Control of Toxic and Explosive Hazards in Buildings Erected on Landfills

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RAPID URBAN GROWTH during the past quarter century has made the reclamation of old refuse landfills economically attractive. These areas often represent a major fraction of the remaining open urban land that is available for residential, commercial, and industrial use. Their value lies not only in the scarcity of open land in a mature city, but also in the fact that often the once-remote dump site becomes enclosed by a high-grade residential and commercial neighborhood. Conversion to recreational uses, such as parks and golf courses, has long been considered an acceptable end use for completed refuse landfill sites, and this practice is still continuing in Los Angeles and many other communities.

Nevertheless, the urgent needs of cities for increased tax revenues have tended to reserve many landfills for commercial use. When buildings are erected on old landfills, however, care must be taken to prevent migration of toxic and explosive gases from the subterranean fill to the interior of the building. When buildings are first erected, seepage of carbon dioxide may become a problem, but within a few months only methane is likely to be a major cause for concern.

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Based on previous studies of old landfills that were converted to recreational areas, Eliassen (*1*, *2*) concluded that organic matter in landfills continues to decompose for periods longer than 30 years. He reported that 4-year-old landfills gave off gases of decomposition having the following average analysis: carbon dioxide, 28 percent; methane, 56 percent; nitrogen, 15 percent; and miscellaneous, 1 percent.

The presence of a high percentage of methane makes the gases combustible and explosive when mixed with the correct proportions of normal air. Also, when the decomposition gases enter an enclosed or partially enclosed space, they may exclude oxygen and make the resulting atmosphere incapable of supporting human life. For this reason, it is generally advocated that provision be made for gas-tight floors and adequate ventilation of sub-basement spaces when buildings are constructed on sanitary landfill areas.

Recent studies by Merz and Stone (*3*) on closely controlled experimental landfills composed of typical domestic refuse (paper, grass, garbage) showed fluctuations in gas composition with time and with depth of fill. Carbon dioxide concentrations were found to be as high as 75 percent by volume, and Eliassen's figure of 56 percent methane was confirmed at depths 15 feet below the surface. Merz and Stone also found that carbon dioxide tended to decrease and methane to increase with age of the fill over a period of 825 days, but they did not predict the total time required to complete destruction

of all the organic matter. Virtually no hydrogen or hydrogen sulfide was found.

Barker (*4*) indicated that the formation of methane in decomposing organic materials results from the action of a special group of microorganisms called "methane bacteria." These organisms are strict anaerobes and are distinct from aerobic methane-oxidizing bacteria which oxidize methane to carbon dioxide and water. Only four species of methane bacteria belonging in three genera (*Methanobacterium omelianskii*, *Methanobacterium formicicum*, *Methanosarcina barkerii*, and *Methanococcus vannielii*) have been isolated in pure culture. An additional four species (*Methanobacterium suboxydans*, *Methanobacterium sohngenii*, *Methanomonas methanica*, and *Methanococcus mazei*), although not firmly established, may also belong to this group.

Barker showed that the methane-producing bacteria appear to be restricted to the use of relatively simple organic and inorganic compounds, such as fatty acids, alcohols, hydrogen, carbon monoxide, and carbon dioxide. Thus, the conversion of trash and garbage to methane in a landfill seems to be a multistage biological process in which some micro-organisms break down complex cellulose, proteins, fats, and so forth into the simple molecules that can be converted to methane by the methane bacteria. Eliassen (*1*) confirmed the presence of a rich flora in sanitary landfills. He recorded up to 975 x 10^6 fungi and 73 x 10^6 bacteria per gram of dry fill after 9 to 18 months and substantial, though lesser, numbers in 4-year-old, undisturbed fills.

Pure culture studies indicate that methane-producing bacteria are most active in the pH range from 6.4 to 7.2 (*4*). Eliassen's data, covering a 3-year period, show pH measurements below the surface of finished sanitary landfills (2–10 feet deep) ranging from 5.3 to 8.5, with a mean close to the neutral point (*1*). Thus, conditions below the surface of refuse fills covered with 6 feet of clean dirt are ideal for the growth of methane-producing bacteria; that is, ample numbers of other organisms (fungi, for example) to convert complex organic molecules to simple substances, complete absence of oxygen, and a suitable hydrogen ion environment.

The dangers associated with building on sanitary landfills are becoming more generally known and, fortunately, opportunities for modifying building structures on the drawing board are increasing. Nevertheless, we believe the potential toxic and explosive hazards in buildings are more widespread than commonly assumed. Within a period of a few years, we investigated marsh gas fires inside the projection house of a drive-in theater and methane-filled cellars in residences adjacent to a large sanitary landfill. Two of our other investigations, of a housing development and a theater erected on refuse-filled land, are described in detail below.

