Tricks of the Trade

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Can rhombic antennas be used for high-power broadcasting? How one of the world's big broadcasters got on the air.

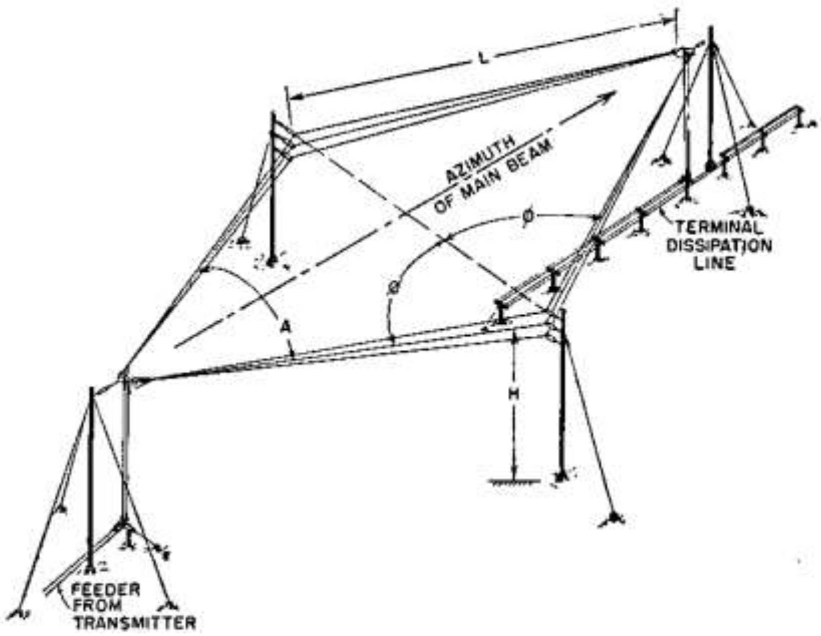


Figure 1. Horizontal rhombic antenna (from Laport [1])

Introducing the rhombic

The first published description of the horizontal rhombic antenna, as shown in **Figure 1**, was in 1931 following its development by Edmond Bruce (1899-1973), also known for his earlier Bruce array, and Harald T Friis (1893-1976), both then of Bell Telephone Laboratories. The equi-sided rhomboid-shaped antenna was commonly used for overseas radiotelephone and press circuits before and during WWII, for both transmitting and receiving. However, during post-War times, the rhombic has earned itself a ‘Marmite’ reputation, particularly since the 1960s when various types of log-periodic antennas, including rotatable versions, had been developed as attractive alternatives

It was said and often repeated, that the rhombic, as one of a group of non-resonant antennas, was unsuitable for high-power broadcasting. As far as the author knows, rhombics have never been used at BBC transmitting stations for broadcast transmission although they have been used extensively elsewhere for HF communications, in particular for point-to-point fixed services.

How does it work?

A simplified explanation of its operation will perhaps assist in understanding the shortcomings of the rhombic.

The antenna comprises four end-fed long wires arranged in a diamond shape. Each of these wires, being several electrical wavelengths long, has a symmetrical radiation pattern with an increasing number of lobes and nulls as frequency is increased but the largest lobes are always those nearest to the direction of the wire. The object of the design is to align the forward major lobes from the wires so that the separate gains of each wire add in phase. However, it is inevitable that the minor lobes remain in the composite radiation pattern, regardless of whether or not the major lobes have been correctly enhanced. While the antenna is in no way resonant, there is an optimum condition of lobe alignment which is frequency conscious.

The physical variables are:

(i) the required take-off angle to suit propagation and required signal path length
(ii) the length of the rhombic sides, usually about four to six wavelengths at the design frequency
(iii) the included angles of the rhomboid
(iv) the height of the wires above ground, often between one and two wavelengths.

It is not possible to control the horizontal and vertical radiation patterns independently but, fortunately, there are design charts to assist the determined DXer **[2]**.

That resistive termination

The basic design of a rhombic provides a bi-directional antenna but use of a resistive termination at the forward end produces a uni-directional radiation pattern. This termination is of no great consequence in the receiving situation where a non-inductive carbon resistor may be fitted directly at the far end of the antenna. However, consideration is necessary when a rhombic is used for transmission because half of the transmitter power output is dissipated in the termination load. Thus, when used with transmitter output powers greater than those customary in point-to-point communications, the dissipation of 50% of the output from the transmitter in the uni-directional version can become an engineering embarrassment. In many situations, though, the power loss of around 3 dB is accepted as a trade-off against the beneficial features of the rhombic.

