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the cover

The illustration on this month's cover is a section of the lower reservoir dam of the Union Electric Company's Taum Sauk pumped-storage project in southeastern Missouri. The concrete, gravity-type dam is 60 feet high from toe to crest and has an overall length of 360 feet. The structure impounds approximately 6400 acre-feet of water and inundates a surface area of 395 acres. The picture shows the downstream face of the dam, which serves as a free crest spillway capable of handling 70000 ft³/s of water. For a detailed description of Taum Sauk and other notable pumped-storage projects in the United States and abroad, see the feature article that begins on page 58.

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World Radio History

Spectral lines

With Dean Ryder away this month traveling at high velocity through Europe, this issue of the "Lines" is undergoing a spectral shift, dropping into the zone occupied by the chairman of his SPECTRUM board of consultants—obviously a shift toward the lower end of the scale. There is nothing, of course, that a member of the odd breed of characters known as "consultants" welcomes more than a slight hint he will be afforded a page on which to express his views. In fact, a slight hint is all that is needed, and he is particularly pleased when he can do this while momentarily out of range of the editor's blue pencil. It so happens, however, that two years' association with your editor in the delicate job of bringing SPECTRUM into being and defining its objectives has brought about a fair convergence in the wavelengths emitted by our respective viewpoints. This month, however, I propose to put aside Jack's prism, and let you use mine. If the results are not entirely satisfactory, he will doubtless tell you and me about it on these pages in the following months.

Why was the Board of Consultants established and what have they been up to? Dean Ryder has programmed our operations. Our objective is "to assist and advise the editor in adjusting the content of SPECTRUM in conformity with our approved editorial policy." Purposely, he selected our membership from a wide range of interests so as to promote wide coverage of the field. To fulfill these responsibilities our primary objectives are to:

1. Set a high standard of performance.
2. Promote a sufficiently large number of competent and interesting articles to build up a backlog of material from which to *select* those which will be most valuable to our members.
3. Encourage our editorial staff in their difficult and important responsibilities in making editorial changes, if necessary, to increase clarity and reader interest.

In addition, each member of the consulting board, because of his unique contact with a specific segment of the electrical engineering field, has become active in suggesting topics and locating authors who are working in the forefront of the art.

One of the first major undertakings of our board has been the encouragement of increased interest in preparation of articles in the power field. Perhaps some readers have thought or have heard from time to time, as I have, that SPECTRUM is not devoting sufficient space to the power industry. We feel, in some respects, that this comment is justified. However, as we all know, the way to get better papers accepted is to have papers submitted. For this reason, with the energetic help of Hendley Blackmon, chairman of the Technical Operations Committee, the help of the Power Group has been enlisted. In Blackie's powerful words, "This Division is inherently a spinning reserve for such a load, if we can devise some way to connect it to the SPECTRUM bus." With encouragement of this kind, power papers have been flowing into headquarters in increasing numbers for consideration.

Woody Gannett in a recent letter to one of our power-oriented readers noted that the power articles that have appeared in SPECTRUM were put there as much (if not more) for the benefit of electronics people as for power people and that, similarly, it is our hope that the power specialists will occasionally find some of the electronics articles interesting and enlightening. This would further one of SPECTRUM's missions, that of advancing each member's knowledge in fields outside the area of his special competence.

Should SPECTRUM occasionally include material which can be found in modern textbooks? Here is another interesting question not without its controversial aspects. Our Editorial Board has discussed this on numerous occasions and probably will bring the subject up from time to time in the future. As we now stand, we believe that we can provide a service to the members if we *occasionally* and very *selectively* include some of the modern textbook approaches to our advancing art. These might be considered as "door openers" or "appetite whetters" leading some members to explore the subject further through suggested references. Time and the spectrum of comments from our members will tell if this is a worthwhile undertaking.

Certainly, in the few months of its existence, SPECTRUM has not yet completely found itself. But I believe that, with the help of competent authors working closely with the enthusiastic and capable editorial staff, real progress is being made. Our editor receives many letters from the readers, some praising, others critical, but the most important thing to remember is that the writers were sufficiently interested in IEEE and its future to take the time to write. We have profited much from the constructive criticism. We and the critics have the same objective—to make the publication of maximum value to the membership, not primarily as a research reference volume but rather a modern, interesting, tutorial core publication of a society that must stay out ahead in a rapidly advancing technology.

W. K. MacAdam
Chairman
Board of Consultants

Pumped storage—an answer to peaking power

In the North Atlantic States alone, plants of almost 10 000 MW of pumped-storage capacity are either projected or under construction. The advantages of this power reserve concept are becoming ever more apparent to public utilities

Gordon D. Friedlander *Staff Writer*

Electric power demand in the United States is increasing on the order of a geometric progression—doubling every decade. To meet this tremendous increase, numerous solutions for power production have been proposed such as power pools, larger and larger generators, and various hydro and nuclear schemes. Although the huge generators are very efficient, they are best adapted for high load factors and, therefore, the urgent problem of meeting peaking capacity has become extremely serious. Many investor-owned utilities have installed diesel, gas turbine, and stripped-down steam units to meet peaking demands, but these stop-gap measures operate at reduced efficiency and are costly to acquire and maintain.

All utilities must be prepared to meet the peaking load of their consumers instantly. To do this, there must be sufficient installed generating capacity to meet

1. The possibility that the consumer demand will be greater than anticipated.
2. The periodic withdrawal of generating equipment from service for inspection, repairs, and maintenance.
3. Unforeseen breakdowns of generating equipment.

The spare generating capacity is called *installed reserve*; and to provide this in sufficient quantity several investor-owned utilities may form an interconnected system throughout two or more adjacent states. Such an interconnected grid generally requires installed generating capacity that is about 10 to 15 per cent above the highest simultaneous consumer load expected in any single hour during the calendar year. Thus, at any given time, there are large sources of potential electric energy that must be kept readily available, and that can be used to generate energy for storage and use at a later period.

Thus, another solution was required to meet the pressing need—pumped storage.

Some historical background

It is of historical interest to note that Frazer W. Gay, an electrical engineer with the Public Service Electric and Gas Company received a patent on April 23, 1929, on a "method for load division in electric-power generation." This patent essentially incorporates all of the classic elements of a pure pumped-storage system.

To quote from the patent application, "... the hydroelectric generating station of this invention utilizes a high-level reservoir that may be conveniently located at a suitable height. . .such as upon a mountain. Water from the high-level reservoir is adapted to. . .operate the water turbines and then flows into a low-level reservoir...

"Motor-driven pumps, that are operated by turbine generators, are utilized to pump the water from the low-level reservoir back into the high-level reservoir for further use. . ."

Pumped-storage proposals have been reviewed numerous times by the investor-owned utilities in the United States, but little interest was shown over the years. Until the end of World War II, American electrical engineering experts gave little attention to the possibility of large-scale pumped-storage schemes. Yet today, American projects, either completed or under construction, vary in capacity from 8 to 2000 MW,[1] with projected capacities exceeding 11 000 MW.

The first major breakthrough for pumped-storage plants came in 1950, when the first reversible pump–turbine unit was designed in this country. In the decade between 1950 and 1960, six plants were either completed or projected, the largest of which is Taum Sauk—rated at 358 MW—built by the Union Electric Company of St. Louis. It went on the line in 1963.

And although the concept of pumped storage owes its existence to the requirements of more economical peaking power, it really attains its greatest value when it ultimately achieves the condition of almost pure *spinning reserve*. This term is analogous to a car engine when it is idling. A required percentage of rated capacity must be rolling on the line constantly to afford stand-by service that can instantaneously go on the line with both low unit kilowatt costs and very low fixed charges.

Pumped storage—and how it works

In its simplest application, a pumped-storage plant consists of two storage reservoirs, of approximately equal capacity, set at a high and a low elevation. The reservoirs are interconnected by a penstock, and a reversible generator–pump station is situated at the lower end of the

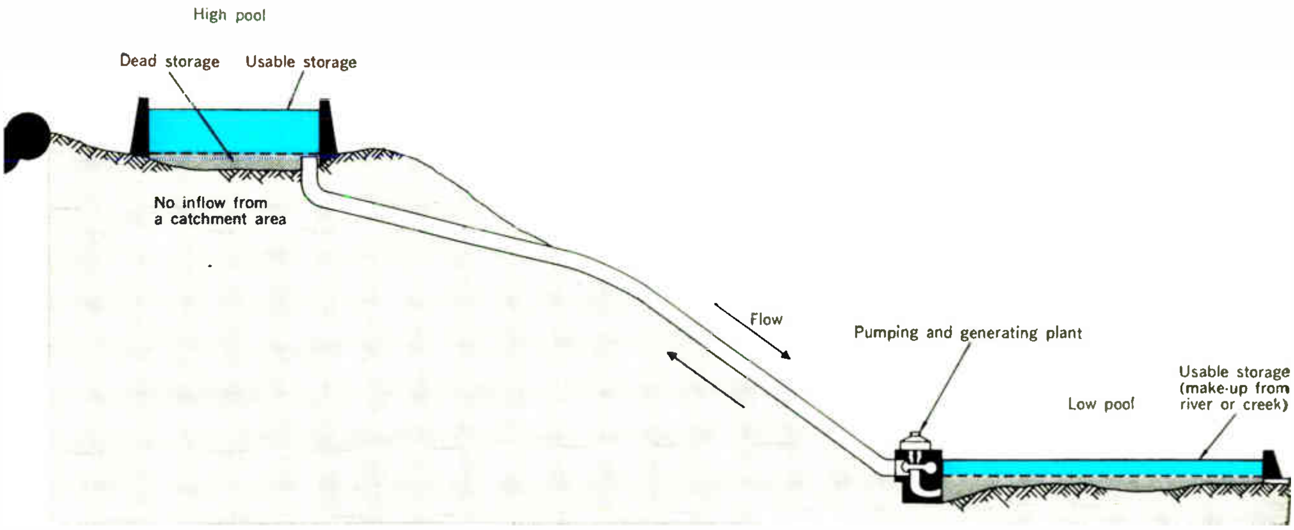


Fig. 1. Diagram of a pure pumped-storage system in which there are two reservoirs of approximately equal capacity, and no inflow from a catchment area to the high pool.

penstock (see Fig. 1). The high reservoir is usually an artificial pool that is formed by diked construction. The only hydraulic flow to fill the high reservoir is that produced by the pumping operation from the low pool or reservoir. Power for the pumping operation is supplied either by an on-site conventional steam–electric power plant, or through the transmission lines from a remote generating plant. The lower reservoir is generally formed by damming a small river or creek to obtain usable storage. The system just described is called the *recirculation type* of *pure* pumped storage.

In this installation, surplus thermal energy available during off-peak hours is utilized to pump water from the lower pool to the upper reservoir against a pressure head. This water is then used to generate energy during peak periods when it flows in the reverse direction through the turbines. Because of friction losses, the pumping head will be greater than the generating head. It is estimated that, on the average, 3 kWh of pumping energy are required to produce 2 kWh of generated energy by the pure pumped-storage concept.

In conventional generating stations, the generating plant must be kept on a stand-by basis during off-peak hours. Thus, the shorter the peak load period, the more expensive it is to generate the additional energy. Therefore, since the reserve generating equipment is available, it is more economical to use this equipment and the energy produced on a full-time basis to pump water—even though there is a one third loss in efficiency.

The basic factors having a direct bearing on the feasibility of a pure pumped-storage project are:

1. Low initial construction and equipment cost per unit of capacity.
2. A system of a practical size that is immediately economical when put on the line, and does not require future expansion potential to achieve this economy of operation.
3. A location reasonably near an existing transmission system for maximum reduction of capital costs of new transmission lines, and the reduction in capacity that results from losses in long transmission circuits.

Mixed pumping systems

In this classification of pumped storage, there are two categories, the *multiple-use* type and the *diversion* type.

Multiple-use pumped storage. As shown in Fig. 2, the multiple-use type differs from the recirculation type in several ways. First, there is a sizable runoff from an upland catchment area to form part of the inflow to the high reservoir, which increases the usable storage and peaking capacity potential available to the system. Then, the high reservoir must have a larger capacity than the low pool. The additional inflow is utilized conventionally through generating units located at the base of the dams for both the lower (run-of-the-river) pool and the downstream release. The additional energy generated by the natural inflow can offset or exceed the losses in the pumping cycle of the pure pumped-storage system. Therefore, the economic advantages of such pumping systems are increased when they can be combined with more conventional hydro power plants where energy can be generated by utilizing the inflow of a sizable catchment area. On some upland rivers a number of pumped-storage projects in series may be feasible to allow the use of the available storage through a greater hydrostatic head staging than would be possible with a single installation of this type.

Diversion-type pumped storage. Figure 3 is an example of the diversion-type plant, wherein water is pumped from a stream or river source against a relatively low-pressure head into an upper storage reservoir. From there the water flows through penstocks to another river through a high-pressure head. This type of installation does not require reversible pump–turbine units, unless the low-head pumping plant at the high stream elevation is also used for energy generation. The inflow to the high stream may be either from a catchment area or reservoir.

Pioneer pumped-storage plants in the United States

The first pumped-storage plant in the United States was the Rocky River plant of the Connecticut Light & Power Company, built in 1928. Its installed equipment consists of one conventional Kaplan-type turbine hydrogenerating unit, and two separate motor-driven pumping units. The turbine is rated at 33 000 hp (about 25 kW), and the pumps at 8100 hp (about 5.6 kW). Until 1950, when a pumped storage unit was installed at the Buchanan (Texas) Dam plant—rated at 7400 kW—Rocky River remained the only pumped-storage unit in the entire country. The four other plants, and their turbine ratings, constructed between 1950 and 1960 are: Flatiron, Colo., 9000 kW; Hiwassee, N.C.—part of the TVA system—59 000 kW; Tuscarora, N.Y., 250 000 kW; and Smith Mountain, Va., 143 000 kW. The Hiwassee plant, with a motor rated at 102 000 hp, was a major link in the chain of progress, and was the first turbine-pump unit installed for the primary purpose of leveling system load curves.

Feasibility factors for pumped storage

One of the prime considerations in feasibility factors for pumped-storage is the selection of a suitable site that will ensure a low cost per kilowatt of installed capacity. This is particularly important because the pumped-storage installation must compete with low-cost thermal peaking capacity.

The cost of dams, dikes, intakes, and other appurtenances is proportional to the amount of dynamic head developed. Also, short waterways between the upper and lower pools, and short transmission lines to load centers will further reduce both construction and operation costs.

The cost of pumping-generating equipment will be high for low-head projects when there is a considerable difference between the maximum head (upper pool full) and minimum head (upper pool empty). The submergence required to inhibit impeller cavitation and water hammer may substantially increase the excavation and overall power plant costs.

Paradoxically, the cost of the power plant and all other necessary appurtenances may be increased by a relatively small percentage in proportion to an increase in installed capacity. Thus, the larger the amount of installed capacity that can be justified for an installation, the less the cost per kilowatt will be.

A pumped-storage project can be built at any site where favorable natural topography and geologic conditions exist. And the available stream source need not be very large. The impounding of a small stream or creek with a small flow is sufficient to produce a sizable lower pool reservoir for a pure pumped-storage project. For example, the 300-acre lower pool and 45-acre auxiliary reservoir of the Yards Creek project in New Jersey—which will be discussed in detail later in this article—were formed in four months' time by damming Yards Creek, a stream whose average summer runoff is about 3 ft^3/s!

Because of the great progress in EHV, large blocks of power can be transmitted economically over fairly long distances. Therefore, in an area served by an interconnected grid system, the only important economic advantage of one site against another is the cost per kilowatt installed.

The cost for pumped storage varies over a considerable range—from about $80 to $114 per kilowatt, the variation depending, of course, upon the many factors just mentioned.

A proposed pumped-storage project requires thorough

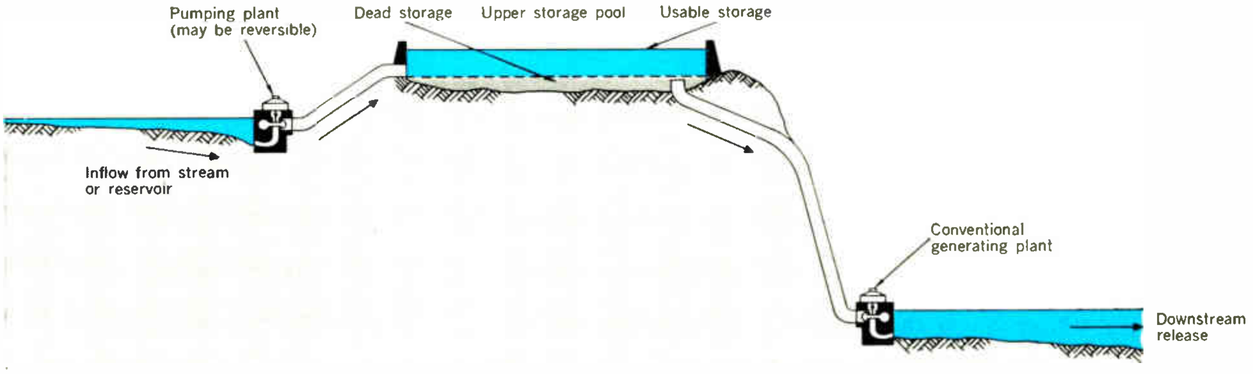
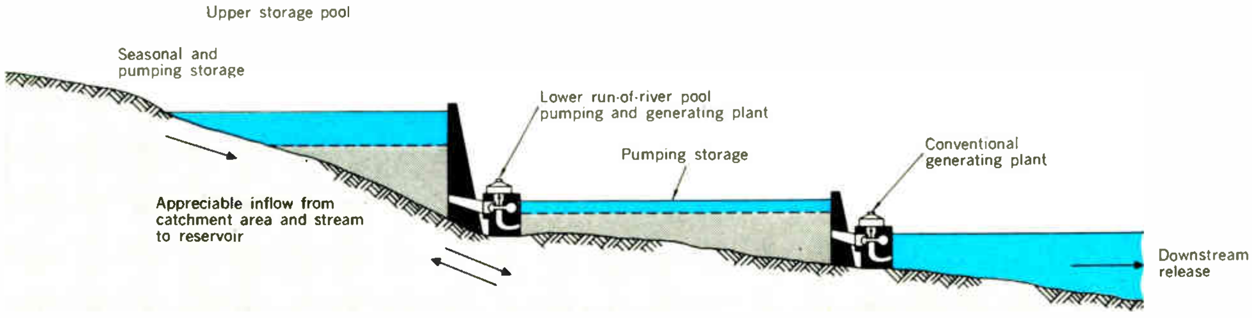


Fig. 2 (above). Schematic diagram of a mixed pumping system that consists of one storage pool, an inflow from a stream and catchment area, and a downstream release. Fig. 3 (below). Diagram of a diversionary pumped-storage scheme in which run-of-river hydro power generation is combined in the overall system.



study and investigation of many alternative plans, since for any potential site, the development plan, size of installation, and modes of operation depend upon the production costs, operational methods, and characteristics of the utility system the project will supplement.

The Taum Sauk plant

The largest pure pumped-storage hydro project completed to date in the United States is the 350 MW Taum Sauk plant of the Union Electric Company.[2] Situated about 90 miles southwest of St. Louis, Mo., the fully automated plant serves primarily for seasonal peaking and emergency reserve. Generating capacity of the Union Electric system is about 2500 MW and the capacity of the Illinois-Missouri pool is about 5000 MW.

Surveys and studies were initially directed to potential pumped-storage sites which were attractive either because of their proximity to the St. Louis area steam plants and load or because they offered an existing lower reservoir. These were all medium-head developments, however, and as the economics proved unfavorable, the search was extended farther afield to find topography yielding a high head. At a point 30 miles from the main transmission system, in the Ozark Mountains, a site was found that would provide an 800-foot head.

The general plan of the several appurtenances of the project is shown in Fig. 4. The lower pool utilizes a group of small streams, with a catchment area of about 87 square miles, whose confluence forms the East Fork of the Black River. A 390-foot-long concrete gravity dam, which rises about 60 feet above its footings (see Fig. 5 aerial view), impounds about 6000 acre-feet of water.

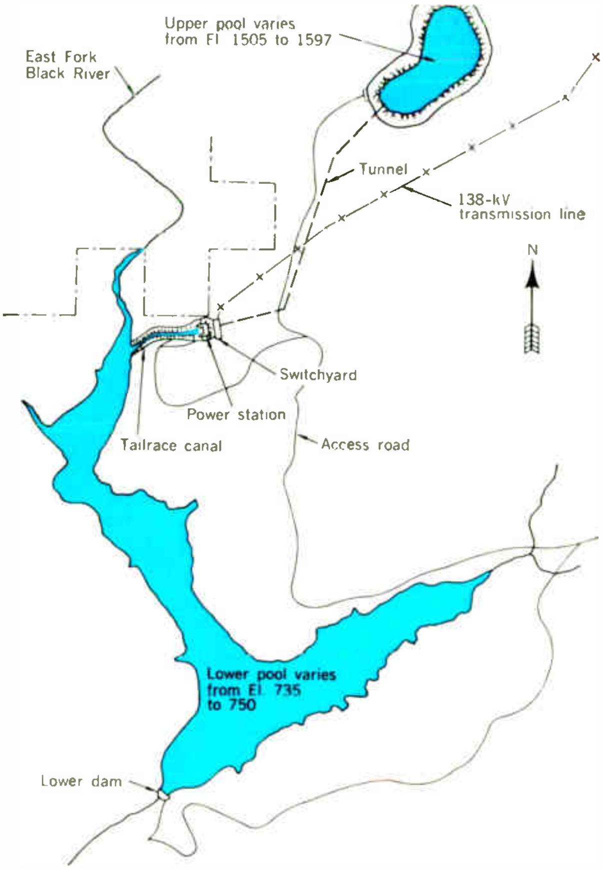
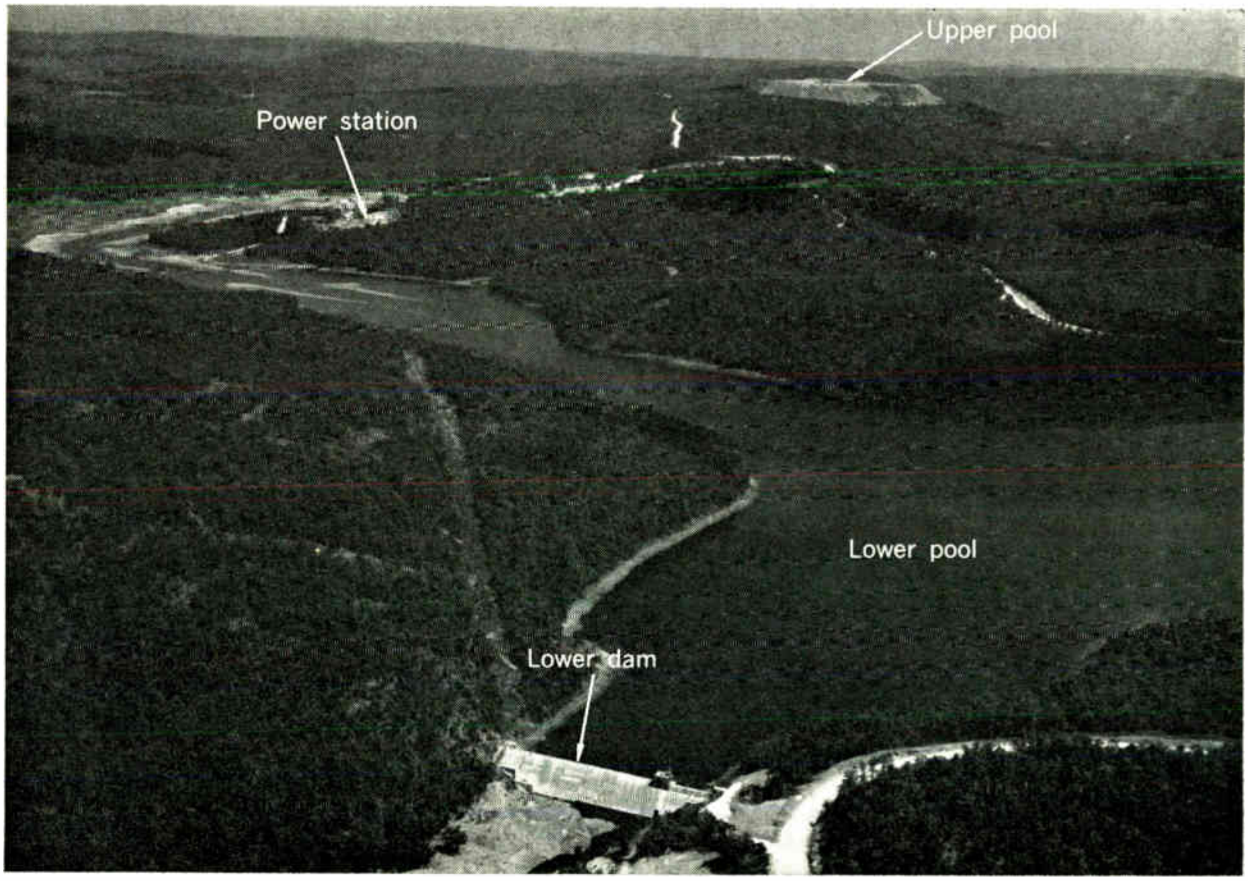
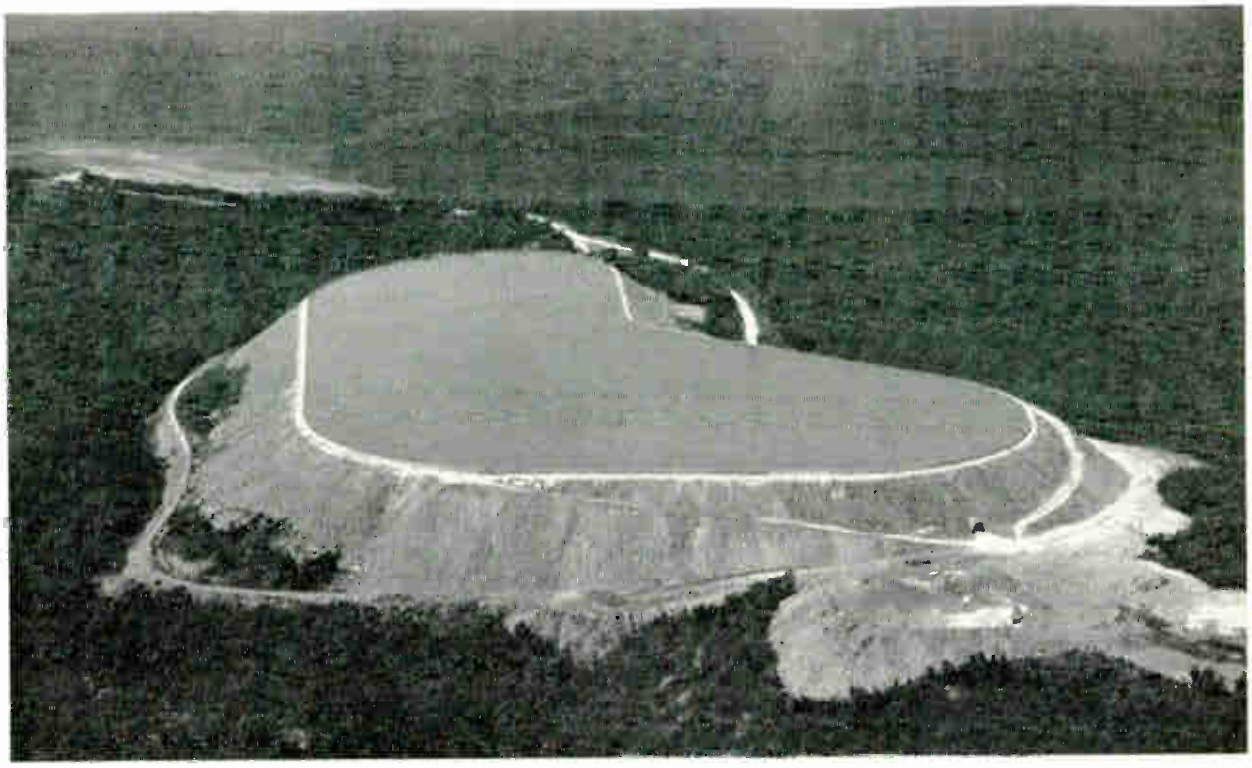
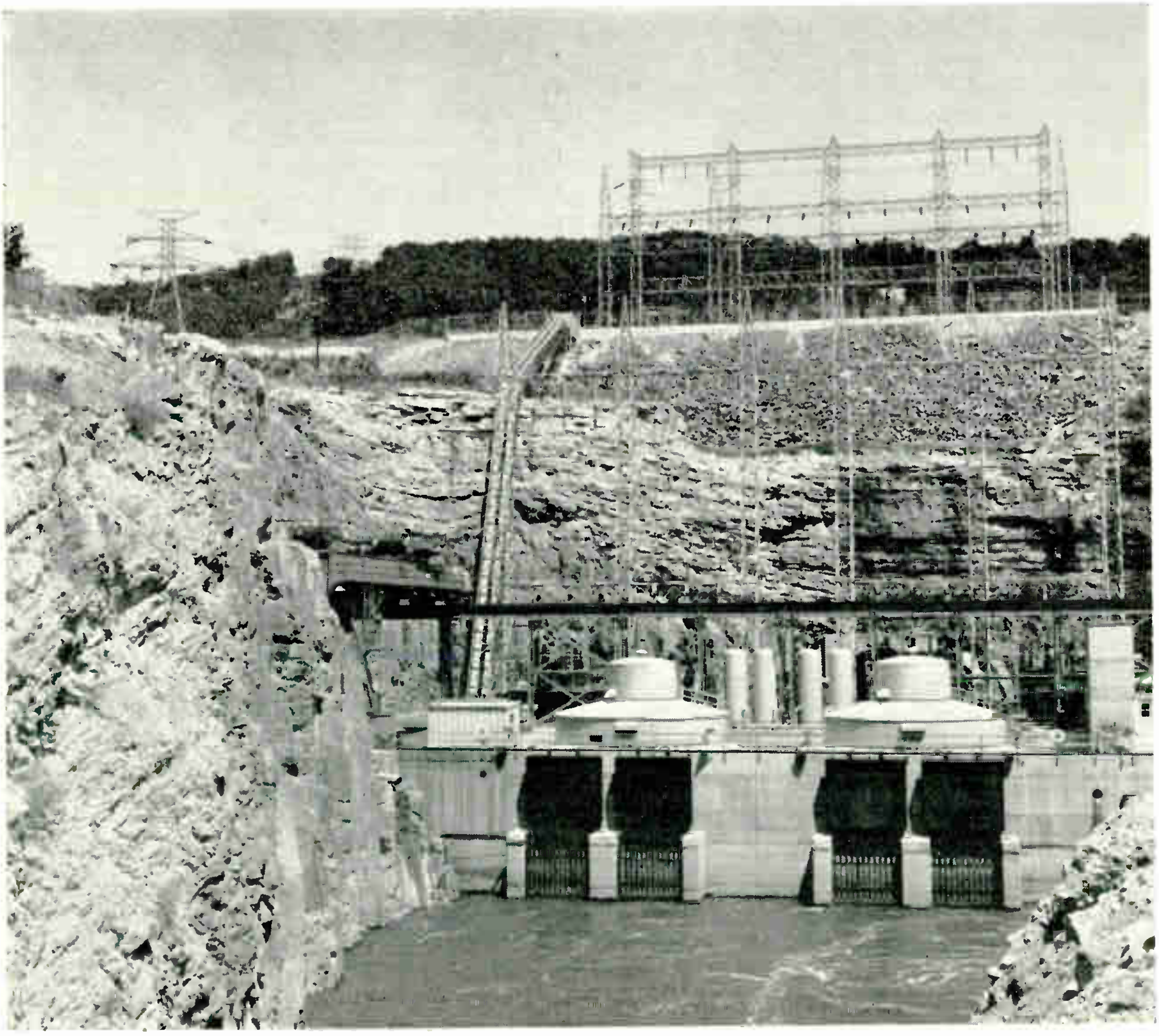


Fig. 4. (above). Map indicates the configuration of the principal elements and appurtenances in plan. Fig. 5 (below). Aerial oblique view shows the topographical features of the Taum Sauk project.





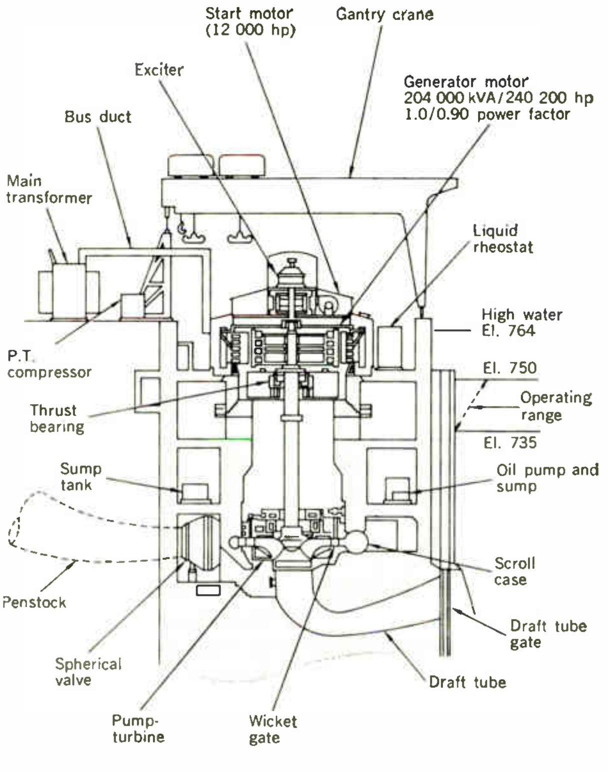


Some 4365 acre-feet of this water, lying between elevations 735 and 750 will be active storage. The dam is provided with one 8- by 10-foot sluice gate and one 20-inch-diameter sluiceway to regulate the downstream discharge. When the volume of water required to operate the system is in storage, the sluices are operated to maintain the combined volume of water in the working ranges of the upper and lower pools at a constant 4460 acre-feet. The sluice gates can handle practically all of the normal stream flow, but a 373-foot-long spillway is provided for discharge flows above the capacity of the sluiceways. The spillway and other appurtenances are designed to handle a maximum flow of 70 000 cubic feet per second—a volume equivalent to flash-flood proportions.

Fig. 6 (left top). Aerial view of the Taum Sauk upper reservoir shows the huge pool at maximum capacity.

Fig. 7 (left bottom). View of the Taum Sauk two-unit power station as seen from the tailrace canal. Note the huge volume of rock cut that was necessary for the construction.

Fig. 8 (below). Diagrammatic profile of the Taum Sauk project is shown together with an enlarged detail of a section through the power station.



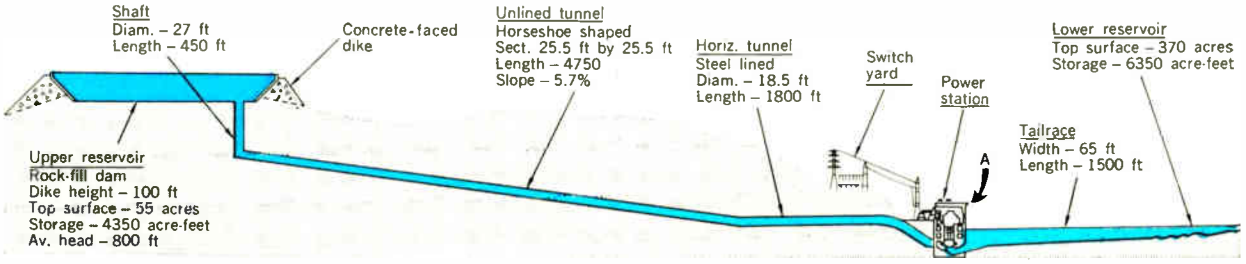
Detail **A**

As indicated in Fig. 4, a 1500-foot-long tailrace canal was excavated at the upstream end of the lower pool to the power station site, and a penstock and tunnel run from the power station to the upper pool. This reservoir is situated atop one of the high porphyry knobs that are characteristic of the Missouri Ozark geography. Rock for the dike that forms this reservoir was excavated from the site. The rock-fill dike encloses a pool that has a top surface area of 55 acres and a circumference of 6562 feet, and that rises 84 feet above the reservoir floor. The top width of the dike is about 12 feet, with natural repose slopes of rock—as dumped—of about 1 on 1.3. The inside of the dike is faced with a layer of reinforced concrete, of a 10-inch minimum thickness, and the floor of the pool is covered by a 4-inch layer of asphalt. Since the upper reservoir (see Fig. 6) has no tributary catchment area, a spillway is not necessary.

Each unit is connected by a leg of a 200-foot-long bifurcated penstock to the 25½- by 25½-foot tunnel. The lower 1800 feet of the tunnel is provided with a 18½-foot-diameter steel liner, as the rock cover alone is not sufficient to withstand the hydrostatic pressure. The liner is of high-strength steel for about three quarters of its length, and this achieved a considerable savings in fabrication and installation costs. The remainder of the tunnel is unlined and terminates at the bottom of a 431-foot-high vertical shaft that extends to the floor level of the upper pool. No headworks, or water flow control apparatus, are provided at the entrance to the shaft from the upper pool. For the infrequent inspection needed, or tunnel repairs, the upper reservoir will be drained.

The Taum Sauk generating plant (see Figs. 7 and 8) has two reversible pump–turbines, each with a rated capability of 175 MW. The dynamic pumping head varies from 764 to 875 feet. Each water wheel is served by a huge spherical inlet valve at the spiral-casing inlet of each unit. The pump impeller (turbine runner) must be deeply submerged to limit cavitation—particularly when the pump–turbine is operating in pumping mode. When starting the unit in pumping mode, compressed air is used to lower the water level in the draft tube so that the pump–turbine runner is unwatered and the starting motor can bring the unit to synchronous speed with minimum load resistance. The main unit is then synchronized with the system and full power is made available for pumping.

Total cost. The original total cost estimate for the project was $50 million, and this figure included $10 million for transmission costs. About $4.5 million of the latter



amount was the estimated requirement to link the plant to the electric system, and the remaining $5.5 million was the amount estimated for the advance installation of system ties. (These ties usually would not be required until two or three years after the completion of the project.) The transmission lines were built within the estimate, but the total cost of the project exceeded the estimate by 5 per cent—exclusive of interest incurred during construction in the prolonged period of testing and preliminary operation of the plant.