Housing Development

A 27-building public housing development, containing 1,500 family units, was constructed on filled land. The composition and age of the fill varied considerably in different locations. In some areas the fill had been added fairly recently and the material was rich in fermentable and putrescible organic matter (for example, garbage), while in other areas a relatively inert fill had been laid down many years ago.

During construction of the buildings (three-story and seven-story apartment houses) a crawl space of approximately 3½ feet was left between the landfill and the basement floor. The foundation walls totally enclosed from 7 to 12 separate crawl-space compartments under each building. Individual compartments varied in size from 500 to 7,500 cubic feet in volume, and there was no gas exchange between the compartments.

On the advice of a consultant, a 3-inch concrete slab was poured directly on top of the fill under each building after construction was well along toward completion. It was anticipated that the concrete slab, resting on the fill and meeting the foundation walls, would be effective in sealing out all gases generated in the fill. Because concrete is somewhat porous for gases and also because cracks in the slab might occur from settling, tests for explosive and toxic gases were considered a wise precaution before the building was occupied.

Of the gases which might be present in the sub-basement crawl spaces, the following were considered the most significant for the purposes of our investigation: oxygen, carbon dioxide,

combustible gases, hydrogen sulfide, and carbon monoxide.

Carbon monoxide is not formed during the decomposition of fill, but the presence of this gas would indicate that illuminating gas was seeping into the sub-basement spaces. If illuminating gas were present, it would react similarly to methane concerning the measurement of combustible gases and it also would tend to displace oxygen and produce an asphyxiating atmosphere. It would be important to distinguish between gases formed from decomposition of the fill and illuminating gas leaks because the remedy for excessive concentrations would depend on the source.

The following criteria were used to evaluate the safety of the crawl spaces under the project buildings.

Oxygen. Concentrations below 17 percent were unsatisfactory because this percentage is considered the lowest value at which man can do physical work with full mental alertness for an extended period. This criterion was important for the maintenance crews because they had to enter the sub-basement areas for repair work.

Carbon dioxide. Concentrations above 2 percent were considered unsatisfactory because they indicated excessive seepage of decomposition gases into the crawl spaces.

Combustible gases. The criterion of safety was considered to be 50 percent of the lower explosive limit of methane, which is 2.5 percent methane by volume.

Carbon monoxide. The presence of carbon monoxide in any concentration was considered unsatisfactory because this indicated excessive seepage of manufactured city gas into the crawl spaces.

Hydrogen sulfide. The presence of hydrogen sulfide in any concentration was considered unsatisfactory because this indicated excessive seepage of gases into the crawl spaces.

Preliminary Survey

About 15 months after the foundations were poured, an initial survey was made. Five buildings were selected as a sample for the preliminary testing. Each building had been erected on different kinds of fill: recent refuse fill, wood from 1938 hurricane, long-standing refuse fill, peat with recent refuse fill, and peat and fly ash.

The following methods and instruments were used to test each of the gases. Oxygen and carbon dioxide analyses were made with Bacharach instruments, based on the Orsat principle of gas analysis. A known volume of air in a sealed chamber was treated by chemical absorbents to completely remove the gas to be measured, and the change in volume provided a direct measurement of the volume of gas removed. Carbon monoxide and hydrogen sulfide were measured with Draeger detector tubes. Combustible gases were measured with combustible gas meters, MSA model 40 and Davis model M–6.

Complete Survey

The results of the preliminary survey indicated a need for further testing. Therefore, the crawl spaces beneath all the dwelling units, the powerhouse, and the administration building were tested. Of a total of 29 buildings surveyed, 15 were found completely satisfactory and 10 completely unsatisfactory. One building bordered between satisfactory and unsatisfactory, and two buildings had satisfactory crawl space compartments at one end and unsatisfactory spaces at the other end. For one building it was not possible to obtain satisfactory samples because there was no access to the crawl spaces from the manholes in the basement floor.

Deficient atmospheres containing only 10 percent oxygen and as much as 6 percent carbon dioxide were found at the completely unsatisfactory locations. Combustible gases between 20 and 24 percent of the lower explosive limit (LEL) were found under three buildings, and concentrations between 10 and 20 percent of the LEL were found under three others. Oxygen deficiency, excessive carbon dioxide, and the presence of combustible gases were noted with each unsatisfactory building. Hydrogen sulfide was not detected in any of the locations. Carbon monoxide was found in only one building, and it was traced to leakage from an illuminating gas service line.

We thought that temperature in the sub-basement crawl space might be an important indicator of the presence of decomposing or fermenting refuse. Measurements made on May 1 showed crawl-space temperatures ranging from 61° to 71° F. However, there appeared to be no significant trend of temperature with respect

to satisfactory or unsatisfactory gas concentrations. When the data were rearranged according to compass direction, a definite trend toward higher temperatures was noted for the spaces on the east and south sides of buildings; these were the sides having the longest periods of exposure to the sun. Based on this information, we concluded that crawl-space air temperature was not important in determining the presence or absence of gases of decomposition.

