Radar COUNTERMEASURES

Equipment for detecting enemy radars, determining their location, analyzing their characteristics and then jamming them electronically or by means of chaff is described. Many of the devices used, such as shf direction-finders, wideband radiators, and the resnatron tube, have postwar applications

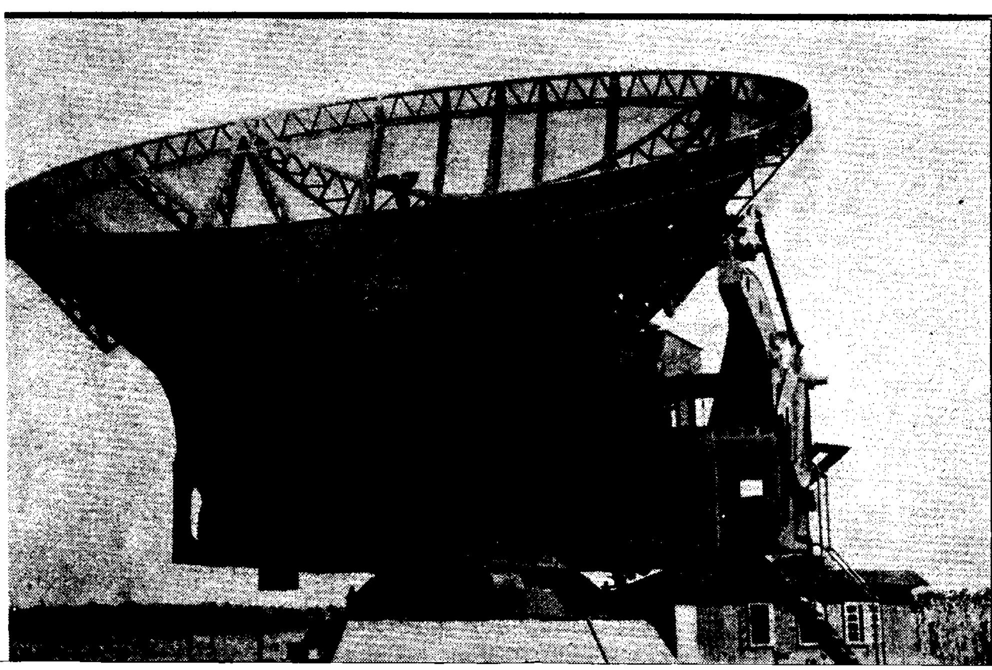
IN THE RADAR WARFARE just concluded there were two major campaigns. The first was to use radar against the enemy; the second to hinder the enemy in his use of radar against our forces. The second campaign was conducted by techniques known as radar countermeasures, (rcm) by which enemy radars were detected and put out of action.

In many ways rcm activity was the most fascinating aspect of the electronic war, since it involved direct contact with the enemy and required all the competitive strategy and inspiration of a campaign in the field. Technically, also, rcm commands attention, not only because the methods used were unique and different from those of radar, but also because many rcm devices have post-war uses which may outrank those of radar.

Radar countermeasures were developed and employed by the British in the early stages of the war. Prior to America's entry, rcm activity was also carried out in our own Army and Navy Laboratories, on a long-range basis. The need for coordinated activity led in 1942 to the formation, under Division 15 of the National Defense Research Committee, of an rcm laboratory at Harvard University. This laboratory was known as the Radio Research Laboratory. Of the $300,000,000 spent by the U. S. on rcm equipment and materials, approximately two-thirds was for equipment developed in this NDRC activity. The remainder was spent developing methods originating with the British, and in the Naval Research Laboratory, Signal Corps, and Air Technical Service Command Laboratories.

Search and Jamming Functions

To knock out enemy radars, two basic functions are involved. The first is a search, conducted with receivers and direction finders, to determine where the enemy radar is located and as many as possible of its technical characteristics. The second is jamming, accomplished by means of aluminum-foil chaff or rope sowed in the sky by airplanes or by rockets fired from the ground and/or the transmission of signals which will interfere with the operation of the enemy equipment. In the initial stages of the program the two functions were separate. The search was conducted to obtain technical specifications and these specifications were sent home for use in the design of a suitable jammer. The jammer was then produced, on the fastest possible basis, and put into action.



