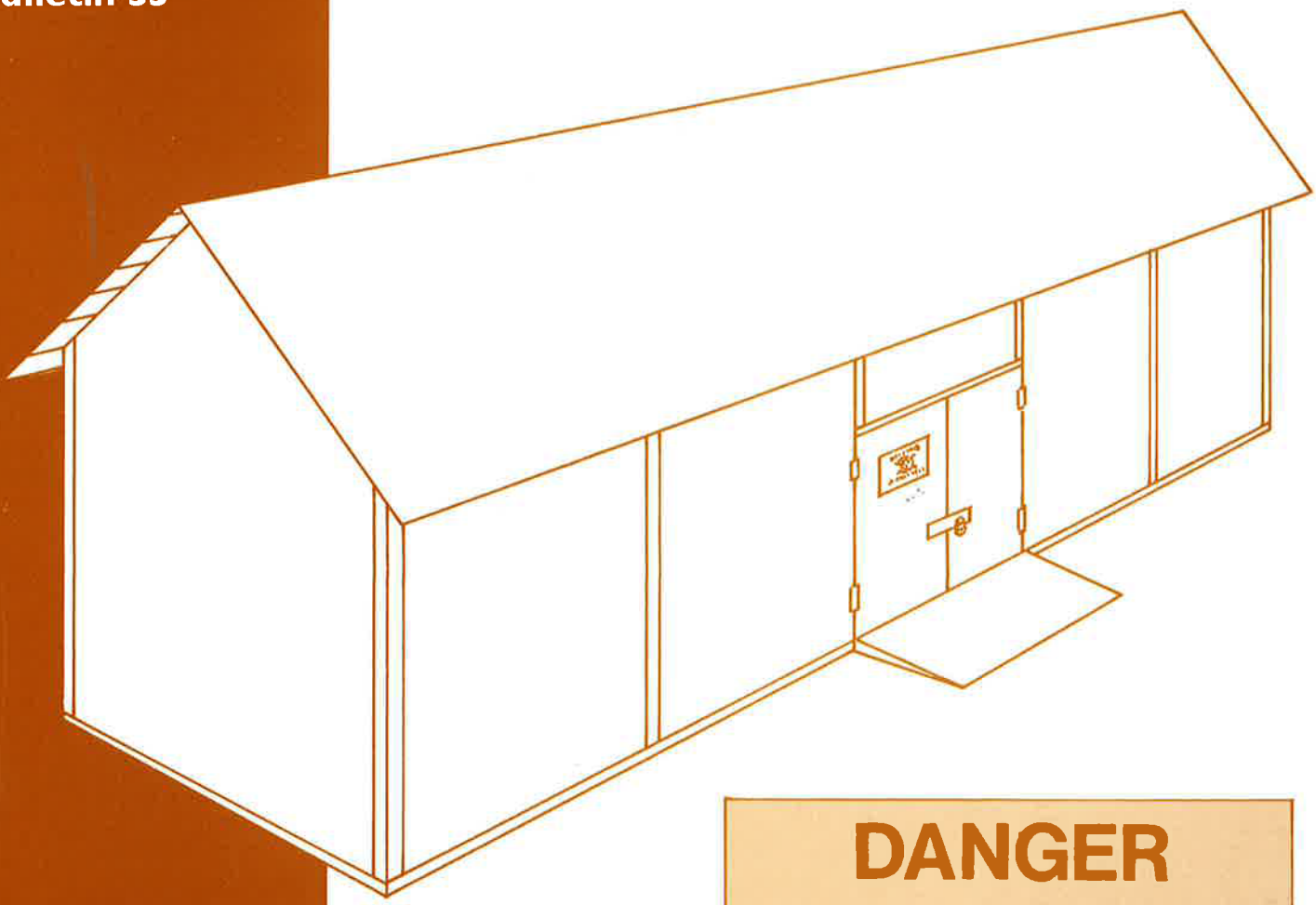
Natural Resources Institute

FUMIGABLE WAREHOUSES
DESIGN AND CONSTRUCTION

Bulletin 53



Overseas
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FUMIGABLE WAREHOUSES DESIGN AND CONSTRUCTION

A. J. K. Bisbrown

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The scientific arm of the
Overseas Development Administration

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Contents

Summaries

SUMMARY

In any grain storage system the control of insects is of paramount importance. The ultimate means of insect control is fumigation. Generally grain is fumigated by covering with a gas-proof fumigation sheet and using either methyl bromide or phosphine. An alternative to sheeting that is becoming increasingly popular is whole store fumigation. Such fumigations will only be successful if the warehouse is properly sealed and the fumigant gas concentration held at the appropriate level for a sufficient time to be lethal to insect pests.

Warehouses of conventional construction can be made fumigable by attention to materials and design. Particular attention is needed to ensure that the roof and walls and their junctions are impermeable to gas.

In this bulletin good design principles are specified and guidance is given on various materials used in the construction of fumigable warehouses. Procedures for carrying out successful fumigations are described.

RESUME

La lutte contre les insectes, dans tout système d'entreposage des céréales, présente une importance prépondérante. La fumigation constitue la méthode optimale pour lutter contre les insectes. la fumigation des céréales est en général effectuée en les recouvrant d'une bâche de fumigation étanche aux gaz et en faisant appel à du bromure de méthyle ou de la phosphine. Une solution alternative à la bâche et dont l'usage se répand de plus en plus, consiste à utiliser la méthode de fumigation de l'intégralité des magasins. De telles fumigations ne sont toutefois effectuées avec succès que si l'entrepôt est correctement étanchéisé et que la concentration du gaz fumigant est maintenue au niveau convenable, pendant une durée suffisante pour permettre la destruction des insectes.

La fumigation des entrepôts d'exécution conventionnelle est réalisable en accordant une attention particulière aux matériaux et aux études de conception. Une attention toute particulière est exigée afin de s'assurer que la toiture, les parois ainsi que leurs joints sont imperméables aux gaz.

Il est précisé dans ce bulletin d'excellents principes d'étude et des conseils sont fournis concernant les divers matériaux mis en oeuvre dans la construction des entrepôts pouvant faire l'objet de fumigations. Les méthodes permettant l'exécution de fumigations menées à bien sont décrites.

RESUMEN

Un factor de crucial importancia, dentro de todo sistema de almacenamiento de granos, es el control de los insectos, siendo la fumigación el método por excelencia para conseguirlo. En general, la fumigación de granos se realiza cubriéndolos con una lámina de fumigación a prueba de gases y aplicando bromuro de metilo o fosfina. Un método alternativo, que está adquiriendo una popularidad cada vez mayor, es la fumigación del entero almacén. Para que este tipo de fumigación resulte en una eliminación satisfactoria de las plagas, el almanén deberá contar con características de hermetismo apropiadas y será necesario mantener la concentración del gas a niveles apropiados y por períodos suficientes.

En la construcción de almacenes tradicionales a utilizar apra fines de fumigación, deberá prestarse atención al diseño y materiales utilizados y, en particular, a la necesidad de que su techo, paredes y uniones sean impermeables al gas.

En este boletín se describen buenos principios de diseño, a la vez que se proporciona orientación sobre diversos materiales utilizados en la construcción de almacenes fumigables. Se describen procedimientos para llevar a cabo satisfactoriamente operaciones de fumigación.

Fumigable warehouses
Design and construction

INTRODUCTION

Fumigations with methyl bromide or with phosphine are well established methods for controlling insect pests in stored commodities. With phosphine the practice of fumigation of a whole store, as distinct from fumigation under gas-proof sheets, is becoming increasingly popular in developing countries, especially for reserve or long-term storage. A main attraction is the simplicity of the procedure. It can be carried out by trained storekeepers without the necessity for fumigation sheets, sand-snakes and other equipment associated with under-sheet fumigation. Furthermore, it enables the fabric of the store to be disinfested simultaneously with the stock, thereby lessening the need for regular spraying with contact insecticides. A higher loading rate can be used because space around internal pillars and fixed machinery does not have to be left for sealing fumigation sheets.

However, there are very few stores that have been designed for this purpose; of these, some are incapable of retaining the critical level of fumigant gas over the period necessary for effective fumigation. There is ample evidence to show that under these conditions insects develop resistance to phosphine gas. The consequence is higher and more frequent dosages with the attendant environmental penalties.

In this bulletin building specifications are outlined with particular reference to the details and materials needed in newly built warehouses intended to be used for fumigation. It is intended to help store owners in briefing architects, engineers or builders. It is not a complete specification and will not replace local professional advice on construction. The principles described may also be applied in planning the upgrading of existing warehouses to allow whole-store fumigation.

A section on testing has been included, since any new or modified warehouse should be tested for gas-tightness before any fumigation of infested grain is carried out, and at set intervals during the working life of the store.

Phosphine is currently preferred for this type of fumigation. The gas is liberated during the fumigation from a solid metallic phosphide formulation, which is easily transportable, easily introduced into a store and relatively safe to handle until it reacts with the water in the air to produce phosphine. The release of gas is slow, continuing for approximately three days.

