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LEAD INDUSTRIES ASSOCIATION, INC.

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SOME OBSERVATIONS OF THE VIBRATION ISOLATION EFFECTIVENESS OF LEAD-ASBESTOS PADS*

"THE SUBWAY SYMPHONY WILL NOT BE HEARD TONIGHT.....OR EVER AT PHILHARMONIC HALL" (Fig. 1). That was the bold claim made by a Lead Industries Association announcement in the New York Times on the opening day of Philharmonic Hall in New York's new Lincoln Center for the Performing Arts. It appears that this is one claim that will not be refuted for years to come. In this paper I would like to review some experiences with railroad and "subway symphonies" that possibly serve as a background to this L.I.A. pronouncement.

Someone has told us that since 1925 the New York Central Railroad System has suggested that all new buildings along Park Avenue north of Grand Central Station be installed on lead-asbestos pads for protection against vibration caused by train passages. Thus, as representative examples, the Waldorf-Astoria Hotel, the new Union Carbide building and portions of the new Pan-Am building over Grand Central Station rest on these pads. And, as you probably know, these pads have been used under numerous other buildings in this country and abroad.

For several years our company, and I'm sure many structural and mechanical engineering firms, have been interested in actual data on the vibration reduction provided by lead-asbestos pads, but it was not until February, 1959, that we were given the opportunity to measure an installation. Working for the architectural firm of I.M. Pei and Associates, we measured the railroad-induced vibration levels in Montreal's Queen Elizabeth Hotel (mounted on lead-asbestos pads) and compared these with vibration levels in a non-isolated 3-floor 50 ft. high concrete structure, the Dorchester Street Bridge, in front of the Queen Elizabeth Hotel. As seen in Figure 2, both of these structures are located directly over a large array of depressed tracks of the Central Station of the Canadian National Railways, and it was possible to measure vibration simultaneously in side-by-side isolated and unisolated building columns (such as at Points "A" and "B" in Fig. 2) for train passages ranging as close as 17 ft. and as far as 220 ft. from the columns. (Incidentally, each single dashed line shown in Figure 2 actually represents two rails in the track bed.) The tape recording you are about to hear is the amplified signal from a vibration pick-up mounted on one of these columns during a train passage on a nearby track (TAPE RECORDING).

*Presented at the 35th annual meeting of the Lead Industries Association, Inc., Drake Hotel, Chicago, Ill., April 29-May 1, 1963

Look Ahead with Lead

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When a column or a beam or a concrete slab or a wall of a building vibrates in this way, it radiates sound that can be heard; or if it vibrates with sufficient intensity, it produces vibration that can be felt. It is important to realize that we can hear the radiated sound of a vibrating structure at lower intensities of vibration than we can feel. It is also important to realize that for earth-borne and structure-borne vibration, the low frequency vibration is transmitted quite well, but higher frequency vibration is more easily absorbed within the structure and is not so well transmitted. Thus, railroads and subways typically produce rumbling sounds when heard inside nearby buildings that are connected by structural paths to the railroad or subway tracks.

We would like to illustrate this point on the frequency content of the vibration or the radiated sound by replaying the last tape recording, but listening only to certain "filtered" parts of the total signal. The original recording that we have already heard contained the full audio frequency range of the signal—from a low frequency of about 20 cycles per second (cps) up to a high frequency of about 10,000 cps. For the "filtered" signal, we will first hear only the 20-75 cps portion, then the 75-150 cps portion, then the 150-300 cps, 300-600, 600-1200 and 1200-2400 cps portions. In most practical situations, the vibration energy contained in the lowest 3 or 4 of these frequency bands is usually of most concern; the higher frequencies are absorbed or dissipated before they travel very large distances. The sounds that we hear may be represented graphically by the vibration level traces shown in Figure 3 (TAPE RECORDING).

Vibration data may also be plotted as shown in Figure 4 to show the general distribution of vibration levels as a function of the frequency bands that we have just heard. Each point in this plot represents the average vibration level in a given frequency band for a particular train passage. In this graph, the vibration was recorded from an unisolated pick-up point at Position "C" on Figure 2. That point was selected because we wanted to learn something about the vibration produced by trains passing over switch joints. The resulting levels are several decibels higher than for conventional track sections without switches. In addition, because of the presence of curved track in this array, some "wheel squeals" were also recorded and are shown in Figure 4.

Following this brief introduction to the basic characteristics of railroad vibration as it manifests itself in buildings, let us return to the discussion of lead-asbestos pads. Figure 5 shows schematically a vertical section through the Queen Elizabeth Hotel and the Dorchester Street Bridge. The isolated and unisolated columns used for vibration measurements are also shown. The actual detail of the isolation joint of the hotel columns is much more complex than indicated in this sketch, because all the underground portion of the column base must also be protected against earth-borne pick-up.

In Figure 6 we plot the difference between the vibration levels in the bridge and in the hotel columns for the low frequency band 20-75 cps. These levels were recorded for column positions just a few feet above track elevation. Note that this plot includes a train passage for each point on the graph, and that trains were recorded for several different distances from the pick-up locations. The difference values shown in Figure 6 are an indication of the isolation effectiveness of the lead-asbestos joints, although these values probably also include some effects of other differences, such as geometry and structure, between the two buildings. Somewhat similar plots were obtained for other frequency bands, but we will not go into the details of those plots here. An interesting effect shown by the data of Figure 6 is that the isolation joint seems to be more effective for the larger horizontal distances than for the shorter distances between the train track and the column involved. This is a rather complex phenomenon and it may be related in some way to the relative amounts of vertical vs horizontal vibration in the earth at increasing distances from the track and the relative isolation capability of the lead-asbestos pads for vertical and horizontal components of vibration.