To determine the rate at which carbon dioxide and combustible gas (methane) were increasing and oxygen was decreasing, the air in two sub-basement crawl spaces in one of the most unsatisfactory buildings was completely cleared with a portable air blower. One of these spaces was flooded with 4 to 6 inches of water and the other was left dry. The gas composition in both spaces was tested 1, 2, 5, 7, 11, and 23 days later. In the first 24 hours after the spaces were resealed, there was a decrease of 2.0 to 2.5 percent in the amount of oxygen present and an increase of 2.0 to 2.5 percent in carbon dioxide content. On subsequent days, the oxygen content increased somewhat and the carbon dioxide decreased until the concentrations appeared to stabilize—oxygen at about 19 percent and carbon dioxide at about 1 percent. Combustible gas reappeared only after 5 days, and for the rest of the observation period it remained at the threshold of detection. No important differences were noted between the flooded space and the dry space.

The tests indicated that (*a*) a column of water several inches high was incapable of holding back the gases generated in the fill under the crawl-space concrete slab, and (*b*) the crawl-space atmosphere was in equilibrium with that in the earth and fill beneath. Therefore, when the spaces were ventilated and closed, the gas concentration on both sides of the sealing slab came to equilibrium in a few hours. Before ventilation, the gases were in equilibrium at an oxygen concentration of 12 percent, a carbon dioxide concentration between 5.0 and 5.5 percent, and a combustible gas concentration between 22 and 24 percent of the lower explosive limit. After ventilation of the crawl space, there were only enough of the gases stored in the fill material to produce the equilibrium concentrations noted above, and the rate of production of gas at that time was too slow to increase noticeably the volume of gases available over the 23-day test period.

From the experiment, we concluded that the rate of increase of decomposition gases in the fill would be quite slow, but this conclusion remained valid for only a short period. Six months later, following the first summer of occupancy, explosive atmospheres were detected in two of the buildings and concentrations in excess of 50 percent of the LEL were found in five others. Six additional buildings showed (*a*) methane concentrations between 10 and 50 percent of the LEL, (*b*) less than 17 percent oxygen, and (*c*) more than 2 percent carbon dioxide. These 13 buildings represented nearly 50 percent of the 27 apartment houses in the development.

The sub-basement areas containing dangerous atmospheres were cleared by displacing the gases with outdoor air blown into the spaces. A small axial-flow, skid-mounted fan (Coppus Vano SM–175 Blower, ½ hp motor) on casters was used for this purpose. The fan could be wheeled by hand from building to building and lowered to basement level on the baby-carriage ramps. The blower delivered 1,500 cfm when equipped with four 25-foot lengths of 12-inch diameter flexible hose (Flexhaust Co., New York City), and it discharged a jet of high-velocity air into the remote corners of the crawl spaces.

Tests indicated that occasional ventilation would be inadequate because a small number of crawl spaces required ventilation about once a week to maintain thoroughly satisfactory conditions. Although all the unsatisfactory spaces were in one general area of the housing development, the distribution within the area was not uniform. In several instances a space which rapidly refilled with methane immediately after being ventilated would be flanked by spaces which contained little or no combustible gas. At first we believed that this curious situation resulted from differences in thickness and porosity of the sub-basement slabs which, according to the contractors, were poured under adverse conditions. Also, by this time the fill in many areas had settled considerably and we thought this might have been a contributory factor.

Sealing Floor Slabs

In attempting to find an inexpensive, easy-to-apply method of making the concrete sub-basement slabs gas proof or sufficiently gas proof so that the ventilation schedule could be reduced to once in 3 to 6 months rather than weekly, we conducted a series of experiments. We believed that if a satisfactory method could be found, it would be less expensive than installing mechanical ventilation equipment and would have the added advantage of requiring little or no maintenance. We therefore attempted to make a gas-tight barrier between sub-basement and fill by treating four sub-basement crawl spaces in one of the following ways.

Space 1. All joints between foundation walls, pillars, and sub-basement slab were filled with two applications of Flintkote C–13–A asphalt emulsion.

Space 2. An entire sub-basement slab was treated with two applications of Flintkote C–13–A asphalt emulsion.

Space 3. An entire sub-basement slab was treated with a single application of Flintkote No. 70 asphalt emulsion. (Both asphalt water emulsions were recommended by the Asphalt Institute and by the Flintkote Co. for this service).

Space 4. An entire sub-basement slab was treated with two applications of water glass (sodium silicate).

