THE UNIVERSITY OF MANITOBA

# EMERGENCY GRAIN STORAGE BINS

by

Ajit Kumar

A thesis

Submitted to the Faculty of Graduate Studies

in partial fulfillment of the requirements

for the degree of Master of Science

Department of Agricultural Engineering
University of Manitoba
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# ABSTRACT

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The amount of grain in storage on a Western Canadian farm fluctuates with crop yields and markets. In the years of over production, emergency structures are needed to store the surplus grain on the farms. During the summer 1975, material choices for the fabrication of emergency bins were reviewed and three bins with different configurations were designed, fabricated and structurally tested. Based on the summer tests, four cross-laminated polyethelene sheeting bins and one polyolefin woven fabric wall-bin, each having a capacity of 36 $m^3$, were designed and fabricated for use in a storage test from September 1975 to June 1976. The cross-laminated polyethelene sheeting bins were permanently supported by wire mesh and the polyolefin woven fabric bin was supported by wooden stakes during filling. To compare the results of emergency bins with permanent bins, one plywood bin and one steel bin were also erected in early fall.

Design variables studied during the storage tests included type, colour and thickness of materials, fastening systems, venting systems, roof fastening materials, extra floor sheeting and supporting systems. Grain spoilage characteristics such as temperature, moisture content, official grade and dockage were compared among all seven bins.

The bin supported by wooden stakes failed during filling and could not be filled to design capacity. The other bins supported by

wire mesh performed satisfactorily except mice chewed holes in the polyethelene sheeting under the snow piled around the bins during winter. The bin which did not have snow piled around it, was not damaged by mice.

Temperature measurements indicated the presence of hot spots on the floors of the damaged bins during spring. These hot spots developed after the snow melted and the water entered the bins through mouse holes. No such problem existed in the one emergency bin which did not have mouse damage.

Except for a small amount of grain, the commercial grade of the grain remained constant during storage in each of the bins, indicating the effectiveness of the bins in preserving grain quality. Grain deterioration in the undamaged bin and permanent bins (around 0.4%) was less than that in the damaged bins. (The maximum grain deterioration in the damaged bins was 3.2%).

The capital cost to a farmer of an emergency bin, 36 $m^3$ capacity, was estimated to be about $200 which is less than the value of the stored wheat. If the bin is used only once, the annual cost amounts to $5.92 per $m^3$. The annual cost reduces appreciably if the bin is used for two years or if the capacity of the bin is increased.

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# 1. INTRODUCTION

In the Canadian Prairie Provinces many farmers do not have enough permanent granaries to store surplus grain and therefore periodically need some emergency storage structures. A permanent granary may be defined as a structure that has an expected useable life of many years and is used for the long-term storage of grain. Whereas, an emergency storage structure is defined as a structure which may have a limited useable life and can be used for short-term storage when the farmer's permanent storage space is insufficient due to high yielding crops or poor markets or both. The amount of grain to be stored in any year that exceeds the farmer's permanent grain storage space is defined as surplus grain.

It may be uneconomical to build a permanent structure of wood, steel or concrete for surplus grain, because the farmer will not utilize the structure in years of average or below average crop production. Fixed costs such as depreciation, interest on investment and insurance on the bin must be paid even though the bin is not used for storing grain. As a result, the total storage cost for permanent bins increases when the bins are used only infrequently.

Due to the lack of well designed emergency structures farmers, during years of surplus production, store surplus grain in barns, machinery sheds or in other farm buildings which do not provide favorable conditions for the safe storage of grain. In many other instances the grain is stored in open piles on the bare ground. Piling grain on the ground is not a good method of storage since the grain is exposed to moisture absorption from the soil, rain and melting snow. Precipitation may soak into the grain pile providing favorable conditions for the growth of mold, insects and mites.

A well designed emergency storage structure, less expensive than permanent structures, is urgently needed by Western Canadian grain growers. The structure must have a design life of 6 to 12 months and be able to hold the grain during this storage period, without deterioration in quality. The empty emergency storage bins should be light in weight, and hence easy to handle. In addition, under emergency conditions, it should be possible to erect the bins on an unprepared site in a few hours with a low labour requirement. Average yearly cost for emergency storage bins should be less than that of permanent bins or any other alternate method used for the periodic storing of surplus grain.

A study by Muir et al. (1973) revealed that the emergency farm bins that are presently used for storing grain on Prairie farms are not suitable for preserving grain quality during winter. Research work conducted on the development of emergency bins by Gamby (1973) at the University of Manitoba resulted in an improved emergency structure. Although the structure withstood the load imposed by the grain bulk, it was not effective in preserving the grain quality for the first winter of storage. Improvements in the design should result in a better structure to preserve grain quality during storage.

The objectives of the research project were:

1. To design a structure which maintains the quality of grain stored under emergency conditions for at least nine months of storage.

2. To fabricate and structurally test the design bins.

3. To study the effectiveness of the bins in preserving the grain quality for at least one winter of storage.

4. To test the tensile strength of the structural materials.

To meet the objectives, three series of tests were carried out. Three bins were designed, fabricated and structurally tested during the summer of 1975. Five emergency bins were designed, erected and loaded in early fall and the condition of the stored grain was monitored for nine months. To compare the condition of grain stored in the emergency bins with the condition of grain stored in permanent structures, one plywood bin and one steel bin were also erected and loaded at the same time. Tests on the tensile strength of Tu-Tuf sheeting and taped joints were carried out in the laboratory.

# 2. REVIEW OF LITERATURE

## 2.1 Variables Affecting Grain Quality

A bulk of stored grain is a multivariate system in which deterioration results from interactions among physical, chemical and biological variables. The important variables which are involved in grain deterioration are: moisture, temperature, oxygen supply, growth of microflora, insects and mites and feeding by rodents and birds (Sinha, 1973). These variables affect the quality of grain as measured by the grade, protein content, fat acidity and milling and baking quality.

Of the various factors influencing the rate of deterioration, moisture and temperature are among the most important. The maximum moisture content and temperature at which grain can be stored safely, depend on the kind of grain, initial condition of grain, granary structure in which it is stored and length of storage period (Pomeranz, 1974). Low temperature offsets the effects of high moisture with respect to the hazards of mold growth and insect development. Similarly, if the moisture content is maintained at a sufficiently low level, grain can be stored for long periods with little deterioration even under storage conditions that are otherwise unfavorable.

The intergranular atmosphere in bulk grain is modified by the respiration of grain and activities of microflora, insects and mites. These phenomena result in depletion of oxygen and production of carbon dioxide, water and heat. In this process of respiration nitrogen content remains unchanged. The volume of oxygen depletion is usually very close to the volume of carbon dioxide production (Pomeranz, 1974).

A high carbon dioxide level in the intergranular air of the grain bulk normally indicates grain deterioration.

Insects, mites and micro-organisms can develop in pockets of grain that have a high moisture content due to moisture migration, entrance of precipitation or initially damp grain. Moisture migration can occur in a grain bulk of uniform moisture content as a result of temperature gradients in the bulk. High moisture contents and high temperatures accelerate the respiratory action. Heat produced by the respiration causes deterioration of grain through scorching of seed, reduction of germination and by providing more favorable conditions for the growth and reproduction of storage fungi, actinomycetes, mites and insects (Sinha et al. 1973).

Grain feeding by rodents and birds which are external biological agents mainly depends on the site of the granary, its design and the material used in its construction (Sinha, 1973). In open piles, the birds eat the grain and make small depressions in the surface. Water soaks into the grain through these depression and thus favorable conditions for mold growth are provided.

## 2.2 Study of Presently Used Emergency Farm Bins

A study of emergency grain storage bins, used in southwestern Manitoba, was carried out by Muir et al. (1973). The research was conducted to study the condition of grain stored in various types of emergency farm bins. Open-topped and polyethelene-covered bins containing the main cereal crops: wheat, oats and barley were studied. A bin, containing barley, covered with bales of straw and a bin, containing oats, covered with loose straw were also studied. The grain had been stored in the bins in the fall of 1969 and the measurements were taken in late spring and early fall of 1970.

The research revealed that grain deterioration during winter storage could be reduced by covering the grain bulk with a polyethelene sheet having a vent at the apex of the cone. Polyethelene-covered bins without a vent in the top of the polyethelene cover provided a more favorable environment for the development of micro-organisms than bins with a vent. The bins of barley and oats covered with bales of straw and loose straw, respectively, had higher moisture contents near the top surface and walls than the open-topped and polyethelene-covered bins.

During summer, deterioration in polyethelene-covered bins was more than open-topped bins. The deterioration probably was caused by precipitation entering through tears which developed in the polyethelene coverings. The polyethelene cover did not permit the surface grain to dry, whereas in the open-topped bins the precipitation entered but the grain could dry after a short period. If the polyethelene cover was in good condition, the precipitation would probably not enter into the grain pile. The researchers determined that the hazards of storing grain in temporary bins were greater than when similar grain was stored in permanent bins.

The research revealed the ineffectiveness of presently used emergency grain storage structures in preventing grain deterioration and therefore, showed the need for well designed grain storage structures which could store grain safely for a short duration.

## 2.3 Development of Emergency Structures

Gamby (1974) worked on the development of emergency grain storage structures. He designed and structurally tested various bin configurations using plastic as a structural material. A conical bin with shaped floor was constructed entirely of polyethelene. During filling, the bin was supported by an interior wooden frame. Upon filling of the bin, failure of the interior wooden frame occurred due to high elongation of the polyethelene. Work on conical bins was discontinued due to the unavailability of low cost high-tensile strength material.

A cylindrical bin with a Fabrene wall, shaped floor and conical roof was next studied. An air inflation system consisting of a furnace fan and air duct was used to inflate the bin during filling. Upon filling, the bin failed due to excessive elongation of the Fabrene. The air inflation system did not function properly. A slight breeze could cause the inflated structure to move excessively. The equipment needed to inflate the structure increased the cost of the system. Moreover, the availability of the electricity at the erection site might be a problem.

A cylindrical bin with Tu-Tuf wall, shaped floor and conical roof was next considered in the study. The bin wall was reinforced with wire mesh to resist the loads imposed by the grain bulk. An improved air inflation system was utilized. The bin was structurally tested and was satisfactory from that stand point. Therefore, three bins of similar design, but with different venting systems, were built and tested to determine their effectiveness in maintaining grain quality during storage. Although the bins withstood the grain load, they were not effective in preventing grain deterioration during a four-month winter storage period.

