AS A RECENT TELEVISION SERIES DEMONSTRATED, THE USE OF RADAR BY BOTH SIDES IN WORLD WAR II WAS OF CONSIDERABLE STRATEGIC IMPORTANCE, WITH THE ADVANTAGE SHIFTING FROM ONE SIDE TO THE OTHER WITH EACH NEW DEVELOPMENT. THIS IS THE STORY OF ONE KEY INVENTION WHICH SWUNG THE BALANCE CONSIDERABLY AND WHICH CONTRIBUTED MUCH TO OUR UNDERSTANDING OF ELECTRONICS.

THE VALVES THAT WON THE WAR

BY IAN SINCLAIR

THE VALVES THAT WON THE WAR

THE ESSENCE OF RADAR is that radio signals sent out from a transmitter will reflect from a target which is large compared to the wavelength of the signals, and the reflected signals can be picked up on a receiver.

The time delay between transmission and reception is then a measure of the range of the object which is reflecting the waves. The wavelength which can be used is of considerable importance, since short wavelengths can detect smaller targets and also need smaller aerials. If we want to use reasonably small aerials and to detect objects about the size of an aircraft, then we must use wavelengths of about one metre or less. The methods which we use to generate these wavelengths are therefore of great importance, and the amount of power which can be delivered to the aerial will decide what range is usable, since the received signal can be detected only if it has an amplitude greater than the noise level of the input stage of the receiver.

Thanks to the use of low-noise input stages, pulse gating, and correlation techniques, we can now recover signals which have apparently been lost in noise, but these techniques were not available in the years of the war.

REFLECTIONS AND SHORTENING

Early radar experiments used standard or slightly modified short-wave radio transmitters, with power output stages which were usually large air-cooled triodes with conventional inductor-capacitor tank circuits. In the early experiments, detection was considered more important than range-finding, and the received signal was allowed to beat with a fraction of the transmitted signal to form a slowly changing beat note from a moving target. These arrangements were sufficient to show that the reflected waves could be detected, but the wavelength was too long (frequency too low) and the power too small for radar as we now know it.

What was needed was a generator of waves of much higher frequency and much greater power. In addition, if such a generator could be made small enough to be carried in an aircraft, a substantial advantage in night bombing would be obtained.

Using conventional triodes, this was impossible. The stray capacitances of a large triode are so large that even the inductance of a short piece of straight wire gives a tuned circuit whose frequency is too low (assuming that oscillation takes place). The power output of such a valve at extremes of frequency is too low in my case.

Fortunately, as so often happens, the foundations for a new type of construction were already laid. These foundations were the magnetron effect on electron beams, and the resonant cavity tuning system.

MAGNETIC SPACES

When electron beams travel from a hot cathode to a positively charged anode, the speed of the electrons is decided by the voltage applied between anode and cathode. Equating the potential energy, eV, with the kinetic energy $\frac{1}{2}mv^2$, for each electron we get:

$eV = \frac{1}{2}mv^2$, where e = electron charge
V = accelerating voltage
m = electron mass
v = electron speed.

From this equation, the electron speed, $v = \sqrt{\frac{2eV}{m}}$

Using modern units, the ratio e/m, the specific charge of the electron, is 1.76×10^{11} C kg^{-1}, so that for 5kV accelerating voltage, the speed of the electron is about 4.2×10^7 ms^{-1}, some 42 million metres per second. At this speed, an electron will cover a distance of 1 cm in 0.24 ns, so that we should have no trouble in generating oscillations of a comparable wavetime if we can use such a beam in an oscillating system.

Now if we apply a magnetic field to such a beam, and direct the magnetic field so that it is at right angles to the direction of motion of the electrons as they enter the field, the path of the electrons will be an arc of a circle whose axis is the magnetic field direction. Equating the magnetic force, Bev, on a moving electron with the force needed to move an electron in a circular path, $\frac{mv^2}{r}$ we have: $Bev = \frac{mv^2}{r}$, so that $r = \frac{mv}{Be}$

BEAM BENDING

Using the value of speed given above, to bend the electron beam into a circle of radius 1 cm needs a magnetic field strength of about 2.4×10^{-2} Wb m^{-2}, about one thousand times the magnetic field strength of the Earth. This is not a particularly large field strength, and it was attainable by either permanent or

