LEAD INDUSTRIES ASSOCIATION, INC.

292 MADISON AVENUE
NEW YORK 17, N. Y.

April 2, 1963

SUBJECT: TRANSFORMER NOISE
REDUCTION USING LEAD

To Members of the Lead Industries Association, Inc.:

We are attaching copy of a paper presented at the Winter General Meeting of The Institute of Electrical and Electronics Engineers, January 27-February 1, 1963, describing "Transformer Noise Reduction with a Close-Fitting Mass-Law Enclosure," by P. N. Adkins, Portland General Electric Company, Portland, Oregon. The enclosure is constructed of steel, sheet lead and fibre glass, and we estimate that in the transformer described at least a ton of sheet lead is used. Mr. Adkins has subsequently soundproofed two additional similar transformers and is currently working on a fourth, which is larger.

It is extremely interesting to note from Mr. Adkins' cost figures that he achieved the reduction in noise at a cost per db of reduction which was less than the additional cost of buying a transformer soundproofed at the factory. While we have no reliable statistics available at the moment, we believe that there are thousands of transformers of varying sizes throughout the country which might warrant this treatment.

We will not attempt any further interpretation of the paper, but because of its thoroughness and clarity urge that you study it. In his conclusions Mr. Adkins states: "In its prototype form, this enclosure surpassed expectations. Future installations will, however, incorporate several changes which should provide greater latitude for construction tolerances. Although the barrier transmission loss is adequate, it is felt that the proportion of lead to steel should be increased, while maintaining the same weight."

We have ordered 2,000 copies of this paper and plan to mail it to a list of over 400 electric utility company engineers. We also plan to publish a shorter version in an early issue of our publication "Lead."

Additional copies of this paper are available from us free of charge in quantities of 25 or less and at our cost of $12.00 per hundred for larger quantities.

Very truly yours,

Executive Vice President

RLZ:mk
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Look Ahead with Lead

Transactions Paper

(Reviewed and Accepted for Publication)

Discussion in Duplicate Due February 15, 1963

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TRANSFORMER NOISE REDUCTION WITH A CLOSE-FITTING MASS-LAW ENCLOSURE

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A paper recommended by the AIEE Transformers Committee and approved by the AIEE Technical Operations Department for presentation at the Winter General Meeting, New York, N. Y., January 27-February 1, 1963. Manuscript submitted September 23, 1962; made available for printing November 27, 1962.

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63-200

TRANSFORMER NOISE REDUCTION WITH A CLOSE-FITTING MASS-LAW ENCLOSURE

P. N. Alkins

Summary: This paper discusses the design and development of a high-attenuation, field applicable acoustic enclosure for large power transformers, based in concept upon the "Field Incidence Mass Law" from the field of acoustic. Free standing and form fitting, enclosures of this type have been designed to provide noise reduction in the order of 15 to 20 decibels in addition to other advantages inherent in a near-total enclosure.

INTRODUCTION

Noise has been defined as unwanted audible sound, and yet not all noise causes complaint or stirs a community into unified action. It has been noted that many relatively intense noises give rise to mild or short-term annoyance, with no formal complaint. In contrast, the low frequency, continuous, all-pervading hum of a large transformer, however comforting to utility engineers, may become a compounding annoyance to neighbors.

"The Power Company" in this case, is a specific corporate person who, in addition to advertising ownership of the offending transformer, is locally available to hear complaints directly from the annoyed neighbor, or indirectly from the courts or various offices of City government upon whom the utility must rely for zone changes and other expansion privileges. In order that its obligation to provide the highest level of service commensurate with cost over a long period of time may be realized, the utility must cultivate an attitude of co-operation with these governing bodies and customers to ensure that expansion and reinforcement will be permitted where and as requirements dictate, not where and as permitted.

This paper will describe the development of a close-fitting transformer enclosure based on the Field Incidence Mass Law, (1) and the application of this method of noise control to a particular transformer bank on the Portland General Electric Company system.

CONCLUSIONS

The acoustic enclosures studied and described in this paper are free-standing, form fitting, nearly total enclosures designed to provide noise reduction in the order of 15 to 20 decibels. This order of noise reduction is shown to be available using mass law attenuation, efficient energy absorption, and nearly complete enclosure.