Small pin holes in the roof membrane of all three bins developed due to roofs flapping in the wind. Poor sealing characteristics of roof-to-wall joint allowed entrance of moisture in each bin, causing small localized pockets of deteriorated grain. Grain spoiled on the floor in a 2.4 cm thick layer probably due to entrance of moisture through small holes punctured in the floors of each bin.

The researcher suggested that an improved structure should result in less grain deterioration during storage. The moisture entrance through the roof-to-wall joint could be eliminated by using a fastening system with closer tolerances. The moisture movement through the floor membrane could be avoided by using more puncture resistant materials. Small holes in the roof membrane could be prevented through either the loading of the roof section or the use of a stronger material for the roof section.

## 2.4 Bin Pressure Theory

Gupta (1971) determined the lateral pressures exerted by wheat in flexible polyethelene containers. He found that Rankine's, Coulomb's and Janssen's equations were not applicable in their present form to predict lateral pressures in flexible containers. The author established an equation to be applicable in predicting lateral pressures in flexible containers. However, the equation is applicable only to containers of diameter, height and wall thickness tested and cannot be used for other sizes of bin. Hence, in this circumstance the more commonly accepted

Rankine's formula can be used to predict the pressures induced by a grain bulk in shallow bins. In general, a shallow bin is one which has a depth less than the least lateral dimensions of the bin. Rankine's formula is:

$$P = 9.8 \frac{1 - \sin \phi'}{1 + \sin \phi'} wh \qquad \ldots (2.1)$$

where:

P = lateral pressure on the bin wall, Pa

w = bulk density of grain, $kg/m^3$

h = depth of grain to the point under consideration, m

$\phi'$ = angle of internal friction

The Canadian Farm Building Code (National Research Council, 1975) recommends use of $\phi$, angle of repose in place of $\phi'$, angle of internal friction and a multiplication factor of 1.25 for the case of surcharge in the bin.

For a bin with surcharge, Eq. 2.1 becomes:

$$P = 12.3 \frac{1 - \sin \phi}{1 + \sin \phi} wh \qquad \ldots (2.2)$$

Circumferential tension in the bin walls associated to predicted lateral pressures can be predicted by the following formula:

$$T = PD/2 \qquad \ldots (2.3)$$

where:

T = circumferential tension in bin wall, N/m

D = bin diameter, m

# 3. MATERIALS SELECTION

## 3.1 Structural Materials

### 3.1.1 Criteria of selection

Desirable characteristics of a material for use in an emergency bin are:

1. resistance to weathering during the desired life of the storage structure.
2. high long wave emissivities to increase radiant heat loss.
3. low short wave absorptivities to reduce solar heat intake.
4. adequate tensile strength to withstand the loads imposed by the grain bulk and low elongation to maintain structure shape during filling.
5. high puncture resistance to reduce moisture entrance through the floor.
6. low water vapour permeability to minimize moisture entrance from the ambient air, rain and snow.
7. low cost per unit area to minimize structure cost.
8. low weight per unit area to facilitate easy handling.
9. availability in large sizes to minimize the number of joints required during fabrication.
10. resistance to attack by external biological agents such as rodents and birds.

### 3.1.2 Material classification and selection

Two types of materials which could be utilized for the construction of grain storage structures were: self-supporting materials and non self-supporting materials. Self-supporting materials, in general, may be defined as materials which do not require external or internal support during erection. Non-self-supporting materials do not possess inherent rigidity and therefore, require support during erection.

The comparisons made by Gamby (1974) between self-supporting materials and non self-supporting materials were reviewed. Self-supporting materials were found to be comparatively costlier and therefore were not studied further. The non-self-supporting materials, used by Gamby (1974) for the construction of emergency structures, were best suited. Recent information on these materials was obtained. The materials that were used were:

1. cross-laminated polyethelene sheeting (trade name: Tu-Tuf) supplied by Sto-Cote Products, Inc., Richmond, Illinois;
2. polyolefin woven fabric (trade name: Fabrene TM) manufactured by Du Pont of Canada Ltd., Montreal.

### 3.1.3 Physical properties

Physical properties and other available information on both materials are given in Table 3.1. Costs per unit area (applicable in Aug. 1975) were calculated based on volume discounts on the materials for 100 bins. Tu-Tuf sheeting is available in rolls of standard widths 1.3 m, 1.8 m, 2.4 m, 3.0 m, 3.7 m, 4.3 m, 4.9 m, 6.1 m, 7.3 m, 8.5 m, 9.8 m and 12.2 m. Widths other than standard and less than 24.4 m may be ordered. Fabrene is available in rolls, but only 1.5 m in width.

Little change in the tensile properties of Tu-Tuf-4 found after 500 h of exposure to weathering. (Test report on cross-laminated plastic film,Job number 72132R, May 24, 1972, Gaynes Engineering and Testing

Table 3.1

Physical properties and information available for materials used in the fabrication of structure.

| Material | Manufacturer | Colour | Tensile strength N/m | Permeance mg/m$^2$-24 h-Pa | Weight g/m$^2$ | Cost ¢/m$^2$ |
|---|---|---|---|---|---|---|
| Tu-Tuf-3 0.07 mm thick | Sto-Cote | white | 5 340 | 0.133 | 83.0 | 40.9 |
| Tu-Tuf-4 0.1 mm thick | Sto-Cote | white | 5 530 | 0.098 | 118.5 | 48.4 |
| | | black | 5 530 | 0.098 | 118.5 | 51.2 |
| Fabrene TM | Du pont | clear, black, blue | 35 000 | low | 179.6 | 76.6 |
| Wire mesh 1.5 m wide | Russel Steel | - | 34 500 | - | 1 032.0 | 68.5 |
| 1.8 m wide | Dominion Bridge | - | 34 500 | - | 1 032.0 | 74.0 |
| Fish netting | Midwest Net & Twine | white | N.A. | - | 33.7 | 31.2 |

N.A.- Data not available.
Data are supplied by manufacturer.

Laboratories Inc., Chicago, Illinois). Fabrene TM retains 33% tensile strength after 5-10 yr weathering. (Letter dated June 16, 1975 from W. J. Real, Sales Supervisor, Industrial Products, Packaging Division, Du Pont of Canada Ltd., Montreal).

For design purposes, the circumferential tension predicted by Eq. 2.3 can be compared with the tensile strenth of the structural materials. If the predicted value is less than the material strength then the structure will be safe, otherwise the structural material must be reinforced with some high strength material to withstand the grain loads. These additional materials are referred to as reinforcing materials. The tensile strength of reinforcing materials must be equal to or greater than the predicted circumferential tension as the grain loads are transferred from the structural materials to the reinforcing materials.

## 3.2 Fastening Systems

Fastening materials are needed to fasten the structural materials together during fabrication. A fastening system must be of close tolerance to minimize moisture entrance through the seam. The fastening systems used by Gamby (1974) were reviewed and Poly-Fastener (trade name) and Tu-Tuf (trade name) adhesive tape were selected. Recent information on these materials was obtained.

Poly-Fastener is a product of Curry Industries, Winnipeg, and costs $96 (applicable in June, 1976) for a roll, 91.5 m in length. It consists of an extruded polyethelene channel and an insert strip. The two sheets of material to be fastened are placed in the channel and the insert strip is snapped into the channel with the help of a special tool. The insert strip forces the covering material in under the flanges of the channel, holding it evenly across the entire length of the channel. The Poly-Fastener can be used as a fastening system for the Fabrene and Tu-Tuf sheeting.

Tu-Tuf tape, clear in colour, is another fastening system which can be used for Tu-Tuf sheeting. It is a product of Sto-Cote Products, Inc., and is available in two sizes of rolls, 5 cm by 55 m and 10 cm by 66 m. It costs $3.90 for a roll 5 cm wide and $12.20 for a roll 10 cm wide (applicable in Oct. 1975).

## 3.3 Reinforcing Materials

As discussed earlier reinforcing materials are employed to reinforce structural materials that are not able to withstand the pressure imposed by the grain bulk. Use of reinforcing material allows the use of low tensile strength material as a wall membrane. Wire mesh, 6 X 6 - 10/10 gauge (15 cm X 15 cm mesh size and 3.25-mm diameter horizontal and vertical wires) used by Gamby (1974), was appropriate as a reinforcing material due to its high tensile strength, resistance to weathering and low cost (Table 3.1). Wire mesh, 1.5 m wide, is only available in rolls, 61 m in length, whereas, 1.8 m wide wire mesh is available in any desired length.

## 3.4 Extra Sheet for Floor

An extra sheet of material can be used to reinforce the floor to prevent the entrance of water through small holes that are punctured by sharp objects underneath the floor. Transparent polyethelene sheet, 0.15 mm thick, can be used as an extra cover for the floor. It costs

50.9¢/$m^2$.

## 3.5 Restraining Materials

Restraining materials can be used to prevent the roof flapping in the wind. Small holes can develop in the roof membrane due to wind flutter (Gamby, 1974), allowing water into the grain bulk. Therefore it would seem to be desirable that the roof be restrained to prevent the development of pin holes. Restraining materials studied were sto-downs, fish netting and rubber tires.

Sto-downs (trade name) a product of Sto-Cote Products, Inc., are plastic grommets and can be used as a restraining material. They also serve as connectors. They are available in packs of 100 at $8.60 and packs of 1250 at $92.40 (applicable in Oct. 1975). Sto-downs consist of a disc and a clip that has both small and large key-holes. The sheet of material to be fastened is pinched around the disk with the fingers. Then the pinched material and disk are inserted through the large key-hole section of the clip and pulled to the opposite small key-hole opening. The holding rope or line is then connected to the large opening of the clip and the other end of the rope is tied to some support.

Nylon fish netting can also be used to restrain the roofs from flapping in the wind (Table 3.1). Netting is available in any desired length but only 3.4 m in width. Old rubber tires can be put on the roofs to restrain flapping.

# 4. STRUCTURAL TESTING DURING SUMMER 1975

## 4.1 Selection of Types and Capacities of Bins

The initial plan was to design, construct and structurally test 36-$m^3$ capacity bins. Because of the unavailability of an adequate stock of grain at the time of structural testing, a bin capacity of 18-$m^3$ was chosen for this phase of the study. Three different types of structures; bag type; cylindrical bin with Fabrene wall and conical roof and cylindrical bin with Tu-Tuf wall and conical roof were selected for the testing. Improvements in the design of the bins, developed by Gamby (1974), were made. The bins were loaded during summer to observe their performance so that necessary improvements in the design could be made before using them in the storage tests.