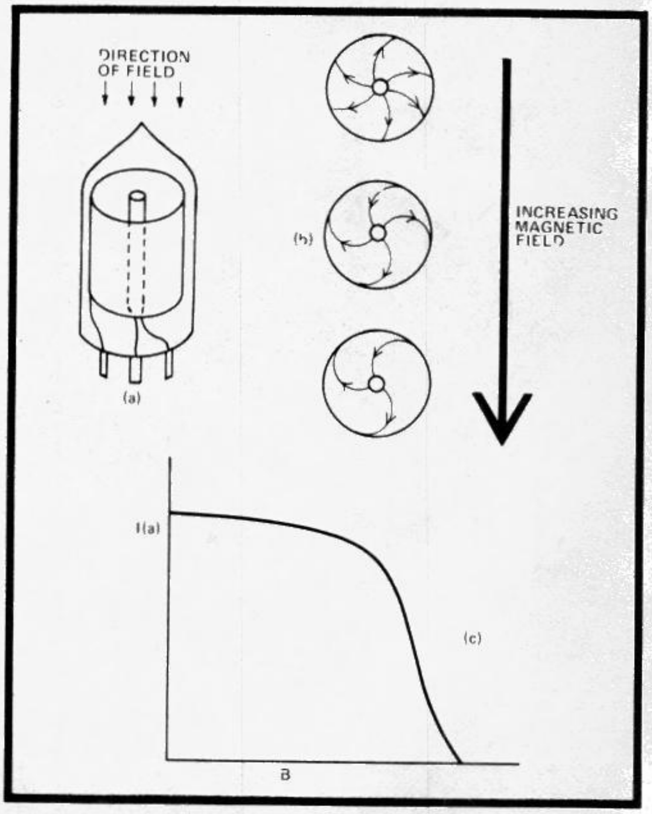


Fig 1. The magnetron effect. (a) Simple magnetron valve, magnet not shown. (b) Paths of electrons as the strength of the magnetic field is progressively increased. (c) Graph of anode current against magnetic field.

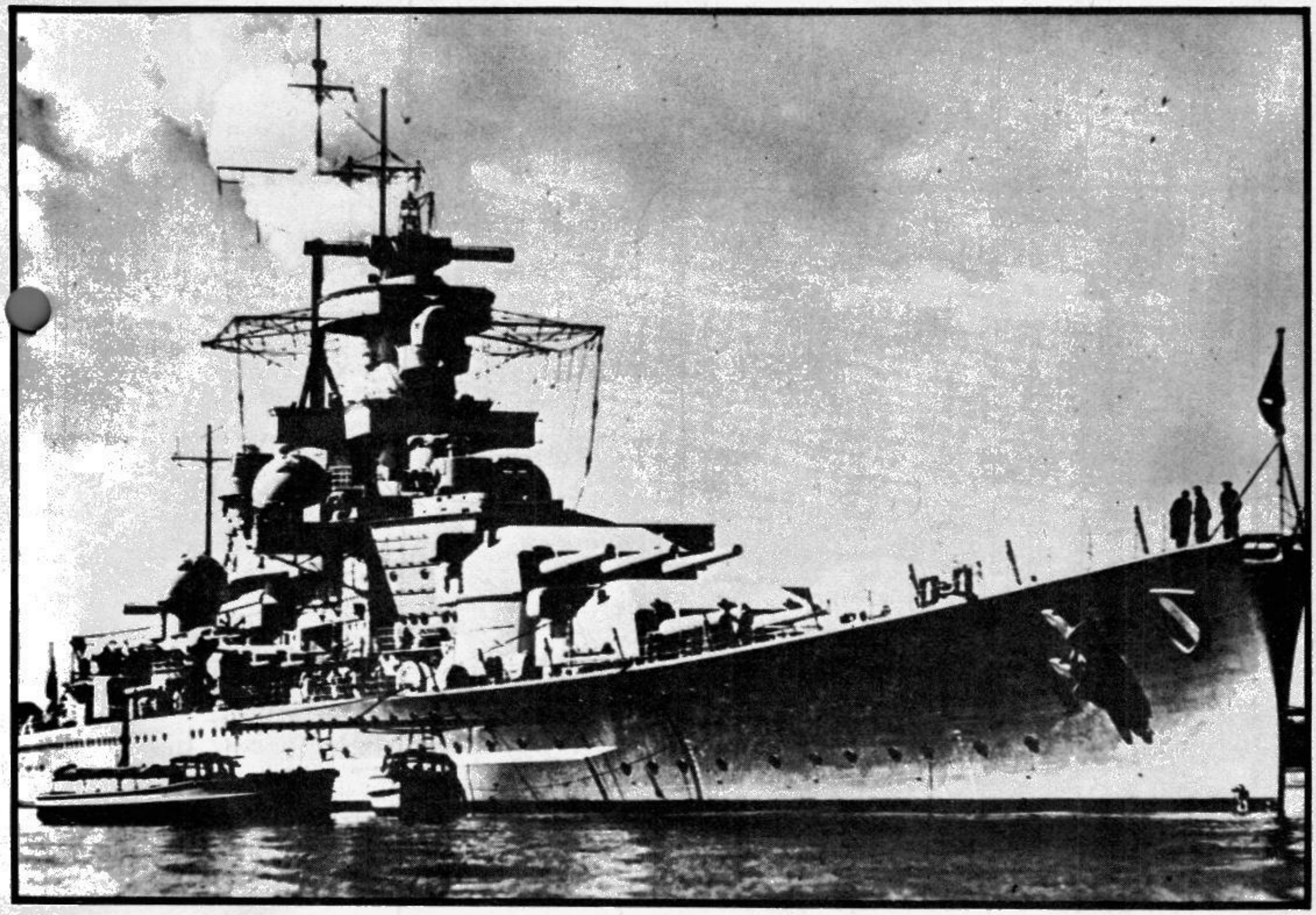
electro magnets. All of this basic theory has been known since early in the century due to the work of J. J. Thomson on the specific charge of the electron.