In view of the potential problems with insect resistance to phosphine, methyl bromide may need to be considered for whole-store fumigation, although to date there is only very limited experience of its use in this manner. An additional benefit is that methyl bromide fumigation is completed within 48 hours, which is useful for goods in transit and for export commodities. However, methyl bromide has to be stored and transported as a liquid under pressure in heavy cylinders, and it needs to be introduced into stores through pipework leading to the exterior of the store. The requirement for store sealing is similar to that for phosphine, but additional consideration should be given to the materials used, since methyl bromide in high concentrations is known to react with natural rubbers and is absorbed by oils.

FUNCTIONAL REQUIREMENTS

Gas retention

A fumigable warehouse must be able to retain a minimum concentration of gas for a specified period. For a successful phosphine fumigation the fumigant gas concentration should be greater than 0.2 mg/litre over a minimum of a 120 hour exposure period. With standard fumigation procedures using the normal dosage, this implies that no more than 10% of the phosphine in the store atmosphere should be lost each day of the fumigation.

General design considerations

The requirement to fumigate cannot be divorced from other warehousing considerations. Warehouses must provide safe storage conditions throughout the storage period and not only when fumigations are being carried out. The requirements include:

- protection against moisture:
  - (i) in air (r.h.),
  - (ii) from the ground,
  - (iii) penetrating rain, and
  - (iv) floods;
- protection against pests:
  - (i) insects,
  - (ii) birds, and
  - (iii) rodents;
- protection against heat:
  - (i) solar induced,
  - (ii) convected, and
  - (iii) internally generated (lights, machinery);
- easy inspection of the produce;
- provision for easy cleaning;
- provision of good working conditions;
- easy maintenance of the building;
- good handling;
- minimizing of operating costs; and
- minimizing of theft.

Design points to achieve these requirements include:

- warehouse sited above the floodplain;
- vapour-proof barriers (damp-proof courses) incorporated in the floor and walls to prevent rising damp;
- a watertight roof;
- adequate disposal of water from the roof;
- rainwater drainage from the surrounding area;
- hardstandings;
- adequate ventilation (for example, four air changes per hour);

- physical barriers to prevent entry of pests;
- the outside surface to be white or metallic to reflect solar radiation;
- sufficient size to allow adequately wide aisles and appropriate stack height;
- ledges (e.g. at wall openings and roof members) sloped with coving at corners to ease cleaning;
- bollards, ladders and easily replaceable parts to protect the building from accidental damage and to make maintenance easier;
- an adequate number and size of doors to allow 'first in – first out' stock rotation and easy handling; and
- security fences and guards.

Inevitably some of these requirements will restrict the ability to seal the warehouse, in particular the need for ventilators to reduce high temperatures. The design must be suitable for both normal use and the fumigation process. The design is therefore a compromise between having the warehouse permanently sealed and meeting operational needs. Any fumigable warehouse though, must be able to be sealed in order for a successful fumigation to be achieved.

BASIC DESIGN AND CONSTRUCTION

General

The general style of construction of a fumigable warehouse will closely follow that of any other warehouse: typically a framed building with solid walls and a pitched roof.

The building must be well constructed and so designed that the resultant enclosed envelope, after any temporary sealing, is sufficiently gas tight to retain the critical concentration of fumigant for the required length of time.

The elements of any building are:

- foundations,
- floor,
- walls,
- roof,
- access doors,
- ventilation, and
- services.

These together affect the integrity of the store, and each must be taken into account when considering the sealing of the gas-tight envelope.

Site selection

Apart from the usual considerations in site selection, extra attention should be given to exposure to wind. Since the transmission of fumigant gas out of the store will be helped by wind-induced pressure differences, a sheltered site is preferable. Loss of gas must be checked if high winds occur during the exposure period. The possible effects of neighbouring buildings and topography on airflow should be considered, as well as the need for ventilation of the warehouse when not under fumigation.

In any store, heat gain has to be reduced to a minimum. In fumigable stores, large temperature differences between day and night cause differential pressures to develop, so increasing loss of gas. The solar heat gain is influenced by the orientation of the warehouse as well as its construction. The average temperature is usually lower if the long axis of the warehouse lies east-west, since, in the tropics, this minimizes the area of wall exposed to the sun.

Another consideration is the effect of the fumigant gas on animals and people near the warehouse. Warehouses should not be sited immediately next to animal houses or human habitation (for example, watchman accommodation).

Size

Although there is no theoretical limit to the size of a warehouse, bearing in mind the time required for sealing and the potential for waste and difficulties in management, a store of about 1000-2000 tonnes is a good practical upper limit. If the store has a flat roof, the top of the stack must be 1.5 m below this to prevent overheating. Wall height should be appropriate for normal stack height, and the floor area should allow minimum space for gangways between stacks.

Foundations

Foundations should be constructed to the appropriate local codes of practice, so that settlement, which could cause cracking in the walls, does not occur. The foundations have to be the right size and type to take the weight of the warehouse without settlement. Five types of foundations may be used depending on local conditions: strip, pad, raft, pile, or pier.

Floors

Floors must be crack-free concrete, constructed with the minimum number of joints. All joints should be filled with a mixture of sand and hot-melt bitumen. All sub-bases must be fully compacted in thin layers to prevent subsidence.

The floor must include a vapour-proof barrier (damp-proof course) that will also act as a gas barrier. Vapour barriers are made from polyethylene film (250 μm) or melted bitumen. This barrier must overlap with the gas seal included in the wall (*see* Figure 1).

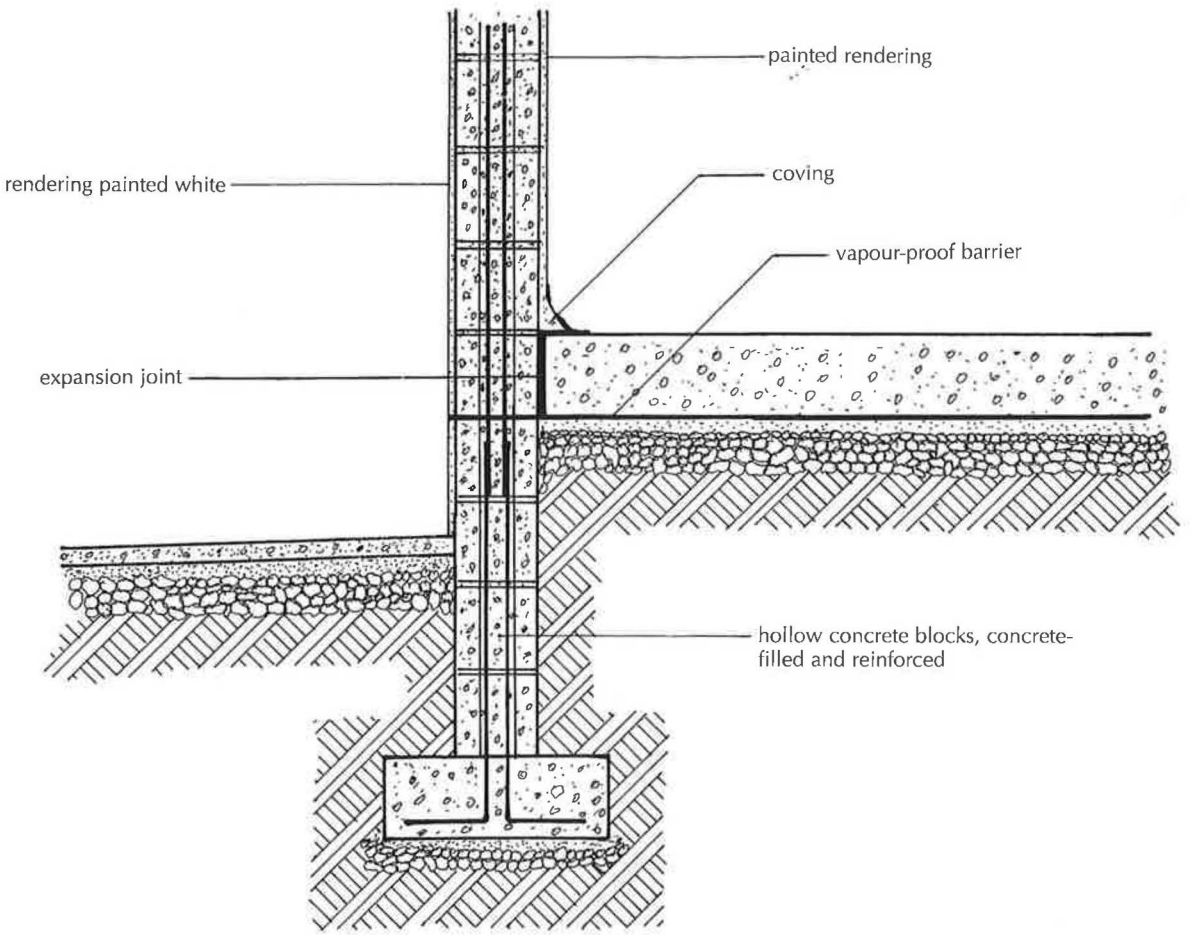


Figure 1 Floor design (cross-section)

If an existing sound floor does not include a vapour barrier, or if it starts to become dusty, a floor sealant may be used to reduce the loss of gas and to improve the working surface.