For medium- and high-power transmitting purposes, the termination usually takes the form of a balanced lossy transmission line of high power dissipation capacity using resistance wire, preferably non-magnetic, corrosion resistant at high temperatures and with a high melting point. Such wires, usually made from alloys containing nickel and/or chromium, are used for electric heating elements in domestic situations, *e.g.* ovens, toasters, hair-driers as well as soldering irons. The most commonly used alloy is Nichrome, an alloy of 80% nickel and 20% chromium, which has relatively high electrical resistivity together with a low temperature coefficient. Other alloy compositions have been employed including Constantan (55% copper, 45% nickel) and Manganin (83% copper, 13% manganese, 4% nickel). Constantan has an advantage over the other alloys of being easily soldered. Wire diameters of *c*. 0.25 inch would have been used for carrying RF power at the level envisaged.

A lightning discharge circuit may be included by wiring an earthed spark gap to the centre of the termination. Static-charge leakage is also required where the antenna may become charged by rain, dry snow or flying sand and electric storms and is easiest to achieve at the end of a dissipation line.

Impedance matching may be achieved by using a tapered intermediate matching line designed for the lowest working frequency, using either exponential or linear taper. Chas. R Burrows noted that, when an exponentially tapered line is used as a dissipative load instead of a uniform line, it is possible to approach more closely the ideal of constant heat dissipation per unit length, making it possible to use a shorter line for carrying RF power at the levels envisaged **[3]**.

Advantages of a rhombic

Compared to a dipole curtain array, rhombics are relatively quick and easy to construct and set-to-work. The total weight is small resulting in the use of simple mechanical support structures and components. The four support poles may be of timber which is inexpensive and is often readily obtainable. Maintenance and repair of rhombics is straightforward and very little adjustment is required in the field. In any case, windage is low leading to fewer storm damage incidents.

The rhombic is capable of giving low take-off angles, despite modest height, together with respectably high-gain and a usefully-directive radiation pattern across a two- or three-fold frequency range. The input impedance, however, is sensibly constant over a far wider frequency range, *c*. 8:1, or sufficient to enable a single antenna to be used across most of the HF range. When used for transmission, antenna voltages and currents are low for the power handled.

With its simple construction, the height of the copper-work can be altered to obtain optimum take-off angle as ionospheric layers change through a sunspot cycle.

Against the above pros there are inevitably cons with the rhombic, the most serious being the physically large area of land required, particularly if several destination target areas are to be provided for in one antenna field and, in the transmitting context, the power loss occurring in the terminating load required to make the rhombic unidirectional. Other disadvantages relate to performance. A multiplicity of radiation lobes are liable to occur in all directions including some rather large secondary lobes despite care being taken in design. There are compromises in the directivity or take-off angle with change in frequency and the horizontal and vertical radiation patterns are, to an extent, interdependent.

For optimum performance, a rhombic antenna should be designed for use at one frequency or a small band of frequencies, to match the predicted propagation pertaining along the ionospheric circuit. However, in most cases, the design centres on the characteristic of the main forward lobe, the compromises being accepted as a trade-off for an antenna which can be used over a wide frequency range.

All considered, the rhombic provides a fairly good performance to capital outlay ratio. It is also quite inconspicuous with its low profile.

BBC's involvement with transmitting rhombics

It was during the mid-1960s that the BBC started using SSB and, later, independent sideband (ISB) programme feed transmissions from Daventry and Rampisham with rhombics directed to the relay sites then located at Ascension Island, Cyprus, Masirah and Tebrau (Malaysia). Feeds of two programmes could be obtained simultaneously from a single dedicated ISB transmission within the fixed-service frequency bands. 'Off-the-shelf' communication equipment was modified to provide a satisfactory audio bandwidth for the programme material. Three Marconi H1200 transmitters were employed, each rated at 30 kW PEP output and, thus, an RMS power of less than 10 kW would have been dissipated in the rhombic terminating load.