Later work had made use of the magnetron effect to measure the specific charge of the electron in a different way, as shown in Fig. 1. A tubular cathode emits electrons which are accelerated to a circular anode coaxial with the cathode. When a magnetic field is directed along the axis of the tube, the path of the electrons curves, and becomes more curved as the strength of the magnetic field is increased. If we plot a graph of anode current against magnetic field strength, the graph shows current dropping as fewer electrons reach the anode, and then reaching zero when the magnetic field is strong enough to prevent the fastest electrons from reaching the anode. Using such a "magnetron" valve made to accurately known dimensions, the value of e/m for the electron could be found to very close limits. The great breakthrough in radar was to realise that this valve structure could be combined with resonant cavities to enable us to generate oscillations in the GHz region.

RESONANCE

In the study of sound waves, any space may have resonances, meaning that sound waves of certain wavelengths, related to the dimensions of the space, will be emphasised; these are resonant frequencies, and designers of loudspeakers go to great lengths to get rid of them. A tube is one type of resonant space, and organ pipes and other wind instruments are examples of resonant tubes used to generate sound waves of various frequencies.

A tube which is resonant to one particular frequency will generate this frequency if the air in the tube is set into oscillation by any disturbance. An example of particular interest in this case is the flute. In this instrument, the player blows air across a small hole in a resonant tube. Air striking the edge of the hole (controlled by the players mouth-shape) builds up a pressure wave which sets the air in the tube into oscillation at its resonant frequency, and the resonant waves in the tube then make the air passing across the hole flutter, keeping up the oscillation. What we have here, translating into familiar electronic terms, is a d.c.



The mighty Scharnhorst. One of Germanys new generation of capital ships. As modern as anything then afloat, fast enough to outrun anything which could outgun her, and armed sufficiently to sink anything fast enough to catch her. Yet the Scharnhorst fell victim to the Magnetron!

The battle of North Cape was the battle which proved the importance of radar in surface engagements. Leaving Norway to attack convoy JW 55B the Scharnhorst was dogged by a series of disasters and unfortunate decisions by High Command which led her, on December 26th 1943 in appalling weather to face the British cruisers Belfast, Norfolk and Sheffield — all radar equipped and using it! Scharnhorst herself had radar equipment, but standing orders prevented its use (as a measure against breaking radio silence!) In the engagement which followed the British ship directed their fire with radar, and by chance destroyed the Scharnhorst radar!

They followed her on radar until the battleship Duke of York came up to engage, also using radar, with her superior armament. Scharnhorst was sunk. Her superior speed and firepower were of no avail.

