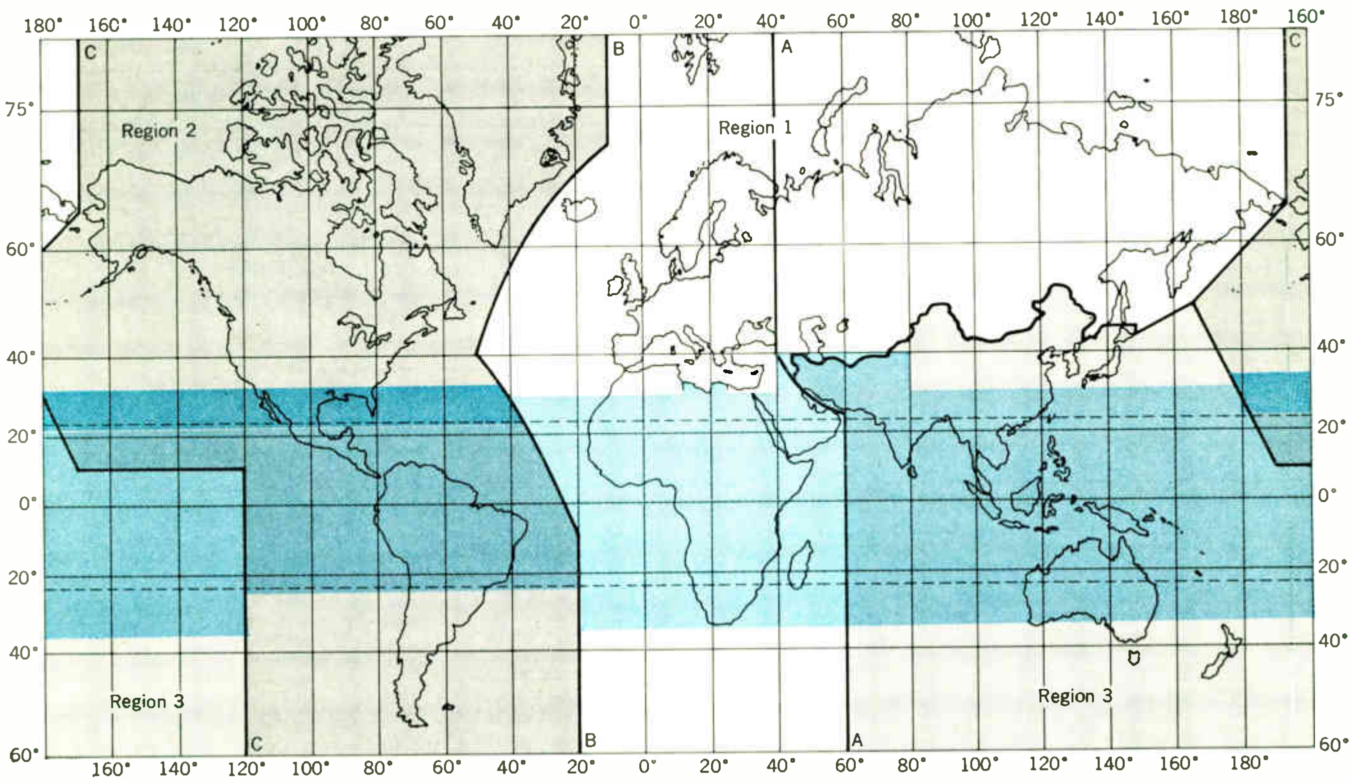
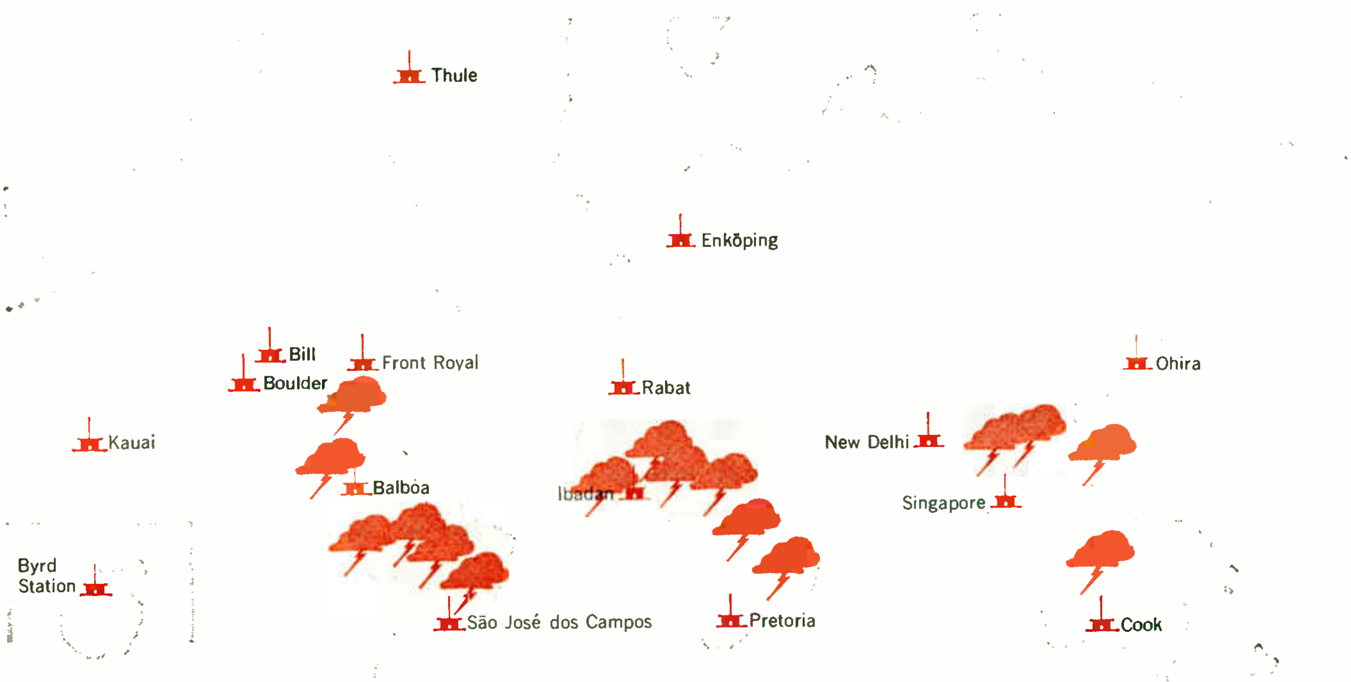


Fig. 2. World regions defined by the ITU. The world is subdivided into three regions for purposes of frequency allocation to various services. Colored band represents the tropical zone.

Fig. 3. Radio stations—part of the CRPL-CCIR research and applied engineering activities—record radio noise originating in thunderstorms throughout the world.



International standardization is particularly important in these days when so many new nations and newly developing countries are trying to attain international recognition. Perhaps the best example for the issue at hand is the International Telecommunications Union (ITU) and its activities; the successful implementation of its objectives depends heavily on standardization and measurement.