## 4.2 Bag Type Structure

A bag type structure without a shaped floor and roof was studied. The advantage of this type of structure is that it requires only one piece of material for fabrication. The use of a single sheet of material minimizes joining during fabrication. In this structure the roof can be tied down at the peak after filling.

Since the structure is fabricated from non-self-supporting material, it requires either an internal or external support system at the time of loading. Internal support system do not appear to be feasible because of the difficulties of installing the support systems in the bin before loading and then removing them, if required, after loading the structure. External support systems such as wire mesh or wooden stakes can be used to support the walls during loading and can be removed after loading.

The bag type structure that was tested had a radius of 2.0 m, a side wall height of 1.2 m, a roof angle of 0.38 rad (angle of repose of wheat, Gupta, 1971) and a capacity of 18 $m^3$ (Fig. 4.1). The structure was fabricated from a 6.1 m by 13.5 m black Tu-Tuf-4 sheet. Poly-Fastener was used to fasten the bottom and wall joints.

Wheat was used as a grain bulk. Assuming the density of wheat at 732 $kg/m^3$, a maximum tension value of 9 940 N/m on the bin wall was predicted using Eq. 2.3. Although the predicted tension value exceeded the actual tensile strength of the material, 5 530 N/m, the bin was tested to observe the overall performance of the structure. No reinforcing material was utilized for wall reinforcement but the bin wall was supported by three persons during loading. A Tu-Tuf sheet was put underneath the structure to avoid grain loss in case of structure failure.

The bin did not perform as expected. The bottom of the bag was not fully loaded with grain. The wall sagged due to excessive elongation of the Tu-Tuf sheet (Fig. 4.2). Further loading of the structure was discontinued when it became impossible to hold the bin wall up due to the high stresses developed in the wall. Because the structure was made without a shaped floor, the floor wrinkled.

The test indicated that modifications in the design of the structure were needed before testing it further. An external support system would be better than holding the bin wall manually.

Based upon the test results, a modified bag type structure with a radius of 2.0 m and side wall height of 1.2 m was designed and fabricated (Fig. 4.1). The structure had a capacity of 18 $m^3$.

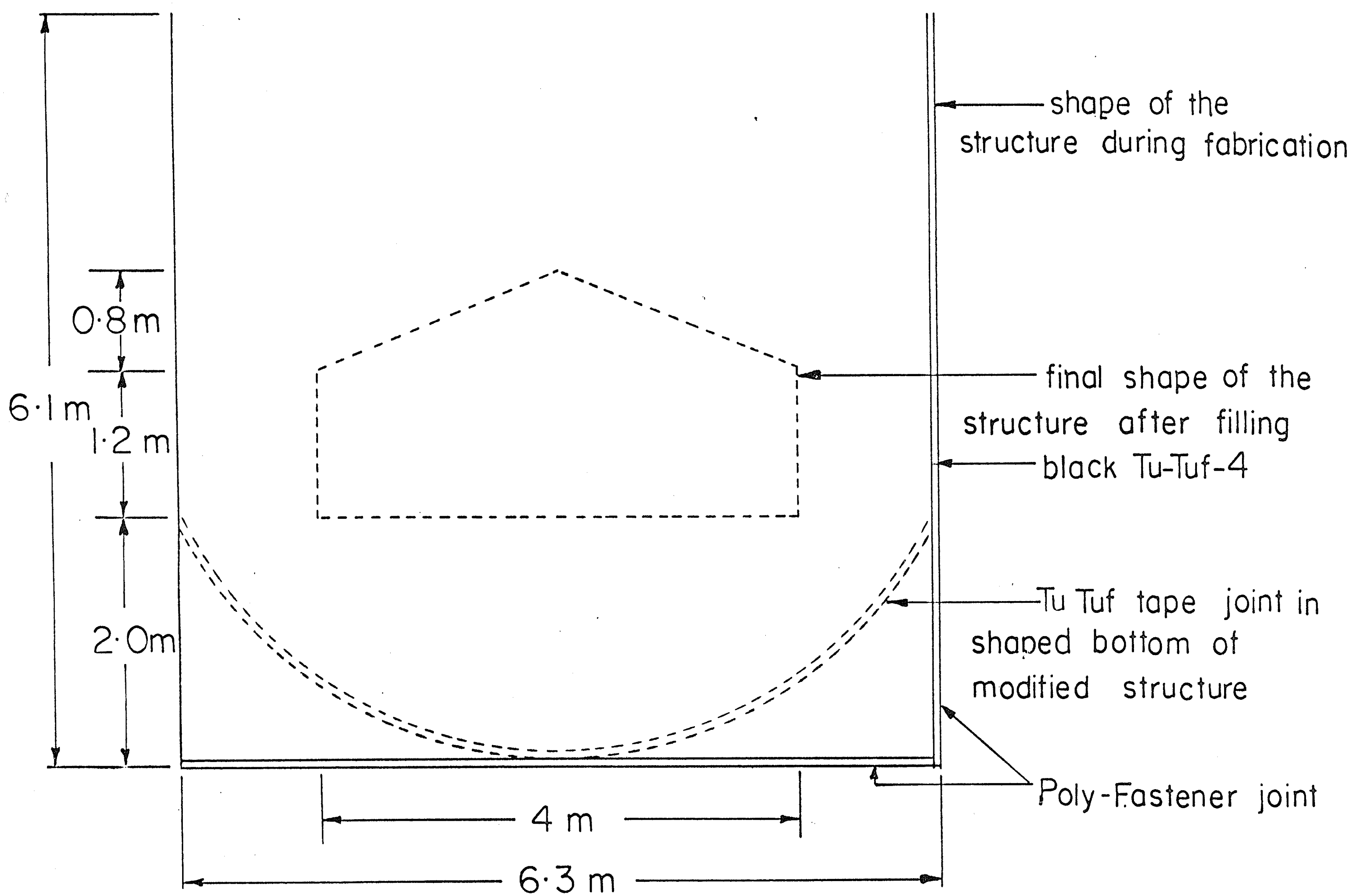



Fig. 4.1 Shape of the bag type structure during fabrication and after filling.

Fig. 4.2 Bag type structure under test.

To minimize wrinkles on the floor and to load the bottom of the structure, the bottom part of the structure was cut in a circular shape (Fig. 4.1). The structure was constructed of black Tu-Tuf-4. The wall and floor joints were secured with 10-cm wide Tu-Tuf tape both inside and outside the structure.

The structure was structurally tested using wheat. The bin could not be filled to the design capacity because of the unavailability of enough grain. The roof was tied down at the peak. It was difficult to pull the roof tight at the peak while standing on it, and as a result, the roof may flap in the wind causing damage to the material. The taped fabrication of the circular floor caused many wrinkles in the Tu-Tuf as well as in the tape which may admit moisture. For these reasons, further work was not continued.

## 4.3 Cylindrical Bin with Fabrene Wall and Conical Roof

A cylindrical bin with shaped floor and roof and a Fabrene wall was structurally tested. The bin, radius 1.9 m and side wall height 1.3 m, had a capacity of 18 $m^3$ (Fig. 4.3).

The floor of the bin was fabricated from a sheet of black Tu-Tuf-4 having a diameter of 4.7 m. This allows for a 20 cm overlap and a clearance of 25 cm above the ground for the floor-to-wall seam (Fig. 4.4a). Keeping the floor-to-wall seam above the ground should prevent the movement of surface water through this joint. A structure with flexible walls such as this one will tend to slump to one side if it is loaded eccentrically. Concentric circles were painted on the floor of the structure to assist in the uniform loading of the bin.