In addition to providing high noise reduction at a cost equal to or lower than other methods, further advantages of this method are:

1. noise reduction in all directions,
2. effectiveness is unaffected by topography,
3. does not require remote transformer cooling,
4. can be applied in the field after complaint,
5. can be nondestructively disassembled,
6. improves appearance of the transformer.

The method of noise treatment described represents a departure from methods commonly considered for field application, and is believed to be unique, economic, and sufficiently effective to warrant further development and application.

DISCUSSION

Noise Control Requirements

The goal of any noise control scheme is to alter the character of a sound field so that it is not objectionable, most frequently by means of noise reduction.

The difficulty of determining the amount of noise reduction that is required of a noise control scheme can better be appreciated after considering the following items:

A. Noise levels "generally considered acceptable" for representative areas are useful as a guide only if it is recognized that they are based upon group rather than individual reaction. The implication is that a noise control scheme should incorporate plans for additional noise reduction beyond that which is indicated by established group acceptability criteria. While these criteria are valid as a guide in an undisturbed area, they are not necessarily valid when applied to an individual or a small group that has been annoyed to the point of complaint.

B. Noise levels "generally considered acceptable" do not take into consideration the predominance of one, two or three component frequencies as is the case of power transformers, i.e., the spectral distribution of energy. This further qualifies the use of these criteria by the fact that ambient noise and transformer noise cannot be compared on the basis of sound level as measured with a Sound Level Meter. Comparison should be based on the distribution of energy in the audible spectrum, i.e., the sound levels in the octaves containing 120 and 240 cps or comparable measurements of ambient and transformer noise made with a narrow band analyzer. The difference thus determined is more reliable for the determination of barrier attenuation requirements.

C. The rate of change of noise level is as important as the amount of change in its effect on the response of a group or an individual. Hence, a large noise reduction brought about gradually over a long period of time will be less effective than a smaller reduction effected in a short period of time. This introduces the psychological effect which may be used to advantage to increase the effectiveness of treatment. Ideally, the most pronounced effect would be achieved by allowing the noise to continue unabated until the last bolt was to be inserted, at which time the noise would be shut off suddenly. This emphasizes the importance of scheduling work for the shortest shut-down period, and returning a transformer bank to service as soon as possible. It follows that considerable benefit might be achieved from artificially augmenting or sustaining transformer noise during the work period.

D. A noise complaint may be an objection to the existence of a substation rather than an objection to transformer noise, in which case no amount of noise reduction will satisfy the complaint. Although a complaint may be suspect, one alternative to immediate treatment is to await legal action as evidence of a serious noise complaint. Since this alternative involves unfavorable publicity and is detrimental to the interests of the utility, the possibility of this type complaint can only be considered as cause for a conservative approach.

The noise complaint which resulted in the treatment developed in this paper, was vehement from the beginning. It necessitated the use of measurement and comparison methods which, as has been pointed out, are not strictly valid, but were consistent with approved techniques and within the capabilities of the measuring equipment available.

The object of complaint was a bank of three single-phase 115-57 kv autotransformers each rated 25/33.3/41.7 KVA, OA/FOA/FOA, standard noise level. The standard noise level for each unit is 74 db_A (db, A scale, based on 15,500 KVA-parts), and field measurements according to NEMA Standard methods indicated this was the noise level of each unit.

A cursory sound level survey was made to determine the validity of the various complaints and further define the problem. That survey, made between twelve o'clock and four in the morning, indicated that several customers had just cause for complaint.

A second, more extensive survey was then made and from it, for analysis and control, a map of sound level contours was drawn. A comparison of that map with contours calculated from the transformer sound level and physical dimensions showed no correllation because of the topography and reflections from nearby buildings. Typical sound levels at various residences are shown in Table I.