The ITU and CCIR

The ITU, a legal international body, was originally established in 1865 and has continuously expanded its activities in accordance with the demands of the times. Its aims are to "maintain and extend international co-operation for the improvement and rational use of tele-communication; promote development of technical facilities and their most efficient operation, in order to improve efficiency of telecommunication services, in-crease their usefulness, and make them, as far as possible, generally available; harmonize the actions of nations in the attainment of these common ends."[6] It has four permanent organs: the General Secretariat, the International Frequency Registration Board, the International Telegraph and Telephone Consultative Committee (CCITT), and the International Radio Consultative Committee (CCIR). The structure of the CCIR represents a fairly good spectrum of the radioelectronic subjects of vital international consequence. Its 14 study groups are concerned with (1) transmitters, (2) receivers, (3) fixed service systems, (4) space systems, (5) propagation, including the effects of the earth and the troposphere, (6) ionospheric propagation, (7) standard frequencies and time signals, (8) international monitoring, (9) radio-relay systems, (10) broadcasting, (11) television, (12) tropical broadcasting, (13) mobile services, and (14) vocabulary. One of the products of the ITU–CCIR is a 640-page *Radio Regulations* handbook (1959)[7] designating among a multitude of other items such measurands as frequency, bandwidth, frequency tolerance, levels of spurious emission (harmonic, parasitic, intermodulation products), transmitter power (carrier mean, peak of envelope) for a number of classes of emission, effective radiated power, antenna gain (absolute or relative), and antenna directivity. The handbook is concerned with measurands characterizing various types of modulation (amplitude, frequency or phase, and pulse), and types of transmission (telegraphy, telephony, facsimile, television, multiple channel, double sideband, single sideband with full, reduced, or suppressed carrier). The *Regulations* include chapters on "Measures against Interference," on "Distress, Alarm, Urgency, and Safety," and on special services stations (e.g., experimental, direction finding, radio beacon, meteorology, medical advice, standard frequency and time).

The ITU (1947 and 1952) has divided the world into three regions (see Fig. 2) for purposes of frequency allocations to various services. Distinctions are drawn between such services as fixed radiocommunication between specific points; fixed and mobile transmission of information on air navigation and preparation and safety of flight; broadcasting for direct reception by the general public of sound, television, etc.; communication between mobile and land stations or between mobile stations; maritime service between coast and ship or ship to ship, including survival craft stations; radio determination of position; fixed or mobile maritime radio navigation, including obstruction warning; aeronautical radio navigation; instrument landing systems providing horizontal and vertical guidance and glide paths; marker beacons; altimetry; direction finding; safety service; earth-to-space and space-to-space station service; radio astronomy; meteorological, hydrological explorations and observations, including automatic radiosonde; amateur service; standard frequency and time service; experimental stations used in research or in developing a new technique.

Space does not permit listing the various programs and questions related to these services with which the CCIR Study Groups are preoccupied even over a limited period of time. It is sufficient to point out, for example, that nearly 400 documents were submitted for approval to the tenth CCIR Plenary Assembly (Geneva, 1963). The overwhelming majority of these documents were based on measurements in one form or other. The following is a sampling of the submitted material:

- Measurement of man-made radio noise
- Sensitivity, selectivity, and stability of television receivers
- Sensitivity and noise factor
- Usable sensitivity of radio receivers in the presence of quasi-impulsive interference
- Choice of intermediate frequency and protection against unwanted responses of superheterodyne receivers
- Multiple-signal methods of measuring selectivity
- Protection against keyed interfering signals
- Methods of measuring phase/frequency or group-delay/frequency characteristics of receivers
- Pulse transmission tests at oblique incidence
- Investigation of multipath transmission through the troposphere
- Determination of the electrical characteristics of the surface of the earth
- Measurement of field strength for VHF (metric) and UHF (decimetric) broadcast services, including television
- Measurement of spectra and bandwidths of emissions
- Bandwidth measurements by monitoring stations
- Tropospheric absorption and refraction in relation to space telecommunication systems

The major United States exponent of CCIR activities seems to be the Central Radio Propagation Laboratory (CRPL), until recently a part of the National Bureau of Standards (NBS) and now of the Institute for Telecommunications Science and Aeronomy, a part of Environmental Science Services Administration. It was no mere coincidence that the CRPL was established at the NBS (as Interservice RPL in 1942); it came about as a result of the close association, interest, and competence in electromagnetic measurements and early NBS research in radio propagation. At one time (around 1952–56) the entire NBS radio standards activity was part of the CRPL.

Under certain conditions radio interference may be detrimental to space communication. Careful determination by measurement of the characteristics of the systems involved will eventually lead to a solution to this difficulty; disagreements in measuring these characteristics in different parts of the globe must be eliminated by standardization and intercomparison of measurement results as applied to various measurands. Figure 3 illustrates the global nature of the CRPL–CCIR research and applied engineering activities.

Significance for international research and trade

All findings in the field of radio astronomy are based on measurements covering the entire coherent electromagnetic frequency spectrum. Radio astronomy techniques are applied to the achievement of precise all-weather marine navigation by the use of solar and lunar radiation. In measuring radiation from the sun and moon at millimeter wavelengths, the effects of antenna efficiency and atmospheric attenuation must be taken into account. Radio astronomy techniques are frequently used to make measurements of atmospheric absorption, refraction, and scintillation with both solar and stellar radiation as the source of RF energy. The National Aeronautics and Space Administration (NASA) program includes projects designed to make basic astronomical observations from above the terrestrial atmosphere by radio techniques at 0.1 to 30 MHz and at submillimeter frequencies. These will include measurement of galactic noise, solar bursts, polarization, and radio spectra.

Electronic measurements of geodetic distances are, in some methods, based on the measurement of phase differences between the emitted and received wave. Other methods may use high-frequency modulated millimeter waves or light waves as carriers. Accuracies involved are of the order of a part in 10^6. Agreement on phase and modulation measurements is therefore very desirable.

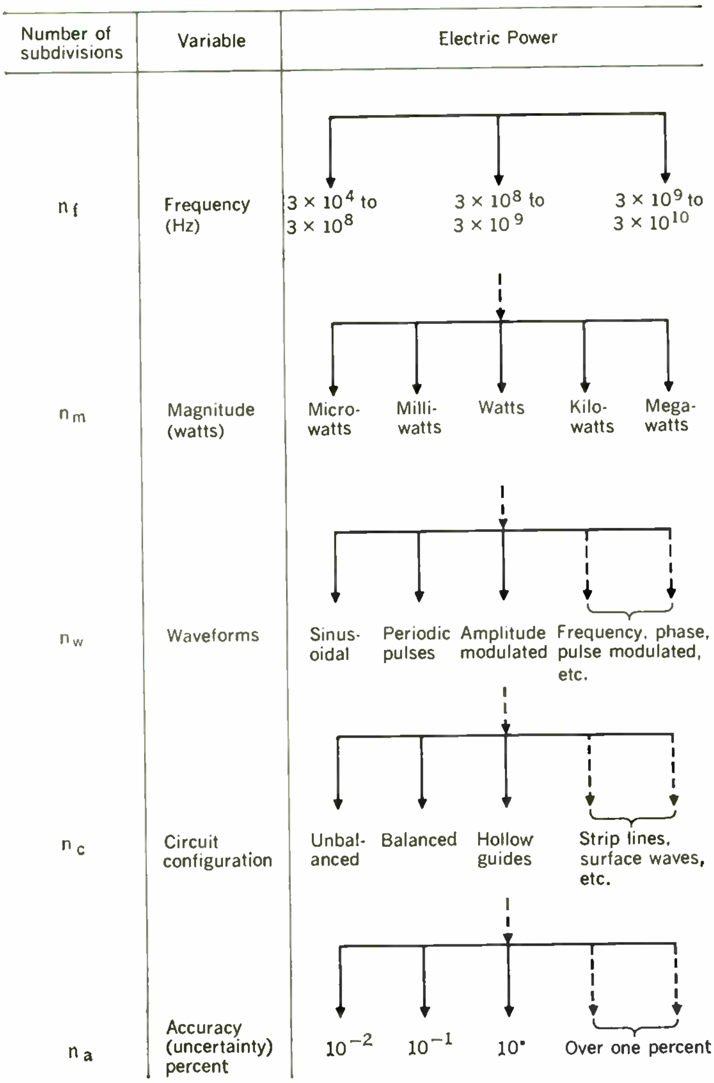
There is also wide international use of radio phase-switching interferometers, spectrum analyzers, cosmic noise recorders, spectroheliographs, maser and laser radiometers, and other similar instruments for observations and automatic continuous monitoring. And one must not forget the recently resumed and intensively accelerated studies under way in many places in plasma physics, which are now becoming a matter for formal international agreement.

