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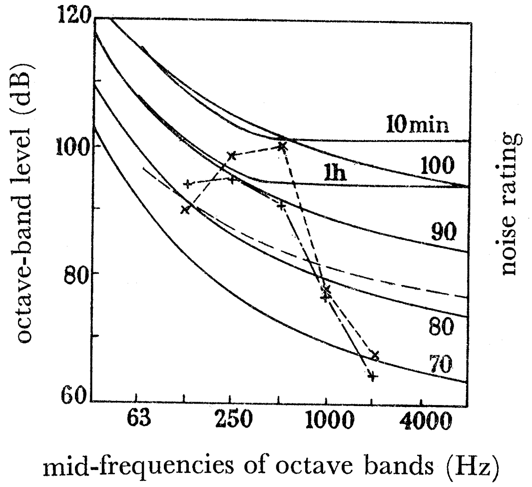
[Plate 7]

Introduction

Power transformers up to 600 MVA, in a single unit weighing 350 tons, have been built for modern generating stations. Auto-transformers up to 750 MVA have been constructed for the 400 kV grid. These large units, shortly to be commissioned, will operate at efficiencies of 99·8 to 99·9 %. A minute fraction ($\sim 10^{-6}$) of the total loss of 1 to 2 MW is



short time exposure for pure tones (Kryter *et al.* 1966)

Hz	100	200	300	400	500	600	
dB for 15 min	114	108	104·5	102·5	101	99·5	permissible daily periods
dB for 1 h	100·5	95	93	92	91	90·5	

sound measurement	maximum sound level (dB)*	minimum sound level (dB)	range (dB)	arithmetic average (dB)	pressure squared average (dB)	difference in averages (dB)	lower bound† (dB)	power level (dB re. 10^{-12} W)	power (W)	loudness index (Stevens)
A	95·2	83·7	11·5	88·4	89·4	1·0	3·5	112·8	0·19	
B	100·0	90·2	9·8	95·3	96·0	0·7	2·6	119·4	0·86	
C	101·8	92·5	9·3	97·8	98·4	0·6	2·4	121·8	1·50	
125 Hz	100·3	81·0	19·3	93·1	94·9	1·8	8·7	118·3	0·67	25
250 Hz	102·0	83·0	19·0	94·5	96·0	1·5	8·5	119·4	0·86	32
500 Hz	100·2	85·0	15·2	90·2	92·0	1·8	5·8	115·4	0·34	31
1 kHz	79·8	70·5	9·3	76·3	76·8	0·5	2·4	100·2	0·01	14
2 kHz	72·0	55·7	16·3	63·9	64·8	0·9	6·6	88·2	0·00	8
										55·4 sones ≡ 98 phons

* All sound levels are given in dB re. 0·2 nbar.
† This is the maximum theoretical difference between the averages for the measured range.
(Values given by Cox (1966) were corrected.)

Figure 1. Summary of noise measurement at thirty-eight positions in the near sound field of a 750 MVA auto-transformer. – – –, deafness risk criterion (Burns 1965): 8 h per day; ——1 h, ——10 min, short time exposure levels for broad-band noise: (Richards 1965; Beranek 1960), permissible daily periods; +, mean pressure squared levels; ×, position 21.

radiated as sound. The octave-band levels near such a transformer exceed the hearing damage criterion recommended by Burns (1965) for regular 8 h exposure (figure 1), but fortunately transformers do not require a driver! In general, only the acousticians who take measurements in the near noise field of the transformer, during its works proving test, are exposed to a risk! Lower down the scale of size, the noise of a transformer may cause annoyance, because substations must be located near or within residential areas to make the distribution of electrical power economic. Transformer noise is a social rather than a technical problem. The stresses due to mechanical vibrations of the tank are less than 0·2 ton/in.^{2} (peak) and the fatigue life is vastly in excess of the economical life (25 years) of the unit (table 1).

TABLE 1. MAXIMUM ALTERNATING STRESSES IN TRANSFORMER TANKS

The alternating stresses were calculated from the vibration measurements.

		values at the position of maximum tank vibration			
transformer rating (MVA)	tank material	alternating displacement (in. peak)	alternating stress (tons/in.^{2} peak)	static stress (tons/in.^{2})	fatigue limit† (tons/in.^{2} peak)
15	$\frac{3}{8}$ in. mild steel	$1{\cdot}3\times10^{-3}$	0·09	5·7	11·6
90	$\frac{3}{8}$ in. mild steel	$2{\cdot}5\times10^{-3}$	0·16	2·8	13·2
750	$\frac{5}{8}$ in. Al alloy	$2{\cdot}4\times10^{-3}$	0·06	3·3	6·8

† The fatigue limit defines the maximum alternating stress (in tons/in.^{2} peak) which the material will survive indefinitely, for the given static stress.

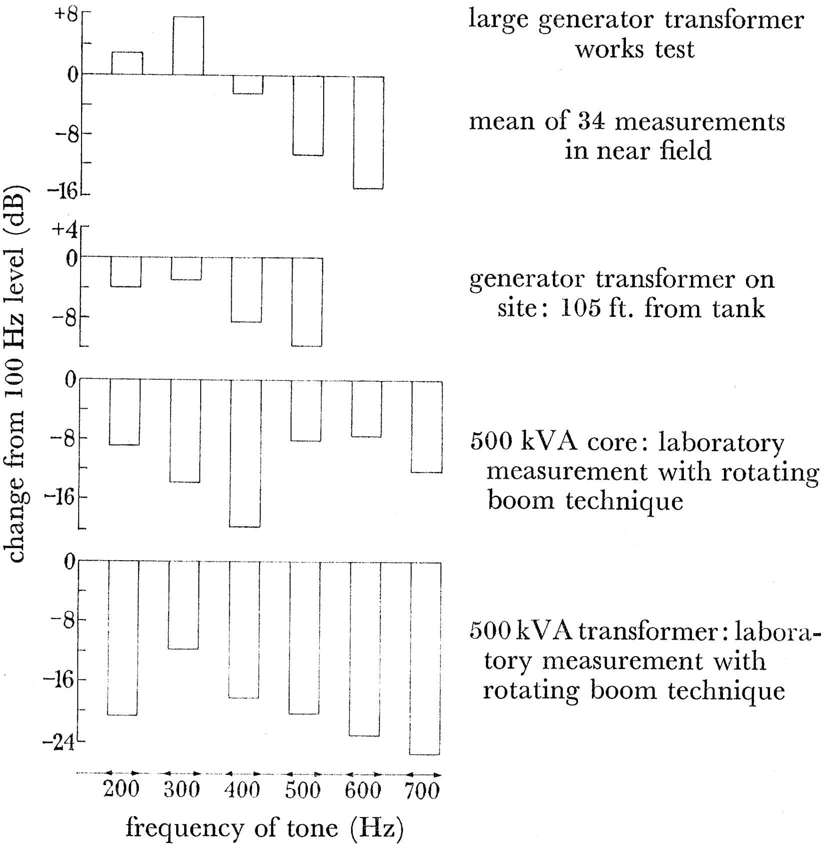


FIGURE 2. Line spectrum of transformer noise.

Transformer noise has a line spectrum (figure 2) and originates wholly in the iron core. A transformer core is assembled from silicon iron laminations, 0·013 in. thick, which abut to form a rectangular magnetic circuit. Alternate layers are overlapped. In modern constructions the joints are mitred instead of butt-lapped (figure 3). Cold-rolled grain oriented 3·1 % Si-Fe steel has replaced the hot rolled 4 % Si–Fe used before 1950. The higher magnetic saturation and lower losses of the new material have been utilized by designing for flux densities of 15·5 kG (and higher) in place of the 13·5 kG density for hot-rolled plate. Transformer sizes and weights, for the same power rating, were thereby reduced and efficiencies raised, but noise levels remained substantially the same. To illustrate this point, we have compared Brownsey's results (1956) for transformers with hot-rolled steel, operating at 13·5 kG, with past and present B.E.B. specifications of noise level against rating (table 2). Brownsey's figures represent 'maximum' sound levels (i.e. 95 % of the population is below the figures quoted). The specifications, we think, reflect the maximum levels of transformers with cold-rolled steel operating at 15·5 kG. Table 2 therefore demonstrates, on this reasoning, that the maximum surface noise levels of transformers, representative of good practice, have changed little over the years.

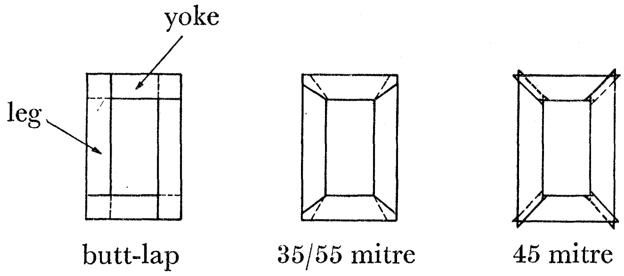


FIGURE 3. Schematic core circuits to illustrate interleaving of laminations.

TABLE 2. MAXIMUM TRANSFORMER NOISE LEVELS REPRESENTATIVE OF GOOD PRACTICE (dB (A))

Tolerances are given in brackets. Where two numbers are quoted, the upper figure refers to the tolerance at the beginning of the period.

	power and voltage rating					
source of information	500 kVA up to 11 kV	5 MVA up to 33 kV	15 MVA up to 33 kV	60 MVA 66 and 132 kV	500 MVA 275 kV	approximate date
Brownsey (1956) (hot rolled, $B_{\text{max.}} = 1{\cdot}35\ \text{Wb/m}^2$)	56	69	76	84	—	up to about 1954
initial proposals for a specification	—	71	77	84	—	*ca.* 1958
B.E.B. specification	53 $\begin{pmatrix}+4\\+2\end{pmatrix}$	66 $\begin{pmatrix}+5\\+2\end{pmatrix}$	72 $\begin{pmatrix}+6\\+5\end{pmatrix}$	80 $\begin{pmatrix}+6\\+5\end{pmatrix}$	—	1960–64
	54	66 (+2)	72 (+5)	80 (+5)	—	1964–66
	53	65	72	82	94	1966

The introduction of oriented steel not only reduced manufacturing costs and running costs, but it also alleviated the transport problem at a time of rapid growth in unit rating. This growth has not abated. 660 MW single-line turbo-alternators, 800 MVA generator transformers and 1000 MVA auto-transformers are now under construction. Transformer engineers, faced with the transport problem once again, have raised operating flux densities, designed aluminium alloy tanks and devised ways of subdividing the transformer and assembling it on site. All these changes have acoustical implications. More sophisticated approaches are being considered, such as gas or vaporization cooling and refrigerated or superconducting windings, but they are uneconomical at their present stage of development.

Grain oriented steel, produced by cold rolling and annealing, is not isotropic. To utilize its higher saturation and lower loss, the direction of the flux in the magnetic circuit must coincide with the direction of rolling. The surface of the steel is insulated by a tough glass-like coating (magnesium silicate/phosphate), about $0{\cdot}2 \times 10^{-3}$ in. thick, which puts the steel in tension. To prepare laminations for core building, the transformer manufacturer slits the rolls of steel to the required width, cuts them to length and anneals the laminations to relieve stresses due to cold working. The magnetic quality of the core steel would be impaired if these stresses were allowed to remain. In a mesh belt furnace, stacks of laminations, up to 12 deep, move slowly through a region of 800 °C, in an oxygen-free atmosphere. In the more modern roller hearth furnace, the plate is annealed in air, the laminations passing rapidly, one at a time, through the hot zone. Roller hearth annealed plate is flatter. Special steels are available commercially, such as 'low residual stress' and 'catenary annealed double phosphate coated', which do not require a stress relief anneal. The catenary annealed material is supplied in rolls slit to the required width. The use of these steels eliminates expensive processes in the transformer works.

Transformer noise measurement

Noise measurements seek to specify the noise nuisance of the transformer at a distant listening point. Ideally the measurements should show sound power and its frequency spectrum and directivity. There is only one way to obtain all this information—by making measurements in the free sound field of the transformer. The measuring positions must be at such a distance from the transformer that it subtends a small angle and the sound is travelling in a known direction. They must also be so far from surrounding objects that reflected sound intensity is negligible. To put these requirements in concrete terms, consider the measurement on a 30 MVA transformer according to the classical 12 point hemisphere (Harris 1957):

size of source: *ca.* 14 ft. × 6·5 ft. × 13 ft. high;
positions of measurement: 12 positions over a hemisphere, radius 90 ft.;
separation from reflecting objects: order of 180 ft.;
permissible background level assuming the transformer is at the acceptable limit: 45 dB (A).

These requirements cannot be met within the manufacturer's works, but might be achieved, for example, on a disused air field. Measurements in an anechoic chamber offer a compromise, by increasing the number of positions but reducing their distance from the transformer. Several transformer manufacturers employ an anechoic chamber for research. We think that the power measurement in the anechoic chamber is accurate and shall return later in this section to a discussion of our reasons.

If directivity information is sacrificed there are two other possible approaches to sound-power measurement, reverberant room measurements and semi-reverberant room measurements. The reverberant room is only suited to a source with a broad-band noise spectrum which produces a uniform sound field. A source like a transformer with a line spectrum produces a sound field with a pattern even in the highly reflective room, and leads to measurement difficulties by requiring a prohibitive number of measurements to compare all possible patterns. A similar difficulty arises in the semi-reverberant space, where the sound field of a transformer may be compared with that of a source of known sound power. In addition, the room may react with the transformer, because the sound source is large, and the power output may differ from the free-field value.

As an alternative to the ideal measurement methods, we may consider the practical conditions for noise measurement on transformers. A transformer suitable for a district load centre, which may well be in earshot of house property, requires a high voltage supply and such auxiliaries as an oil conservator and often a pump and fans. For economic reasons it is therefore likely to be tested in the electrical test area of the manufacturing works. The factory provides a constant background noise, even during meal breaks, which drowns measurements distant from the transformer. Economic pressures also restrict the amount of clear space around the transformer free from reflecting objects which distort the sound field.