Operational statistics. Figure 9 shows the operating cycle of the pumped-storage plant when it is used entirely for peaking service. It will be noted that under full load the upper reservoir may be emptied in about 8 hours and can be restored in about 12½ hours. The expected performance of the two reversible pump–turbines in conjunction with the reservoirs is shown in the three performance graphs, Figs. 10, 11, and 12.

The Yards Creek—Kittatinny Mountain project

One of the largest pure pumped-storage projects now under construction is the Yards Creek power project at Kittatinny Mountain, adjacent to the Delaware River and near the Delaware Water Gap between New Jersey and Pennsylvania. The ultimate construction of three dams and six reservoirs on Yards Creek, the Delaware River, and its tributaries, will be achieved in three phases over a ten-year period. The facilities will be used jointly by the Public Service Electric and Gas Company, Jersey Central Power & Light Company, and the New Jersey Power & Light Company.

Last July, this writer had the privilege of visiting the construction site of the Yards Creek pumped-storage project with Morris D. Hooven, a former president of AIEE, and the consulting engineer for the Public Service Electric and Gas Company. This first phase of the mammoth power development project is about 65 per cent completed as of this writing, and two of the three pump–generator sets are scheduled to go on the line by the Spring of 1965. The three pump–generator units will have a rated capacity of 330 MW.

The scope of the first phase of building what might be called a "giant storage battery" will include an upper reservoir on Kittatinny Mountain (see Fig. 13), a lower reservoir on Yards Creek, and a small auxiliary reservoir for seasonal storage purposes. The lower reservoirs will be interconnected by a system of conduits and spillways.

The upper reservoir is situated in a natural fold or cup formation on the easterly slope of the Kittatinny Moun-

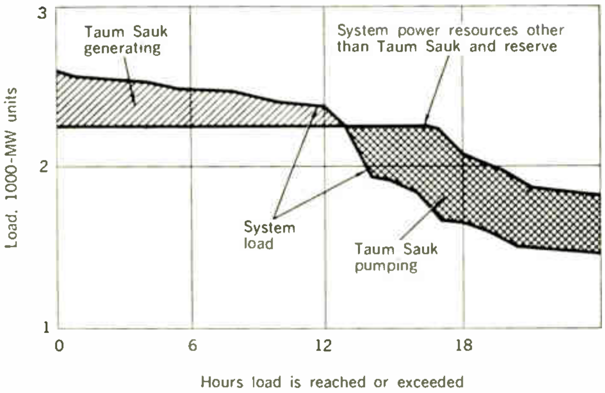


Fig. 9. Operating cycle of the Taum Sauk plant, when used exclusively for peaking service, is shown on the load duration curve.

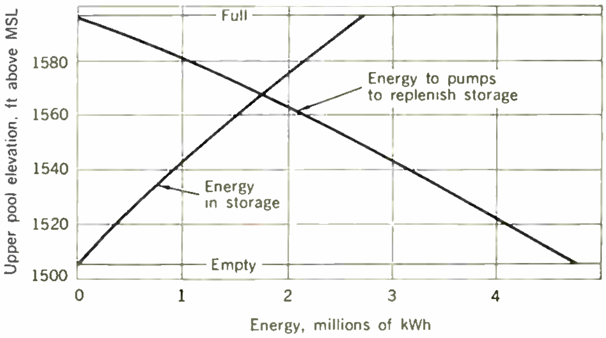


Fig. 11. Taum Sauk performance curves show upper pool elevation plotted against energy output in kilowatt-hours.

Fig. 10. Performance curves of the two reversible pump-turbines are shown, with upper pool elevation as the ordinate, and plant output or input as the abscissa.

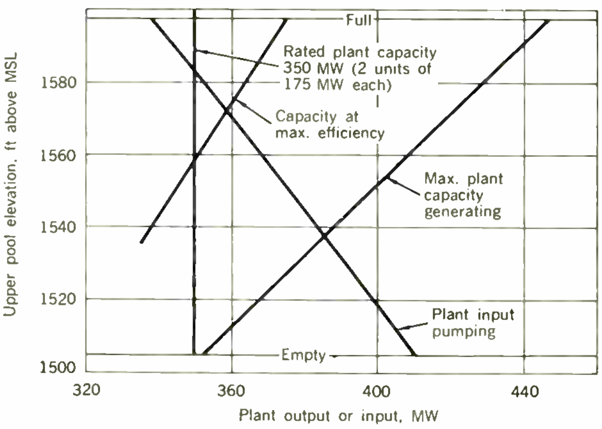
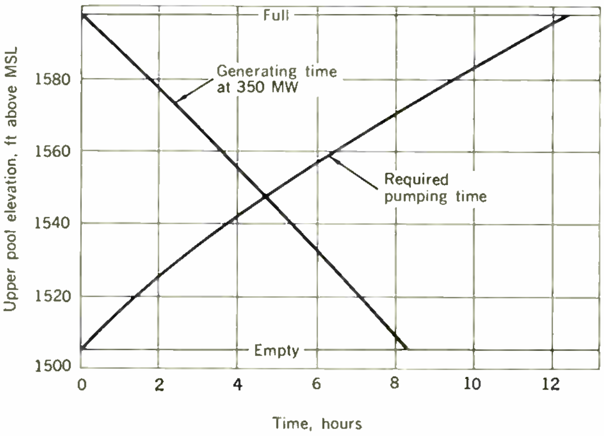


Fig. 12. Curves of generating time and pumping time are shown for the two pump–turbine units.



tain summit, and it will be enclosed by the construction of earth- and rock-fill dikes. This reservoir will have a water surface area, at maximum operating pond level, of 160 acres, and its invert will be at an elevation of 1560 feet above mean sea level (see Fig. 14).

The lower reservoir is impounded by an earth dam that is equipped with an outlet conduit and spillway for flood conditions, and it will cover an area of about 310 acres when at maximum operating level. The auxiliary reservoir, also located in the Yards Creek valley, is maintained to equalize the lower reservoir level, and to make up for water lost through evaporation and downstream releases.

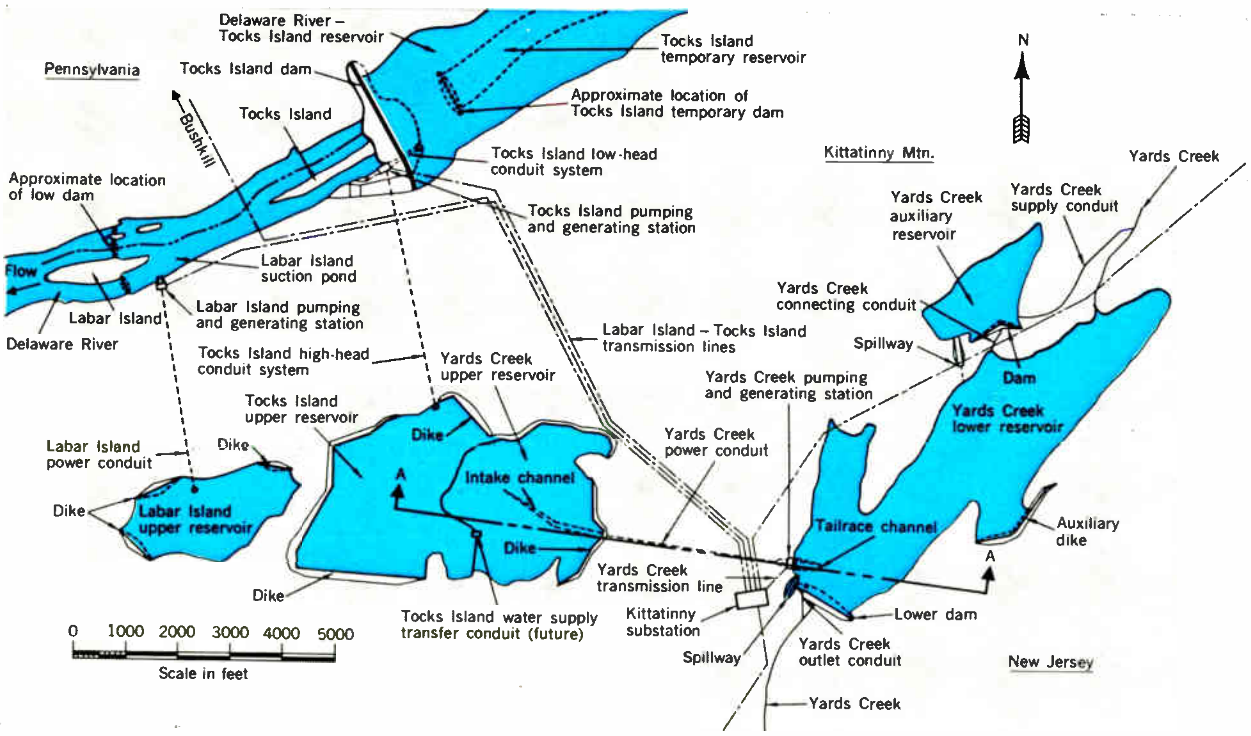
Interconnecting the upper and lower reservoirs will be accomplished by a concrete-lined tunnel, 20 feet in diameter, that has been blasted through the quartzite rock formation for a length of 1548 feet. Figure 15 shows the lower portal of this tunnel, where it joins the steel penstock. During the construction of this portion, 58 000 cubic yards of rock were excavated. The slope of the tunnel bore is 17 per cent (that is, the vertical drop is 17 feet for every horizontal run of 100 feet), and the lower 200 feet of its length, where the tunnel makes the transition into the penstock, will contain an interior steel liner.

An intake channel, leading into the tunnel forming the headworks—1500 feet long by 150 feet wide by 100 feet deep—was line-blasted through solid quartzite. Over 200 000 cubic yards of rock were excavated to form this channel and the entrance ramp to the pressure tunnel.

The single-conduit penstock (Fig. 16) is 19 feet in diameter at the upper end and necks down to 18 feet in diameter toward the bottom of its 2158-foot length. And the structural steel plating varies between 1 inch and 2 inches in thickness to withstand the tremendous pressure of the 750 feet of head. Just above the generating station, the penstock divides at a trifurcation branch into three penstock conduits, and then drops through three short rock tunnels to the three pump-turbine units.

The pumping and generating station is a multilevel

Fig. 13 (top). Comprehensive map indicates the scope of the three construction phases of the Kittatinny Mountain pumped-storage projects. Fig. 14 (bottom). Profile shows section through Yards Creek phase of the Kittatinny Mountain development.



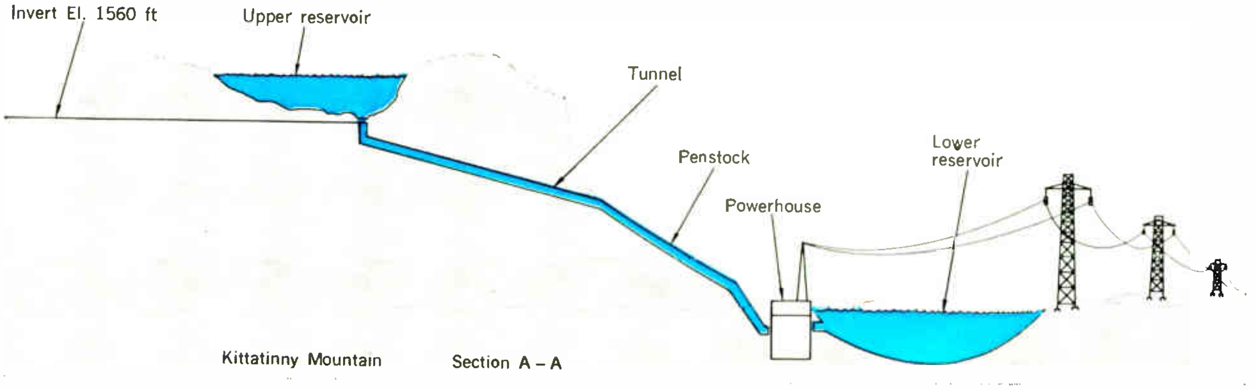
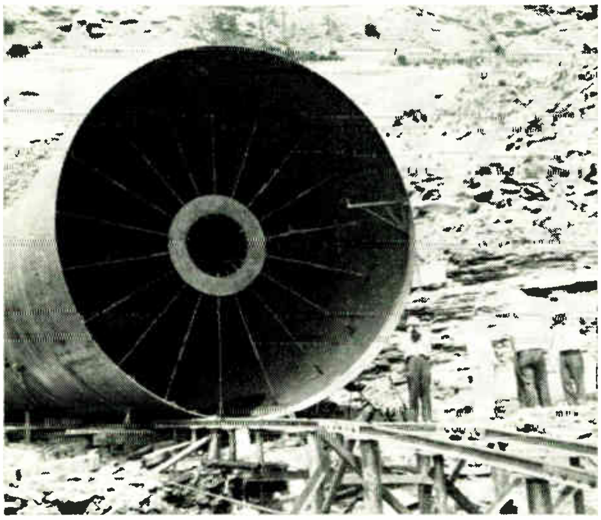
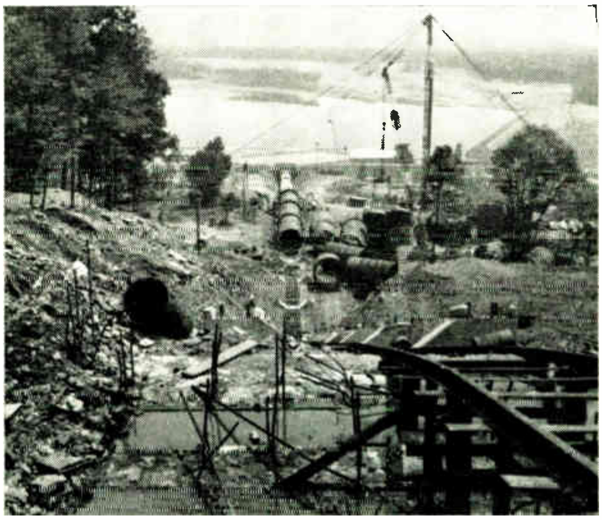


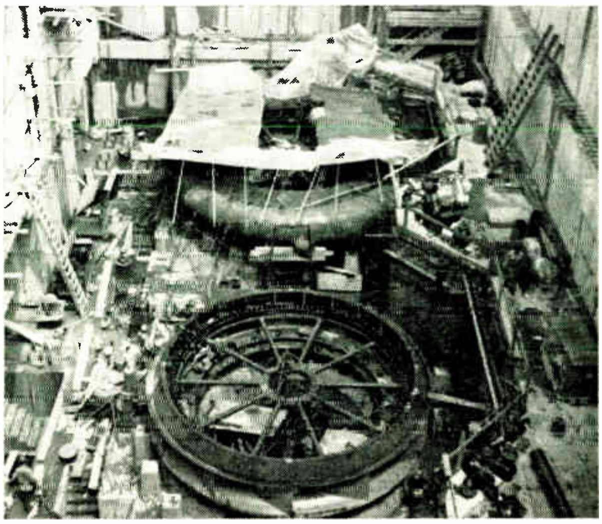
Fig. 15 (top). A section of the 19-foot-diameter steel penstock for the Yards Creek project is positioned during the construction operations.

Fig. 16 (middle). View of the penstock construction taken from the lower portal. Note the railway track used to erect and align the huge penstock sections.

Fig. 17 (bottom). Two of the three reversible pump–turbine units are shown being erected in the Yards Creek powerhouse. Each unit is rated at 110 MW.







reinforced concrete structure measuring 160 feet in length by 90 wide by 82 deep, and fills the excavation that was blasted from a solid-rock formation near the right abutment of the lower reservoir dam. This portion of the project required construction behind an earth- and rock-fill cofferdam. Presplitting blasting techniques were used by the construction contractor to assure clean splitting of the Martinsburg shale formations for both the power plant excavation and the formation of the tailrace canal.

The three reversible pump–turbine units (Fig. 17) for the power plant are each rated at 150 000 hp, at an operating head of 656 feet in the pumping mode. These vertical units, being fabricated by the Baldwin-Lima-Hamilton Corporation of Philadelphia, are the largest units of this type ever built for an eastern utility installation. The motor–generators were built by the General Electric Company, Schenectady, N.Y., and will have a rated capacity of 110 000 kW each in generating mode, and 186 000 hp when working as motors.

A huge 275-ton-capacity gantry crane, for the installation and removal of the pump–turbine and motor–generator units, rides on the roof of the generating station.

Ebasco Services Inc., of New York City are the consulting engineers for the design of the Yards Creek Project; Burns & Roe, Inc., are the construction managers; and the prime contractor is C. J. Langenfelder of Baltimore. The construction cost of this first phase of the three-phase ultimate development is $27.6 million.

The second phase. The three investor-owned utility companies presented their application to the Delaware River Basin Commission on July 17, 1963, for approval of the second construction phase. This phase includes the construction of two dams (as shown in Fig. 13), one of which—at Labar Island—would be permanent, and the other—at Tocks Island—would be temporary. The Tocks Island temporary reservoir would be impounded by the 10-foot-high temporary dam. This structure would be strategically located in the Delaware River to serve as a cofferdam for the ultimate construction of the permanent dam, which would be situated some 1300 feet downstream. The temporary reservoir would form an upper pool in the river for 3800 acre-feet of low-head storage.

The Labar Island suction pond, created by a low permanent dam, would form a reservoir containing space for about 500 acre-feet of water—400 for power storage and 100 for dead storage.

The Labar Island pumping and generating station will contain one reversible pump–turbine and motor–generator unit that has a rated capacity of 240 MW when generating and 350 000 hp when pumping.

The Labar Island upper reservoir will be formed by diking and damming the existing Sunfish Pond (see Fig. 13) to form a reservoir of approximately 4000 acre-feet of usable storage.

This scheme would involve pumping from the suction pond to the upper reservoir during off-peak periods, and the release of water from the upper reservoir for generating during on-peak periods. To maintain a required flow in the river at all times, releases would be made from the temporary Tocks Island reservoir during periods of pumping from the suction pond, and water would be stored behind the temporary dam at times when water is released into the suction pond for generating purposes.

Figure 18 shows the scope of the Labar Island pumped-storage project together with a cross section of the dam,

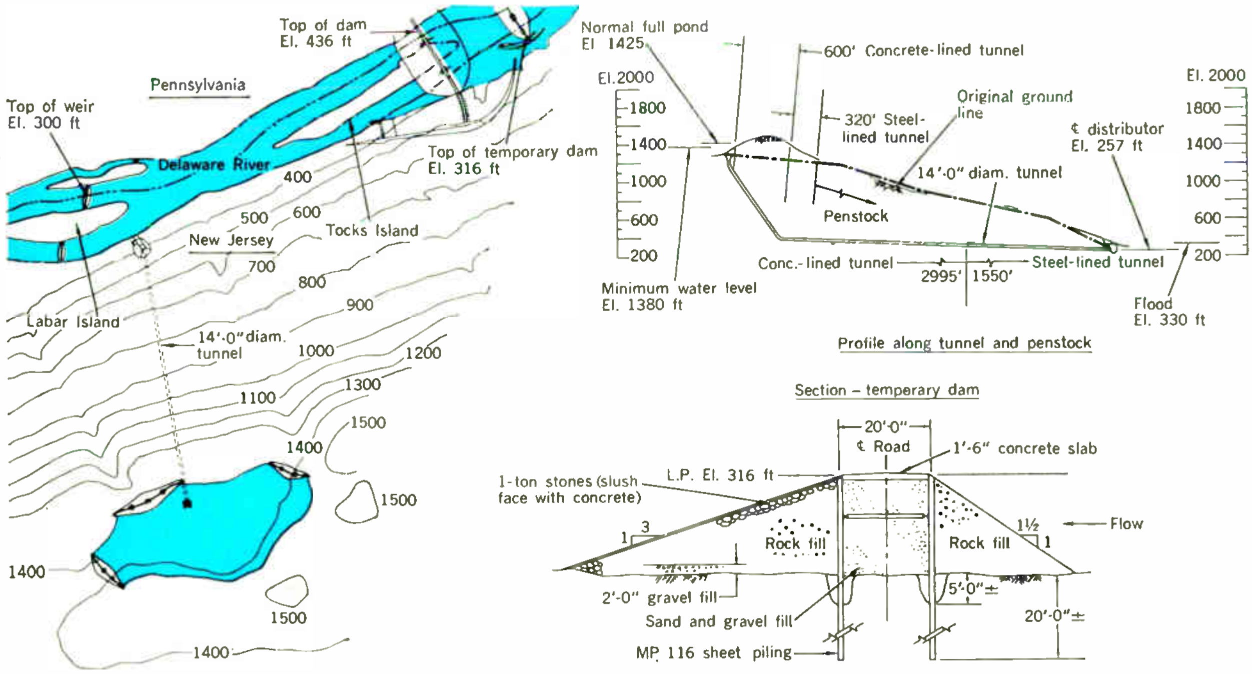


Fig. 18. The scope of the Labar Island (second phase) pumped-storage project is indicated in this design drawing. The Labar Island upper reservoir is at lower left.

and a profile along the tunnel and penstock.

Figures 19 and 20 are storage curve graphs for the Delaware River temporary reservoir and the Labar Island upper reservoir.

The third phase. In the third, or Tocks Island, phase of the project, a series of dams and dikes on the western slope of the Kittatinny Mountain summit will form the Tocks Island upper reservoir, with space for about 10 000 acre-feet of water storage. This reservoir would be formed along its eastern perimeter by a common dike with the Yards Creek upper reservoir. Ultimately, the two reservoirs would be arranged for interconnection so that they could be used jointly for the water supply purposes of the State of New Jersey as needed.

The *pièce de résistance*, however, of this phase of the overall project will be the construction of the Tocks Island dam (see Fig. 21). This earth- and rock-fill structure would be 3200 feet long, rising 160 feet above the river bed. A 472-foot-wide, gated concrete spillway, capable of passing a design flood flow of 300 000 ft^3/s, would be cut into the New Jersey abutment. This spillway would have a concrete crest surmounted by ten radial gates each 40 feet long by 33 high.

The reservoir from minimum elevation 356 to elevation 410 will provide 410 000 acre-feet of long-term, or active, storage for water supply, power, and recreation use. Short-term storage of 275 000 acre-feet will be available for flood control between elevation 410 and elevation 428.

Fig. 19. Storage curve graph is plotted for the Labar Island project in operation with temporary dam.

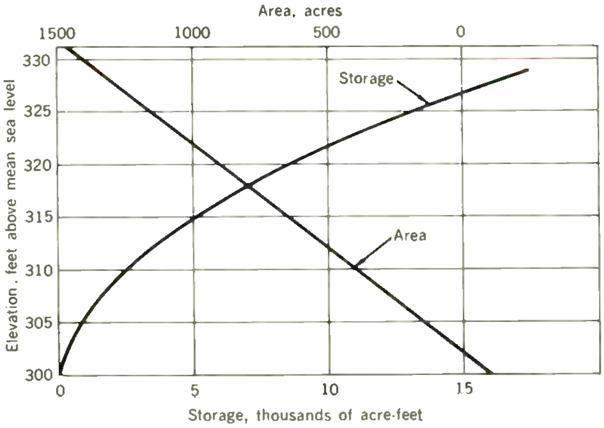
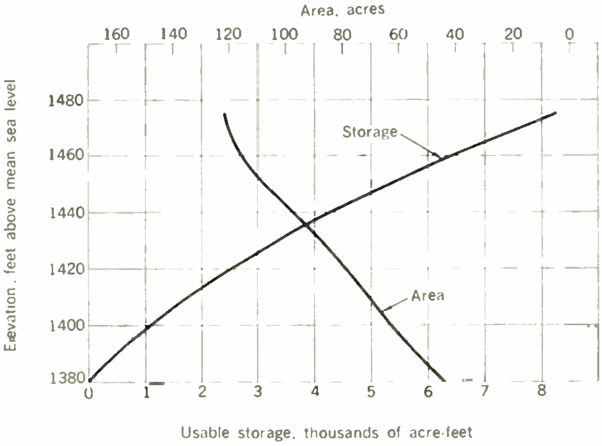


Fig. 20. Similar storage curve graph is shown plotted for the Labar Island upper reservoir.



Also in this phase, the Tocks Island pumping and generating station will be built. The proposed facility will contain three reversible pump–generator units, each having a rated capacity of 250 MW in the generating mode, and 420 000 hp in the pumping mode, for a total additional capacity of 750 MW. A single conventional hydroelectric turbine and generator installation would have little capacity value, but it would be included in the station for making releases into the suction pond to compensate for withdrawals from the pond when pumping occurs during off-peak periods.

Essentially, the Tocks Island project will eventually function both as a pure pumped-storage and a mixed-pumping diversion-type generating plant. The power station will operate in generating mode both as a run-of-the-river hydro plant through a low-head conduit system from the Delaware River water impounded behind the Tocks Island dam, and through a high-head conduit system from the Tocks Island upper reservoir (see Fig. 13).

To complete the project, the Tocks Island and Labar Island conduit systems would tie together and interconnect the various reservoirs and pumping–generating stations. Also, a tie will be made with the Yards Creek upper reservoir to permit New Jersey to divert Delaware River water for purposes other than power production. The Labar Island–Tocks Island transmission lines will involve two or more 230 000-volt transmission lines along a single right of way that extends from the Labar Island power station via the Tocks Island station to a terminal in the Kittatinny substation.

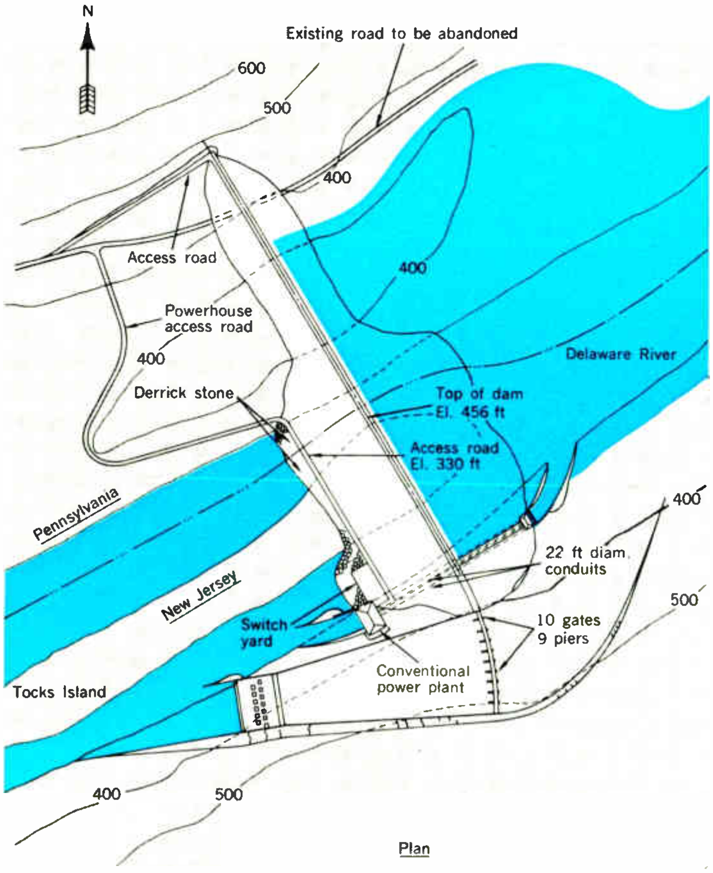


Fig. 21. U.S. Army Corps of Engineers' plan for the proposed Tocks Island dam includes a conventional power plant, gated spillway, and other appurtenances.

The New Jersey electric utilities expect to utilize the peaking capacity that will be generated by the Labar Island pumping and generating station as early as 1967, and the Tocks Island phase may be completed by 1974.

The second- and third-phase projects, when completed, will provide an additional 990 MW, for a grand total of over 1200 MW.

The schematic diagram (Fig. 22) indicates the gross heads under which the pumped-storage power generation schemes will operate when all three phases (Yards Creek, Labar Island, and Tocks Island) are completed.

As an indication of the relative economy of pumped-storage plant construction, the Delaware River Basin Report estimates that the cost of a conventional steam–electric plant, with 20 000 kW of dependable capacity, would cost $21.5 million—or $1075 per kilowatt of dependable capacity. The New Jersey utilities' second- and third-phase pumped-storage projects, with a dependable capacity of 990 MW, to be built at an estimated cost of $80 million, would provide power at a unit cost of about $81 per kilowatt.

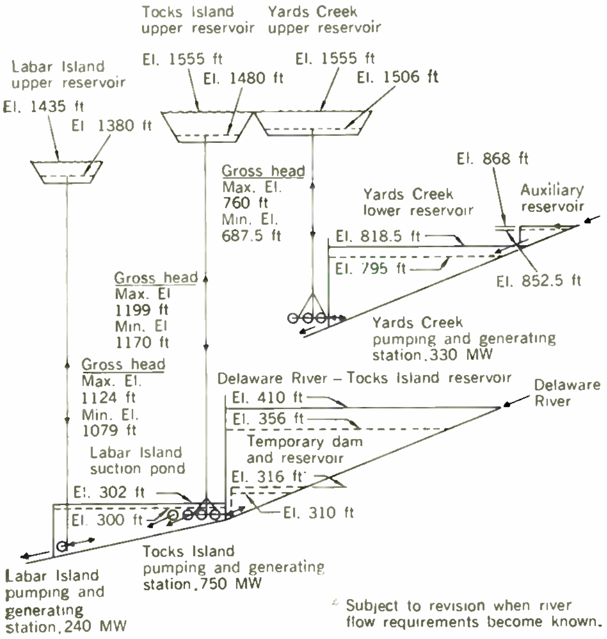
Ebasco Services Inc. are the consulting engineers for the design of the second and third phases of the overall project. The U.S. Army Corps of Engineers, however, will design and build the Tocks Island dam.

Con Edison's Cornwall project

The proposed pure pumped-storage project to be built by the Consolidated Edison Company of New York, Inc., at Cornwall-on-Hudson, about 50 miles above Manhattan, will probably be the largest hydroelectric installation of this type in the United States.

Essentially, the project will be situated adjacent to the west shore of the Hudson River, in the immediate vicinity

Fig. 22. Schematic diagram indicates the gross heads under which all three phases of the Kittatinny Mountain projects will operate.



of one of the highest promontories in the area, the famous Storm King Mountain. The installation will consist of eight pump turbine generator sets rated at a normal output of 225 MW each, and with a maximum capacity of 250 MW each at an average net head of 1050 feet between the upper and lower pools. The first unit will go on the line about three years after construction is commenced, with a target date for all eight units on the line one year later.

Upper reservoir dams. An upper storage pool will be situated in a natural basin about a mile south of the Storm King Mountain summit (see Fig. 23). Five dumped rock-fill, rolled earth-fill core-type dams will be required to dike the basin and create a reservoir of approximately 25 000-acre-foot capacity, with a surface area of about 240 acres. Between the dams, natural embankments and declivities will contain the usable storage. The combined length of the dams will be about 5000 feet, and the highest, from foundation to crest, will be about 270 feet. The crest elevation will be at 1170 feet above mean sea level.

Intake and pressure tunnel. An ungated circular-weir intake of the "morning glory" type will be located at the bottom of the upper reservoir, and will lead to a 40-foot-diameter concrete-lined pressure tunnel (see Figs. 24 and 25) that will run about 10 000 feet north from this pool to the power station. A concrete-lined manifold, under a 600-foot solid rock cover to ensure the cancellation of all pressure stresses caused by the superimposed weight of the rock, effects the transition from the pressure tunnel to eight individual penstocks (Fig. 26). From the tunnel intercept, each penstock measures 14 feet in diameter. Their construction will be as shown in the Fig. 24 sections. At the southerly side of the switchyard, the penstock diameters will be throttled down to 10 feet, and each will lead to a 96-inch oil-operated spherical valve at the scroll-case entrance.

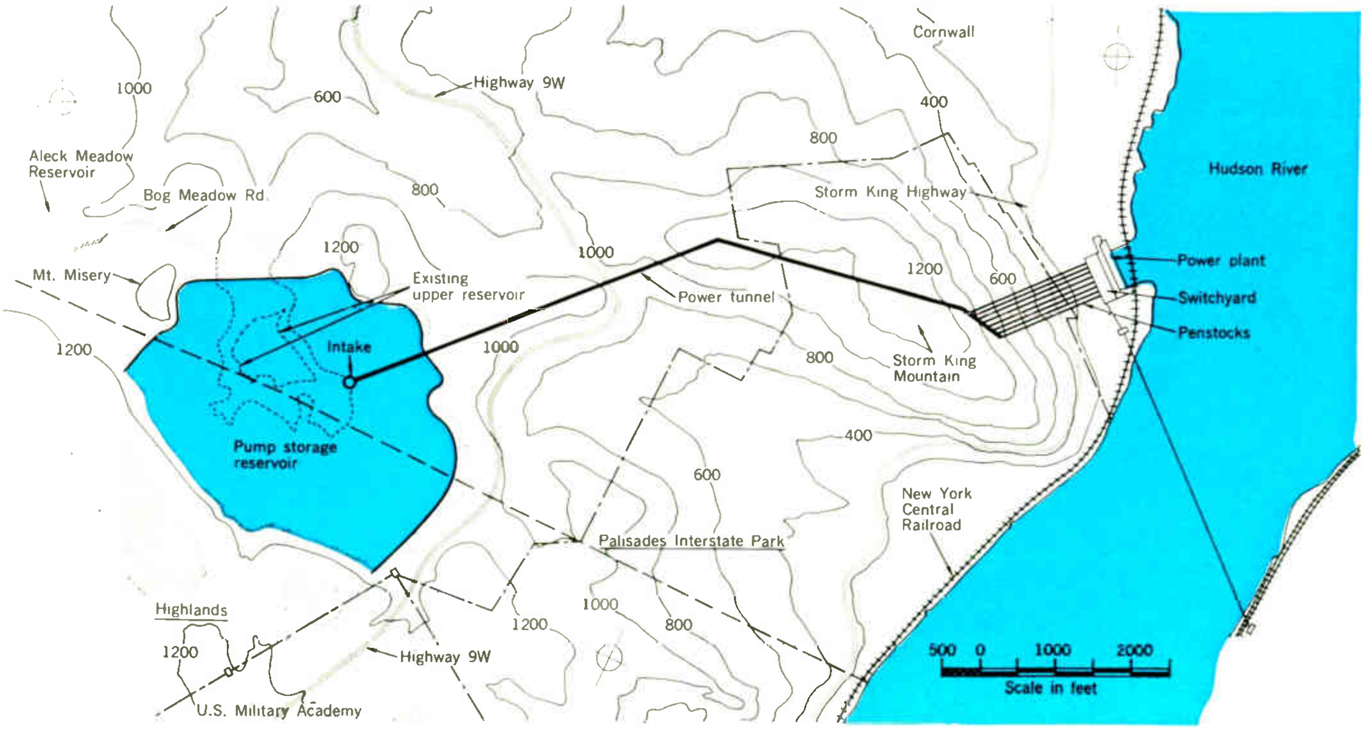
Power station and substation. As indicated in Fig. 25, a pumping–generating plant of the semioutdoor type, with units located below the upper deck level of the reinforced concrete substructure, will be constructed to house eight motor–generator, pump–turbine units. The Francis type pump–turbines will each have a pumping capacity of 2550 ft^3/s at 1020 feet of dynamic head, and will require 350 000 hp. Phase-reversing switches will be placed in the galleries between the generators and the transformers. Circuit breakers, switchgear, and busses will be located south of the station at about elevation 115, terraced into the hillside.

To provide adequate insurance against cavitation during the pumping cycle, the center line of distributor will be set at elevation −50.0. Thus the setting required to inhibit cavitation during this cycle is much lower than that normally required on the generating cycle. A compressed air system will be provided to depress the tail water, and thus facilitate starting by limiting the inrush surge as the pumps are gradually accelerated to synchronous speed before the wicket gates are opened to absorb the pumping load.

Tailrace. An open tailrace will be excavated in rock immediately outstream of the draft tube tunnel extensions (see Fig. 26), and will terminate in the Hudson River—the body of water that functions as the natural lower reservoir and water supply to the project.

Transmission. The power plant will be connected to Con Edison's electric system by two 345-kV transmission circuits that will cross the Hudson River in a pipe-type submarine cable crossing, and from there power will be carried by pipe-type circuits for a distance of approximately 1.6 miles to the Cornwall East switching station; then by overhead transmission to Con Edison's Millwood substation in Westchester County. Here, they will be connected to two existing circuits to be rebuilt for 345-kv

Fig. 23. Comprehensive site plan indicates the overall scope of Con Edison's Cornwall project.