We trade abroad; we buy and sell electronic gear—transmitters, receivers, computers, electronic microscopes, measuring equipment, etc. We place contracts abroad. United States industry installs plants abroad and uses equipment and components interchangeable with those used at home. Operation of these undertakings will greatly benefit from international conformity of measurements. A dealer in Europe will not buy many television receivers from the United Kingdom if his national laboratory finds them poorer in sensitivity and selectivity than United States specifications indicate; yet the discrepancy may be caused by lack of agreement on microvolt and attenuation standards. A world market requires availability of replacement components having closely identical electrical characteristics such as frequency discrimination, conversion gain, power dissipation, voltage breakdown, and magnetic and dielectric properties. The importance of agreement on national standards used to establish these characteristics is apparent. Many countries manufacture their own components, which are or will be physically interchangeable thanks to the efforts of the International Standardization Organization (ISO).

Activities of "Approval Boards" for imported products in a number of European countries and the lack of participation of the United States in international standardization were recently brought to the attention of United States companies and should stimulate their interest in measurement agreement.[8,9] Approximately 40 leading United States electronic manufacturers participated in the second International Exhibit of Industrial Electronics (September 1965) in Basel, Switzerland, where 600 firms from 12 countries were represented.

The limited scope of one article does not permit discussion of numerous other instances supporting the need of international agreement, such as the rapidly growing activity in the areas of telecommunication satellites, the activities of such organizations as the International Union of Geodesy and Geophysics, the Committee on Space Research, the International Radio Scientific Union (URSI), the CCITT, the World Meteorological Organization, and the International Electrotechnical Commission (IEC).

Fig. 4. Possible number of measurands of electric power at frequencies of 30 kHz to 30 GHz.



The inadequacy of existing agreements

The BIPM has to date established and is directing international agreement on length, mass, time, luminous intensity, and on two quantities in electricity, namely, resistance and dc electromotive force. The uncertainty (another way of stating "accuracy" or "inaccuracy") at the BIPM in determining the value of a nominal one-ohm

I. Completed international intercomparisons orginated via URSI

Quantity	Frequency, GHz	Magnitude	Countries	Year	Agreement Range
Power mount efficiency	10	10 mW	U.S., U.K., Japan	1957	1–5%
Power mount efficiency	10	10 mW	U.S., Japan	1958–1963	1%
Power	0.3, 0.4, and 1	50–400 mW	U.S., U.K., Canada, Japan	1959–1965	0.1–2.25%
Attenuation, coaxial lines	0.25 and 1	10, 20 dB	U.S., Canada	1963–1964	0.004–0.06 dB/20 dB
Attenuation, hollow waveguides	10	3, 10, 20 dB	U.S., Canada	1964	0.05 dB/10 dB
Permittivity at 25°C	to 30		U.S., U.K., Canada	1964	0.2–0.4% on real component, two parts in 10^6 on loss tangent

II. International intercomparisons in progress (Sept. 1965) orginated via URSI*

Quantity	Frequency, GHz	Magnitude	Countries
Power	34.5	5 mW	U.K., Japan
Attenuation, hollow waveguides	10	6 dB	U.S., Japan
Permittivity to 1300°C	Microwaves		U.S., U.K.
Q standards, coils	0.03–0.05		U.S., German Federal Republic
Noise	10		U.S., U.K.
Power, film bolometer	10	10 mW	U.S., U.K.
Voltage	to 1	10^{-6} to 1 V	U.S., Sweden

* Intercomparisons are also in progress on attenuation (3 GHz), impedance (8.2 to 12.4 GHz), noise (8.2 to 12.4 GHz), and voltage (to 1 GHz) between two countries. Termination is indefinite.

III. International intercomparisons in progress and planned under BIPM

Quantity	Frequency, GHz	Magnitude	Countries	Year to Begin
In progress:				
Power, hollow waveguides	10	10 mW	Japan, U.S.S.R., German Democratic Republic, Hungary, U.S.	1965
Power, coax	3	10–100 mW	U.S.S.R., U.K., U.S., Canada, German Democratic Republic	1965
Permittivity	10		U.S.S.R., U.K., U.S., Canada	1965
Planned:				
Power	10		U.S.S.R., Japan, France, Canada, Australia, German Federal Republic, Italy	1966

dc resistance in terms of the absolute unit of resistance is of the order of five to ten parts per million (ppm). Approximately the same uncertainty exists in the case of the dc nominal one volt. For purposes of this discussion, we will assume that the BIPM is determining the one-ohm and one-volt standards to an accuracy of 10 ppm or 0.001 percent. We see from Fig. 1(A) that the dc watt could conceivably be derived from the dc volt and the ohm; at a first glance it might appear that the maximum uncertainty in the watt ($P = V^2/R$) would be 0.003 percent. The RF volt [from Fig. 1(B)] may then be derived from the dc watt and the ohm. However, as a result of using the ohm again, the uncertainty in the RF volt may increase to 0.004 percent. Following the same line of reasoning down to, for example, CW sinusoidal field strength (one of the most important quantities from the international point of view), we might expect its uncertainty to increase to no more than 0.005 percent because of the added uncertainty in length measurement. Yet the uncertainty of calibrating a field strength meter at 300 MHz at the NBS is about 15–20 percent.

Accumulation of uncertainty. The several orders of magnitude discrepancy in the accuracy of field-strength measurement is a result of continuous degradation of accuracy in the many intermediary steps between the BIPM quantities and the field strength as a measurand at the NBS. The accumulation of this uncertainty is shown approximately as follows:

The value of RF voltage as determined, for example, by the National Bureau of Standards two-thermistor voltage bridge is given by[10]

$$e = \frac{R_T}{(R_T + R_b)\left(1 + \dfrac{R_{T1}}{R_{T2}}\right)} \times \left[\frac{R_{T1}}{R_{T2}}(V_{R2} - V_{R1})(2V_0 - V_{R2} - V_{R1})\right]^{1/2}$$

where e is RF voltage, R's with subscripts are various dc bridge resistance values, and V's with subscripts are various dc voltage values in the circuit. The uncertainties are contributed by

- The BIPM, in a value of one volt dc (≈ 0.0005 percent)
- The NBS "primary" standard (≈ 0.0007 percent)
- The NBS "working" standard (≈ 0.0008 percent)
- Commercial precision potentiometer (precalibrated at NBS) (≈ 0.01 percent)

As a result, values of the individual dc voltages of one-volt levels can be measured with an uncertainty of about 0.01 to 0.02 percent.

V_0 is of the order of 10 volts or higher and a ratio box may introduce an additional uncertainty.

The bridge employs calibrated fixed and variable precision resistors; this results in another uncertainty equal to or larger than that for the dc voltage. Note the number of times the measured voltage and resistance values are used in the equation.

Causes of other uncertainties are instabilities (drift) of the sources of the dc and RF power, contact and thermal emf's, and ambient-temperature variation effects even in a temperature-controlled laboratory. The total uncertainty at 300 MHz sums up to about one percent.

To establish validity of this result, independent methods were used to check the voltage bridge and the agreement between them was within one percent.

Let us turn now to the expression for field strength

$$|E| = \frac{e}{l_H} \text{ volts/meter}$$

where e is the RF emf measured, say, directly by a relatively high-impedance silicon crystal voltmeter across the gap at the center of a dipole antenna, and l_H is the effective height of the antenna in meters. We now find other uncertainties. Calibration of the crystal voltmeter, its loading effect on the antenna, and the uncertainty in the value of l_H result in an overall uncertainty (say in a field-strength value of one volt per meter) of ± 12 percent.