TABLE I

Summary of Sound Level Survey Results

Customer	Distance	Min. Ambient (2-4 a.m.)	Trans. Noise Level Only	Resultant Level	Increase in Level
A	140 ft.	30 db_A	49 db_A	49 db_A	19 db_A
B	200	30	44	44	14
C	340	30	47	47	17
D	500	30	39.5	40	10

The column headed "Increase in Level" indicates the amount by which the minimum ambient noise level was increased by installation of the transformer tank. The minimum ambient level shown is a condition occurring only momentarily and is approximately 5 db below the normal for that time of night.

From this it was judged that a transformer sound level reduction of at least 10-15 db would be required. A reduction of this order would not render it inaudible, but should sufficiently reduce the probability of future complaint.

In consideration of plans for future system additions, and recognizing the probability that noise problems would arise with increasing frequency in the future, the decision was made not just to solve this problem, but to become familiar enough with transformer noise problems in general that analyzing and prescribing treatment for future problems would be relatively painless. After estimating the costs of various methods of achieving the necessary noise reductions, it was decided that the knowledge and experience to be gained by constructing a barrier of our own design would more than offset a reasonable increase in cost over that of a manufacturer's design if such increase did, in fact, materialize.

Design Considerations

To date, the most reliable method of achieving substantial noise reduction in an existing installation has been to insert a masonry barrier between the noise source and critical observer. The primary effect of this treatment is to distort the sound field by reflection and is always accompanied by a noise level increase in a non-critical area. Application of this method, as in this case, is often made difficult by the physical arrangement of the substation and local terrain features. If the noise reduction requirements are such that three or four walls and possibly a full or partial roof are required, it may be necessary to install cooling equipment outside the enclosure. While these obstacles are not insurmountable, they do add considerably to the cost of treatment.

These and other considerations prompted the search for a method of treatment which was effective, compact, and economical and did not require additional cooling or remote installation of cooling equipment. These requirements could be fulfilled by a barrier constructed between the radiators and the transformer tank if:

1. a high enough transmission loss could be built into the barrier,
2. the increase in sound level between the barrier and tank (buildup) could be limited,
3. it did not impair the function of the transformer,
4. the cost of treatment by this means was commensurate with noise control requirements.

To consider the ideal situation, the noise reduction that would be achieved by covering a uniformly radiating source with a perfectly attenuating barrier would be given by equation (1), in which K represents that fraction of the total area which is covered. This function is plotted in Figure 1. Development of this equation will be found in Appendix II.

$$db = 10 \log (1 - K) \qquad (1)$$

As might be expected, covering half the radiating area results in a reduction in radiated power of 3 db (or half power).

However, no barrier is infinitely attenuating, and so it is desirable to modify equation (1) to include the effect of finite barrier transmission loss (see Appendix III). This may be done in effect, by replacing that part of the original source "removed" by a perfect barrier with a source equal in area, but whose strength is equal to the original source level minus the barrier transmission loss. The resulting attenuation may then be given as a function of the part of the original source area covered, and the barrier transmission loss as in equation (2).

$$db = 10 \log (1 + K (10^{-0.1(TL)} - 1)) \qquad (2)$$

where: db = resultant noise reduction
K = fraction of original area covered by barrier
TL = barrier transmission loss in decibels

A family of curves showing some solutions for this equation is given in Figure 2.

With reference to Figure 2, it can be seen that the benefit that might be attributed to increasing the barrier transmission loss is lost unless great care is taken to provide nearly perfect coverage. It will later be shown that it is not difficult to attain a barrier transmission loss of 30 db, hence the sound level reduction achieved is primarily dependent upon the extent of coverage with the barrier transmission loss as a limit. It should also be evident that the last few per cent coverage would be increasingly expensive.

In practice, several things contribute to limit the effectiveness of this idealized enclosure. The physical configuration of the transformer, the location of valves, guages, and other devices for which access must be provided, and close proximity of radiators all serve to increase the physical complexity of the enclosure. In some cases, fixtures must pass through the wall of the enclosure and must be isolated from it since anything that bridges the space between the enclosure wall and transformer tank will transmit acoustic energy.