On a floor position one floor above the tracks (at elevation 92 ft. in Figure 5), the Figure 7 data were obtained. This plot probably represents a more realistic picture of the effect of column isolation because the measurement positions include a more composite collection of several possible horizontal and vertical paths between the train tracks and the measurement positions. Here it is seen that in the frequency bands of 20 to 300 cps, the vibration levels in the isolated structure are about 5 to 12 db lower than in the unisolated structure.

Based on this and some other supporting data from the Montreal tests, we have tentatively assigned about 8 db as the average value of low frequency isolation that was achieved by the 1 inch thick lead-asbestos pads used under the Queen Elizabeth Hotel.

The typical construction of a 1 inch thick lead-asbestos pad is as shown in the section of Figure 8. Two 3/8 inch thicknesses of asbestos, separated by a steel stiffener sheet, are contained within a 1/8 inch thick lead jacket, which is sealed closed while the entire assembly is held under a pressure of about 200 psi. The area of the pad can be made to fit the column base requirements, although for very large bases, several pads may be laid side by side to make up the total area. In typical installations the surface loading on the lead-asbestos pads falls in the range of about 500 to 1000 psi. For a pressure of about 1000 psi, the pad compresses about 1/8 inch from the original nominal 1 inch thickness.

In the case of the Queen Elizabeth Hotel, "millboard asbestos" was used. The short fiber asbestos used in millboard requires the addition of binders to hold the fibers together into the mat form and this results in an asbestos material that is only 88% asbestos content by weight. The longer fiber "roll fire felt" more nearly holds itself together without binders and thus is 99% asbestos content by weight. Since the asbestos fibers are the principal resilient element in the pad, we believe it is worth the small extra cost to use "roll fire felt asbestos".

Before leaving the Montreal scene, we wish to mention that certain portions of the Cruciform Building, now known as the Royal Bank of Canada Building, and other smaller buildings in the same Place Ville Marie Development* (all located over or nearly over the array of tracks of Figure 2 between the Tunnel Entrance and the Dorchester Street Bridge) were installed on lead-asbestos pads and the results have

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* A project of Webb and Knapp (Canada) Ltd.

Architects:	I. M. Pei and Associates
Associate Architects:	Affleck, Desbarats, Dimakopoulos, Lebensold, Michaud and Sise
Structural Engineers:	Brett Ouellette Blauer Associates
Structural Engineering Consultants:	Severud-Elstad-Krueger Associates

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been very gratifying. (For a short time a few weeks ago, during the early morning commuting period, I was in one of the new buildings two floor levels directly above the two tracks that come out of the tunnel entrance, and I was not able to hear or feel any train passages, although admittedly I was in a fairly noisy corridor for these observations. The architects corroborate these findings.)

Let us now return to the "subway symphony" at Lincoln Center's Philharmonic Hall*. The next tape recording is the sound of a subway passage as heard inside the subway tunnel shown in the cut-away section of Figure 9. The nearest track in this tunnel is about 56 ft. from the corner of Philharmonic Hall and about 150 ft. from the nearest inside seating area of the Hall. There are four tracks in the tunnel: two locals and two expresses. The local stop is just off the bottom of the figure, so one local is slowing down and the other local is speeding up during the passage beside Philharmonic Hall, while the expresses pass through at normal speed. A train passes by on each track about every 4 or 5 minutes during evening operation (TAPE RECORDING).

One of the design requirements set early in the history of the new Philharmonic Hall was: "There must be no subway noise inside the Hall!" This has served as a guiding principle in the design of the structure of the building. The basic design features incorporated into the building to control earth-borne and structure-borne subway noise and vibration have included (1) the use of lead-asbestos vibration isolation pads under all columns of the building, (2) the insertion of a vibration isolation joint in many of the exterior and interior walls and partitions at or near the basement level, and (3) the use of a "resilient" lining, consisting of glass fiber pads and washed, graded crushed stone around all underground exterior walls on the north and east sides of the building facing the subway.

Excavation work at the site of Philharmonic Hall was started in 1959, and by October 1961 the basic concrete structure of the building was essentially completed. At that time a subway vibration measurement program was carried out at the building to determine the effectiveness of the vibration isolation designs. At the time these measurements were made, the exterior glass walls of the building, many of the interior partitions of the buildings, and the doors of the main hall were <u>not</u> installed. Thus, it was not possible to achieve a sufficiently low background noise level inside the hall to even expect to hear subway noise. However, with the use of very sensitive vibration measurement equipment, it was possible to detect subway passages that would normally not be heard by ear, even in a very quiet environment. Knowing the amount of the structural vibration, it was possible to calculate approximately the amount of noise that would be radiated by that vibrating structure. We were also able to compare the noise and vibration levels with levels that had been previously measured in this same location before Lincoln Center was even started, and other comparisons could be made with levels measured in Carnegie Hall which was known to be bothered by subway noise.