Then there are the additional uncertainties of calibrating a given field-strength meter consisting of an instrument case and a dipole antenna in terms of the above standardized field $|E|$. The instrument generally includes an RF attenuator, a high-gain receiver, and indicating circuitry. The limited flatness with frequency and limited stability of these components further increase the uncertainty to about $\pm$15–20 percent.

This illustrates how the uncertainty in the value of a measurand escalates from an order of ± 0.005 percent (which one might expect from "basic" BIPM quantities) to an order of ± 20 percent in a top national facility. One hardly needs to point out the futility of relying on the international agreement on the dc volt and ohm alone.

The CCIR unanimously adopted at the 1963 Plenary Assembly (Geneva), "for regulation enforcement purposes" to at least one GHz, a requirement that the errors contributed by the field-strength measuring instrument itself (including the antenna, receiver, and recording equipment) should be less than ± 2 dB (approximately 25 percent in voltage); this applies to all levels down to 2 microvolts per meter.[11]

To meet the foregoing requirement, it would be necessary to calibrate all field-strength meters in one top-echelon standardization laboratory (e.g., at NBS), because no allowances can be made for differences between leading national standardization laboratories of various countries and certainly not for degradation of accuracies between these laboratories and the steps leading to the production-line instruments. To have all the field-strength meters in use throughout the world calibrated in one national laboratory is obviously an impractical approach. The solution must be found in (1) reducing the uncertainty within the top laboratories of various countries, (2) establishing limits of agreement internationally, and (3) making certain of proper correlation between national laboratory and production-line uncertainties. Unfortunately, not one of these steps has yet been accomplished. To compound the problem further, there seems to be no agreed-upon definition nor a standard statement defining the accuracy of a "field-strength measuring instrument"; this is apparently the case internationally as well as nationally, at least in the United States. Some United States manufacturers specify the accuracy of their field-strength meters when used as two-terminal voltmeters (minus the antennas), others specify the accuracy of the attenuator alone or of the frequency dial alone, and still others avoid the issue altogether. The presence of modulation and noise in the carriers complicates the picture further. Yet the need of agreement of the order of plus or minus one to two decibels seems evident, for example, for telecommunications satellites[12] as well as in other modern applications.

Quantities and measurands for agreement

It is advisable first to consider the various quantities we employ and consequently have to measure in radioelectronics at the frequencies in question. There are relatively few major quantities involved, and essentially all of them are shown in Fig. 1(B); namely, power, impedance, voltage, current, attenuation, permittivity, permeability, noise, and phase shift. However, there are literally hundreds of measurands to be dealt with, and for the following reason:

The term "measurand" was previously defined for this discussion. The number of measurands into which the major quantities need be subdivided depends on a number of variables (or parameters), properties of materials, and conditions. These include: (1) frequency range of the quantity; (2) magnitude (dynamic) range; (3) circuit configurations involved (e.g., balanced vs. unbalanced, open-wire lines, coaxial lines, strip lines, hollow guides, surface waves, free space); (4) waveform (sinusoidal, broadband, modulated); (5) properties of components, materials, and media (e.g., linear vs. nonlinear, isotropic or nonisotropic, unilateral or multilateral, active vs. passive, electron density of plasmas); (6) environmental conditions (e.g., ambient temperature, humidity, and pressure); and (7) accuracy (e.g., for use as top national standard, or for standardization facility of a large corporation or systems development concern, or for the production-line and maintenance operation). Figure 4 illustrates, as an example, the number of measurands of the quantity of electric power above audio frequencies; the number is equal to the product $n_f n_m n_w n_c n_a$ as defined in the figure. If we assume an optimistic average of two to three subdivisions (each requiring various measurement techniques or a considerable modification of one or more basic techniques) and if we limit ourselves to top national accuracies (at which international intercomparison is to be made) there may be as many as 32 to 243 power measurands. A close estimate of the actual measurands involved for all quantities will require careful consideration and is beyond the scope of this discussion; however, even a conservative estimate will indicate that scores of measurands should be intercompared internationally at this time. The current activities in the Radio Standards Laboratory (RSL) of the NBS may be used as an index in this respect,[13] even though, in the opinion of many workers in the field, the number of measurands included there is far from adequate. Excluding frequency and time delay projects, the RSL is at present working on various stages of standardization of over 50 measurands.

Order of priority

A collective assignment of priorities to specific measurands for international intercomparisons may reasonably be based on the following criteria: (1) importance of the measurand to projects of international significance; (2) degree of complexity and economic cost of measurement techniques for tolerable uncertainties; (3) prevalence of the measurand in equipment on the international market; and (4) the extent of international cooperation in frontier-type scientific research and development using the measurand. Even a cursory examination of the activities of the ITU–CCIR (briefly indicated above) may serve as an illustration for the first kind of criterion. The scope of the CCIR problems involves all the measurands in the area under consideration. Some of the measurands entering the problem of radio interference, for instance, have not as yet been standardized despite the obvious serious national and international difficulties caused by interference. There is still no standardized method, for example, of evaluating the performance of an impulse generator or of how to treat the so-called "quasi-peak" measurements of a "noise and interference meter." Clearly all measurands entering the problem of radio interference should be assigned high priority; these include all measurands involved in CW sinusoidal field strength as well as many others.

One could list here numerous complex problems within the scope of NASA to illustrate the second type of criterion for priorities. The problems are concerned with those accuracies needed for adequate missile guidance systems, direction finding through the ionosphere, radio characteristics of the troposphere, space transmission loss and phase changes, dynamics of the ionosphere, sun–earth research as it affects radio noise, radio characteristics of terrain, and many others.

It should not be too difficult to assign proper priorities to measurands on the basis of international commerce and such worldwide commercial undertakings as that of the Communications Satellite Corporation. Every modern technically developed or developing country is presumably planning its radioelectronic future in terms of a worldwide market rather than in terms of a domestic one; this is at present particularly true of European countries, and perhaps of the United States and Japan. The increase in the number of "international" conferences, symposia, colloquia, and in the number of participants from abroad in the United States technical conventions and many other technical meetings certainly attest to the importance of the international market as a source of intercomparison priorities.

Finally, a basis for priority assignments may be found in such frontier-type research activities as signal transmission through plasmas (e.g., rocket exhausts) or in the field of biomedical and medical electronics. The hazard presented by near fields of high-power antennas is of great concern to all, and international intercomparison of measurement results as well as the need for standardization of limits of radiation cannot be overemphasized; this measurand should be assigned its proper place on the list of priorities.

Accomplishments to date

At present there seem to be three international organizations actively engaged in organizing and encouraging international intercomparisons at frequencies above audio: IEC, URSI, and CIPM.