Walls

The warehouse walls must be free from cracks. Holes due to scaffolding bars should be filled with mortar. Corrugated sheet walls should be avoided, since although they may initially be sufficiently gas tight, if specially treated as indicated for roofs, the risk of minor damage leading to leakage is very high. Masonry walls of brick or solid concrete blocks, built with fully mortared joints, are preferable. Hollow concrete blocks, whilst structurally adequate, are not recommended for a fumigable store unless filled with concrete and reinforced.

It must be recognized that most masonry is sufficiently porous to allow high rates of gas transmission, and it is essential to render walls with a cement/sand render of one part cement to three parts sand, 10–15 mm thick, and then to paint them. For a gas seal, a minimum of two or three coats of bitumen/talc paint or other proprietary paint with similar gas-proofing properties should be applied to the interior surface after at least one coat of primer.

Where walls meet columns, the joint must be designed in a way that will minimize the risk of cracking and allow movement of the building. Steel columns must be encased in concrete. Sealing of the joint between the wall and column is easier if the inner wall is flush; the columns should protrude from the exterior face of the building, not the interior. Expansion of the walls must be allowed for by including expansion joints. These must be filled with a material impermeable to gas, for example, mastic or a bitumen-based filler, leaving no gaps (*see* Figure 2).

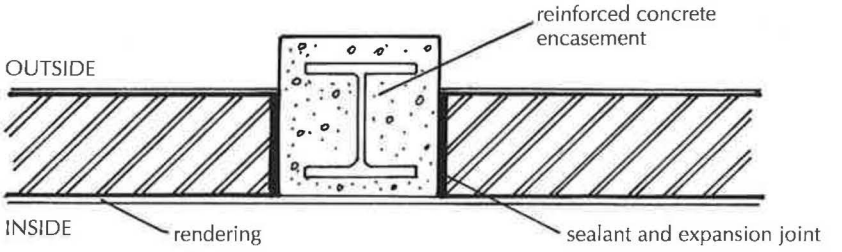


Figure 2 Sealed expansion joint in wall

The wall/floor junction has to be carefully built to prevent leakage of gas; any proofing in the floor must be continuous with that in the wall (*see* Figure 1).

The interior and exterior of walls should be a light colour, preferably white. The exterior colour is to reflect heat; the interior colour is to make inspection easier and to improve the lighting in the warehouse. Natural lighting may be improved by the inclusion of glass blocks in the walls. This will give natural lighting without destroying the gas proofing. Roof lighting is not recommended.

Roof

The main function of a warehouse roof is to protect the produce inside it from rain, and to dispose of the water without any of it entering the store. Another function is to provide shade from the sun. There are several different types of roof including pitched, flat and domed. The most common is the pitched roof.

Pitched roofs should be corrugated metal sheet construction on steel supports. (Timber roof beams are unsuitable because there would be excessive movement.) These roofs have many small gaps and holes where the sheets join and where they are fastened. The roof must be designed to minimize movement that would open these gaps under the stresses of wind, rain or thermal expansion. For structural stability the design must include sufficient purlins and the correct

number of holding bolts for the sheet sizes used. All holes and gaps along the edge of sheets must be sealed.

The roof sheets should be as large as possible to reduce the number of joints. The inclusion of transparent sheets to act as roof lights is not recommended since solar heating will increase the internal temperature. The life of the transparent sheets is shorter than the metal roofing sheets and they are difficult to replace. Rather than a ridge joint, which is extremely difficult to seal, curved or bent sheets should be used at the apex. The sheets must overlap at the long edges by two corrugations (150 mm) and at the ends by at least 150 mm. The join between the sheets must be sealed with a mastic or butyl rubber sealant. For this to be effective the sheets should be cleaned with a solvent to remove any grease before fixing. The washers on the holding-down bolts of the roof sheets must be sealed with bituminous fibre washers or butyl rubber washers under a metal diamond washer, with a butyl sealant or mastic jointing compound to complete the sealing (*see* Figure 3).

The laying of sheets should commence from the eaves and at the corner furthest from the prevailing wind. The side laps will then be pointing away from the wind, preventing air or water from being forced into the lap (*see* Figure 4).

The ridge of a roof requires particular attention as large pressure differences develop in this region when the wind blows. It is quite difficult to seal because of thermal movement and the change in direction.

If a curved roof is used there is no change in direction and the ridge cap is eliminated. If a ridge cap has to be used, the gaps due to the corrugations have to be filled with a sealant; this may be an expanded foam or a type of mastic.

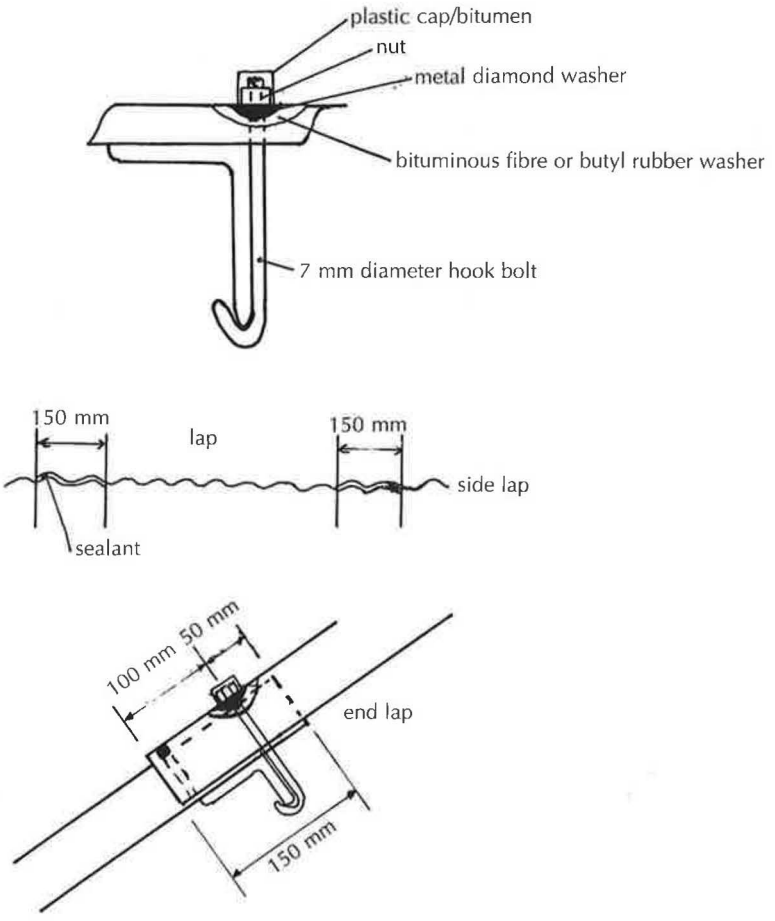


Figure 3 Fixing down roof

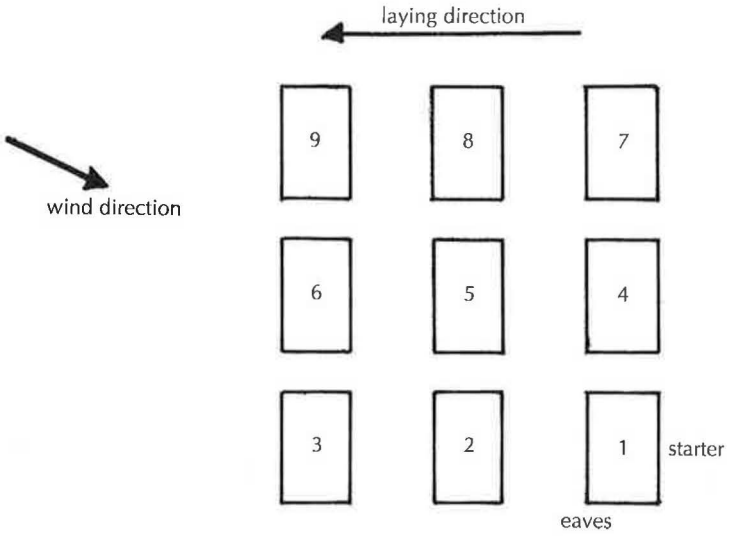


Figure 4 Laying of sheets

Painting of a roof is expensive. It may occasionally be necessary to paint the exterior of the roof white for interior temperature control, if the exterior metallic finish surface is not sufficiently reflective. Painting may also be of some value in sealing joints if the gas permeability is too high. The paint has to be able to withstand temperatures of up to 50°C, a certain amount of movement due to thermal expansion, and should be relatively impermeable to gas. For specification of paint see section on paints, p. 13.

Flat roofs are used in a few countries. If they are used in fumigable warehouses there should be no cracks or gaps in the roofing layer. They should include a continuous layer of polyethylene film (>250 μm) or an unbroken bitumen layer or coating 5 mm thick, and be of concrete slab construction.