The answer to the demand for prediction of annoyance, given these measuring conditions, has been a prescribed pattern of measuring positions close to the transformer. These are in the near field of the source where the transformer noise is loud compared with a typical background or the reflected noise from objects at a reasonable distance. Frequency analysis is too costly for routine tests, but 'A' weighting of a sound level meter was originally intended to represent the frequency response of the human ear at the intensity of a typical disturbing noise, and has been widely used for prediction of annoyance. Therefore the measurements are made on 'A' weighting. This has been the approach of the American N.E.M.A., the British B.E.B. and the German V.D.E. specifications for the measurement of transformer noise. These specifications are compared, in essentials, in table 3.

The German specification describes two methods, one for formal noise tests and one to be used for routine comparisons. It is the second, comparison method, which is closely comparable with the American and British methods. The first method is more elaborate and less practical in industrial surroundings. For a particular 600 MVA generator transformer the measuring positions would lie on a rectangle approximately 13 m × 19 m (43 ft. by 62 ft.). The size of the further space necessary to avoid interference from reflexions is debatable. One interpretation of the German specification (item 10 in table 3) would require an increase of 5 m + half the width of the tank, to test the fall-off requirement in a direction perpendicular to the major axis of the transformer. A large reflecting surface, such as a wall, would clearly have to be located even further back. The other interpretation is that the measurement positions must be shown to lie within an undisturbed zone. On the unlikely assumption that this could be achieved with reflecting surfaces 3 m from the measurement rectangle, the minimum space required is a large area, 19 m × 25 m (62 ft. by 82 ft.). This method also includes a measurement not on 'A' weighting; a

TABLE 3. COMPARISON OF BRITISH, AMERICAN AND GERMAN SPECIFICATIONS FOR THE MEASUREMENT OF TRANSFORMER NOISE

	B.E.B.	N.E.M.A.	V.D.E.
(1)	defines measurements from a 4 ft. high string contour to define surface of transformer with optional allowance for major projections below cover level but not actually at 4 ft. level	defines measurements from a vertical surface on a string contour round a projection of the transformer on a horizontal surface	defines measurements from the transformer surface
(2)	ignores minor projections—valves, etc.	ignores minor projections—valves, etc.	ignores minor projections and non-radiating parts—valves, wheel bases, conservators, etc.
(3)	measuring positions not precisely specified, measurements to be *ca.* 12 in. away, 4 ft. above ground or half the height, whichever is the less, and not more than 3 ft. apart, subject to a minimum of six readings in a horizontal direction along the major sound producing surfaces	measuring positions precisely specified—starting at the main drain valve and proceeding in 3 ft. intervals in a horizontal direction. Measurements to be 1 ft. away, at half height for transformers up to 8 ft., $\frac{1}{3}$ and $\frac{2}{3}$ height for transformers over 8 ft.	describes two forms of test: (1) a type test; (2) a test for purposes of comparison. (1) requires measuring positions which are precisely specified: four positions at half the height of the transformer and opposite the centres of the four sides for transformers up to 1·6 MVA, with four further intermediate positions above this rating. The distance from the transformer surface is 1 m up to 1·6 MVA, 3 m to 60 MVA, and 5 m above 60 MVA (2) also requires positions which are precisely specified; four positions at half the height opposite the centres of the four sides and $\frac{1}{2}$ m from the surface, with further positions at 1 m intervals horizontally along the sides from these
(4)	all specify measurements at no load, at rated voltage and frequency		
(5)	a separate test is specified for forced cooling plant, with positions on a 10 ft. radius from the centre of the plant; test to be agreed	microphone positions shall be six feet from any part cooled by forced air during the test	where transformers are equipped with fans, a measurement shall be made with them running and shut down
(6)	all readings on A weighting	all readings on A weighting	all readings on A weighting except that an additional measurement for (1) shall be a frequency analysis at one position at the centre of a long side
(7)	background shall be at least 7 dB and preferably 10 dB below the combined noise; no method of correction is mentioned	background shall be at least 7 dB and preferably 10 dB below the combined value; corrections are prescribed for differences of 7, 8, 9 and 10 dB	background should preferably be at least 8 dB below the combined level, corrections are prescribed for differences of 8 to 7, 6 to 5, and 4 dB
(8)	the value quoted for the transformer shall be the arithmetic average of the dB (A) readings	the value quoted for the transformer is the arithmetic average of the dB (A) readings	the value quoted for the transformer is the arithmetic average of the dB (A) readings (with the measurement distance used)
(9)	reflecting surfaces nearer than 10 ft. may influence the reading; readings obviously so influenced may be disregarded by agreement with the purchaser	there shall be no reflecting surface other than the floor nearer than 10 ft.	for (2) sound-reflecting surfaces must be located at least 3 m away from the transformer
(10)	—	—	for (1) the measurements can be deemed substantially free from reflection effects if on doubling the distance of the microphone from the transformer a decrease of sound level of at least 4 dB is achieved
(11)	a meter complying with the British standard specification for precision sound level meters shall be used	a meter complying with the 'American standard for sound level meters' Z 24.3 shall be used	a meter as specified in DIN 5045 shall be used

frequency analysis is to be made at one position opposite the centre of the long side. This seems an unrewarding procedure in view of the complex and asymmetrical radiation patterns of the frequency components of noise measured around transformers. Polar distributions of the noise measured around three small transformers are shown in figure 4. It is difficult to make a comparable measurement around a large transformer, but frequency analyses at all the B.E.B. measuring positions around a 600 MVA transformer are shown in figure 5 and suggest a much more complicated pattern.

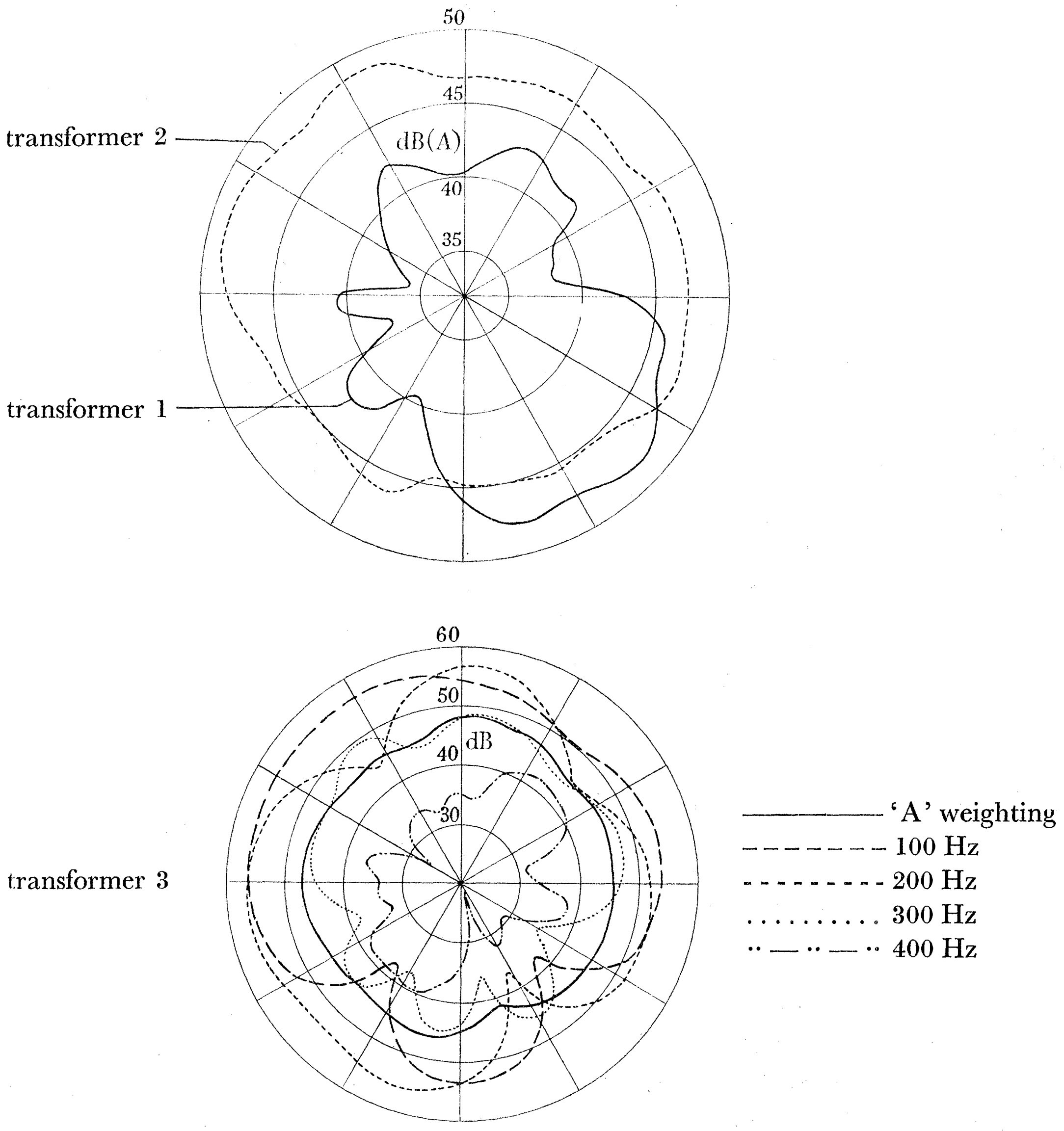


Figure 4. Polar distribution of noise around three 500 kVA transformers measured at 70 in. radius.

The other three methods of measurement recognize the practical difficulties of routine measurement in a factory, in specifying that reflecting surfaces must be 10 ft. or 3 m from the transformer, and in the corrections for background noise in the German and American specifications. In practice, background correction on the assumption of r.m.s. addition of noise and background is somewhat suspect since the modern factory is likely to have a strong synchronous component in its noise. The British specification makes no mention of such correction,[†] but includes a clause on the effect of reflecting surfaces unavoidably positioned less than 10 ft. from the transformer: 'any readings clearly so influenced may, by agreement...be disregarded...'. In practice the irregularities of sound levels measured around transformers are large and it would be difficult to attribute any particular rise in level to reflexion. Figure 6 shows the average distribution of levels of readings around twelve transformers of identical design, measured without reflecting surfaces nearer than 10 ft., and compares this with the distribution around a particular transformer.

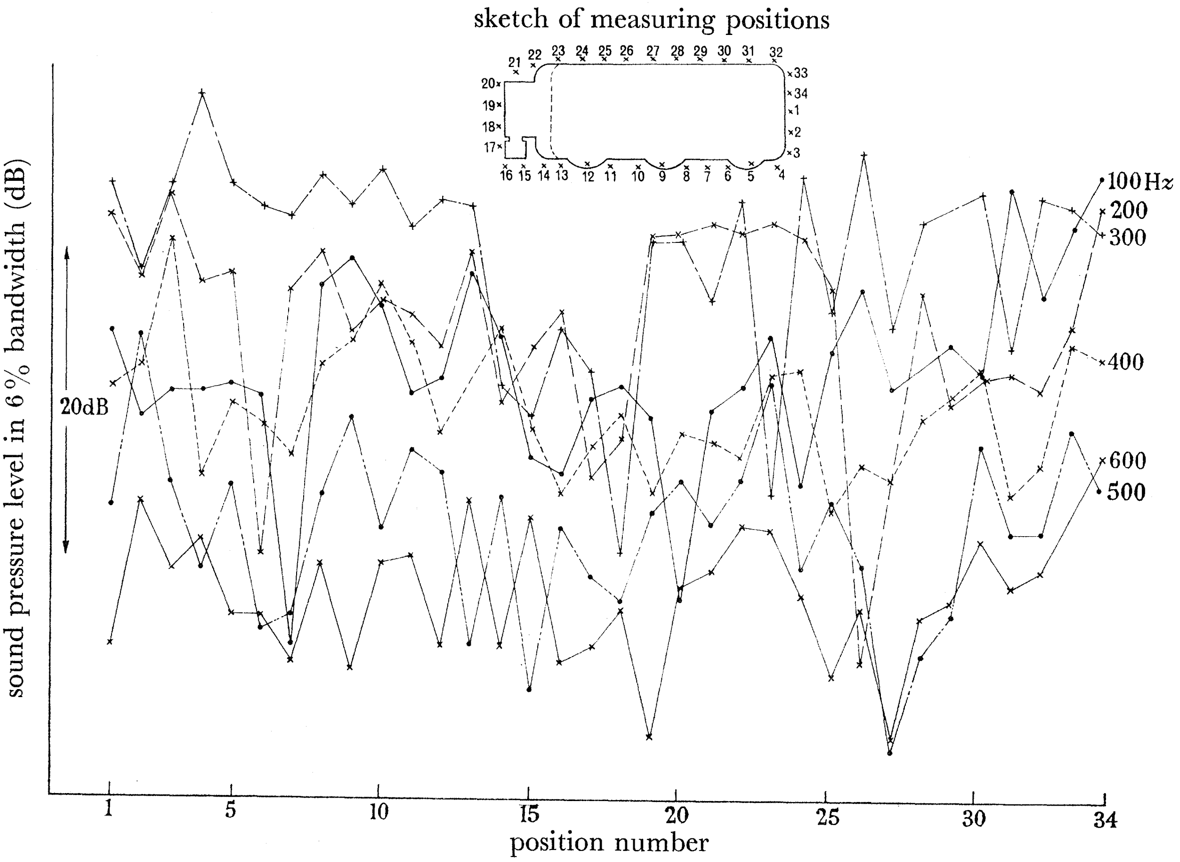


FIGURE 5. Frequency analysis using B & K 2107 at B.E.B. specification positions around 600 MVA transformer

All the specifications define the final figure to be allotted to the transformer as the arithmetic average of the dB(A) readings. This is only an approximation to the ideal method of averaging for assessment of sound power. In this the mean value of sound pressure squared is calculated and used to form the final decibel value.[‡] The difference between the values is usually small (figure 1) but depends on the range of values and their distribution; for example a group of 95 readings having a range of 20 dB has a maximum possible difference between the averages of 9·2 dB. In a series of practical measurements

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[†] Current proposals for a revised version include correction for a level between 7 and 10 dB above background.

[‡] It can be readily proved that, unless the individual readings are equal, the arithmetic mean noise level is always less than the average pressure squared noise level. The averages are equal if, and only if, the individual levels all have the same value.

with this number of positions, differences between the averages were found up to 5 dB. This is, however, a possible cause of random scatter in transformer noise levels which may obscure small effects of differences of construction.