On New Years Day 1944 Admiral Dönitz reported to Hitler "Without serviceable radar equipment it is no longer possible for surface forces to fight the enemy."

supply (the player's breath), a resonant tuned circuit (the tube of the instrument), and postive feedback (the effect of the resonant waves on the breath stream.

A similar effect can be expected using a beam of electrons. A circular cavity cut into a block of metal will act as a tuned circuit, using the inductance of the conducting material and the stray capacitance between sections at (momentarily) different potentials. This is a resonant cavity, and the wavelength of resonance is related to the size of the cavity. When such a cavity oscillates, both electric and magnetic fields will exist, and these will be rapidly alternating fields, going through a cycle of building up in one direction, dying away, reversing, building up in the reverse direction, dying away and so repeating millions of times per second.

Can we carry the similarity a little further, and imagine a small slot in the cavity? At such a slot, alternating electric and magnetic fields will exist, and these will alternately repel and attract an electron beam which is just skimming past the slot like the breath of the flautist. Would such an arrangement give enough positive feedback to keep a resonant cavity oscillating? At the beginning of the war, only experiment could decide, and it fell to Randall and Boot, working at Birmingham, to perform the crucial experiment, so creating the first cavity magnetron oscillator. This valve was capable of supplying U.H.F. oscillations at power levels greatly in excess of any previously obtained at such frequencies, the perfect answer to the demands of the radar system.

Fig 3. A coastal defence tower. Standing some 360 ft high, the apparatus was used to detect low flying intruding aircraft which were flying too low for normal stations to detect them. Lone raiders often adopted this tactic to reach specified targets, or to make photographic records.

CAVITY MAGNETRON

The cavity magnetron combines the principles of the resonant cavity with the earlier magnetron valve. The cathode is a tube coated with electron emitting material, and with a heater winding inside for starting the electron emission. The anode is metal block, finely machined to a circular profile with a set of resonant cavities breaking into the inner surface of the block. The whole valve is evacuated and sealed, and then mounted between the poles of a strong permanent magnet. Since it would be inconvenient to run the cathode at earth potential and have the metal anode and its cooling fins positive, the anode is earthed (and connected to waveguide through a thin "window") and the cathode run at a negative voltage.

When an accelerating voltage exists between the anode and the cathode, the electrons are accelerated from the cathode, and the magnet shapes the beam so that its shape is circular, brushing past the ends of the cavities as it tries to reach the anode. For a given strength of magnet, the voltage between anode and cathode would have to be the correct value for the beam to take the correct path, but this value is fortunately not too critical. The movement of the beam excites the cavities into oscillation, and the oscillating cavities in turn will alternately repel and attract the beam.