Roof-to-wall junction

The roof-to-wall junction of a warehouse is perhaps the most troublesome to seal. There are usually at least three different materials (brick/wood/metal) that meet at an angle. Any sealing must accommodate differential movement between the materials. For warehouses of the size considered here, the roof should overhang the wall by at least one metre, making it necessary to seal round the rafters supporting the roof overhang. When corrugated roof sheets are used, all gaps left by the corrugations and the angle of the roof should be filled through the thickness of the wall with cement/sand mortar. The exposed surfaces of the mortar should then be painted. A sealant should be applied between the mortar and the roof sheet to allow for expansion of the roof, differential movement and flexing of the roof due to wind. A method of sealing is shown in Figure 5.

Doors

The number of doors required for operating the warehouse should be a minimum. It is advantageous to position doors in pairs facing each other on opposite walls to aid ventilation after a fumigation (*see* Figure 6). Often two doors will be sufficient for a store holding up to 1000 tonnes. The door size should be at least 1.5 m wide by 2.5 m high to allow two labourers carrying bags to pass.

The doors should be steel, of rigid construction to minimize warping, and with as few joints as possible. For joining steel sheets, welding is preferable; welds must be continuous, not spot-welds, and be carefully inspected to ensure gas tightness. Bolted joints are only acceptable for joining sheets when they are supported by a rigid frame member, and it is advisable to use mastic to seal between the sheets. Riveted joints between sheets are unlikely to be gas tight.

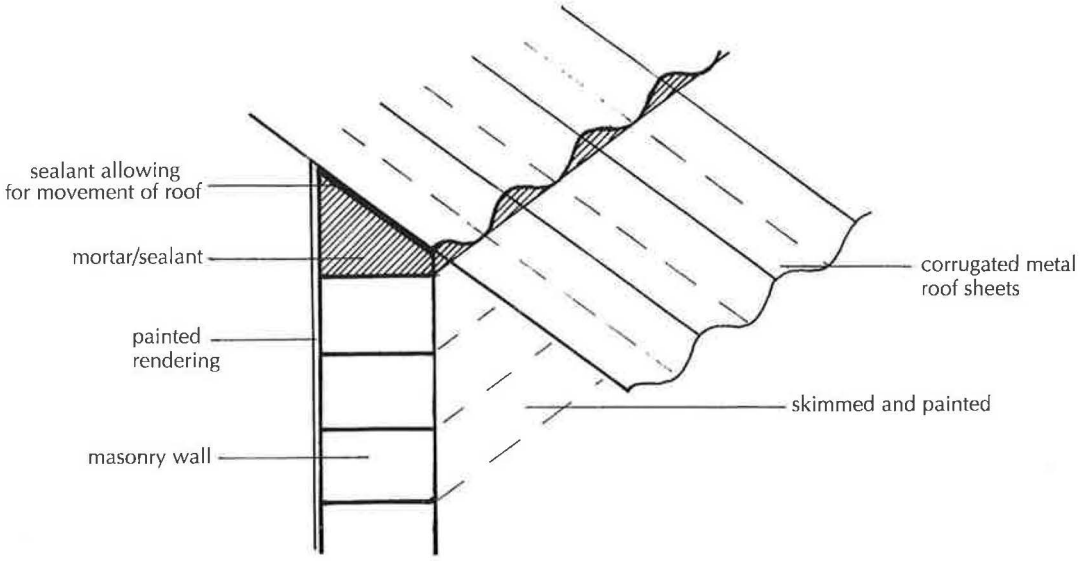


Figure 5 Sealing of roof

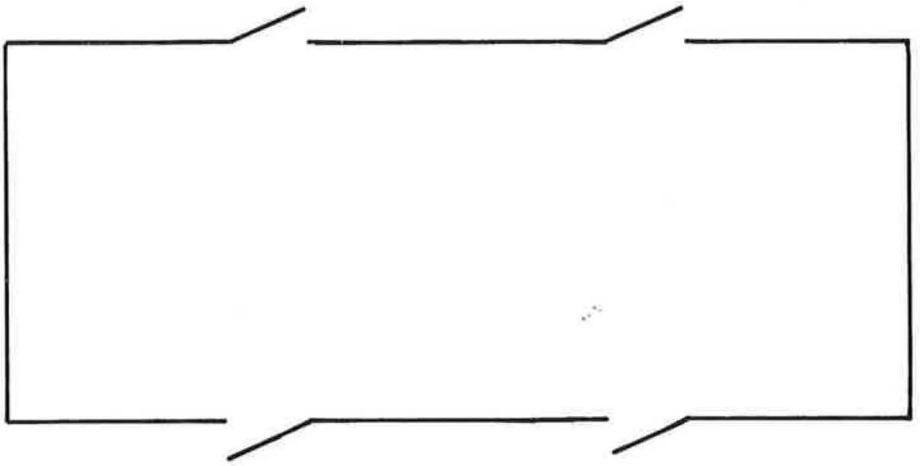
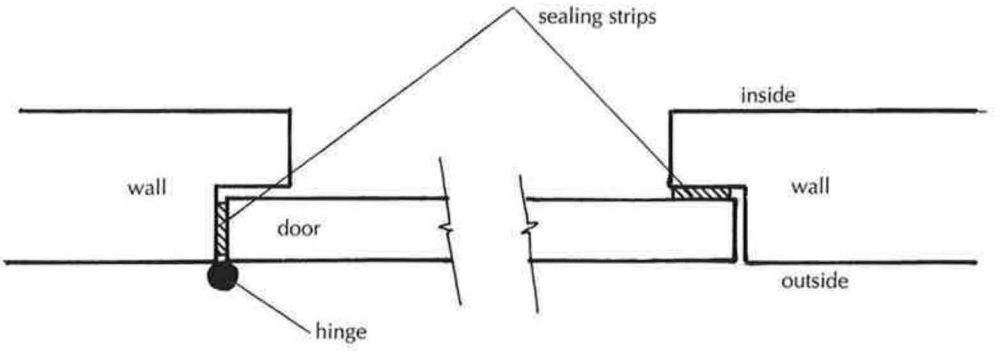


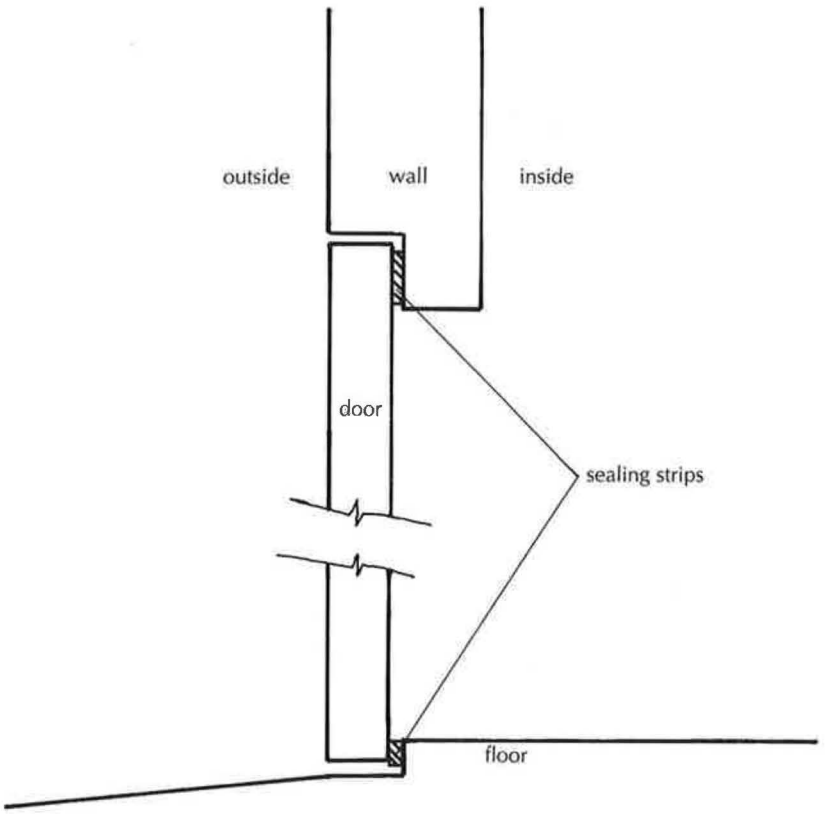
Figure 6 Position of doors

Doors must be designed to be opened from the outside, as it is dangerous to enter a warehouse after fumigation until complete venting of the gas has been carried out. Doors may be detachable (lift-off) or hinged; sliding and roller-shutter doors cannot easily be sealed. A detachable single-piece door is easier to seal but more difficult to operate than a hinged door. Hinged doors are generally preferable since they help management and are less likely to be damaged. A single-hinged door is preferable to double-hinged doors because there are fewer gaps to seal.