Five days after the applications, the atmospheres in treated and adjacent nontreated sub-basement spaces were tested for the presence of combustible gases. We found that the applications had had no appreciable effect. Theorizing that the coatings may not have had sufficient time to dry before the spaces became filled with gas again, we ventilated the treated spaces once more and retested 3 days later. Substantial quantities of combustible gases were found during these tests also, and we concluded that treating the sub-basement slabs to make them gas tight was not a practical procedure.

Merz and Stone (*3*) reported gas pressures ranging up to 13 inches of water gauge in their experimental sanitary landfill pits. It is not clear from their report whether these excess pressures arose from gas-production activity, expansion of the gases because of heating (temperatures as high as 158° F. were measured in their anaerobic pits), or atmospheric pressure changes. Any or all of these factors, as well as the effects of wind pressure and tidal variations on subsurface water levels at the ocean-side site of the housing development, provide an adequate explanation for the rapid seepage of gases through the treated concrete floor slabs.

Rate of methane diffusion in sub-basement spaces of buildings erected on refuse landfills

Clock time	Elapsed time since ventilation (minutes)	Percent lower explosive limit (ventilated for 1 hour prior to start)
14:10	0	0
14:45	35	3. 5
15:00	50	6. 5
15:35	85	16. 0
20:30	380	105. 0

Gas Data

The gas data were studied closely to ascertain the effect of tides and rainfall. No significant or consistent effect from these natural phenomena was noted on the concentration of combustible gases in the crawl spaces. The possibility that tides and rainfall might influence gas concentrations could not be ruled out, however, because of the over-riding influence of relatively large reservoirs of gases below the buildings. Other factors, including temperature and secondary bacterial reactions, also affected gas-producing processes.

During the second spring and summer of building occupancy, methane production increased markedly. From April to July, dangerous concentrations were found a total of 62 times in 22 sub-basement spaces. In August, the third year. During May of the third year, methane production began to decrease and it continued at a reduced but highly significant level through fall, winter, and early spring of gas concentrations suddenly increased again and methane readings averaged three times those of April. Methane generation again reached a peak during July and August. By this time measurements had been conducted long enough to show a definite seasonal variation in

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combustible gas concentrations in the sub-basement spaces.

Each year combustible gas concentrations increased in early spring and peaked during July and August, and then they slowly declined until minimal readings were noted during January and February. We believe that the seasonal variations were associated with subsurface temperatures in two ways: (*a*) rising temperatures in the spring stimulated microbial activity and increased gas production, and (*b*) higher underground temperatures increased the pressure of the existing gas reservoirs against the floor slabs and thereby increased upward seepage.

During the first 3 years of building occupancy, progressive changes in gas composition were noted. At first the sub-basement spaces which held abnormal gas concentrations showed as much as 8 percent carbon dioxide, as little as 10 percent oxygen, and less than 1 percent methane. Obviously, the air in the sub-basement spaces was being displaced from below by concentrations of gas containing approximately 20 percent carbon dioxide and 0 percent oxygen.