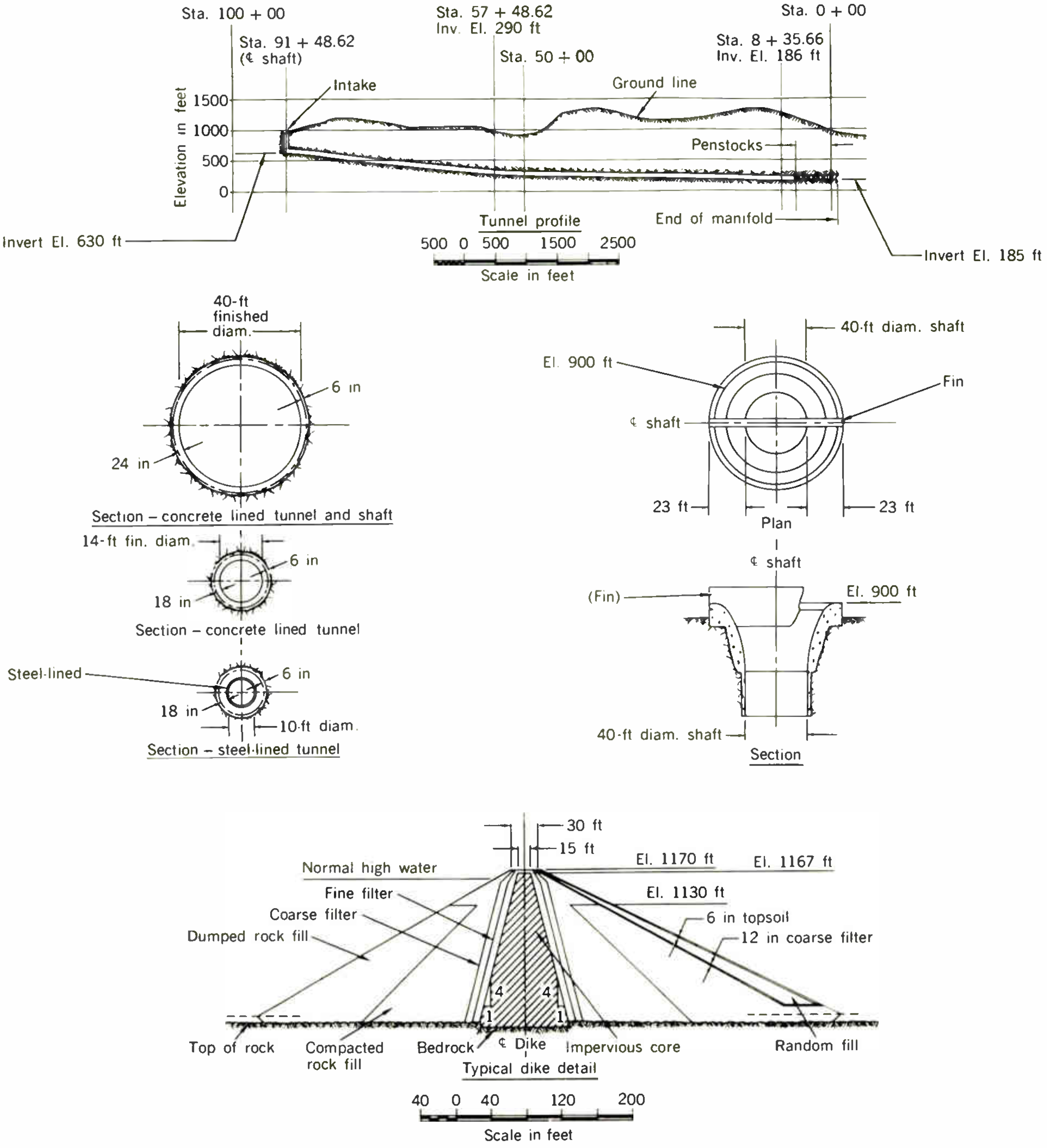


Fig. 24. Sections and details are shown for the proposed Cornwall pumped-storage development.

operation. These circuits run south to the new Sprain Brook substation in Yonkers.

Generator motors. Eight 3-phase, 60-cycle generator motors will be installed initially, each having a continuous rating of 258 MVA at 60°C temperature rise. Each generator–motor will be provided with a direct-connected starting motor of the wound-rotor induction type, capable of accelerating the generator–motor from standstill to synchronous speed, with tail water depressed, in about 10 minutes.

Gantry crane. For installation, maintenance, and servicing operations of the pump–turbines, generator–motors, penstock valves, and draft tubes, an electric traveling gantry crane of 750-ton-capacity will be provided.

Control and modes of operation. Normally, the units will be started in automatic sequence by remote control from Indian Point, some 15 miles away. There will also be conventional manual control from local control boards. To facilitate testing and maintenance of the control circuits and equipment, each unit will also have complete automatic control on its unit control board—thereby duplicating the remote arrangement. On each control board there will be a master control selector switch, together with the necessary master relays for four modes of unit operation: PUMPING, GENERATING and two modes of SPINNING (pumping or generating). The master selector switch will have three positions: LOCAL MANUAL, LOCAL AUTOMATIC, and REMOTE AUTOMATIC.

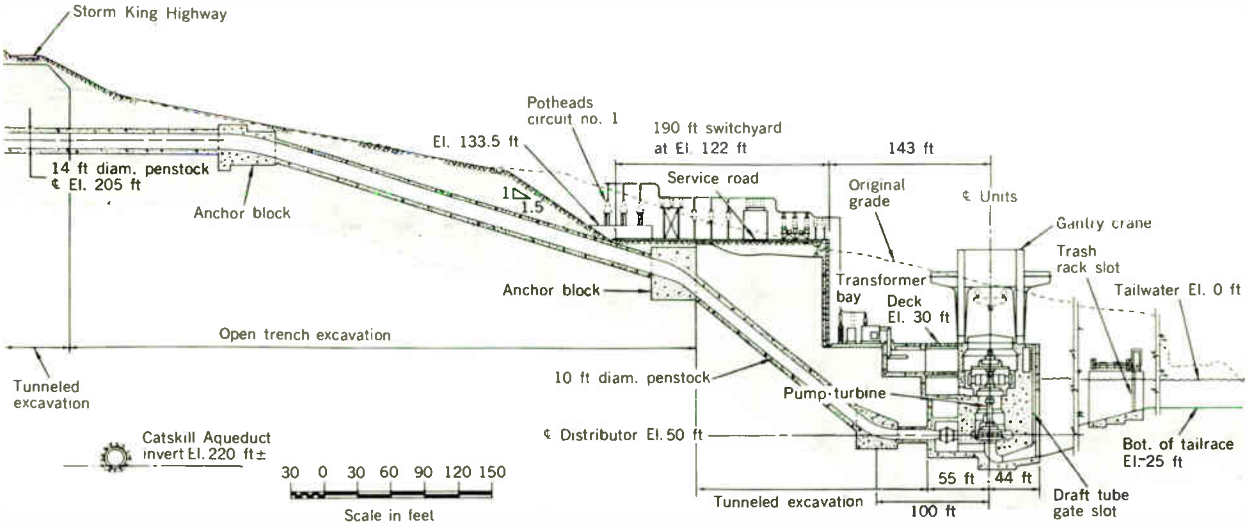
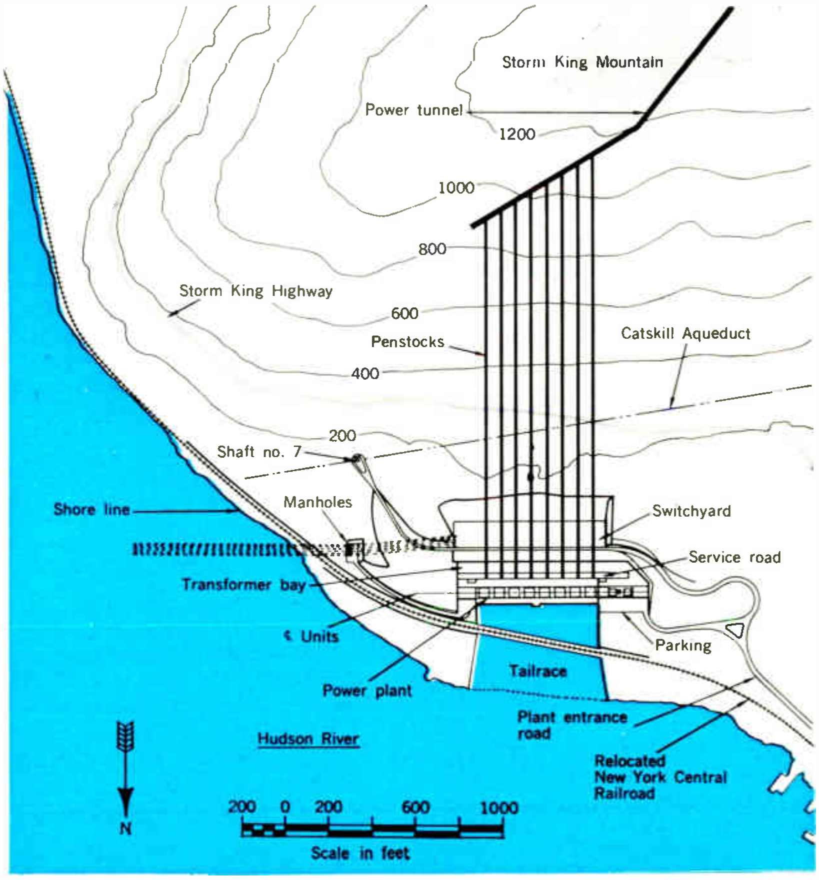


Fig. 25 (above). Cross section of typical penstock and pump–turbine unit at Cornwall. Note the amount of cut necessary from original grade for the construction of the power station.

Fig. 26. Plan view shows the concrete-lined power tunnel and its transition into eight individual penstocks that will serve each of the eight power-generating units.



The economic evaluation of Cornwall

An economic evaluation of the project has been made by comparison with the costs of a conventional single-reheat thermal plant of the same capacity installed in New York City. The cost of such a thermal plant of 1800-MW capacity is estimated at $225 million—or $125/kW.

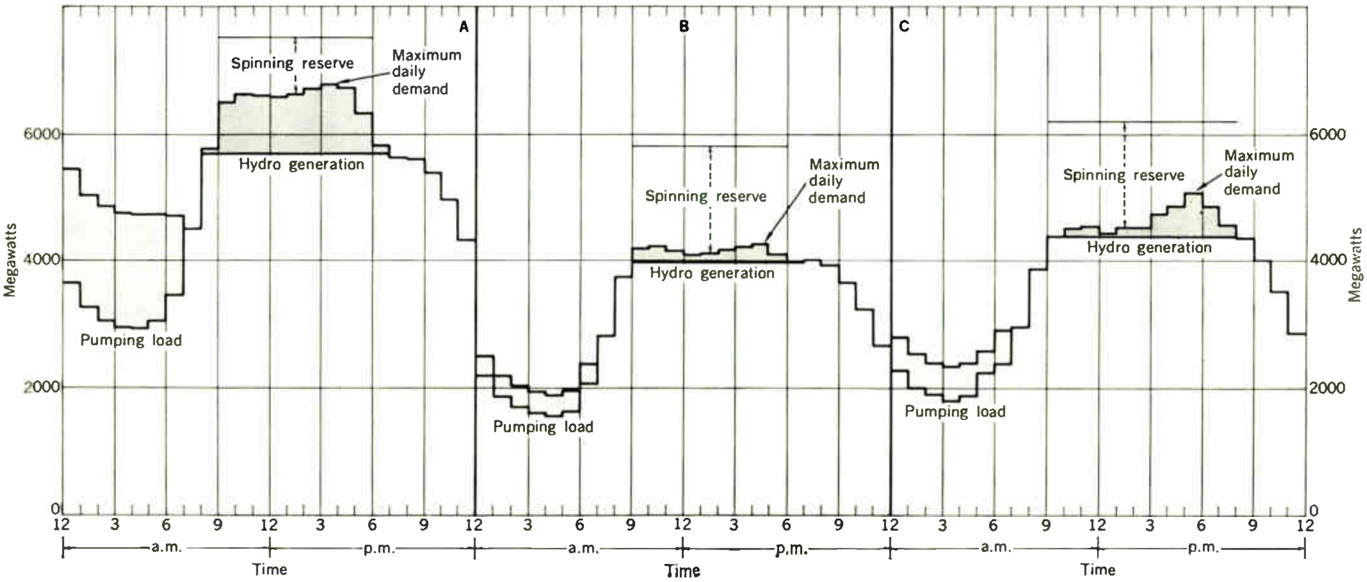
In the relative evaluation of a pumped-storage and a thermal plant, it should be recognized that the former is a peak load facility with generation limited to peak load periods. Generation for the Cornwall project has been estimated at 650 000 MWh for a typical year, and results in an annual capacity factor of 4.1 per cent. The comparable thermal plant, however, would supply initially both base load and peak load energy, and is estimated to have a generated output of 10 650 000 MWh, with an annual capacity factor of 67.5 per cent. For comparison, therefore, the thermal plant is credited with the fuel replacement cost for base load generation of 10 000 000 MWh at a system fuel cost of approximately 3.4 mills/kWh.

Operation and maintenance expenses for the project have been estimated on the basis of labor requirements for completely automatic operation and maintenance experience as reported for other hydro projects. The operation and maintenance expenses for the thermal plant are based on Con Edison's experience with existing modern plants.

I. Economic evaluation of pumped storage vs. conventional steam reheat plant

	Reheat Plant		Cornwall Plant	
Installed capacity, MW		1800		1800
Number of units		2		8
Plant investment, millions of $				
Generation		225.000		129.400
Transmission				32.020
Total		225.000		161.420
Total per kW		0.125		0.090
Annual generation (10^6 kWh)				
Peak load		650		650
Base load		10 000		
Total		10 650		650
Annual capacity factor (per cent)		67.5		4.1
Annual fixed charge rates (per cent)				
Generating plant		13.35		10.90
Transmission plant				11.35
Annual costs	Total, millions of $	Per kW-yr	Total, millions of $	Per kW-yr
Fixed charges				
Generating plant	30.038	$16.69	14.105	$7.84
Transmission plant			3.634	2.02
Total	$30.038	$16.69	17.739	$9.86
Fuel	29.522	16.40	2.509	1.39
Operation and maintenance	4.950	2.75	1.830	1.02
Total	64.510	$35.84	22.078	$12.27
Credit to reheat unit				
Replacement for base load generation	—34.240	—19.02		
Net cost of 1800 MW capacity and peak load generation	30.270	$16.82	22.078	$12.27
Differential annual cost in favor of Cornwall plant			8.192	$4.55

Fig. 27. A—Graph shows operation of Cornwall pumped-storage plant during maximum summer weekday in 1968. B—Shows operation of plant during minimum summer weekday in 1968. C—Indicates operation at Cornwall on a typical December weekday in 1968.



The cost of pumping energy is estimated on the basis of supply from Con Edison's thermal plants at an approximate incremental cost of 2.6 mills/kWh—which is equivalent to about 3.9 mills/kWh of hydro generation.

The economic comparison of the project and an equivalent thermal plant is given in Table I. This comparison indicates an economic advantage for the pumped-storage project of $8.192 million per year, or $4.55/kW per year.

The anticipated operation of Cornwall under normal conditions is illustrated in Fig. 27. The graphs show normal generating and pumping cycles, and the spinning reserve available on typical days in 1968 (the year that the project is expected to be in operation). The spinning reserve indicated is on the basis of the name-plate rating of 1800 MW. The pumping cycles shown provide for the restoration of water storage to maximum level each night, with pumping limited to seven nocturnal hours. Energy for pumping will be provided by Con Edison system thermal plants, or by purchase from interconnected grids.

Week-end pumping is not anticipated under normal operating conditions. Such pumping will be required only when the project generating and reservoir drawdown is greater than the amount that can be restored by pumping during the following night—a condition that might occur during periods of forced outage of capacity. This is illustrated by the Fig. 28 graph, which is based on the following contingency conditions:

1. Loss of the largest unit (through mechanical failure, routine maintenance, or repair servicing) on Monday before 8:00 a.m.
2. Placing in service a unit to provide, on cold standby, spinning reserve capacity equal to the next largest unit, on Tuesday.
3. The largest unit unavailable for the entire week.
4. Support from interconnected systems unavailable.
5. The avoidance of load decrease by voltage reduction or other means.

The generating–pumping cycles shown in Fig. 28 are based on the preliminary performance curves shown in Fig. 29. These curves, however, indicate that the 25 000 acre-feet of water storage provided by the project will be adequate to meet the system requirements under contingency conditions without assistance from the interconnected grid.

The total cost of the Cornwall project, including additional transmission facilities, has been estimated at $161.42 million, or $89.70 per kilowatt of name-plate capacity.

Other major pumped-storage projects

Niagara power project. One of the largest and most unusual pumped-storage projects, operating on both a run-of-the-river hydro basis and a pure pumped-storage basis, is the Robert Moses Niagara power plant.

Operation of this vast hydro complex without a dam[3] is possible because the Niagara River draws its water from the huge tributary area of the Great Lakes, which forms the world's best reservoir. The Great Lakes feed the rivers so uniformly that the maximum seasonal flow is only about twice the minimum flow. On some of our great rivers this ratio of maximum to minimum flows is as high as 35 to 1.

As shown in the Fig. 30 map, maximum power is obtained from the Upper Niagara River by diverting the

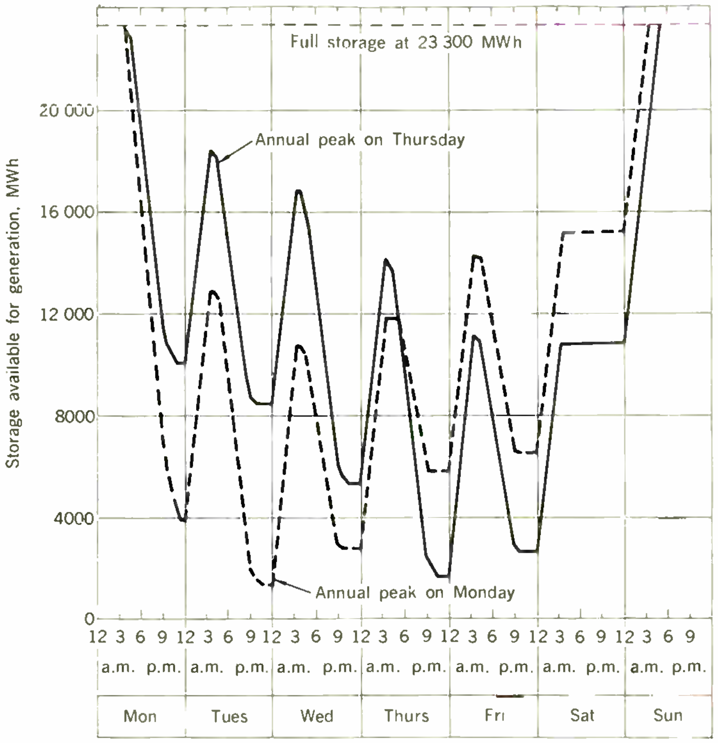
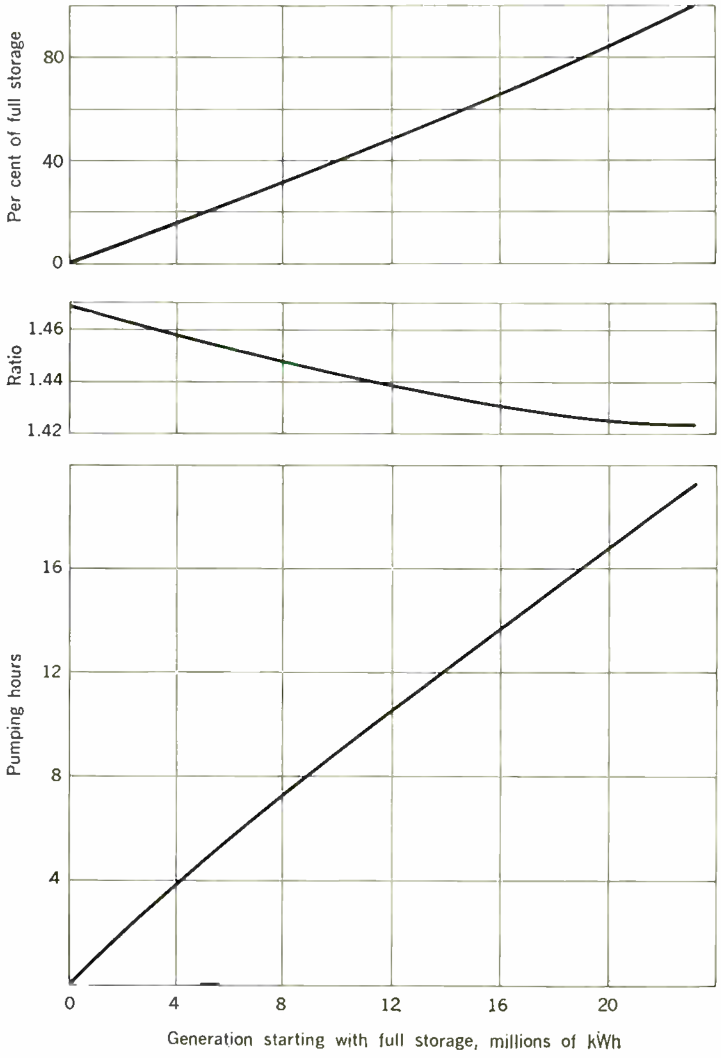


Fig. 28 (above). Graph shows contingency operation of Cornwall plant under abnormal conditions. Fig. 29 (below). Estimated performance curves for Cornwall pumped-storage plant.



water about 2½ miles upstream from the Falls into two covered intake channels, each of which is a 700-foot-long concrete structure, with 48 slotted openings, to take in water from 13 to 26 feet below the river surface. Huge water gates control the flow of water to two parallel, cut-and-cover tunnels, which carry the water by gravity flow a distance of 4¼ miles to an open canal that forms the Niagara generating plant forebay. The forebay, 4000 feet long by 500 wide by 110 deep, serves both the pumping–generating plant and the major hydro plant.

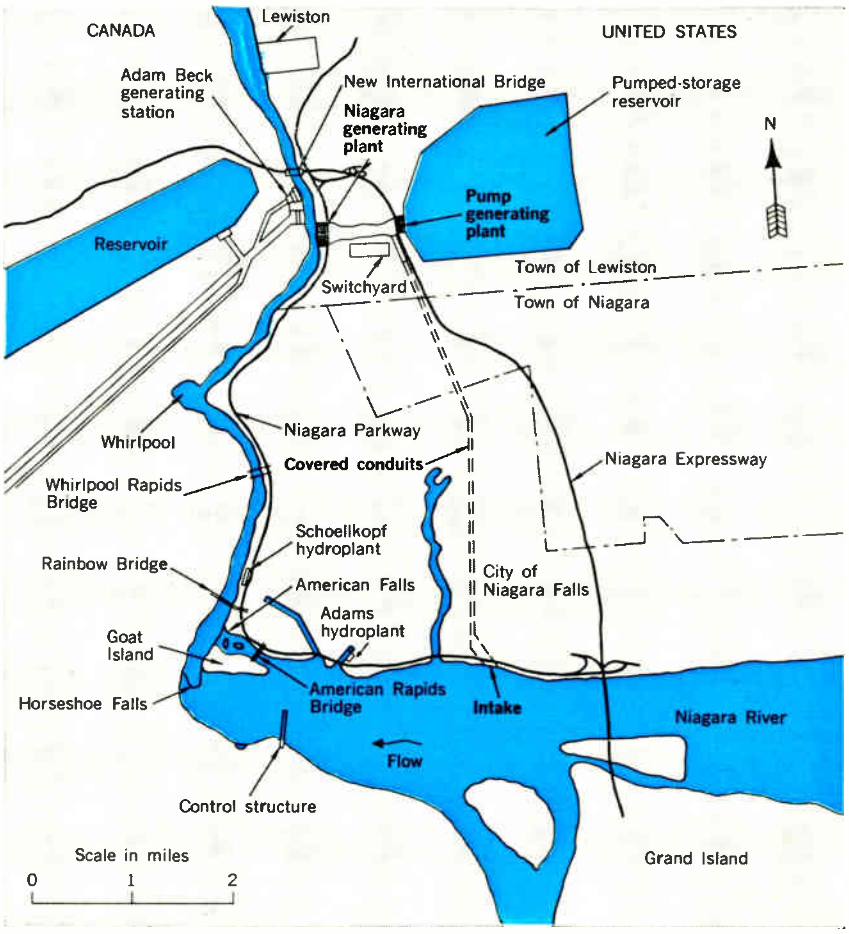
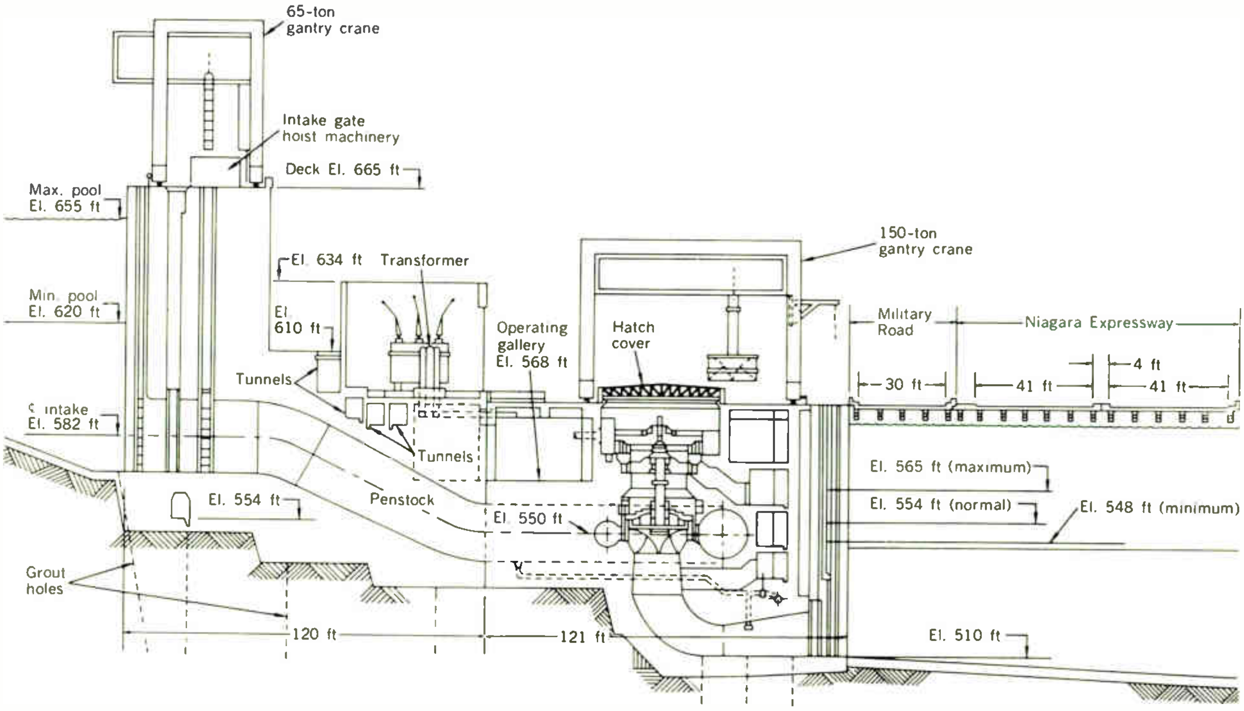


Fig. 30 (right). Map of Niagara frontier area showing the locations of various run-of-the-river hydro and pumped-storage installations.

Fig. 31 (below). Cross section through a typical unit of the Niagara pumping–generating plant. Note the low-head feature of this installation.



The pumping–generating plant will lift the extra water available during nocturnal flow as much as 100 feet for storage in a high pool reservoir to meet peaking capacity demand. The 974-foot-long concrete structure, which is 240 feet wide by 160 high, contains 12 fixed-blade non-feathering Francis-type pump–turbines, rated at 28 000 kW when operating under a net head of 85 feet. After flowing through the pump–turbines in generating mode, the same water then passes through the turbines of the main plant, thus augmenting the natural diurnal flow.

The two generating plants have an installed capacity of almost 2200 MW. A typical unit of the Niagara pumping–generating plant is shown in Fig. 31.

Smith Mountain project. Another major project which must be mentioned is the Smith Mountain development. This two-phase project will ultimately provide 580 MW of dependable peaking capacity through the utilization of run-of-the-river hydro augmented by mixed pumped storage. Situated on the Roanoke River in southeastern Virginia, the development consists of two dams, one at Leesville, and the other—a high horizontal arch dam—at Smith Mountain Gap, about 40 miles southeast of Roanoke. The pumped-storage project will provide an initial dependable peaking capacity of 440 MW (of which 40 MW will be at Leesville), and 2.1 million kWh of dependable daily peaking energy.

The total cost of the project, exclusive of transmission facilities, is estimated at $44.7 million, or about $101.50 per kilowatt.

The Smith Mountain project was designed for the Appalachian Power Company by the American Electric Power Service Corporation, with Ebasco Services Inc. retained as consulting and design engineers for the hydro, civil, and mechanical engineering phases of the development.

Pumped storage in the United Kingdom. As mentioned earlier in this article, pumped storage did not attain widespread favor among power people in the United States until after World War II. In fuel-poor Great Britain, however, pumped-storage possibilities created considerable interest many years ago as a means for saving coal that was being used for an equivalent capacity in old steam–electric equipment having a low efficiency factor. And as the geography of the British Isles includes mountain ranges—whose individual peaks rise up to a 4000-foot altitude in Wales and Scotland—many fast-moving streams are created by large upland catchment areas, and natural mountain lakes and pools are suitable for high-level reservoirs. Thus the pumped-storage concept was readily adaptable to the topography of many sites.

One of the earlier pumped-storage plants was built at Ffestiniog in North Wales. This station contains four 90-MW reversible pump–generator units that operate under a dynamic head of 1000 feet. The plant was designed primarily to operate in pumping mode for seven hours during five successive nights of the week, and to function in generating mode for four hours each following day. But, in actuality, the units are operated on generating, pumping, or spinning reserve duty for periods up to 22 hours a day, and may change from one cycle to another with much greater frequency than was originally planned. Sometimes the pumping mode may occur during the day to absorb surplus system energy and maintain the high-pool levels near capacity to develop maximum generating capability during the evening peak.

Cost estimates have indicated that the Ffestiniog plant has achieved a net saving as high as $16.80 per kilowatt over a conventional thermal plant of the same capacity.

At present, the North Scotland Hydro Board has four major pumped-storage projects either under construction or in the planning stages. The largest and most unusual of these will be the Cruachan underground power station. This plant, scheduled to go on the line in 1965, will contain four 100-MW pumping–generating units to operate under an average dynamic head of 1200 feet. The station will utilize the famous Loch Lomond as a reservoir.

A notable feature of this plant will be the adaptation of a single, fixed-blade Francis runner for the dual function of pumping and generating. This will permit one wheel to do the work of two, and will afford a substantial reduction both in power plant dimensions and equipment weights. The estimated construction cost of Cruachan is about $40 million.

Some future developments

The increasing popularity of the pumped-storage concept was indicated by the number of papers[4] presented on this subject at the 1964 American Power Conference (April 14–16). The paper submitted by C. D. Galloway, I. H. Landes, and W. D. Marsh of the General Electric Company, "The Role of Pumped Storage in Generation Systems," indicated that the method may afford some relief from the inherent low-load factor of utility systems. And the authors speak of a computer program to calculate optimum pumped-storage hydroelectic operation and its ancillary costs.

Meanwhile, our counterpart power experts in Europe have been busy in the development of the horizontal type of reversible pump–turbines, such as those used in the la Rance tidal power project in France. Also, they are working on a variable-pitch mixed-flow turbine that has a more restricted head range than the conventional Francis turbine, but that will yield improved efficiency, particularly where part-load operation is an important factor.

Essentially, the outlook is bright for the continued construction of pumped-storage projects over the next several years. By the end of that time, other methods of economical power generation for peaking capacity—such as gas turbines—will probably be more advantageous in terms of cost per kilowatt installed.

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Microwave power engineering

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Microwaves for power (rather than communications) is today beyond a state of mere speculation. Interest in powering a hovering vehicle from the ground, power transmission via waveguides, and industrial potentialities have spurred the development of a technology that has already transmitted and utilized power efficiently

Introduction

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Transmission of electric power has been accomplished traditionally with the use of wire or cable. But now a new technology is emerging—microwave power engineering—whereby power is transmitted at microwave frequencies (X and S bands) without wires and through hollow pipes.

Transmission of power by RF waves is not a new concept. The renaissance of serious interest in it, however, is probably due to two factors. First, the evolution of new microwave power techniques in recent years has made the generation, transmission, and rectification of power at microwave frequencies look more attractive. Second, there has been considerable interest in finding a means for powering hovering vehicles from the ground.

Although a great deal of work remains especially in microwave rectification and in vehicle antenna and waveguide transmission, efficient transmission of microwave power at commercially significant quantities—through space from earth to hovering vehicles and through oversized waveguides along the surface of the earth or immediately below it—seems possible of attainment in the foreseeable future.

The following discussion covers both elementary theory and experimental work in three major areas: microwave power generation, transmission by physical waveguide structures and radiation beams, and rectification. Transmission is treated somewhat more extensively than generation or even rectification since it is one of the major bottlenecks impeding the future growth rate of this technology.

It is hoped that this symposium in print will attract more interest in and support for a technology that has already proved feasible and that is becoming more and more important.

Microwave power generation

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Power transmission by microwaves is today beyond a state of mere speculation. Two concurring factors are responsible: general interest in improving the state of the art of microwave power generation, and the evolution of new techniques[1] with which to accomplish the desired improvement. Fig. 1 indicates the great growth rate of microwave power at wavelengths suitable for microwave power transmissions. The recent growth rate at both X and S bands has been such that the power has nearly doubled every year since 1958. The power level at S band, for example, has risen by a factor of 25 over the period of the last five years to a level of 400 kW of CW power.

The rapid growth in microwave power generation was brought about with the use of two types of microwave tubes. Power at X-band frequencies was generated in a klystron, and that at S-band frequencies by means of an Amplitron. Both of these devices will be examined in some detail.

The superpower Amplitron

The Amplitron[2–5] is based upon the well-known continuous-cathode crossed-field interaction principle[6,7] to which the conventional magnetron oscillator also belongs. The device, shown schematically in Fig. 2, consists basically of a cathode to emit electrons, a slow-wave circuit arranged concentrically around this cathode to provide a means for introducing an RF wave with which the electrons can interact, and a static magnetic field arranged parallel to the axis of the cathode. To place the device in operation, a dc electric field from an external power supply is imposed between the cathode and anode, and its magnitude progressively increased. The electric field first causes electrons to leave the cathode, around which they rotate in concentric circles, because of the presence of the magnetic field. Their angular velocity increases with the applied electric field until, at a critical value of the field, the electrons rotate around the cathode with nearly the same angular velocity as the RF wave injected into the RF circuit. At this point of synchronism, the electrons form into spokes of space charge. These rotating spokes of space charge then induce RF currents in the RF circuit.

In many ways, the rotor configuration formed by the spokes of rotating space charge is analogous to the rotor of a conventional low-frequency alternator. Both types of rotors perform work on the fields established in the circuits within which they rotate; they both convert energy from one form into another. In the common low-frequency generator, the rotor is turned by mechanical torque, and mechanical power is converted into electric power. In the Amplitron, torque is provided by the behavior of an electron in static electric and magnetic fields that are "crossed" or normal to each other, and dc electric energy is converted into microwave energy.

The Amplitron is a special type of continuous-cathode crossed-field device in that it has two sets of terminals and behaves as a broadband amplifier. In the Amplitron, the induced RF currents add up in the direction of the output and cancel in the direction of the input, and the

Fig. 1. Progress in microwave power generation from a single vacuum envelope as a function of time.

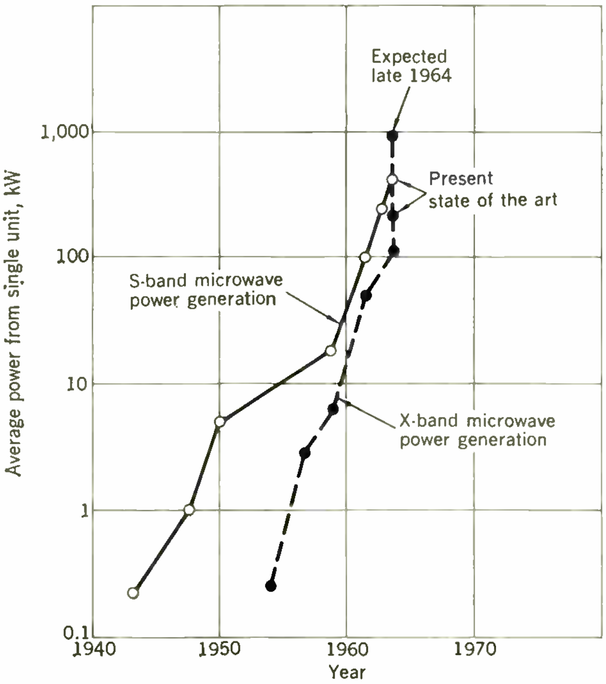
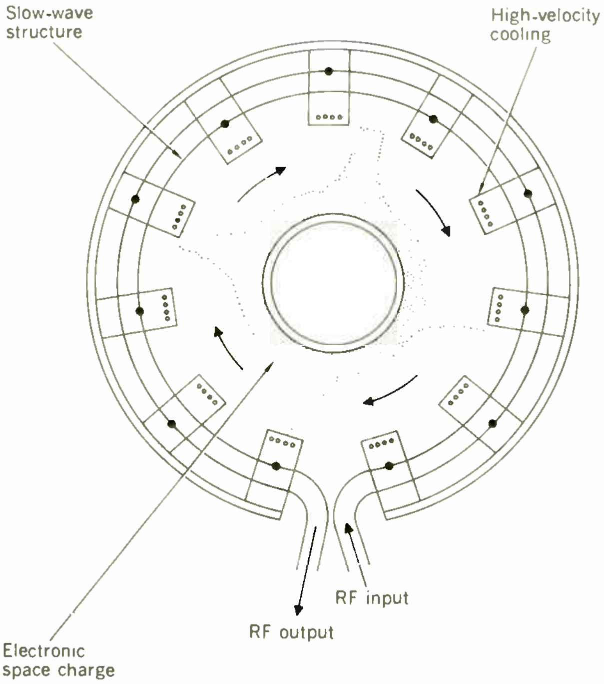


Fig. 2. Schematic diagram of the Amplitron (Raytheon).



frequency and phase of the induced RF power are rigidly controlled by the frequency and phase of the driving power.

A further understanding of the operation of the Amplitron and its qualifications for a superpower generator can be gained by following the path of an electron from the cathode to the anode of the device. Since the dc power supply is connected between the cathode and anode of the device, an electron as it leaves the cathode has the full potential energy of the power supply. After leaving the cathode, it is either pulled very rapidly into one of the spokes of space charge or it is returned very rapidly to the cathode, depending upon the phase of its emission with respect to the rotating space charge spoke. If it enters a rotating spoke, a small part of its original potential energy is then converted into kinetic energy associated with the synchronous rotation of the spokes. From that time on, potential energy is converted directly into RF energy as the electron travels from the cathode to the anode.

Because of their motion, however, the electrons still have some residual energy when they strike the anode. This energy is converted into heat which must be dissipated. The superpower Amplitron uses a very efficient liquid-cooling method,[8,9] which will handle dissipation densities of several kilowatts per square centimeter of anode area. This cooling is accomplished by forcing water to flow at high velocities through a multiplicity of small cooling channels located in the tips of the vanes as shown in Fig. 2. The amount of dissipation handled is minimized by the high operating efficiency of the Amplitron, which is typically 70 to 80 per cent.

Fig. 3. Efficiency as a function of power level for the QR1224 Amplitron.