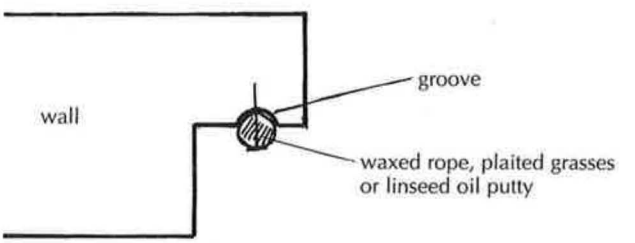
A permanent sealing strip of waxed rope, butyl rubber or neoprene around all the edges of the doors should be installed, to seal the doors when closed. Temporary sealing strips can be made of linseed oil putty, plaited natural fibres, for example, raffia or sisal, or old sacking material soaked in vegetable oil. The sealing strip should be easy to repair when damaged or deteriorated. Provision must be made for additional sealing when fumigations are being carried out. Usually the joins between the doors and wall or frame, and between doors and floor, are sealed using adhesive tape, which may be paper, plastic film or fabric based. Another method of sealing is to use an inner curtain which can be drawn across and sealed when fumigations are carried out (*see* Figure 7).



Horizontal section



Vertical section



Alternative method of sealing

Figure 7 Sealing of doors

Ventilators

Ventilators should be included for maintaining produce quality during storage, and for providing acceptable working conditions. The number of ventilators used should be a minimum, equally divided between two opposite walls to achieve the greatest air-exchange per unit area of ventilator. Very occasionally fan ventilators may be justified; in these cases special provision will be necessary to seal the apertures. Ridge ventilators should not be used as these are very difficult to seal.

All ventilators must be controllable by shutters. The operation of the shutters (for example, temporary sealing) must be safe and provision of permanent-access platforms with ladders should be considered.

The face of the shutter should preferably be one piece of flat sheet metal to eliminate any joints that may permit leakage of the fumigant gas. If a joint is needed, it must be welded and be carefully inspected to ensure it is gas tight. Sealing is similar to that for doors (*see* Figure 8).

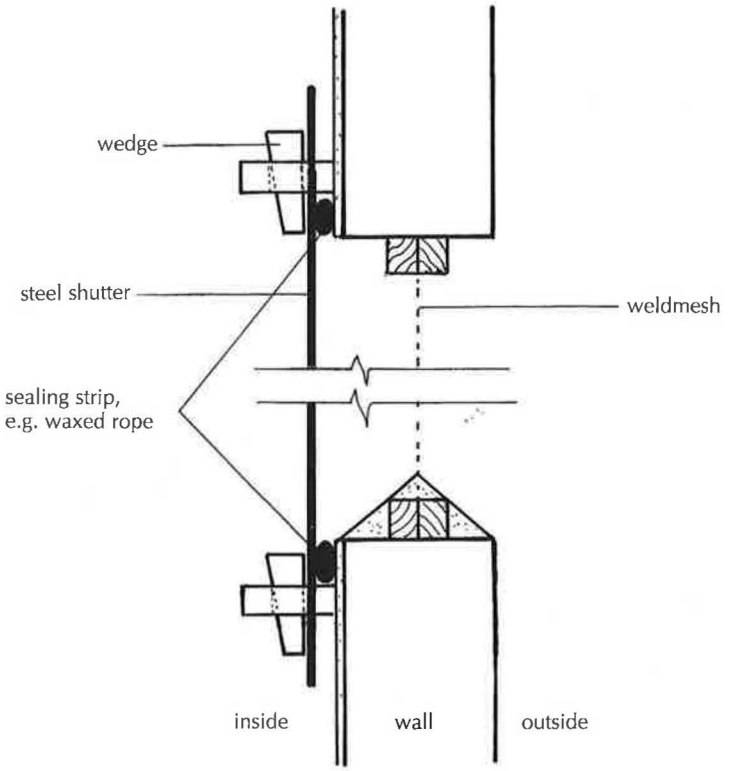


Figure 8 Sealing of ventilators

All ventilators must be permanently screened against entry of birds by the permanent inclusion of welded steel mesh over the opening. Proofing against flying insects is not recommended; fine netting is very brittle and tends to get clogged up with dust.

Hygiene

As with any grain store, the warehouse interior should be designed to facilitate cleaning. Portal frames are preferable to trusses for a roof since there is a smaller surface area on which dust can collect. Crevices should be avoided, by encasing steel columns and rounding all wall/wall and wall/floor junctions with a cement fillet (*see* Figure 9).