The principal targets of Allied countermeasures in Europe were Wurzburg antiaircraft radars such as this unit. The Germans had 4000, representing a billion-dollar investment. Jamming reduced their effectiveness to 25 percent of normal

Ten million pounds of aluminum foil (chaff and rope) were dumped on Europe by Allied bombers to produce radar smoke screens within which German radars could not detect Allied bombers. Each package of chaff, one of which is shown being dispensed, contains several thousand dipole reflectors

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Later, the two functions were combined in equipment of such flexibility that virtually all types of enemy radar could be detected and jammed in a single operation.

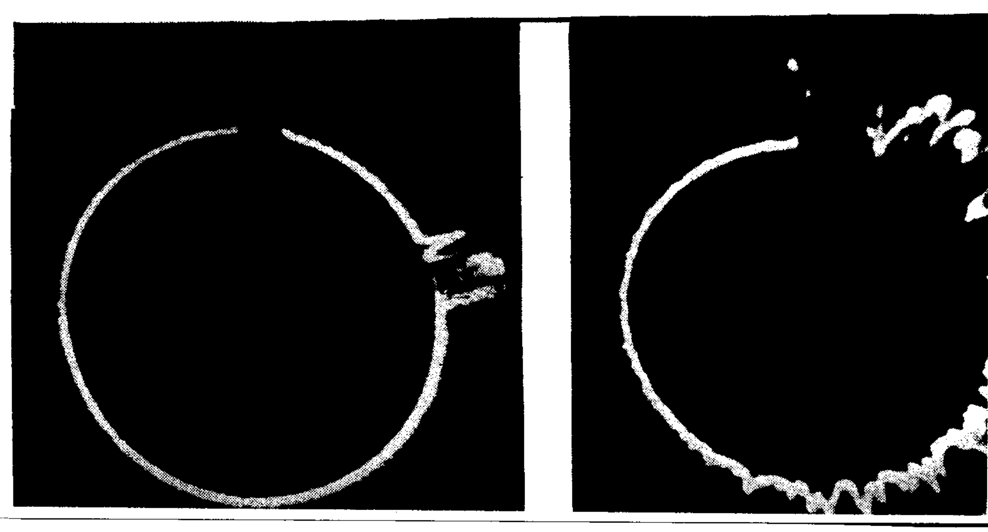
Some idea of the equipment flexibility required may be obtained from the accompanying table, which lists jamming transmitters, search receivers and direction finders. Since the enemy had, within reason, a free choice of frequency, it was necessary to build a group of continuously tunable search receivers and direction finders to cover virtually the entire radar spectrum, from 25 to 6000 mc. Moreover, since the choice of pulse width lay with the enemy, bandwidths wide enough to accept a variety of pulses were required.

In the jamming transmitters the same continuously tunable frequency range was required. Moreover the transmitters were of necessity the continuous-wave variety, since they had to block out echo signals which might occur at any time, depending on the timing of the enemy radar and the distance to its target. Moreover, the highest possible power was required, continuously, to blot out the enemy indicators at great distances. In the interest of conserving power, suppressed-carrier transmitters were often used, modulated with random noise over a bandwidth of several mc.

Underlying the design of these search and jamming equipments are several basic relationships which put the enemy radar at a fundamental disadvantage. In the first place, a radar must transmit at high power to detect targets at useful distances.