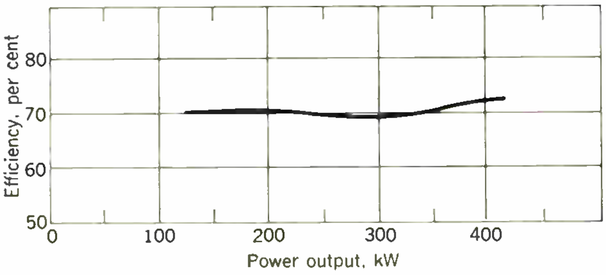
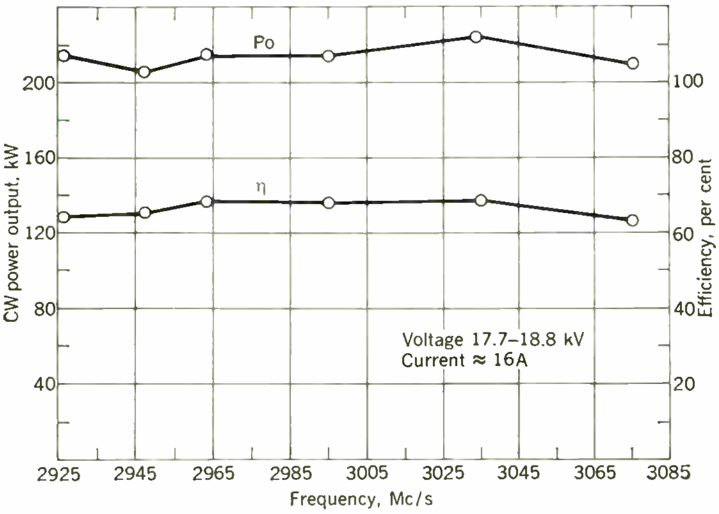


Fig. 4. Performance of the QR1224 Amplitron.



Amplitron performance features. The success of the Amplitron approach to the efficient generation of large amounts of power is indicated by the 10-cm QR1224, which has been operated at over 400 kW of CW power. The efficiency-vs.-power output performance of the QR1224 Amplitron is shown in Fig. 3. It will be noted that over 400 kW of continuous power has been obtained with an overall efficiency of approximately 70 per cent at an operating potential of 20 kV. Further tests at higher voltage and magnetic field are expected to result in both greater power output and higher efficiency. The gain of the Amplitron is a nominal 10 dB, and drivers are available for it. In Fig. 4 the bandwidth of the QR1224 is seen to be of the order of 150 Mc/s or 5 per cent.

The QR1224 Amplitron is a nonthermionic device; that is, current flow in the device is not dependent upon a cathode which must be heated to a high temperature so that it will emit electrons as in most electron tube devices. As indicated in the description of the operation of the device, some electrons that leave the cathode are immediately returned to the cathode—not, however, before receiving some additional kinetic energy from the RF field. In high-power tubes, this energy is sufficient to enable the impacting electrons to excite the emission of more electrons than are returned. If a suitable secondary emitting material is used, the cathode can be kept cold at all times, under either operating or starting conditions. In the latter case, the injected RF is sufficient to start the secondary emission. The material of the cathode in the QR1224 is pure platinum, which has a high secondary emission ratio and which also has an advantage in stability over secondary emitting cathodes employing oxide films or other compounds. This type of cathode is expected to permit exceptionally long life (in the tens of thousands of hours), and to represent a significant advance over thermionic cathodes that are often limited in life and sometimes sublimate low-vapor-pressure materials upon other parts of the tube.

A second novel feature of the QR1224 Amplitron is the use of an ogive-shaped output window so that a small-gain horn can be located behind it and the output power of the tube radiated directly into a parabolic or ellipsoidal reflector. This technique, which is applicable to other types of superpower tubes, has been most successful in eliminating both the output window problem and the problems of handling large amounts of power in conventional waveguides.

The high efficiency of the Amplitron is important not only in limiting the cost of the power supply and cooling equipment, but because efficiency determines the amount of RF output power that can be obtained from an Amplitron with a fixed amount of anode dissipation capability. The approximate relationship between power output, anode dissipation, and efficiency may be expressed as

$$\text{RF power output} = \text{anode dissipation} \times \frac{n}{1 - n}$$

where n denotes the efficiency.

The RF power output varies directly with the factor $n/(1 - n)$, which is 2.3 for 70 per cent efficiency, 4 for 80 per cent efficiency, and 9 for 90 per cent efficiency. It is therefore important to note that specially designed Amplitrons have been run with overall efficiencies as high as 90 per cent and that it appears within the realm of possibility to extend these principles to the design of the superpower Amplitron.

Despite the significant increases in power level that the higher efficiency may make possible, the power requirements of some applications of microwave power transmission are so great that new device approaches must be developed. One proposed crossed-field device approach that provides a greatly increased anode and electron interaction area is the electromagnetic amplifying lens.[10] As indicated in Fig. 5, this approach handles both the input and output power in a quasi-optical fashion, which greatly eases the window problems as well as permitting the increased size of the interaction area.

The superpower klystron

In a high-power linear-beam tube (a klystron or traveling-wave tube), a cylindrical electron beam is generated by an electron gun and focused through an aperture in the accelerating anode. Once formed, the electron beam is focused or collimated, generally by a strong axial magnetic field, while it passes through the interaction circuits of the tube. Finally, after passing through the circuits where it interacts with the RF electromagnetic fields, it is released by the focusing fields. It then expands to a much greater diameter before it is intercepted by a collector, where the energy of the spent beam is dissipated in a heat exchanger.

In the generation of large amounts of microwave power, it is most significant that the tube can be regarded as divided into three regions. In the first of these—the electron gun region—the high-power beam is emitted by a cathode, and accelerated and focused through an aperture in the anode. Only direct voltages are present in this region. Area convergence ratios of 10 to 100 from cathode area to focused beam area are commonly employed, with greater convergence possible. Because the electron gun region is free from RF fields, the cathode is not bombarded or back-heated by accelerated electrons. Modern cathode materials have demonstrated continuous emission capabilities under these conditions greater than one ampere$\cdot$cm^{-2} of area with life expectancies greater than 10 000 hours. The electron beam generated will therefore have a current density of the order of 100 amperes$\cdot$cm^{-2}. If an accelerating potential of several tens of kV is employed, the power density of the electron beam will be several megawatts$\cdot$cm^{-2} of area. These orders of magnitude are typical of present-day technology.

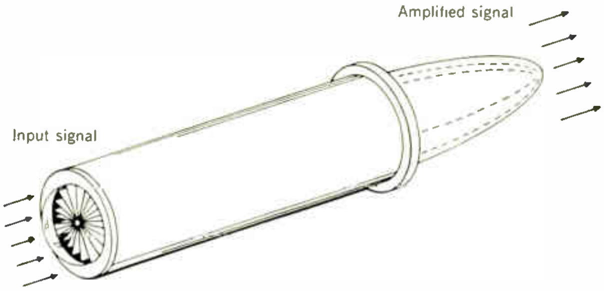
The second region of the tube is the interaction region. In this region the electron beam has been formed and is constrained by a focusing field to maintain an approximately constant diameter while passing through the interaction circuits. Normally no direct voltages are present in this second region, and with no RF fields present, the beam would travel at a constant velocity. In a klystron, the interaction circuit consists of a chain of resonant cavities. The electron beam passes through apertures, or gaps, in these cavities, and interacts with RF fields within the cavities. With the cavities properly tuned, a small signal injected into the first of the cavities is greatly amplified as it passes through the chain of cavities, and a large amount of power can be extracted from the final cavity.

In a traveling-wave tube, the interaction circuit can be any of a variety of propagating circuits. For high-power tubes, forms of loaded waveguide are commonly employed. Interaction with the electron beam and amplification of an injected electromagnetic wave will occur when the velocity of the propagating wave is roughly synchronous with the electron velocity. A small signal at the circuit input can be greatly amplified and extracted at the output. In either a klystron or traveling-wave tube, the electron beam passes through the interaction circuits with only a small fraction of the beam actually intercepted by the circuits. With a well-designed beam and focusing structure, the beam interception by the interaction circuits can be substantially less than one per cent. In spite of the high power, the heat generated in the circuits by beam interception density in the electron beam is relatively small, permitting the heat to be controlled by conservative cooling techniques. Frequently, heating of the interaction circuit by generated RF currents constitutes a more serious problem than beam interception.

After leaving the interaction region, the electron beam enters the third region of the tube, the collector region. At the entry into this region, the beam is released by the focusing fields, which are terminated. As in the electron gun region, there are no RF fields. The beam then expands rapidly in diameter because of the forces of mutual repulsion of the electrons, and the power density in the beam is correspondingly reduced. The interior metal surface of the collector is placed where the power density is sufficiently low, typically of the order of a few hundred watts$\cdot$cm^{-2}, and the heat generated by the beam interception is removed by a heat exchanger, typically in the form of liquid-coolant channels. Although the dimensions of the interaction circuit in the second region are limited in physical size for electromagnetic reasons, the collector can be made almost arbitrarily large, and the problem of heat dissipation reduced to a manageable one wherein any of a variety of cooling techniques, conventional or not, may be employed.

Of the two main types of high-power linear-beam tubes, the traveling-wave type has special virtue in the millimeter wave region where circuit field strengths become a limiting factor. The klystron is most at home in the microwave region—wavelengths between one meter and one cm. In this range, when effective effort has been ap-

Fig. 5. The electromagnetic amplifiying lens approach to superpower.



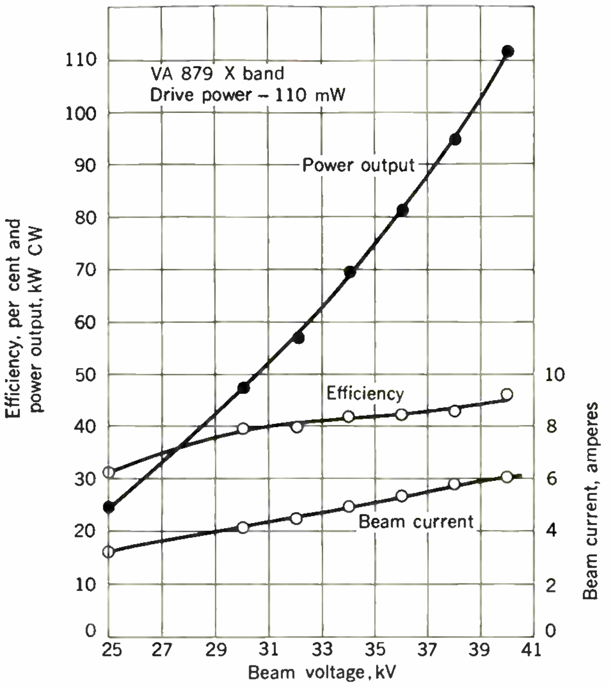


Fig. 6. Performance of the 100-kW VA879 klystron (Varian).

Fig. 7. Performance of the multibeam ZM6602 klystron (with permission of GE).

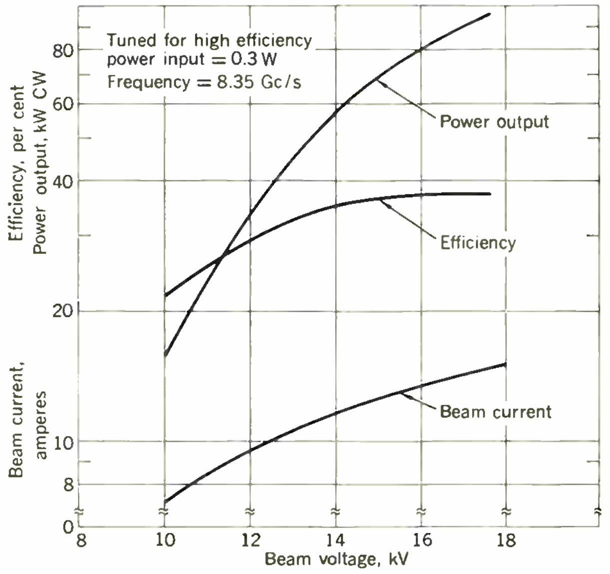
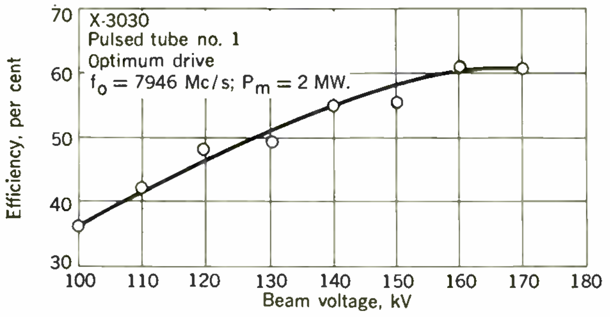


Fig. 8. Efficiency of the distributed-interaction pulsed prototype of the 1-MW X-band klystron (with permission of Eimac).



plied, the klystron has developed the most power of any tube type.

By continuous refinement and evolution of design techniques during the last decade, power capabilities of linear-beam types have been greatly increased. The greatest development effort in CW klystrons has been in the X band, the highest frequency band usable for reliable atmospheric transmission. Therefore, rather than reopening the controversial subject of scaling laws and figures of merit, let us assume that three cm is about an optimum wavelength (through the atmosphere) and review tube progress there.

For ordinary klystrons, the output power available in catalog tubes has increased steadily. Fig. 1[11] shows the temporal rise in ratings of typical X-band (Varian) klystrons. In addition, klystrons of "conventional" design are commercially available that are capable of producing over 100 kW of continuous power in the lower frequency region between 2 to 10 Gc/s. Progress in efficiencies of these tubes has not been so dramatic, although typical klystron efficiency of 30 per cent ten years ago has been raised to 45 per cent today. It is interesting and significant, however, that progress in power and to some extent in efficiency has not been based on new materials or principles, or even on pushing the available ones to their limits, but rather by improved engineering of a device whose theoretical limitations are far above the practical ones. Conventional traveling-wave tubes have similar capabilities, but have not received as much attention in this high-power range. Continuous power in excess of 30 kW at over 40 per cent efficiency has been generated by a laboratory traveling-wave tube at 8 Gc/s.

In the gain figures of klystrons it is hard to describe "progress," because it has always been possible to get as much gain as is desired in a narrow-band tube. A gain of 60 dB is common with complete stability.

An example of the current state of the art in conventional klystrons is the VA-879A, a four-cavity amplifier requiring electromagnet focusing. Figure 6 gives operating data. The tube has been tested to 120 kW output, limited by power supply, and is rated at 100 kW.

The question of length of life in the case of CW klystrons is often raised and occasionally answered. The actual life data are always confused by the fact that most failures are random accidents. The tubes do not wear out. Depletion of active cathode material would not be felt for many years with modern impregnated cathodes. Some of the most common causes of failure are waveguide arcs which destroy the vacuum window, coolant system failure (such as by scale formation), and heater filament burnout. In applications where these "accidents" are prevalent, one may find tube life averaging under 1000 hours. Where the accidents are controlled we see data such as the following from a lot of VA-856, 2-kW klystrons in a single type of system: so far, five tube failures at life hours of 13 732; 11 110; 2268; 14 397; and 13 650.

The superpower tubes have not been used in quantities to get statistical life data. There are no inherent physical reasons they should differ from medium-power tubes whose performance is recorded, except that the danger of waveguide arcs increases rapidly with power level. At 50 or 100 kW extreme care must be taken with electric contacts in the waveguide, and cleanliness must be attained.

A variety of refined techniques are currently being explored in various laboratories to increase the power capabilities of these tubes and to increase their efficiency. One approach has been to use multiple electron beams, up to ten, in a single vacuum envelope, thereby reducing the power required in each beam and reducing the operating voltage of the tube. These beams interact with resonant circuits, which may be considered either as close-coupled parallel cavities or as extended cavities excited in a higher-order mode that has a high field at each electron-interaction gap. The coupling is strong enough to solidly lock in phase all gaps in a cascaded stage. These multiple-beam klystrons have produced power of the same order of magnitude and efficiency as the single-beam klystrons. Figure 7 gives the associated performance data of a recent multiple-beam klystron.

In high-frequency klystrons, one of the most severe limitations on power is the output cavity. Heating by circulating current can detune or melt the cavity, and high RF fields can cause field emission breakdown. By dividing the stored energy among many parallel cavities, the multiple-beam klystron can raise these limitations. Another approach to the problem is the "extended interaction" cavity, in which the RF field is spread over a number of interaction gaps along a single beam. These gaps are coupled into a short, resonant section of slow-wave circuit. In this sequential interaction, the effect is more complicated than simple subdivision of the fields and currents, because each gap adds a modulation to the electron beam which is felt at all downstream gaps. This can result in increased efficiency of the high-frequency klystron tubes.

An effort is currently under way at Eitel-McCullough to produce 1 MW of continuous power at X-band frequencies (i.e., 8 Gc/s) using distributed interaction circuits. Efficiency of the order of 55 to 60 per cent is expected, and has been demonstrated in low-duty operation. Over 200 kW of average power has been generated to date. In this tube the circuits are cavities with several gaps and drift tubes in series, and are resonant; i.e., they have a standing wave along their length. A short-pulse RF tester has operated at 60 per cent efficiency at 2-MW peak, and a 2-MW dc beam has been tested successfully. Figure 8 illustrates the efficiency of a distributed-interaction pulsed prototype of the 1-MW X-band klystron (Eimac).

Significant improvements in efficiency to over 50 per cent have also been demonstrated by another distributed-interaction hybrid traveling-wave tube, the Twystron (Varian trademark) utilizing a combination of klystron and traveling-wave tube interaction circuits. The output circuit of this tube is a section of traveling-wave circuit instead of a resonant standing-wave cavity. While originally introduced for more bandwidth, the circuit also reduces RF fields, advantageous for high power, and is more efficient. Over 50 per cent efficiency is reached in the S band instead of the 45 per cent of a comparable simple klystron. In a klystron research project at Lincoln Laboratory and at Cornell University, increases in efficiency to 70 per cent have been demonstrated at lower power levels through the use of dc voltage jumps in the interaction region.

Conclusions

The Amplitron approach to superpower generation has made available 400 kW of CW power at a wavelength of 10 cm from a single tube. Outstanding features are its high efficiency of 70 per cent and its use of a pure-metal nonthermionic cathode with potential for very long life. A continuation of the crossed-field device approach into even higher power levels would make use of new structures with larger internal interaction areas and quasi-optical handling of the input and output microwave power.

No major inherent limitations on power capabilities of linear beam tubes are apparent at this time. Experimentation and progress are expensive, however, so the future rate of advancement will undoubtedly be controlled by economic considerations, rather than by major technological limitations.

In the X band, klystrons are "on the shelf" to 100-kW CW, and 1 MW is predicted. Efficiency is over 45 per cent, with 55 per cent probably on the way. Less work has been done at other frequencies, but results are scalable, at least downward. Tube life is inherently over 10 000 hours. Klystrons can be paralleled for more power; eight have been fed to a common waveguide.

Waveguides—general

G. Goubau U.S. Army Electronics Research and Development Laboratory

High-power microwave transmission is hampered primarily by the relatively high transmission loss of waveguides. Because of the skin effect, the current flow in any guiding structure is restricted to very thin surface layers. Assuming one and the same current distribution on a conductor, the loss increases with the square root of the frequency. Therefore, efficient power transmission by microwave requires the transmission of wave fields or modes which are associated with very low currents on the guiding structure.

Much more favorable is the situation in regard to electric breakdown. The power-carrying capacity of most waveguides is high enough to meet any reasonable requirement.

There are three classes of waveguides, whose performance is basically different from the physical point of view:

1. The closed waveguides,[12] where the entire field is shielded from the environment.
2. The surface waveguides, where the field is essentially on the outside of the guiding structure.
3. The beam waveguides, where the field consists of a wavebeam of special field configuration, which is guided by reconstituting the cross-sectional field distribution at periodic intervals.

Each of these three classes comprises several types of waveguides, but only those adaptable to microwave power transmission are considered here. The following survey gives a short account of the properties of the various kinds of waveguides from the viewpoint of high-power transmission.

Closed waveguides

The best-known and most widely used closed waveguides, coaxial cables, can be employed at microwave frequencies, but they can carry less power and are less efficient than tubular guides and thus will not be discussed here.

The most common types of tubular guides are the rectangular and the circular waveguides. Each can propagate several wave modes with differing field configurations. There are two kinds of modes: one has an axially directed electric field component and the other an axially directed magnetic component. The modes of the first kind are called E modes or transverse magnetic (TM) modes; and those of the other H modes or transverse electric (TE) modes. Field patterns of the two most important modes, the TE_{10} mode in rectangular guides and the TE_{01} mode in circular guides, are shown in Fig. 9(A). Each mode has a lowest frequency, the so-called cutoff frequency f_c at which the mode ceases to propagate. This frequency depends on the mode and the dimensions of the guide cross section. The phase velocity (v_p) of each mode is greater than that of light c, but approaches this velocity if $f \gg f_c$:

$$\frac{v_p}{c} = \left[1 - \left(\frac{f_c}{f}\right)^2\right]^{-1/2}$$

The power-carrying capacity[13] depends on the wave mode and the frequency, but primarily on the cross-sectional area of the guide. A plane wave in air of normal temperature and pressure can propagate 1.11×10^4 MW per square meter, assuming a breakdown field strength of 2.9×10^6 volts per meter. Since the field distribution over the cross section of a waveguide is not uniform, the average power-carrying capacity per square meter is smaller. The TE_{10} mode in rectangular guides can propagate a maximum power, in megawatts, of

$$P_m = 5.5 \times 10^3 \sqrt{1 - \left(\frac{\lambda}{2a}\right)^2}\, A$$

where A is the cross-sectional area of the guide in square meters and a the larger side of the guide cross section in meters. For instance, if the cross section is 1 by 0.5 meter and the wavelength $\lambda = 1$ meter or less, P_m ranges between 2380 and 2750 MW. The power-carrying capacity of the TE_{01} mode in a circular guide of radius R is, in megawatts,

$$P_m = 1.68 \times 10^4 \sqrt{1 - \left(\frac{\lambda}{1.64\,R}\right)^2}\, R^2$$

For a tube diameter of one meter, P_m reaches 4200 MW if λ is sufficiently small. These examples illustrate that the power-carrying capacity of tubular waveguides is very high and presents no practical limitation to high-power waveguide transmission. P_m could even be increased by pressurizing the guide.

The situation is less encouraging with respect to the transmission loss. The most reliable operation of waveguides is at frequencies so low that only one single mode, the fundamental mode, is propagated. In this case, mode conversion problems are avoided and the wave propagation is little affected by dimensional variations of the guide. Also, bends and curves in the layout of the guide present no serious problem.

The fundamental modes of the rectangular and the circular waveguides are the TE_{10} mode and the TE_{11} mode, respectively. The latter is a degenerate mode; this means there are actually two identical modes whose field patterns are rotated against each other by 90 degrees. Thus, the circular guide does not provide single-mode conditions. In rectangular waveguides with the standard side ratio, 1:0.5, single-mode condition exists within the wavelength range $a \leqq \lambda < 2a$. The smallest loss L occurs at the lower limit of this range; i.e., at $\lambda = a$, and has the value, in dB/km, $L = 0.30\, a^{-3/2}$.

Assuming a guide cross section of 1 by 0.5 meter and a frequency of 300 Mc/s, the loss is 0.3 dB/km. In other words, 50 per cent of the energy is lost over a distance of 10 km. This loss is about two orders of magnitude greater than that of conventional high-power lines.

Now, let us consider transmission in oversized waveguides where the dimensions of the guide are so large that $f/f_c \gg 1$. Under this condition there are many modes which can propagate simultaneously. If there is any irregularity in the guide, the desired mode is partially converted into other modes. This mode conversion is particularly troublesome in communication because the various modes have different phase velocities and their superposition causes severe phase and delay distortions. Fortunately this kind of distortion is of little concern in CW transmission. However, mode conversion also causes increased transmission loss. Since the desired mode is the one which has the lowest attenuation, energy transferred to other modes is absorbed at a higher rate. The prevention of mode conversion is a difficult problem, particularly if there are bends or curves in the guide. To date, this problem has been solved satisfactorily only for the TE_{01} mode in circular guide and only in regard to communication where much higher losses are permissible.[14]

Let us now assume an oversized guide without irregularities. The attenuation of any mode is extremely high near the cutoff frequency. With increasing frequency the attenuation decreases and, in general, passes through a minimum and rises again. An exception to this rule, known since the early days of waveguides, are the TE_{0n} modes in circular guides. Their attenuation decreases indefinitely with increasing frequency. More recently, Karbowiak[15,16] showed that the attenuation of most modes, even those in rectangular guides, theoretically decreases with frequency if the frequencies are sufficiently high.

As an example of the theoretical loss in oversized waveguides, we consider the TE_{01} mode in the circular guide. The loss in a copper tube of radius R, if $f \gg f_c$ and λ and R in meters, is, in dB/km,

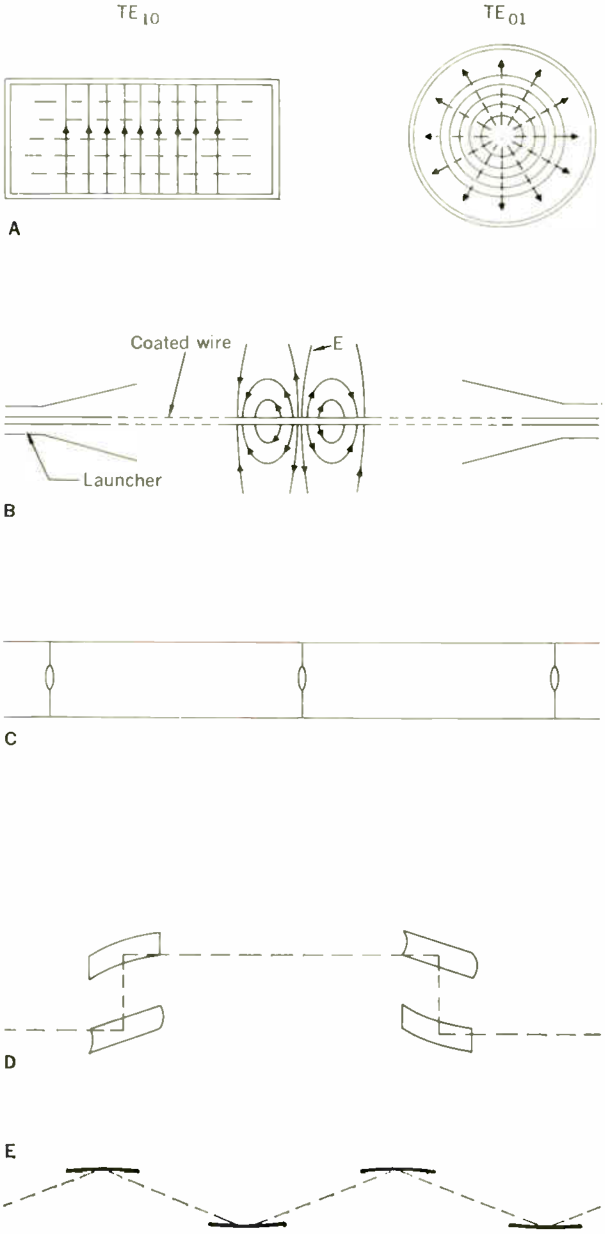
$$L = \frac{3.8}{R^3}\lambda^{3/2}\, 10^{-2}$$

For $R = 50$ cm, $\lambda = 10$ cm, one obtains 0.01 dB/km. This loss is more in line with the loss in conventional high-power transmission. Considering the large size of the guide and the problem of preventing mode conversion, the outlook for high-power CW transmission by means of oversized waveguide is also not encouraging. Of course, the dimensions could be reduced by using higher frequencies. However, the problem of preventing mode conversion would be even more difficult.

Surface waveguides

Of the various kinds of surface waveguides, only the single-conductor surface-wave transmission line is usable for very-high-frequency transmission over distances of miles. The more commonly known two-wire line is very sensitive to nonsymmetries, and its applications at frequencies in the VHF range and higher are limited to rather short lengths.

Fig. 9. Various types of principal waveguides for microwave power transmission: A—Closed waveguide. Shown are cross-sectional fields of the TE_{10} mode in rectangular guide and the TE_{01} mode in circular guide. Solid line, E field; broken line, H field. B—Surface: single-wire transmission line. C—Beam: lens-type waveguide. D—Beam: double-reflector waveguide. E—Beam: elliptical reflector waveguide.



The single-conductor surface-wave transmission line[17-19] consists simply of a dielectric-coated wire. The propagated mode is a TM mode with axially symmetrical field; see Fig. 9(B). The phase velocity of this mode is a few per cent smaller than that of light. It decreases slightly with increasing frequency and increases with decreasing thickness of the dielectric coat. The line requires special terminations for launching and receiving the surface wave mode. These terminations usually consist of metal horns as shown in Fig. 9(B).

Being an open waveguide the line is affected by environmental conditions, primarily by deposits of ice and sleet on the wire. High-power transmission would prevent the formation of these deposits. But there is still a loss increase caused by rain, though this effect diminishes rapidly at frequencies below 1000 Mc/s.

As in the case of closed waveguides, the application of the guide to high-power transmission is limited by the transmission loss. The loss consists of (1) launching loss (i.e., a radiation loss at the terminations); (2) conductivity loss in the wire; (3) dielectric loss in the dielectric coat; and (4) installation loss, which is essentially radiation loss caused by unavoidable bends in the line.

The launching loss is independent of the length of the line and depends mainly on the experience of the design engineer. Losses of less than 3 per cent per termination have been achieved.

Conductivity and dielectric loss are complicated functions of the conductor dimensions and the frequency. A wire of one-cm diameter with a polyethylene coat of 1.1-mm thickness, for instance, has at 300 Mc/s a conductivity loss of 2.15 dB/km and a dielectric loss of 0.2 dB/km. Although the loss can be made smaller than in this example by the use of larger conductors, it is still very high from the viewpoint of CW power transmission. Considering, however, the small amount of material involved (in contrast to closed waveguides), the line might still be useful for high-power transmission over short distances, where weight considerations are important—for instance, in transmission from the ground to a helicopter platform.

Beam waveguides

Beam waveguides are based on reiterative wave beams; this refers to wave beams whose cross-sectional field distribution is reconstituted at periodic intervals[20,21]. In the so-called lens-type guide (only this type is of interest in regard to power transmission), iteration is performed by reconstitution of the cross-sectional phase distribution of the beam. This can be done by means of lens-shaped "phase transformers" as in Fig. 9(C) or by reflective means as in (D) and (E). In Fig. 9(D) two reflectors are used for the iteration. They displace the beam laterally, and simultaneously perform the phase transformation. Since the phase transformation can be done separately in two perpendicular directions, cylindrical reflectors may be used as shown in Fig. 9(D). The setup in Fig. 9(E) uses elliptical reflectors for the iteration of the beam, which is propagated along a zigzag path.[22]

For a given path length D, between successive iterations the beam diameter is at a minimum if the focal length of the lenses or reflectors is $D/2$. However, there is no focusing in the geometric optical sense as the diameter of the beam varies only by a factor of $2^{1/2}$ along the path from one phase transformer to the next.

The transmission loss of a beam waveguide is essentially determined by the inherent lens losses or the conductivity losses of the reflectors. Diffraction losses can be made negligibly small. For the double-reflector arrangement of Fig. 9(D) with copper as the reflector surface, transmission loss in dB/km is

$$L = \frac{0.30\lambda^{-1/2}}{D}$$

if the electric field is polarized parallel to the reflectors. D and λ are in meters.

If we assume a wavelength of 10 cm and a spacing $D = 300$ meters, which is approximately the spacing of the towers of high-tension lines, then $L = 0.003$ dB/km, which is commensurable with the loss of conventional power lines. However, the beam cross section would have to be greater than 10 by 10 meters. For 10 by 10 meters the diffraction loss just equals the reflection loss. The power-carrying capacity would be 1.68×10^5 MW. The dimensions are smaller for higher frequencies, but then rain and fog would affect the transmission loss. These are, of course, theoretical data, since to date there is still little experimental information available on beam waveguides.

Conclusions

High-power transmission by waveguides is primarily hindered by the relatively high transmission loss. Although theoretically there is the possibility of achieving losses that compare with those of conventional power lines, they have not yet been verified experimentally.

The beam waveguide

N. I. Heenan   Raytheon Company

As Goubau has already pointed out, the transfer of power between a source and collector by means of electromagnetic wave beams can be accomplished if there are beams whose (phase and amplitude) distribution in a transverse plane repeats itself at periodic intervals. That such beams exist had been theorized, and that they may be approximated in practice has been demonstrated in the last few years. The important work in this area was that of Goubau, who reported the invention of the beam mode waveguide in 1959.[23] Since 1960, this work has been independently confirmed and extended by many others, notably workers at the Bell Telephone Laboratories. Confirmation of the theoretical results in the millimeter range (23 Gc/s) by the construction of a beam-mode transmission line was reported in 1961 by Goubau and Christian,[21] while Brown and Heenan[2] have transferred power utilizing these principles both in the millimeter range (36.5 Gc/s) in 1962 and in the S band (2400–3100 Mc/s) in 1963.

Beam-mode waveguide

Figure 10 depicts a wave beam propagating principally along the Z axis from left to right. The energy at first converges toward a point in the plane, ω–ω', of the beam waist and then diverges. The phase distribution in the plane A–A' determines the direction in which the beam propagates, and the amplitude distribution determines the extent (or area) of the beam in which the bulk of the energy is contained. If at plane B–B', the phase distribution is identical with that at A–A', the beam will repeat itself and energy can be passed between a launcher and collector by a series of such iterations.

Considering the case where the energy storage in plane A–A' is negligible and where the amplitude spectra of the elementary waves of which the beam is comprised are real, the theory shows that the transverse field components at B–B' and A–A' are conjugates of each other. Hence, a phase transformer can be placed at B–B' which reconstitutes the field that exists at A–A' and causes the beam to repeat itself.

Of particular interest are those beams that can be transformed with the use of simple lenses or reflector-type phase transformers. Such beams are comprised of elementary waves that propagate in directions differing very little from the direction of the beam axis. This restriction permits a simplification of the amplitude and phase terms of the integral representation of the transverse field components, thereby permitting the modes of the wave beam to be determined in terms of tabulated functions. It turns out that the amplitude distribution of the mode having the highest energy concentration on the beam axis is Gaussian; hence, these beams are called Gaussian beams.

It is necessary too, to determine the extent of the beam; i.e., the contours within which a given fraction of the total energy of the beam is contained and the effect of employing phase transformers of finite dimensions. This has been done and it is shown that at least 90 per cent of the energy can be focused in a circle of a one-wavelength radius. The principal effect of the finite dimen-

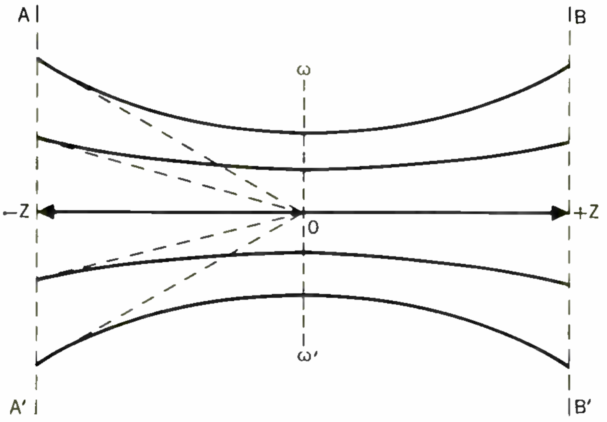


Fig. 10. Electromagnetic wave beam: single iteration (of total length D and showing the focal plane $\omega O \omega'$).

sions of the phase transformer is a diffraction or scattering loss that can be reduced by reasonably sized transformers to extremely low values; see Fig. 11.

From the curve in Fig. 11 marked "Lens type," it is seen that a loss L of less than 0.01 dB per iteration is obtainable when $R^2/\lambda D = 1$, while for a loss of 0.6 dB per iteration $\pi R^2/\lambda D = 1$, where R is the lens or reflector radius and D is the iteration distance; i.e., the distance between successive phase transformers in an iterated beam-mode waveguide. From classical theory of the far field for uniform illumination of a circular antenna of radius R, the distance between the first nulls reaches $2R$ at a distance D when the relation $R^2/D\lambda = 0.61$ is satisfied.

We wish now to generalize and present three equations for transmission of energy over a distance D from an aperture of radius R_1 to an aperture of radius R_2. These equations are listed in Table I.

Launching and collecting beam modes

An important aspect of the transfer of power by electromagnetic wave beams and one on which much remains to be done is the launching and collecting of a Gaussian beam. The theory of receiving antennas indicates that the antenna aperture distribution when the antenna is transmitting must be the complex conjugate of the incident field for maximum collection of energy. Analytically, this is expressed as

$$\text{Power collected} = \int_A \frac{E \cdot E^*}{\eta}\, dA$$

where E is the incident electric field in the aperture plane; E^* is the resultant E field in the aperture plane when the receiving antenna is used as a transmitter; η is the intrinsic impedance of free space (377 ohms); and A is the aperture surface. E fields outside the aperture surface are assumed to be of zero amplitude.

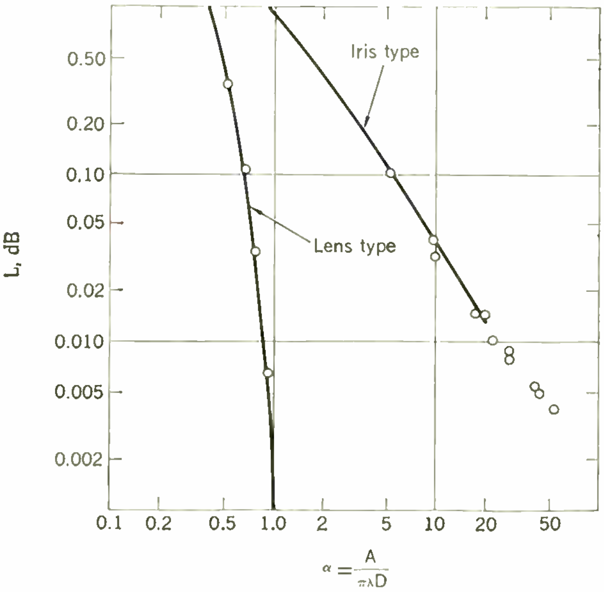
Thus, for both the collector and launcher, the aperture distribution must be Gaussian. This requirement means that horn antennas which have been used to date can, at best, produce only good approximations to the required amplitude distributions. Leaky wave radiators properly arrayed[24] may be capable of providing a better answer because of their low side lobes and the ease with which pattern shaping can be accomplished.