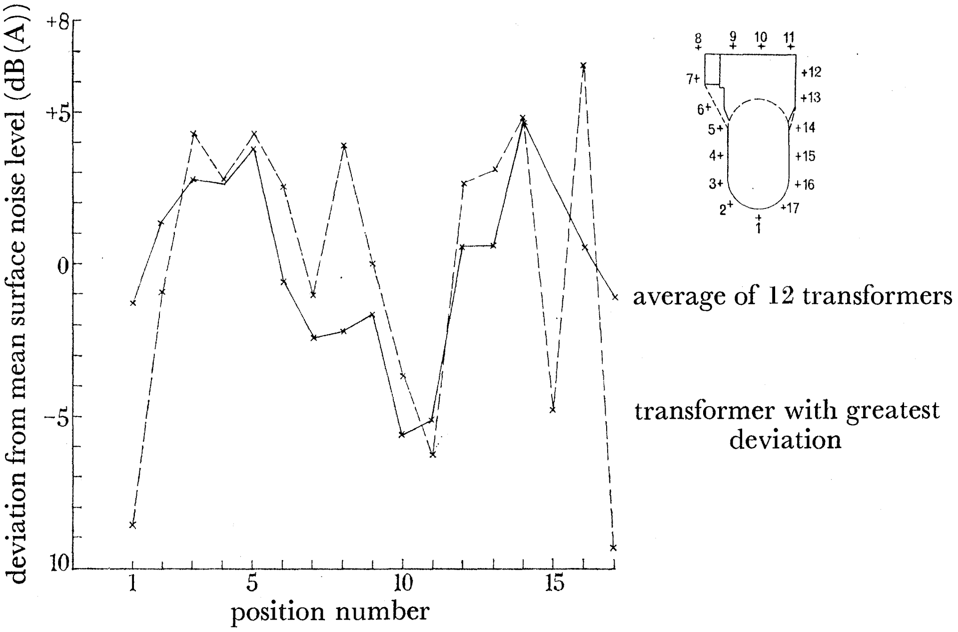


FIGURE 6. Distribution of surface noise around twelve identical transformers.

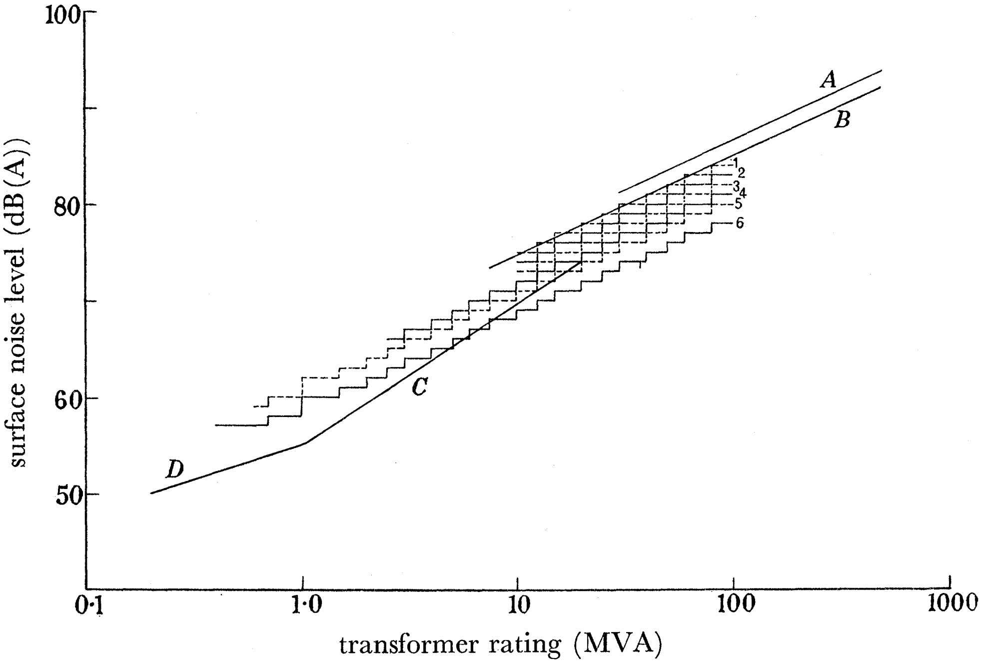


FIGURE 7. Comparison of B.E.B. and N.E.M.A. recommended maximum sound levels for transformers without fans. 1 to 6, N.E.M.A.: 1, 1300 kV B.I.L. and above; 2, 1175 kV B.I.L.; 3, 900, 1050 kV B.I.L.; 4, 750, 825 kV B.I.L.; 5, 450, 550, 650 kV B.I.L.; 6, 350 kV B.I.L. and below. *A* to *D*, B.E.B.: *A*, transmission and station transformers 275 kV; *B*, transmission and station transformers 132 kV and 66 kV; *C*, transformers up to and including 33 kV; *D*, transformers up to and including 11 kV.

Many measurements following the specifications have been made: the results have shown empirical relationships between kVA rating and noise level for various types of transformer. More recently they have formed the basis of curves of acceptable noise level against kVA rating. Examples of the British and American recommendations are shown in figure 7. Brownsey discusses the shortcomings of the NEMA recommendations in his book (1956). A general criticism of the curves is that they reflect trends in transformer production rather than set limits based on community reaction. For example, it may be unnecessary and uneconomic to restrict the surface noise level of, say, a 210 MVA, 132 kV generator transformer to 88 dB(A) if the sound radiation from the power station dominates the noise level at a distant listening point.

The recent change in the B.E.B. specification from ordinary grade sound level meter to a precision one could add some unnecessary complications to transformer noise measurement. If we consider the I.E.C. specifications (1961, 1965), the probable or actual base for future national specifications, there are three important changes from the ordinary to the precision grade:

(1) Reduction of the tolerances on over-all frequency response (e.g. ±1 dB from ±3·5 dB at 100 Hz): this is a definite advantage of the precision sound-level meter.

(2) Stricter requirements for the directional response of the microphone: to satisfy this requirement over the full frequency range of the specification may require the use of a small microphone which sacrifices sensitivity when compared with a microphone which achieves the same performance over the transformer noise-frequency range.

(3) Removal of the effects of the meter body and the operator on the response of the microphone to plane waves: this requires some form of extension to separate the microphone from the meter body and operator, further reducing sensitivity, and may give little advantage in the complex sound field near a transformer.

Some measurements have been made using a Brüel & Kjaer sound-level meter to compare techniques of measurement for the effects of the presence of the meter body and operator. The meter was used in the normal way with the axis of the microphone normal to the transformer surface. The measurements were repeated, again with the hand-held meter, positioned so that the axis of the microphone was horizontal and parallel to the surface. Finally the microphone was used with axis normal to the surface, mounted on a tripod with a 3 m extension cable leading to the meter. The differences in response are comparable to the scatter of measurements, but indicate that the use of the meter parallel to the transformer reduces the average level by 0·5 dB, while the use of the tripod gives a further 0·5 dB reduction.

Where the problems of space and cost are less, it has been possible to improve measurement techniques. Figures 8 and 9 show apparatus which has been used to collect information on small transformers. The microphone is moved around the transformer on a boom driven by a synchronous motor. The electrical output is fed to a frequency analyser and is then recorded on a level recorder whose chart movement is synchronized with the rotation of the boom. In an extension of this system, completed last year, discrete measurements are made at 95 positions on the circle. The readings are digitized and punched on to paper tape for computer processing, which can include background correction, and averages by sound pressure squared rather than the arithmetic mean of decibel readings.

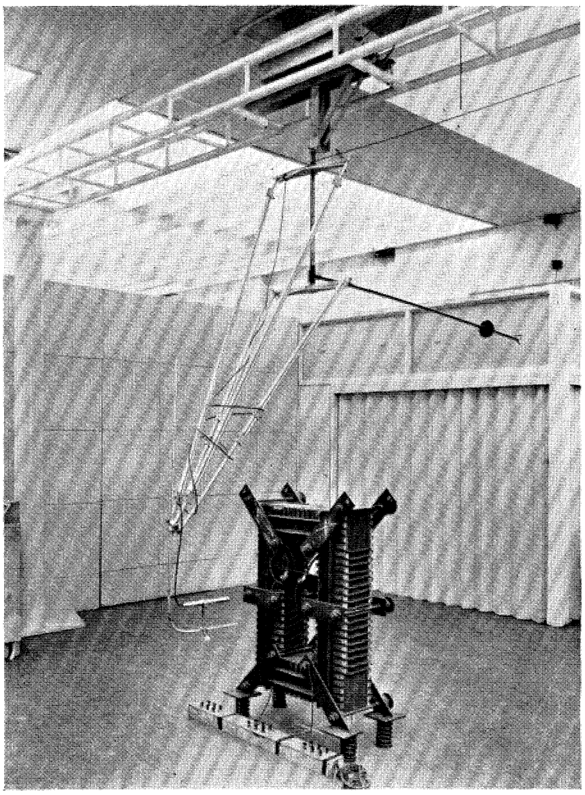


FIGURE 8. Rotating boom technique.

A sound power measurement was made with the apparatus on a 500 kVA three-phase core. The noise measurements were made in a cleared space in the laboratory. The only step towards anechoic conditions was to cover the nearer walls by acoustic fibre tiles. Circular traverses were made around the core in five horizontal planes. The elevations were chosen such that the circles fell on a hemispherical surface whose centre was the vertical projection on the ground plane of the geometric centre of the core. Measurements were taken at hemisphere radii of 55, 80 and 110 in. The results, presented in table 4, are interesting because they do not vary with the hemisphere radius. We think that they demonstrate that reflexions from the test-room walls and ceiling are insignificant and that the answer represents the true sound power of the core. To test our belief, a sound-power measurement on a loudspeaker source was made in an anechoic chamber and repeated in the core-testing position. For this group of tests a twelve-point hemisphere measurement of conventional type was used, both in the anechoic chamber and in the laboratory; a temporary wooden floor was erected in the anechoic chamber. The power levels agreed generally to better than 1 dB. The implication of this experiment to the sound-power measurement on a large transformer is that near field results may be used for estimating the acoustic power, provided it has been demonstrated that the answer is independent of the area of the surface around the source over which the measurements have been made. The question arises whether the B.E.B. measurement positions can define an accurate average level over the '1 ft. string contour surface' around the transformer. We think that often they do. In support we present tables 5 and 6. Table 5 demonstrates that the average level is independent of height. The results of a power measurement by the rotating boom

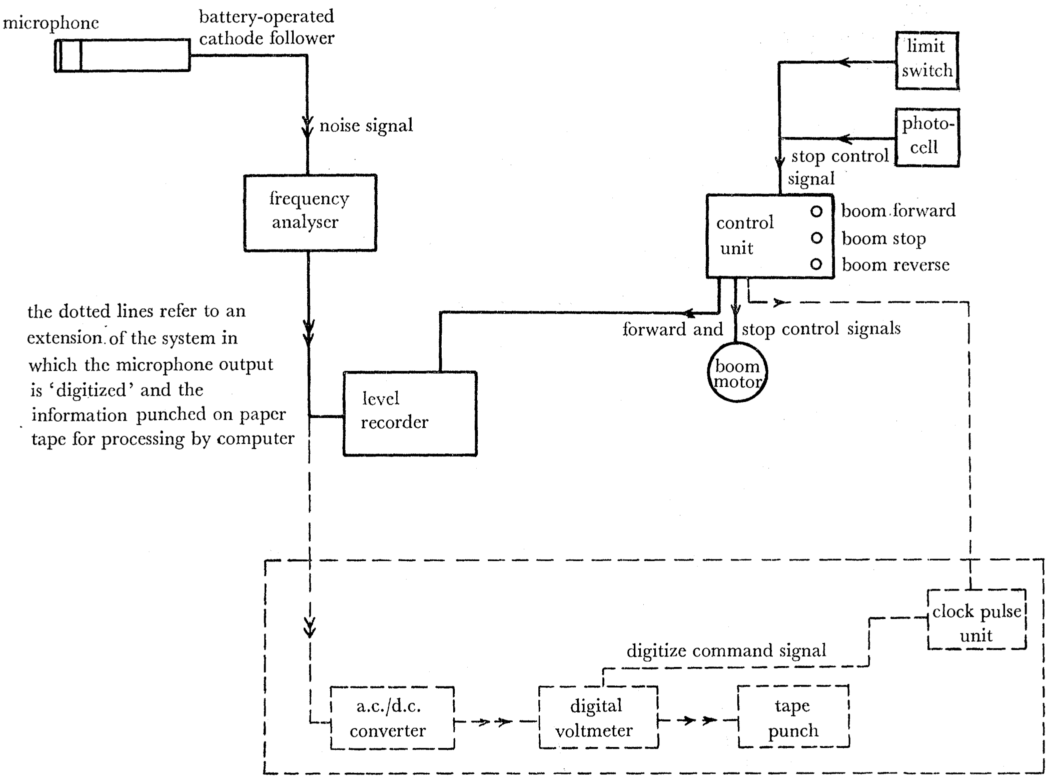


FIGURE 9. Electrical circuit of recording system.