The Foreign and Commonwealth Office transmitting station in the Ashdown Forest near Crowborough, the home of Aspidistra, had also carried BBC transmissions using two 100 kW HF transmitters installed during WWII **[4]**. Crowborough, or 'Aspi' as it was always known operationally, had over the years been equipped with a range of antenna types including curtains, a log periodic and dipoles but also with rhombics as there had been lower power communications facilities on site.

For many years, the chief engineer at Crowborough was Harold Robin, who was educated at Oundle, a public school unusual in providing practical instruction in engineering workshop practice for boys who were "more interested in lathes than Latin" **[5]**. He was ever resourceful and always willing to develop hitherto-untried ideas in order to achieve a result. After all, it was under Robin's leadership that the 600 kW MF transmitter, Aspidistra (named from the song), was obtained and successfully installed underground despite wartime limitations to available effort and materials. Again, later, high-power Doherty-type MF broadcast transmitters were devised in modules which could be air-freighted overseas without the need for heavy modulation transformers.

Latterly there were two rhombic antennas at Crowborough which were beamed on 114° for SE Europe, reversible to 294° for North America (RH3) and on 196° for North Africa and SW Europe (RH2). Nichrome loads were constructed, capable of handling the unproductive half-power from each antenna, the load for RH3 being located at the centre of the rhombic with feeders running to each end of the antenna and associated switching to interchange feeder and termination as shown typically in **Figure 2**.

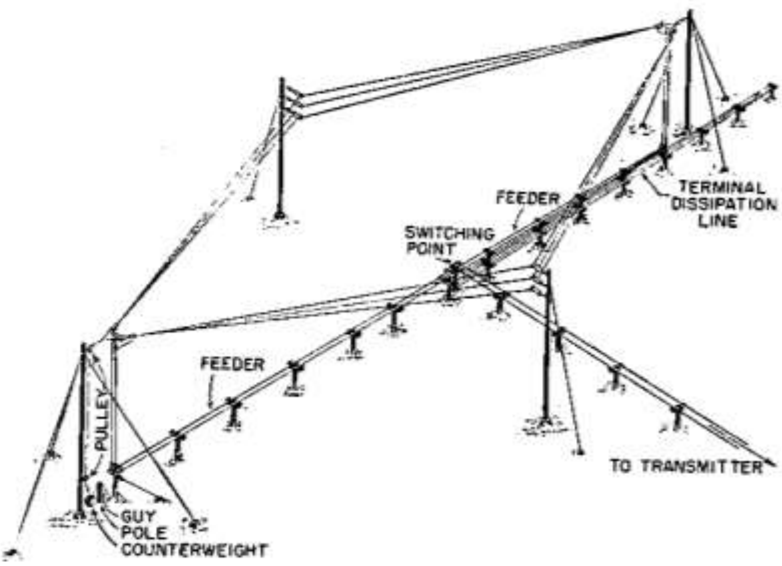


Figure 2. Horizontal rhombic antenna with feeders arranged for reversing pattern (from Laport [1])

The southerly rhombic was *c*. 30 m high and calculated to produce take-off angles ranging from 20° at 9 MHz to 8° at 18 MHz. Rhombic 3 was some 45 m high giving take-off angles from 14° at 7 MHz to *c*. 5° at 18 MHz. Over the same frequency ranges, the corresponding gain figures for RH2 were shown at *c*. 12–19 dBi and, for RH3, *c*. 15–21 dBi. Rhombic 3 would have been *c*. 300 m from end-to-end **[6]**.

USA caught short

During mid-1941, the US Government was very aware of the drums of war and their Foreign Information Service started providing war news and commentary for the existing short-wave stations to use on a voluntary basis. Until then, HF had only been used by several US organisations for commercial broadcasting for their own purposes, generally employing low power transmitters.

After the Pearl Harbor incident in December 1941, the United States found itself without international broadcasting facilities. The Office of War Information (OWI) took over all US-based short-wave outlets in 1942 to carry what became Voice of America (VOA) as well as Forces broadcasts. These outlets amounted to around a dozen transmitters with the most powerful being 75 kW.

VOA started broadcasting in 1942, within three months of the Japanese attack, initially using BBC transmitters to Europe, augmented by the motley selection of US transmitters and antennas.