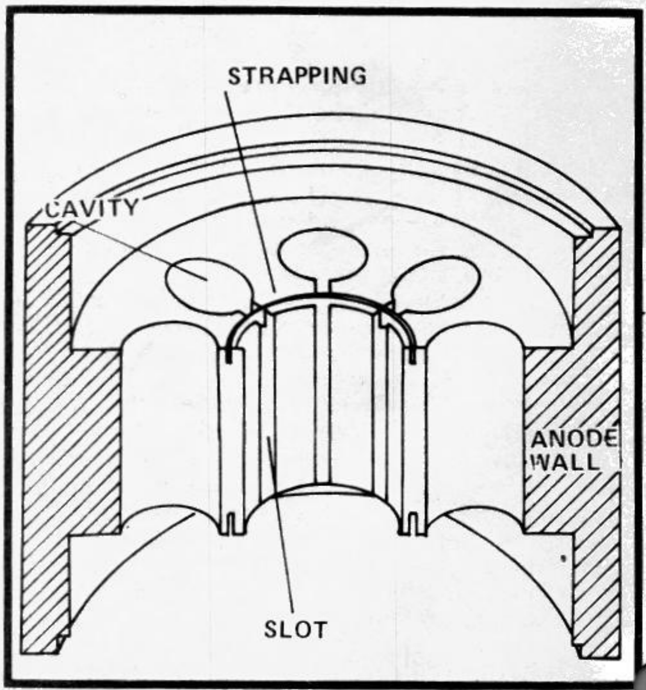
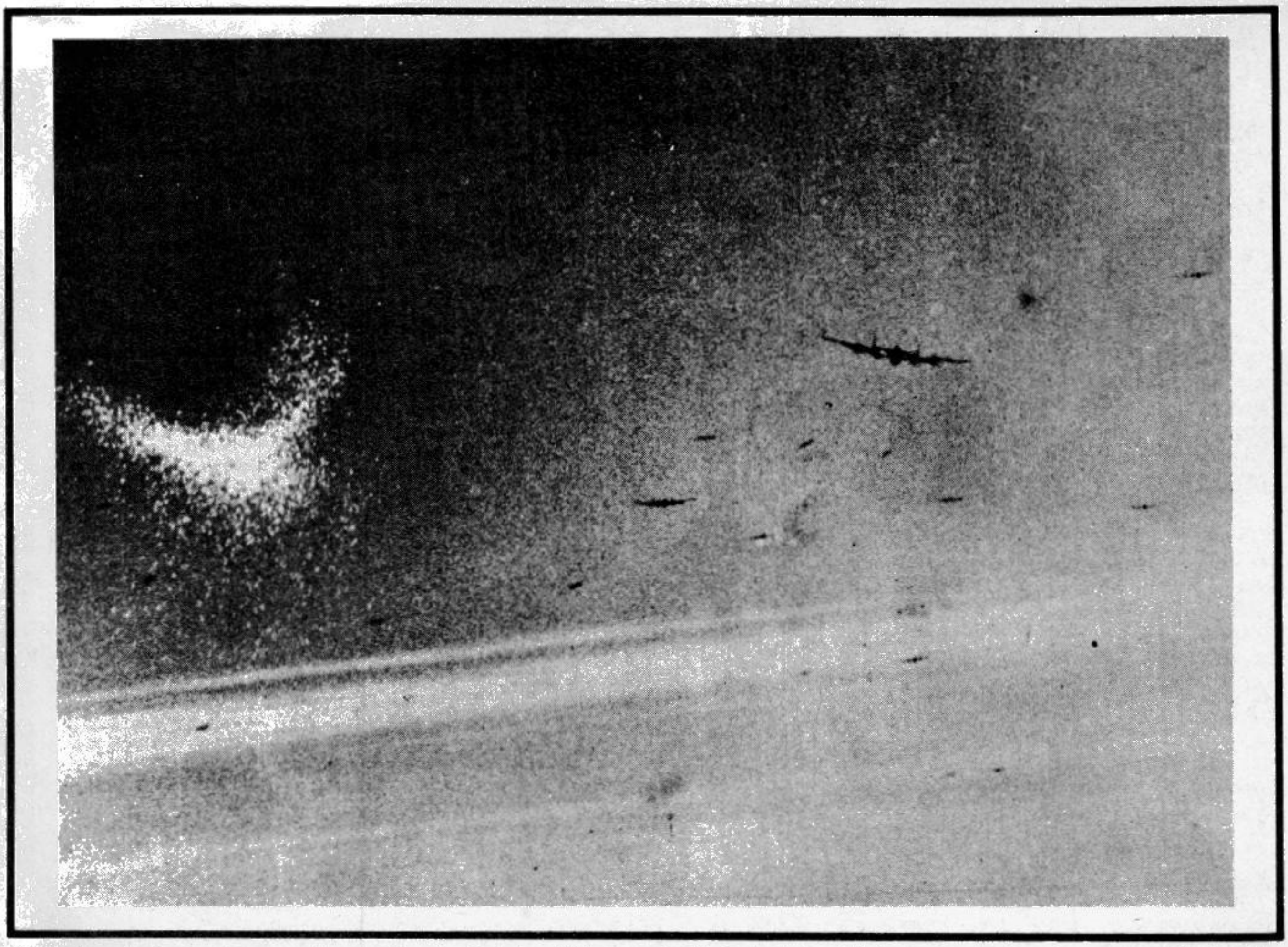


Fig 4. Cross-section of a cavity magnetron, which in this case uses cavities of cylindrical shape, linked to the anode by slots. The strapping links can also be seen. Other cavity shapes are also used.



PHOTOGRAPHS BY COURTESY OF IMPERIAL WAR MUSEUM.

The photograph shows a Lancaster bomber dropping 'window.' This was shredded aluminium foil, dropped to confuse German ground radar. The beams were scattered by the foil, giving totally erroneous readings upon re-receipt. In the background can be seen some of the other aircraft in the raid, in this case a 1,000 bomber attack on Essen.

The foil is the silvery shimmer to the left of the photograph, scattering as it falls.