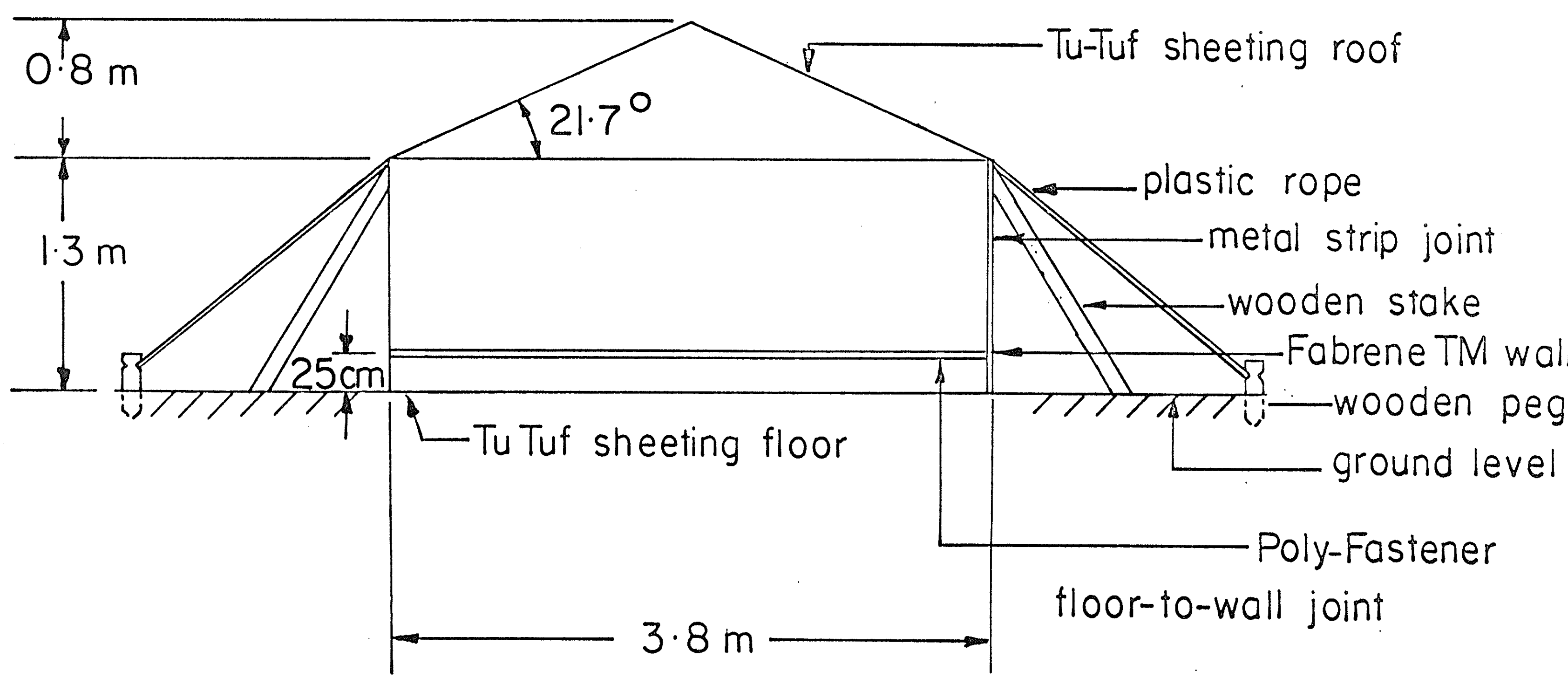
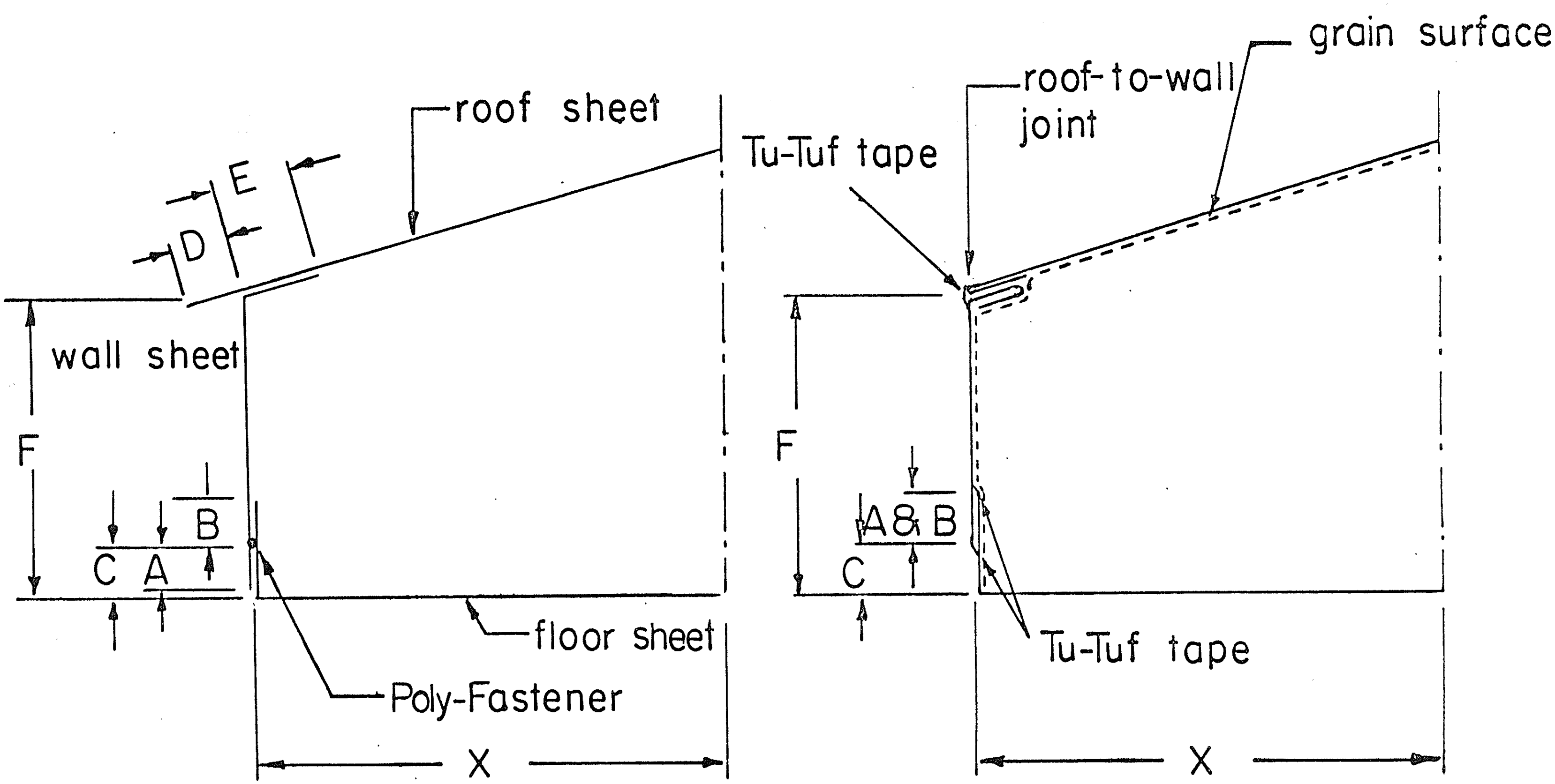



Fig. 4.3 Cylindrical bin with Fabrene wall and conical roof.




a) Poly-Fastener floor-to-wall joint

b) Tu-Tuf tape floor-to-wall joint

Fig. 4.4 Floor-to-wall and roof joints in emergency bins. (The dimensions indicated by the letters are given in Table 4.1).

Table 4.1

Dimensions of the overlaps shown in Fig. 4.4, cm

| Letter code | Poly-Fastener floor-to-wall joint | | | Tu-Tuf tape floor-to-wall joint |
|---|---|---|---|---|
| | Fabrene-wall bin | | Tu-Tuf bin | Tu-Tuf bin |
| | $18\text{-m}^3$ capacity | $36\text{-m}^3$ capacity | $18\text{-m}^3$ capacity | $36\text{-m}^3$ capacity |
| A | 20 | 20 | 20 | 20 |
| B | 20 | 20 | 20 | 20 |
| C | 25 | 25 | 25 | 25 |
| D | 25 | 25 | 25 | 25 |
| E | 25 | 15 | 55 | 65 |
| F | 130 | 140 | 130 | 140 |
| X | 190 | 260 | 190 | 260 |

A piece of Fabrene TM, 1.5 m by 12.8 m, was used for the fabrication of the bin wall. The height of the bin was limited by the size of Fabrene sheets which were only available in 1.5 m width. The dimensions of the overlaps for floor-to-wall and roof-to-wall joints (Fig. 4.4a) are given in Table 4.1.

The roof was fabricated from a black Tu-tuf-4 sheet, 4.7 m in diameter. To obtain the conical shape of the roof with a slope of 0.38 rad, a 0.44 rad segment could be removed from the roof material (Gamby, 1974). To prevent water entrance through the cut joint, the segment was not removed but was folded and taped to give the conical shape to the roof.

Poly-Fastener was used for the floor-to-wall joint. The wall joint was formed by placing the Fabrene sheet ends between two metal strips that were bolted together.

A circumferential tension of 10 200 N/m was calculated using Eq. 2.3. Fabrene with a tensile strength of 35 000 N/m (Table 3.1) was able to withstand the loads imposed by the grain bulk, therefore no reinforcing material was needed to support the structure during loading. Since the structure was made of non-self-supporting material, it required a wall supporting system during erection and loading. A supporting system consisting of 8.5 cm X 37.5 cm wooden stakes 1.8 m long, wooden pegs, 0.6 cm thick plastic rope and angle iron was used (Fig. 4.3 and 4.5).

While filling the bin with wheat, it did not perform well. Gusts of wind caused the bottom of the bin to move excessively during erection and loading. High elongation in the Fabrene resulted in

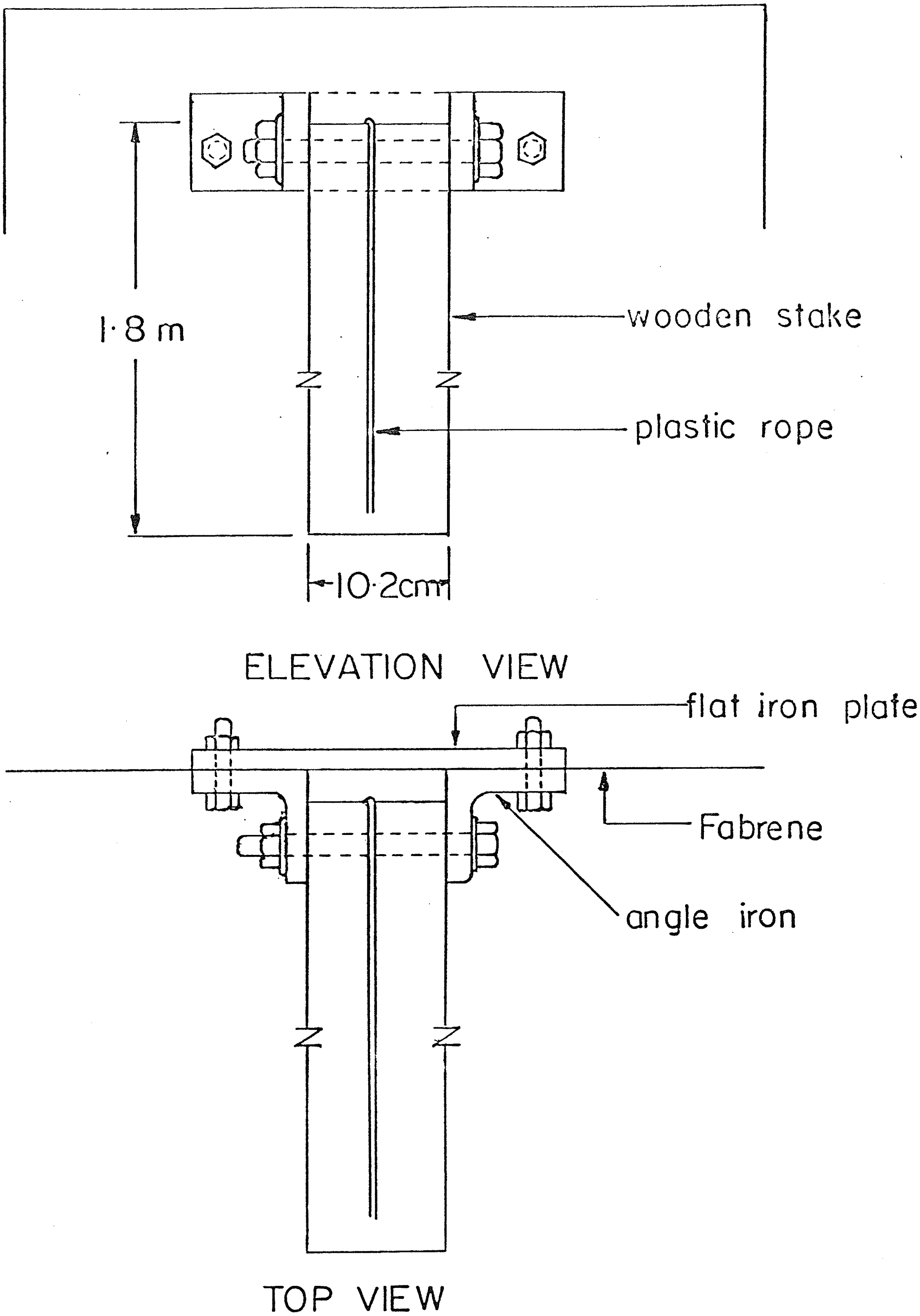



Fig. 4.5 Supporting system for Fabrene wall

sagging of the bin wall. Wooden pegs had to be provided along the base of the structure to prevent an excessive increase in the bin diameter.