Meanwhile, the administration hastily made plans for a rapid expansion in short-wave transmission equipment, calling in leaders of the big broadcasting equipment manufacturers, RCA, General Electric and Westinghouse, to discuss the need for six 200 kW HF transmitters to broadcast mainly to Europe within two years. An outsider that was not a transmitter manufacturer as such was also invited to the meeting. The Crosley Corporation of Cincinnati was present on the strength of its experience in high-power MF broadcasting and in building some short-wave equipment in-house. Crosley's chief engineer RJ (Jim) Rockwell was able to accept the challenge, largely because the work would not interfere with Crosley's other contributions to the war effort – as it would in the case of the big broadcasting equipment manufacturers.

The problems to be overcome included a general lack of experience of HF at over 100 kW. Suitable valves had yet to be developed, the performance of insulators, variable capacitors and HF transmission lines was unknown at the required power level and high power fault interruption required researching – all against a background of wartime restrictions that included shortages of raw materials, components and manpower **[7]**.

A short history lesson follows to explain the driving force behind the Crosley Corporation, as there are some interestingly-entwined threads. One man with keen ambition and great resourcefulness seems to have been a key figure in enabling the desired advances in short-wave broadcasting.

Introducing Powel Crosley, Junior (1886-1961)

Mr Crosley was a larger-than-life showman, inventor, entrepreneur, industrialist and one-time owner of the Cincinnati Reds baseball team. In group photographs, it always seemed to be Powel Crosley towering above the others.

He manufactured consumer products ranging from radios to cars in Cincinnati, Ohio. He was extremely inventive but, fortunately, had a younger brother Lewis Crosley with good business sense. The philosophy of the company was to provide good service and satisfaction to the customers. The first successful venture was into motor accessories and gadgets, particularly for the model-T Ford. Later in his career he was manufacturing refrigerators and patented the idea of having storage shelves in the doors. He got into motor manufacture and achieved moderate success with a very economical model for its time. Boy George was said to have owned a small Crosley sports car.

Crosley started making crystal sets only as a result of being asked for one by his son and finding out, from a 25-cent book, that he could manufacture a crystal set for far less than was being charged by the other makers. He then went on to produce inexpensive regenerative radio receivers. In 1921, Crosley started using a 20 W transmitter from his own home to provide a signal for the new listeners to tune to. He then established the Crosley Broadcasting Company to provide more appealing entertainment broadcasts and boost sales of the radios made by his own company. In 1922, Crosley was granted a licence by the Federal Radio Commission (FRC) to broadcast using the call sign WLW, named after the 'World's Largest Warehouse' **[8]**.

Crosley had adopted some of Henry Ford's production techniques. To sell more radios, he progressively increased his transmitter power until, by 1924, he was using 1000 W and then, claiming a USA 'first', 5000 W in 1925. Each successive power increase enabled Crosley to capture a much greater potential audience from the more densely-populated eastern seaboard and Great Lakes areas of the US. In 1927, Crosley was allowed to raise power to 25 kW regularly and to 50 kW on an experimental basis. In 1928, the station moved to its current site at Mason, about 20 miles north-east of Cincinnati, using a 50 kW Western Electric transmitter. WLW then claimed to be the first US commercial station using 50 kW on medium-wave. But the power race did not end there **[9]**.

The big rig

In 1933, WLW began construction at Mason of the first-ever 500 kW MF station with the approval of the FRC. The RCA transmitter incorporated the 1928 Western Electric 50 kW as driver with some sub-contracting to General Electric and Westinghouse. There was considerable built-in redundancy in the design. Three paralleled power amplifiers, each with four valves in parallel-push-pull, had the secondaries of each output coupling transformer connected in series to pass RF power to the antenna feeder. Two modulator amplifiers operated in parallel but, again, with their output transformer secondaries in series to modulate the RF stages. The antenna was an 800 feet half-wave Blaw-Knox diamond-shaped vertical.

From 1934, WLW was allowed to use the full power on an experimental basis only and using the callsign W8XO. However, by the end of that year, the station was required to reduce power at night to avoid causing interference within the service area of a Canadian station nearly 400 miles away on the adjacent channel frequency **[10]**. However, this imposed power reduction was short-lived as two 'spoiler' masts were erected at WLW to reduce the strength of signals in the offending direction to the equivalent of the former 50 kW transmissions.