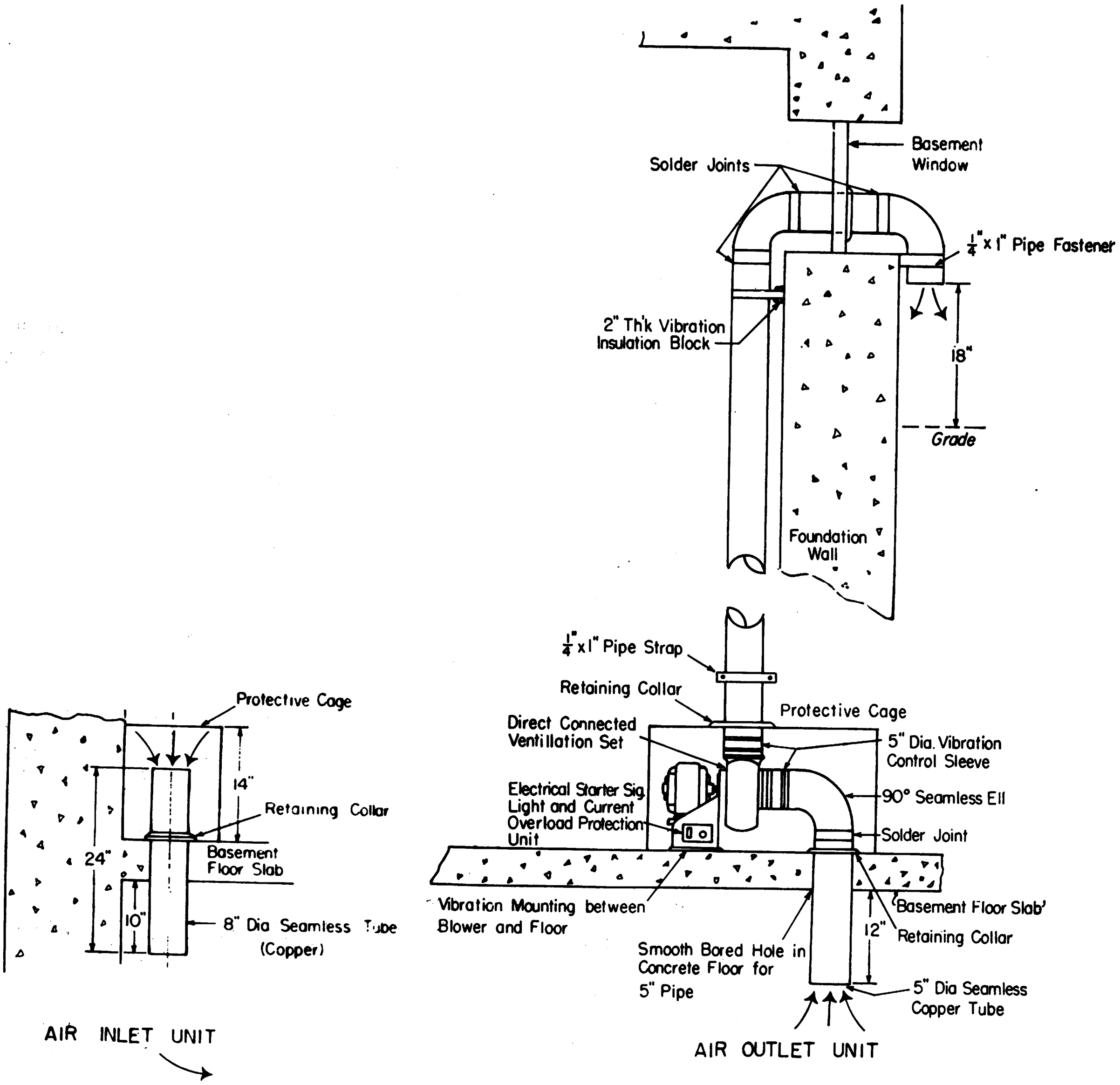

Figure 1. Sub-basement mechanical ventilation equipment

Six months later, oxygen concentrations had increased to 17 percent or more, carbon dioxide had decreased to 1.5 percent, and methane had increased to 5 percent or more.

Theoretically, when the foundations were backfilled a quantity of air was mixed with the partially rotted fill and trapped below the sub-basement floor slabs. The deeper, undisturbed layers of fill were likely to have remained anaerobic and to have continued the production of methane by methane-producing anaerobes. When the methane diffused to the upper layers of fill, where oxygen was present, the aerobic methane-using bacteria were able to convert it to carbon dioxide. This accounts for the presence of high carbon dioxide concentrations soon after construction was completed. After some months had elapsed all the trapped air was stripped of its oxygen, and from then on methane production predominated.

Mechanical Ventilation

The rate of methane seepage into 19 of the sub-basement spaces located in five different buildings was so rapid during the second and third years of the housing development's existence that repeated use of the skid-mounted fan became a distinct burden on available service personnel. The rapid rate of methane diffusion in certain sub-basement spaces during this period is shown in the table. Six hours after the spaces containing explosive concentrations