The support system did not perform satisfactorily. The wooden stakes had to be adjusted several times during loading which required loosening and tightening of the nuts and bolts. As well, fabrication of the support system involved a considerable amoung of labour.

Test results indicated that some modifications should be made before using the Fabrene-wall bin for a storage test. A new supporting system which could be easily fabricated and installed would be desirable. The bottom of the structure should be held tight to prevent flapping in the wind.

### 4.4 Cylindrical Bin with Tu-Tuf Wall and Conical Roof

A cylindrical bin with a Tu-Tuf wall was designed for a structural test (Fig. 4.6). The bin had the same dimensions and capacity as the Fabrene-wall bin. The difference was that Tu-Tuf sheeting was utilized as a wall membrane instead of Fabrene. Tu-Tuf is a low tensile strength material therefore the wall had to be reinforced.

Wire mesh, 12.9 m in length, was chosen to reinforce the Tu-Tuf wall. Due to unavailability of 1.5 m high wire mesh which would have been sufficient, a 1.8 m high wire mesh was used. The wire mesh had a tensile strength of 35 000 N/m which was greater than the calculated circumferential tension of 10 200 N/m.

Tu-Tuf-4 black sheeting was selected as a structural material for floor, wall and roof. The wall was fabricated from a piece of material 1.8 m X 12.8 m. (Tu-Tuf sheeting was not available in the

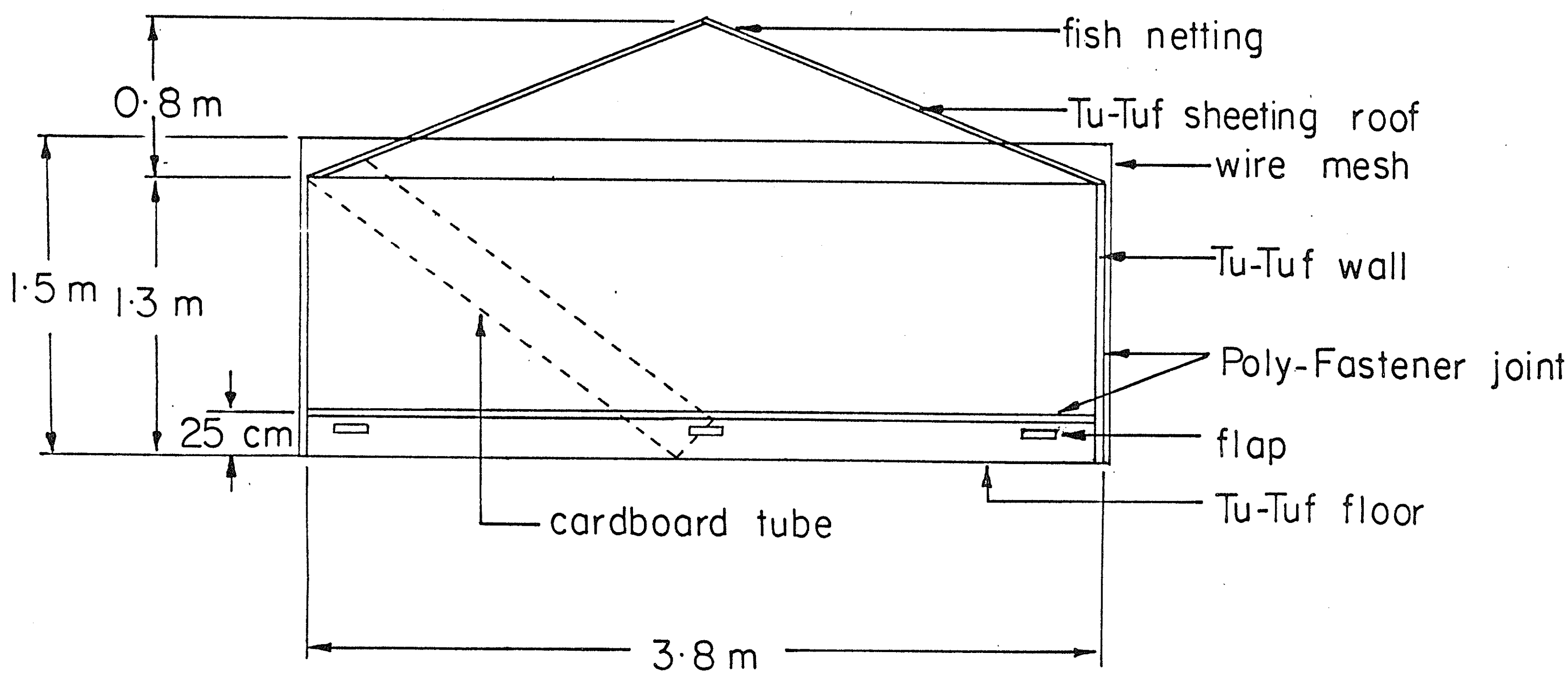



Fig. 4.6 Cylindrical bin with Tu-Tuf wall and conical roof.

desired width, therefore 1.8 m wide sheeting was used). Excess material was left over at the top of the wall (Fig. 4.4a and Table 4.1).

Both floor and roof of the structure were fabricated from Tu-Tuf sheets 4.7 m in diameter. Tu-Tuf flaps, 15 cm X 15 cm, were taped 2.0 m apart around the base of the structure.

The floor-to-wall joint (Fig. 4.4a and Table 4.1) and wall joint were completed using Poly-Fastener. A stronger joint was not needed for the wall because the wire mesh withstood the grain loads.

The wire mesh was erected along a 3.8 m diameter circle drawn on the ground. The fabricated structure was confined inside the wire mesh. To prevent flapping in the wind, the top of the bin wall and bottom flaps were tied to the wire mesh with sto-downs. A 2.3 m long, 25 cm diameter cardboard tube was placed inside the bin (Fig. 4.6) to facilitate unloading.

The structure was filled with wheat and covered with a shaped roof. No fastener was used for roof-to-wall joint. To prevent the roof flapping in the wind, the roof was covered with fish netting. The ends of the fish netting were tied to the wire mesh.

For unloading, the roof was taken off. Because the angle of the cardboard tube did not match that of the grain auger, the grain auger could not be inserted inside the tube. Unloading was accomplished by inserting the auger directly into the grain bulk.

From a structural standpoint, the test results were satisfactory. The bin wall withstood the grain loads. The structure was stable during loading and unloading.

When erecting the wire mesh, it moved laterally on the ground due to wind pressure. This problem could be rectified by driving wooden pegs into the ground around the base of the wire mesh and thus restricting its movement. The angle of repose of wheat was estimated to be 0.35 rad by measuring the cone angle of the grain pile. This value was taken for the design of subsequent bin roofs.

# 5. STORAGE TESTS

## 5.1 Emergency Storage Bins

The objective of the storage test was to observe the condition of the grain in polyethelene emergency bins of different configurations during a storage period of nine months. Different design variables were selected to be studied under farm conditions (Table 5.1). Based upon the results of structural tests during summer 1975, the cylindrical bin with Tu-Tuf wall and conical roof was chosen for storage tests. Four Tu-Tuf emergency bins of similar design but of different configuration were built. One extra Tu-Tuf emergency bin was constructed to replace any test bin that failed during storage. A cylindrical bin with a Fabrene wall and conical roof was also built. Minor modifications in the design of the temporary support system for the Fabrene-wall bin were made.

### 5.1.1 Structural components

Each emergency bin had a design capacity of 36 $m^3$. The different design variables (Table 5.1) were arranged to compare their suitability during the storage tests (Table 5.2). The diameter and sidewall height of each bin was 5.2 m and 1.4 m, respectively.

The floors and roofs of all bins were fabricated from Tu-Tuf sheeting. The floors were fabricated from 6.1 m diameter pieces to allow for a 20 cm overlap with the wall material and a 25 cm clearance for the floor-to-wall seam above the ground (Fig. 4.4b). The roofs were fabricated from 6.1 m diameter pieces leaving excess material for the roof-to-wall joint (Fig. 4.4b and Table 4.1). A 0.39 rad segment

Table 5.1

Design variables in storage tests.

| | |
|---|---|
| Material type: | cross-laminated polyethelene sheeting (Tu-Tuf)<br>polyolefin woven fabric (Fabrene) |
| Material thickness: | 0.06 mm<br>0.10 mm |
| Material colour: | black<br>white |
| Joint fastener: | 5-cm Tu-Tuf tape<br>10-cm Tu-Tuf tape<br>Poly-Fastener |
| Flooring: | single Tu-Tuf sheet<br>extra polyethelene sheet |
| Wall support: | steel mesh<br>temporary wooden stakes |
| Roof fastening and restraining material: | sto-downs<br>fish netting<br>Tu-Tuf tape<br>rubber tires |
| Roof vent: | cardboard tube<br>polyethelene cap<br>no vent |

Table 5.2

Structural components arrangement for emergency bins.

| Strctural components | Bin 1 | Bin 2 | Bin 3 | Bin 4 | Bin 5 |
|---|---|---|---|---|---|
| Floor | white Tu-Tuf-4 and clear poly-ethelene sheet | white Tu-Tuf-4 | white Tu-Tuf-4 | black Tu-Tuf-4 | black Tu-Tuf-4 |
| Sidewall | black Tu-Tuf-4 | white Tu-Tuf-4 | white Tu-Tuf-4 | Fabrene TM | black Tu-Tuf-4 |
| Roof | black Tu-Tuf-4 | black Tu-Tuf-4 | white Tu-Tuf-4 | white Tu-Tuf-2 | black Tu-Tuf-4 |
| Floor-to-wall seam | Tu-Tuf tape on both sides | Tu-Tuf tape on both sides | Poly-Fastener and Tu-Tuf tape on both sides | Poly-Fastener | Poly-Fastener |
| Wall joint | Tu-Tuf tape | Tu-Tuf tape | Poly-Fastener | metal strip | Tu-Tuf tape |
| Roof fastening and restraining material | Tu-Tuf tape | Tu-Tuf tape and sto-downs | Tu-Tuf tape | Tu-Tuf tape | fish netting |
| Roof joint | Tu-Tuf tape | Tu-Tuf tape | Tu-Tuf tape | Tu-Tuf tape | Tu-Tuf tape |
| Vent | cardboard tube | polyethelene cap | no vent | no vent | no vent |
| Wall support | permanent wire mesh | permanent wire mesh | permanent wire mesh | temporary wooden stakes | permanent wire mesh |

was folded and taped on both sides to give a conical shape to the roof sheet. Eight flaps, 15 cm X 15 cm, were taped 2.2 m apart around the base of the bins.