TABLE 4. SOUND POWER MEASUREMENT ON A 500 kVA THREE-PHASE CORE

50 Hz, 15 kG leg flux density.

hemisphere radius, R	R = 55 in.			R = 80 in.			R = 110 in.		
	A	C	100 Hz	A	C	100 Hz	A	C	100 Hz
power level dB (re. 10^{-12} W)	(69·6)	77·6	76·0	(69·7)	77·6	75·1	(69·7)	77·8	74·9
power (μW)	—	58	40	—	58	32	—	60	31

TABLE 5. VARIATION OF SURFACE NOISE LEVEL WITH HEIGHT

	surface noise level dB (A)			
height ...	3 ft. 6 in.		7 ft.	
transformer mounting / flux density ...	100 %	120 %	100 %	120 %
none	72·3	82·1	72·6	82·0
solid rubber blocks	73·2	81·8	73·0	82·3
ribbed rubber pads	72·1	81·8	71·9	82·0

TABLE 6. COMPARISON BETWEEN MEASURED AND CALCULATED SOUND POWER LEVELS FOR TWO DISTRIBUTION TRANSFORMERS

	transformer 1		transformer 2	
measurement or calculation	A	C	A	C
measured surface noise level (dB) (B.E.B. specification)	46·4	55·5	48·6	64·1
sound power level, dB re. 10^{-12} W (calculated from surface noise levels)	58·3	67·4	60·5	76·0
sound power level, dB re. 10^{-12} W (measured by rotating boom technique)	55·0	67·0	60·9	76·2

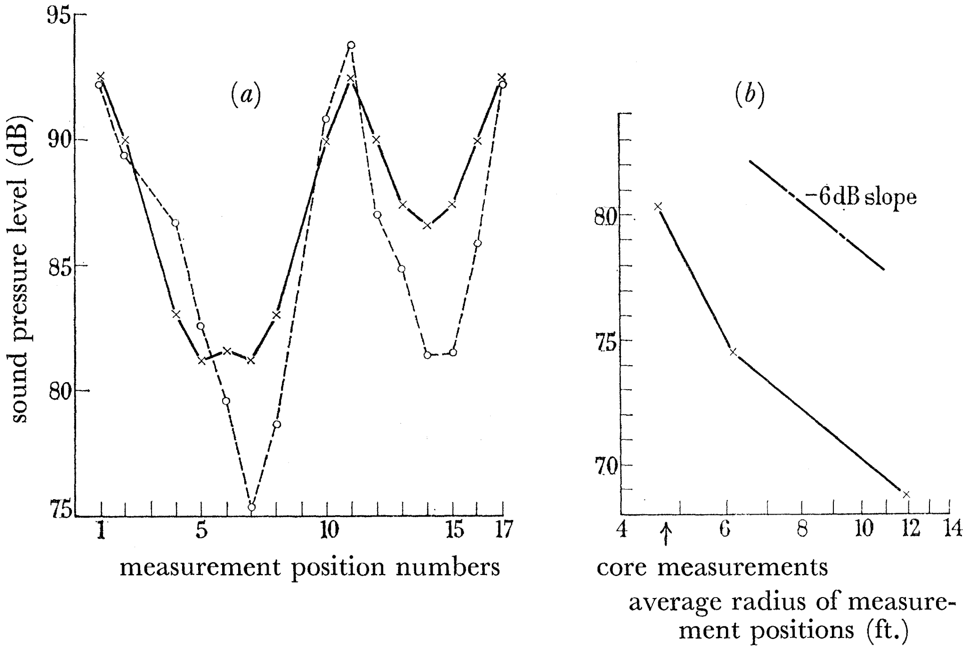


FIGURE 10. (*a*) Comparison of calculated and measured sound pressure levels at 1 ft. from transformer. ○, measured (average of 3 ft. 6 in. and 7 ft. measurements); ×, calculated. (Both C weighting.) (*b*) Relation between mean sound pressure level and the average radius of the measurement positions.

technique and a calculation from the B.E.B. average level are compared in table 6, for two oil-filled distribution transformers. The comparison is satisfactory except for the 'A'-weighted result for transformer 1. It is significant that this transformer had a highly directional radiation pattern on 'A' weighting (figure 4).

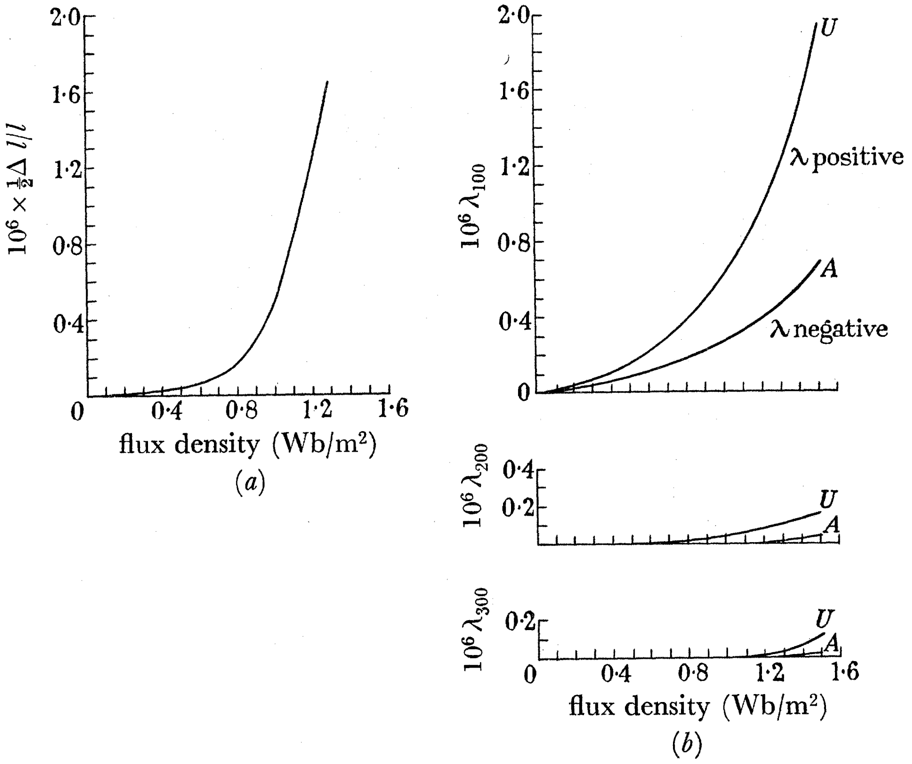


Figure 11. Magnetostriction of grain-oriented 3 % silicon iron at zero stress. (*a*) D.c. technique (Brailsford 1941); sample: 24 in. × 2 in. × 0·14 in. (*b*) A.c. technique (Dobie 1967). Epstein lamination: 12 in. × $1\frac{3}{16}$ in. × 0·13 in.; flux distortion at 1·5 Wb/m²: 3rd, 3·3 % *A*; 10·3 % *U*. 5th, 1·5 % *A*; 1·05 % *U*. *A*, annealed; *U*, unannealed.

Transformers are in general complex, not point, noise sources. A case is known, however, where the individual sound pressures measured 1 ft. from the tank obeyed the inverse square law (figure 10*a*). In most other instances, a useful approximation for the calculation of the far field of the transformer, up to about 100 ft., is obtained on the assumption that the average surface noise level is related by the inverse square distance law to the average radius of the measurement positions. Figure 10*b* presents the average values of a set of measurements around a 15 MVA core in air and of two sets of measurements around the completed oil-filled transformer. The three average levels follow approximately an inverse square law relationship, although the individual readings (not shown) do not.

Magnetostriction

The vibrations of the core are caused by the two mechanical effects of the magnetic flux, attraction and magnetostriction. Both effects are independent of the polarity of the alternating magnetic flux and the core therefore vibrates at twice the supply frequency. The magnetic pull per unit area is proportional to the square of the flux density. The physical relationship between the magnetostrictive strain and flux density is illustrated in figure 11, where λ_{100} denotes the amplitude of the 100 Hz alternating strain. The unannealed sample elongates on magnetization, whereas the annealed sample contracts (Brownsey & Maples 1966) (negative magnetostriction). Both mechanisms generate even and odd harmonics of the fundamental 100 Hz core vibration (table 7), because the flux is not sinusoidal in individual laminations and the magnetostriction curve deviates from a square law. Transformer noise therefore consists of pure tones, from 100 Hz up to about 1000 Hz (figure 2). The spectrum changes with flux density. It is also influenced by resonances of the core and tank, and the physical size (radiation efficiency) of the unit.

Table 7. Mean vibration velocities of two single-phase cores

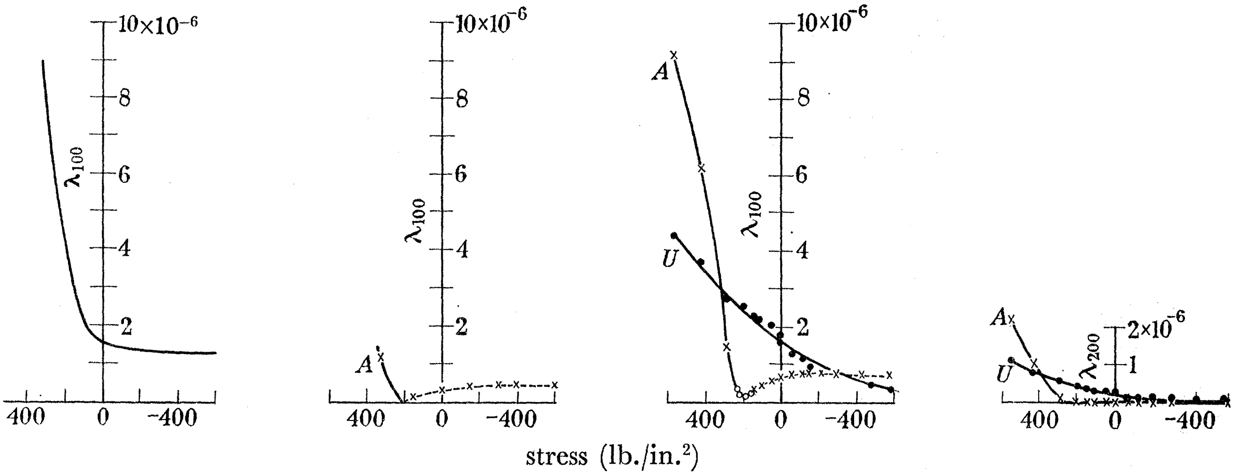
The difference in the mean pressure squared noise levels of the cores, measurements averaged over a hemisphere, was 5·3 dB (A), 9·5 dB (C) at 15 kG.

	core 1: mean vibration velocity level (dB)				core 2: mean vibration velocity level (dB)			
	longitudinal vibrations		transverse vibrations		longitudinal vibrations		transverse vibrations	
frequency (Hz)	15 kG	17 kG	15 kG	17 kG	15 kG	17 kG	15 kG	17 kG
100	71·6	72·8	76·5	80·5	61·8	64·8	74·1	78·7
200	66·2	67·8	77·6	86·6	57·3	61·7	70·1	78·5
300	60·2	65·4	65·4	73·0	48·8	57·8	60·7	68·5
400	55·7	59·6	—	—	49·7	54·6	—	—
500	62·8	63·6	—	—	55·1	60·5	—	—
600	55·8	62·4	—	—	47·9	56·7	—	—
700	48·4	53·8	—	—	44·2	49·6	—	—
‘A’ weighting	65·1	68·9	72·4	77·6	57·0	66·0	63·8	72·6

Table 8. Comparison of noise levels of small distribution transformers

					cores		completed units		
								rounded mean noise levels at 12 kG (dB (A))	
steel maker	grade of plate	maximum loss (W/lb.) at 15·0 kG	annealing furnace	mitre	no. tested	rounded mean noise levels at 12 kG (dB (C)) (rotating boom)	no. tested	rotating boom	B.E.B. spec.
1 (British)	46	0·46	roller hearth	35/55	10	57	—	—	—
	51	0·51			10	60	2	41	43
	56	0·56			5	62	2	43	45
2 (British)	46	0·46			10	58	5	40	43
	51	0·51			10	59	3	43	45
	56	0·56			5	59	1	44	47
3 (American)	W–58	0·44			10	59	3	41	43
2 (British)	46	0·46	mesh belt	35/55	5	60	2	46	48

The magnetostrictive strain of hot-rolled steel depends on its chemical composition. A steep fall in magnetostriction is reported (Brailsford 1960; Reiplinger 1960) for silicon contents greater than about 4 %. Zero magnetostriction is apparently reached at 6 to 7 % silicon addition. Negative values are observed for higher Si contents. Above $4\frac{1}{2}$ % Si content the steel becomes brittle at room temperature and its magnetic saturation density is low. According to Reiplinger (1960), grain oriented 3·1 % Si–Fe, used in modern transformers, has a lower specific loss and magnetostrictive strain the greater the degree of grain orientation. We observed a similar relationship between noise level and specific loss on batches of small distribution transformers of the same rating and design (table 8). The two observations suggest that magnetostriction and not attraction due to flux transfer may be the dominant cause of noise.



(*a*) Morrill (1960) (*b*) Brownsey (1966); $B_{\text{max.}}$ = 1·50 Wb/m² (*c*) Dobie (1967); (*d*) Dobie (1967) $B_{\text{max.}}$ = 1·51 Wb/m²

FIGURE 12. The sensitivity of the magnetostriction of grain-oriented 3 % silicon iron to a mechanical stress in the direction of the flux. Magnetostriction: ——, positive; ○, transitional; – – –, negative. Stress: positive, compression; negative, tension. *U*, unannealed; *A*, annealed.