The radar operates by reflection of its signals, which introduces attenuation of the radar signal proportional to the fourth power of the distance to the target. The search receiver detects the radar signal by one-way transmission, which is at-

Chaff, aluminum halfwave dipoles of various lengths, tuned to the Wurzburg radar frequencies. Each strip is embossed and crimped along its length to assure wide dispersal and reasonable rigidity after being thrown from the aircraft



Effect of chaff on Wurzburg type-J indicator. At left, normal indication of Allied bombers (at right of circle). Right, a trail of chaff some 16 miles long totally obscures the bombers. These shots were taken from a German training film

EQUIPMENT FOR RADAR COUNTERMEASURES

Jamming Transmitters

Frequency Range (mc)	Designation and Code Name	Band-width (mc)	Output Power (watts)		Description and Radars Jammed
			Carrier	Side-bands	
25–100	ARQ-8 Dina	0.15	0	40–20	Suppressed carrier, single sideband. German EW, Jap GL and SLC
85–150	APT-3 Mandrel	3	12–9	3–2	Grid-modulated MOPA. German EW
90–220	APT-1 Dina	6	0	15–8	Suppressed carrier, single sideband. German EW, Jap GL and SLC
200–550	APQ-2 Rug	7	20–5.5	5–1.25	Line oscillator, doorknob tubes. German coastal, Jap torpedo planes
450–720	APT-2 Carpet	7	8–3	1.6–0.6	Same as APQ-2. German Wurzburg GL
475–585	APQ-9 Carpet III	7	20	5	Parallel plate, using 8012's. German Wurzburg GL
350–1200	APT-5 Carpet IV	2.5–3.0	30–5	——	Lighthouse-tube cavity oscillator. German Wurzburg GL
150–780	APT-4 Broadloom	7–10	150	——	Current-modulated c-w magnetron. German Wurzburg GL
300–2500	APT-9	2–8	25–10	10–3	Cavity oscillator
2230–4030	APT-10	——	25–50	——	Tunable c-w magnetron, four heads to cover range

Search Receivers

Frequency range (mc)	Desig-nation	Input power (watts)	Description
25–100	ARQ-8	75 a-c	Dinamate, used with Dina and tuned electronically to transmitter frequency. Superheterodyne
40–3000	APR-4	90 a-c, 9 d-c	Bandwidth 4 mc or 0.5 mc. Single-dial tuning. Four r-f heads cover range Motor-driven sector sweep. Superheterodyne
1000–3100	APR-5	150 a-c, 25 d-c	Coaxial-antenna input, cavity oscillator. Crystal mixer. Superheterodyne
3000–6000	APR-8	150 a-c, 25 d-c	Same as APR-5, but mixer operates on local oscillator harmonics. Waveguide input. Superheterodyne

Direction Finders

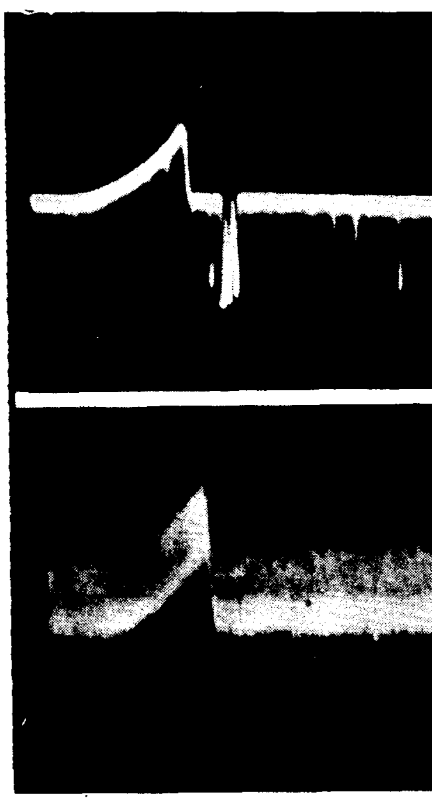
100–450	APA-24	————	Vertical Adcock plus horizontal dipole, manual remote control. Null indication
300-1000	APA-17	125 a-c, 50 d-c	Whirling radiator for use with any search receiver. C-r indication on maximum of antenna pattern