The close proximity of the barrier wall to the transformer tank causes adiabatic expansion and compression of the enclosed air. It has been noted by others that if not controlled, this phenomenon may be responsible for an apparent six to ten decibel increase in the source sound level. Control of this form of buildup may be accomplished in an enclosure of this type by lining the cavity with dense blankets or blocks of glass fibre to provide viscous losses. In the described enclosure, a two-inch thickness of dense fibreglas was mounted approximately one inch from the barrier. It was estimated to be adequate to limit the apparent increase of source noise level to 3 db. Subsequent measurements indicated that this noise level increase was no more than 3 db.

The physical irregularity and non-uniform radiation of the transformer tank causes bending waves (2) to be set up in the surface of the enclosure, which in turn re-radiate sound. The introduction of bending waves also makes panel resonances possible at frequencies other than those characteristic to transformer noise. The presence of bending waves makes it necessary to provide damping to dissipate energy transmitted in the wave, limiting the amplitude of standing waves set up on the surface. This damping can be obtained by use of a barrier material having high internal losses (mechanical hysteresis) such as lead. General or spot application of damping after construction could also be used.

If the noise source was a uniformly radiating flat surface it would radiate plane waves. A barrier constructed parallel to the surface would encounter sound waves impinging normally on its surface, and no bending wave could be set up. If, in addition, the fundamental self-resonant frequency of the barrier panel were sufficiently low, it would not be excited by a sound wave of the frequencies encountered in transformer noise, hence damping treatments would be unnecessary.

In the absence of resonances, a panel attenuates sound in proportion to the logarithm of the squared product of frequency and panel surface weight. Hence, at a given frequency, doubling the surface weight would increase transmission loss by six decibels. By the same token, doubling frequency would have the same effect. This is the Field Incidence Mass Law 1, 3, reduced to equation (3).

$$TL = -5 + 10 \log \left(1 + (1.4 \times 10^{-3})(fW)^2\right) \qquad (3)$$

where: TL = diffuse field transmission loss in db
f = frequency in cps
W = surface weight of panel in $\#/ft^2$

By equation (3), a barrier having a surface weight of ten pounds per square foot would have a transmission loss of 28 db at 120 cps (the fundamental transformer noise frequency), 34 db at 240 cps and 40 db at 360 cps (the second and third harmonic frequencies respectively). Applicability of this equation does, however, rely upon "limpness" and internal hysteresis to prevent deviations in transmission loss which would result from resonances at integer multiples of the basic panel resonant frequency.

In view of these problems and in consideration of the restricted space available, the barrier section used was composed of 1/16 inch lead sheet laminated to ten gage steel with epoxy resin compound. A two inch curtain of 6½ pound density fiberglas was mounted approximately one inch from the barrier to provide viscous loss within the cavity. The barrier and supporting structure was free standing and isolated from the transformer. Those pipes and fittings which, of necessity, passed through the barrier were isolated and sealed with compliant neoprene gaskets.

A lined, sheet metal roof was extended from the edge of the tank top and fastened with sheet-metal screws to the top edge of the barrier, ensuring a permanent, weather-tight enclosure. The roof is the only intentional bridge between the tank and barrier, and was considered acceptable because of the flexibility of the roof, and the vibration node at this point on the tank. The top of the particular transformer being treated was not considered to be an active noise source for four reasons: 1) the small area, 2) the direction in which it radiated, 3) effective mass due to bushings, etc., 4) the gas-filled cavity under the top. A typical panel section and other views of the enclosure are shown in Figures 3 through 9, Appendix I.

Design Evaluation

After the completion of the first of three enclosures, sound level measurements were made first without radiators, and then with radiators in place. Measurements indicated the sound level of the tank had been reduced 22 db_A to 52 db_A (NEMA method) with good uniformity. Reinstallation of the radiators raised the sound level to 57 db_A giving a net reduction of 17 db_A. The loading effect of the radiators on the tank is not known quantitatively, but the result was that of adding to the transformer tank noise level a second source whose level was 56 db_A. It can be surmised from this that to achieve any further significant noise reduction, the radiators must be isolated from the tank.

There was no indication of panel resonance, nor did sample measurements inside the enclosure indicate a significant buildup of noise.

Based on these findings, the two remaining transformers of the bank were similarly treated. Similar measurements indicated sound levels three to five decibels higher than that of the first unit, and were characterized by vibration antinodes. Performance was improved by subsequent relief of spot contacts.