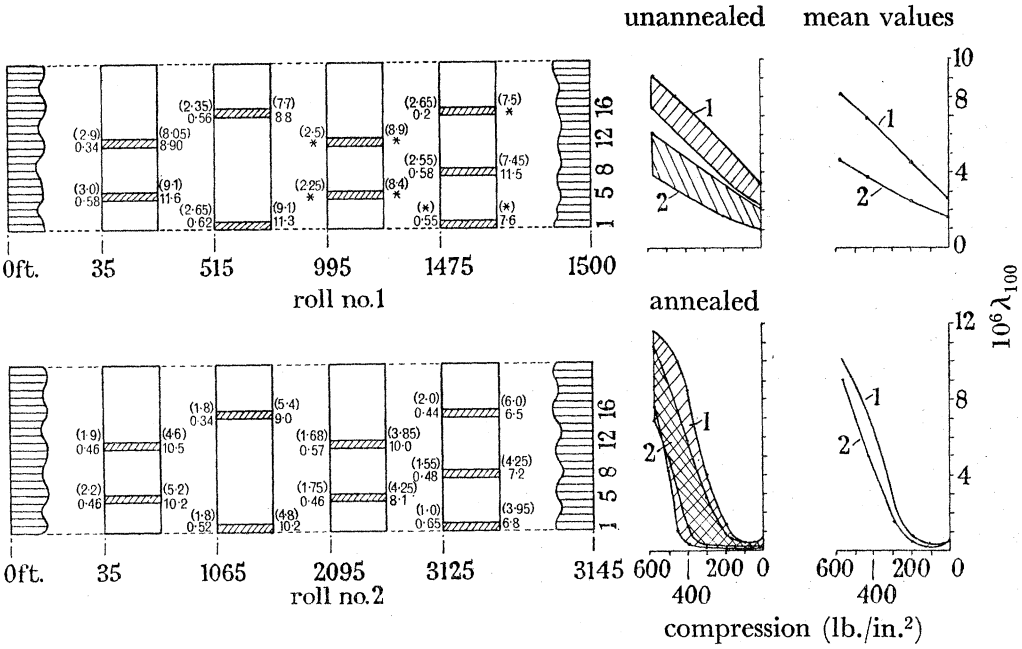


FIGURE 13. Variation of magnetostriction within a roll and between two rolls. The shaded rectangle refers to the position of the Epstein lamination in the roll. Numbers in brackets refer to unannealed values. Numbers on left refer to zero stress. Numbers on right refer to 576 lb./in.² compression. * Indicates no figures available. Maximum flux density, 1·5 Wb/m.²

The magnetostrictive strain of grain oriented steel is sensitive to a mechanical compression of the lamination in the direction of the flux (Brownsey & Maples 1966; George, Holt & Thompson 1962; Morrill 1960) (figure 12). The strain at zero stress is negative for the annealed sample and positive, and of higher magnitude, for the unannealed sample. The annealed sample is, however, more sensitive to stress, the magnetostriction changing sign at a certain compression. The knee of the curve varies from sample to sample (figure 13), depending presumably on the magnitude of the pretension applied by the coating. Figure 13 shows that the variations occur within a roll and between rolls. The average magnitude and scatter of our magnetostriction measurements are similar to those measured by Brownsey & Maples (1966) (figure 14). In our experience all the annealed samples have negative magnetostriction at zero stress. The important deduction, we suggest, is that magnetostriction is not uniform over a core lamination (Whitaker 1960). The lamination cannot, therefore, merely extend or contract, but must also vibrate in a direction at right angles to the plane of the sheet. Time and temperature parameters of the stress relief anneal (George *et al.* 1962) and the type of annealing furnace probably affect the result. From tests on three groups of five Epstein samples, we could not distinguish between a laboratory anneal and annealing in a works mesh-belt or roller hearth furnace. Figures 13 and 14 can of course be criticized on the grounds that a much larger number of samples ought to have been tested, that Epstein-sized samples are too small to highlight differences between furnaces and that the variation of magnetostriction over core laminations cannot be deduced from measurements on a few samples cut from the roll. In the next stage of the study of magnetostriction and noise, measurements on full-sized laminations (say, for a small distribution transformer) should be attempted.

At right angles to the rolling direction, the specific loss is of the order of three times (Grossen 1962) and the magnetostriction can be of the order of 30 times the value in the direction of orientation. Risch (1962) measured ratios up to about half this value (table 9). Magnetostriction ratios 'across texture/along texture' of the order of only 4 were measured by one of our colleagues.

The annealed laminations from which a transformer core is assembled are not perfectly flat. Shallow waves, dimples and edge imperfections due to slitting can be observed on close examination. In the process of clamping the core, the curved sheets are flattened and compressive and tensile stresses are induced in them. The stress sensitivity of the magnetostriction of oriented steel is therefore a vital parameter. The stress pattern in a core depends not only on the departure from flatness of the individual laminations but also on the type of constraint imposed by the clamping arrangement. Laminations are not equally flat, nor do they have the same distribution of magnetostriction at zero stress. The induced stress pattern, which itself has a variance, increases rather than diminishes the scatter of magnetostriction (figure 14). With cores of the same duty and design, the scatter of noise levels can therefore be expected to occur as the sum of the three variances. Transformer manufacturers use an apparatus to measure lamination flatness, originally developed by Wilkins & Thompson (1962), in which the pressure to compress a stack of laminations is measured. The strain energy is worked out from the area under the force/displacement curve. The 'equivalent compressive stress' in the stack can therefore be calculated. Figure 15 presents a typical force/displacement curve and also relative values of the equivalent compressive stress for annealed and unannealed grain-oriented steel. Wilkins & Thompson (1962) reported that the reductions in 100 Hz noise levels of the cores they tested correlated with magnetostriction data if flatness and stress sensitivity of magnetostriction are taken into consideration.

The measurement of magnetostriction is difficult. A recent 'round robin' between various laboratories gave variations up to 2 to 1 for the same sample. In the authors' apparatus the magnetostriction of single Epstein samples is measured by a pair of lead

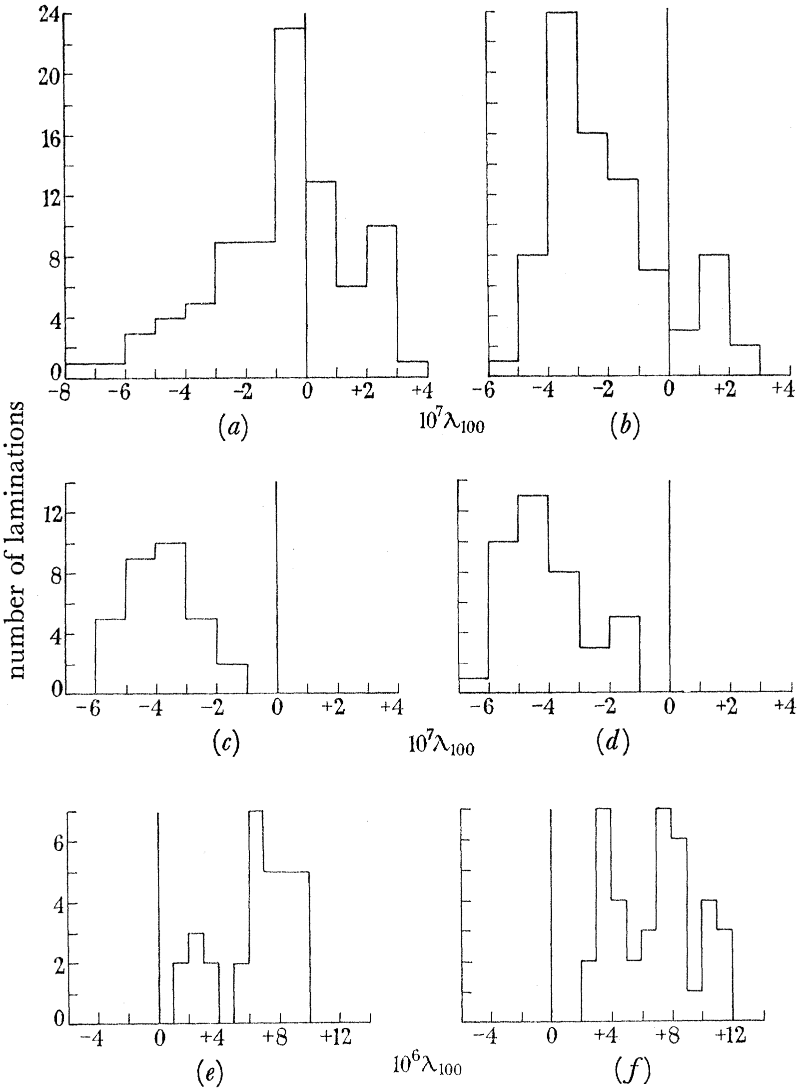


FIGURE 14. Scatter of magnetostriction strains. (*a*) 85 Annealed laminations (12 in. × 2·75 in.); steelmaker 1 grade 46; zero stress; flux density, 1·55 Wb/m^2 (Charles 1965). (*b*) 82 annealed Epstein laminations; grade 46; zero stress; flux density, 1·50 Wb/m^2 (Brownsey 1966). (*c*) 31 works mesh-belt furnace annealed Epstein laminations from 8 rolls, steelmaker 1: grade 46; zero stress; flux density, 1·51 Wb/m^2. Mean: $3·8 \times 10^{-7}$. Coefficient of variation: 31 %. (*d*) 40 works mesh-belt furnace annealed Epstein laminations from 9 rolls, steelmaker 2: grade 46; zero stress; flux density, 1·51 Wb/m^2. Mean: $4·3 \times 10^{-7}$. Coefficient of variation: 30·6 %. (*e*) As (*c*) at 576 lb./in.^{2} compression. Mean: $6·5 \times 10^{-6}$. Coefficient of variation: 40·3 %. (*f*) 39 laminations as (*d*) at 576 lb./in.^{2} compression. Mean: $7·0 \times 10^{-6}$. Coefficient of variation: 38 %.

TABLE 9. MAGNETOSTRICTION FOR MAGNETIZATION AT RIGHT ANGLES TO THE DIRECTION OF ROLLING

source	material	anneal	flux direction relative to rolling direction						
				$10^6\,\lambda_{100}$ at $B_{\text{max.}} = 1{\cdot}2$ Wb/m^2					
				supplier 1		supplier 2		supplier 3	
Risch (1962)	unoriented electrical steel, 0·9 W/kg at 10 kG	not annealed	along	4·2		3·6		1·9	
		not annealed	perpendicular	2·6		—		1·6	
		annealed at 800 °C	along	—		—		1·1	
				at $B_{\text{max.}} = 1{\cdot}2$ Wb/m^2: mean of two samples					
				$10^6\,\lambda_{100}$		$10^6\,\lambda_{200}$		$10^6\,\lambda_{300}$	
				zero stress	576 lb./in.^{2}	zero stress	576 lb./in.^{2}	zero stress	576 lb./in.
authors	unoriented electrical steel	annealed	perpendicular	1·55	2·60	0·27	0·45	0·07	0·08
				$10^6\,\lambda_{100}$ at $B_{\text{max.}} = 1{\cdot}5$ Wb/m^2					
				supplier 1		supplier 2		supplier 3	
Risch (1962)	grain oriented steel, 0·5 W/kg at 10 kG	not annealed	along	2·8		3·9		2·4	
		annealed at 800 °C	along	0·9 (–)		1·5 (–)		1·8 (–)	
		not annealed	perpendicular	13·6		11·6		10·5	
		annealed at 800 °C	perpendicular	16·6		16·9		14·8	

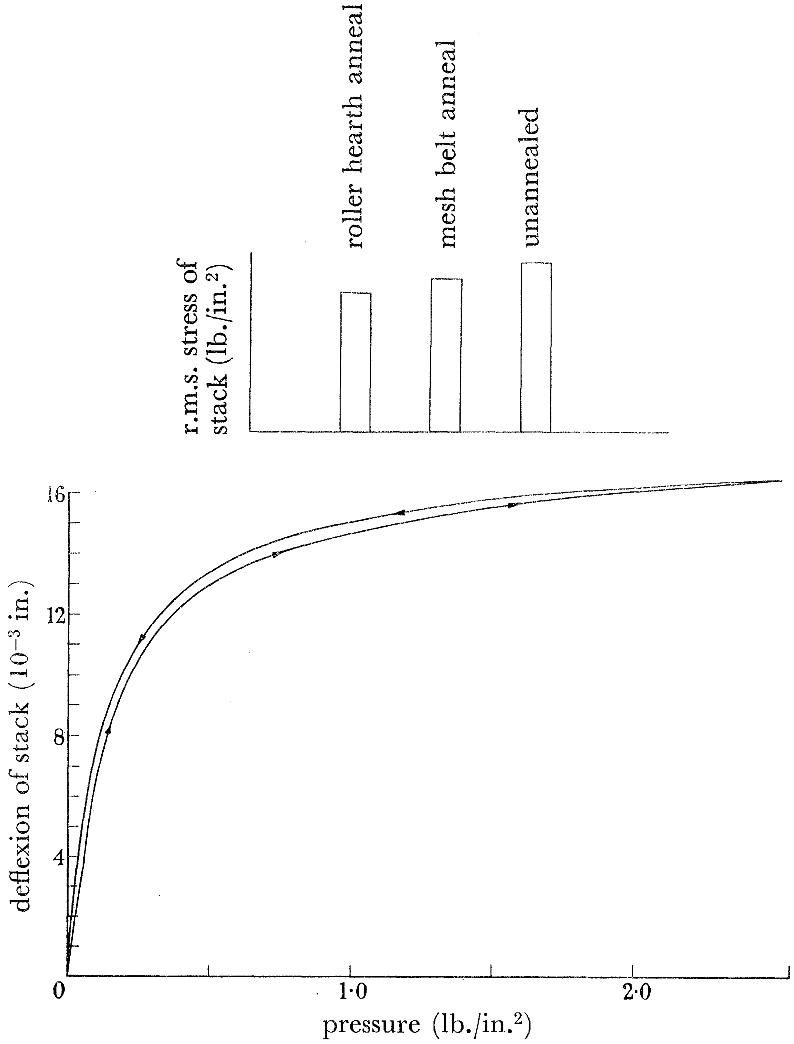


FIGURE 15. Flatness of 3 % Si-Fe coreplate. Top, comparison of effective stresses in plates at full compression. Grade 46.

zirconate titanate gramophone pick-up cartridges, 10 cm apart, whose outputs are fed to a differential amplifier and from there to a Brüel and Kjaer frequency analyser. The pick-ups are mounted on a framework which slides inside a field coil. The sample under test is normally placed in the centre of a bakelite block, milled flat to ±0·001 in., which slides inside the framework. The field coil has a graded winding (the ampere-turns increase approximately as the square of the distance from the centre), which gives a flux density over the centre 10 cm of the sample uniform to ±3 %. The sensitivity of the pick-ups was determined against an accelerometer calibrated by the National Engineering Laboratory. A glass block was prepared of the same size as the bakelite block, but ground to a surface flatness of ±0·0001 in. Epstein samples have been tested on each block, with and without an oil film between the sample and the block. We found that the results could be reproduced to ±15 %, provided the sample was flat and was carefully repositioned, and within that range did not depend on the block or the oil film. Since the apparatus was first constructed, facilities for putting the Epstein sample in tension or compression were added. Its major disadvantage is that the flux becomes distorted above a density of 15 kG.

Some observations on the origin of transformer noise

In addition to the periodic elongations of the legs and yokes of the core, directly attributable to magnetostriction, large transverse vibrations have been measured (table 7). Milner (1961) refers to the excellent film made by Ferranti Ltd, in which the extremely complex vibrations of a single phase core have been animated. It has been suggested that the total radiated power is equally divided between longitudinal and transverse motions, if their magnitude and phase are taken into consideration, and that therefore half the noise energy of a core is derived from vibrations of magnetostrictive origin and the other half from vibrations due to magnetic attractions between laminations (cross-fluxes). However, a consequence of the lack of uniformity of magnetostriction is that a lamination cannot merely extend in the plane of the sheet, but must also buckle and bow ('writhe'). It is not necessary, therefore, to postulate cross-fluxes to explain the existence of transverse vibrations.