The IEC is a nongovernmental organization affiliated with the ISO as its electrical division. Its aims are "to facilitate the coordination and unification of national electrotechnical standards not already covered by the statutes of any other recognized international organization. The Commission issues international recommendations which express as nearly as possible an international consensus on the subjects dealt with. These international recommendations are issued to assist the National Committees in their efforts towards harmonizing their national standards with these recommendations insofar as national conditions are concerned."[14]

Another, and perhaps more explicit, statement of the two aims of the IEC is "(1) improving understanding between electrical engineers of all countries by drawing up common means of expression: unification of nomenclature; agreement on quantities and units, their symbols and abbreviations; and graphical symbols for diagrams, and (2) standardization of electrical equipment proper, involving the study of problems of the electrical properties of materials used in electrical equipment, standardization of guarantees to be given for certain equipment as to the characteristics, methods of test, quality, safety, and dimensions controlling interchangeability of machines and electrical equipment."[15] Among its 56 committees (as of 1965), there are a number apparently directly concerned with agreement in measuring electrical quantities at frequencies above audio. However, the emphasis seems slanted toward unification of writing specifications on instruments manufactured by industry rather than on securing worldwide agreement on the magnitudes of measurands as obtained by top-echelon national facilities. For example, the scope of the IEC Committee on Measuring Instruments is "to prepare international recommendations for electrical measuring instruments for measuring electrical quantities (such as indicating, recording, contact instruments, watthourmeters, etc.) and their accessories, as well as for electronic measuring instruments and other electronic apparatus (having no measuring element) to be used in association with other instruments (valve voltmeters, signal generators, oscilloscopes, etc.) for measuring electrical quantities."[16]

The URSI is classified as "semigovernmental"[17] with aims "(a) to promote and organize researches requiring international cooperation, and the scientific discussion and publication of these researches; and (b) to promote the setting up of common methods of measurement as well as the intercomparison and standardization of the measuring instruments used in scientific work." The "members" of the union are "National Committees instituted either by the National Academy or the National Research Council or by any other national institution or association of national institutions recognized by the government."[18]

The International Bureau of Weights and Measures is classified as "intergovernmental" with responsibilities for "(a) the conservation of international prototypes of the metre and the kilogram, and spreading the adoption of the metric system throughout the world; (b) periodic comparisons of national standards with international prototypes; (c) work related to the unification of electric, photometric and thermometric units; (d) in general, the determination of physical units useful in precision metrology, and the perfecting of measuring processes favorable to progress in all branches of metrology."[19] The BIPM is ultimately responsible, through CIPM, to the General Conference of Weights and Measures. The latter is composed of delegates of all contracting governments. The BIPM has laboratory facilities internationally owned, administered, and maintained (located in a suburb of Paris, France).

A comparison of the above brief descriptions of the three organizations clearly indicates that the most appropriate one for undertaking the responsibility of establishing and maintaining international agreement in the area under discussion is the BIPM. Nevertheless, the IEC carried on limited activities in this area until about 1957. The URSI is to be credited for all the intercomparisons since 1957, and BIPM entered the arena in 1965 with the inauguration of the first three international round-robin intercomparisons, bearing for the first time an official stamp of intergovernmental authority.

Tables I, II, and III show the status of the activities by URSI and BIPM–CIPM as of 1965. Briefly, all intercomparisons completed and actively in progress as of September 1965 were organized at the initiative of URSI; these include power at 0.3 to 35 GHz, attenuation at 0.25 to 10 GHz, permittivity at 1000 Hz to 30 GHz, noise at 10 GHz, voltage to 1 GHz, impedance at 10 GHz, and Q (figure of merit) of inductors at 45 to 50 MHz. The first three organized by the CIPM are on power at 10 GHz in hollow waveguide, on power at 3 GHz in coaxial lines, and permittivity at 10 GHz at 25°C.

Future goal

If we are to single out one particular goal as the most desirable in the immediate future, it is the establishment of competence and installation of laboratory facilities at the BIPM. This would enable intercomparison of the measurands in question on the premises of BIPM in the way that it is being done for, say, dc resistance. A. V. Astin, director of the NBS, as the United States representative to the CIPM, has been pursuing this objective during the last several years. The major advantages would be (1) the possible abandonment of the circular "round-robin" intercomparison procedure in favor of the more economical and more expedient central laboratory procedure, and (2) the provision of a facility for calibration services to national standardization laboratories of countries taking new development steps in this area.

In the circular procedure, the objects used in the intercomparison are sent in rotation from laboratory to laboratory, requiring many months and sometimes years to complete a task. In addition, preliminary arrangements and correspondence to fix a time schedule, and to agree on various details such as presentation of results, environmental conditions, etc., consume considerable time on the part of each participant. Because of this, the number of participants per circle has to be limited. However, central procedure eliminates many of these difficulties. Any interested laboratory sends its objects into one central location, while test conditions and requirements of a central laboratory such as BIPM may be made known far in advance to all national laboratories. The prospect of accomplishing the abovementioned goal depends to a large extent upon the effectiveness of efforts to promote the expansion of the BIPM program by the countries that support it.

Conclusion

It would perhaps be best to conclude by restating the following near maxims: (1) There can be no science and no modern industry or commerce without measurements. (2) The objective of measurement is to obtain the same number (within given limits) for a specific measurand (in terms of approved units and standards) at any time, in any laboratory, and in any country. (3) Uncertainties are introduced in every step required to derive a new measurand from existing measurands. (4) Because of the accumulating uncertainties, international intercomparison is needed to establish agreement on derived measurands in addition to the agreement on the basic quantities.

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Turning a science into an industry

An interview with Dr. Robert Noyce,
a young scientist–executive of the integrated circuits industry

Dr. Robert Noyce is a young scientist whose personal growth in the solid-state electronics industry has been as phenomenal as that of the industry itself—so much so that many of his friends and former schoolmates (also still young) think of him as a new-style Horatio Alger hero. In fact, things moved so fast for Noyce that he is able to tell the story that not long after he began directing the operations of Fairchild Semiconductor in 1959, he got a petition "from everybody in the place asking me to park my 1946 Ford out in the back because it ruined the looks of the building to have it parked out in front."

He received his Ph.D. in physical electronics from M.I.T. in 1953 after earning his bachelor of arts degree at Grinnell (Iowa) College with a double major in physics and mathematics. He did advanced semiconductor research and development for four years, including work with William Shockley, before cofounding Fairchild Semiconductor Corporation in 1957. He became the general manager in 1959, and directed the skyrocketing growth of that company which by 1961 had already become the largest producer of high-performance silicon transistors in the world. In addition to retaining the direction of the Semiconductor Division, he recently was named a group vice president of the parent company.

Dr. Noyce has guided the development of a number of "firsts" in the semiconductor industry, including the double diffused silicon mesa transistor, the planar process for the production of transistors, and practical integrated circuits. He has contributed to the design theory and development of junction transistors, field effect transistors, and p-n-p-n switches, as well as to the basic recombination theory in junctions. He holds a dozen patents relating to the solid-state electronics field.—*N.L.*

Growth of the integrated circuits industry

Dr. Noyce, would you mind telling us how the integrated circuits industry looks to you nowadays? In particular, what do you see as the major changes of the last year?

First of all, if we look back over this past year and try to pinpoint the major changes, one of the first things to note is that volume production of integrated circuits has arrived. We now have a tremendous demand in the market place for integrated circuits, whereas a year ago there was probably an overcapacity in the industry. At the present time, anybody who has integrated circuits for sale can sell them. We're getting past the pilot production stage into real volume production. I estimate that, as of today, more than 25 percent of Fairchild's total transistor shipments are those incorporated in integrated circuits.

Is there a specific reason why it's growing so rapidly just now?

I think that in 1964 we were still in the process of convincing the customer that integrated circuits were the answer, and that by the end of the year this conversion was complete. The people who can use integrated circuits are now ordering them in volume. Instead of 10 000-piece orders, we receive requests for quotations on quantities of a half million or a million.

Both government and commercial?

Yes, both government and commercial. Again, this is a change. In '64, most of the applications of integrated circuits were government applications. In '65, a significant number of integrated circuits—perhaps half of the unit volume—were going into commercial applications.

Another symptom of the trend is this: In 1964, our shop, which makes integrated-circuit testers, was our largest commercial customer for integrated circuits. This is no longer true today. Many of the commercial computer manufacturers are using integrated circuits in their new equipment.

The other thing that's happened—and this is part and parcel of the same thing—is that whereas a year ago the yields on integrated circuits were still questionably low, they now are being produced just as transistors were a couple of years ago, with high yields and efficient production techniques.

Are you talking about digital circuits only?