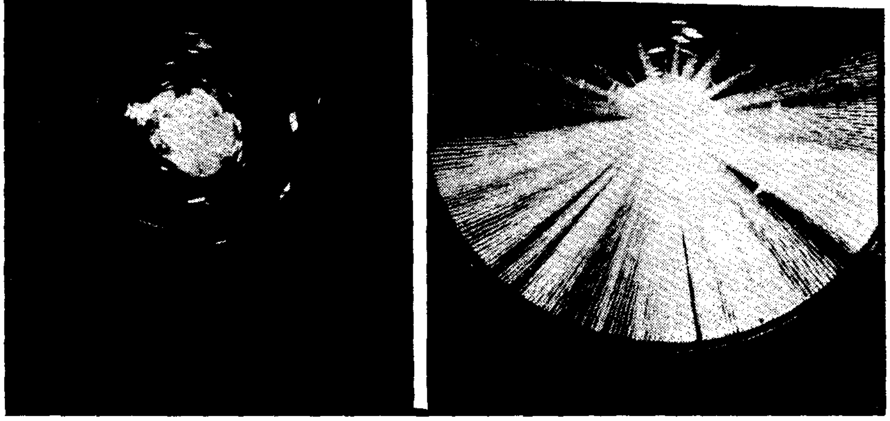
tenuated only as the square of the distance. Consequently, a radar signal can be detected at distances far greater than the maximum range at which the radar can see a target. In the second place, the direction to the source of the radar signals may be observed by the use of a directional antenna on the search receiver. Two or more bearings so obtained reveal the location of the radar. Radar reconnaissance can thus be carried out, with airborne search receivers for example, without fear of detection by the radar itself.

The same favorable discrepancy exists between radar range and jamming range, since the jamming signal competes only with a weak reflected echo on the radar screen. Consequently, a jamming power level in the tens of watts is sufficient to compete with a radar peak power in the hundreds of kilowatts. This advantage is reduced, however, by the necessity of jamming with a c-w signal, and so the average power of the jammer is often nearly as great as the average power of the radar.

The accompanying table illustrates the frequencies, power levels and bandwidths of the jamming transmitters. Power in the tens of watts, modulated over bands up to 10 mc, is obtained at frequencies up to about 700 mc using triode tubes, notably the door-knob types. Cavity resonators, using disk-seal (lighthouse) tubes, give about the same performance at frequencies up to 2000 mc. For higher power levels, especially at the highest frequency ranges, c-w magnetrons are used. One important example is the Broadloom jammer, which produces 150 watts

Electronic jamming, caused by noise-modulated c-w transmissions tuned to the radar frequency. Above, normal scope. Below, echo pulses obscured by artificial noise produced by jamming signal





Effect of electronic jamming on plan position indicator (ppi). Left, normal indication. Right, radial traces, brightened by jamming signal, obscure echo signals

of cw carrier up to 780 mc.

Modulation of the jamming signal is, of course, essential to achieve the maximum blanketing effect. Experience has shown that random noise, such as may be obtained conveniently from the space current of a gaseous vacuum tube, provides the most effective modulation waveform. Noise modulation, received by the radar, has the effect of multiplying enormously the normal noise level present in the radar receiver.