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*A project of Lincoln Center for the Performing Arts, Inc.
Architects: Harrison and Abramovitz
Structural Engineers: Ammann and Whitney

A large number of measurement positions were located within the dotted region of the building, ranging in elevation from the basement (which is at about the elevation of the subway tracks) up to an elevation one floor above the orchestra floor seating area. The orchestra floor is about 35 ft. above subway track elevation. More than 150 subway passages were recorded; most of these were recorded simultaneously at two or three different positions.

Figure 10 serves as a sample to show the locations and the vibration levels in the 75-150 cps frequency band for 15 of the measurement positions in the building proper but outside the auditorium area. Note that for most positions, two directional components of vibration are shown. The numbers shown in the circles are the median values obtained from several subway passages. For these tests the vibration levels are given in decibels above 10^{-6} g acceleration. We will not go into detail on the interpretation of these levels at this time.

Figure 11 serves as a sample to show the locations and the vibration levels in the 75-150 cps frequency band for 5 measurement positions inside or near the main hall. Position 17 was in the stage area, Position 18 was at a poured concrete wall near the edge of the main hall (this wall is enclosed by another interior wall in the completed hall), and Position 19 was in the forward part of the orchestra floor seating area, representative of those seats nearest the subway.

The measured subway vibration levels at Position 19 in the seating area nearest the subway are plotted as a function of frequency in the lower shaded area of Figure 12. These levels are seen to be about 10 db below the "vibration criterion" levels that were set for the hall. This means that subway passages cannot be heard inside the main hall even during the quietest background when the orchestra may be preparing for recording sessions. Even though these measurements were made nearly a year before Philharmonic Hall was opened, the data gave the assurance that the vibration levels were satisfactorily low. We believe no one has heard a subway passage inside the auditorium area since its completion.

Also shown on Figure 12 is a plot of some earlier vibration levels obtained in Carnegie Hall for nearby Seventh Avenue subway passages. These were definitely audible inside the hall.

One other significant comparison is shown in Figure 13. In 1958 an establishment known as Harvey's Bar occupied the corner of the present site of Philharmonic Hall, near the subways. In Figure 13 the upper shaded area gives the vibration levels measured at a wall and a floor position in the basement of Harvey's Bar about 53 ft. from the nearest subway tracks. The lower shaded area gives the range of vibration levels measured at four positions in the basement of Philharmonic Hall not more than about 6 to 10 ft. from the original measurements in Harvey's Bar. On the average, the vibration levels in the basement positions of Philharmonic Hall range about 15 to 30 db lower than those for the similar location in Harvey's Bar. The distance to the subway tracks is essentially the same for both groups of readings, so we believe the large improvement can be attributed to the new construction. We do not know how much of this difference might be due to the more massive construction of Philharmonic Hall, but we believe that the column isolation joints, the wall isolation joints, and the "resilient" lining of the exterior underground walls all share a large part in achieving the lower vibration levels.

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This report gives only a very brief summary of the data obtained in this measurement program, but the results do indicate a significant reduction in subway noise and vibration compared to what would have been expected for conventional construction.

From these results we have tentatively assigned a value of about 10 to 15 db for the low frequency vibration reduction achieved with the use of lead-asbestos pads and the remainder of the isolation design. We wish to mention, however, that the thickness of the pads used at Philharmonic Hall is 3 inch* for a group of columns nearest the subway and tapers off in approximately 1/4 inch steps each 30 ft. further removed from the subway. In addition, we emphasize that the entire building was carefully designed and constructed to assure that no rigid connections would bridge the isolation joints and short circuit the effectiveness of the pads. In order to achieve the full capability of lead-asbestos pads, or of any isolation material, it is always necessary that careful attention be given to these details, both in the design and in the execution of the design.

In reviewing the Montreal and the Lincoln Center work, we have mentioned noise reduction values of 8, 10 and 15 db. What do these values mean to us in actual real-life situations? In the next tape recording we will listen to the structure-borne vibration signal of a typical train passage. In the middle of the first train passage we will introduce a 3 db signal reduction for a few seconds so that we can get a personal feeling for the magnitude of a 3 db change. We will then replay the same train passage and introduce a 10 db signal reduction; and in the final replay we will introduce a 20 db signal reduction (TAPE RECORDING).

We might summarize those signal changes as follows:

1. The 3 db change was just noticeable but was not large enough that we would be impressed by the change. If we had a serious noise or vibration problem, a 3 db reduction probably would not be enough to solve the problem.

2. The 10 db change was a significant reduction and would represent a noticeable improvement in the intruding noise that might be heard in an office, restaurant, hotel, hospital, apartment or retail shop. This improvement is worth achieving. It could make an intolerable situation tolerable or a tolerable situation acceptable. In a typical good installation of lead-asbestos pads, this amount of noise reduction can be achieved. Another way of judging the effectiveness of such an installation is illustrated by the fact that railroad or subway noise heard, for example, on the second floor of an isolated building would probably be heard all the way up to the fourth or fifth floor of an unisolated building.

3. The 20 db change was a dramatic change and would usually be sufficient to eliminate a most serious noise or vibration problem. We caution that a conventional installation of lead-asbestos pads alone probably will not achieve this amount of improvement, although it might be possible to attain this with very special vibration isolation designs involving lead-asbestos pads plus other isolation treatments.