The sidewalls of the Tu-Tuf bins were fabricated from pieces of Tu-Tuf-4, 1.8 m X 17.2 m. Wire mesh, 1.5 m X 17.0 m, was used as a reinforcing material for Tu-Tuf bins.

The sidewall of the Fabrene-wall bin was fabricated from a section of Fabrene 1.5 m X 17.2 m (refer Fig. 4.4a and Table 4.1 for joint overlaps). The support system did not require any fabrication. It was similar to the system used during the summer tests except that sto-downs were used instead of angle irons, nuts and bolts.

Poly-Fasteners and Tu-Tuf tape joints were tested in the laboratory before using them on the test bins. For Tu-Tuf sheeting, the Tu-Tuf tape joint was stronger than the Poly-Fastener joint. Whereas for Fabrene, the Poly-Fastener joint was stronger than the taped joint. Therefore in the Fabrene-wall bin, Poly-Fastener was used for the floor-to-wall joint. To determine the fastening material performance on long-term exposure to weathering, both Tu-Tuf tape and Poly-Fastener were used for floor-to-wall joints in Tu-Tuf bins.

The condition of the structural components of the bins was continually checked during the storage period. The restraining and fastening materials which did not perform satisfactorily were replaced or modified when necessary.

### 5.1.2 Venting system

Ventilation of the space between the grain surface and the roof may be helpful in removing some of the excessive moisture accumulations in the upper layers and in removing excess heat in hot weather or in cooling the grain during winter.

The purpose of using different types of venting systems in the test bins was to observe the moisture migration patterns and magnitude of moisture accumulation and compare them with each other.

Two different types of venting system were constructed for Tu-Tuf bins 1 and 2. Both bins had black roofs so venting methods could be compared with each other and with bin 5 which had no vent.

The vent on bin 1 was constructed of cardboard tubing (trade name: Sonotube) with a diameter of 25 cm and length of 75 cm (Fig. 5.1). Two holes, 15 cm X 15 cm, were cut diametrically opposite, 10 cm from the top of the tube. Three holes, 15 cm X 15 cm, were cut with equal circumferential spacing, 5 cm from the bottom of the tube. To prevent entrance of precipitation through the vent into the bin, a 40 cm long metal container was placed over the cardboard tube and bolted to the tube at two places. After covering the filled bin with the shaped roof which had a 25-cm diameter hole at the apex, the vent was inserted into the grain bulk through the roof hole to a depth of approximately 30 cm. Then the vent was taped on the roof.

The vent on bin 2 was constructed of Tu-Tuf sheeting. A 25-cm hole was cut at the apex of the roof. A piece of the Tu-Tuf sheeting, 77 cm in diameter, was folded into a conical shape (same cone angle as for the roof) and was placed over the hole with 25-cm overlap. The covering piece was taped to the roof at 8 equal circumferential spacings leaving gaps for air circulation (Fig. 5.2).

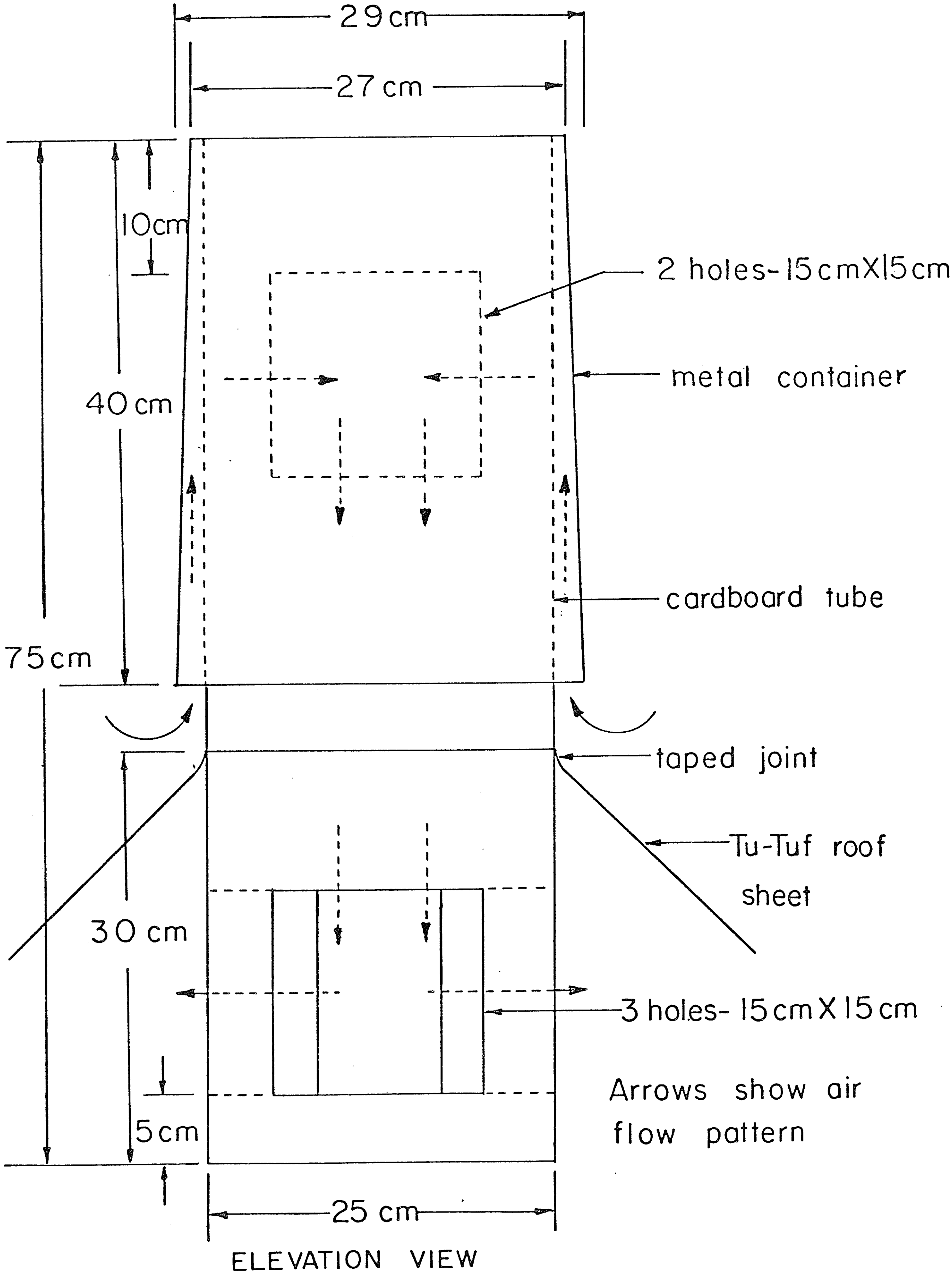



Fig. 5.1 Cardboard vent at the apex of bin.

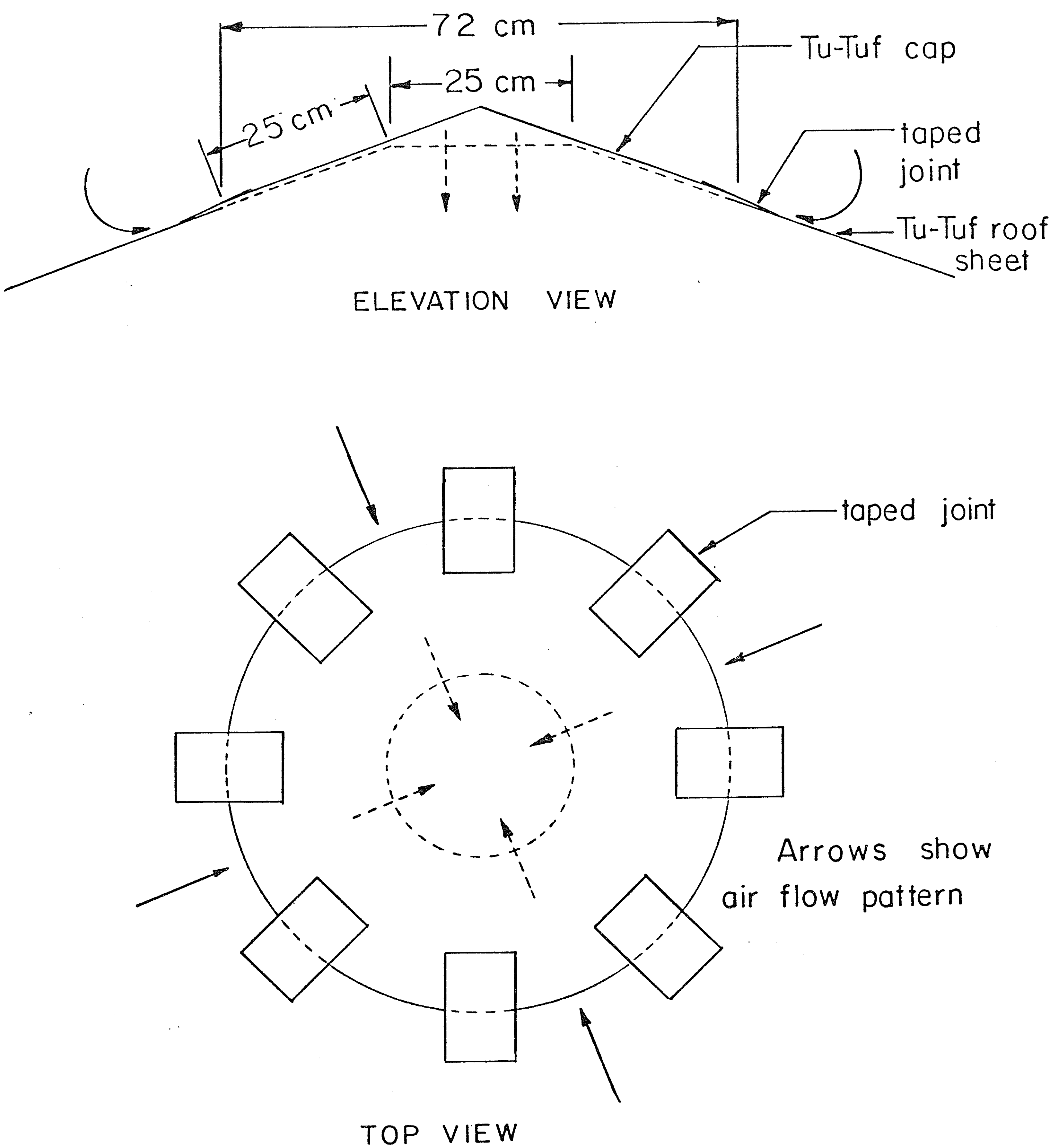



Fig. 5.2 Polyethelene vent.