Search Techniques

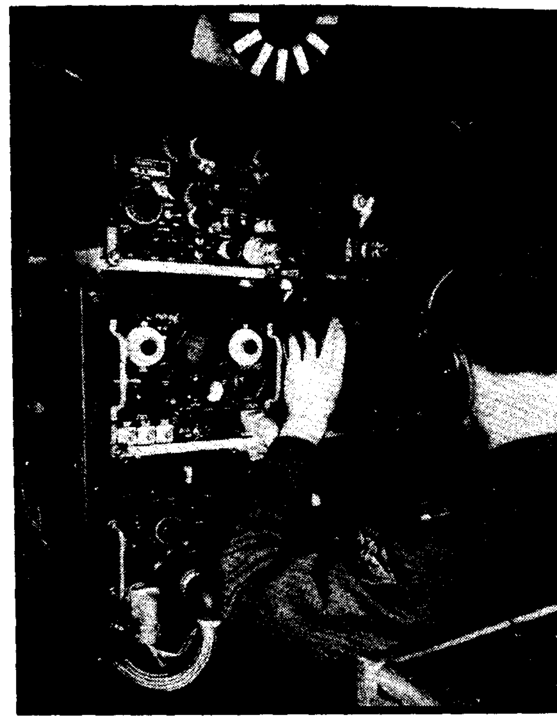
The technique of searching for enemy radar signals, as a preliminary to jamming them, consists simply in tuning the search receiver repeatedly over the radar spectrum. This is not only difficult technically, but physically tiring. The technical difficulties reside in the great width of the spectrum to be covered. One excellent example of how the problem is solved is the AN/APR-4, which covers the range from 40 to 3000 mc, using four r-f heads. The tuning is motor driven over a frequency sector which can be selected by the operator, thus relieving him of a considerable physical burden. An automatic tape-recording system is available to record the frequency at which signals are detected as the spectrum is swept, thus further reducing the attention demanded.

The simplest method of observing the radar signals is by an aural indication. Radar pulses are transmitted at repetition rates which lie within the audible spectrum. Moreover, the pulse represents, in effect, a high degree of overmodulation on a c-w carrier, and this modulation can be recovered in a conventional second detector, amplified at audio frequencies, and fed to headphones. When a radar signal is intercepted a whine (repetition frequency plus harmonics) is heard in the headphones. The strength of the signal varies periodically as the radar beam sweeps past the search plane. So long as this variation continues, the radar is searching. But if the signal becomes steady, at maximum volume, the chances are that the radar has detected the search plane and is tracking it. Appropriate action is then taken to avoid enemy gunfire and aircraft.

While aural or tape-recording methods serve to identify the presence and carrier frequency of the enemy radar, they give little indication of the pulse characteristics. A cathode-ray pulse analyzer (oscilloscope) is available to determine the pulse repetition rate, the pulse width, the pulse shape and relative amplitude. Such an analyzer gives important clues to the type of radar under observation, since it reveals the radar's maximum range, minimum range, and range accuracy.

Wideband Radiators

Implicit in the wide frequency ranges covered by search and jamming equipment is the necessity for radiators which will cover these ranges without excessive tuning adjustments. The Radio Research Laboratory undertook to develop antennas which would cover frequency ranges of several thousand megacycles without any adjustment whatever. One of the most spectacular of these antennas is an approximately cylindrical structure which covers the range from 950



Search and jamming equipment on a Navy rcm plane: from top to bottom: antenna selector switch, APT-1 electronic jammer, panoramic adapter (to sweep receiver frequency) pulse analyzer, cathode-ray d-f indicator (in use by operator), second jamming transmitter, and search receiver (hidden by operator)

to 2900 mc, a frequency ratio of 3-*to*-1, matching the transmission line throughout this range. In general, the wideband antennas make use of the principle that a thick, stubby radiator has low stored energy and hence responds well over a wide band. Several of the wideband radiators are of the turnstile type, two dipoles at right angles, extending through massive collars.