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*Made up of stacks of thinner pads with a maximum thickness of 1 1/2 in. for any one pad.

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One other major caution that we wish to mention is that the information given here represents but two buildings of hundreds that have been so isolated. We feel that we must continue to be conservative in our claims and cautious in our designs involving lead-asbestos pads until we have more data on more actual field installations. Hence, we urge a conservative use of the data that we have presented here.

In bringing this review to a close we will hear next a tape recording that was obtained in a very nice restaurant in New York City located directly above a subway line (TAPE RECORDING). And now we will hear a subway passage as recorded in our own office at 101 Park Avenue in New York City, which I estimate to be about 80 ft. above the subway track (TAPE RECORDING).

From these recordings I believe we can realize that any major city having railroads, subways, elevateds and expressways and feeling the pinch of crowding buildings closer and closer together probably has need for protective measures against the intrusion of noise and vibration caused by our various transportion systems. We have evidence that lead-asbestos pads can play an important role in this problem area.

Acknowledgment

The work of the acoustics consultant in the railroad and subway vibration aspects of the two major projects described in this paper consisted of evaluating the intensity of the noise and vibration problem and setting certain basic guidelines for the protection of the critical parts of buildings against the intrusion of the noise and vibration. The real work of developing the designs and incorporating them into the building structures has been the job of the architects and the structural engineers. There are many individuals who share in that work, but I want to especially recognize those with whom I worked for I know they had difficult and important roles in the designs of the buildings. For the Cruciform Building in Montreal, this includes Henry Cobb and Don Gorman of I.M. Pei and Associates, John Brett and Roger Nicolet of Brett Ouellette Blauer Associates and Fred Severud of Severud-Elstad-Krueger Associates. For Philharmonic Hall, Dan Sella of Harrison and Abramovitz and Tyge Hermansen of Ammann and Whitney were instrumental in working out the actual isolation designs, and Joe Tilney of Harrison and Abramovitz and A.J. Allio of Fuller-Turner-Walsh-Slattery gave the essential care and supervision at the job site that produced the successful results.

LIST OF FIGURES

4. Typical range of vibration levels measured at unisolated Point "C" of Figure 2 for train passages over nearby switches and curved rails.

5. Schematic vertical section of bridge and hotel structures showing relative locations of columns used in vibration measurements.

6. Measured difference in vibration levels between hotel and bridge columns at 20-75 cps for various distances to train tracks. Vibration in isolated hotel column is lower than in unisolated bridge column.

7. Measured difference in vibration levels between hotel and bridge structures one floor above tracks for typical track activity below and to the side. Vibration levels in hotel always lower than in bridge structure for the same train passage.

8. Section of typical 1 inch thick lead-asbestos pad.

9. Approximate location of Philharmonic Hall in relation to subway tracks in tunnel under Broadway.

10. Section through Philharmonic Hall approximately along Building Line 12 (see Fig. 9), showing vibration measurement positions and general location of isolation joints. Circled numbers are median subway-induced vibration levels, in db re 10^{-6} g acceleration in 75-150 cps frequency band, for horizontal or vertical components.

11. Measurement Positions 17, 18 and 19 inside and nearby Positions 14 and 16 just outside the main hall.

12. Comparison of measured vibration levels at orchestra seating Position 19 with criterion levels and Carnegie Hall levels.