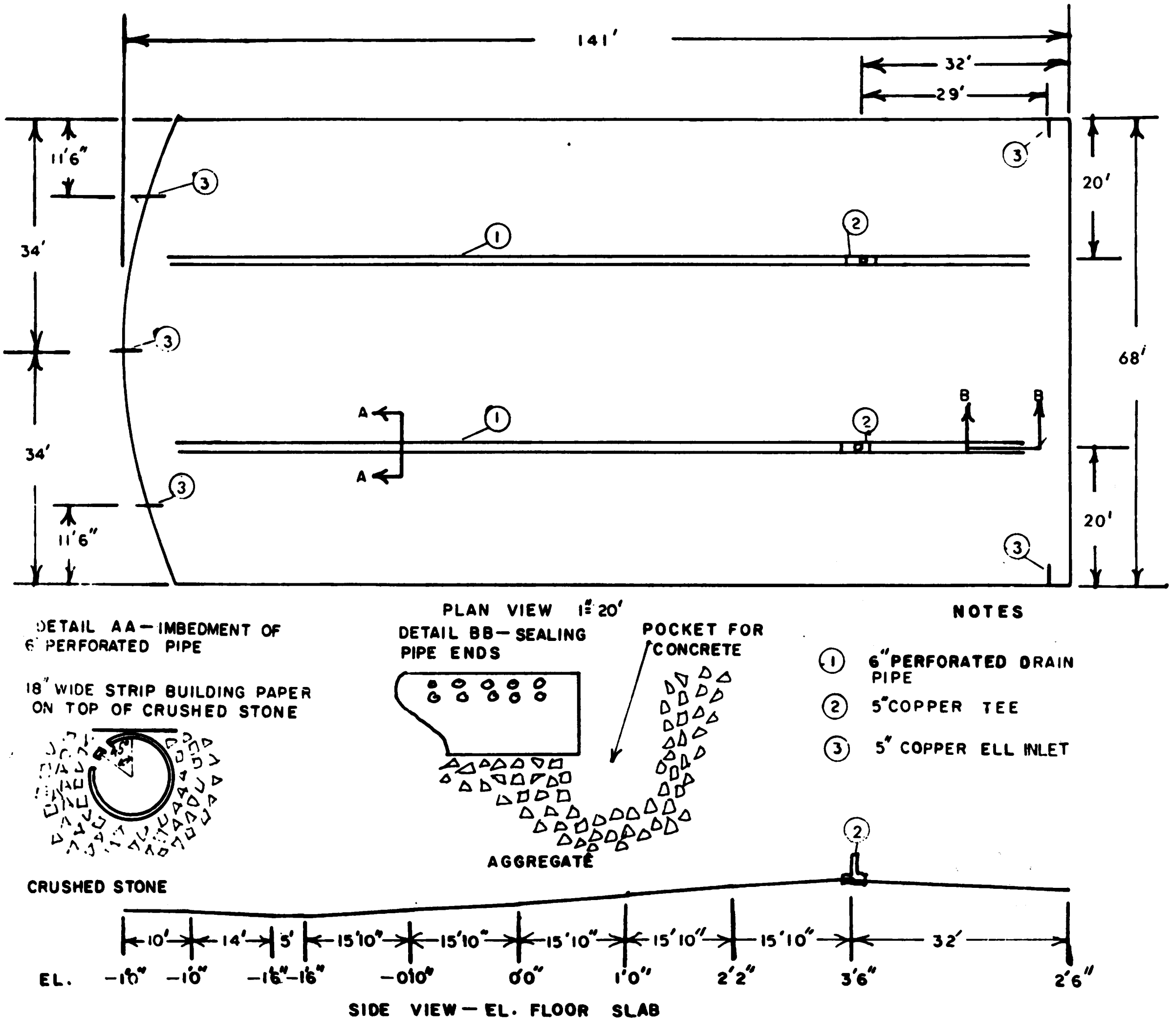

Figure 2. Outline of theater built on reinforced concrete floor slab over layer of crushed stone