COMBINATION LOCK

The combination of these effects causes the beam alternatively to strike and then be repelled from the anode, so that the oscillations in the cavities can have very large voltage amplitude, of the order of the applied voltage. Similarly, by using a large cathode, high beam currents are possible so that the peak power developed in one cycle of oscillation can be very large. At the same time, the size of the magnetron is modest, since the radius of curvature of the electron beam is small, and the power dissipated would melt the anode if the beam were applied continuously. The answer here was to pulse the beam by applying a short (1 µs or less) negative pulse of several kV amplitude to the cathode at a repetition rate of1 000 pulses per second or so. By using this technique, the power developed during a pulse, which could be of thousands of cycles of the microwave frequency, could be many kilowatts, giving excellent range, yet the average power, and hence the heat dissipation, would be only a thousandth of this value, since the valve would be on (in this example) for only one microsecond in each millisecond.

DEVELOPMENTS

Inevitably some development was needed. The early cavity magnetrons were unstable, changing frequency for no apparent reason. This is a problem which also afflicts those learning to play wind instruments, because all resonant cavities will resonate to harmonics (multiples of frequency) of the lowest note which is possible (the fundamental). The resonant cavities of the magnetron have the further complication that two sets of oscillations are taking place in them, oscillations of magnetic field and oscillations of electric field. The cure was to shape each cavity to make one mode of oscillation dominant, and to use cavities which were interconnected, with alternate cavities "strapped" so as to reinforce the desired frequency of oscillation.

In addition, the tendency of magnetrons to burn out their cathodes too quickly was found to be due to the extra heating caused by the beam current. This could be counteracted by using the heater only for starting the tube, switching it off whenever the magnetron started to oscillate so that the beam current could then provide the heating.

FROM THE NORTH CAPE TO OVENS

Nowadays, the magnetron is still the high power, high frequency microwave signal source, used in radar, in microwave ovens, and in materials research. The advantage which the cavity magnetron gave us during the war was of major importance, and the advantage, unlike so many others before and since, was never quite lost. ●

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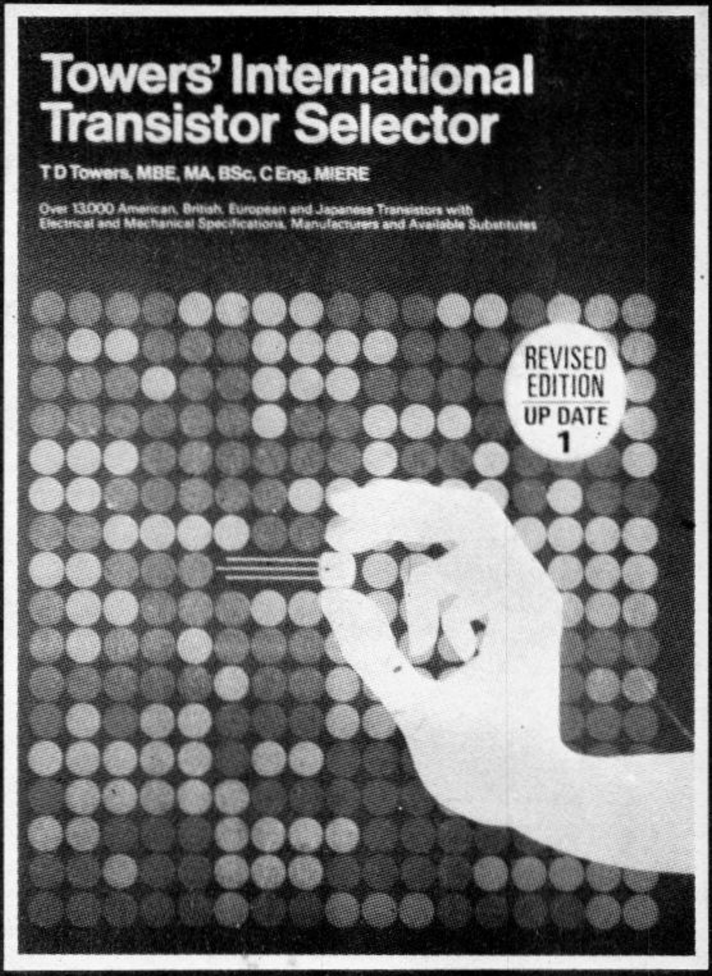

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