I. Generalized results for the transmission of microwave energy between two axially displaced apertures

$R_1R_2/D\lambda$*	Illumination	Energy at Receiver in R_2, per cent
0.61	uniform	84
1	Gaussian	99.98
$\frac{1}{\pi}$	Gaussian	86.5

* Similar results obtained for square and rectangular apertures.

Fig. 11. Diffraction loss per iteration in beam waveguides, where D is the iteration length.



Experimental results

In this section only the results of actual transfer of microwave power experiments are discussed. Other work has been carried out to verify the theoretical results.

The experimental beam-mode transmission line used by Goubau and Christian consisted of ten phase transformers and a launcher and collector. Each phase transformer was a pair of lenses mounted back to back to minimize reflection losses from the lens surfaces. Each lens was 8 inches (16 wavelengths) in diameter and the iteration length was 40 inches (80 wavelengths). The launcher and collector were identical—each consisting of a lens and a conical horn. The conical horn was of four-inch diameter at the mouth, and the throat matched the standard millimeter waveguide.

With this arrangement, the total power lost was 1.9 dB (35 per cent). This consisted of a 10–11 per cent loss in the ten phase transformers and a 12 per cent loss in both the launcher and collector.

At Raytheon's Spencer Laboratory, single-iteration transfer systems have been built and experimentally tested in the K band (26.5 Gc/s) and in the S band (2400–3100 Mc/s). In the S-band experiments, the phase transformer used was an ellipsoidal reflector and the system was designed so that the reflector converts the lowest-order mode of the confocal system launched at the first focal point into the lowest-order mode of the system whose focal plane passes through the second focal point. Diagonal horns were used because they are known to have essentially equal beam widths in the four principal planes. Moreover, it can be shown[25] that in the E and H planes the aperture distribution approximates a Gaussian curve closely, while in the 45° plane it approximates a truncated Gaussian curve. With this arrangement the collection efficiency between a $1\lambda^2$ launching horn, 15λ from the reflector and a $25\lambda^2$ collector 75λ from the reflector was just over 50 per cent in both the K and the S bands.

Extrapolations and extensions

Although the experiments described are modest in nature they do represent a verification of the theory for the transfer of power in the Fresnel zone. At the present state of the art, the crossover point in cost between a

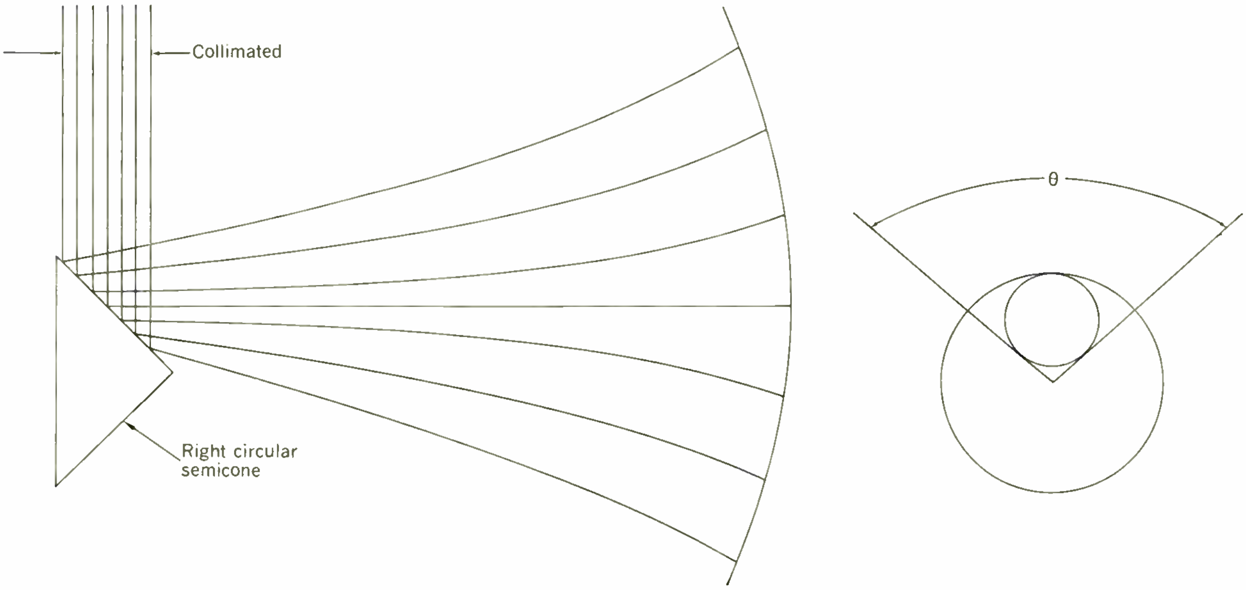


Fig. 12. Reflection of a circular Gaussian beam to form a sector beam.

single reflecting surface and an array of smaller surfaces has an aperture size of 250 feet. Assuming then a 250-foot reflector operated in the S band ($\lambda = {}^1/_3$ foot) the iteration length for a beam mode waveguide is 125 000 feet. The beam waist at 63 000 feet contains 90 per cent of the energy within a diameter of 177 feet and the power lost per iteration is one dB.

The ability to collimate the energy in a beam of uniform diameter permits redirection and reshaping of the beam with ease. For example, a right circular semicone placed coaxially in the beam waist will convert the beam into a thin, flat sheet of uniform thickness moving essentially in a radial direction with a 360° coverage. Displacement of this cone off the axis will produce a thin, flat sheet beam in an angle θ that is less than 360°; see Fig. 12. It is not hard to envisage 360° azimuthal and zenith stabilization of a beam-riding device in this manner. Too many other possibilities exist to be enumerated here, but one of these, taken from reference 22, is included as Fig. 9(E) in the previous section.

Conclusions

The theory of power transfer of electromagnetic energy between apertures of known area and separation is available. Some experimental work has been done to confirm the theory and some attempts at launching the low-loss beam mode have been made. Much more remains to be done in the latter category in antennas, costs remain to be minimized, and power transfer of 90 per cent and over remain to achieved.

Free-space transmission

W. C. Brown   Raytheon Company

The renaissance of serious interest[26–28] in the transfer of power by radio waves is doubtless the result of technological gains in microwave radar and communication systems over the past 25 years, and also the more recent demonstration that microwave energy should be generated at power levels appropriate to some applications of wireless power transfer. In turn, the availability of microwave power focused attention upon the problems of developing an efficient RF-to-dc converter and upon antenna systems suitable for efficient power transfer. When the problems were solved, modest laboratory experiments were set up for the first time in the efficient transfer of meaningful amounts of power by means of a microwave beam and associated conversion components.

The experiments

The first experiments[1] were demonstrated to a group of Department of Defense officers and officials at the Spencer Laboratory of the Raytheon Company on May 23, 1963. In this experiment, a magnetron was utilized as the energy source, providing an output of 400 watts at a frequency of 2450 Mc/s. This power was used to illuminate a 9.5-foot-diameter ellipsoidal reflector that concentrated the energy around the second focal point of the ellipse 18 feet away into a spot size 2 feet in diameter; see Fig. 13. A diagonal horn with a two-foot aperture was used as a receiving antenna and was terminated in the standard S-band waveguide. A close-spaced thermionic diode rectifier was then used to convert the received microwave power back into dc power at values of current and voltage suitable for the operation of a conventional dc motor. The rectified power was 103 watts, representing a combined transmission and rectification efficiency of 26 per cent.

The various efficiencies involved in the power transfer are:

Efficiencies	Per Cent
Feed horn launching	77
Beam:	86
Spillover at reflector (4%)	
Aperture blockage, mismatch and reflector losses (7%)	
Spillover at collector (4%)	
Collector aperture	77
Closed-spaced diode rectifier	51
Overall	26

The overall efficiency of a power transfer system employing microwave beams would involve the efficiency of the microwave generator. The particular magnetron used in this experiment was comparatively low. However, in any high-power transfer system, a superpower Amplitron could be used at efficiencies of 70 per cent or more. The use of 70 per cent efficiency would then provide a dc-to-dc transfer efficiency, including all elements of the power transfer system, of 18 per cent.

In addition to the experiments on power transfer making use of a close-spaced thermionic diode rectifier, experiments involving a large number of semiconductor diodes arranged into a combined receiving antenna and rectifier were conducted at the Spencer Laboratory. In these experiments, 180 watts of rectified dc power have been obtained, utilizing the same transmitting antenna but with a higher-powered transmitter.

Observations

Table II shows the various conversion and transmission efficiencies that have been experimentally obtained at microwave frequencies, together with an estimate of improvements which may be expected over the next several years.

In Table II, the 72 per cent efficiency of the 400-kW CW QR1224 Amplitron has been used. However, 80 per cent has been achieved in some "off-the-shelf" pulsed Amplitrons, and 85 per cent on some experimental UHF Amplitrons. Further improvement to 90 per cent should be possible.

The microwave power transmission efficiency of 52 per cent represents the first preliminary work done in this area and the theory justifies the eventual realization of 90 per cent. In the RF-to-dc conversion area, the 85 per cent predicted efficiency for the future cannot be wholly justified on the basis of present theory or technology, but the successes that have already been obtained with a modest investment of effort would indicate substantially greater achievements in the future.

Some thoughts concerning the relationship of these initial experiments to the future unfolding of the technology of power transmission by microwave beam may be of interest. Growth of a new technology is preceded by and often initiated by experiments that in retrospect are modest. Subsequent growth is then often dependent upon component development. The interesting situation with respect to the transfer of power by microwave beam is that there is on the shelf antenna and microwave-generator equipment capable of immediately extending by a thousandfold the power and distances involved in the laboratory experiments just described. Because existing rectifiers may be grouped together in large numbers, the reconversion of the microwave power into dc power is also well advanced.

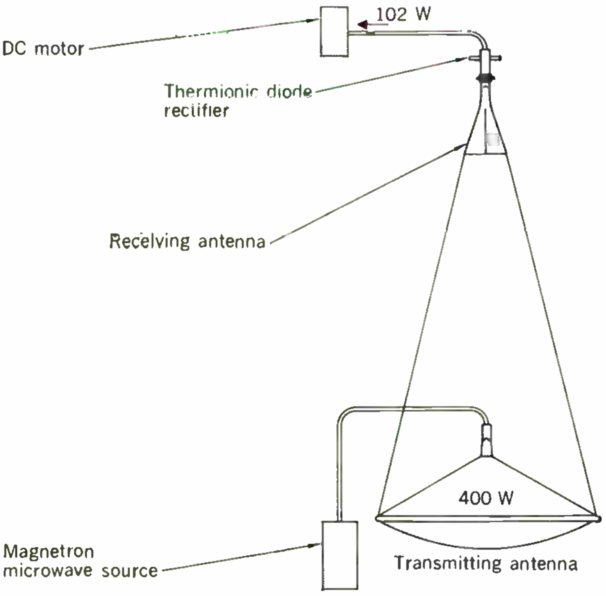


Fig. 13. Schematic diagram of the power transfer experiment.

II. Present and expected efficiencies

	Per Cent Efficiency	
	Present Maximum	Improved
Dc-to-RF conversion, Amplitron	72	90
Microwave transmission, point to point	52	90
RF-to-dc conversion, semiconductor diode	70	85
Overall	26	69

Conclusions

It may be stated that efficient transfer of power involving the conversion of dc into microwave power, the free space transmission of the microwave power, and the rectification of the microwave power at the receiving point have been successfully achieved in the laboratory. On-the-shelf technology will make it possible to extend greatly the distances over which power may be transferred by microwave beam and the amounts of power so transferred. As a result, contingent upon finding suitable applications, the growth of this new technology could be most rapid.

Rectification of microwave power

W. C. Brown *Raytheon Company*
R. H. George *Purdue University*

Direct conversion of microwave energy into dc power is relatively new to research and development, probably because there was no need for a conversion device until its desirability was recognized in connection with power transfer by microwave beam. Lacking an efficient direct electric converter, early protagonists of microwave power transmission relied upon an approach that would first convert the microwave energy into heat, which then generated electric energy indirectly with the use of some type of heat engine. In addition to the complexity of this arrangement, the best expected overall efficiency from microwave power to dc power is well below 25 per cent.

Fortunately, several devices have been recently developed that will directly convert microwave energy into dc energy at acceptable efficiency. Recent development has been greatly influenced by potential aerospace applications that require high power-handling capability in proportion to the weight of the device, a need for high redundancy and reliability, and an output impedance compatible with coupling it into such useful devices as electric motors. The aerospace application has the additional requirement of a nondirectional antenna, which makes it desirable to break up the total antenna aperture into a large number of separately terminated small-aperture antennas. This requirement ultimately led to a successful attempt to combine the receiving antenna and rectifier into one device termed the "Rectenna," an acronym for rectifying antenna.

Notwithstanding this aerospace influence, it is expected that rectifier technology will eventually cover a broader field. The various possible rectifier approaches will therefore be reviewed, with special emphasis upon those already explored to some degree.

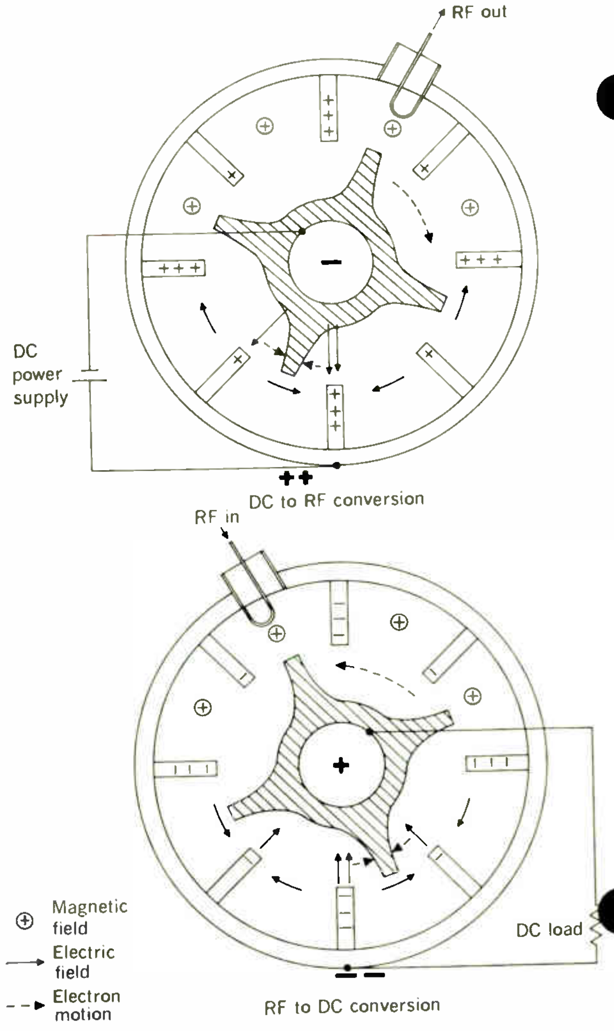
Rectifiers may be classified in several different ways. One classification is into solid-state and electron-tube devices, for—unlike the situation which exists in microwave power generation—it appears that there will be considerable competition between these two approaches. Another classification would be a breakdown into high-impedance and low-impedance devices. Rectifier analogs of microwave tubes tend to be high-impedance devices with low-current and high-voltage outputs, whereas diode rectifiers of both the solid-state and electron-tube type tend to be low-impedance devices.

Microwave tube analogs

The rectifier analog of the magnetron[30] was selected for one of the earliest approaches to a microwave power rectifier because of the recognized high efficiency and power-handling capacity of the device. The RF-to-dc conversion process of the device is in theory a remarkable dual of the dc-to-RF process. The magnetron operates on the basis of strong interaction between the synchronously rotating RF field and spokes of space charge whose configuration is determined by the RF field. As indicated in Fig. 14, the distinction between the magnetron device when it is operated as a dc-to-RF converter and when it is operated as an RF-to-dc converter is in the direction of rotation of the space charge and the polarity of the potential between cathode and anode. In either case, the electrons confront a strong electric field and a force is established between this field and the electron. The electron is held in a more or less fixed relationship to the RF field but the electron itself is moving. In the dc-to-RF conversion case, the electrons move in a direction opposing the force, and work is performed on the RF field in an amount equal to the force times the distance moved. Energy is conserved since the electron moves radially outward with the dc electric field, thus taking energy from the dc field.

In RF-to-dc conversion, the electrons would move in the direction of the field rather than against it. Hence, work is done on the electron by the RF field and the electron again moves radially outward but against the dc

Fig. 14. Schematic representation of the dual nature of dc-to-RF and RF-to-dc conversion in the continuous-cathode crossed-field device.



electric field between cathode and anode, thus delivering dc energy to the external load. Unfortunately the RF-to-dc magnetron converter does not work well because of the difficulty of freeing electrons from the cathode surface against the uncooperative dc field polarity. To free electrons, the RF field of the converter has to be run at values that are too great for either high circuit or electronic efficiency.

The injected beam crossed-field device[31] avoids this problem since the electrons come from a gun outside the RF interaction area. Tests made on a crossed-field backward-wave oscillator run as an RF-to-dc converter, as shown in Fig. 15, were quite successful and generated as much as 160 watts of dc output at 40 per cent efficiency. The success of this approach strongly suggests end injection of electrons into the magnetron geometry illustrated in Fig. 14.

The klystron rectifier by Yu[32] and Hayt[33] shows definite promise. In this approach it is proposed to use a very small part of the received RF to excite the input cavity of a klystron and to velocity-modulate the beam in the ordinary way. The bulk of the received energy is introduced into the output cavity in a phase relationship to the velocity-modulated beam, giving the bunched electrons a sizable kinetic-energy boost. In the collector region of the tube, these electrons deliver energy to a dc field by interaction with a depressed collector. Computed efficiencies for this type of operation are of the order of 60 to 80 per cent.

Figure 16 shows a completely self-sufficient electrostatically focused klystron rectifier that requires only RF power input for its operation. Three inputs provide, respectively from left to right, the heater power, the buncher power, and the accelerator power. The bunching of the electron beam takes place in the buncher and the two subsequent cavities. Each bunch, reaching the accelerator, is phased to receive a large amount of RF energy and each emerges with a velocity much higher than the corresponding anode voltage. This excess kinetic energy allows the major portion of the beam to reach the primary collector, which is connected through a load to the cathode. Optimum efficiency[32] occurs when a fraction of the beam is rejected by the primary collector through the proper choice of the load resistance. This portion of the beam is collected by a secondary collector connected to the cathode. Although the figure does not show current flow to the cavities at the anode potential, this current exists as a result of leakage and interception; and the out-of-phase electrons give up energy to the RF. The total anode current is estimated at about five per cent of the beam current; therefore an appropriate power supply is required. For the low-power rectifiers, a thermoelectric generator, as shown in the figure, may be used, while in the high-power operation a smaller

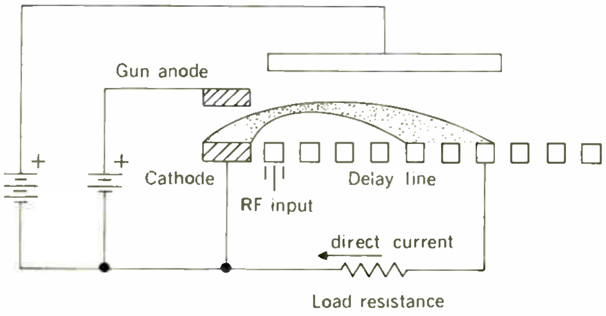
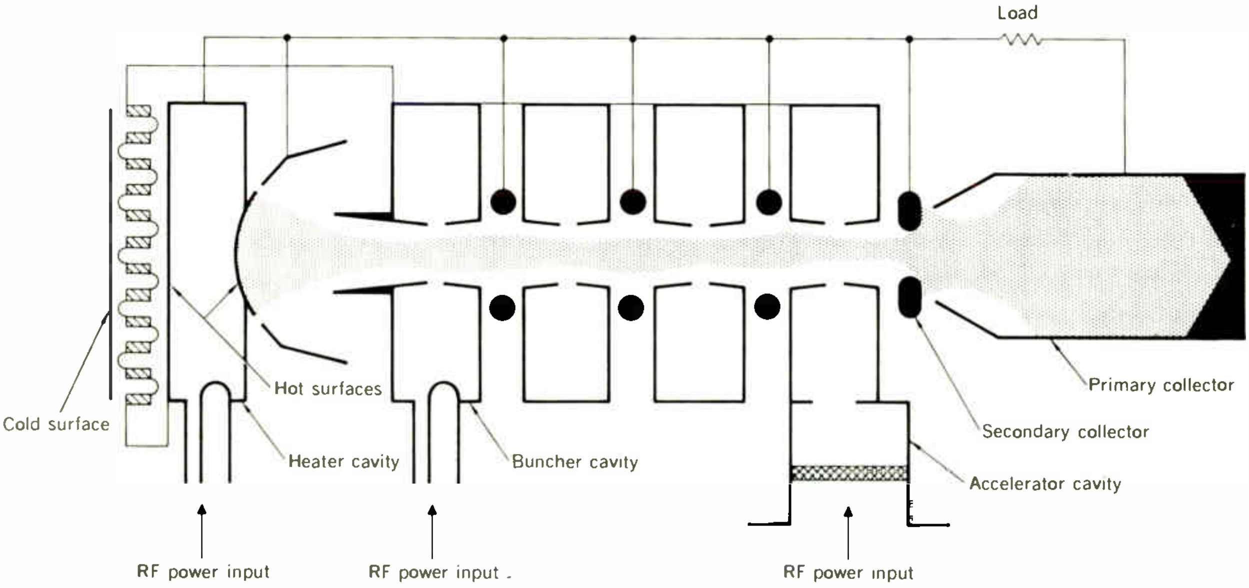


Fig. 15. The "microfier" is an injected beam crossed-field device which has operated satisfactorily as an RF-to-dc converter (Raytheon).

Fig. 16. Diagrammatic sketch of electrostatically focused klystron rectifier using thermoelectric generator as anode bias (Litton).



klystron rectifier is used. In connection with the thermoelectric anode power supply, it must be pointed out that the klystron rectifier has a much higher conversion efficiency and power-to-weight ratio than the pure thermoelectric device.

Closed-spaced thermionic diode

As previously indicated, RF-to-dc converters that are analogs of microwave tubes tend toward dc outputs with high potentials and low currents. However, there is one electron tube, usually not considered a microwave tube, that does have low-impedance output characteristics and is capable of operation at frequencies up to at least 3 Gc/s. This is the close-spaced thermionic diode rectifier.[34] The close-spaced thermionic diode is of some historic importance—it was used in the first experiments in the efficient transfer of meaningful amounts of power by microwave beam. In addition to its low-impedance output characteristics, which made it possible to drive directly a dc motor in the experiments, the close-spaced thermionic diode is characterized by efficiency in the 40 to 50 per cent range, good power-handling capability, and low weight in relationship to its power-handling capability. Figure 17 shows typical dc output vs. RF input characteristics of the QR1222. A maximum continuous dc of 900 watts was obtained from the device with an efficiency of 50 per cent.

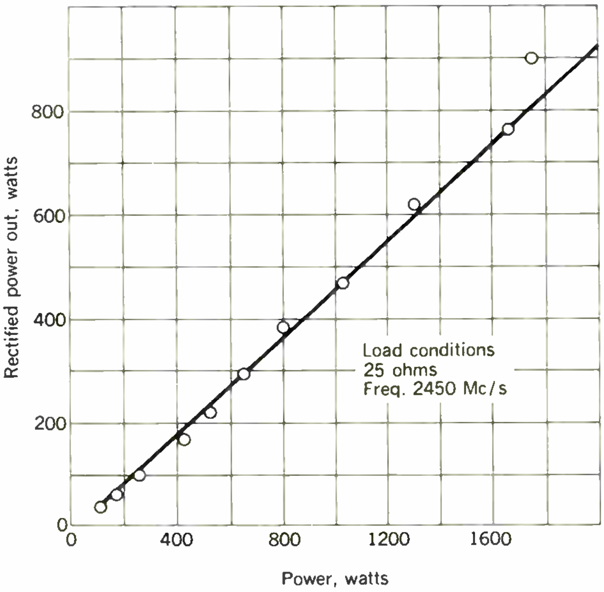
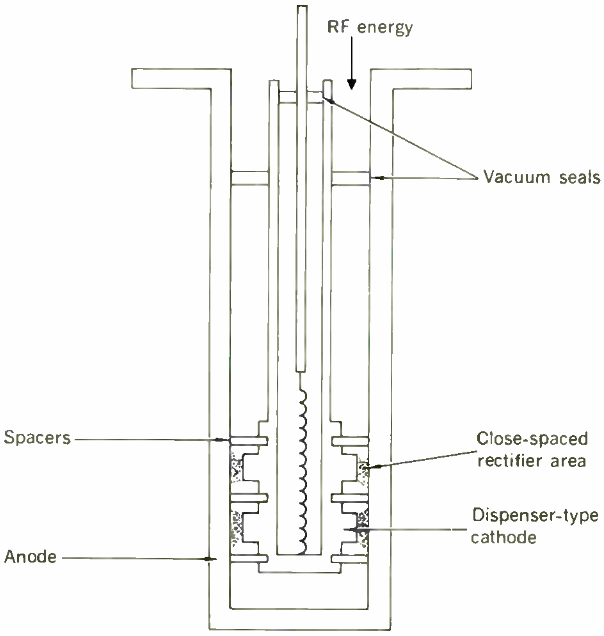


Fig. 17. The relationship of rectified dc power output to RF power input for the close-spaced QR1222 thermionic diode rectifier (Raytheon).

A cross section of this rectifier is shown in Fig. 18. From an RF circuit point of view, the diode consists of a single section of a low-pass wave filter, which is shunt fed and matched into an RF input coaxial line feed. The wave filter is operated at the upper cutoff frequency. The emitting cathodes are coincident with the capacitance elements of the wave filter. The displacement current in the cathode-to-anode gap is several times the conduction current, leading to an effective operating Q of the order of 10 to 20. The close spacing between cathode and anode (i.e., ~ 0.005 inch) reduces transit time effects to an acceptable value. Circuit losses are appreciable, and in operation they are sufficient to keep the cathode hot without the need of a heater. The dc load is coupled directly between cathode and anode, and because of the high RF frequency the internal capacity of the tube behaves adequately to smooth out any ripple in the dc output.

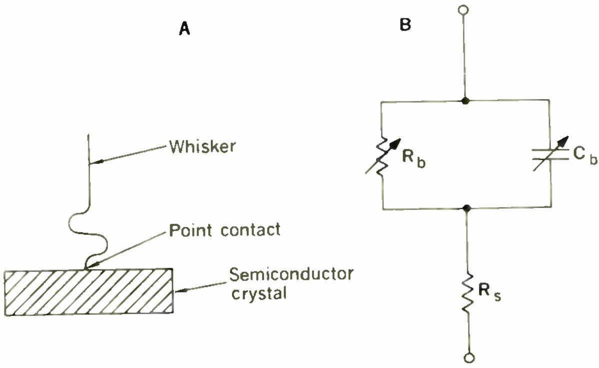
Fig. 18. Schematic of the construction of the close-spaced thermionic diode rectifier.



The semiconductor diode

At Purdue University[33,35–37] the discovery was made that the point-contact semiconductor diode, in use for many years in microwave receiver mixing circuit, can also be used as an efficient microwave power rectifier. Although its power-handling capability is small (measured in the tens of milliwatts), it was used in large numbers in a single assembly to produce tens of watts of power at efficiencies of more than 50 per cent when operated

Fig. 19. Construction and equivalent circuit of the point-contact semiconductor diode.



within an enlarged waveguide at a frequency of 2450 Mc/s. The importance of this work went largely unrecognized until the need for a nondirectional antenna in connection with aerospace applications focused attention on the possibility of using large numbers of semiconductor diodes in a configuration that would result in a nondirectional lightweight combined receiving antenna and rectifier. In the resulting study made under the sponsorship of the Raytheon Company, not only was substantial realization of these objectives obtained, but it became evident that this configuration of small diodes deployed over a large area could easily dispose of dissipated energy by both convective and radiation cooling. For either type of cooling, the heat sources are located very close to the heat sinks, eliminating the need for long, heavy, heat-conductive paths.

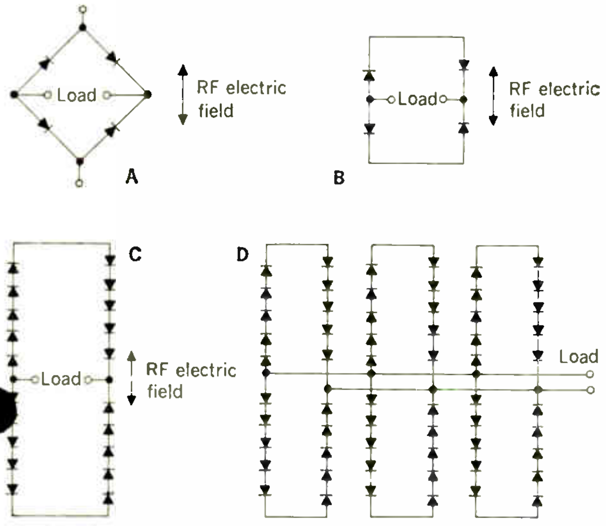
In Purdue's investigation of semiconductor diodes as microwave power rectifiers, it was determined that the silicon point-contact diode was superior to other forms. Junction types of diodes appear to have less efficiency because of the longer lifetime of the charge carriers in this type of device. The silicon point-contact diode was found to be more efficient than the germanium type, and because it will operate satisfactorily at a much higher temperature, it is capable of handling more dissipation and therefore higher power.

Basically, a point-contact diode consists of a rectifying junction formed by the contact between a fine whisker-like wire and a semiconductor crystal on whose surface it bears, as shown in Fig. 19(A). The equivalent circuit of such a device is shown in Fig. 19(B). In it, R_s is the spreading resistance, or simply the ohmic resistance of the crystal element; R_b is the barrier resistance, which is high in the reverse direction for small applied voltages and which decreases exponentially in the forward direction to a value much less than R_s for large signals; and C_s is the barrier capacitance. In the microwave power rectification application, the major loss in efficiency is caused by the spreading resistance.

In the microwave power rectification application, the diodes are usually arranged in bridge rectifier circuit configurations of varying degrees of complexity as shown in Fig. 20, where (A) and (B) are electrically equivalent.

An array of this configuration was tested by inserting it into an enlarged S-band waveguide and matching it to the guide by means of a movable reflecting plate back of the device. When tested, the device gave the efficiency–power characteristics shown in Fig. 21, where the dc load has been varied to provide different dc voltages across the terminals. The high efficiency of this device, particularly at the lower values of power output, is noteworthy.

Fig. 20. Various configurations of bridge-type microwave rectifiers employing point-contact semiconductor diodes.



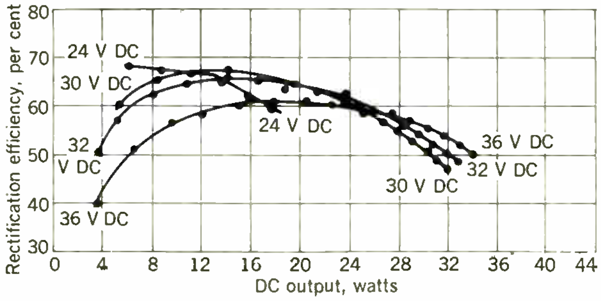


Fig. 21. Efficiency performance of the 680-diode configuration.

Fig. 22. Configuration of a dipole "Rectenna," a combined rectifier and receiving antenna. A solid-state bridge rectifier terminates each of the half-wave dipoles, which are spaced approximately one-half wavelength from each other (Purdue-Raytheon).

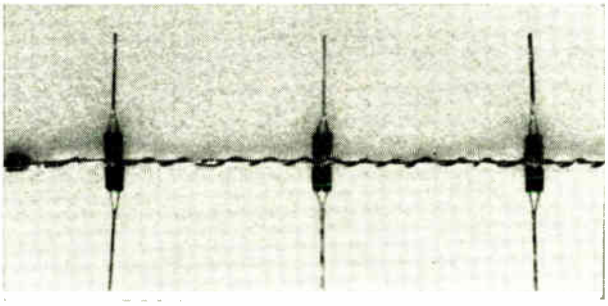
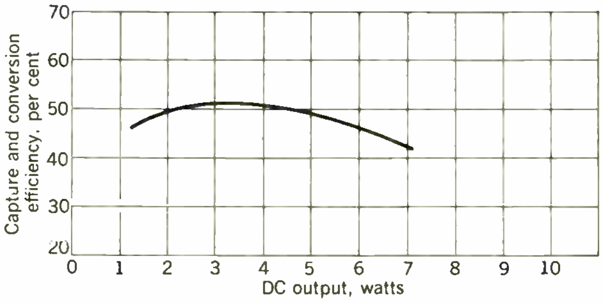


Fig. 23. Combined capture and rectification efficiency of the "Rectenna" shown in Fig. 22. This test result was obtained from a 28-dipole array with the dipoles connected in series on the dc side. Test frequency was 2440 Mc/s; load resistance was 3510 ohms; and area of the array was 1.5 square feet.



The Rectenna

One of the first experiments in a combined receiving antenna and microwave rectifier proposed by the Raytheon Company is shown in Fig. 22. The array[26,36] consists of a number of half-wave dipoles situated approximately one half wavelength from each other, and each terminated with a bridge rectifier with a single diode in each arm of the bridge. A reflecting plate about one quarter wavelength behind the diode array was provided. The dc outputs were connected in series. The combined RF capture and RF-to-dc conversion efficiency of the device as a function of dc output is shown in Fig. 23.

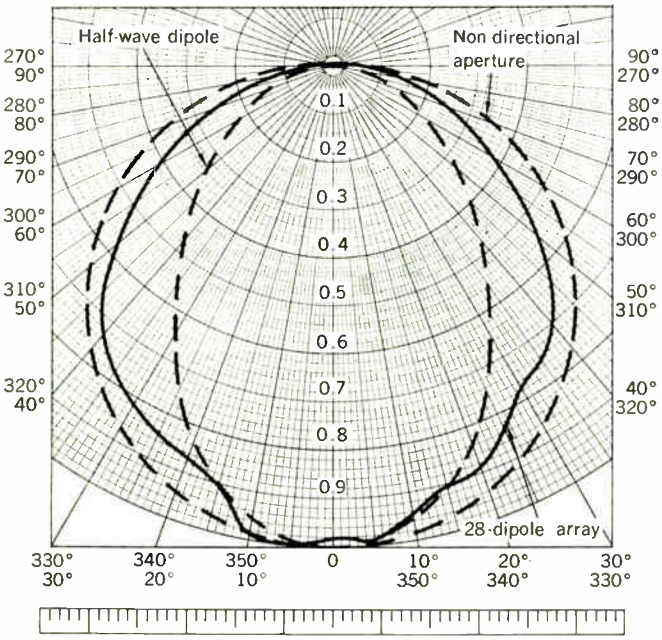
Perhaps the most striking aspect of the performance of the combined rectifier and antenna is its nondirectional properties, as shown in Fig. 24 where it is compared with the theoretical behavior of a single half-wave dipole and with a completely nondirectional aperture. It is observed to be better than a half-wave dipole.

Because of the highly efficient, nondirectional, and convenient-cooling properties of the Rectenna, it is being further developed and has been used in the laboratory along with the close-spaced thermionic diode for efficient power transfer experiments as described in the previous section.

The multipactor rectifier

A microwave (vacuum) rectifier based on the multipactor (i.e., multiple electron) discharge has been proposed recently.[38] The term "multipactor" is derived from the words "multiple electron impact."[39] A multipactor discharge consists of a thin electron cloud that is driven back and forth across a gap in response to an RF field applied across the gap. For the discharge to be self-sustaining, the secondary emission coefficient of the surface of the electrodes must be greater than unity, and the magnitude and frequency of the applied RF field must be adjusted so that the electron cloud traverses the gap during the half-cycle of the RF field. Under these conditions, successive impacts of the electron cloud produce a greater electron density and the secondary electrons created at each impact are driven to the opposite electrode, producing additional secondaries. Thus, the discharge current builds up. As the electron density increases, however, mutual repulsion causes some of the electrons to fall out of step with the field and thus limit the maximum electron density to a value controlled by the secondary emission coefficient.[40]

Fig. 24. Nondirectional properties of the "Rectenna." All dipoles are connected in series and vertically polarized. Aluminum plate reflector mounted behind dipole array. Load resistance held constant at 3500 ohms. Test frequency is 2.44 Gc/s.



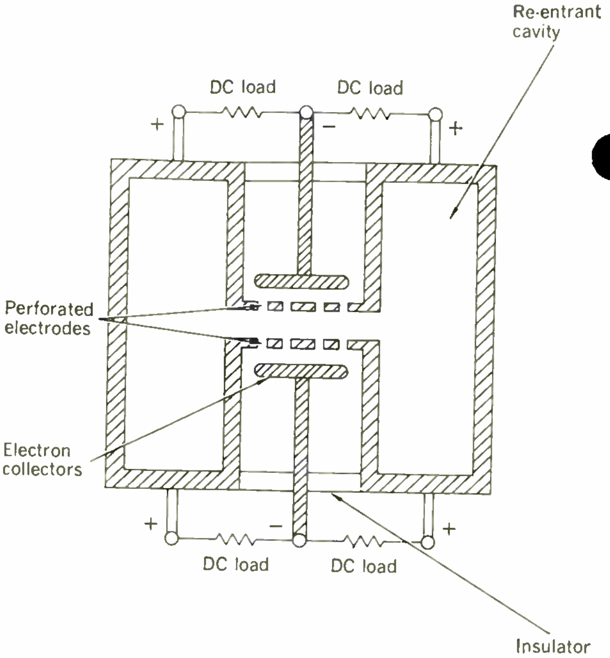


Fig. 25. Full-wave multipactor rectifier cavity.