The February 1934 issue of 'Broadcast News' (USA) reported that, during commissioning tests on the new transmitter, an unmodulated output carrier power of 800 kW had been achieved and more than 700 kW with 100% sine wave modulation applied **[11]**. This 500 kW medium-wave transmitter was the elder sibling to 'Aspidistra' (genders not confirmed!). Once in service, advertising rates for WLW, 'the Nation's Station', increased to match the extended coverage area. The station was clearly audible over a wide area, including the UK late at night, and stories were told of even having listeners in Buckingham Palace.

Much to the chagrin of other broadcasters who were not allowed similarly to enjoy the commercial advantage of an 'experimental' privilege to compete by using higher power transmitters, some also suffered interference to their own transmissions. During 1936–1938, there were 15 applications from other stations wishing to increase carrier power to at least match that of WLW, including that from WJZ in New Jersey who had actually ordered a similar 500 kW transmitter from RCA **[10] [12]**. Certainly, a 10 inch concentric feeder, suitable for 500 kW operation, had been installed in 1937 in readiness for use with a 750 foot mast at the WJZ Bound Brook site **[1]**.

In 1938 the US Senate succumbed to the US media lobby and adopted the 'Wheeler' resolution that having more stations with power greater than 50 kW was against the public interest. The FCC, then having been 'asked' by the US Senate, imposed an overall power limit of 50 kW to all US MF broadcasting and did not, in 1939, renew the authorisation for experimental 500 kW operation at WLW **[10]**. Thus, WLW reverted to 50 kW but, after the next renewal request from WLW was refused and all appeals procedures exhausted, the 500 kW transmitter was shut down except for short authorised night test periods as W8XO, some allegedly intended for European listening for propaganda purposes. Powel Crosley is reported to have commented bitterly that 50 kW was not that many more horsepower than a couple of speeding Buicks.

The W8XO tests enabled both output power and reliability to be improved such that, by the end of WWII, the transmitter managed 600 kW output with ease and 1000 kW if really needed. The RCA transmitter is still in place at Mason and WLW remains the only medium-wave station in the States to have operated at 500 kW.

However, the transmitter ordered by WJZ remained unsold and in mothballs until a certain Mr Harold Robin struck a deal with cheque in hand in 1941 **[4]**.The future Aspi transmitter had been modified by RCA for quick frequency changing as well as 600 kW operation before WLW/W8XO had that capability.

Entry of the re-circulating (re-entrant) rhombics

The size of the United States of America and the extent of its interests in Central and South America justified the use of short-wave broadcasting to increase audiences of US radio stations seeking trade, publicity or status in the bureaucracy-free domain. Manufacturers advertised their wares and religious organisations spread their gospels.

As already noted, Crosley had been trying to extend their coverage by using short-waves. By 1942, they already had two HF transmitters, one running 50 kW and the other 75 kW, one of which was a conversion from old MF equipment while the other was a composite assembled from more than one source. The antenna system included two re-entrant rhombics which had been proven in use for WLWO (for WLW-Overseas) and more were to be built alongside the WLW site **[13]**.

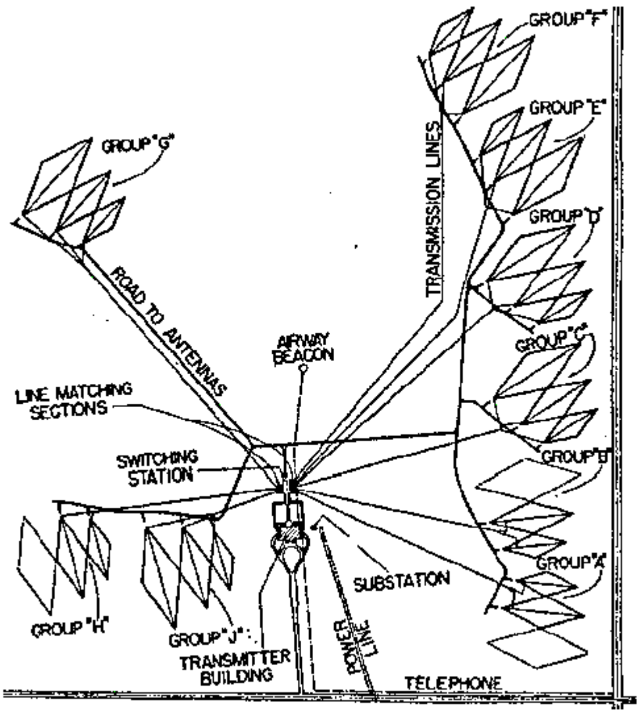
By Spring 1944, the first of the new-build 200 kW transmitters was running at the new Bethany HF site, less than two miles west of WLW, and the whole station with six transmitters was operational using 24 high-efficiency re-entrant rhombics in a little over two years from that first meeting, despite a small engineering staff and wartime obstacles.