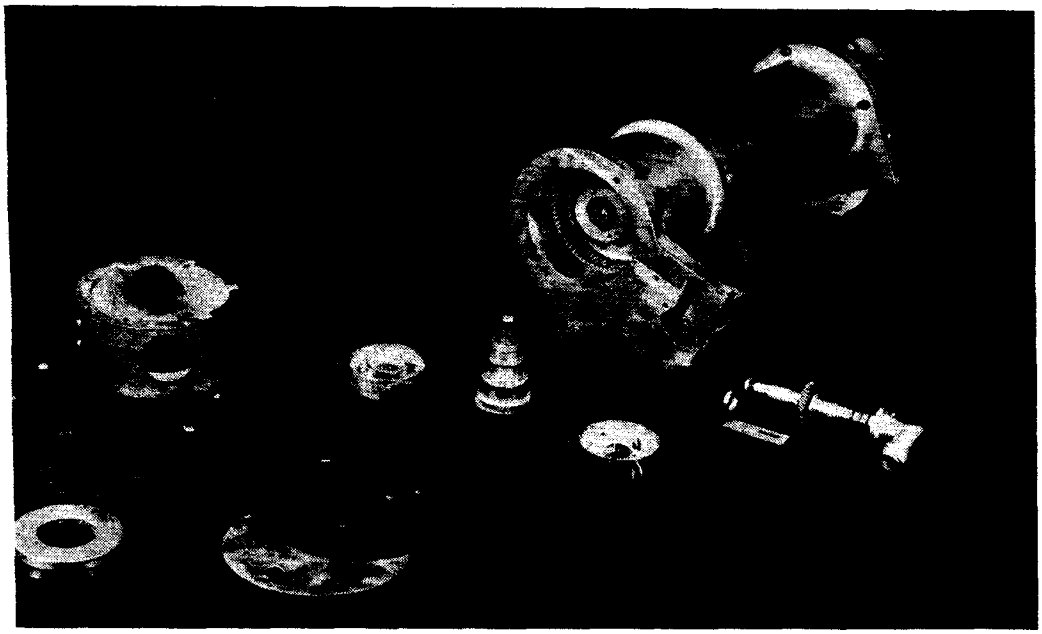
Closely allied with the wideband antennas are suitable direction-finding structures. The direction-finding problem is complicated by the fact that the enemy may choose vertical or horizontal polarization at will. In the AN/APA-24, which operates in the range from 100 to 450 mc, a four-element Adcock system is used to receive vertical polarization, and a single horizontal dipole is used for horizontally-polarized signals. The system operates on the null of the pattern.

For higher frequencies (300 to 1000 mc), an automatic direction finder was produced, using a continuously rotating radiator. A cathode-ray oscilloscope, with polar sweep, indicates the strength of the received signal and plots a polar diagram on the c-r screen, the maximum of which indicates the direction of the radar under observation. This equipment, when observing a point source, plots the polar radiation diagram of the antenna in use. It has found much use in measuring the polar diagram characteristics of developmental antennas.

Chaff Dipoles and Rope

An effective way to confuse enemy radar operators is to simulate targets by dispersing large quantities of reflecting material in the sky. The most efficient material for this purpose, from the standpoint of echo area per unit weight, is aluminum foil cut in strips one half wavelength long at the enemy radar frequency. Such dipole strips, when used by the British, were called window. The American version is known as chaff. Three quarters of the entire wartime production of aluminum foil, some 20,000 tons in all, was devoted to the manufacture of chaff. Allied aircraft dispensed hundreds of packages of foil strips, each containing several thousand dipoles, on every flight over enemy territory. The material was designed to disperse widely and to remain aloft as long as possible, thus providing a radar smoke screen within which following aircraft could avoid detection by gunfire-control radars below.

While apparently a simple device, chaff presented many interesting technical problems. The primary objective was to obtain as large as possible a reflecting area from a given weight of aluminum foil. This implies thin, pliable foil which tends to bend when thrown into the slip stream of the aircraft. Such bending causes interweaving of the strips in tangled bird's nests which present little area and fall rapidly. Moreover, adjacent strips of foil tend to adhere to one another, preventing rapid dispersal. These problems were solved by embossing the foil and crimping each strip along its length to give it rigidity. Chaff thus manufactured is highly dispersive and falls at the slow rate of 150 feet per minute. The material most widely used over Europe was tuned to the region 450 to 600 mc, which covered the operating frequencies of the German Wurzburg fighter-direction and gunfire-control radars.