Multipactor discharges can be used to give both half-wave and full-wave rectification. The full-wave rectifier (Fig. 25) utilizes a re-entrant microwave cavity with the electric fields concentrated at the center of the cavity where the secondary emitting electrodes are located. These electrodes are perforated to allow some of the electrons to stream through the holes to electron collectors. So long as the retarding dc load voltage does not exceed the kinetic energy of the electrons escaping from the multipactor discharge, all of the electrons will be collected. As a matter of fact, to achieve maximum rectification efficiency and to minimize possible secondary emission at the electrode collectors, it is desirable to operate the rectifier so that the dc load voltage approaches the kinetic energy with which the electrons escape from the cavity—i.e., the electron impact voltage.[38] Let us assume that all of the microwave power is concentrated in the multipactor discharge (the RF losses due to RF surface currents on the walls of the cavity are presumed negligible). If the dc load voltage has been set equal to the electron impact voltage, the efficiency for microwave rectification is then theoretically 59 per cent.

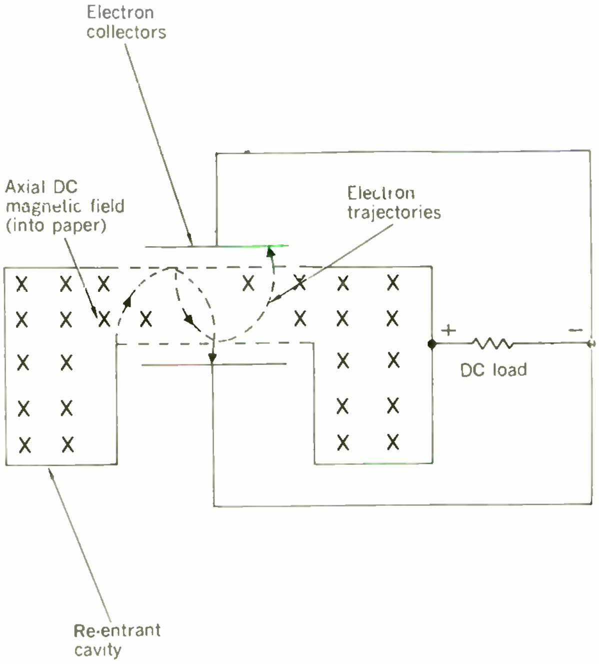


Fig. 26. Single-cavity full-wave rectifier (theoretical efficiency ~59 per cent).

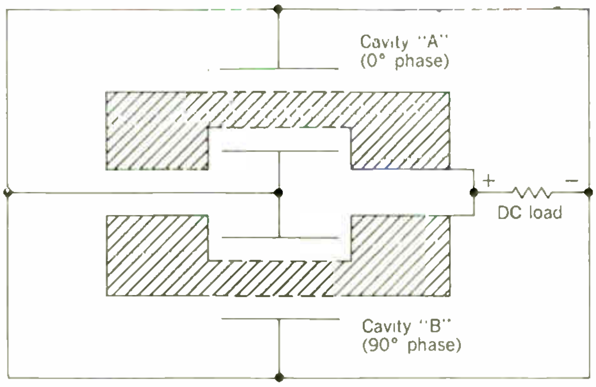


Fig. 27. Dual-cavity two-phase rectifier (theoretical efficiency ~92 per cent).

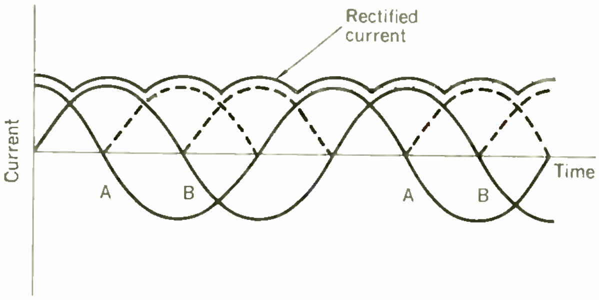


Fig. 28. Rectified output current waveforms from dual-cavity rectifier.

For typical operating conditions in the X band (10 Gc/s) it is shown that the power dissipated in the multipactor discharge is approximately 40 times the RF cavity dissipation due to RF surface currents. This assumption seems justified.

The rectification efficiency of the simple multipactor rectifier previously discussed can be considerably improved by the addition of an axial dc magnetic field and a dual waveguide phase-shifting network. The geometry used is shown in Figs. 26, 27. Figure 26 shows the essential features of the rectifier with the magnetic field. Here we consider an RF cavity with the cross-sectional form of a ridged waveguide. The frequency and amplitude of the RF field and the amplitude of the dc magnetic field are adjusted so that the electron paths graze the opposite electrode in the manner indicated. This grazing incidence markedly increases the secondary emission coefficient. As indicated in Fig. 26, the full-wave type of rectification is obtained within a single cavity.

In Fig. 27 the RF power is equally divided into the dual cavities A and B. The wave in cavity B, however, is shifted in phase by 90 degrees with respect to that in cavity A. Thus, the rectified output currents are as indicated in Fig. 28. In effect, the phase shift gives the equivalent of a two-phase full-wave rectified output and thus increases the rectification efficiency over that obtainable with the simple single-phase full-wave rectifier. McFarland gives an analysis of an idealized polyphase rectifier.[41] This analysis suggests that the two-phase full-wave rectifier would have a rectification efficiency approaching 92 per cent or approximately $\pi/2$ times that of the single-phase circuit. This indicates a significant improvement in rectification efficiency; however, a more detailed analysis including the effects of waveguide losses is required to determine more accurately the anticipated improvement. It is evident that this procedure of subdividing the input power and phase shifting could be extended to give the equivalent of polyphase rectification.

In addition to potentially high efficiency, the rectifier appears to have other inherent advantages. Since the discharge occurs in vacuum, the rectifier would appear to have high peak power capabilities. Further, since heating occurs at surfaces that can be water cooled, it would also appear to be capable of high average power. Tests of multipactor discharges applied to transmit-receive (TR) tubes, have indicated peak and average power capabilities of megawatts and kilowatts, respectively, at S-band frequencies. Further, these experiments with TR tubes indicate response times of about 7 RF cycles, which would correspond to approximately one ns in the X band.[39] Thus, it would appear that microsecond radar pulses could be rectified, which may be particularly advantageous for long-range power beaming. Finally, the rectifier has the advantage of simplicity, inasmuch as no filament or anode power supplies are required nor are magnetic fields always necessary.

Conclusions

In summary, the development of the RF-to-dc conversion device may be considered as in its early formative stages with practical devices for some types of application now available and with great advances from several different approaches expected for the future.

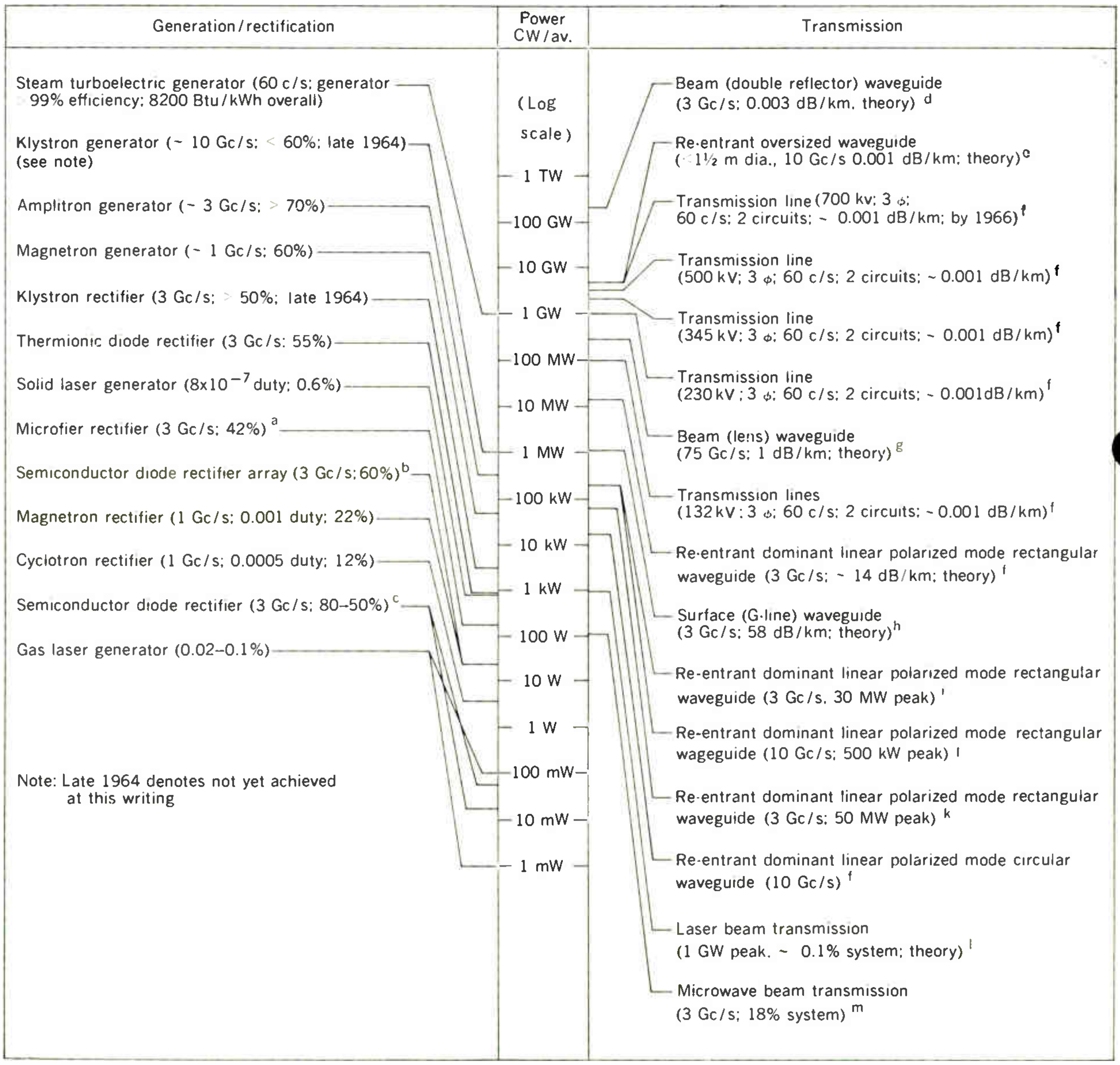
Summary

E. C. Okress American-Standard, Research Division

Growth in microwave power generation has been rapid, centering around two types of microwave tubes (see Fig. 29)—the klystron[42] at X band and the Amplitron[2] at S band. They are already capable of 200-kW CW and 400-kW CW, respectively. Present high efficiency of the Amplitron (> 70 per cent) is expected eventually to reach 80 to 90 per cent. The efficiency of the klystron is significantly lower (∼50 per cent) with 60 to 70 per cent probably on the way.

Waveguides comprise three general classes: closed, surface, and beam. Their relatively high transmission loss—the result of the far greater operating frequency range compared with conventional ac power (3–10 Gc/s vs. 60 c/s)—is the weakest link in microwave power engineering. To maintain high efficiency, permissible attenuation must be far lower than that tolerable for communications. For example, the maximum attenuation for efficient CW power transmission through a closed or re-entrant waveguide should not exceed 0.001 dB/km, which is one thousandth of that tolerable for communications.

Fig. 29. Power generation, rectification, and transmission capabilities.



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[a] Re-entrant beam crossed-field type, or planotron. (Microfier denotes Raytheon trademark.)

[b] Bridge circuit contains 680 diodes

[c] Maximum efficiency of 70–80 per cent at 10–20 MW.

[d] 200 meter spacing, 10 by 10 meter beam cross section, 2.9 by 10^6 volts per meter electric breakdown in air at normal temperature and pressure (NTP).

[e] Circular electric mode with continuous mode filtering, realized to date at only communications power.

[f] 2.9 by 10^6 volts per meter for NTPA, electric breakdown.

[g] 10 meter spacing, 40-cm diameter lens.

[h] 10 standard-wire-gauge copper wire, 75 A, TM mode.

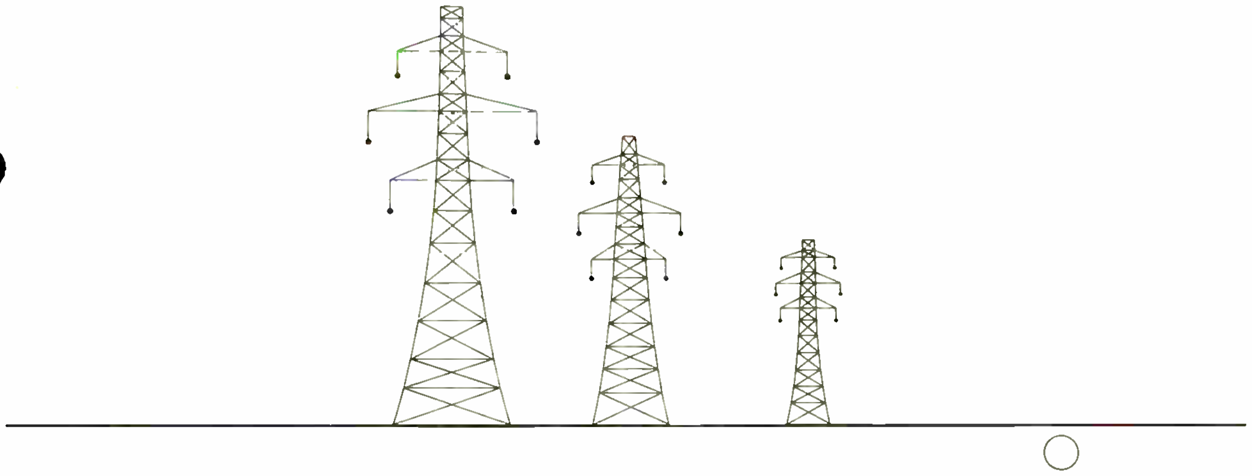
[i] SF_6 at 5 psig; WR 340 waveguide; air-cooled.

[j] SF_6; WR 137 waveguide, water cooled.

[k] SF_6 at 28 psig; WR 284 waveguide.

[l] From input to generator to output from converter. Range: ∼ 200 miles.

[m] From input to generator to output from rectifier. Range: ∼ 18 feet at 3 Gc/s.



Towers (of parallel double 3-phase circuits)	1	2	36	Waveguide: circular, TE$_{01}$ Mode	
Voltage, kV/tower	700 (exper.)	400	132	Diameter: ~ 1 meter	1½ meters
Total power, GW CW	4	4	4	2	4
Circuits/tower	2	2	2		
Phase	3	3	3		
Frequency	60 c/s	60 c/s	60 c/s	10 Gc/s	
Line (ohmic) attenuation, dB/km	~ 0.001 (not "bus to bus")			~ 0.001	
Corona loss:					
Normal, kW/mi	2			negligible	
Rain, kW/mi	< 200			none	

Fig. 30. Power capability of transmission lines (based on minimum annual transmission cost) and re-entrant oversized waveguide with air at normal temperature, pressure, and humidity.

Such low attenuation may be realized with a re-entrant oversized waveguide designed for the circular electric mode provided continuous extraneous mode filtering[43] can be developed at least as successfully as it has been for communication purposes. This may not prove to be as difficult as it seems because of the simpler single frequency and pioneering (communication) achievements pointing the way.

Since waveguide power capacity is high enough to meet any reasonable requirement, a solution to the attenuation problem will place the waveguide under plausible consideration as a more desirable means of transmitting power than the conventional open-wire three-phase transmission line. Under normal temperature and pressure, its power-handling capacity can match the 700-kV three-phase two-circuit transmission line now under development[45,46] (see Fig. 30). This is a capability of the order of 4 GW. Placing the waveguide under gas pressure can substantially increase its power-handling capacity without a corresponding increase in size. In addition, it can be buried, affording greater military security and reducing the right-of-way problem in urban areas.

With respect to microwave radiation beam or "wireless" power transmission, laboratory developments are encouraging, primarily as a result of the efforts of a few pioneers in the United States[1,47] and, apparently to an undetermined extent, in the U.S.S.R.[48] Interest in a technique for high-duty illumination of a hovering vehicle has spurred the development of an extremely lightweight self-rectifying dipole antenna array. This antenna will provide an alternative to the self-contained vehicle power supply. The parabolic sheet antenna has been shown to be theoretically impractical for efficient microwave power transmission.[49] It is too cumbersome and too critical in adjustment ($\lambda/10$), and it is too limited in size (1000λ) for hovering vehicles at the desired distances between near space and synchronous orbit.[49,50]

Promising microwave rectifiers are the thermionic diode,[51] point-contact semiconductor diode,[35] the electrostatically focused klystron,[32] and the multipactor.[38] The crossed-field type[30,37] (magnetron rectifier and microfier) has not yet achieved its theoretical expectations.[52] Generally speaking, with respect to CW power and efficiency, the microwave rectifier has not developed to the same degree as its generator counterparts. However, there is no inherent technical limitation to the development of the microwave rectifier as an efficient and high-power device, and it would be expected to respond favorably to a greater level of interest and support.

As a result of the substantial advances that have recently been made in the technology of microwave power engineering, it is expected that there will be an increasing interest in applying this new technology. As the new technology matures, it may be possible to apply it successfully in direct competition with other existing technologies for the generation, transmission, and utilization of power.

Thanks are due R. B. Nelson for current developmental information on klystron generators; S. P. Yu of Litton Industries for current information on the klystron rectifier; and P. P. Keenan for the multipactor rectifier. The authors are also indebted to V. C. Vannicola for some current information on waveguide power capabilities, and to General Electric and Eitel-McCullough for permission to use their klystron data.

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Optical computing techniques

The properties of coherent light have found practical application in the performance of many operations on signals. In addition to solving spectral analysis and filtering problems, optical techniques can be used for analog computations

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During the past decade, optical techniques have received increased attention from a growing number of physicists and engineers. This increased activity has stemmed in part from the invention of the laser and in part from a realization that optical configurations can be used to perform a wide variety of operations on signals. Moreover, methods have been devised whereby two-dimensional optical operations can be converted to a multiplicity of one-dimensional operations.

Although both coherent and noncoherent techniques have been employed for analog computations, the former are by far the more versatile and useful. In coherent configurations the phenomenon of diffraction is employed. If a lens is placed a focal distance away from a transparency, the light at a focal distance from the lens on its output side is distributed according to the two-dimensional spectral analysis of the object.

By the addition of a cylindrical lens to this configuration, the equipment is converted to one with multichannel capabilities. In this case, instead of a single two-dimensional analysis of the transparency, a number of one-dimensional spectral analyses are obtained.

If it is desired to perform simple filtering operations on signals, an optical system can be arranged in which two configurations of either of the types described are in tandem. One can operate upon the spectrum at an intermediate plane so that the output image reflects the effects of these changes. In one simple case, a pass band in an optical filter is merely a transparent region in the spectral plane; a stop band, on the other hand, is an opaque spot that is placed at the appropriate point in the spectral plane.

Another operation of interest is that of multiplication, which arises in conjunction with autocorrelation, cross-correlation, convolution, and other linear operations. Multiplication is achieved optically by imaging one transparency on another.

Optics configurations are capable of performing essentially any linear operation on a function of a single variable. In most cases one has the choice of using the optics as a single two-dimensional channel or as a multiplicity of one-dimensional channels. In the latter case 50 channels per millimeter can be achieved easily. By means of 35-mm optics, with 27 mm active, there is a capability of some 1350 channels.

Basic diffraction phenomena

Much of the capability of optical equipment as a computing tool arises from diffraction phenomena. For this reason, two basic configurations that appear repeatedly in computing applications will be described:

1. A configuration using a spherical lens, which produces two-dimensional diffraction (Fig. 1).
2. A configuration consisting of a spherical lens in conjunction with a cylindrical lens, which produces a multiplicity of one-dimensional diffraction patterns.

In Fig. 1, S represents a source of light, L_1 represents a collimating lens, P_1 represents the input plane in which a transparency is placed, and L_2 is the spherical lens, which is the essential element for producing a two-dimensional diffraction pattern. The two-dimensional spectrum of the transparency in P_1 is exhibited in P_2.

If the distribution of light in P_2 is to be the two-dimensional spectrum analysis of the density distribution of the transparency in P_1, it is necessary for P_1 and P_2 to be spaced a focal length on either side of L_2. If $f(x, y)$ represents the amplitude of light emerging from P_1, the distribution of light amplitude in P_2 is given by

$$F(\alpha, \beta) = \iint f(x, y)^{jk(\alpha x + \beta y)} dx\, dy \qquad (1)$$

In this equation, the amplitude of the light in P_2 is given by $F(\alpha, \beta)$. Here k represents the wave number of the light, and α and β represent the direction cosines of the diffracted beam with respect to the x and y axes.

The configuration in Fig. 1 produces a single two-dimensional diffraction pattern. This equipment can be converted to a multichannel one-dimensional diffraction equipment by the addition of a cylindrical lens between P_1 and P_2, to give the configuration shown in Fig. 2. In this case the distribution of light in P_2 is given by

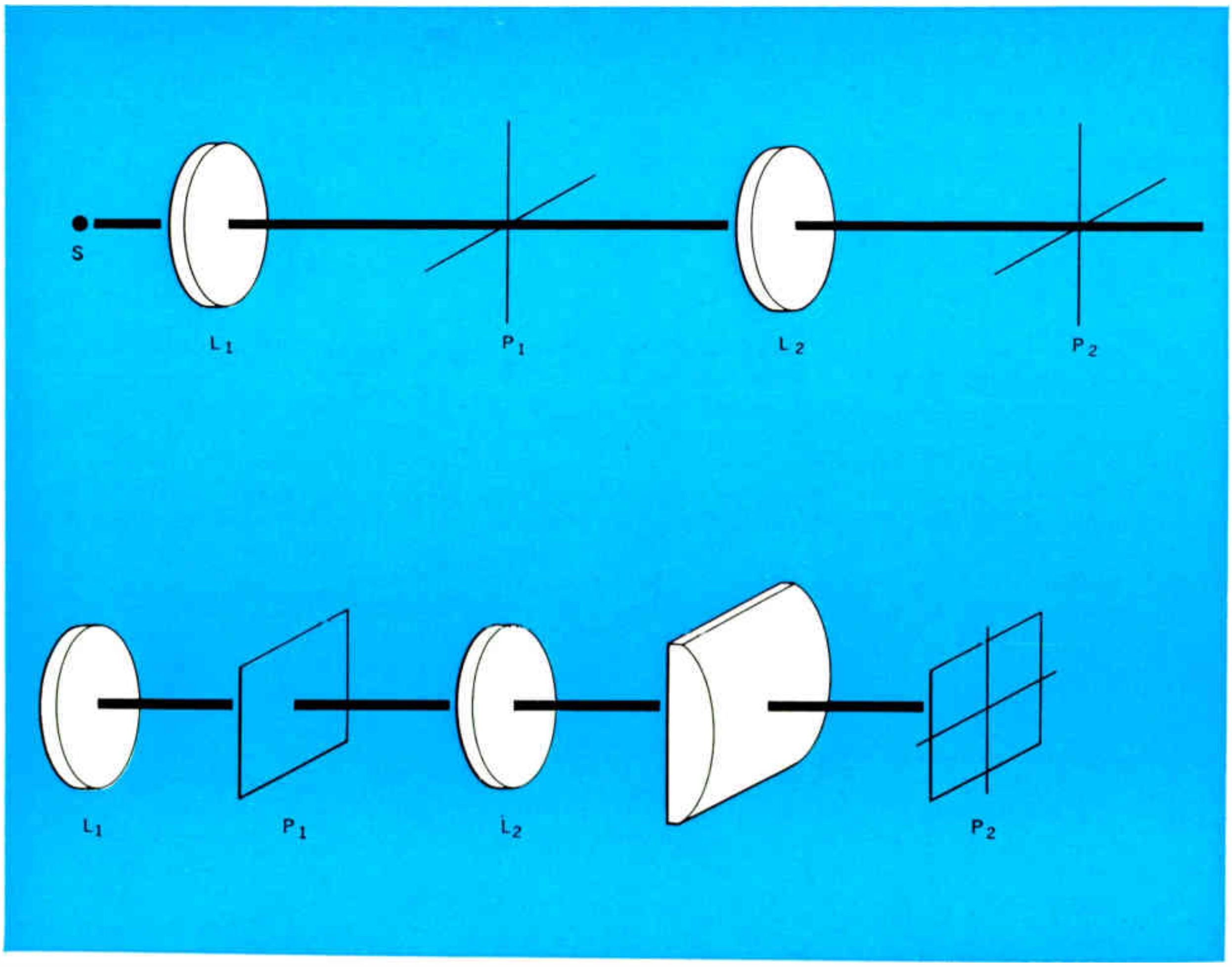
$$F(\alpha, y) = \int f(x, y)\, e^{jk\alpha x}\, dx \qquad (2)$$

It will be noted that this expression indicates distribution corresponding to a multichannel spectrum analysis. The parameter y is an index referring to a given channel.

Filtering operations and spectrum analysis

Optical equipment can be usefully employed in a number of filtering and spectrum analysis operations.

Fig. 1 (top). Configuration for use in two-dimensional spectrum analysis. Fig. 2 (bottom). Configuration for multichannel one-dimensional diffraction.



If a display of the spectrum is the desired output, the configurations shown in Figs. 1 and 2 are used. For two-dimensional spectrum analysis, the two-dimensional signal to be analyzed is recorded on a transparency by whatever means are appropriate to obtain this image; for example, a photograph may be taken of the object or a line-by-line build-up of the image may be used. In the multichannel case a number of separate lines must be recorded.

If a transparency is placed in plane P_1 of the optical configuration shown in Fig. 2, the output will consist of a multiplicity of spectral analyses, each input having its corresponding output channel in P_2.

Where it is desirable to perform filtering operations upon the recorded signals it is usually necessary to view the signals corresponding to these altered spectra. Alteration of the spectrum and viewing of the result are accomplished by modifications of the optical figurations of Figs. 1 and 2 to those shown in Fig. 3(A) and (B), respectively.

These configurations permit operations on the spectra by band-pass and band-stop filtering in plane P_2. A pass band is achieved by having a transparent region at the appropriate position in P_2; a band stop is achieved by locating an opaque spot in P_2.

A common application of these techniques is contrast improvement in photographs. Because low contrast is a consequence of an average illumination level that is large compared to the fluctuations in illumination level, a reduction in the average will increase the contrast of the image. If an opaque or partially transparent spot is placed on the optic axes in plane P_2 of Fig. 3(A), all

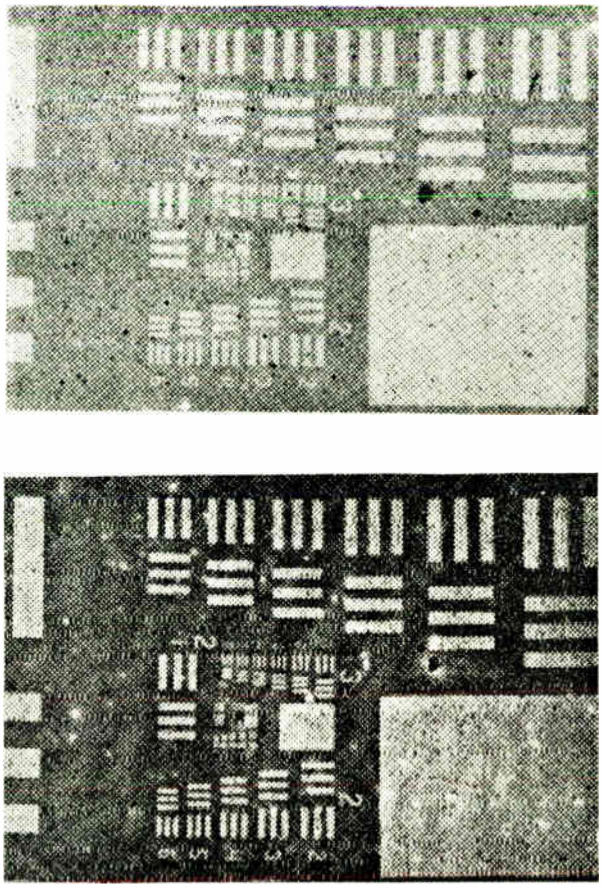
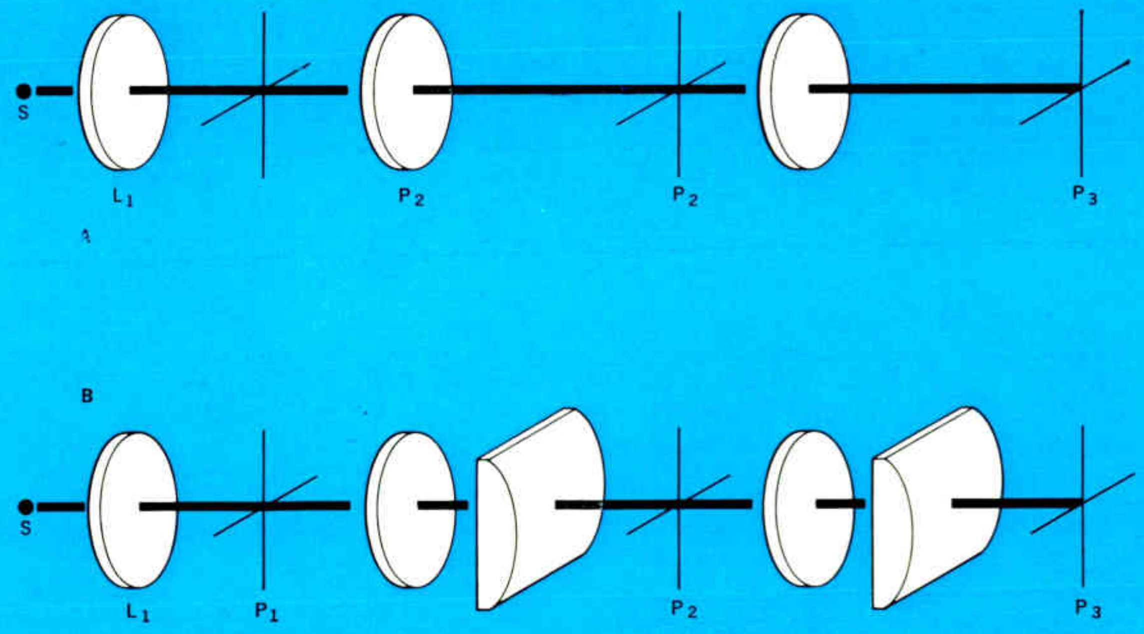


Fig. 4. Contrast improvement.

Fig. 3. Configurations for performing filtering operations on recorded signals. A—Two-dimensional diffraction. B—Multichanne' one-dimensional diffraction.



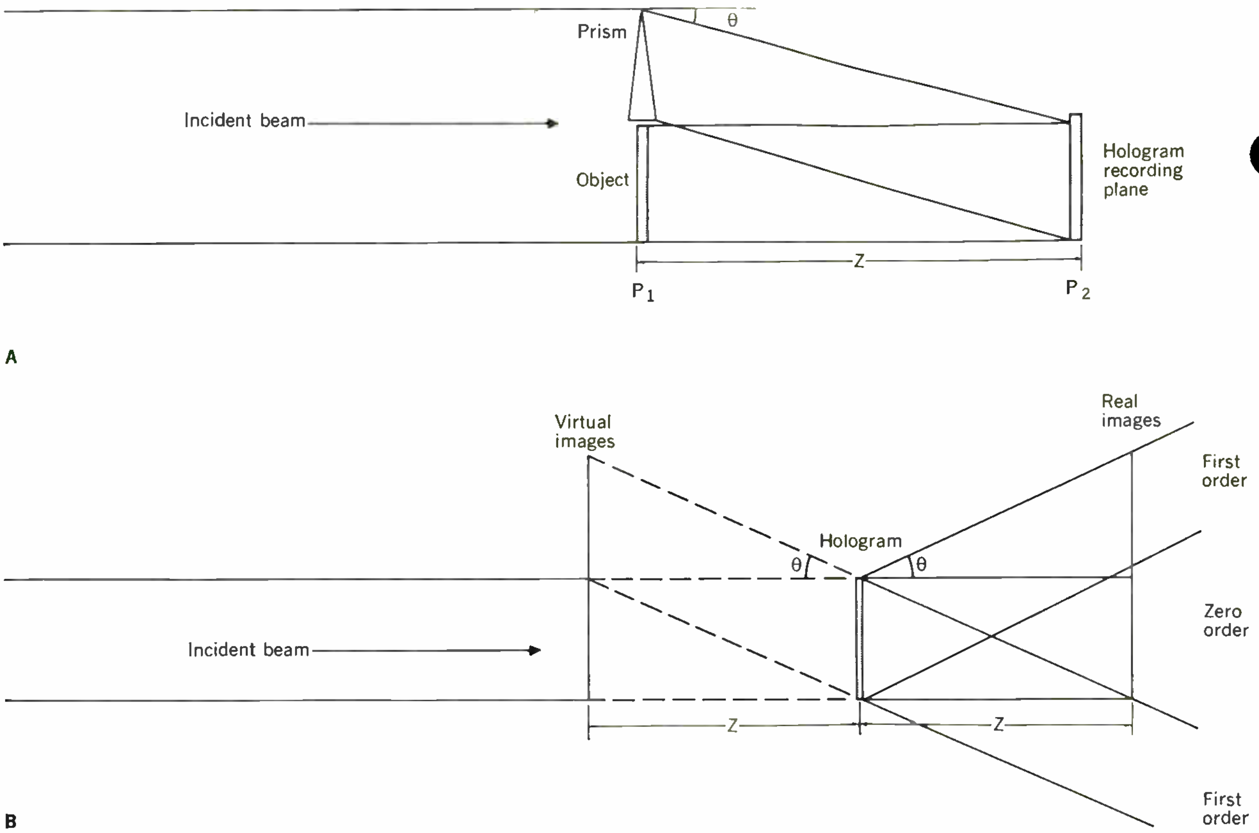


Fig. 5. A —Wedge technique for producing a two-beam hologram. B—The reconstruction process. Low-quality conventional reconstructions occur on the hologram axis; high-quality reconstructions occur in the first-order diffracted waves.

or part of the dc component (average illumination) will be removed. Figure 4 shows an example of the improvement in contrast that can be achieved by this means.[1] In the multichannel one-dimensional case, for which the configuration of Fig. 3(B) is appropriate, a wire can be used to remove the dc component simultaneously from all of the channels.

A more complicated filtering operation can be achieved by placing in P_2 a transparency having a density that varies as a function of position. Since position in P_2 corresponds to specific values of the spectral variables, the effect is that of a filter that changes the relative magnitudes of the spectral components.

Sometimes the filter can be made with the equipment arranged as in Fig. 3(A) or 3(B). In this case, an object whose spectrum is desired is placed in P_1. An unexposed photographic plate is placed in P_2 and exposed by the light incident upon this plane. The processing of the film as a positive (by reversal or by contact printing of a negative) gives the spectrum corresponding to the object. Pass bands at appropriate locations pass the spectrum corresponding to the object used in making the filter. Such a filter is extremely useful for enhancing a given object while suppressing other objects in the field. A more difficult filter to make is one in which phase variations are desired. The problems in making filters of this kind arise largely from the short wavelengths of light.

In the most general case, both the magnitude and phase shift of the spectra should be variable. Here two transparencies may be placed in contact in P_2—one having a varying density and the other having a varying phase shift. There are many instances in which this type of filtering is useful. Information theory indicates that in a number of cases it is desirable to pass a signal through a matched filter. In general the matched filter will require a variation of both magnitude and phase. The difficulty in achieving sufficient accuracy in the phase filter, however, has brought about a search for techniques that are equivalent but in which the recording of density alone is sufficient.

At least two such techniques have been successfully demonstrated. In one case, use is made of the fact that the Fourier transforms of a symmetric function are real. The object whose spectrum is desired is printed with appropriate symmetry so that its transform is real.

A second scheme for achieving the equivalent of a complex filter (magnitude and phase shift both variable) makes use of a technique recently demonstrated by Leith and Upatnieks[2] and by Vander Lugt.[3] In this case a recording is made in which both phase and magnitude are preserved but in which this information can be recovered from a transparency having density variations only. The configuration required is shown in Fig. 5. In this equipment the object whose spectrum is desired is illuminated with coherent light.

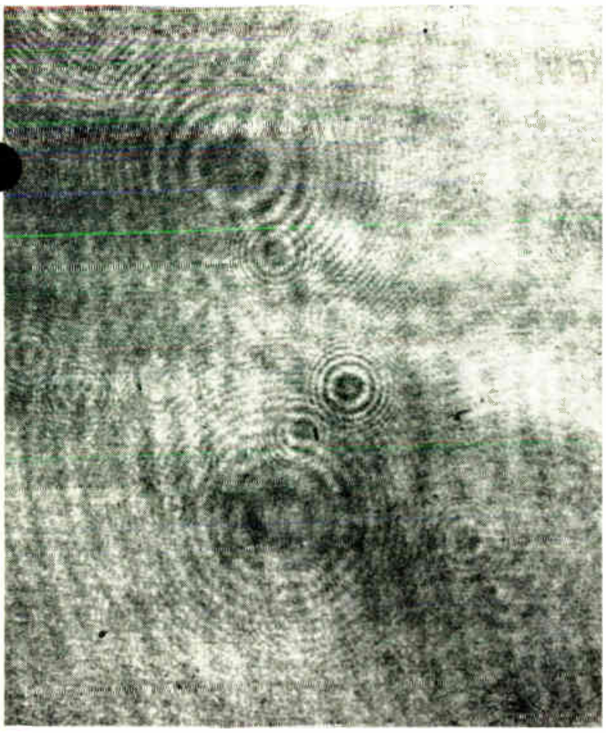


Fig. 6. Hologram produced by means of a photographic transparency of a scene.

Fig. 7. Reconstruction of the scene of Fig. 6.

A hologram is produced by recording on photographic film the interference pattern resulting from the illumination of some object with a wavefront from the same source; see Figs. 6 through 8. The reference wavefront is made to be incident upon the recording film at an angle so that the phase of the incident light progresses linearly across the film and becomes a carrier for the information-bearing part of the signal.

Let $A_1e^{j\varphi_1}$ represent the signals, incident upon the photographic plate, which have come from the transparency. Both A_1 and φ_1 are to be considered as functions of x and y. Let the reference signal have the form $A_0 e^{j\varphi_0}$. Here, too, A_0 and φ_0 are functions of x and y. The amplitude of the light incident on the photographic plate is given by

$$A(x, y) = A_1e^{j\varphi_1} + A_0e^{j\varphi_0} \tag{3}$$

The intensity I recorded on the film is given by

$$\begin{aligned} I &= |A|^2 = |A_1e^{j\varphi_1} + A_0e^{j\varphi_0}|^2 \\ &= |A_1|^2 + |A_0|^2 + 2|A_0|\,|A_1| \cos(\varphi_1 - \varphi_0) \end{aligned} \tag{4}$$

It will be noted that the recorded intensity contains terms dependent both upon the amplitudes and upon the phases of the signals. The recorded hologram has the form given by (4).