13. Comparison of measured vibration levels at approximately the same location in 1958 and 1961.

LOG OF TAPE RECORDINGS

1. Vibration record of train passage (overall).

2. Vibration record of train passage.
   Overall, 20-75, 75-150, 150-300, 300-600, 600-1200, 1200-2400 cps.

3. Subway passage as heard in 65th Street Station at Philharmonic Hall.

4. Train passage with 3 db, 10 db, 20 db signal changes.

5. Subways as heard by structural paths in Stouffer's restaurant.

6. Subway as heard by structural paths in BBN-New York office, 80 ft. above track.

FIGURE 1 will not be heard tonight...or ever at Philharmonic Hall

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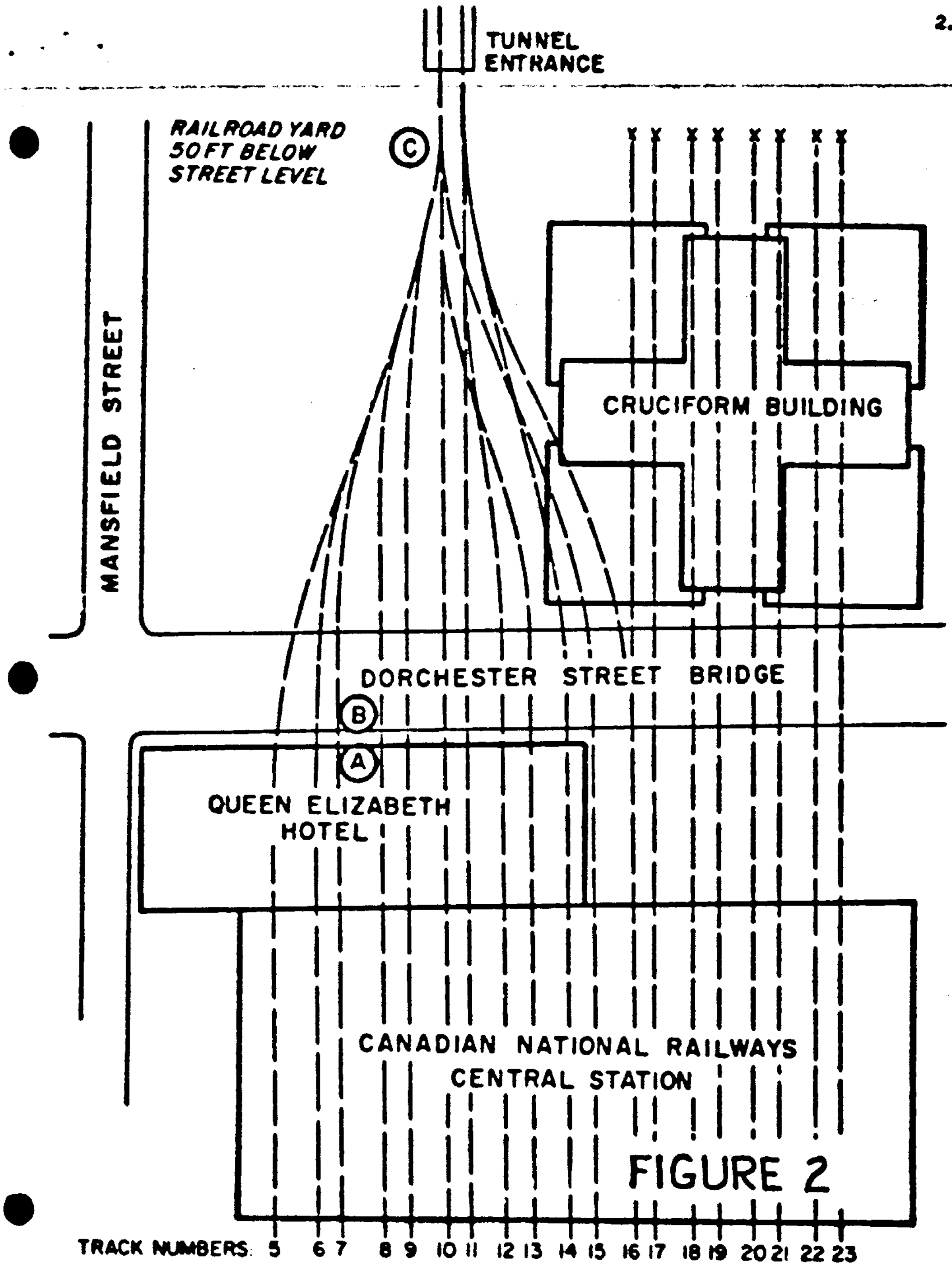

FIGURE 2

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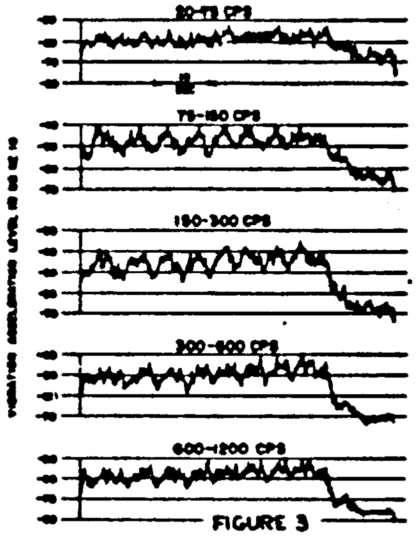