Magnetic attractions are most likely to occur in the corner regions of the transformer core, where the continuity of the iron path is interrupted at the junction between leg and yoke laminations (figure 3). It has been suggested that cross-fluxes also occur in the legs and yokes remote from the corner, due to variations in lamination thickness and permeability. Three distinct effects occur in the corner regions: (*a*) magnetic flux crosses the air gap between abutting laminations, creating a system of magnetic forces in the plane of the core; (*b*) the flux turns through 90° and therefore follows a path in the iron along which the magnetic properties of the steel are inferior and the magnetostriction is high; (*c*) flux also leaves or enters a lamination from the one above or below, producing not only attractions but, due to flux concentrations, also increased local values of magnetostriction. The mechanisms are understood only in broad principle. The distribution of the flux in the core is not known in detail. The calculation of the vibrations of a core, including its resonances, under the combined system of magnetic and magnetostrictive forces, has therefore not been successful. It is well known that if a core is designed with a smaller 'unfavourable' corner volume, its iron loss and noise level are reduced. The argument about the precise origin of transformer noise remains unresolved. It is not merely an academic argument. Halving a power flow reduces the sound pressure level by 3 dB. If the equal energy hypothesis is correct, money invested in research on magnetostriction would be wasted.

A further attempt to solve the problem was made recently by the Electrical Research Association in collaboration with the authors and other engineers. Three small single-phase cores were assembled from fully annealed grain-oriented 3·1 % silicon iron, mumetal and radiometal 36. Each core was built from laminations 12 in. long by 2·75 in. wide, singly interleaved, to give a window area of 9·25 by 9·25 in. and a square cross-section. About 10 % of the laminations prepared for core building were set aside for magnetostriction measurements (figure 14) by a strain gauge technique. The magnetostriction of mumetal and radiometal was relatively insensitive to a compressive stress, as measured on four samples of each material. The 100 Hz acceleration amplitudes were measured at 88 positions over the core surface. The 100 Hz component of the core noise was determined with the rotating boom technique in an anechoic chamber. The cores were mounted on soft springs. All the 100 Hz measurements, magnetostriction, vibration and noise, were made over a range of flux densities.

To correlate the three sets of measurements, the 100 Hz noise component was plotted against the vibrations and magnetostrictive strains expressed as levels, in dB. The results are presented in figure 16. With the exception of the Si–Fe magnetostriction levels (but not the Si–Fe vibration levels), most of the other results lie in the same band. The silicon iron magnetostriction levels run approximately parallel to this band, but are displaced to the left, consistent with the knowledge that the magnetostriction of unstressed silicon iron is lower than under a compressive stress. If the measured magnetostriction strains are raised by a factor of 5, the magnetostriction levels are moved 14 dB to the right and approximately fall in the band of the other results. The curvature at the lower end may be due to experimental difficulties in measuring very low noise levels and magnetostrictive strains. The slope of the band is unity, which implies that doubling the magnetostriction doubles the average vibration and therefore raises the 100 Hz noise component by 6 dB.

On the basis of simple attractions between laminations, one would expect a relation between the level of the 100 Hz noise component and $20 \log_{10} B^2_{\text{max.}}/Y$, where $B_{\text{max.}}$ is the peak flux density and Y is the Young modulus of the core material. Figure 16 indicates that this is not the major factor.

We are inclined to the view that: (i) flux transfers between laminations, at regions remote from the corners, do not occur; (ii) at the corners the forces due to cross-fluxes between adjacent laminations cancel each other; (iii) the magnetic forces, from flux crossing the air gap, produce vibrations only in the plane of the core; (iv) the transverse vibrations are caused by variations in magnetostriction, accentuated by the stress pattern in the clamped core. Therefore to reduce noise at source, the core steel should have five properties: constant thickness, low magnetostriction, stress insensitivity, homogeneity and flatness.

The 'effective magnetostriction' in a fully clamped core therefore ultimately depends

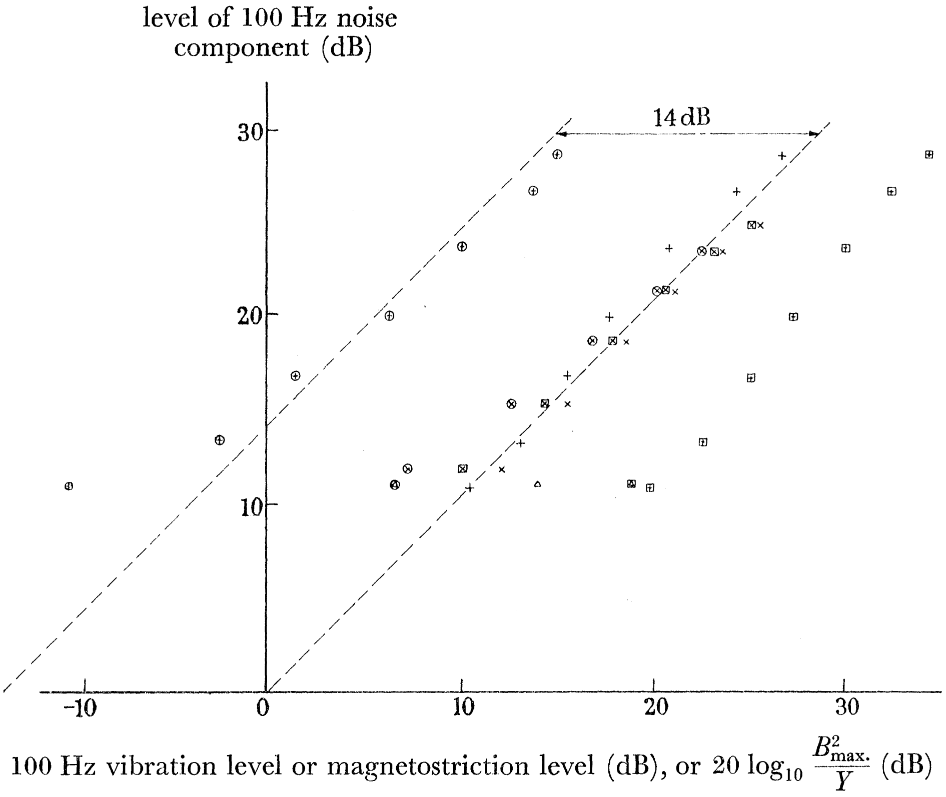


FIGURE 16. Comparison of magnetostriction, vibration and noise.

	vibration level	magneto-striction level	$20\log_{10}\frac{B^2_{\max.}}{Y}$
radiometal	×	⊗	☒
mumetal	△	◬	⍍
silicon iron	+	⊕	⊞

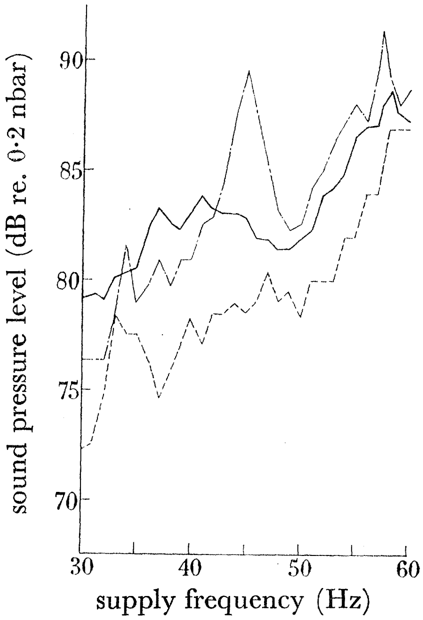


FIGURE 17. Average sound pressure level around geometrically identical transformer cores.

both on the steel maker and the transformer manufacturer. The former must aim to put a steel on the market with the above five properties. In preparing the material for core building, the transformer manufacturer must take care in cold working the steel, in annealing it, in handling the finished laminations and in building and clamping the core. Core design should aim at a uniform flux distribution, a minimum 'corner volume', an even core temperature and a mechanical structure with high damping. In principle, the resonances of the core can be calculated (Jordan, Reinke & Taegen 1962; Henshell, Bennett, McCallion & Milner 1965) and core dimensions chosen which avoid the major frequencies of the exciting forces. In practice we doubt whether the exercise is worth while. Noise measurements on three identical 15 MVA cores failed to reveal a consistent behaviour with frequency (figure 17).

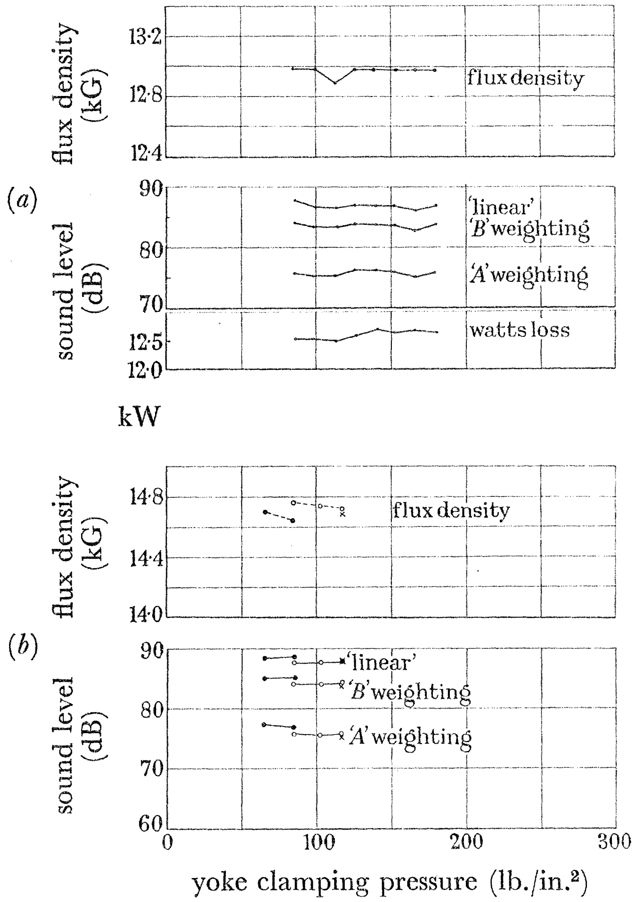


Figure 18. The effect of core clamping pressure upon core noise level. (*a*) 15 MVA core; grade 46, steelmaker 2; ratio of leg/yoke clamping pressure = 1:1. (*b*) 25 MVA core; grade 46, steelmaker 1; ratio of leg/yoke clamping pressure = 1·325:1. ●, With slings and core support; ○, slings and core support removed; ×, slings and core support removed with some leg bolts slackened to give a clamping pressure of 100 lb./in.^{2}.

For a given conventional clamping arrangement, the clamping pressure is not critical. An insignificant change in noise level with clamping pressure was observed on two large cores of butt-lap and bolted construction (figure 18). The 25 MVA core was fitted with high tensile steel bolts to cover a 2 to 1 range in pressure, set by a torque spanner. In one test some bolts were slackened, to give an uneven pressure distribution, but this again did not alter the noise level. The explanation is that a pressure of a few pounds per square inch is sufficient to flatten the laminations (figure 15) and that thereafter the equivalent compressive stress in the stack is constant. For constructional reasons (the core must be lifted for example) a more rigid core assembly is required and therefore over the practical range of clamping pressures little change in sound level is to be expected. The stress pattern in the core is, however, a function of the constraints in relation to the undulations of the laminations. Therefore one method of clamping is not as 'quiet' as another.

From the magnetostriction data presented in the last section, it is probable that hot rolled steel at 13·5 kG and the flatter grain oriented 3 % Si–Fe at 15·5 kG operate at the same value of effective magnetostriction in the clamped core. The value may not be significantly different if the oriented steel were left unannealed. One cannot avoid the comparison with noise. The introduction of oriented steel made little difference to transformer noise levels and indeed some unpublished results of which the authors are aware suggest that neither does annealing. The basic material factors have only recently become a little clearer. Noise reductions at source can be expected in the future.

The effect of production changes on the noise levels of transformers

The annual output of transformers by a large British manufacturer may be of the order of several million kVA of plant. A small sample of the production is tested for noise, to control quality and to determine the effect of changes in design and construction. Large transformers are not mass produced like cars. They vary not only in power rating, voltage ratio, impedance, flux density, iron loss and weight, but also in many other aspects relevant to noise, such as the design of the core, the shape of the tank and the position of the tap-changer and the coolers. The problem is therefore how to analyse the accumulated noise data.

In one simple analysis which we have attempted, the transformers were first divided into constructional groups, irrespective of their size. The transformer was classified according to its core design, described by four parameters: core material and anneal, leg to yoke joint, yoke section, clamping arrangement. The logic for this choice follows naturally from the discussion of magnetostriction and the origin of transformer noise of the previous sections. The main cause of noise is magnetostriction. Flux transfer is a contributory factor. A core vibrates in a complicated manner due to (*a*) the interaction of the non-uniform flux and stress distribution in the core with the corresponding non-linear relationships of magnetostriction; and because (*b*) the core steel is not flat; (*c*) the core has mechanical resonances. Four features of core construction are therefore likely to influence transformer noise: (i) the type of core steel; (ii) the slitting, cutting and annealing processes; (iii) the magnetic path (e.g. leg to yoke joint, round or flat yoke); (iv) the clamping arrangement.

The basic parameters which determine the noise level of a transformer are, however, the total weight of the coreplate and the flux density. An empirical formula was derived some years ago to calculate the transformer surface noise level (L_A) from these two factors. It was based on the results available then for interleaved, bolted or banded core constructions (groups 1, 3 and 4 in figure 19), which at that time formed the bulk of the transformer production. The formula reads:

$$L_A = k_1 \log_{10} W + 20 \log_{10} 0{\cdot}02f + k_2(B_L - k_3) + k_4,$$

where L_A (dB(A)) is the transformer surface noise level, W (lb.) is the total weight of coreplate, f (Hz) is the frequency, B_L (kG) is the leg flux density, and k_1, k_2, k_3, k_4 are constants.