Let us consider, next, the effect of illuminating a transparency upon which this signal has been recorded in a configuration appropriate to the reconstruction of the image. Let us then perform a two-dimensional spectrum analysis upon each of the terms in (4). To do this, however, it is useful to be more specific regarding the nature of A_0 and φ_0.

The reference signal used in recording the hologram is a plane wave incident at some angle upon the photographic plate. This implies that A_0 and φ_0 are of the form

$$A_0 = \text{constant} \qquad \varphi_0 = kx \sin\theta = \omega_0 x \tag{5}$$

The phase φ_0 becomes a carrier for the phase information contained in φ_1. It is important to choose the effective carrier frequency ω_0 so that it is higher than the frequency content in A_1.

The term corresponding to $|A_0|^2$ will correspond to a distribution of light near the optical axes; the light corresponding to the $|A_1|^2$ will, to a greater or less extent, resemble the image on the transparency in Fig. 5(A). The signals resulting from the third term of the final expression in (4) can be considered as the result of two terms as given by

$$\begin{aligned} &2A_0A_1 \cos(\varphi_1 - \varphi_0) \\ &\qquad = A_0A_1e^{[j(\omega_0x-\varphi_1)} + e^{-j(\omega_0x-\varphi_1)}] \end{aligned} \tag{6}$$

Each of the terms in (5) represents the signal $A_1e^{j\varphi_1}$ with all its phase and amplitude information. The carriers indicate signals traveling in different directions. Two images are produced, one to the left of the optic axis and one to the right. To arrive at this conclusion, use is made of the translation theory of Fourier analysis, which states that a multiplying factor of the form $e^{j\omega_0x}$ results in a translation of its transform.

It is significant that the light incident upon P_2 at the location of each of these images contains information concerning both the phase and the amplitude of the original image. If the stops in the optical system are arranged to remove terms arising from the spectrum of the terms $|A_0|^2$ and $|A_1|^2$ and one of the terms corresponding to the last term of (4), a reconstruction that reproduces both the amplitude and phase of the object is achieved. Since this technique can be used for generating a complex signal, which is the most general form, it should find wide application in filtering problems.

It is to be noted that although the reconstruction produced an image with both the phase and the amplitude characteristics of the original object, the recorded signals were positive real quantities—namely, the intensities given by (4).

Linear operations

Optical equipment can be assembled to perform many linear operations, including autocorrelation, cross-correlation, convolution, matched filtering, ambiguity function display, integration, etc. In this section the configurations that can be used to perform these operations will be given, together with a brief discussion of their operation.

Autocorrelation and cross-correlation. The important linear operations of autocorrelation and cross-correlation will be considered together since the equipment needed to mechanize the operations is identical. Cross-correlations and autocorrelations involve the operations performed in (7) and (8), respectively:

$$\varphi_{fg}(x_0) = \int f(x)\, g(x - x_0)\, dx \tag{7}$$

$$\varphi_{ff}(x_0) = \int f(x)\, f(x - x_0)\, dx \tag{8}$$

It will be noted from (7) and (8) that to mechanize these operations, techniques are needed for performing multiplication, translation, and integration. A configuration capable of performing a multiplicity of autocorrelations or cross-correlations is given in Fig. 9. In this figure the source and collimating lens to the left of P_1 cause a plane coherent wave to be incident on the transparency $f(x, y)$.

The optics between P_1 and P_2 causes the multichannel spectrum analysis of $f(x, y)$ to appear in P_2. The optics between P_2 and P_3 performs a second multichannel spectrum analysis of the signals in P_2; thus, incide upon P_3 is the function $f(x, y)$. If one looks through P_3 toward the source, the distribution of light will be the product $f(x, y)\, g(x, y)$.

If the holder containing the function $f(x, y)$ has a provision for transporting the transparency along the x axis and if this displacement is through a distance x_0, then the distribution of light in P_3 looking toward the source will be the product $f(x, y)\, g(x - x_0, y)$.

The combination of spherical and cylindrical optics between planes P_3 and P_4 causes a multichannel spectrum analysis of the light distribution emerging from P_3. Hence, the distribution of light in P_4 is described by

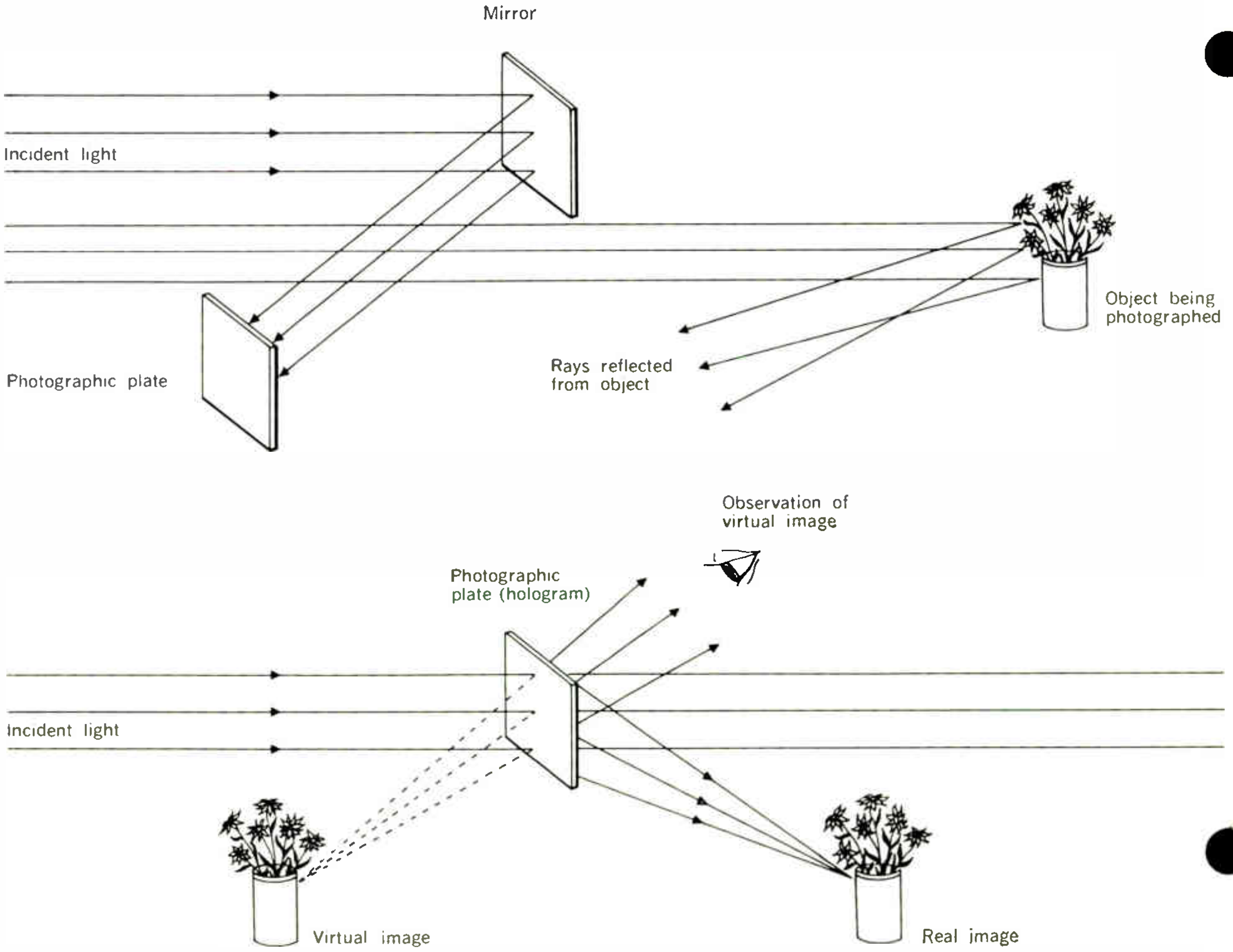
$$\varphi(x_0, y; \alpha) = \int f(x, y)\, g(x - x_0, y)\, e^{j\varphi z}\, dx \tag{9}$$

where

$$\alpha = \frac{2\pi}{\lambda} \sin\theta$$

It will be noted that this equat ion resembles (7) except

Fig. 8. A—Basic technique for making a hologram. B—Reconstruction of the image.



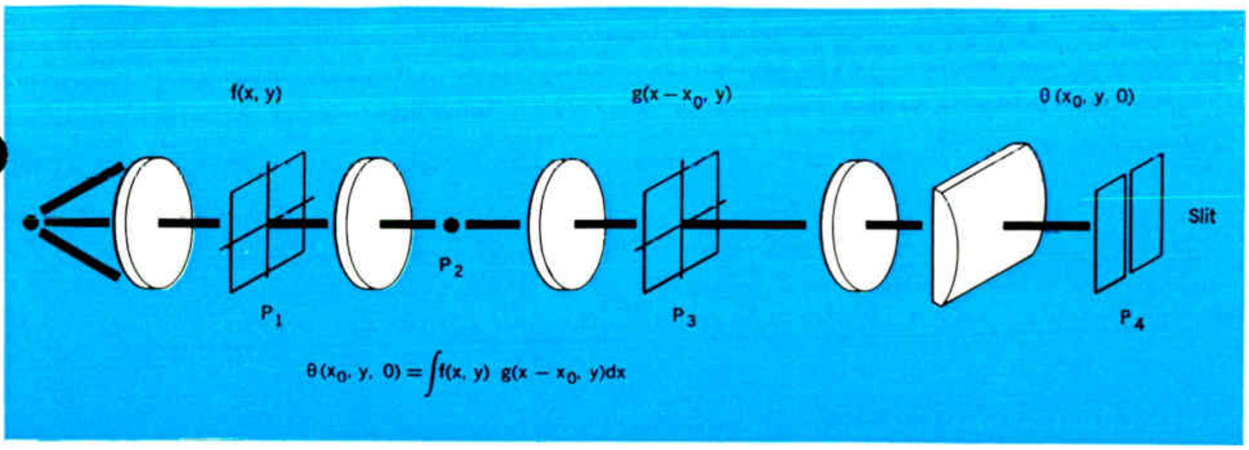


Fig. 9. Cross-correlator configuration.

that many operations are performed (one for each value of y) and that the factor $e^{j\alpha x}$ appears as a factor in the integrand. In (9), $\alpha = 0$ corresponds to the light in a slit parallel to the y axis. If only the light in this slit is recorded, the exponential factor in (9) assumes the value of unity. In this case, (9) becomes identical with (7) except for its multichannel feature. This result is written as

$$\varphi(x_0, y, 0) = \varphi_{fg}(x, y) \tag{10}$$

As P_3 is transported, at a given position in P_4, there will appear an amplitude of light corresponding to the value of the cross-correlation function for that value of the displacement x_0. This autocorrelation function can be recorded by transporting a film past the slit. The configuration in Fig. 9 is, thus, capable of performing a large number of simultaneous correlations. To perform an autocorrelation by means of this configuration, one uses a second copy of $f(x, y)$ in P_3.

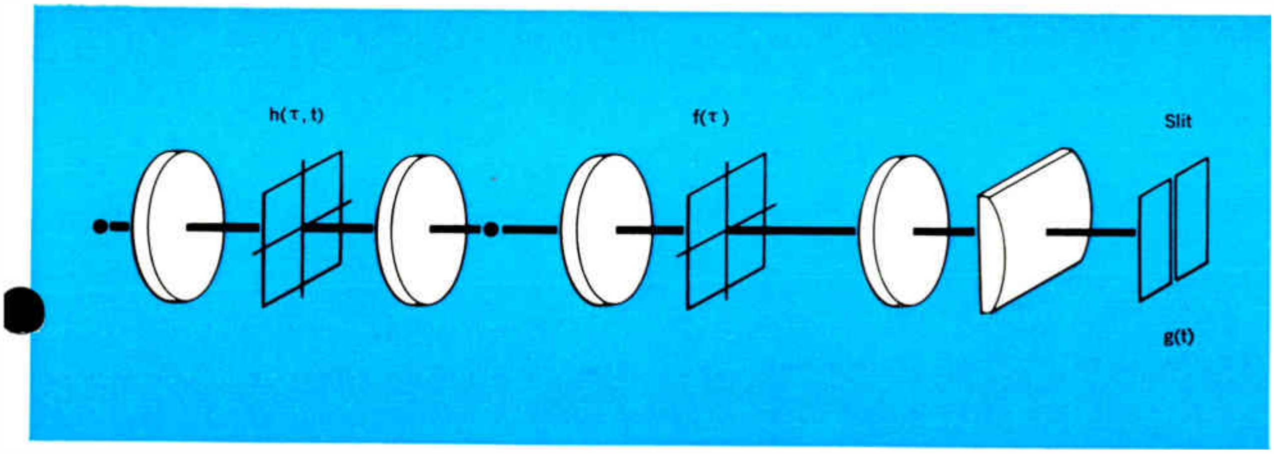
In Fig. 9 a relatively complicated optical arrangement is used to image plane P_1 onto P_3. This configuration is necessary to remove errors that arise from bias levels used in recording the signals in P_1 and P_3. There are many instances in which information theory indicates autocorrelations or cross-correlations as optimum signal detection or parameter estimation operations. The configuration of Fig. 9 permits the performance of a number of these operations concurrently. There is no difficulty in recording onto film a density of 50 cycles per millimeter. Hence 35-mm film can be used to perform simultaneously more than 1000 simultaneous autocorrelations or cross-correlations.

Optical implementation of a general linear operation. The most general linear operation [0] on a function $f(t)$ to produce an output $g(t)$ can be written in the form

$$g(t) = 0[f(t)] = \int h(\tau, t) f(\tau)\, d\tau \tag{11}$$

In this equation, the nature of the operation to be performed determines the kernel function $h(\tau, t)$. The fact that (11) represents a general linear operation is discussed in texts dealing with functional analysis.

Fig. 10. General linear operation configuration.



Pertinent discussions have also been given by L. A. Zadeh.[4]

The operation given by (11) may be effected by the configuration of Fig. 10. If one looks toward the left, the light amplitudes in the plane containing $f(\tau)$ contain the product of $h(\tau, t)$ with $f(\tau)$.

Between the transparency $f(\tau)$ and the output slit in which $g(t)$ is found is a pair of lenses, one spherical and the other cylindrical. This arrangement performs the function of causing the line-by-line spectral analysis of the light in the $f(\tau)$ plane to be displayed in the output plane. The distribution of light in the output plane is given by (12).[5] It will be noted that this equation is a somewhat more general operation than that described by (11), and that it describes a two-dimensional distribution of light in the output plane.

$$I(t, \omega) = \int h(\tau, t)\, f(\tau)\, e^{-j\omega\tau}\, d\tau \qquad (12)$$

If ω is set equal to zero in (12), the equation becomes identical to (11). Thus, the performing of a linear operation expressed as (11) is accomplished simply by observing the light in the output plane that is present in the central slit. The location of this slit corresponds to ω equals 0 in (12). The result may be written as

$$g(t) = I(t, 0) \qquad (13)$$

Thus, performing a general linear operation optically requires the configuration shown in Fig. 8(A)—together with the ability to record on two transparencies the functions $h(\tau, t)$, which represent the operations to be performed, and the function $f(\tau)$, which represents the function upon which the operation is to be performed. The result of the operation is present in a centrally located slit in the output plane of the equipment.

It can be shown that if a number of linear operations are to be performed in tandem, the sequence can be represented by a single equivalent operation. Hence, (11) not only represents a single operation but also can be employed to represent a sequence of linear operations if desired.

The optical technique has been successfully used in a number of signal processing situations. Spectrum analysis, autocorrelation, cross-correlation, and matched filtering are all special cases of linear operations, as are differentiation and integration.

Examples

Optical techniques for spectrum analysis often have been applied to vibration analysis problems. Here recordings of vibration data onto photographic film have been made using density modulation of the film. The result is a recorded format of density (representing vibration amplitude) versus time (represented by distance along the film). The insertion of such a record with a multiplicity of traces into P_1 of Fig. 2 gives the corresponding frequency analysis in P_2. The result can be recorded onto a film in P_2, or photoelectric readout can be performed. A group of these components, mounted on an optical bench designed for ease of their rearrangement, is commercially available.

In the case of cross-correlation, vibration analysis again provides an example. Vibration data from a number of points have been recorded and the cross-correlation of these data from different points has been performed. The output may be sensed either photographically or by photoelectric means.

In other cases, pseudorandom codes have been recorded and cross-correlated. The results observed experimentally closely duplicate those predicted by the theory.

Finally, with respect to many problems, the optical configuration remains relatively variant; to change the problem one simply changes the signals recorded on the transparencies.

Conclusions

Through use of the properties of coherent light, optics can provide a versatile and powerful tool for performing a number of operations on signals.

The configurations and operations described in this article are by no means exhaustive. It is hoped, however, that sufficient information regarding fundamentals has been presented that the reader can proceed to use optical computing as a means to solve those problems appropriate to the technique.

The author gratefully acknowledges permission given him by E. O'Neill for the use of Fig. 4 and to E. N. Leith, J. Upatnieks, and the Optical Society of America for the use of Figs. 5 through 8.

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The current state of the science of marine navigation

A review of the past fourteen years' work in marine safety systems shows many major advances in fulfilling basic requirements. Characteristics of five complementary systems are compared.

C. M. Jansky, Jr. *Jansky & Bailey*

There are four basic marine safety requirements that, properly implemented, substantially improve safety in marine navigation and expedite the movement of ships. These four requirements, which I had the opportunity to set forth in 1950,[1] and all of which could have been met even in 1950, are as follows:

1. The navigating officers of a ship should be able to detect both the relative and absolute position of all other vessels with which there is danger of collision. This calls for an adequate ship's radar.
2. It should be possible for the ship's navigating officers to establish contact and intercommunicate almost instantaneously with their counterparts on other ships within a range of at least 20 or 30 miles. Also, the same capability should exist between ships and shore stations concerned with supplying navigational and operational information or the control of marine traffic.
3. When there is intercommunication between the officers of two vessels within radar range, it should be possible for those on either vessel to identify on the radar scope the response representing the other regardless of the presence of a number of vessels in the immediate area.
4. The navigating officers of a ship should know the ship's position at all times. The degree of accuracy required is dependent upon the position of the ship with respect to shore as well as upon other conditions affecting safety.

These four requirements should be met at all times regardless of visibility conditions.

In 1950, I stated that (1) there was available scientific knowledge which, if properly applied, would make it possible to meet all four requirements; (2) the cost of meeting these requirements would be small compared with the monetary savings resulting from the more expeditious movement of ships; and (3) there would be a substantial improvement in marine safety which could not be measured monetarily. In view of the differences of opinion and viewpoint that still exist with respect to the importance of the stated requirements as well as the relative merits of the various radio and electronic devices proposed for meeting them, it may not be inappropriate at this time for a porthole navigator (see definition in box) to review the progress of the past 14 years.

The author defines

My definition of a porthole navigator is a scientist or engineer who has spent substantial time on the bridges of ships studying the application of science to marine navigation. It is one thing to be such a student of marine navigation. It is quite another to be the navigating officer responsible for the safety of a ship, its passengers, and its crew. As a porthole navigator who has spent hundreds of hours on the bridges of ships, this is a difference in viewpoint I try never to forget.

Requirement 1—Ship-borne radar

With respect to Requirement 1, there have been many improvements in both ship-borne and shore-based radar. These are not discussed in this article except to mention true motion and automatic plotting techniques. The experimental work now being carried on by the United States Coast Guard with RATAN is also worthy of note.

Requirement 2—A universal navigational maritime radiotelephone system

Much progress has been made in the development and activation of a radiotelephone system capable of meeting Requirement 2. The history of this development may be briefly summarized:

In 1946 and 1947, Jansky & Bailey, acting as consulting electronic engineers for Lake Carriers' Association (member companies include practically all companies operating large United States flag Great Lakes vessels), undertook experimental studies directed toward developing a Great Lakes multichannel, very-high-frequency (VHF) marine radiotelephone system. This was necessary because the traffic density resulting from the great increase in navigational traffic on the Great Lakes medium-frequency (MF) radiotelephone system was already resulting in congestion. (Today at least 80 per cent of the Great Lakes radiotelephone traffic falls into the navigational, operational category. The remainder is public correspondence traffic.)

As a result of these VHF studies, Jansky & Bailey, on behalf of Lake Carriers' Association, submitted evidence before the United States Federal Communications Commission (FCC) for a multichannel, calling-channel, working-channel VHF system for the Great Lakes. In 1951 the FCC adopted regulations establishing such a system. (I gave the testimony, wrote the briefs, and personally handled the oral argument in this proceeding before the FCC.) The Canadian government adopted regulations providing for substantially the same system in Canadian waters.

The Great Lakes VHF system furnished the pattern for the European 28-channel VHF system established at a Regional International Telecommunications Union (ITU) Conference held at The Hague, Netherlands, in January 1957. The Hague VHF allocations and regulations were adopted for world-wide application almost verbatim at the ITU Radio Conference held in Geneva, Switzerland, in 1959. This system, when fully activated, is capable of meeting Requirement 2, that is, providing a means by which navigating officers on ships in a given area can establish contact and intercommunicate with each other and with those at shore radiotelephone stations concerned with marine navigation.

While the fundamental operational principles incorporated in The Hague–Geneva VHF marine radiotelephone system were first developed in United States and Canadian waters, namely the Great Lakes, it must be recorded that the only opposition to their world-wide application came from certain United States commercial interests and certain members of the United States Delegation to the Geneva 1959 ITU Radio Conference. Except on the Great Lakes, where VHF radiotelephone operations are in complete accord with international practice, VHF radiotelephony is at present much more extensively used for handling navigational functions in European than in United States waters.

It should be noted that United States Coast Guard shore stations and vessels, as well as vessels operated by the Military Transport Service, together with a limited number of United States flag ocean-going commercial vessels, are being equipped for the international multichannel VHF marine radiotelephone system. However, the strong opposition of certain United States commercial interests to the basic systems philosophy set forth in the Geneva 1959 International Maritime VHF Radio Telephone Regulations and the resultant derogation of these international regulations by the FCC in writing its own regulations, has materially retarded the development of marine navigational radiotelephony in U.S. waters other than the Great Lakes.

Harbor guidance systems in Europe

The rapid activation in Europe of the international VHF radiotelephone system coupled with improvements in high-definition shore-based radar and ancillary devices has prompted the development in many European ports of highly efficient harbor guidance systems. Mention should be made of the systems at Southampton, Liverpool, and the Thames River, England; the approaches to Rotterdam and Amsterdam, Holland; Hamburg, West Germany; Le Havre, France. This list is not complete but it illustrates the progress made in Europe.

Harbor guidance systems in the United States

While there are some simple applications of shore-based radar to harbor guidance, there are no harbor guidance systems in United States ports that in efficiency and complexity compare with those in Europe. While a number of considerations have contributed to this situation, one factor that without doubt has retarded the development of adequate harbor guidance systems in United States ports has been failure to accept and equip shore stations and vessels for the international multichannel VHF radiotelephone system. Adequate universal radiotelephone facilities are essential for the operation of a complete harbor guidance system. In Southampton, for example, the handling of all necessary radio navigational traffic requires a total of 11 VHF channels.

Requirement 3—A marine radar identification system

The third requirement for safety in marine navigation set forth in 1950 was for a device which, when coupled with the use of radiotelephony, would enable the observer of a radar scope to identify positively the particular radar response representing the ship with which he had established communication. No progress has been made in meeting this requirement. There are those with an initimate knowledge of marine navigation who hold that there is no requirement for a marine radar identification device or system. However, discussions I have had with others, including some directly concerned with the operation of harbor guidance systems, convinces me that there is such a requirement and that it needs active study.

Requirement 4—Accurate determination of a ship's position

Requirement 4 states that a navigating officer know accurately the geographical position of his ship at all times. The degree of accuracy required depends upon many considerations. To illustrate, under normal conditions the exact position of a ship in mid-ocean may not be important. However, if a distress situation develops, the rapidity with which rescue craft can reach the scene, or perhaps the possibility of reaching it at all, may depend upon the accuracy with which the ship's position can be reported.

There are numerous devices and systems available for the determination of a ship's position including (1) dead reckoning, (2) celestial observations, (3) radio beacon systems, (4) hyperbolic radio systems, (5) shipborne radar, (6) radiotelephone or radiotelegraph reports from shore-based radar stations. Of course, not all systems are available in all areas or at all times.

Before discussing the characteristics of certain electronic marine position-finding systems now in general use, I would like to call attention to an operational procedure that should be accepted as basic by all concerned with marine navigation, namely—a good navigating officer never relies entirely upon any single position-finding system unless conditions force him to do so. When possible, he uses all systems or devices available to him. As a porthole navigator on a well-equipped, well-run ship* approaching the coast of Europe, I watched the navigating officers determine the ship's position by six different methods.

Five important radio or electronic position-finding systems are:

1. Consol
2. Marine beacons
3. The Decca Navigator system
4. The Loran A system
5. The Loran C system

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* The Holland America Line *S. S. Rotterdam.*

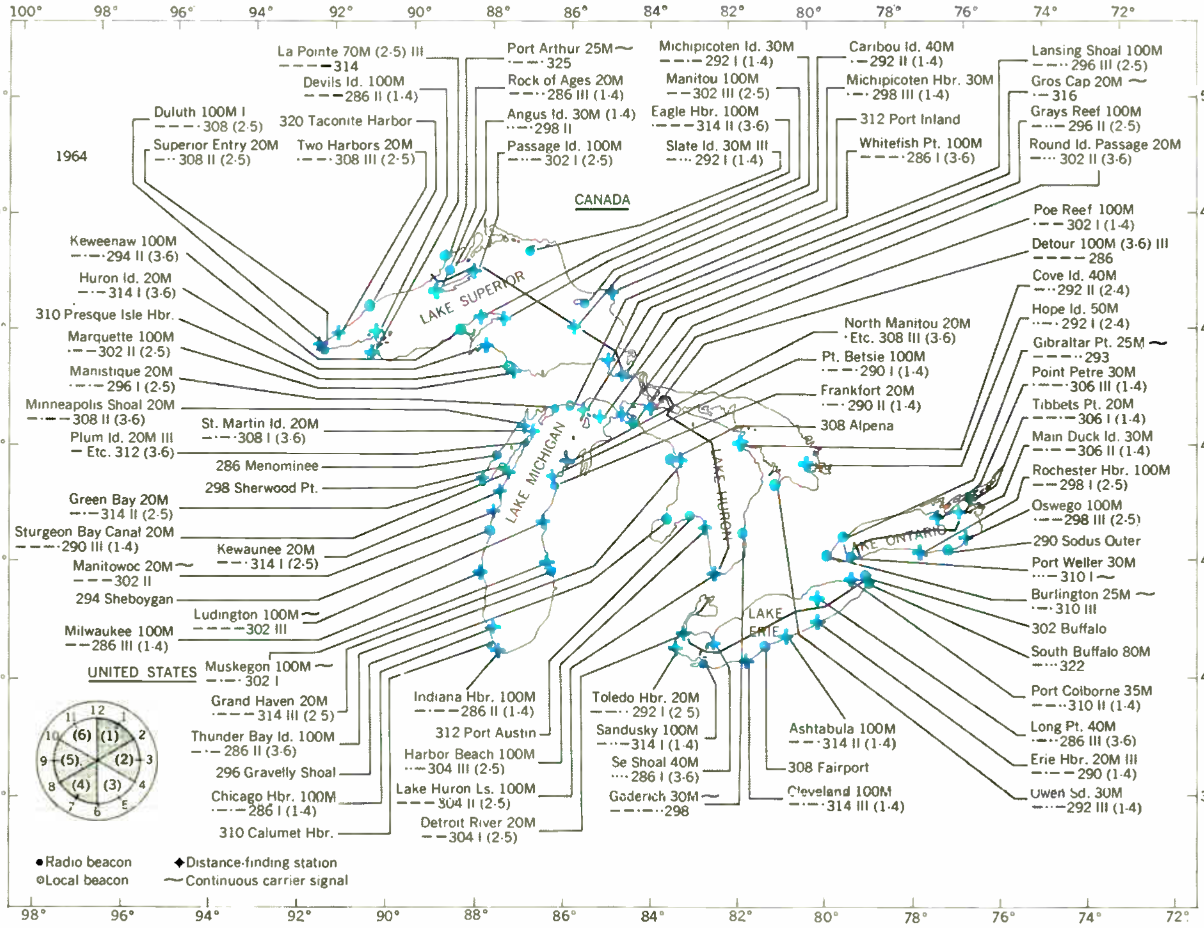


Fig. 1. Great Lakes marine radio beacon system stations operated by the United States Coast Guard and the Canadian Department of Transport. Most radio beacons (see key) must share a group frequency with other beacons. Each is assigned definite minutes of operation in a prearranged sequence. Frequency in kc/s appears after the characteristic signal identification. Sequence within a group is indicated by a Roman numeral. Service range is in miles. Identification consists of dots and dashes. Certain beacons marked with a waved line superimpose the identification signal on a continuous carrier when they are transmitting. When a Roman numeral is shown, the characteristic signal is transmitted for one minute, silent two minutes. These radio beacons transmit during two 10-minute periods during clear weather, but during all periods in low visibility. Scheduled periods of clear weather operation are shown in brackets (see clock face diagram). If no clear-weather schedule is indicated the signal is transmitted during all 10-minute periods. If no Roman numeral is shown, the identifying signal is transmitted continuously. At certain stations, the radio beacon and fog signal are synchronized for distance finding (see key). Local beacons, or marker beacons, are low power, for local use only. They operate continuously on the frequency shown before the name, transmitting a series of ½-second dashes for 15½ seconds, silent 14½ seconds, except as indicated.

A thorough study of these systems and their use, together with a survey of the present state of the art, will show: (1) that these five systems are not competitive but that they complement each other; (2) with one possible exception, each of the five systems is in use today by large numbers of nonmilitary vessels; (3) there does not exist today any single radio or electronic position-finding system capable of meeting all marine position-finding requirements; (4) insofar as the navigation of nonmilitary vessels is concerned, there is no likelihood that in the foreseeable future there will be developed and implemented any position-finding system which would make any of the five obsolete. This statement in no way reflects on the possible value and usefulness of position-finding systems now under test or visualized for the future. Since a competent marine navigating officer uses all the information available to him, the data obtained from these new systems will be used along with data obtained from existing systems.

Consol and Consolan

Consol was developed primarily as a radio aid for air navigation. However, it is used also as a marine navigational aid. The system gives bearing and position data.

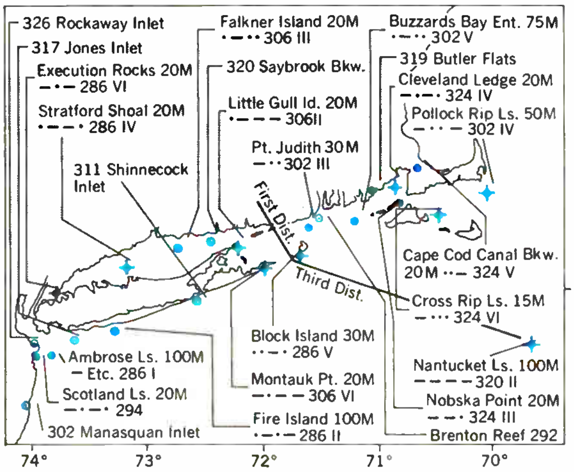
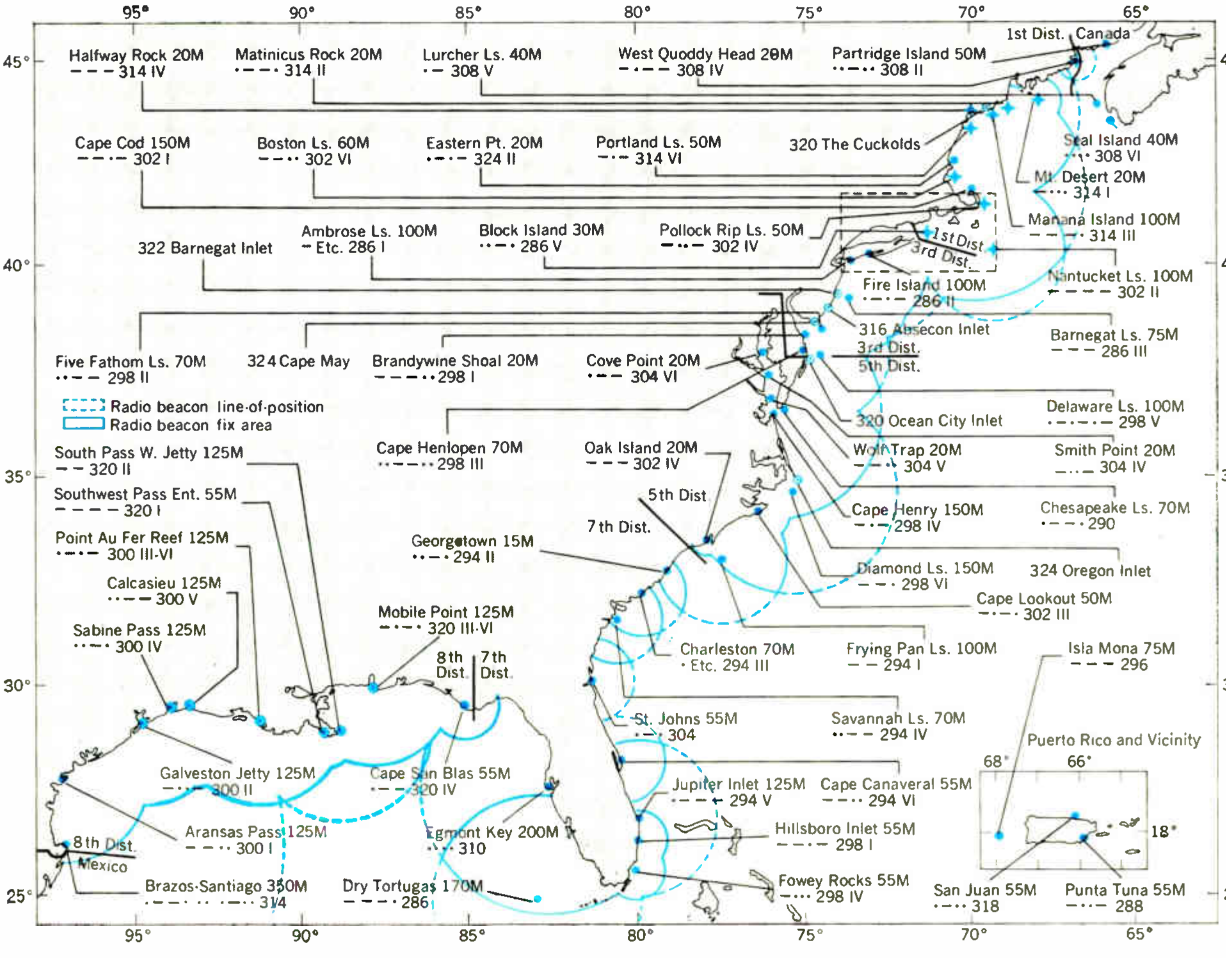


Fig. 2. United States Coast Guard radio beacon system on Atlantic and Gulf Coasts (below and left). Because of frequency sharing, radio beacons (see key) in the same general geographical area are divided into groups of up to six beacons transmitting on a single frequency with the sequence being repeated continually. Each radio beacon transmits for at least one minute out of each six-minute period regardless of weather conditions. If less than six radio beacons are assigned to a sequence group, one or more of the beacons may transmit during two of the six one-minute periods. The explanation for sequence, service range, characteristic identification, frequency, distance-finding stations, and local-use marker beacons is the same as in Fig. 1, except that the characteristic signal of all beacons is superimposed on a continuous carrier when they are transmitting, and the last ten seconds of the minute are devoted to a long dash for maximum bearing accuracy, with manual operation. Also, marker beacons transmit ½-second dashes for 13½ seconds, silent 1½ seconds.



Consolan is a slightly modified version of Consol. While quite accurate bearing data can be obtained when the receiver is not too far distant from a Consol station, accuracy decreases with distance. Also, there is a minimum distance from a Consol station within which the data obtained are not useful.

The Consol system is important because the only ship-borne equipment necessary to use it is a good selective radio receiver capable of receiving continuous waves on the frequencies radiated by the stations used. Those who desire to use the system should obtain much more detailed information.