Prolonged surveillance of top-oil temperature in these transformers indicated that thermal insulation of the tank resulted in earlier application of second and third stage cooling, but did not increase the peak load temperature. It was therefore not necessary to derate the transformer bank.

As was mentioned previously, construction clearances were extremely limited. Detail design and fabrication was done in the field for the first unit, and was closely supervised. Fabrication of the second and third units was done, without modification, from the original patterns and measurements with only moderate supervision. It is believed that manufacturing and construction tolerances were the cause of the trouble experienced with these units.

Installation of this type enclosure is now planned for a three phase transformer of the same total rating as has been described. The transformer has been purchased with additional clearance between the tank and fixtures in expectation that construction problems will be minimized. Header arrangement of coolers on the new transformer promises considerably less noise from this source.

Cost of Treatment

The cost of treating this transformer bank was approximately $21,000 or $410 per db per transformer and represents 0.8% per db based on the transformer cost. By comparison, an offending transformer may be replaced by a new one purchased with reduced sound level. This choice would represent an additional cost of 1% to 1.3% per db plus changeout costs (and fixed charges on the existing tank until it can be used in the event it is made idle).

Further comparison is provided by the estimated cost of 0.7% per db for a three wall masonry barrier, acoustic treatment of the barrier, and commercially available panels applied to the transformer to achieve the same noise reduction.

Summary Conclusions

This paper has briefly described the development of a compact, demountable and effective acoustic enclosure built by Portland General Electric Company.

In its prototype form, this enclosure surpassed expectations. Future installations will, however, incorporate several changes which should provide greater latitude for construction tolerances. Although the barrier transmission loss is adequate, it is felt that the proportion of lead to steel should be increased, while maintaining the same weight. This would provide greater limpness, reducing the effect of stiff joints between plates, and reducing the likelihood of standing waves due to vibration and bending waves. It is also felt that more efficient absorption in the cavity and more complete isolation and closure around pipes would provide a worthwhile improvement in reliability.

As previously noted, radiators and their fans will always be a problem with this type enclosure. Some configurations appear to be inherently quiet, but at this time little is known about them as a noise source and so must remain a matter for judgment.

REFERENCES

1. Noise Reduction, Leo Beranek, McGraw-Hill 1960, pp. 275-301

2. Ibid., 280-361

3. Handbook of Noise Control, Harris, McGraw-Hill 1957, Ch. 22, pp. 7-10

APPENDIX I

CURVES AND PHOTOGRAPHS

(SEE FIGURES 1 THROUGH 9)

APPENDIX II

Development of Equation (1)

The term decibel, in the field of noise control as in other fields, is used to define the intensity of a sound in terms of a standard intensity by the following relationship.

$$db_2 = 10 \log (P_2/P_1)$$

where P_2 = the power intensity of a sound being specified, in watts/m^2

P_1 = reference intensity, 10^{-12} watts/m^2

db_2 = sound intensity level which might be indicated by a sound level meter

The total power emanating from a source of area $\underline{A}$, and level $\underline{db_2}$ is then

$$P_2A = P_1A \times 10^{0.1(db_2)} \text{ watts.}$$

A perfectly attenuating barrier with an area $\underline{A_1}$ absorbs

$$P_2A_1 = P_1A_1 \times 10^{0.1(db_2)} \text{ watts.}$$

That power which remains to be radiated is the difference

$$P_4A = P_2A - P_2A_1 = P_1 \times 10^{0.1(db_2)}(A - A1) \text{ watts.}$$

The power intensity resulting from the redistribution of this power over the original area $\underline{A}$ is

$$P_4 = P_1 \times 10^{0.1(db_2)}(A - A_1)/A \text{ watts/m}^2$$

which, when referred to the defined reference level P_1 is

$$P_4/P_1 = 10^{0.1(db_2)}(A - A_1)/A$$

$$db_4 = 10 \log (P_4/P_1) = db_2 + 10 \log (1 - (A_1/A))$$

The difference between this resulting sound intensity level db_4 and the original level db_2 is the attenuation $\underline{db}$ of equation (1)

$$db = db_4 - db_2 = 10 \log (1 - K) \qquad (1)$$

where $A_1 = KA$

APPENDIX III

Development of Equation (2)