## 5.2 Permanent Storage Bins

To compare the effectiveness of emergency bins in maintaining grain quality with the effectiveness of permanent bins, one plywood bin and one steel bin were erected. The plywood bin and steel bin had capacities of 52 $m^3$ and 60 $m^3$, respectively (Fig. 5.3 and Fig. 5.7). Both bins had wooden floors on sills 12 cm high. An extra steel ring was put on the steel bin to give more head room for sampling the grain.

## 5.3 Test Procedure

### 5.3.1 Loading and unloading

Farmers would need the emergency bins for surplus grain in early fall when harvesting their crop, therefore in late September 1975 each test bin was erected. The Tu-Tuf bins, 1, 2, 3 and 5 were filled with 27 t of freshly harvested grain. The Fabrene-wall bin could not be filled to design capacity because it began to collapse and was therefore filled with 18 t (Fig. 5.5).

All Tu-Tuf bins were erected in the manner described in Sec. 4.3. Before erecting the wire mesh, wooden pegs were driven into the ground around the bin base. The wire mesh was confined within the peg boundary to restrict its movement. A grain auger with an adjustable spout was used for loading.

The grain was stored in the bins during the fall, winter and spring seasons and was emptied in early summer. (It is anticipated that most farmers would empty their emergency bins in early summer when the ground was dry enough to haul the grain when seeding was completed). Bins 1 to 4 were unloaded on 31 May and 2 June 1976.

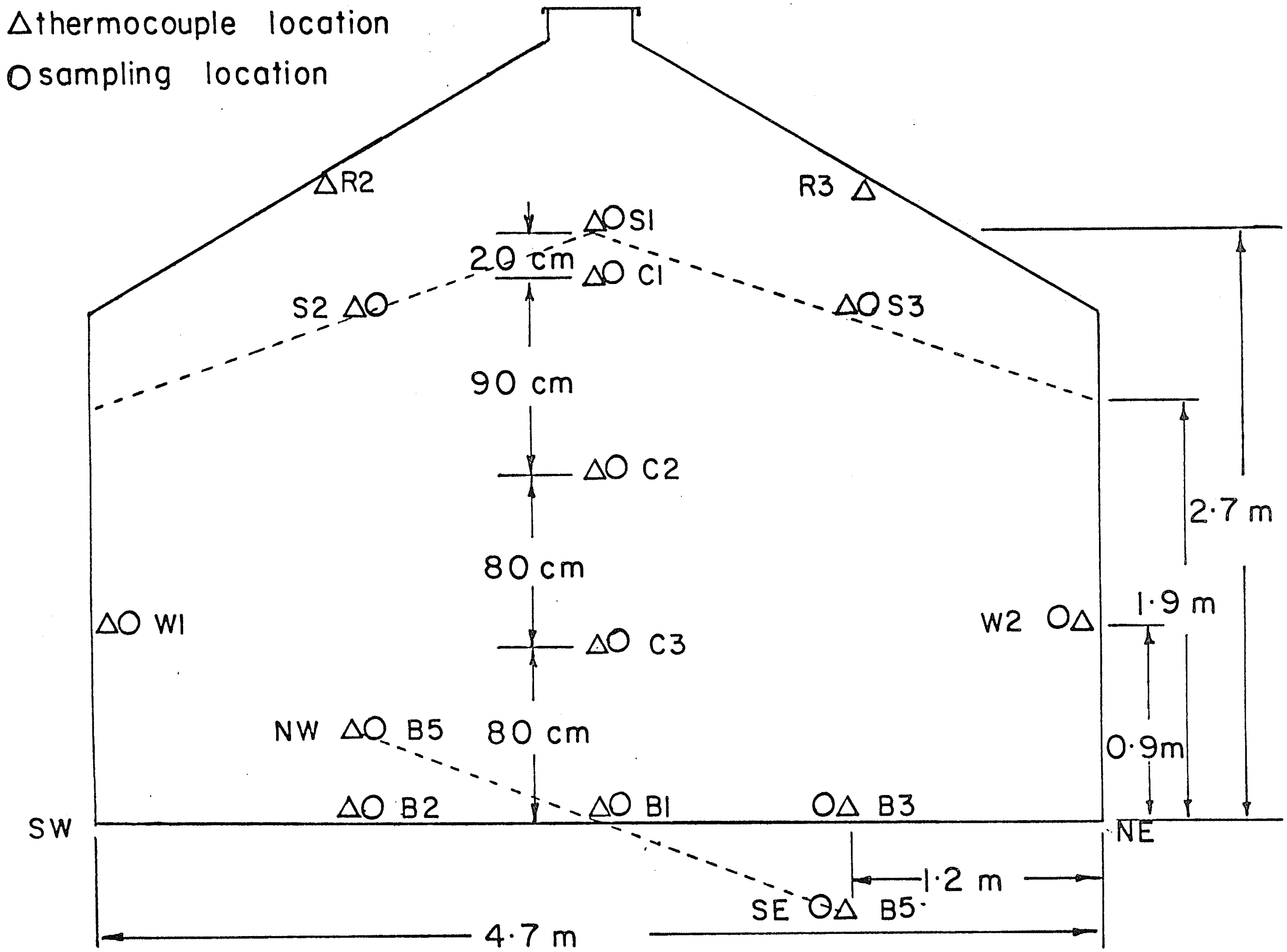



Fig. 5.3 Plywood bin.

O sampling location
Δ thermocouple location

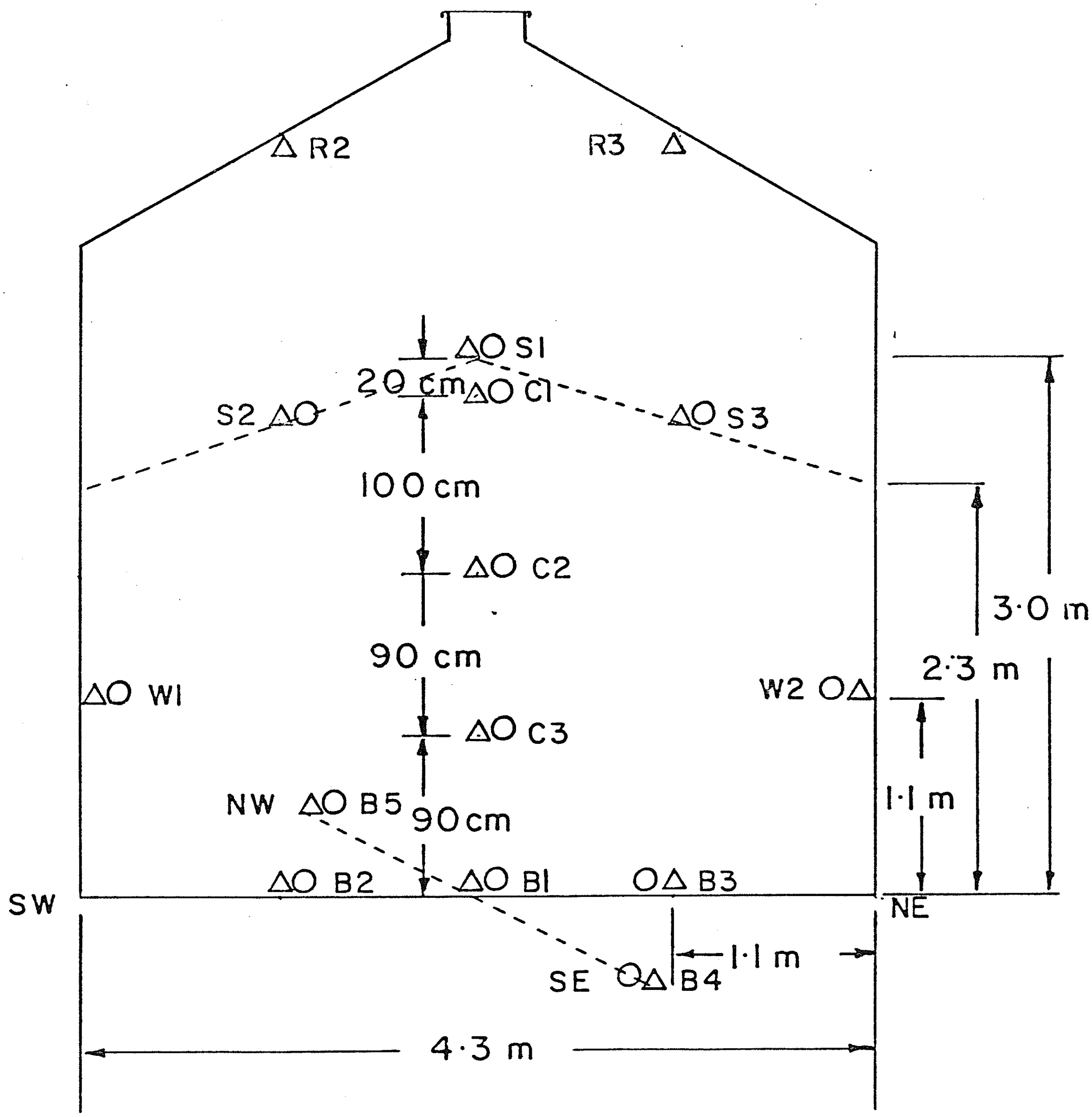



Fig. 5.4 Steel bin.