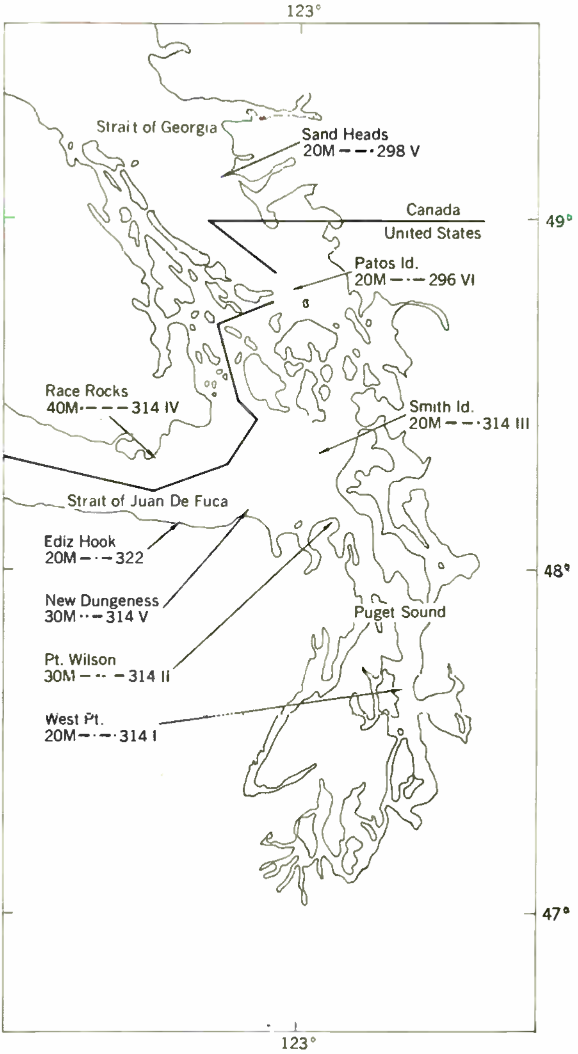
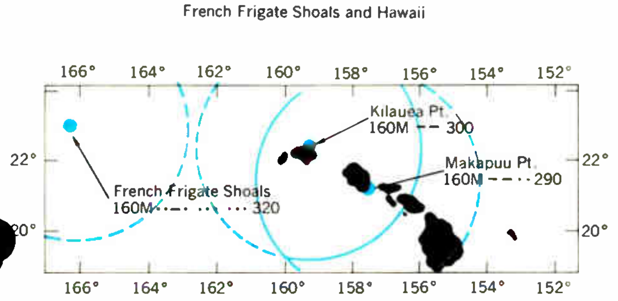
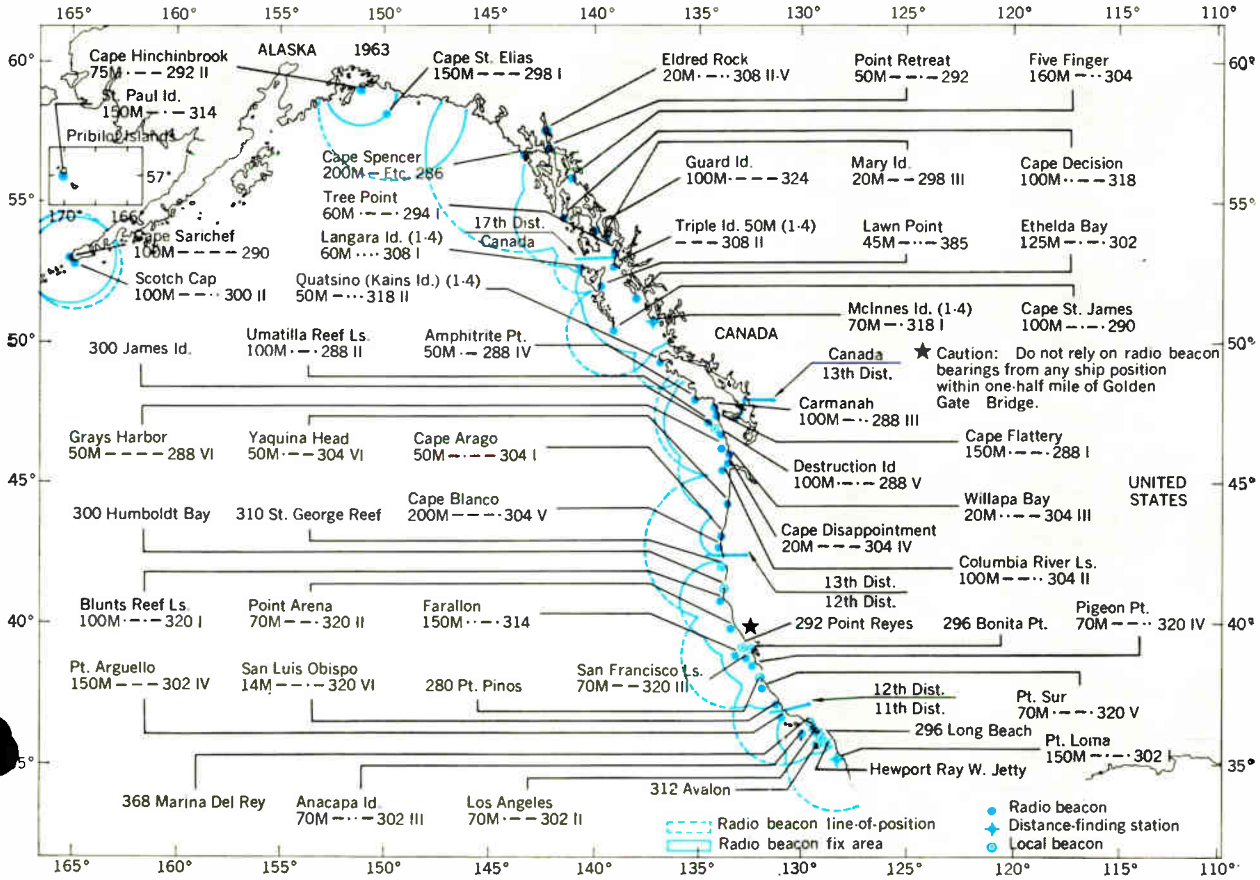


Fig. 3. U.S. Coast Guard radio beacon system on Pacific Coast (right and bottom) and islands (center). Explanation is the same as that for Fig. 2. Certain Canadian radio beacons retain the clear-weather operating schedule. These beacons have the period of operation designated by [1–4], meaning the first 10-minute and the fourth 10-minute period of each hour. In low visibility they operate during all periods on their designated sequence.





★ Caution: Do not rely on radio beacon bearings from any ship position within one-half mile of Golden Gate Bridge.

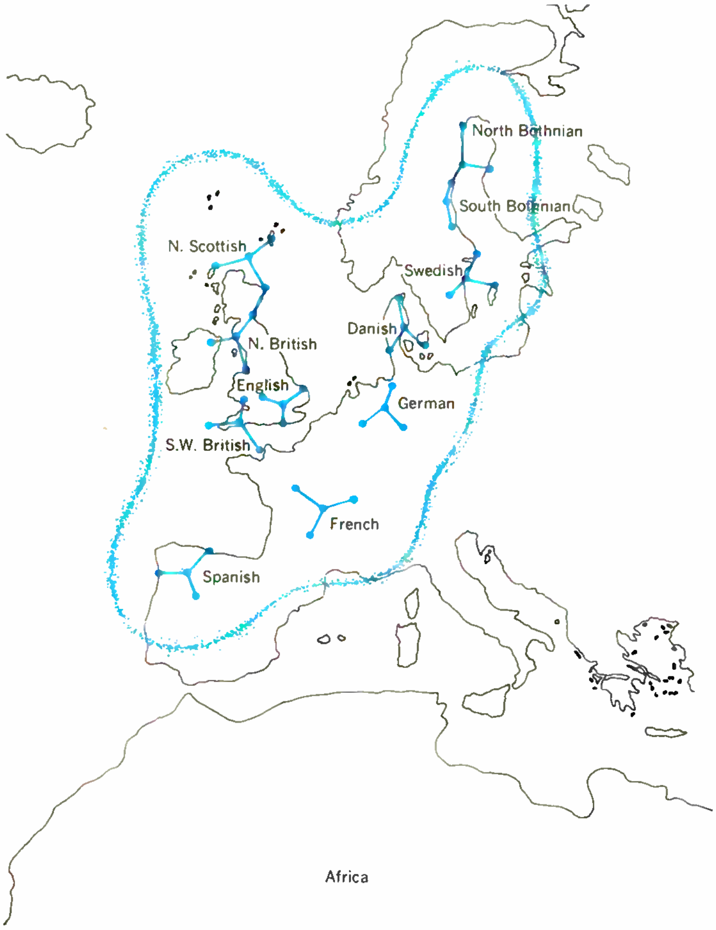


Fig. 4. West European coverage of the Decca Navigator system.

There are seven Consol stations in Europe (one each in Northern Ireland, Norway, and France and two each in Spain and Russia) operating on seven radio frequencies in the band 257 to 263 kc/s. There are three stations in the United States, at Miami (190 kc/s), Nantucket (194 kc/s), and San Francisco (192 kc/s). Ranges extend from 25 miles out to approximately 700, 1000, or perhaps 1400 miles depending upon conditions.

United States and Canadian shore-based radio beacons

Figures 1, 2, and 3 show the locations of marine radio beacons operated by the Coast Guard in the United States and a number of those operated by the Canadian Department of Transport. There are, of course, similar types of beacons in other areas. These marine radio beacons use radio frequencies in the band 285–325 kc/s.

Many vessels, large and small, are equipped with radio beacon receivers. The Coast Guard and the Department of Transport are constantly improving the characteristics of the beacons they operate. One major recent improvement is a very substantial reduction in the width of channel occupied by a given marine beacon signal by simultaneous transmissions on two frequencies separated by 1020 c/s, the amplitude of one being approximately 50 per cent that of the other. In recent years there have been made available improved types of shipborne beacon receivers, some using cathode-ray presentations and some with automatic features.

Decca, Loran A, and Loran C position-finding systems

The Decca Navigator, Loran A, and Loran C marine position-finding systems are all classified as hyperbolic in that a line of position is determined by the difference in time required for radio signals from two specific stations to reach a point of reception. A chain of hyperbolic position-finding stations must have at least three stations since a ship's position is determined by the intersection of two hyperbolic lines of position. Here the similarity ends. Decca, Loran A, and Loran C were developed to meet different requirements and each meets a different marine navigational need. It is important that the comparative characteristics of these three systems be understood.

The Decca Navigator System (Decca) radio stations transmit continuous waves. Each Decca chain requires several separate radio frequencies in the bands 70 to 86 kc/s and 112 to 130 kc/s. Both Loran A and Loran C are pulse systems. The stations of a particular Loran A chain all operate on one of three specific radio frequency assignments, namely 1850, 1900, or 1950 kc/s. Different pulse repetition rates are used by each pair of stations in a chain. Loran C stations all operate on 100 kc/s.

The base line distance between any two stations of a Decca chain designed primarily for marine use is usually not less than 80 miles or more than 120 miles. For Loran A this distance is approximately 350 to 500 miles whil for Loran C the separation is from 600 to 1400 miles. These base line distances illustrate the different operational requirements for which each system was designed. Definitions of range and accuracy can be misleading unless they are given in complete detail. However, perhaps the following general comments will not be considered too superficial.

Decca is a highly accurate short-range system, which yields useful results out to medium distances. Loran A is an accurate medium-to-long-range system. Loran C is a highly accurate longer range system when used with adequate receiving equipment. Rather than defining the terms short, medium, and long in miles, it may be more helpful to show the coverage areas of the three systems throughout the world as they exist today. Figures 4, 5, 6, and 7 show the coverage areas of existing Decca chains when only the stations of one chain are used. Figure 8 illustrates the additional coverage areas available where the technique of cross-chain fixing is applied. This technique involves the determination of one line of position using a pair of stations in one chain and a second line of position using a pair of stations in another chain.

Figure 9 shows Loran A coverage throughout the world. Figure 10 shows Loran C coverage throughout the world. The coverage areas shown for the Decca, Loran A, and Loran C systems are for stations now in operation. They do not show the coverage of stations planned for the future for any of these systems.

All coverage areas shown are based on the assumptio that with each system the receiving equipment used is capable of taking maximum advantage of the capabilities of the system. For instance, it is assumed that with the

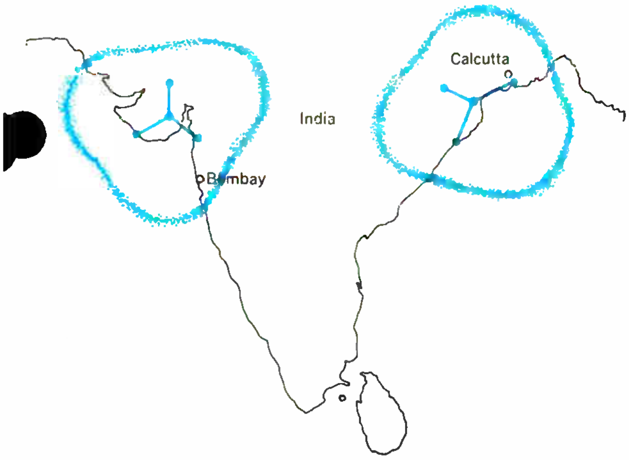


Fig. 5. Indian coverage of Decca Navigator system.

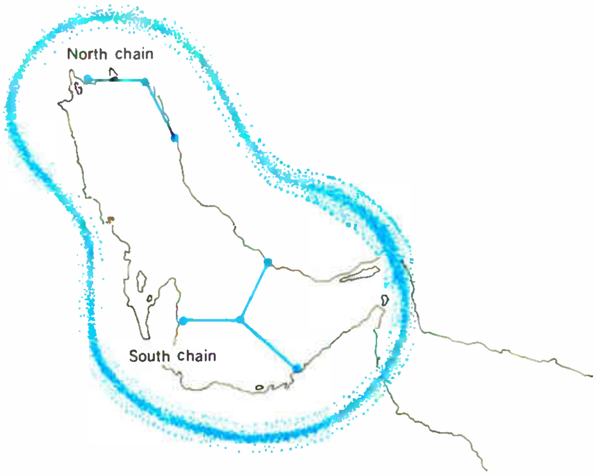
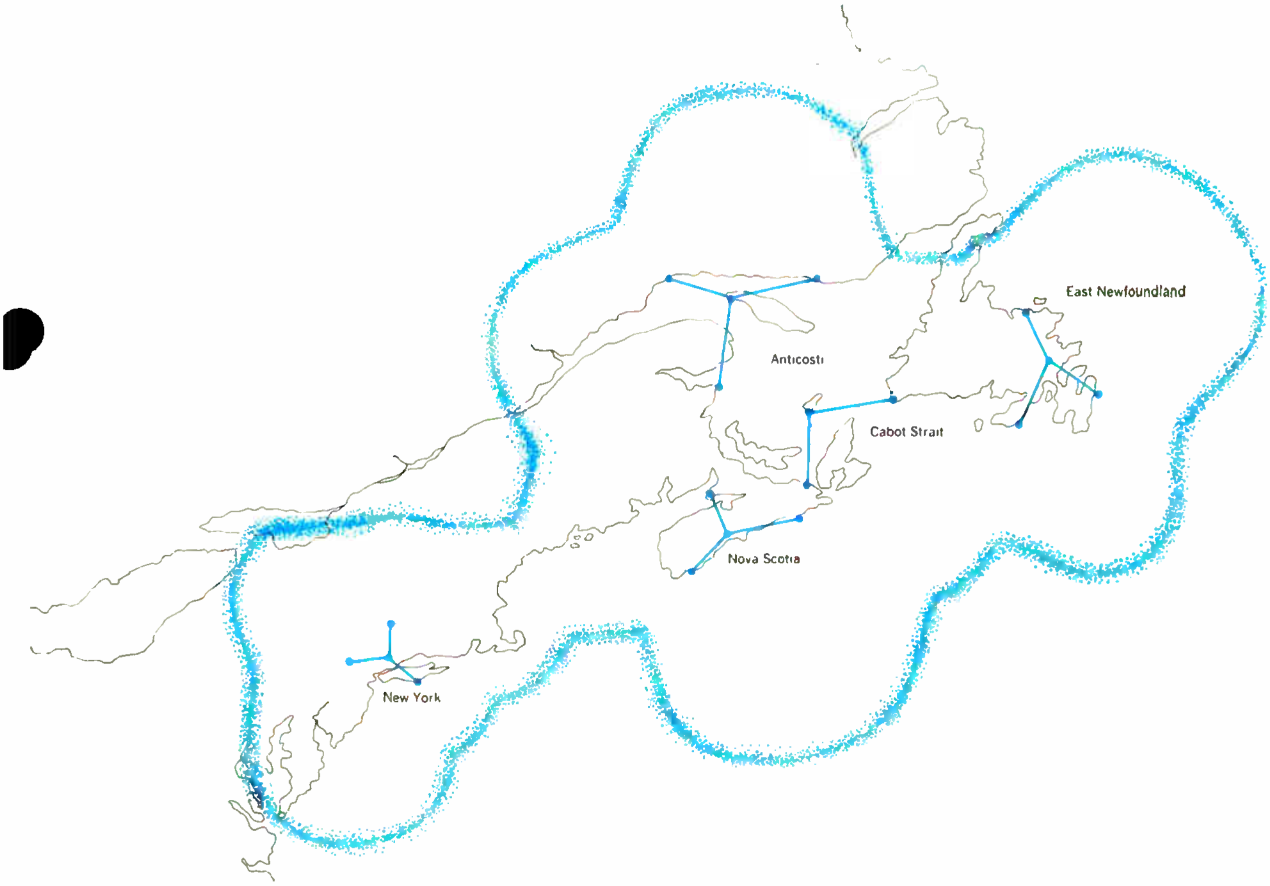


Fig. 6. Persian Gulf coverage of Decca Navigator system.

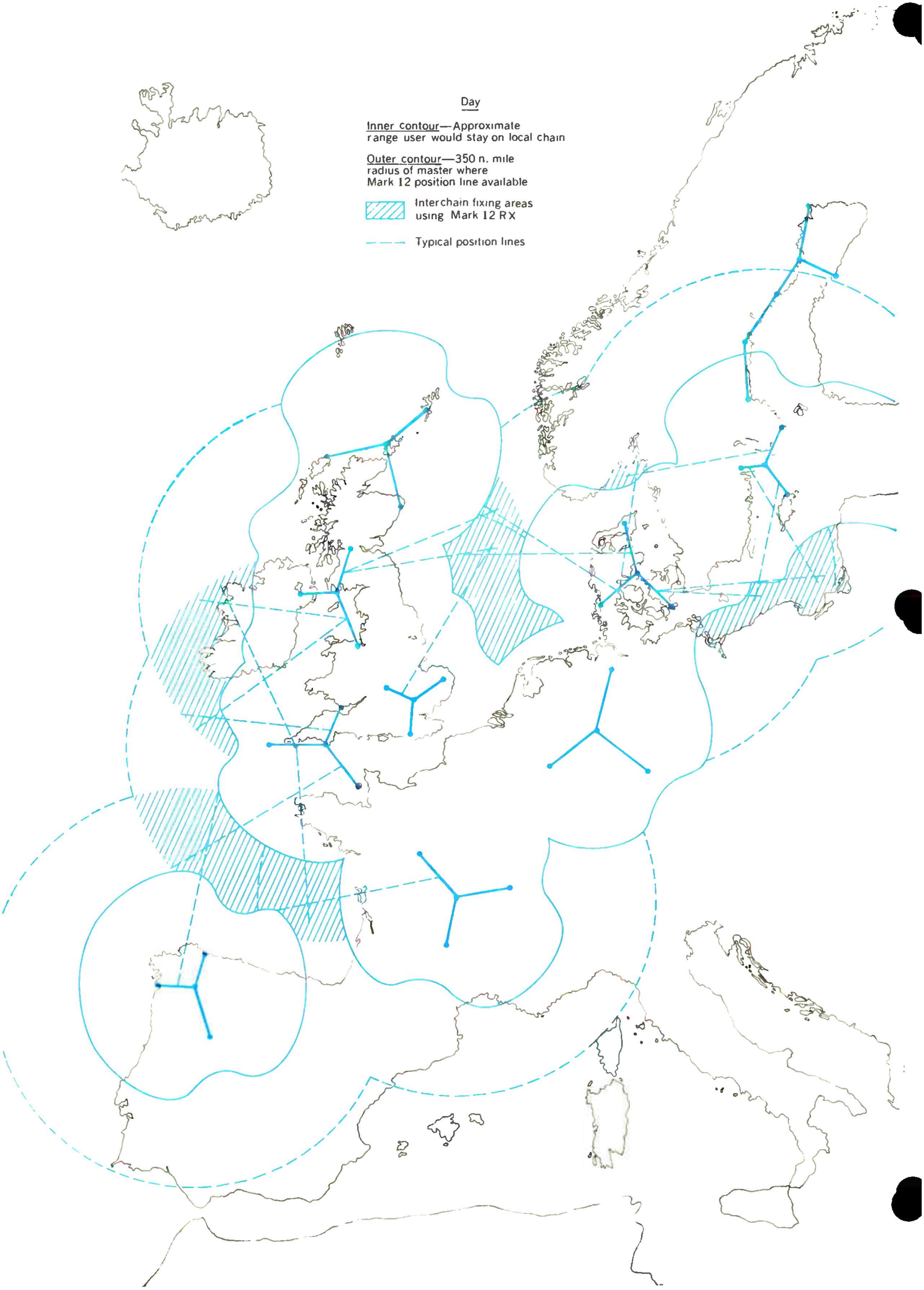
Fig. 7. Decca Navigator coverage of eastern Canada and New York areas.



Decca system the latest model marine receiver (Mark 12) will be used. This receiver is an improvement over older models as it extends the lane identification range out to and somewhat beyond the range at which accurate posi-on within a lane can be determined. To achieve the maximum accuracy possible throughout the coverage areas shown for the Loran C system, it is assumed that an adequate receiver capable of discriminating between ground and sky waves is used.

Beyond stating that the coverage areas shown for the three systems are based on the assumption that these areas are applicable *only* if adequate receiving equipment is used, I will not comment on the operational characteristics of equipment available today. However, it may not be out of place to point out that there are three factors of importance with respect to the characteristics of ship-borne equipment. These are complexity, ease of manipulation, and cost. The ease and rapidity with

Fig. 8. Technique of cross-chain fixing gives Decca system added coverage in western Europe.



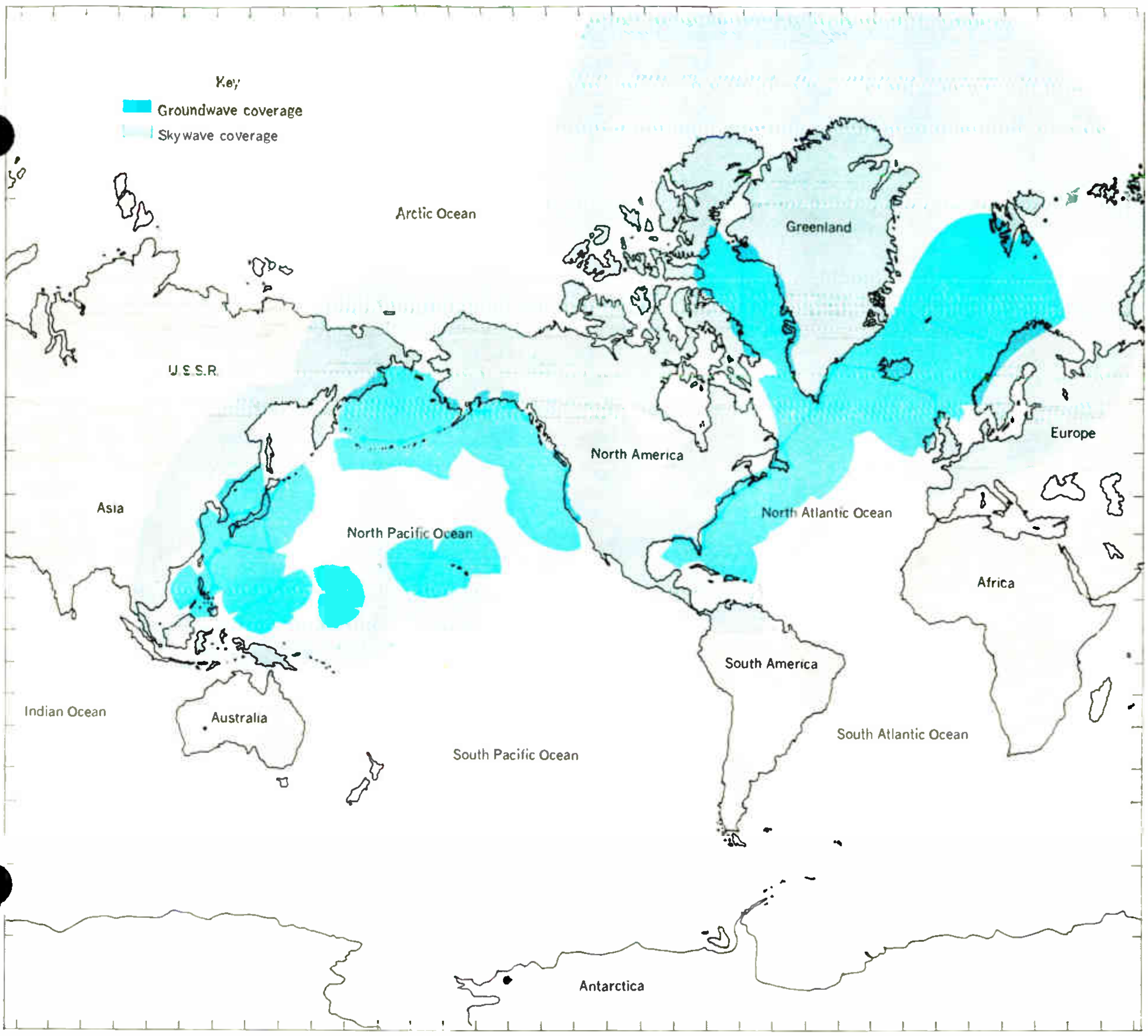


Fig. 9. World-wide coverage areas given by Loran A system.

which a ship's position can be determined are important, particularly in confined waters, and at all times on vessels where the number of navigating officers is limited. On such vessels the officers on watch have many diversified duties and the time available for apparatus manipulation is restricted.

Simultaneous use of two or more systems

In certain areas, it may be desirable to use one position-finding system to determine one line of position and a different system to determine a second line. The result may be a more accurate position fix than is obtainable with one system alone.

The following experience is cited as an illustration of how the Loran A and Decca systems can be used simultaneously in certain areas to yield position finding data not available with the same degree of accuracy from either system alone. While on the *S.S. America* in the North Atlantic at a position approximately 14° west longitude, 51° north latitude, I participated in a determination of position utilizing signals from a Loran A chain having one station on Iceland and a second station on one of the Faeroe Islands simultaneously with signals from a Decca chain in southwestern England. The two lines of position were approximately at right angles, thereby giving a more accurate position fix than could have been obtained from either system alone. The Loran A station pair was 700 nautical miles distant while the Decca chain was 400 miles distant. Both distances are approximate and may be taken as illustrative of comparative daylight range for transmission conditions as they existed at the time, February 1963.

Summary

Since 1950, much progress has been made with both ship-borne and shore-based radar. Today, there exists an international multichannel VHF radiotelephone system which, when used properly, meets an important navigational communication requirement. (On the high seas the distress communication requirement is met

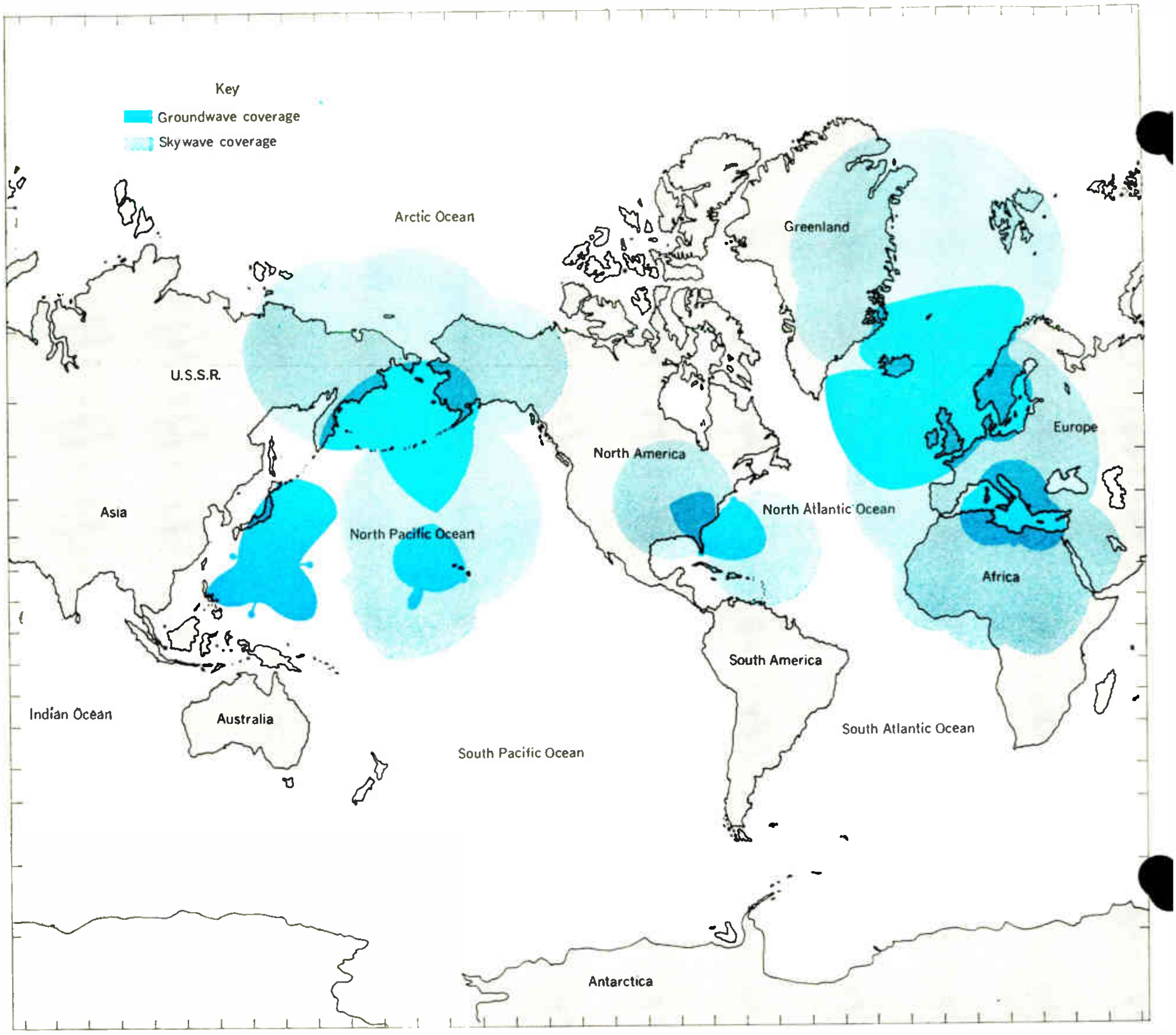


Fig. 10. World-wide coverage areas given by Loran C system.

primarily by radiotelegraphy while on the Great Lakes it is met by a 2000-kc/s band radiotelephone system.)

While no progress has been made toward the development and activation of an adequate electronic marine radar identification system, there is increasing evidence to the effect that there is a real requirement for such a system. I hope there will be further study of this subject.

Much progress has been made since 1950 in the development and implementation of electronic marine position-finding systems. Objective consideration of the requirements for marine position finding, in light of the current state of the art, will show:

1. A competent navigating officer never relies solely upon a single position-finding system unless he has to do so. Rather he uses all systems available to him.
2. Consol, radio beacons, Decca, Loran A, and Loran C are today all available to shipping in areas where their stations can be received.
3. These five systems were developed to meet different requirements. They are noncompetitive and, in fact, the services rendered complement each other.
4. While the development of new position-finding systems may be expected (e.g., satellites, etc.), there is no likelihood in the foreseeable future that any of the five systems listed will be rendered obsolete.

I wish to express my appreciation to all those who have assisted by supplying data, information, and helpful criticism. Unfortunately, their number is too great to permit listing by name. It includes officers and engineers of the United States Coast Guard, engineers and other personnel of the Decca Navigator Company Limited and its associated companies, the Secretary-General and certain members of Comité International Radio-Maritime, as well as engineers and others in the Jansky & Bailey Divisions of Atlantic Research Corporation.

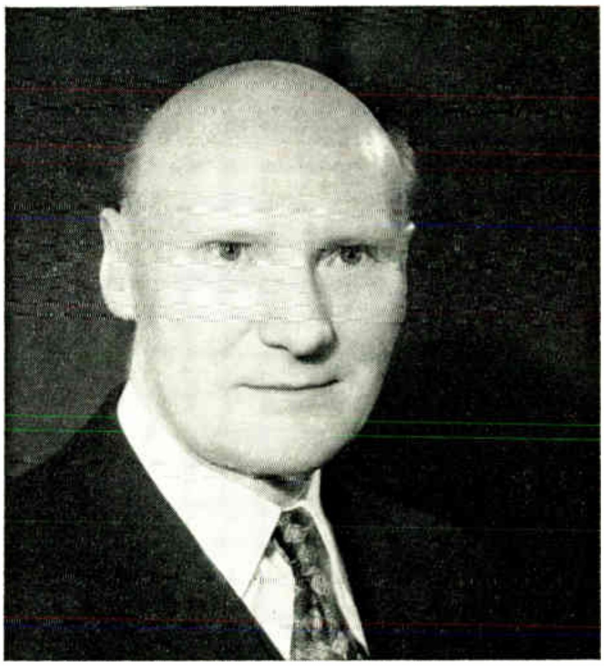
This article, based on an address given before the 20th Annual Meeting of the Institute of Navigation, New York City, June 15, 1964, is printed here with the permission of the Institute of Navigation.

REFERENCE

1. Jansky, C. M., Jr., "The Retarded State of the Science of Marine Navigation," presented at joint meeting of U.S. Institute of Navigation, Radio Technical Commission for Marine Services, and Radio Technical Commission for Aeronautics, Sept. 1950.

Technological challenges to educating engineers

Ernst Weber *Polytechnic Institute of Brooklyn*



Within the last hundred years, the United States and several of the Western European countries have made a transition from a predominantly agricultural society to a technological society. And since such changes—which affect the total society—are exponential in rate, this transition is most evident over the last 25 years.

One hundred years ago, the farsighted Senator Morrill pressed for and obtained from Congress the Land Grant Act, which really initiated technical education on a scale commensurate with the long-range objectives of the United States. But only since about 1940, according to a recent study by *Scientific American*, has the rate of increase in the nation's total manpower in science and engineering grown faster than the population, and it now grows at nearly four times the rate of the labor force. Similarly, according to the same study, the percentage of top officials of corporations with scientific or technical training rose from 6.8 per cent in 1900 to about 20 per cent in 1950, and by 1963 had reached 36 per cent.

The adjustment of engineering education

Engineering education itself has adjusted slowly to the growing demands of our technological society. From the turn of the century and far into the 1930s, preoccupation with technical material that could immediately be applied to the creation of the industrial enterprises produced technicians of admirable skill. The tremendous wave of modern science with its many new discoveries made its impact during World War II and has not yet been fully absorbed into the foundations of modern engineering; it has, in fact, somewhat dislocated engineering curricula. Little serious attention has been paid to the growing and widening range of responsibilities that engineers must assume and in which they have so far only sketchily become interested.

A democracy such as ours—with jealous division of legislative and executive powers, with emphasis upon respect for the individual and the guarantee of freedom of expression and of worship—cannot and must not solve the problems of modern technological society by planned economy, through regimented use of manpower. Only a fully informed public with free individual choice of the mode of living, yet inspired by a sense of service to this democracy, can be expected to find solutions to the socioeconomic and sociopolitical problems brought about by the progress of technology. It is natural that every one of the dynamic forces in this society—the entrepreneur, the union leader, the political aspirant, the would-be bureaucrat, and others

—will exercise the maximum influence to achieve a solution that from its particular viewpoint would serve society best, society in this case usually being a particular cross section, and not confined to a particular group of individuals. I would, in any case, eliminate at once from this discussion the self-seekers—who are not the representative types, or our democracy would have crumbled long ago.

In this play of many forces (some in ascendancy, some declining), the elected government serves to guide and control, principally through the legislative process. It has become more and more obvious, however, that supplementation will be required of the generally excellent legal competency by sound and objective technical advice and guidance. Again, the first recognition was given by the establishment of the National Academy of Sciences in 1863, when technical education was in its infancy. With the ascendancy of engineering and its obvious major technical contributions to society expressed in the technical leadership freely accorded this country since World War II, the establishment of a National Academy of Engineering is being pursued actively.

The engineer's role in society

Naturally, I shall claim a leading role for the engineer in our technological society, not necessarily the role of politician, although a sizable contingent of technically experienced men in Congress would be advantageous, as in any other representative group of our social forces. I am thinking of more leading roles for the engineer in industry, commerce, and banking; in Federal government agencies dealing with national and international issues; in state and city governments, where technical problems become key issues; and even in courts of justice and in law firms. To qualify for such responsibilities, it is necessary to modernize engineering education and to enlarge its scope from that of an "Institute of Technology" or "Polytechnic Institute" to that of a true "Technological University."

The leading engineer of the future—like some self-taught engineers of broad gauge in the past—must, above all, be able to communicate with the much larger groups educated in other disciplines and often entirely devoid of scientific or engineering concepts. As manager, he must accept responsibility to society: the investors, the employees, the consumers. His decisions should balance properly long-range consequences against short-time effects by considering society as a system of many varied components with diversified reactions.

Engineering education, therefore, must comprise, in the space of the basic four years to which most leading institutions have subscribed, a firm foundation of science (including mathematics), a broad basis in systems engineering with computer science and project work in selected disciplines, exposure to social sciences and economics, and an active appreciation of the humanities. A principal objection to many courses in social sciences available today to engineering students is the usual abstract nature or complex sequence of detailed studies when, in fact, relatedness to present-day society would be most important. The same objection holds for many of the programs in economics, and thus individual engineering disciplines offer instead their individual, and often individualized, brands of engineering economics—which seldom constitute better substitutes. In both these areas, new approaches are needed that link the few firmly established concepts to the practical situations of present-day society, here as well as abroad, in order to develop a critical and evaluative attitude. This means, in turn, the training of a new generation of university teachers who recognize in the evolution of such courses an important contribution to the leadership in our technological society.

Undergraduate programs so oriented should produce young men rooted in science, broadly competent in engineering, conscious of the social responsibilities and appreciative of human values.

The deepening of technical competence to the point of creative design should be reserved to graduate study for the Master's degree with a thesis to illustrate and exercise the mastery of the chosen discipline. Further extension of studies toward the Doctor's degree should then stre innovation and research, which are of equal importance in advanced engineering development.

Instead of deepening his technical competence, the engineering graduate could of course select a graduate program in management, in finance, in law, or in any other area in which he might expect to possess special qualifications and for which the basic engineering education is a foundation permitting active participation in our technological society.

The challenges to engineering education will not be met merely by more technical training or by more years of study. They will be met only if enough engineering students can be persuaded to become, above all, engineers—and only secondarily electrical or mechanical or chemical engineers. Of our total graduating classes, even now, only a small fraction ends up in research and development laboratories, and only a small fraction will have both qualifications and opportunity to contribute in a major measure to the scientific and engineering literature. By far the largest number of engineering graduates of ability today regret the lack of meaningful exposure to the problems of human relations, to elements of management, and to real appreciation of the arts and literature. If we in the engineering profession are to make our full contribution to this technological society, we must motivate our graduates to recognize the tremendous scope of responsibilities before them, to prepare themselves fo these responsibilities, and to dedicate their lives to serv to our society as a true profession demands.

Full text of an address presented at the Engineering Management Conference, Cleveland, Ohio, Sept. 17–18, 1964.