The development of equation 2 follows closely the power balance method of Appendix II. The original sound intensity level is taken as db_2 and again results in a total radiated power of

$$P_2A = P_1 \times 10^{0.1(db_2)}(A) \text{ watts.}$$

A perfectly attenuating barrier again absorbs a portion determined by its area A_1

$$P_2A_1 = P_1 \times 10^{0.1(db_2)}(A_1) \text{ watts.}$$

Acoustic transmission loss of a barrier is ten times the logarithm of the ratio of the source side power intensity to that quantity measured on the receiver side. Expressed in decibels it is the numerical difference between the sound intensity levels,

$$TL = db_2 - db_3$$

The effect of finite acoustic transmission loss can then be obtained by replacing that part of the original source represented by area A_1 by a new source equal in area to A_1 and having a strength equal to

$$db_3 = db_2 - TL$$

The total power radiated by the barrier is then

$$P_3A_1 = P_1 \times 10^{0.1(db_2-TL)}(A_1) \text{ watts.}$$

By a power balance, the total radiated power is now

$$P_4A = P_2A - P_2A_1 + P_3A_1 \text{ watts.}$$

$$= P_1 \times 10^{0.1(db_2)}(A) - P_1 \times 10^{0.1(db_2)}(A_1) + P_1 \times 10^{0.1(db_2 - TL)}(A_1)$$

$$P_4A = P_1 \times 10^{0.1(db_2)}(A - A_1 + A_1(10^{-0.1(TL)})) \text{ watts.}$$

The power intensity resulting from redistribution of this power over the original area $\underline{A}$ is

$$P_4 = P_1 \times 10^{0.1(db_2)}(1 - (A_1/A) + (A_1/A)(10^{-0.1(TL)}))$$

Referring this to the reference level P_1,

$$P_4/P_1 = 10^{0.1(db_2)}(1 - (A_1/A)(1 - 10^{-0.1(TL)}))$$

$$db_4 = 10 \log (P_4/P_1) = db_2 + 10 \log (1 - (A_1/A)(1 - 10^{-0.1(TL)}))$$

The difference between the resulting sound intensity level, db_4, and the original level, db_2, is the attenuation, db.

$$db = db_4 - db_2 = 10 \log (1 - K (1 - 10^{-0.1(TL)})) \qquad (2)$$

where $A_1 = KA$

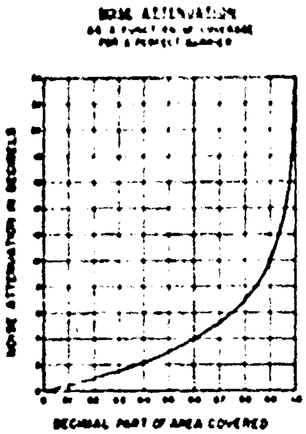

Fig. 1.
Noise Attenuation. A curve showing the noise attenuation that would be achieved under ideal conditions if a part of the source area is covered by a perfect barrier, i.e. the solutions of equation (1).

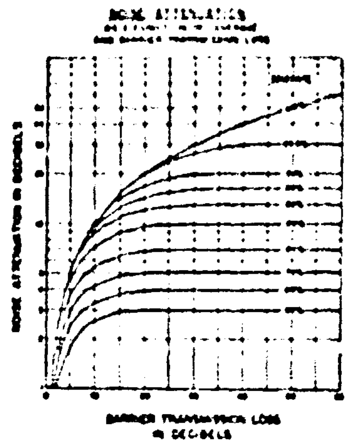

Fig. 2.
Noise Attenuation. A family of curves showing the noise attenuation that would be achieved under ideal conditions if a part of the source area is covered by a barrier having finite acoustic transmission loss, i.e. some solutions of equation (2).

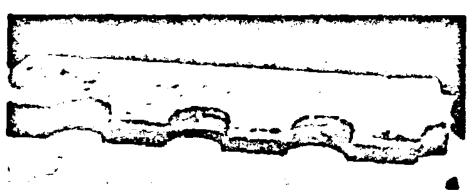

Fig. 3.
A typical barrier panel section showing two-inch thickness of 9 lb. density fiberglas, one inch air space, and laminated lead and steel.