FIGURE 3

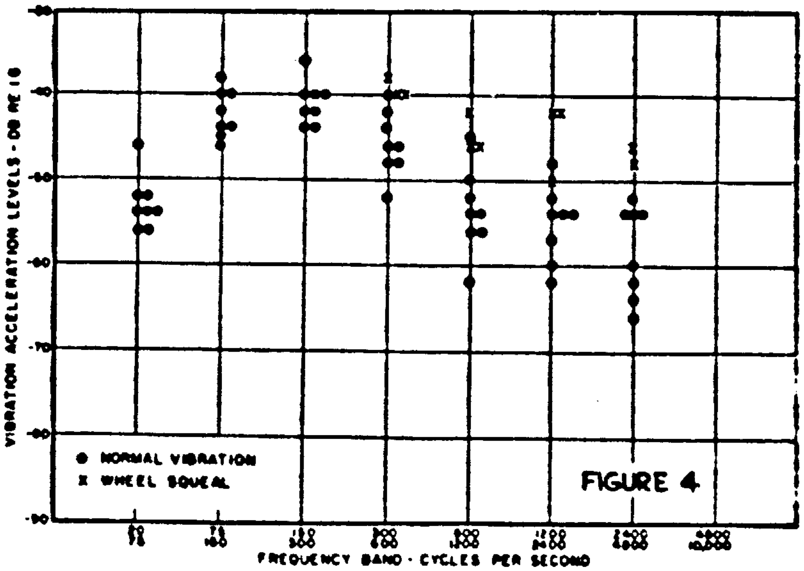

FIGURE 4

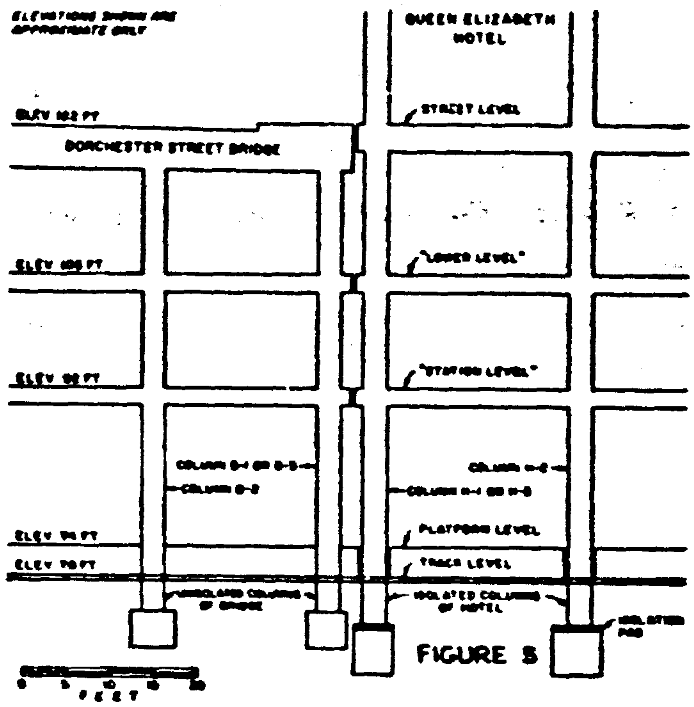

FIGURE 5

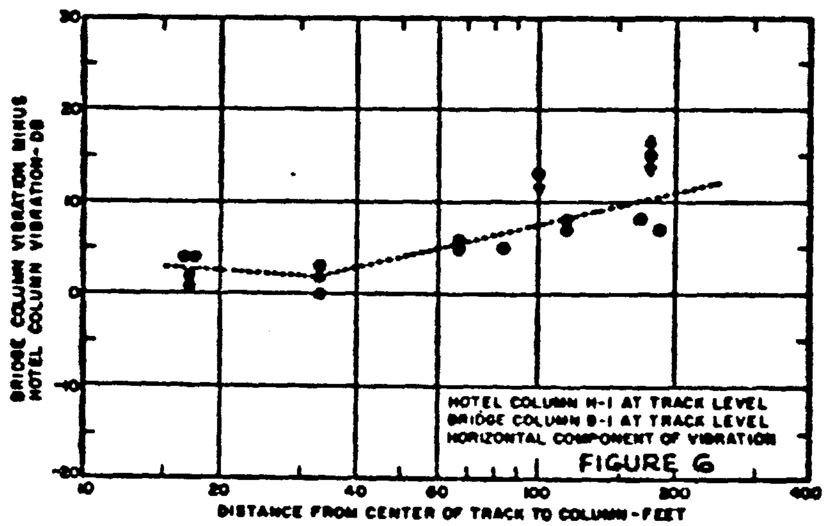

FIGURE 6