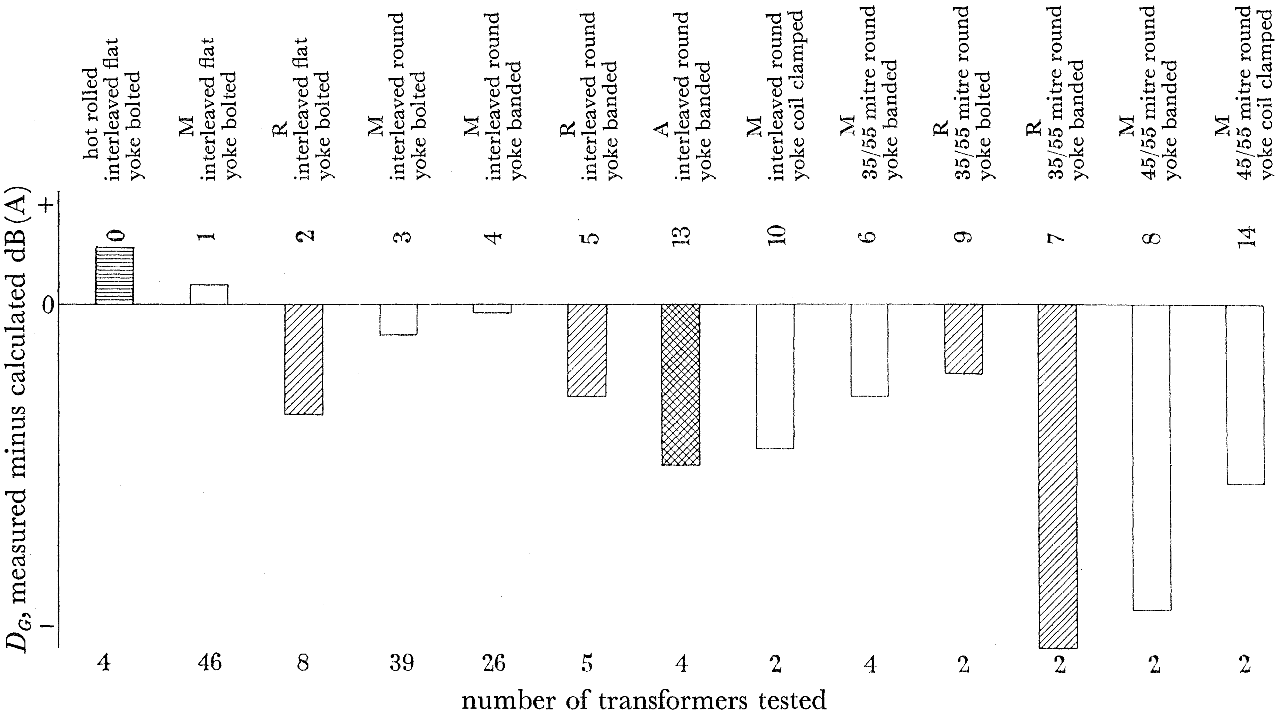


FIGURE 19. Noise quality factors D_G for large cores. M = mesh belt anneal, R = roller hearth anneal; British plate. A = not annealed (American catenary annealed plate).

One objective of the analysis was therefore to examine whether the formula still held for the larger number of results for groups 1, 3 and 4 which had since become available. The other aim was to find the group (and therefore the combination of constructional features) which made least noise, amongst the remainder. The procedure was to calculate the mean difference D_G, for each group, between the measured noise levels and the values by the empirical formula. D_G can be interpreted as a 'noise quality factor' for the group, provided n, the number of transformers, is sufficiently large.

The results of the calculations are presented as histograms in figures 19 and 20. It is clear that the empirical formula continues to represent the older form of core construction. There has been no significant shift in D_G for groups 1, 3 and 4 with time. The implication is that the magnetostriction of normal grade 46 grain oriented steel has not improved. On the other hand, when modern plate and core construction are combined, significant noise reductions can be achieved. The surface noise level of a transformer can therefore be estimated from the weight and construction of the core and the flux density. The equation

$$L_A = k_1 \log_{10} W + 20 \log_{10} 0{\cdot}02f + k_2(B_L - k_3) + k_4 - D_G,$$

where D_G is the noise quality factor of the group, usually gives an answer within ±2 dB of the measured value.

Transformer noise levels are often compared on an MVA basis, particularly between rival manufacturers. One transformer may be 8 dB(A) higher than another of the same rating, and eyebrows are raised! The difference may not in fact reflect the quality of manufacture, since the comparison must take weight, flux density and D_G into account.

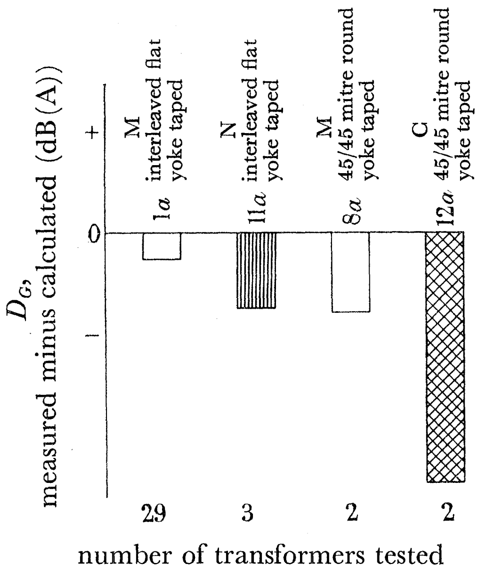


FIGURE 20. Noise quality factors D_G for small cores. C, not annealed (British catenary annealed steel); N, not annealed (low residual stress steel); M, mesh belt anneal (British steel).

TRANSFORMER NOISE AND COMMUNITY REACTION

A transformer can be represented as a point source, to a first approximation, at the geometric centre of the tank and the divergence of sound can be assumed to be hemispherical. We have seen that, in general, only the average level around the transformer is related by the inverse square distance law to the average radius of the measurement positions. The horizontal propagation of sound in air is a complex process (Parkin 1962; Parkin & Scholes 1965). A theoretical calculation of the sound level at a distant listening point must take a variety of factors into account, the effect of the ground, wind, temperature gradients, the topography of the terrain and scattering due to air turbulence. Air absorption is usually negligible at transformer frequencies. The 'corrections' are frequency dependent and a precise calculation is not possible from the data published so far. A calculation by the inverse square law, without corrections, gives noise levels which broadly agree with measurements up to about 100 ft. Beyond this distance the calculated noise levels are too high. A better agreement with measurements is obtained from Brownsey's attenuation/distance relation (Brownsey 1956), which relates the decrease from the average surface noise level of the transformer with distance from the tank surface.

The Building Research Station has proposed a procedure for assessing community reaction to industrial noise, based on dB(A) levels. The procedure is outlined in appendix XV of the Wilson Committee report. We have applied the technique to estimate public reaction to transformer noise on a few occasions and suggest that it is worthy of wider use.

A typical example is the extension of an existing substation (figure 21). Shortly after two new transformers were commissioned, complaints were received from residents in a row of houses whose back gardens faced the site. In the investigation, noise levels were measured at various locations in the area and in the near field of the two transformers. A calculation was made of the noise level expected in regions 1, 2, 3 and 4 (shown shaded in figure 21) due to all the transformers on the substation. The results are compared with the measurements in table 10. A strong standing wave field was observed near the house, noise maxima occurring at 6 ft. intervals in the direction of the substation. Sound energy was clearly being reflected by the house and one would expect the measured value to be greater than the calculated free-field value, as indeed it was.

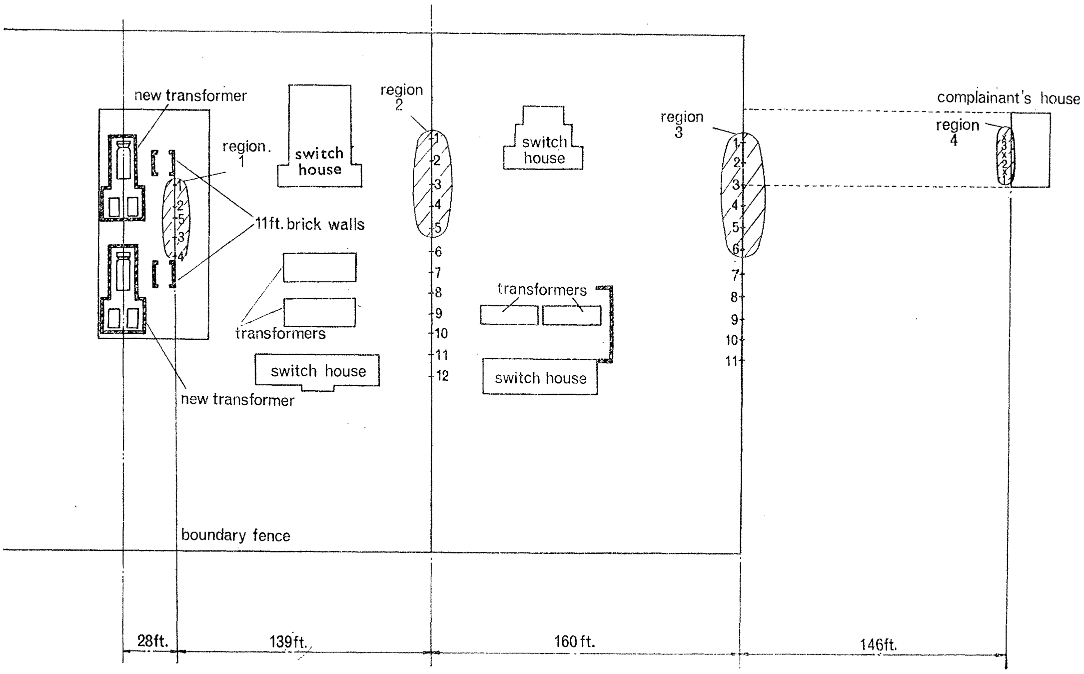


FIGURE 21. Extension of substation.

TABLE 10. COMPARISON BETWEEN MEASURED AND CALCULATED NOISE LEVELS DUE TO ALL TRANSFORMERS ON SUBSTATION SITE

(*a*) Brownsey; (*b*) inverse square law.

	mean noise level (dB (A))		
region	calculated (*a*)	calculated (*b*)	measured
1	72·6	73·5	68·5
2	60·6	62·1	60·2
3	53·4	56·2	53·5
4	47·9	52·8	51·3

Community reaction was assessed by the B.R.S. procedure for the two cases of interest, before and after the extension of the substation (table 11). Measurements were not available for the former case. The 'allowance' under 'district' in table 11 is open to debate. The Building Research Station's procedure suggests an allowance of (0) for a 'suburban or urban, no road traffic' type of district and of (+5) for a 'residential urban' location.

Since an 'A' road runs near the houses, the (+5) allowance should perhaps be chosen, although otherwise the location is clearly suburban. Such a choice would err on the side which gives the transformer noise the 'benefit of the doubt', but none the less the prediction is that complaints are to be expected.

TABLE 11. PREDICTION OF COMMUNITY REACTION TO TRANSFORMER NOISE

basic level (dB (A))	allowances (a)	(b)	(c)	(d)	(e)	(f)	total	total + basic (dB (A))
50	−5	0	−5	0 to +5†	0	0	−5 to −10	40 to 45

conditions	noise level (dB (A)) calculated (Brownsey)	measured	prediction of complaints	actual complaints
before	42·7	—	sporadic	?
after	47·9	51·3	yes	yes

(a) Note.
(b) Regularity.
(c) Time of day.
(d) District.
(e) Duration.
(f) Other factors.

† 'A' road near houses.

In predicting community reaction by the B.R.S. procedure, an allowance should be made to the surface noise level of the transformer for tap position and load. The B.E.B. specification refers to a measurement at no load and normal flux density. In operation, an increase in flux density of 10 %, for example, raises the surface noise level by 2 to 4 dB (A). A hypothetical example will illustrate the procedure that we recommend.

New substation: two 30 MVA 11/132 kV transformers are to be installed 500 ft. from the nearest houses in a residential urban district. Will the residents complain?

B.E.B. specification for a 30 MVA 11/132 kV unit: 79 dB (A)
allowance for tap position and load: 4 dB (A) (say)

total for two units: 86 dB (A) approx.
attenuation over 500 ft. (Brownsey 1956): 41·5 dB (A)
hence noise level outside nearest house: 44·5 dB (A)

basic level (dB (A))	allowances (a)	(b)	(c)	(d)	(e)	(f)	total	total + basic (dB (A))	predicted level (dB (A))	complaints
50	−5	0	−5	+5	0	0	−5	45	45	sporadic

(a) Note.
(b) Regularity.
(c) Time of day.
(d) District.
(e) Duration.
(f) Other factors.

Although the public reaction procedure relates to noise outside dwellings, the complaints arise from people disturbed inside. The 'basic level' takes account of this factor but whether it requires some adjustment for transformer noise should be decided: (i) by applying the criteria and comparing with actual community reaction in as many cases as possible; (ii) by measuring octave band levels inside and outside houses in these cases and applying the noise rating procedure of Kosten & van Os (1962).

The example quoted underlines the need to consider the transformer noise problem at the planning stage. Information on the prevailing wind direction, on wind strength and the number of windy days per annum (subdivided into summer and winter) would be useful, to estimate the probable change in the attenuation/distance relation. The substation should be located downwind from the nearest houses so that the attenuation is increased. In some of the more sophisticated procedures for estimating public reaction, allowances are suggested for summer and winter, any economic tie between resident and operator, resident's previous noise experience, public relations and other local factors. Good public relations and the planting of trees and shrubs to make the site unobtrusive might carry an allowance of +5.