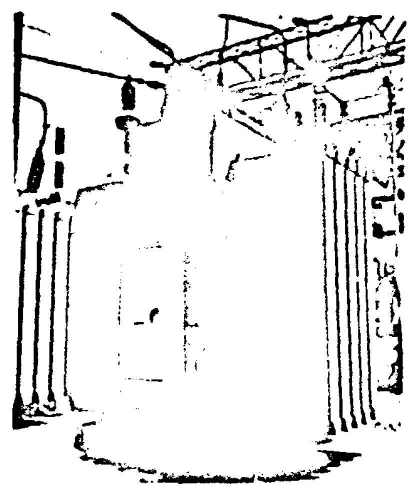

Fig. 4. View of transformer to be treated.

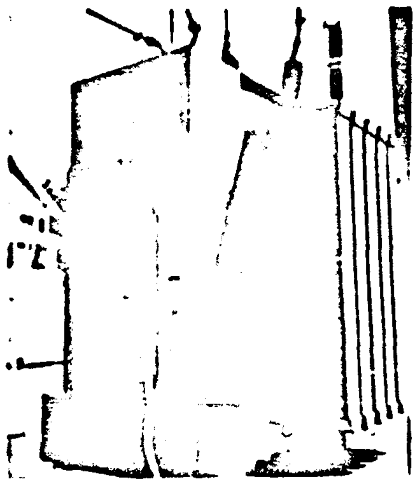

Fig. 5.
View of transformer with nearly completed enclosure. Opening between enclosure and foundation remains to be closed.

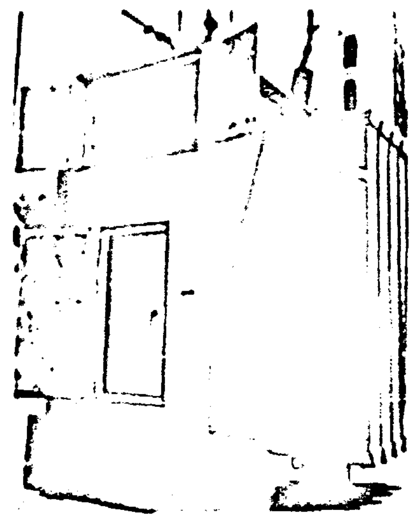

Fig. 6.
View of nearly completed enclosure showing access to control devices. Individually removable panels and pump housings provide occasional access to interior.

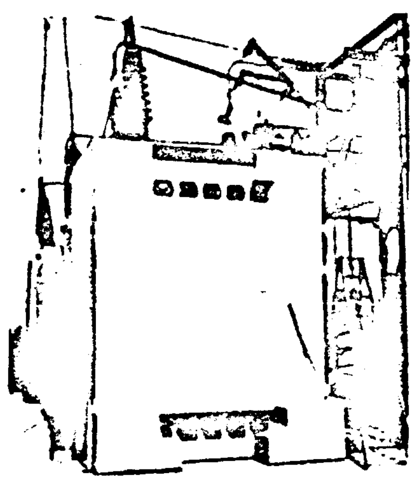

Fig. 7.
Side view of enclosure showing intricate fitting around radiator valves.

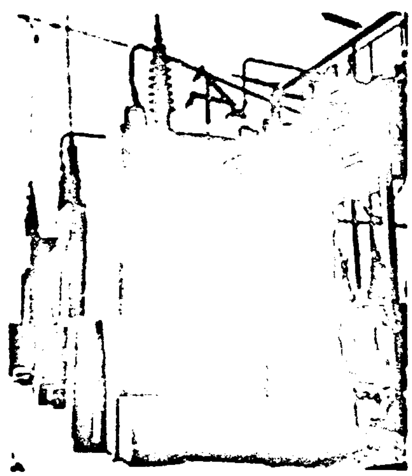

Fig. 8.
Side view showing radiators in place. Clearance between inner radiator element and enclosure is approximately 1/16 inch.