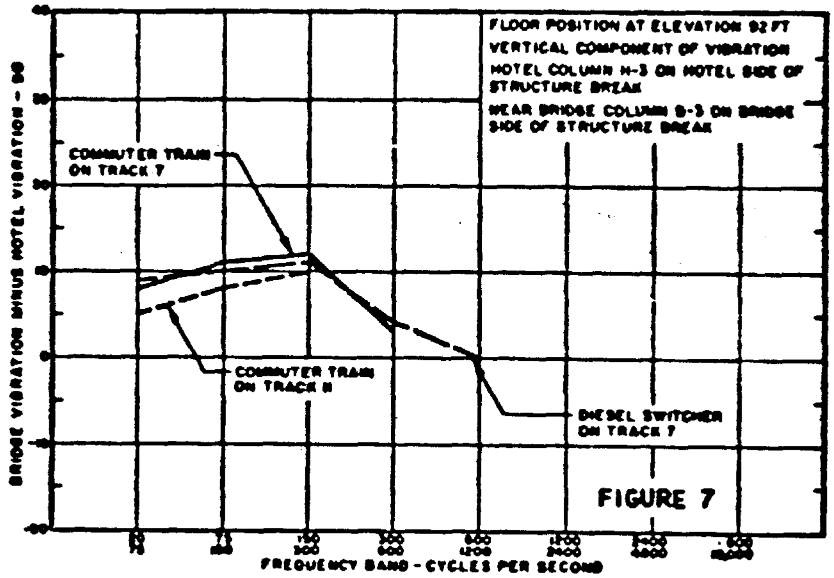

FIGURE 7

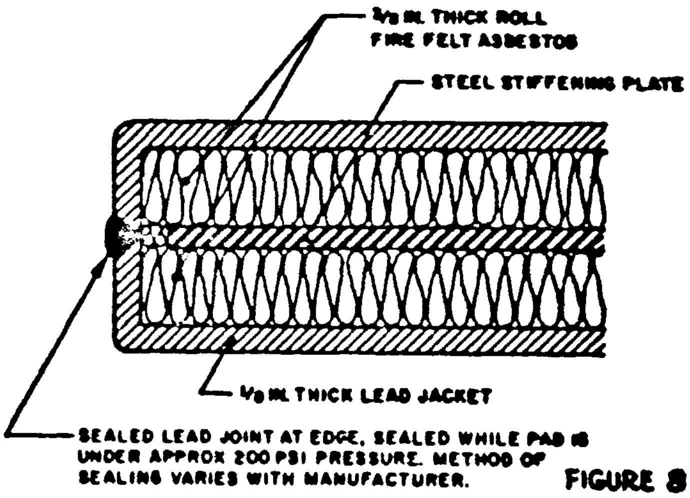

FIGURE 8

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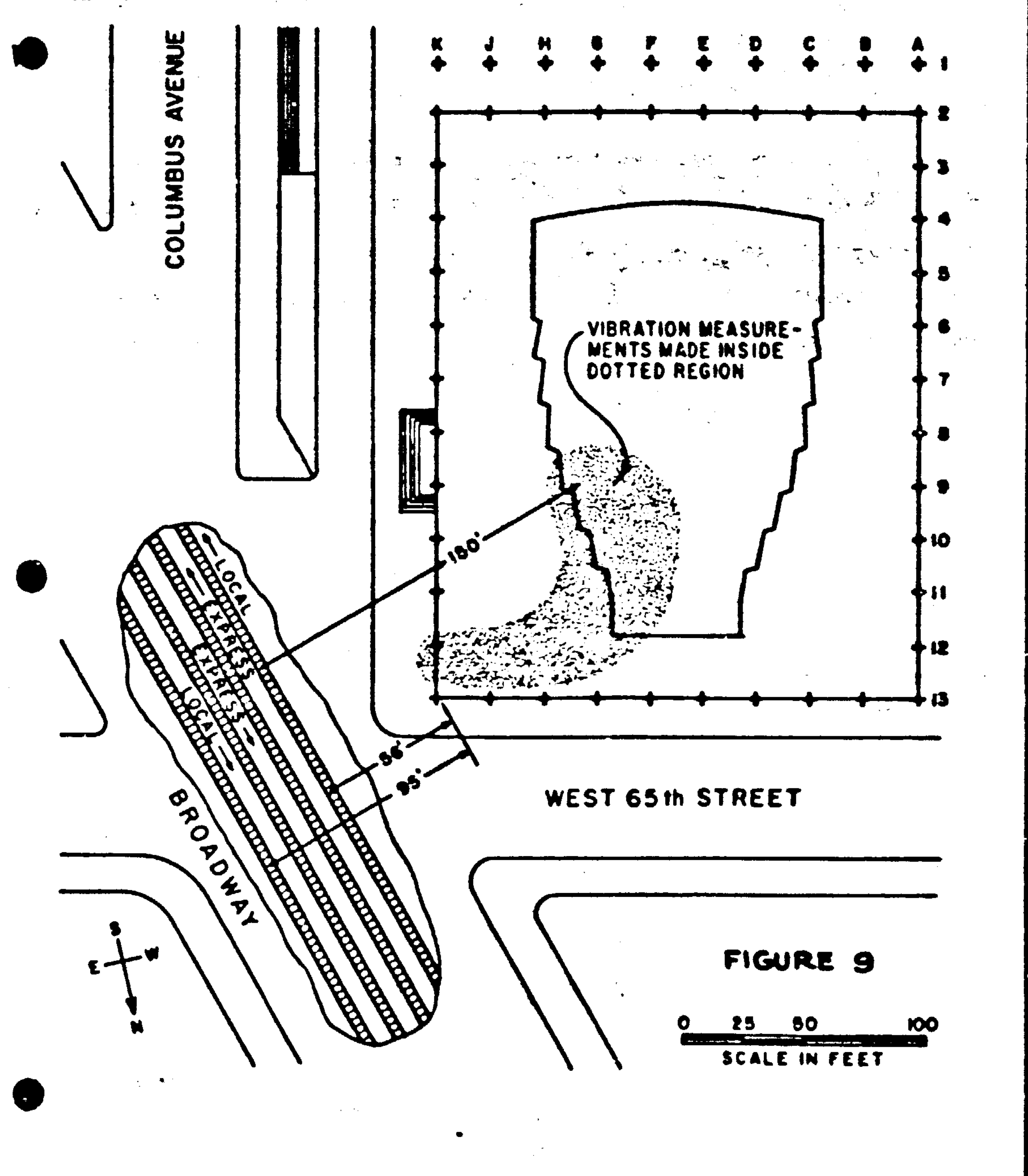