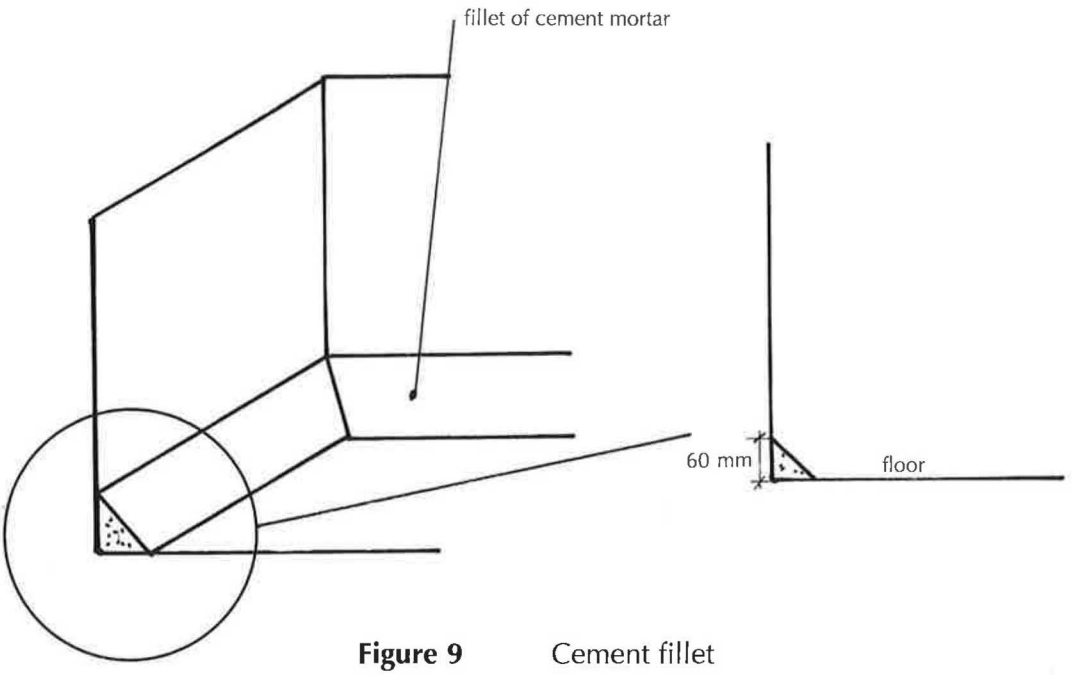


Figure 9 Cement fillet

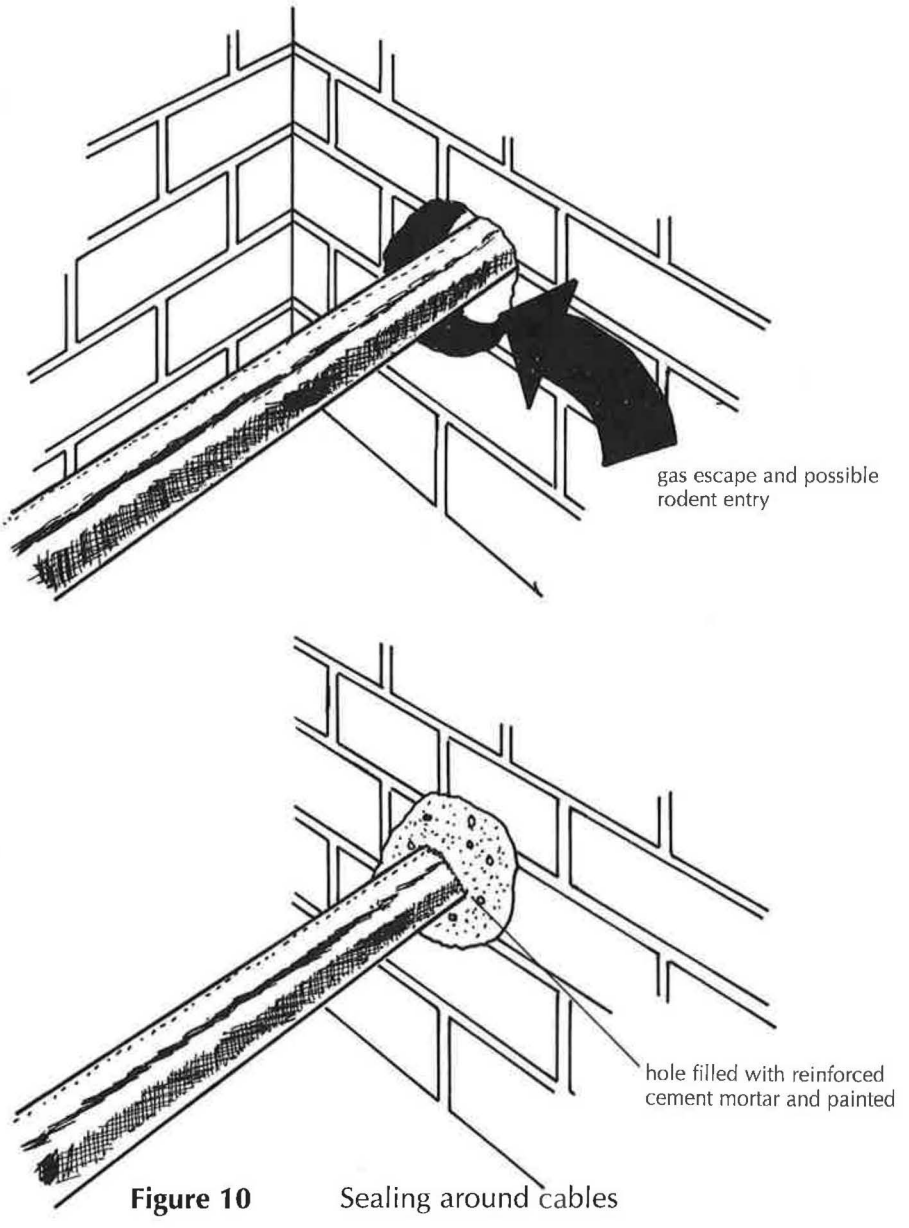


Figure 10 Sealing around cables

Electrical work

Phosphine gas reacts with copper and copper-containing metals such as brass, and repeated fumigations may cause electrical circuits to become inoperable because of build-up of reaction residues. Any electrical system using copper cable and parts has to be sealed against the ingress of gas. All entry points of cables into the warehouse should be sealed to prevent leakage of gas (*see* Figure 10).

Gas measurement

Phosphine can be measured away from the building using a gas meter. Small-bore nylon capillary tubes should be placed with one end in the warehouse and the other passing through an aperture in the wall or door frame to the outside. Where the tubes pass to the exterior the area around the tubes should be well sealed and made gas tight. Two sampling tubes should be fixed in each warehouse, at different locations.

MATERIAL SPECIFICATION

General

Porous materials must be avoided, or adequately sealed. Materials used must not react chemically with the fumigant gas, or must be protected from it. Paints and sealants must be durable, and resistant to high temperatures (>50°C). Materials used on the exterior of the building should resist degradation by sunlight, and will usually need to include ultra-violet inhibitors.

High-quality workmanship, with an appropriate degree of supervision during building, is essential if satisfactory results are to be achieved.

Paint

Choice of paint

Different paints are used on the various materials in the warehouse. The choice of paint will depend on the particular combination of properties required, e.g. gas retention, solar reflectivity, protection of materials, sealing of surfaces, and appearance. The paint should provide an unbroken continuous film to prevent loss of fumigant. Recommended paints are shown in Table 1.

Table 1 Recommended paints for fumigable warehouses

Surface	Primer Types/no. of coats	Top-coat paint Types/no. of coats
Rendered walls	alkali-resistant /1	oleoresinous /3 synthetic resin /3 bitumen/talc /3
Galvanized sheet	zinc chromate /1 calcium plumbate /1	oleoresinous /3 synthetic resin /3 bitumen/talc /3
Steelwork	metallic lead /1 calcium plumbate /1 zinc chromate /1	oleoresinous /3 synthetic resin /3
Timber	lead based /2 aluminium /2	oleoresinous /2 synthetic resin /2

Preparation of surfaces

Inadequate preparation of surfaces is a common cause of defective paintwork. Some surfaces require only to be brushed down but others need washing and scraping to remove dirt, dust, loose deposits or defective paint. Oil, grease and stains must be removed by suitable solvents. Concrete and cement must be allowed to dry fully throughout before painting commences.

Surfaces must have sufficient key for the type of paint that is to be applied. Additional key can be provided by rubbing down with an abrasive. After rubbing down it is important to remove all residues by thorough washing with clean water. Surfaces must be dry before paints are used.

Mastics and sealants

Mastics and sealants are the only practical method of gap filling. They are used to seal joints against gas loss, rain, air, and dust. They must adhere to the sealed surfaces but be sufficiently flexible to allow some relative movement. They may be required to extend and contract daily due to diurnal moisture and temperature changes.

Movements are usually small and fairly slow, but where the components are restrained by friction a sudden slip can occur causing the mastics to fracture.

Joints must be sufficiently wide to accommodate the expected movement, but excessive width wastes mastic, which is costly, and the mastic may deform. Consequently the width of mastic-filled joints must be related to the properties of the mastic to be used, the expected movement of the joint and its design. Where necessary, backing materials such as fibreboard, rope or expanded plastics should be provided to limit the depth of mastic (*see* Figure 11).

Mastics are made in consistencies suitable for application by hand with a knife or trowel, by gun, by pouring or as a preformed strip or tape. The mastic must be compatible with the method of application and the type of joint.

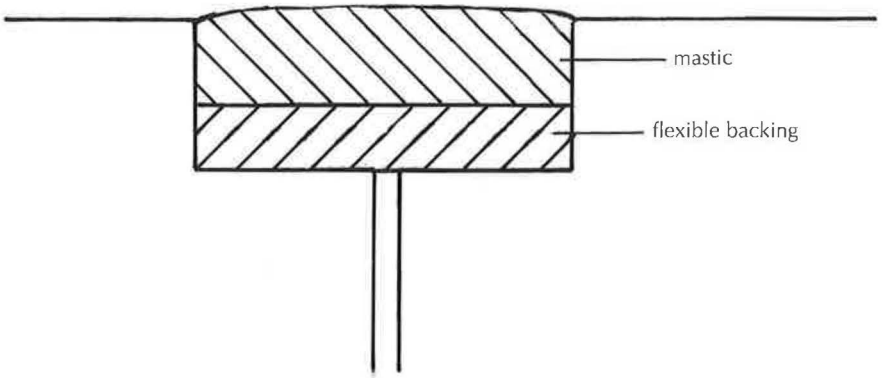


Figure 11 Design of joint

Expanded foams

Expanded foams can be used in a variety of ways to help with the sealing of a warehouse. Expanded foams are produced from liquid resins, usually by mixing two components just before application. Compressed air may be used to help with the foaming.

Expanded foams have the following properties:

- very low thermal conductivities;
- on application they expand to fill voids;
- the foam is closed-cell and therefore impermeable;
- good chemical resistance;
- usable over a wide temperature range;

- good adhesion with many materials;
- the density of the foam is directly proportional to the mechanical properties;
- chemically inert; and
- good flexural strength.

Such foams can be used to help in sealing new or old warehouse buildings.

SAFETY

All fumigant gases are toxic to man as well as to insects. Precautions must be taken to ensure that personnel do not accidentally inhale any fumigant by entering the store while it is under fumigation, or by the escape of gas into adjoining buildings. If there is no relevant local legislation, the following rules may be applied:

(i) A supervisor trained in fumigation techniques should be appointed. His responsibilities for safety of personnel and the public extend throughout the fumigation, including:

- during temporary sealing;
- during the application of the correct quantity of fumigant in the specified manner;
- for the duration of the fumigation; and
- during airing of the warehouse.

(ii) No occupied building, for example, an office, should abut onto a fumigable warehouse.

(iii) All doors into the warehouse should be lockable and during a fumigation the operator or a responsible person should hold the keys. A store must not be entered during a fumigation.

(iv) Warning notices must be prominently displayed on all doors into the warehouse during a fumigation, and removed when the store is safe to enter. These notices must be easily understood by everyone, even people who cannot read, and should include a locally recognized symbol, such as a skull and crossbones, in addition to a warning in words such as 'Poison gas – extreme danger'.

(v) At the conclusion of a fumigation, during venting of the store, the fumigation operator or responsible person should ensure by physical barriers or otherwise that access by unauthorized persons to the store is prevented. At the end of a fumigation using methyl bromide extra care should be taken as the concentration of gas will be higher than if phosphine is the fumigant.

(vi) To avoid complacency, warning notices should be removed when the store is safe to enter.

SECURITY

The necessity for a well sealed building, and the strict management practices essential for safety during fumigations, will usually mean that a fumigable store is a secure store.

TESTING AND CERTIFICATION OF WAREHOUSES

It is not generally practicable, or meaningful, to test individual samples of construction materials for permeability to gases. A warehouse must be assessed for its fumigability as a whole. Suitable procedures are given in Appendix A. Such

procedures require the atmosphere in the store to be analysed at intervals, for which sampling tubes must be passed from outside; suitable sealing must be applied around the tube. It may be useful to install a permanent sealable aperture through which sampling tubes can be passed as required. This will permit monitoring of fumigant concentration at any time.

A warehouse must be tested by a qualified inspector before a new store is accepted and before the first whole-store fumigation is carried out. He must carry out a test fumigation and a visual inspection using a standard inspection form (*see* Appendix B). The owner should establish and adhere to a consistent method of certification of the warehouse. National authorities should decide whether there is a need for an official system for certification of fumigable warehouses before use.