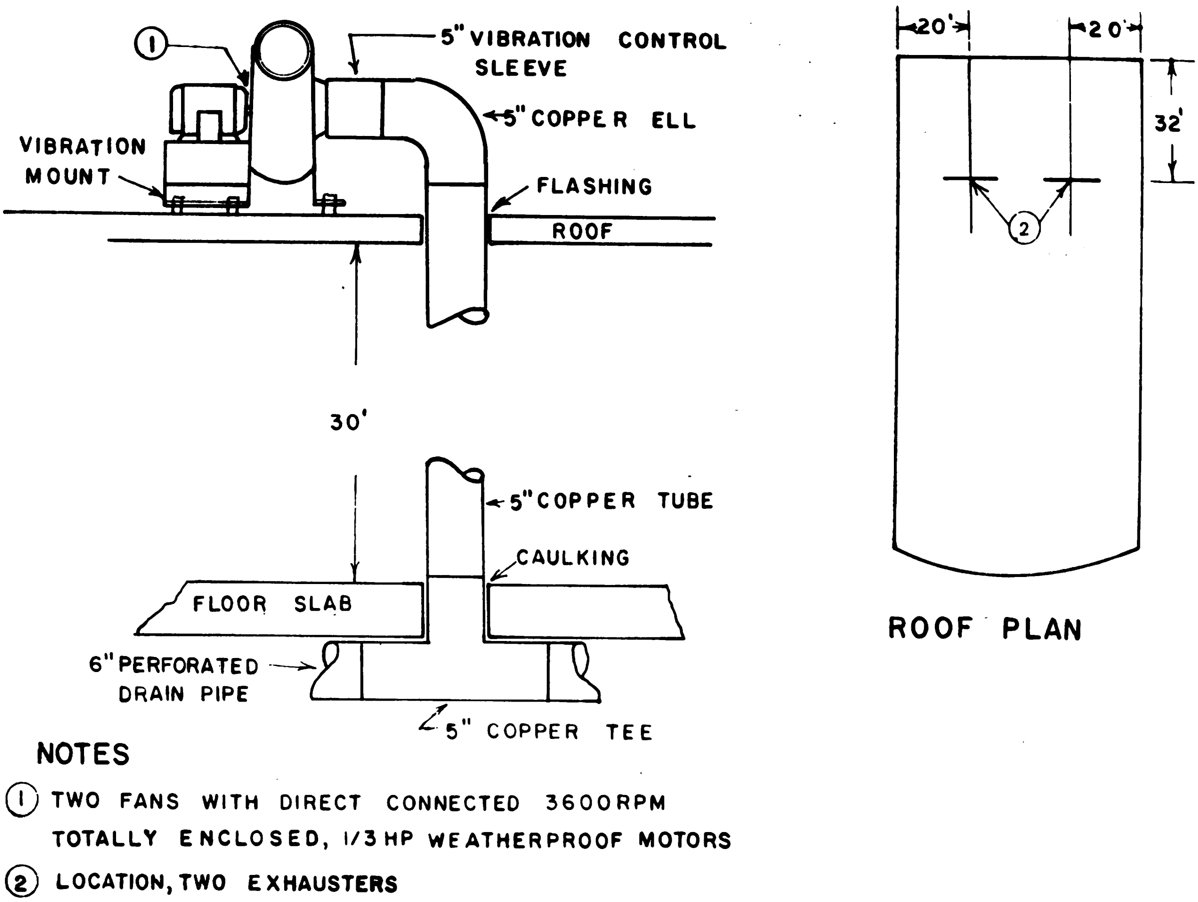

Figure 3. Section view of air exhauster on roof of theater

of methane were thoroughly flushed with air, the explosive concentrations were again present. We therefore decided to ventilate these spaces continuously with individual, automatically operated centrifugal blowers.

The mechanical equipment used and the manner in which it was applied are shown in figure 1. The inlet and outlet units were installed at opposite corners of the ventilated space so that incoming air would sweep across the entire area. Access to the sub-basement spaces was through 5-inch diameter holes drilled, with diamond-tipped hole cutters, through the 6-inch thick floor slabs of reinforced concrete. Pilferage was discouraged by enclosing the ventilation equipment in locked steel cages. The ventilation blowers equipped with nonsparking wheels were capable of exchanging 150 cfm, sufficient to provide approximately two air changes per hour. Although 150 cfm is not a large ventilation rate, it proved adequate to prevent accumulations of detectable quantities of combustible gas.

Decline in Gas Evolution

Three years after initial occupancy the rate of gas evolution began to decline. After 5 years no significant gas concentrations were detected, even when the ventilation blowers were turned off. In all, continuous testing extended over 7 years. Eliassen's prediction that 30 or more years would be needed for complete decomposition of landfills (*1*) was not confirmed at this location. Two possible explanations are: (*a*) although it was believed that the worst gas conditions occurred over areas of most recent rubbish fill, the fill material may have been older than we assumed; and (*b*) heat transmitted deeply underground through the heavy concrete foundation walls of the tall apartment houses