FIGURE 9

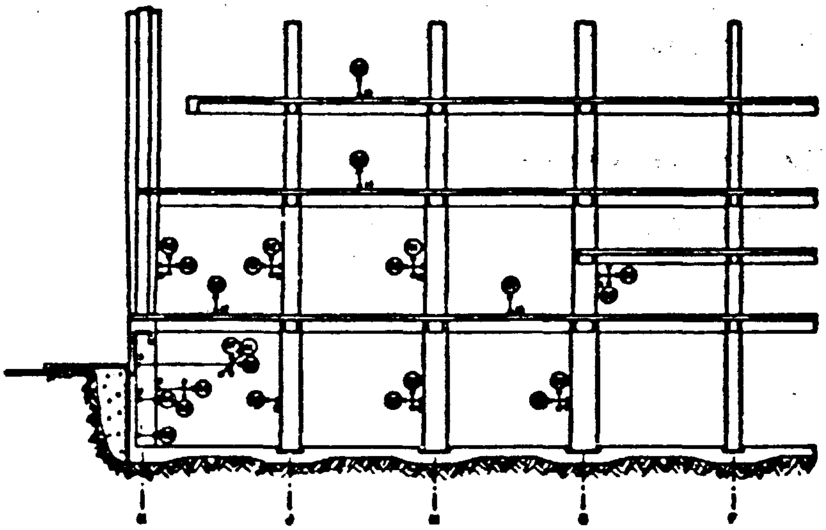

FIGURE 10

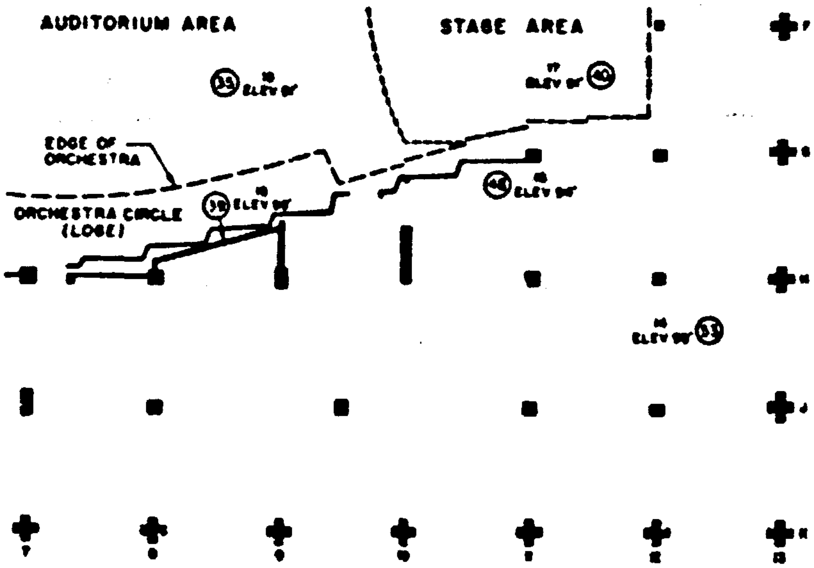

FIGURE 11

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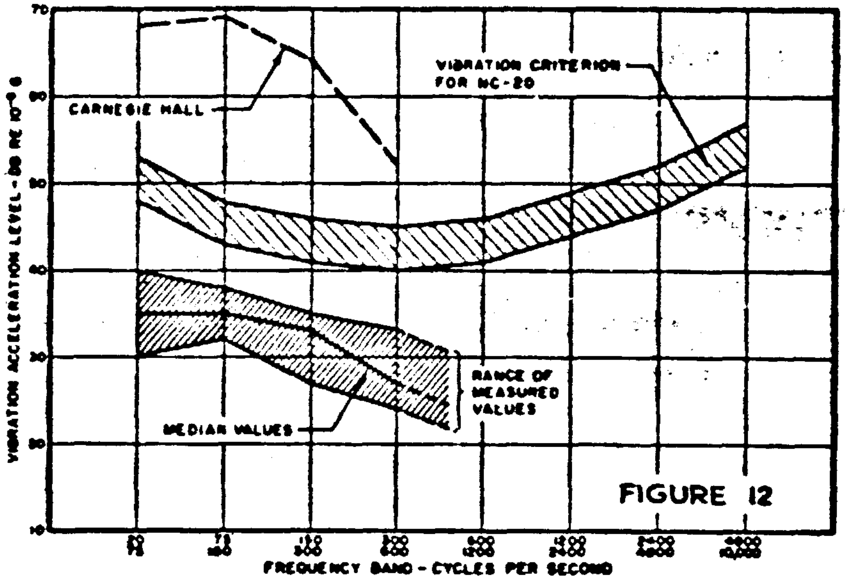

FIGURE 12

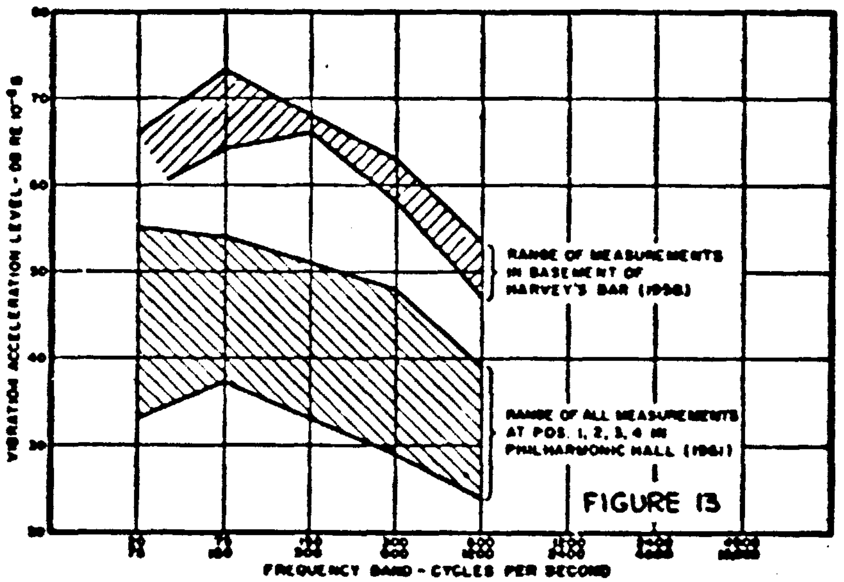

FIGURE 13