MAINTENANCE

After the warehouse is built and is proved to be fumigable, it must be maintained in this condition. If any part of the warehouse is allowed to deteriorate, the warehouse will no longer be gas tight.

Regular inspection is necessary and an inspection and maintenance schedule must be drawn up on hand-over to the final user. It may be useful to include in the procedures an annual test, for renewal of the certificate confirming that a warehouse is fumigable.

Different parts of the warehouse will deteriorate at unequal rates. Paint surfaces will need renewing at regular intervals, depending on their location and purpose. Seals on doors and ventilators will need renewing when inspection reveals deterioration that may cause gas loss. Other parts of the warehouse will need renewing or repairing as required.

SUMMARY OF RECOMMENDATIONS

Design features

- Sheltered sites to avoid excessive winds
- Non-porous enclosure and all possible leaks sealed
- Materials and finish to minimize internal temperature variations
- Adequate foundations to minimize settlement and cracks
- Crack-free floors having joints filled with mastics and including a vapour-proof barrier
- Solid masonry walls, painted, with expansion joints filled with a mastic sealant
- A corrugated sealed metal roof of sufficient strength, using curved sheets where available, overlapping by at least 150 mm. The sheets laid from eaves and away from prevailing wind
- A minimum number of sealable steel doors for efficient operation, opposite one another and opening from the outside
- Minimum number of eaves ventilators opposite each other, with sealable shutters
- All electrical circuits sealed against fumigation gases
- All entry points of cables and pipes sealed
- Correct surface preparation, choice of paint, application, and number of coats of paint to achieve an unbroken film
- Correct design of joint and choice of mastic/sealant with good surface preparation to seal joints and gaps

- Use of painted expanded foams where necessary to seal internal surfaces of warehouse
- Good supervision necessary in all stages of construction and operation of a fumigable warehouse

Operation

- Safety is paramount
- All fumigable warehouses to be assessed by an independent expert and a certificate that a warehouse is fit for whole store fumigations to be issued
- Maintenance of fumigable warehouses to ensure a gas-tight envelope is sustained

SUCCESSFUL WHOLE STORE FUMIGATION TO PREVENT DEVELOPMENT OF FUMIGANT-RESISTANT INSECT STRAINS

A fumigation must be both safe to the personnel performing the operation and effective so that all insects are killed. Poor fumigation practice will result in a proportion of the insect population surviving in the commodity or on the store fabric. Insects develop resistance when successive generations are subjected to sub-lethal concentrations of the fumigant. As resistance increases both the concentration of fumigant and the exposure period required to attain complete mortality increase markedly. Continuous selection for resistance results in insect populations which become impractical to control. There are already examples of resistant populations which cannot be controlled cost-effectively with phosphine. Such insects can only be controlled with methyl bromide.

Very few buildings have been designed for whole store fumigation. However, the advantages of this procedure are such that buildings are used regardless of their suitability. Frequently, poor quality fumigations occur and failures result. If such fumigations are to be undertaken it is essential that the building be assessed in advance and, where necessary, rendered suitable. Furthermore, because it is often difficult to obtain an adequate degree of gas tightness, it is vital to monitor and evaluate the fumigation, during and immediately before the termination of the operation, otherwise failure may occur without being appreciated. Some practices and procedures to be applied to and in existing buildings to reduce the potential for resistance to occur are described below.

Methyl bromide

Methyl bromide is used to fumigate flour mills and small fumigation chambers which have permanently installed networks of piping for application. An advantage of using methyl bromide is that the required concentration can be maintained by releasing additional fumigant, easily, during the exposure period. Without forced circulation using a fan to enable the gas to be thoroughly mixed with air, only limited penetration of the commodity would occur, particularly in large stores over 1000 tonnes in capacity. However, this gas is rarely used in fumigable, commercial bag stores. For this reason, the remainder of the description pertains principally to the use of phosphine.

Phosphine

Phosphine preparations generate gas when they come into contact with atmospheric moisture. During a fumigation the concentration of phosphine increases until the preparation is exhausted; thereafter the rate of gas loss is directly related to the leak characteristics of the enclosure being fumigated. The rate of phosphine generation is determined by:

- *chemical composition*: magnesium phosphide generates phosphine more quickly than aluminium phosphide;
- *formulation*: tablets generate phosphine more rapidly than sachets;
- *temperature*: the higher the temperature the more rapid the chemical reaction; phosphine fumigations are not recommended for commodity temperatures below 15°C; and
- *moisture*: the amount of atmospheric moisture influences phosphine generation; in a dry climate below 25% r.h. generation will be very slow and after a five-day exposure period the formulation may be only partially decomposed.

Where a storage structure is only marginally suitable for fumigation, it is advantageous to use a formulation which generates phosphine slowly since this will allow a longer period of compensation for leakage from the enclosure. Alternatively, successful fumigations of such structures can be achieved using a split application, with half the dosage being introduced at the beginning of the fumigation and the remainder after 48 hours. The second application must be completed without losing phosphine from the building under fumigation. This may be achieved by using a resealable port in one wall of the building and a system of pulleys and ropes so that small bags of the phosphine preparation can be attached to the rope and fed into the building.

Dosage rates

The duration of any phosphine fumigation will depend on various factors, including the climatic conditions and the insect species to be controlled. In general, a minimum of 120 hours is required for complete elimination of pest populations, though this period may have to be extended to 168 hours. By definition, a fumigable building is one where, after applying the recommended dose, the concentration of phosphine must not fall below 0.2 mg/litre at any time during the exposure period. Similarly, with methyl bromide the minimum CT product (gas concentration × duration of exposure) will be not less than 200 mg/hour/litre at the end of the 24- or 48-hour exposure period, and at no time must the concentration be less than 3 mg/litre. These standards refer to the entire store air space and to any produce stored.

Regardless of the quantity of produce in store, the dosage must always be based on the *volume* of the store which is to be fumigated. The dosage rate should be 1.5 g of phosphine per m^3. Each tablet produces 1 g; a sachet, 11 g; a plate, 33 g; and a 'strip', 528 g of gas; other preparations may be available. Manufacturers' instructions on dosage rate should always be followed. The total amount of the preparation for the particular store should be carefully calculated. It is important to note that some preparations are packed in resealable containers, while others are not; in these cases, the dosage should be calculated to the nearest full container.

Temporarily sealing buildings for fumigation

Even with purpose-built fumigable stores there will be a need for temporary sealing of different parts of the structure. This sealing will have to be carried out particularly well in buildings not specifically designed for whole store fumigation.

All external gaps and openings in the buildings must be made good. A variety of materials can be used; in Pakistan, mud plastered over gaps between doors and door frames was found to be satisfactory. Voids should be covered with plastic sheet sealed with adhesive tape. A check must be made to ensure all seals are in place before the fumigant is introduced; most tapes will not adhere to whitewashed walls.

Ventilators require particular attention as they may be difficult to seal. They may be in a poor state of repair with broken window glass, warped frames and

inoperable opening and closing mechanisms. These should be treated as for voids. Sliding and roller doors are more difficult to seal than hinged steel doors and should also be treated as voids.

Monitoring fumigations

Phosphine concentrations in air can be measured directly with a robust, portable gas meter, at the push of a button. The meter must be calibrated before use.

Once the fumigant has been dispensed readings should be taken at approximately six-hourly intervals until generation of phosphine has been completed and then at 12-hourly intervals until immediately before the fumigation is terminated. Records must be kept which show the position of the sampling line, the date and time of the fumigation and of the measurements of gas concentration.

Gas concentration may be recorded in parts per million (ppm) and converted to mg/litre using the following formula:

$$X \text{ mg/litre} = 5.4578 \times (P/273+T) \times Y/10\,000$$

where P is the barometric pressure in mm, T is the temperature in °C and Y is the gas concentration in ppm.

If only the minimum phosphine concentration has been maintained then either the temporary sealing is at fault, or the building is not intrinsically suitable for full store fumigation.

If it is not possible to take readings according to the above schedule, it is essential to take one reading immediately before ventilation. On each occasion three readings should be taken and the two which approximate one another recorded.

Fumigation procedure

All sealing must be in place and only one access door open. The phosphine preparation must be unopened and distributed around the store. If tablets are used these should be placed on shallow trays to facilitate recovery of spent residues. There must be sufficient illumination for pest control operators to place phosphine preparations safely, without falling over obstructions, such as bags, left lying on the floor.

The officer-in-charge will follow normal procedures for phosphine fumigations:

- checking of sealing of building;
- briefing of staff;
- checking of dosage rates;
- ensuring an adequate number of respirators and canisters are available;
- ensuring that after completing the exposure of the phosphine preparation all staff leave the building;
- sealing of the exit door; and
- placing of warning notices.

At the end of the exposure period (five or seven days), operators wearing respirators should open all doors to ventilate the building. Once this has been completed, all residues must be disposed of safely by mixing them into a bucket of water to which a little detergent has been added. Empty containers must be collected and counted to ensure that the correct number have been recovered, warning notices removed and a certificate of clearance issued to the person in charge of the store.