No, both digital and linear. Digital circuits have ten times more unit volume than linear, but that's because they are easier to design and have wider applicability.

Yields and costs

In a recent interview, Dr. Noble of Motorola suggested that to achieve high yields they must rely on wide tolerances and conservative equipment design. Is your approach to high yield different?

No, it isn't. This has been true of integrated circuits pretty much since the beginning. For resistors, instead of designing to one percent tolerances, the cheaper way is to design for 10 or 20 percent tolerances and put in the extra gain necessary to make up the difference in performance. With today's technology you couldn't possibly make a digital circuit that requires high-tolerance resistors. The same is true of linear integrated circuits. You've got to consider the limitations of integrated circuit processing in order to be able to come up with practical designs. No one would ever design a television receiver with one percent capacitors or one percent resistors if he wanted to sell it to the general American public.

The place where we are still in trouble in linear integrated circuits is with finite bandwidths or with tuning elements in which we do need precision. But in commercial practice, in anything but measuring equipment, you don't work with high component tolerance. What you work with is a twiddle knob somewhere—a volume control, a tunable coil, a tunable capacitor. It is very hard to put that type of element inside an integrated circuit.

There are techniques for putting adjustable resistors in circuits; IBM is doing this with the 360. This can be done in various ways. For example, you can anodize a thin-film tantalum resistor to bring it down to any level of tolerance you want. But this incurs a cost structure for the component that is quite different from just making it and taking it as it comes off the end of the line.

In general, however, we have pushed the yields up and the cost down so that today, for any given digital function, you can do the job cheaper with integrated circuits than you can with discrete components, if you consider the assembly cost of the component. In fact, in most cases, considering component costs alone, it is cheaper to use microcircuits than to use individual components. This certainly has been the motivation for the commercial people to go into integrated circuits. And in some military systems, there is justification, in terms of weight, reliability, and so on, for using integrated circuits.

The packaging problem

What relation do such factors bear to the argument about throwaway cost?

If you consider the reliability of the integrated circuit and the fact that the circuit costs no more than the transistor did, eventually you must come out ahead in your throwaway cost also, because you don't have to throw it away so often. And the chunk that you do throw away costs the same as it did before. In terms of pluggable units, it's just a question of how small a chunk you make. Also, in almost every piece of equipment on which reliability studies have been made, the connector cost and the connector reliability constitute one of the major limitations in the system. You have to throw things away because the connectors don't work. Recently, we have put much more emphasis on the interconnection problem, and new packages have been introduced. A lot of work has been done in packaging; there's a lot yet to be done.

Toward greater complexity

You spoke earlier about adequate yields. What does this mean in terms of numbers of integrated circuits produced?

It depends on the complexity of the circuits, but let's say that the yields of the simpler integrated circuits are running comparably with transistor yields throughout the whole process. This is a fairly high yield. Now, it is this success that opens up the next possibility in integrated circuits. I have always felt that the original motivation for going into integrated circuits was economic. A few years

I'm convinced that we can find out the causes of loss of yield. This is now a science instead of an art.

ago, the process was to make many, many transistors, cut them apart, mount them individually, and then put them all back together again. But this was ridiculous. Just by going to modules larger than transistors, we obviously can produce a set of transistors much more cheaply because we don't simply cut them apart and wire them together again. We eliminate all that labor. In particular, if we consider the question on the basis of per-transistor cost, we can probably reduce the cost of the transistor, with present integrated circuits techniques, something like five to one because of the savings in labor.

The next step beyond this is to go another order of magnitude in the complexity of the circuit being made. This presents some problems. One is the same yield problem that we had in going from the single transistor to the integrated circuit. If your yield is 0.95, and you go to ten times the complexity, you have nothing left. So you have to build the yields up. Certainly, though, this question of getting adequate yields is a simple economic question. If it is to the advantage of the manufacturer to do more research, in order to understand how to increase yields, he will do so. At a point where your yield is 95 percent, you can only save 5 percent of your cost by increasing yields, and it may be much more economic to leave it at that than to invest in the research program necessary to improve the yields. If we go up to another order of magnitude in complexity, the economic motivation to do research to increase yields is again very clear.

Another problem is to define what we should make that is ten times as complex as what we're making today. At present we're making simple Boolean functions out of which you can assemble any type of logical function that you want. After we proceed another order of magnitude in complexity, we either must make every one different, or we must reorient the system's thinking as to how a system is realized.

One of the easier approaches in this respect, and perhaps the first that will be successful, will be complex memory arrays; that is, the production of very regular, well-defined functions that can be made arbitrarily large and still be useful. The other attack may be to build specific subsystems—let me call these integrated functions instead of integrated circuits—such as digital differential analyzers and storage registers. You want specific functions that are used generally rather than the Boolean functions out of which you normally build such system functions.

The third problem in going to large arrays is that of whether or not to make every unit different. One possible solution is the use of much more automatic methods, so that conceivably one could make every unit different. For instance, no two automobiles are alike; they're a different color or have different accessories. This is done on the assembly line with minimum confusion by keeping track of things by computer. So we are studying methods of doing more of our job by automatic techniques.

Have you built much automated equipment?

For me, the real impetus to move toward integrated circuits came when I realized how it could be done. I also became convinced that it was a very economic move as well.

No, we have not. We're still trying to define what makes sense. We are working hard on these problems, and the direction is very clear. If we're going to make individual transistors, we've got to know circuits in order to define the transistors; if we're going to make integrated circuits, we've got to know the systems that the integrated circuits will go into. And if we're going to make integrated functions, we have to be aware of the next level beyond that in order to define these functions. This is one of the reasons why we have set up a Digital Systems Research Group—to try to define some of these problems and to point the way to the most likely solutions.

So this forces you into a new field?

That's right. We must have knowledge we weren't required to have before in order to guide our own development. We could get this guidance from our customers, but if we do so, we're blown by every wind and whim of the customer group. They say, "I want this or that," and we have no way of evaluating whether it makes good sense or not. In order to guide our own activities best, we must have some way of judging which are the most likely and which the least likely solutions. We cannot simultaneously follow every possible solution. There just isn't that much talent available. So one has to pick and choose a bit.

With regard to the yield problem, we also are examining methods of redundancy, so that we need not achieve 100 percent yield. However, the question is whether it is cheaper to put the money into finding out the causes of the loss of yield, or to put it into redundancy. Sometimes redundancy makes things so complicated that you actually lose ground. Certainly, in very regular circuit arrays it looks as though the redundancy does some good. But with random arrays, building redundancy appears to be very difficult. I'm convinced that we *can* find out the causes of loss of yield. The point is that this is now a science instead of an art. The areas where there are no explanations for things happening are getting smaller every day because of the research that is going on.

Do you have a large group doing basic research on this kind of thing?

Yes. Several years ago, we started out in the laboratory with this basic tenet: There is no loss of yield that we cannot understand if we study it carefully enough. The basic reason for the increase in yields in integrated circuits of the complexities that we are making today has come from this kind of a program. The largest cause of loss of yield is eliminated, then the next largest, and so on. We are now working at yields we would not have believed possible five years ago.

Moving away from research

Dr. Noyce, you spent quite a few years in basic research. Do you keep very close, personally, to research now?

Not particularly. I read the progress reports, and that's about all. I both miss and don't miss doing research. It's very exciting to be in a position where you are influencing the work that's going on, trying to set the stage for it. Still, after growing up with a baby, you don't like to abandon it. You'd rather keep in touch, to stay aware of what's going on, but there is less and less time to do this and more and more time that must be spent worrying about other kinds of problems—people, organization, production, marketing, and all the rest of what makes an industry rather than what makes a science.

Did you find the transition from being a physicist and researcher to being an executive of research and industry difficult, or was it natural for you?