Oscillator of APT-9 jamming transmitter, using disk-seal tube. This oscillator covers the enormous range of 300 to 2500 mc with a power output of 10 to 25 watts, continuous wave

Since the resonance of the foil strips extends over a band only 8 percent of the center frequency (at 3 db down), it was necessary to provide two lengths in each package, roughly 10 and 11.5 inches long. About 1000 such dipoles, dispersed at an average separation of about four inches, were found to equal the echo area of a heavy bomber. The weight of these 1000 dipoles in the latest version of the material was only 2 ounces. Each heavy bomber carried with it sufficient chaff to simulate 700 bombers, and dispensed it at regular intervals over areas known to be protected by radar-controlled gunfire. Large areas of the German countryside thus became littered with aluminum strips, which were used by the natives to decorate Christmas trees.

On the indicator of a gun-fire control radar, the chaff-dispensing aircraft appears as if it were reproducing itself. As the pulse representing the aircraft moves across the indicator screen, additional pulses appear behind it and remain stationary. As the chaff disperses, the pulses assume an amorphous shape in which succeeding aircraft are nearly invisible. Aircraft outside the cloud of dipoles are not hidden. Aircraft behind (but not within) the cloud are detected by signals which pass through the dipoles.

The most effective protection against German radar-controlled flak was a combination of electronic jamming by transmitters tuned to the radar frequencies, and chaff dipoles. In addition to adding to the general confusion on enemy indicators, electronic jamming protected the first plane in a flight as well as succeeding planes. This combination reduced the effectiveness of anti-aircraft fire to about 25 percent of normal, which saved the U. S. forces an estimated 450 aircraft and 4500 casualties. The value of these aircraft alone more than equalled the cost of the countermeasures program directed against German flak. During the height of the campaign, 20 billion dipoles were scattered on Germany and France each month.

In the Pacific, chaff was not used to any great extent because the Japanese radars used many widely different frequencies, which would have required as many different sizes of chaff to combat them. Instead, very long strips of aluminum foil, about one half inch wide and 400 feet long, were dropped, sometimes supported from small parachutes. This device, known as rope, was effective over a very wide range, covering all of the many frequencies employed by the

Typical wideband antenna structure, used to cover wide frequency range of jamming transmitter. Known as a fish-hook, this radiator produces circularly polarized signals to jam regardless of the polarization of an enemy antenna

Jap equipment. Eventually, each B-29 carried 600 pounds of this material on every mission. This weight necessarily subtracted from the bomb load, but was well worth it.