At least 24 hours must elapse before stock is moved out of the store, and before that a careful examination should be made to see if any live insects have survived. It is most likely that survivors will be eggs and pupae, so a sample of the commodity should be obtained and checked during the following four weeks for newly emerged adults. If there are live survivors the fumigation has not been a success. The reason for this must be determined, particularly if it is intended to repeat full store fumigation in the building.

On no account should a fumigation be attempted where there is any doubt that it can not be carried out successfully.

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Appendices

APPENDIX A TESTING FOR GAS-TIGHTNESS

Phosphine decay

The concentration of phosphine gas can be easily measured using a simple meter. The gas mixture in the warehouse is drawn through the tubes into the meter by use of a small pump or syringe.

The actual concentration of the fumigant gas can be measured and plotted for an empty warehouse over a suitable time period. If the empty warehouse retains the required concentration of gas for the minimum time for a successful fumigation then whole-store fumigation is possible.

The main problem with this method is that a specialist is needed to do the test. The method involves the use of a poisonous gas and great care is needed. Using an aluminium phosphide preparation the test takes several days, because the emission of the gas is slow. Also, the cost of the test is high because it requires a full dose of fumigant.

Carbon dioxide and other tracer gases

Carbon dioxide (CO_2) is usually readily available in most countries (it is used in the soft drinks industry particularly) and can be used to determine leakage rates in buildings. The warehouse and sampling tubes are prepared in the same way as for testing with phosphine. A known concentration is injected (or placed, if used in its solid form of 'dry ice') into a building. The concentration used depends on the range and sensitivity of the meter available to monitor the gas concentration. The gas mixture in the warehouse is sampled and the concentration measured using a portable meter. The time taken for the concentration to fall by 50% is known as the half-life. The half-life indicates the suitability of a building for whole-store fumigation. For phosphine fumigation, where the maximum allowable loss of gas per day is 10%, the minimum half-life of the CO_2 or tracer gas is five days.

Carbon dioxide is not poisonous and is only dangerous at high concentrations. A specialist does not need to be present. The test can be completed within a working day because the rate of gas loss can be calculated with sufficient accuracy after 6 hours; the half-life point does not need to be achieved.

Carbon dioxide, though easily obtainable, may be difficult to transport to remote regions. The CO_2 will either be available as dry ice that will evaporate, or in heavy pressurized cylinders. The concentration of CO_2 is measured using a portable CO_2 meter based on an infra-red or thermal conductivity detector of suitable sensitivity. Some meters have an integral pump. Background CO_2 may need to be considered depending on the range and sensitivity of the meter.

Special tracer gases (e.g. sulphur hexafluoride) can be used instead of CO_2. A smaller quantity may be used as there is no background gas. A sensitive detector is used, calibrated for the particular tracer gas. A similar half-life to that for CO_2 is required. The tracer gas will probably have to be specially imported into most countries. Specialist equipment would also probably have to be imported for measuring the gas concentration.

Overall, if a specialist fumigation operator is available, the most useful method of testing is with the fumigant that is to be used in the store, e.g. phosphine. A meter purchased for initial test purposes could also be used for testing the effectiveness of routine fumigations. If a specialist is not available and a commissioning engineer needs to test a store, a tracer gas or CO_2 can be used.

APPENDIX B EXAMPLE OF SURVEY FORM

NATURAL RESOURCES INSTITUTE
FUMIGABLE WAREHOUSE STORE SURVEY

Name of site:	No. of warehouses:
Location:	
Warehouse no.:	Operator:
Rated capacity (tonnes):	
Dimensions: (outside/inside) Height (eaves),	Length Width Height (ridge)
Calculated capacity:	Duration of storage:
Orientation:	Date of construction:
Type of construction (e.g. framed, load bearing):	
Whole store fumigations carried out:	
Attached: sketch site plan: plan and elevation of store: any other details:	
Surveyor:	Date:

STORE ELEMENTS: PRESENT CONDITION AND PERFORMANCE

FLOOR (plinth)					
Height above grade (ground level):					
Material: concrete slab/brick/concrete/other					
Thickness:		Cracked/holed: Yes/No			
Vapour barrier: absent/present/not known					
Finish:		Sealants (coatings):			
Joints:		Joint filler:			
Rodent entry (holes): Yes/No					
Score	GOOD 1	FAIR 2	UPGRADE 3	REPAIR 5	REJECT 5

FLOOR/WALL JOINT:					
Sealing method: Effectiveness: Particular problems:					
Score	GOOD 1	FAIR 2	UPGRADE 3	REPAIR 4	REJECT 5

WALLS					
Loadbearing/infill between columns: Size of columns: Material of columns: Column flush internally: Yes/No Wall/column intersection: Filler: Thickness of wall: Materials: concrete block (hollow/solid/not known) brick (solid/cavity) stone/other Plastered/rendered inside: good/fair/poor/bad/none outside: good/fair/poor/bad/none Damp-proof course: Yes/No Weepholes: Yes/No Expansion joints: Yes/No Condition: Good/fair/poor Evidence of: rodent entry: Yes/No damp: Yes/No Finish: inside colour: outside colour: Type of coating/paints: Entry of cables/pipes properly sealed: Yes/No Holes or cracks: Yes/No					
Score	GOOD 1	FAIR 2	UPGRADE 3	REPAIR 4	REJECT 5

ROOF/WALL JOINT					
Sealing method: Effectiveness: Particular problems:					
Score	GOOD 1	FAIR 2	UPGRADE 3	REPAIR 4	REJECT 5

ROOF					
Type: flat/pitched/other Materials: concrete/bricks/precast slabs/CI/Al/other Thickness: Frame material: concrete/steel/timber Roof overhang: Yes/No Finish: inside colour: outside colour: Sealants (coating): Yes/No Material: Sheet overlap: Joint overlap: Sealing between sheets*: Fixings: Sealing of fixings*: Defects*: Evidence of water entry: Yes/No					
Score	GOOD 1	FAIR 2	UPGRADE 3	REPAIR 4	REJECT 5

* inspect in closed store without internal lighting

RIDGE					
Design: Sealing: Effectiveness of sealing: good/fair/poor/bad Estimated area of openings per metre length: Particular problems:					
Score	GOOD 1	FAIR 2	UPGRADE 3	REPAIR 4	REJECT 5

DOORS					
Total number of doorways: Location: long sides (no.): short sides (no.): Type: hinged/sliding/roller/lift-off Hung on inside/outside wall: Dimensions: width: height: No. of doors/doorway: Personnel door: Yes/no Material: wood/steel Construction: Clearance: at wall: at floor: Between double doors: Sealing strip: present/absent on doors/frame condition: Fixing of frame: sound/unsound Sealability: Operate from outside: Yes/No Lockable: Yes/No Rodent entry: Yes/No					
Score	GOOD 1	FAIR 2	UPGRADE 3	REPAIR 4	REJECT 5

WINDOWS AND VENTILATORS					
Number of windows:			of ventilators:		
Location:					
Type:			Controllable: Yes/No		
Dimensions:			Total area:		
Shutters: Yes/No			Material: Thickness:		
Fixing of frame: effective/not effective					
No. of glasses in each ventilator/window: Broken window panes: Yes/No					
Screened: Yes/No			Sealing strip: Yes/no		
Sealability:					
Score	GOOD 1	FAIR 2	UPGRADE 3	REPAIR 4	REJECT 5

SCORE SUMMARY (in terms of fumigation)		
	Score	Comment
Floor		
Floor/wall		
Walls		
Roof/wall		
Roof		
Ridge		
Doors		
Ventilators/windows		
TOTAL		

Note: Score 0 if not included in building

Suggested analysis

If any one part scores 5 then building is not fit for fumigation.

Total score:

Below 10: suitable for fumigations with no upgrading.

10 – 15: suitable for fumigations but some maintenance needed.

15 – 20: suitable for fumigations after improvements are made.

20 – 25: not suitable for fumigation, repairs needed.

Over 25: not suitable for fumigation, major structural repairs needed.

Care must be taken if any one item has a much higher score than other parts.

CONCLUSION ON SUITABILITY FOR WHOLE STORE FUMIGATION

Assessment from visual inspection:

Assessment from tracer gas test:

Assessment from concentration v. time graph of a trial fumigation:

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The Bulletin series presents the results of research and practical scientific work carried out by the Natural Resources Institute. It covers a wide spectrum of topics relevant to development issues ranging from land use assessment, through agricultural production and protection, to storage and processing.

Each Bulletin presents a detailed synthesis of the results and conclusions within one specialized area, and will be of particular relevance to colleagues within that field and others working on sustainable resource management in developing countries.

Fumigating durable food produce in a sealed building can be much more convenient than treating the same commodity under a series of gas proof sheets. **Fumigable warehouse: design and construction** describes how suitable buildings can be constructed and how existing buildings could be modified to render them sufficiently gastight. It also describes precautions to take in order to avoid fumigation failures and the development of insect resistance.

This manual is intended for those designing new warehouses which will be used for whole store fumigation and for those who wish to use existing buildings for the same purpose. It is particularly aimed at those in developing countries.