First of all, I felt that moving from research into research management was an easy transition because I was confident that I could do the job. I could direct the work and see that it was channeled properly so that there wasn't any great personal trauma involved in the switch. The change from directing a research program into directing a complete commercial program, however, was quite a traumatic experience. I didn't know whether or not I could do the job. I was ill-prepared to do it. I didn't have any manufacturing experience really. I didn't have any marketing experience. I didn't have any financial experience. Consequently, it was with a great fear of inadequacy that I got into this administrative type of role. However, as time has gone by, I have realized that other people are inadequate too, and it is just a question of whether you are less inadequate than the next man.

The impetus toward integrated circuits

When did you first become aware of the way the whole semiconductor industry was going to grow? Was it when you were working with Shockley?

That was back in 1956, and certainly there was some discussion then about the fact that if we were going to make computers go faster, we were going to have to get them smaller because the propagation delay just down a piece of wire was getting to be a significant fraction of the total propagation delay with the advanced equipment. So the motivation to go smaller was apparent then. There was a lot of discussion in the literature about making lots of components at once—batch fabrication—and making things that would carry out functions instead of making individual components. But as far as I was concerned, the real impetus came when I realized *how* it could be done, not that it would be desirable to do it. Both of these are necessary. You've got to realize that it would be desirable to reach a given goal and then you've got to have a method of getting to that goal before you can really jump in with both feet and start dumping effort into it. I suppose the time that it became apparent that we could do this was after the development of the planar process, when you could see that beyond this we could do all of the interconnection without the labor of running individual wires from one point on the circuit to another. This dates back to just before 1960.

Was it a forceful realization?

Yes, it was. I recall very vividly calling a group of technical people together and saying, "Look, this is possible. Now, let's explore every possible way that we could do it besides this way, and what it would mean." And from there on out, we laid out a program to go ahead and do it. It was a very conscious decision at that point. And we convinced ourselves that it was a very economic one as well.

Working with Shockley

How did you like working with William Shockley? Was he a good teacher?

He is certainly one of the most creative men that I've ever known in my life, or hope to. He had a marvelous way of simplifying a problem and getting at the fundamental part of it, cutting away all of the extraneous information and getting a model simple enough to be handled mathematically or experimentally. I think it must be the same working with any really creative individual—the ideas flow so fast that it keeps you busy trying to keep up. Consequently, your rate of learning is very, very high because you are working so hard to understand what is being given to you. This is a characteristic of a good professor at an advanced level.

The organization of research

Does this kind of thinking lead you to organize your research projects in a definite way? I mean, do you try to have essentially very good teachers with small groups around them?

Unfortunately, there aren't enough very good teachers to go around. When you find them, certainly this is the way you want to organize. You want your creative men to influence as many people as possible.

Other than that, about all you can hope to do in your research program is to have such an organization in such an environment that you foster creative thinking. Perhaps you can't stimulate it, but you can foster it if it appears. I think that most of our laboratories really depend on that—enough freedom of thought so that if a man becomes interested in a direction that looks fruitful, and if it looks as if he'd get somewhere, you let him go ahead and pursue it until either he does get somewhere or proves to himself that he can't.

The organization of a research crew, I think, is one of the most fascinating organizational problems. First of all, it's very difficult to measure the output—at least on a short-term basis. You can, though, on a development activity. You can say, "This is the kind of schedule that we ought to be able to meet with this development activity," and if it's not met, you don't have the right people doing it. But in a long-term research program in general, the people who are doing it are in the best position to evaluate it, not the people who are supervising it. So that the people who are supervising the program are more dependent on their ability to judge *people* than they are dependent on their ability to judge the work that is going on. Over a long term, somebody who has had a record of creative work probably will continue, so you can depend somewhat on that.

The biggest problem

To wind up back in integrated circuits, what do you see as the single biggest technical problem now?

It's difficult to define a single problem, but probably the most challenging problem now is finding the economic way of going to this order-of-magnitude-larger complex array of integrated circuits—the yield problem, the question of what you should make and how you should make it. It's the problem that I think has the greatest economic motivation behind it as well, because just as the integrated circuit cuts the cost of a particular digital function an order of magnitude, going to the next level has the same potential of cutting the cost by a similar amount. This really means then that logic control functions will be so much cheaper than they are today that the breadth of applicability can be enormously expanded. Beyond that, solid-state devices still cannot compete in the high-power high-frequency area. I don't know that these devices ever will compete, but if we find the right phenomenon maybe they will.

Special Conference Report

Purdue Conference on Instrumentation for High-Energy Physics

W. A. Higinbotham *Brookhaven National Laboratory*

It is interesting to note that all the radiation detectors used in high-energy physics have been developed in the last 20 years. The bubble chamber is a natural successor to the Wilson cloud chamber, which has been displaying tracks since 1912. Bubbles are formed along the ionized particle tracks by suddenly reducing the pressure in the liquid. The earliest radioactivity measurements were made by the observation of alpha particle scintillations in zinc sulfide in a dark room, and materials for a scintillation counter were available in the thirties. However, it was not until the early fifties that suitable phosphors were combined with photomultipliers to produce high-energy scintillation detectors. The last five years have seen rapid development of the spark chamber for delineating particle tracks.

In the past, this sort of instrumentation was largely developed by the experimenters themselves—and to a considerable extent this is still the case. Meetings of the American Physical Society are too crowded for presentation of instrumentation papers, and high-energy instrumentation has not had a proper forum for discussion in many years. The Purdue Conference was the third *ad hoc* conference on this subject. The first was at Berkeley in 1960; the second at CERN (Geneva) in 1963. Credit for initiating the Purdue Conference goes to Prof. Lew Kowarski, a pioneer in nuclear physics in France, a director of Saclay, and a leading scientist at CERN, who is currently teaching at Purdue. He was ably assisted by Prof. G. W. Tautfest and other members of the Purdue Physics Department. Purdue's School of Science subsidized the endeavor and made personal arrangements for the delegates' comfort. The proceedings of the conference have been published as a special issue of the IEEE TRANSACTIONS ON NUCLEAR SCIENCE (vol. NS-12, no. 4, Aug. 1965). The IEEE Nuclear Science Group plans to participate in, and possibly to assume responsibility for, future United States conferences on high-energy instrumentation.

Bubble-chamber data processing

The published proceedings present an excellent review of the current status of high-energy instrumentation, with 13 invited review papers and 39 contributed papers. The current workhorse in this field is the liquid hydrogen bubble chamber, which is viewed by three cameras to provide stereo photographs of the particle tracks. Several million pictures per chamber are produced each year. The pictures first are scanned for interesting events, then the coordinates of these events are precisely digitized, and finally the kinematics of the events are computed and classified on high-speed computers. Until recently the scanning and digitization were primarily manual processes, but in the last five years several methods of semi-automatic processing have been under development. One method is the use of a relatively small computer to monitor human operators at scanning tables. The operators select the events of interest and trace out the tracks with a cursor, pressing a button to read coordinates from position digitizers. The computer makes sure that coordinates of tracks and fiducials are taken in the proper order, and that the data satisfy certain uniformity criteria, thus cutting errors in half and making good operators out of average operators. The computer also performs format and bookkeeping functions. There are many projects of this sort, several of which were described in some detail.

At the other extreme is the system developed by Paul Hough and Brian Powell at CERN. The heart of the system, which has been implemented at CERN, Brookhaven, and the Lawrence Radiation Laboratory, is a precision, mechanical flying-spot scanner, on line to a computer. The ultimate objective is an entirely automatic pattern-recognition measurement and analyzing system. The total number of coordinates in a picture is more than a computer can currently hold, so the present systems require preselection of significant tracks by human operators who record enough information to guide the computer. Even so, the mechanical and programming problems have been substantial. A typical event requires precise measurement of direction, curvature, and bubble density on at least three tracks in each of three views, correctly interpreted in the presence of crossing tracks, noise, and variations in image density. The current status is reported in considerable detail. All three centers have operating systems. The rough, manual scans go at a rate of about 12 events per hour, and the computer digitization and processing at 70 events per hour. The precision

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and reliability are comparable to hand scanning, though the cost is still somewhat higher.