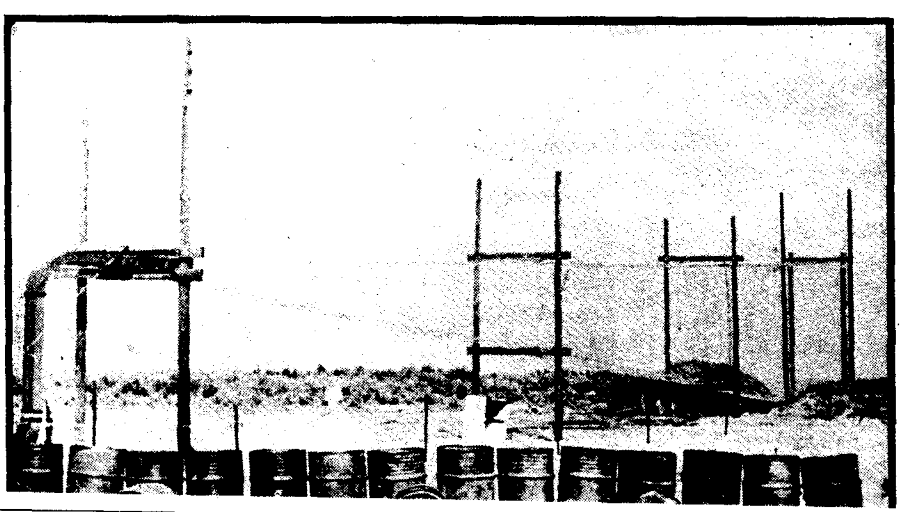
Tuba and the Resnatron

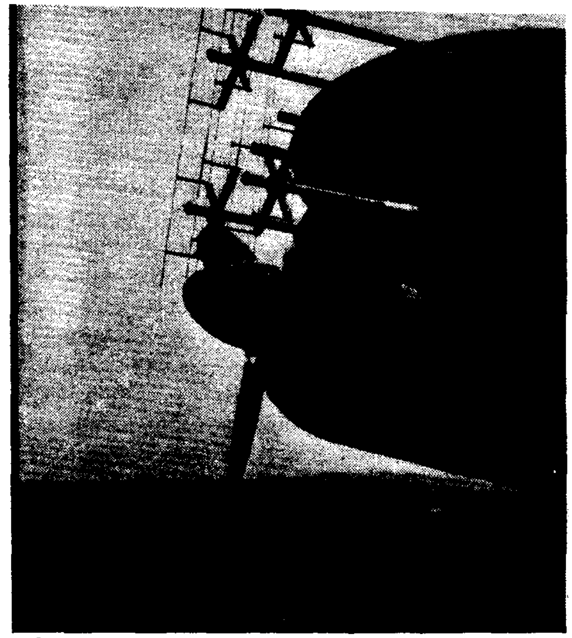
Perhaps the most spectacular of all rcm developments was the high-powered ground-based jammer known as tuba. Beginning in 1942 the Germans installed airborne Lichtenstein radars in their night-fighters, operating at about 500 mc, and designed to detect night-flying British bombers. So successful was this German equipment that consideration was given to an airborne jamming equipment to be carried in the British planes, but this plan was abandoned when it became clear that the Germans could locate the bombers from the ground by accurate d-f equipment. So it was decided to install a super-power jammer on British soil, aimed at the coast of France and intended to blot out the screens in the night fighters as they chased the bombers home. To achieve this result, the highest possible power was required. Calculations indicated that tens of kilowatts, continuous wave, tunable from 375 mc to about 600 mc would be required to cover the possible tuning range of the German equipment with a sufficiently strong signal. The highest c-w power achieved up to that time at that frequency was measured in the tens of watts.

The answer was found in the resnatron, a water-cooled, continuously-pumped tetrode which overcomes the effects of electron transit time by a 90-degree phase shift introduced between grid and plate circuits. This tube achieved the astounding power output of 30 kw, continuously, at a frequency of 500 mc, and was pushed to an output of 100 kw for short periods. The upper frequency limit of the tubes developed for tuba was found to be about 700 mc.

The original design was modified to permit tuning it through the range (about 200 mc) over which the Lichtenstein airborne radars could be shifted by simple modifications. The tuba equipment consisted of two oscillators, noise modulators, power supplies, etc, mounted in trucks. Two oscillators were required to cover the frequency range, not only for convenience in tuning the resnatrons themselves, but also to permit the

Radiator of the tuba jammer, a chicken-wire horn 150 feet long. Based on the south coast of England, and fed with 30 kw of c-w power at 500 mc, this equipment successfully jammed the Lichtenstein radars over Europe. Note 22-by-6-inch waveguide feeding horn at left





Antenna of German Lichtenstein airborne radar, operating at about 500 mc and used on night fighters to combat Allied bombers. This successful equipment led to the development of a super-high-power jammer known as tuba

use of waveguides. Since a waveguide of given crossection can transmit power over but a limited range of frequency, two systems were used to cover the band. The waveguide cross-sections were respectively 16 by 6 inches and 22 by 6 inches, which is easily the largest waveguide system ever used. The radiator itself was a sectoral horn, constructed of chicken wire supported on telegraph poles, 150 feet long from neck to mouth. Work on tuba began in America early in 1943. The first operation against the enemy began from the south coast of England June 1944. In that month the Germans changed to a radically different type of airborne interception radar.

Aside from its military success, the resnatron is a major milestone in the history of electron tube development. It can develop more power than, perhaps, can be used economically for any peace-time purpose at frequencies above 100 mc. While its modulation capabilities have not been thoroughly investigated except for random noise waveforms, the advance indications are that it can be modulated in frequency, phase and amplitude over very wide sidebands. Its importance in the future of f-m and television broadcasting can scarcely be doubted.—D.G.F.