The complement of short-wave transmitters at Mason and Bethany was then three 200 kW complete transmitters, with a further three similar RF channels powered and modulated from their counterparts across the hall as well as the earlier 50 kW and 75 kW transmitters, all products of the Crosley talents.

As will be seen from the Bethany site plan (**Figure 3**), the rhombics were arranged in nine groups heading towards South Africa (A), West and Central Africa (B), Spain and North Africa (C & D), Europe (E, F & G) and the Caribbean and South America (H & J). Six groups contained three antennas each while the other three groups only two each. Each group was fed by 525 Ω transmission lines. The 300 Ω output of the transmitter-antenna selector switch matrix was matched to the 525 Ω lines by multi-step quarter wave broad-band impedance transformers. The VSWR of the feeders from the antenna back to the matrix was claimed to be less than 1.1:1 **[13]**.

Many of the advantages noted for rhombic antennas were particularly relevant to their operation in North America while some of the disadvantages, such as their use of land, were not a great problem for the US. Rhombics could be erected without the need for expensive and difficult to obtain raw materials. The shortage of steel, for example, led to the use of wooden line poles for supporting the rhombics, two at each corner with sleeved butt joints to achieve a height of 90 feet (think 'Wichita Lineman'!) **[7]**.

Figure 3. The antenna layout at VOA Bethany



prior to 1951. From *The History of VOA Bethany*. By courtesy of Clyde G Haehnle, obtained from the Barry Mishkind website [13]

Figure 4. The commemorative QSL card issued for Bethany's 50th anniversary showing the curtain array support towers. By courtesy of David Snyder, last Plant Manager at Bethany, image obtained from the National VOA Museum of Broadcasting at the historic VOA-Bethany station building (www.voamuseum.org)

VOA, probably for expediency, relied greatly on rhombics in the early years as they were quick and inexpensive to build and easy to set to work, providing a 'quick-fix' entry to international broadcasting. Even the reinstatements following WWII favoured rhombics. However, in 1951, as part of an expansion of facilities following the onset of the Cold War, three large tower structures were built near the centre of the Bethany site to carry two bays of high-gain curtain arrays. These arrays were to improve feeders beamed to Europe and North Africa for relay and replaced some of the earlier rhombics. A commemorative QSL card issued for Bethany's 50th anniversary in 1992 (**Figure 4**) shows the towers dominating the sky-line compared with the lower profile of the rhombic support poles.

It is interesting to note that the other US-funded short-wave broadcasters, Radio Free Europe (RFE) and Radio Liberty (RL), who started in 1950 and 1953, respectively, at first utilised rhombics at their Lampertheim, Germany, and Gloria, Portugal, sites although antennas of other types, including curtains, were added later. Playa de Pals, Spain, opened in 1959 with nine curtain arrays but with diplexing. Youtube has a spectacular but saddening clip of the simultaneous destruction of the Pals antenna field including several 540 foot towers in March 2006 after operations closed in 2001 **[14]**.

However, the case for rhombics appears to be soundly vindicated as, according to an RFE/RL Year Book, the 1980s modernisation was to include the provision of a high-power rhombic at Holzkirchen, Germany, capable of working at a carrier level of 500 kW.