In keeping with the long-range Hough–Powell system goals, automatic pattern recognition is also being pursued. At Brookhaven, the Marr–Rabinowitz program is being used experimentally to measure small angle scattering, which cannot be reliably detected by visual scanning. At Berkeley, all parts of an automatic system have been tested in prototype, and the group under Howard White expects to have a fully automatic system in operation next year.

Another sophisticated film-scanning system has been developed by Prof. Irwin Pless of M.I.T., which is different from the aforementioned system in at least two respects. The flying spot is generated with a cathode-ray tube under the control of a computer, and the scan element is a line segment rather than a spot, which helps to distinguish a line pattern from noise and which gives slope as well as coordinate information. The precision and linearity, about one part in 40 000, is rather remarkable for a CRT system. Again the goal is fully automatic processing, but it is too early to tell which system will be more efficient. (Needless to say, many people have been involved in all of these systems and credit is duly extended in the papers so briefly summarized in this report.)

There are many specialists who would (and do) argue that automatic pattern recognition is not the best technique since the human is so good at it. They have developed systems to link people and machines, hopefully making best use of the capabilities of both. The SMP (scanning and measuring projector), developed at Berkeley, has been copied at several institutions, and a good operating system was on display at Purdue. The bubble-chamber picture is projected on a scan table. A semi-automatic mechanism performs an accurate digitization of all points that fall within a small aperture. An operator guides the aperture along the tracks of interest, pressing the record button. Coordinates are fed directly to a computer, which filters out points not associated with the tracks, averages the "good" points, and notifies the operator if certain criteria are not satisfied. One medium-capacity computer can monitor several scan tables.

After track data have been recorded in any of these systems, the tracks have to be reconstructed in three dimensions, and the energy, momenta, and interaction kinematics computed—a succession of sophisticated programs that consume considerable time on even the fastest computing systems. The Lawrence Radiation Laboratory plans to use a 3.3×10^{11}-bit photodigital store in conjunction with a CDC-6600 computer system for the analysis of large numbers of bubble-chamber events.

Spark chambers and data processing

The bubble-chamber liquid is mechanically expanded, giving a sensitive time of the order of 100 μs. By magnetic analyzers and other techniques, various primary particles may be selected for injection, but nevertheless one must accept whatever interactions happen to occur in the chamber volume during the sensitive time. Consequently, certain types of experiments can be more effectively performed with individual scintillation counters, Cerenkov detectors, target, magnets, etc., to select specific types of particle interactions. Development of the spark chamber makes possible both fast detector selection and track delineation throughout a volume. Progress has been rapid, and the variety of designs and applications were the center of attention. The early chambers had 10 to 20 electrodes of about one-square-foot area, spaced about ½ inch apart. External counters triggered the high voltage, applied to alternate plates, and sparks striking along the ionized track were photographed by stereo cameras. New developments described at Purdue include wide-gap chambers, digital readout chambers, and several techniques for scanning spark-chamber photographs.

Soviet physicists have played an active role in spark-chamber development, especially in the wide-gap chambers, which have interelectrode spacings up to 20 inches and require high-voltage pulses of several hundred kilovolts. Prof. K. Strauch of Harvard reviewed recent progress in the United States. Such chambers may be operated so that sparks form from one electrode to the other, or the spark formation process may be interrupted, giving a string of short streamers along the ionized tracks. High definition can be obtained in large volumes, though the low light output poses problems.

About a dozen papers described systems for scanning spark-chamber photographs. In many respects they are similar to the bubble-chamber analysis systems. However, since spark chambers can be triggered, only significant tracks appear in most of the photographs. Generally, the number of sparks to be measured is very much less than the number of bubbles in bubble-chamber pictures, so the scanning systems may be simpler. One, developed at the University of Southampton, England, uses a commercial closed-circuit television system and a multichannel analyzer. Many of the systems use CRT scanners, slaved to computers.

The other exciting trend is toward direct readout systems. An obvious technique is to replace the film cameras with vidicon cameras. The track-defining sparks last for a fraction of a microsecond. Scanning the vidicon takes at least several milliseconds, which is compatible with the recovery time of large chambers. A second technique is acoustical, employing several acoustic pickups around the perimeter of each gap. A third technique makes use of parallel wire grid electrodes, the wires being threaded through magnetic cores. This technique has been applied to a large-scale experiment at Brookhaven, which was operated on line to a high-performance digital computer. In this experiment the spark gaps were not properly a "chamber" but were separated and distributed over a distance of about 150 feet to provide high angular resolution. The spark plane sensitive time was about ½ μs and the recovery time was about 1 ms. Some 100 or more events were recorded and analyzed during each particle-producing accelerator burst (one burst per two seconds). The Brookhaven computer system has also been used with scintillation counter arrays or hodoscopes, which have poorer spatial resolution but are very much faster.

Conclusion

The Nuclear Science Group is gratified that the proceedings of this excellent meeting have been published in the IEEE Transactions. This issue should be of interest not only to the members of the IEEE Nuclear Science Group but also to many others whose interests lie in the fields of nuclear instrumentation, computer applications, and pattern recognition.

Authors

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Dr. Finn is the author of a number of published papers on the subjects of reactor physics, the history of physics, and characteristics of the modern science museum. He is currently completing a source book dealing with the history of thermoelectricity and also is performing a detailed investigation of the experimental telephone equipment used by Alexander Graham Bell.

Toshikazu Kawakami, managing director and member of the Board of Directors, Japanese National Railways, was born in Hiroshima, Japan, in 1912. After graduating from the Electrical Engineering Department of Hokkaido University, he joined the Japanese National Railways in 1936 and was in charge of railway electric power and electrification until 1954. In 1955 he became head of telecommunication, signaling, and electronics, and in 1960 was appointed deputy chief engineer. In July 1962 he became director of the Electrical Engineering Department, and in May 1963 he assumed his present position of managing director. His main duties as deputy chief engineer involved the construction of the New Tokaido Line, as well as the application of electronic computers to this project.

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Hans Mark was born in Mannheim, Germany, in 1929. He emigrated to the United States in 1940 and became a U.S. citizen in 1945. He received the A.B. degree in physics in 1951 from the University of California (Berkeley). In 1954 he received the Ph.D. degree in physics from the Massachusetts Institute of Technology. He remained at M.I.T. as a research associate until 1955 and then accepted a position as research physicist at the University of California's Lawrence Radiation Laboratory. In 1958 he rejoined M.I.T. as assistant professor of physics. In 1960 he returned to Lawrence Radiation Laboratory to become Experimental Physics Division leader and associate professor of nuclear engineering at the University of California's Berkeley campus. In 1964 he became chairman of the University's Nuclear Engineering Department in Berkeley while continuing as a research physicist at Lawrence.

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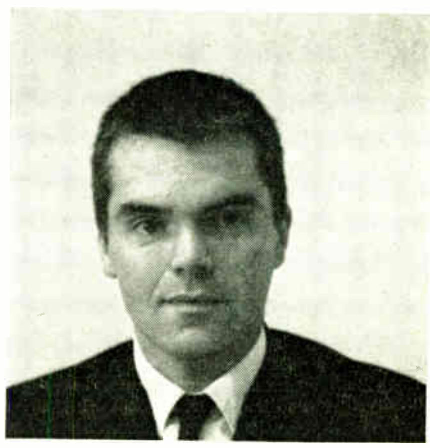

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