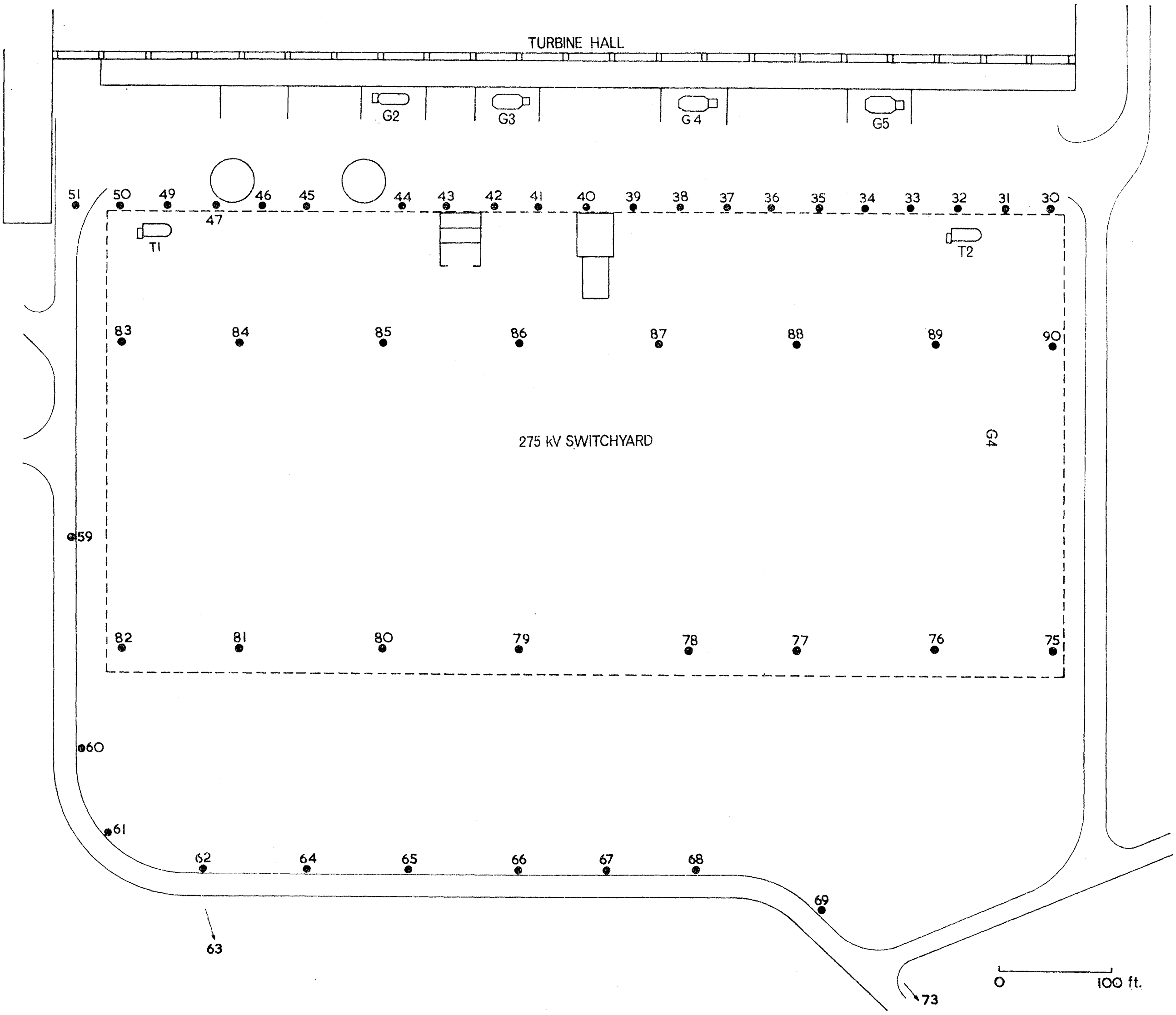


FIGURE 22. Power station noise measurement positions.

An entirely different problem is afforded by the sound radiation from the generator transformers at a power station. Noise measurements were taken at many points near a 1000 MW power station, but particularly on the side facing the transformers (figure 22).

A calculation was now made, using Brownsey's attenuation/distance curve, of the dB (A) levels one would expect at these measurement positions due to *all* the transformers on the site. To estimate the surface noise levels of the generator transformers, measurements at 15 ft. from the tank were extrapolated back to the tank surface, basing the increase again on Brownsey's curve. In fact only two transformers were measured in this manner; the others were assumed to be similar. Measurements were also made around one of the station transformers; the other was assumed to be similar. The results of this calculation are compared with the actual measurements in figure 23. We think that they show that the far noise field is dominated by radiation from the power station rather than from the transformers. The implication is that the noise of a generator transformer is not as critical as that of a distribution transformer. The experiment also underlines Mattei's contention (1966) that the acoustical problem of a plant must be studied in its entirety, rather than consider the noise of items of plant in isolation.

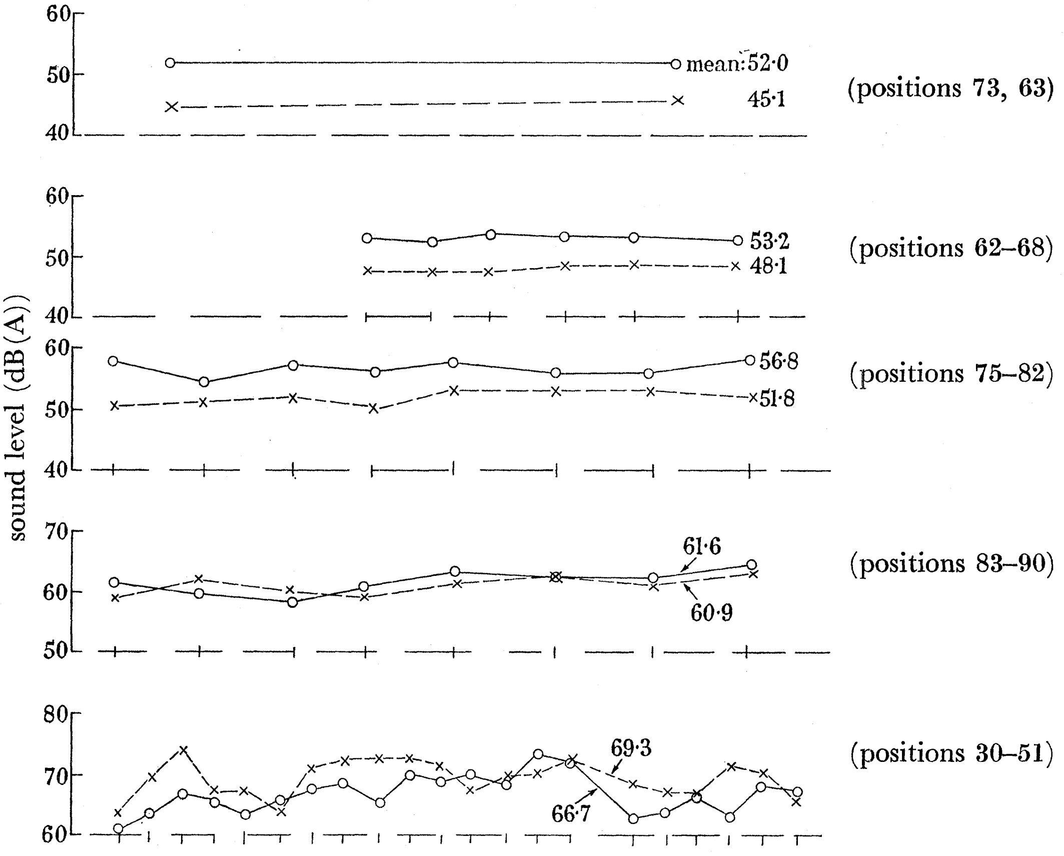


Figure 23. Sound levels in front of generator transformers. ○—○, Measured values; ×---×, calculated values.

Reduction of transformer noise

In passing directly to the problem of community reaction to transformer noise, we have deliberately omitted a large and important section of the over-all problem—the transfer of energy through the oil and its radiation by the tank. We have done this so that the paper shall not be of undue length. We hope to write on these other aspects on another occasion. Before leaving the matter, we want, however, to state our view on transformer noise reduction. Basically, transformer noise can be reduced (i) at the source, by control of the magnetic to mechanical properties of the steel and of the core; (ii) by acoustic design of the whole transformer structure, based on the concept of impedance; (iii) by energy conversion to heat in the transmission path.

We have fully discussed item (i) in the previous sections. A great amount of experimental work, relating to (ii) and (iii), has been described in the literature. There is a lack of order in the published results, and in our own research in this field, in the sense that a noise reduction technique cannot be formulated as a general design calculation. The only technique which has yielded very large noise reductions is enclosure of the transformer. Yet here too there are conflicting results, concerning chiefly the necessity for an absorbent lining. At least three ways of calculating the performance of an acoustic hood have been put forward.

Conclusions

1. The large British transformers shortly to be commissioned will radiate several watts of power as sound.
2. Transformers operate unattended and there is therefore generally no risk of hearing damage. Under different circumstances, for example the works proving test, ear protection should be worn by personnel working close to the tank for more than half an hour.
3. Transformer noise levels appear to have changed little over the last 20 years, because improvements in the core steel and in transformer manufacture have been utilized to build smaller and more efficient transformers. The absence of a major decrease in noise levels can be explained in terms of the magnetostriction and flatness of the steel.
4. The B.E.B. specification for near-field measurements recognizes the practical difficulties of noise measurement in a transformer works. The rules are realistic and the measurements provide answers which are adequate for the prediction of transformer noise at a distant listening point.
5. A strict interpretation of the standard on precision sound level meters could introduce some unnecessary complications to transformer noise measurement.
6. The B.E.B. recommendation of acceptable noise level against kVA rating probably imposes an unnecessarily severe restriction on the noise levels of generator transformers.
7. The primary cause of transformer noise is the magnetostriction of the grain-oriented silicon iron laminations.
8. To reduce noise at source the core steel should have five properties: constant thickness, low magnetostriction, stress insensitivity, homogeneity and flatness.
9. Core design and manufacturing processes affect transformer noise levels.
10. The Building Research Station’s procedure for predicting community reaction is recommended for substation planning.
11. The noise of a generator transformer must be considered in relation to other noise from the power station plant.
12. With our present knowledge, transformer noise-reduction techniques cannot be formulated as exact design calculations.

The authors are greatly indebted to their many colleagues, too numerous to mention all individually, both within their own organization and outside it, who have collaborated with them on transformer noise research over the years. They also want to thank the C.E.G.B., Area Boards, The Electricity Council, C.E.R.L., the C.E.G.B./Industrial collaborative committee and the ERA for their co-operation in the investigations and the Directors of C. A. Parsons and Co. Ltd for permission to publish.

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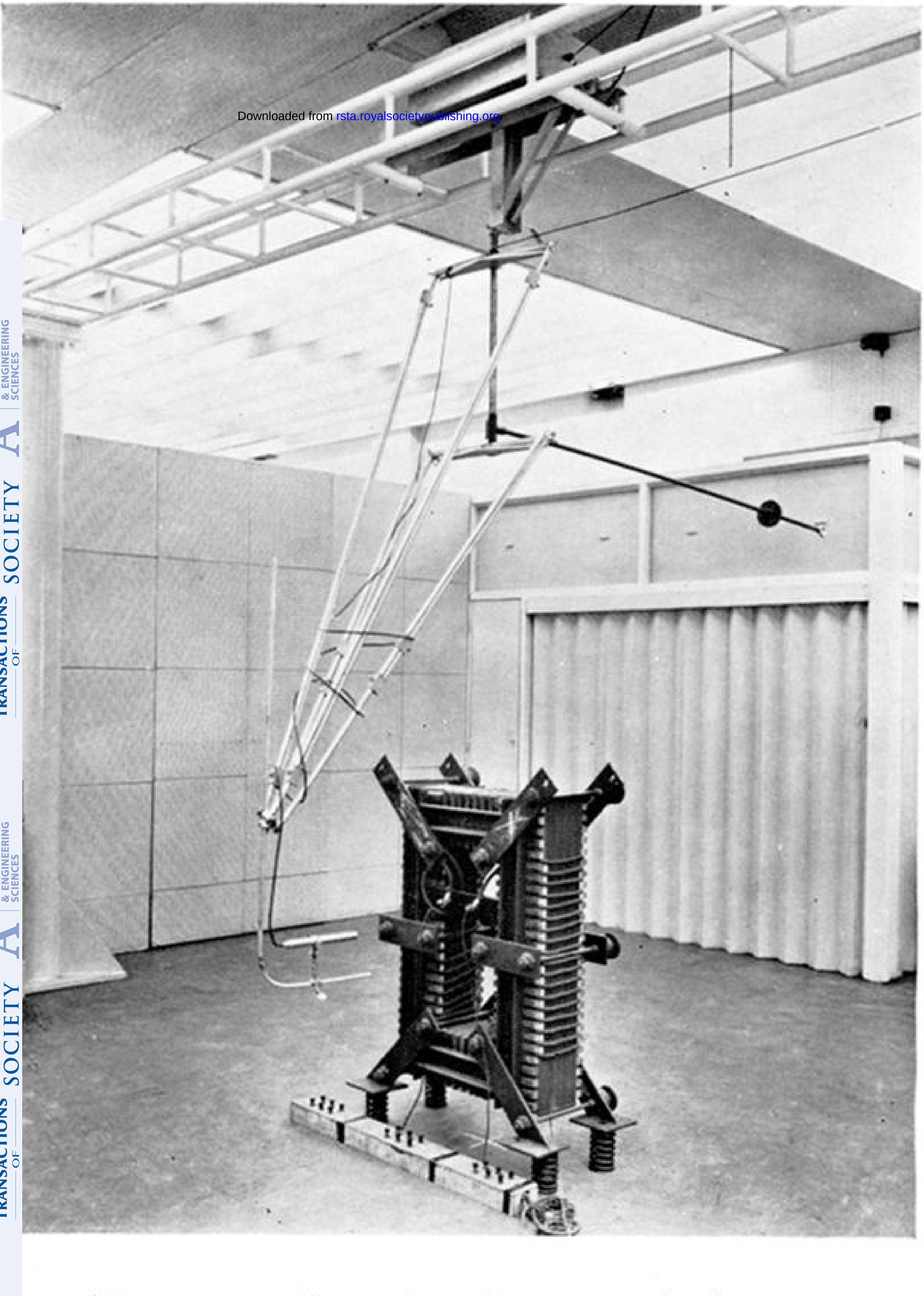

FIGURE 8. Rotating boom technique.