Tom Rauch W8JI has summarised the efficiency increase possible with the re-entrant termination lines, as follows: "There are ways to use this power but, generally, very little appears in rhombic resources. Efficiency and gain could be improved if we recirculated termination power. Rather than converting the power to heat, we could recombine the termination RF back into the main feeder system. Such recombining or recirculating schemes would be fairly simple, although they would require readjustment if the operating frequency was changed. A recirculating system would comprise an impedance matching network or stub and phasing system to bring the termination signal back in phase with the applied power. By recombining power that would otherwise be wasted as heat back into the feed system, system gain would increase 2–3 dB" **[15]**. Clyde G Haehnle, who was among those who built and worked at the Bethany site, gives figures claiming that the use of recirculation enables all of the power entering the rhombic to be radiated towards the target area **[13]**.

It is only fair to say that the Crosley Corporation was not the only builder of 200 kW HF transmitters for the OWI contract. However, Bethany contributed far more kilowatts of RF power towards VOA's wartime targets than any other site, using Crosley designed and built equipment.

Rhombics were used by other WWll VOA sites as well as the later overseas relay sites, except for Woofferton in the UK, which had been designed and built for the BBC. However, by the 1950s, the critically-tuned re-entrant rhombics had fallen out of favour and dissipative line terminations were installed to enable the natural frequency flexibility of the rhombics to be used.

It was not until the mid-1980s that the old wooden support poles for Bethany's rhombics were replaced with steel towers. The Crosley transmitters at Bethany were decommissioned in November 1989 and VOA Bethany, the creation of Crosley Corporation, closed in September 1995. The antenna towers were demolished but the more modern transmitters were moved to Iranawila, Sri Lanka.

Crosley's other war efforts

One should not ignore some of the other work undertaken by the Crosley factory during WWII in addition to the Bethany transmitters. Crosley manufactured proximity fuses, more than any other firm and with several production design innovations. General George Patton said the fuses helped win the Battle of the Bulge while Churchill gave credit for their potency against the V-1 ‘doodlebugs’. Crosley Corporation also produced much radio equipment, including the BC-654 transceiver, main part of the Signal Corps Radio SCR-284, which was introduced in North Africa during Operation Torch. Many more units gave support later in Normandy for Operation Overlord.

Wikipedia also lists portable cook stoves and B-29 gun turrets, as well as 'morale receivers' for listening to the VOA broadcasts in German occupied countries.

Crosley after Crosley

After the end of WWII, Powel Crosley Junior, just turning the age of 60, ensured his pension by selling WLW and Crosley Corporation, including the broadcasting interests, to the Aviation Corporation (AVCO). Radio manufacture continued and television production was added later, still using the name of Crosley until 1956, by which time business had declined. Powel Crosley Junior died in 1961 of a heart attack at the age of 74.

Part of AVCO's electronics division became the subject of a management buy-out in 1973 to form the Cincinnati Electronics Corporation. The new company manufactured avionics, space technology, radar and infra-red systems as well as electronic warfare equipment but has since changed hands in a series of acquisitions, notably in 1981 by GEC-Marconi who sold it on in 1988 to their North American affiliate CMC Electronics, formerly the Canadian Marconi Company, to better integrate Marconi's North American operations **[16] [17]**.

After an evaluation at Greenville, North Carolina, of 500 kW HF transmitters from four different manufacturers, VOA awarded, in 1988, a large contract to GEC-Marconi for an option on manufacturing and installing more than 30 high-power HF and MF transmitters. A proposed 16-transmitter relay project for VOA and RFE/RL in the Negev Desert, Israel, did not go ahead because of environmental concerns mainly regarding the paths of migratory birds.

Just around 20 transmitters were actually “Made in the USA” by Cincinnati Electronics Corporation, in reality a scion of Powel Crosley Junior's former broadcast empire including the radio station WLW.

DIY rhombics

By way of closing this round-up of rhombic antennas, a brief hark back to the transmitter scheduling office at Bush House where the author and his colleagues were often called upon to reply to listeners' letters when they sought technical advice on reception. Their need for better receiving aerials was discussed over coffee. It was even suggested that ‘freebie-packs’ each containing four acorns should be sent to help the prospective listener improve his lot. Instructions would, of course, have been enclosed with the pack explaining how a rhombic should be directed towards BBC transmitting sites.

Acknowledgements & References

The author acknowledges with grateful thanks to David Snyder, Clyde Haehnle and Barry Mishkind for allowing and enabling reproduction of Bethany images.

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