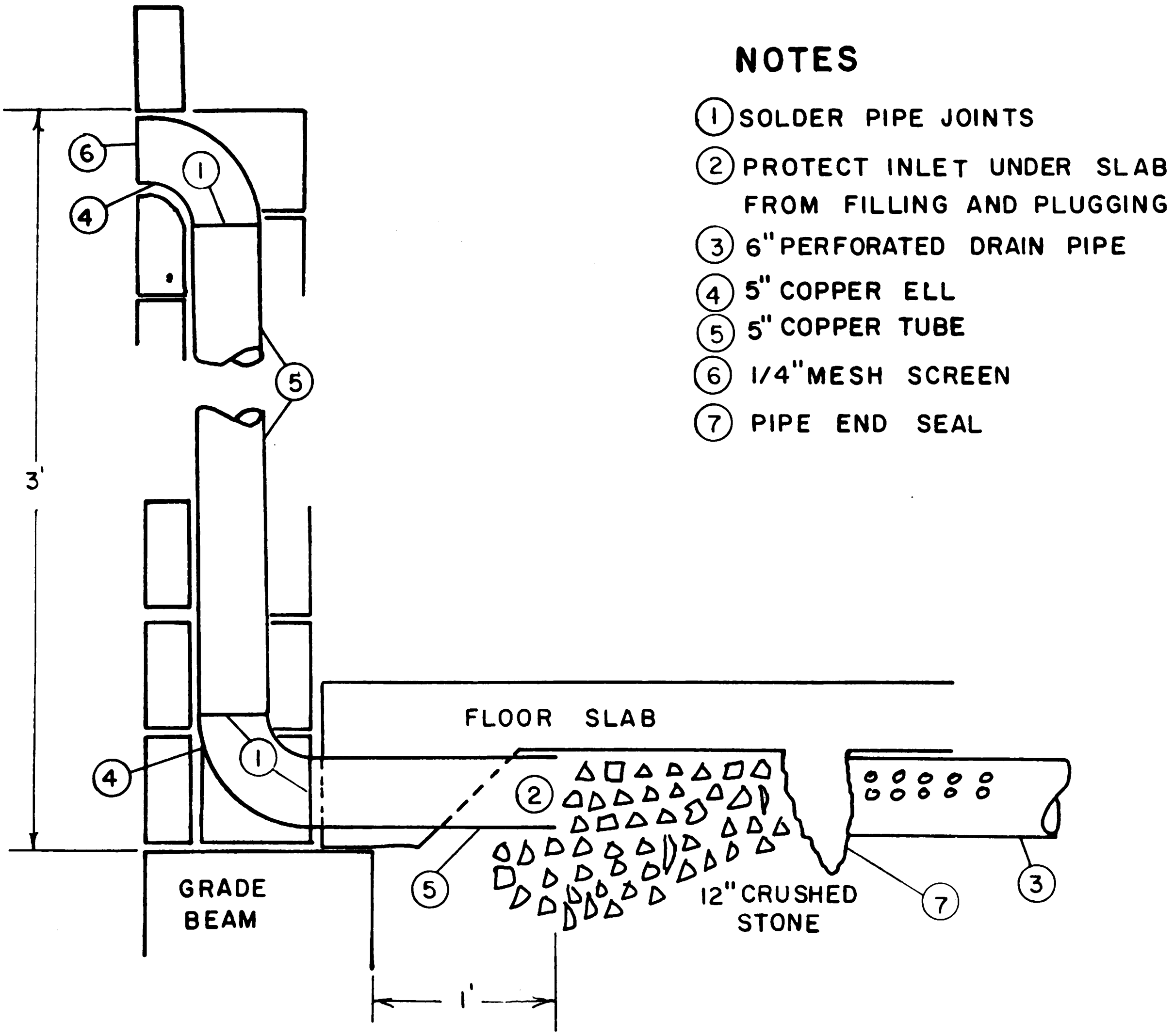

Figure 4. Section view of air inlets located in side walls of theater

may have greatly speeded up bacterial action, especially during the colder months of the year, and completed the decomposition of the fill material in a much shorter period. We favor the latter explanation.

Theater

The problems associated with building on refuse-filled land were recognized before construction began on the theater, and it was possible to include preventive measures in the design of the building. The basementless, 800-seat theater was built on a reinforced concrete floor slab over a layer of crushed stone. An outline of the building and the complex slopes of the floor slab, characteristic of theater construction, are shown in figure 2.

Based on our experiences at the housing development, we concluded that a poured concrete floor slab could not be depended on to hold back gas seepage arising from the decomposing refuse fill below, especially after the building settled and the floor cracked. Unlike the apartment buildings with large unobstructed sub-basement crawl spaces, the theater was erected directly on the ground over a thin layer of crushed stone. Venting the underslab area after the building was completed would be a formidable task. We therefore decided to include a mechanically operated underslab ventilation system in the building structure.

Two runs of perforated drainpipe, 6 inches in diameter, were embedded in the crushed stone fill of the underslab (fig. 2). The pipe was turned so that its perforations were about 45° to the side, and the top of the pipe was covered with strips of building paper to prevent the perforations from becoming filled with concrete when the floor slab was poured. Both ends of the pipe runs were sealed with concrete when the floor slab was poured (fig. 2), so that the perforations would be the only remaining openings. These openings would then act as restricting orifices in parallel and would draw in equal amounts of air along the entire length of the 120-foot-long pipelines.

Underslab gases were vented by two centrifugal exhausters located on the roof of the theater (fig. 3), and replacement air was drawn in under the slab from five vents located in the side walls of the structure (fig. 4). Each exhauster was rated for 350 cfm against a static resistance of 3 inches of water gauge and was equipped with a totally enclosed, weatherproof, direct-connected motor so that motor-drive enclosures were not needed. A pilot light for each unit was installed in the manager's office so that operation of the units would be under constant surveillance.

Summary and Conclusions

The principal hazard associated with construction on refuse-filled land arises from anaerobic production of combustible gases by methane-producing bacteria. Gas-tight construction over landfills appears to be difficult, if not impossible, because of gas pressures under the structure resulting from biological gas production.

During investigations of gas levels in a housing development constructed on sanitary landfills, unsafe methane concentrations were found in a high proportion of the buildings. A concrete slab laid on top of the fill did not prevent gases produced in the fill from penetrating into the buildings. Several sealants were tested and found inadequate.

The results of periodic gas samplings conducted over several years in the sub-basement spaces of a number of buildings indicated that organic fill located around and under heated buildings becomes completely degraded in approximately 5 years, releasing methane at a proportionately rapid rate. This produces a severe explosion hazard unless suitable methods of aerating and venting are employed. Continuous mechanical ventilation at a rate of one or two air changes per hour adequately reduced methane concentrations.

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