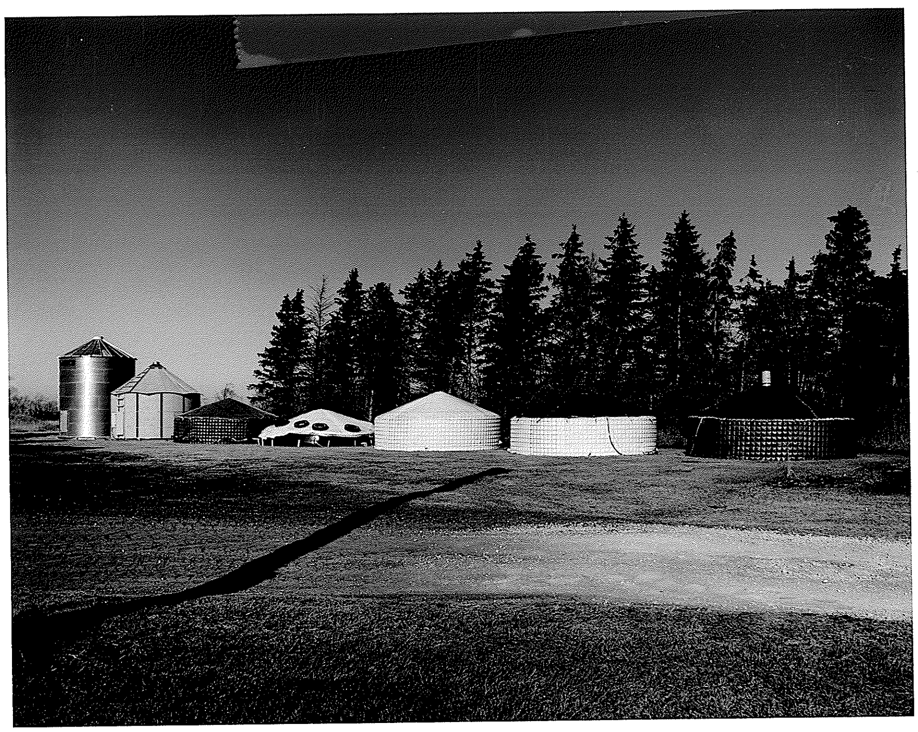


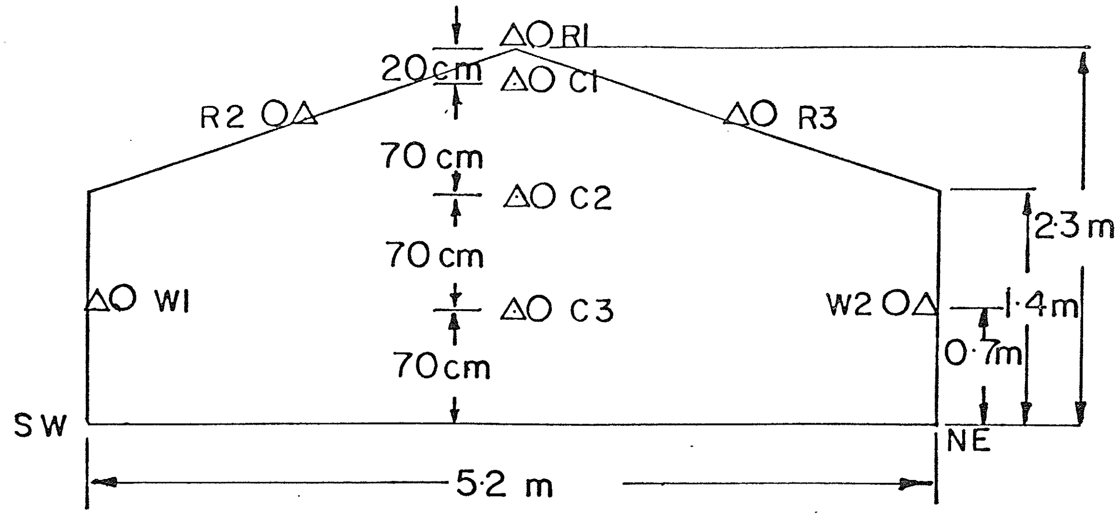
Fig 5.5 Storage bins under test, fall 1975.

Due to bad weather conditions and non-availability of truck, the remaining three bins were not emptied until 23 June to 30 June 1976. The bins were unloaded in the manner described in Sec. 4.3.

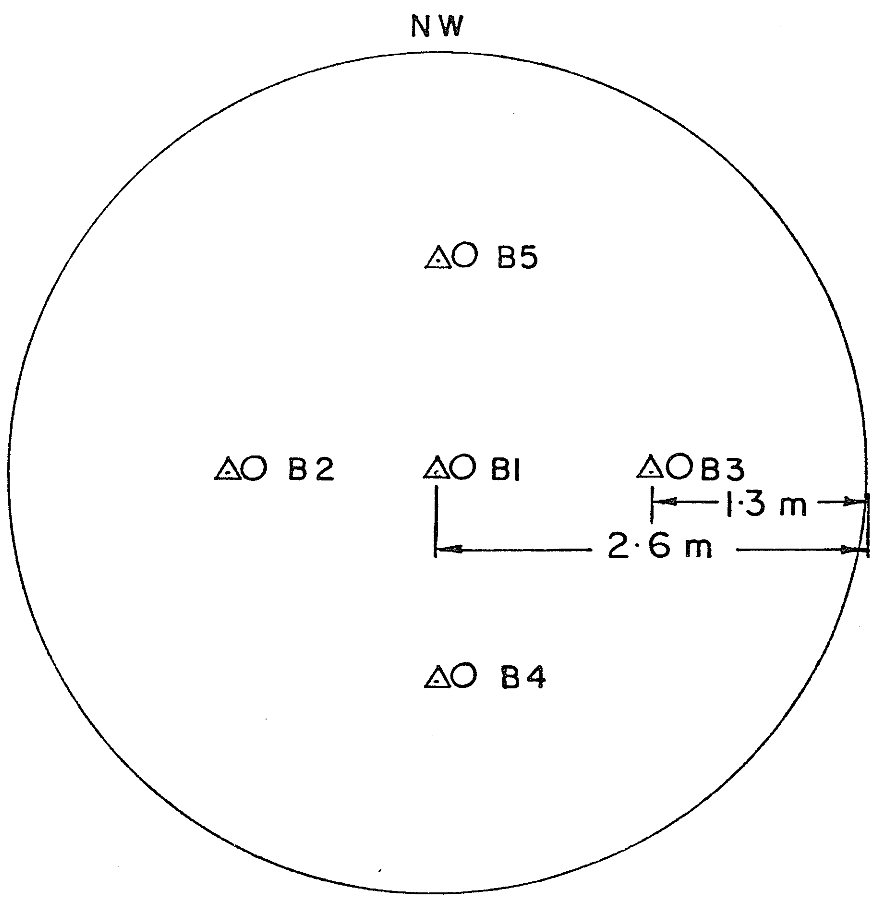
### 5.3.2 Temperature measurement technique

Temperatures were sensed at 13 locations in each emergency bin (Fig. 5.6) and at 15 locations in each permanent bin (Fig. 5.3 and Fig. 5.4). The 0.81-mm diameter copper-constantan thermocouples were employed for temperature measurements. The thermocouples were taped on the floor, wall and roof at their respective positions before filling the bins. For thermocouples located along the centre axis of the emergency bins, a 10 cm X 10 cm wooden piece was placed at the bottom centre and a 1.4-cm diameter by 2.5-m long rod was manually held vertically on the wooden piece. The thermocouples were attached to the rod with a plastic cord in such a manner that removing the rod after the bin was filled, did not change the thermocouple locations. During filling, one person held the rod vertically until the grain trapped the upper thermocouple. Then the rod was pulled out of the grain bulk leaving the thermocouples at their positions. In bins 6 and 7 which had wooden floors, a nail was driven into the floor centres and a plastic cord was tied along the centre axis. Thermocouples were taped along the cord at their respective locations. The top thermocouple was placed after filling each of the bins.

The thermocouple outputs were sensed with a digital indicator (manufactured by United Systems Corporation, Dayton, Ohio), range $-190^{\circ}C$ to $400^{\circ}C$, with minimum graduations of $0.1^{\circ}C$. The temperatures were measured monthly during winter but frequency of measurement was




ELEVATION VIEW




TOP VIEW

Fig. 5.6 Thermocouple and sampling locations in the emergency bins.
(Thermocouple locations in 'TOP VIEW' are on the bin floor).

more during fall and spring when greater biological activity could be expected. The roof and wall temperatures of each bin were recorded hourly on May 27, 1976 to determine how rapidly different materials were affected by solar radiations.

### 5.3.3 Sampling technique

During filling and emptying of the bins, grain samples were taken from each truck and from 13 locations in each bin (Fig. 5.3, Fig. 5.4 and Fig. 5.6). Samples were taken at different locations in each truck using a car probe. The truck samples for each bin were combined and passed through a Boerner sampler to obtain composite samples. During the unloading of each bin, additional samples were taken from the areas of suspected high moisture content. During the storage period on March 22, 1976, five samples were taken using a tropedo probe from the centre axis and the top surface (southwest side) of each bin. Again on April 29, 1976, four samples were taken from along the central axis. A more complete sampling could not be taken during the winter or spring because of the possibility of irreparable damage to the Tu-Tuf sheeting during sampling. The samples were stored in plastic bags in a cool room until tests could be performed in the laboratory. Moisture content of each sample was determined with a Halross Model 919 moisture meter. Moisture contents of samples from each bin were also taken by oven drying at 130°C for 19 h, to check the accuracy of the moisture meter. Grade and dockage of each composite sample was determined by the Canadian Grain Commission using their standard methods.

## 6. LABORATORY TESTS PROCEDURE

Qualitative tests on the tensile strength of Tu-Tuf sheeting and taped joints were carried out in the laboratory during the winter of 1975-76 to determine the materials resistance to weathering. Three replications of each sample were run. Black and white Tu-Tuf sheets and joints made with 5-cm and 10-cm Tu-Tuf tape were tested in the laboratory before and after being exposed to outside winter weather for 10, 22, 44 and 76 days. White Tu-Tuf sheet with a 10-cm tape joint and unjoined black Tu-Tuf sheet were tested at $-22^{o}C$ to determine the effect of low temperature on tensile strength. To determine the deterioration of black and white Tu-Tuf sheeting after nine months of weathering, tests were run on material samples cut from bins 1 and 2 at the termination of the storage period. Samples were taken from the black Tu-Tuf roof of bin 1 and from the floor, wall, wall-to-floor joint (outside and inside the bin) and wall joint (outside and inside the bin) of bin 2. More extensive sampling from other bins could not be done because of the possibility of using these bins for subsequent storage tests.

For the tensile strength tests, a specimen of the dimensions given in Fig. 6.1 was prepared. The ends of the specimen were sandwiched between two wooden blocks and a metal container was attached to the lower wooden block. Sand was poured into the container at a uniform rate until the specimen failed. The load at failure was determined by weighing the sand and container.

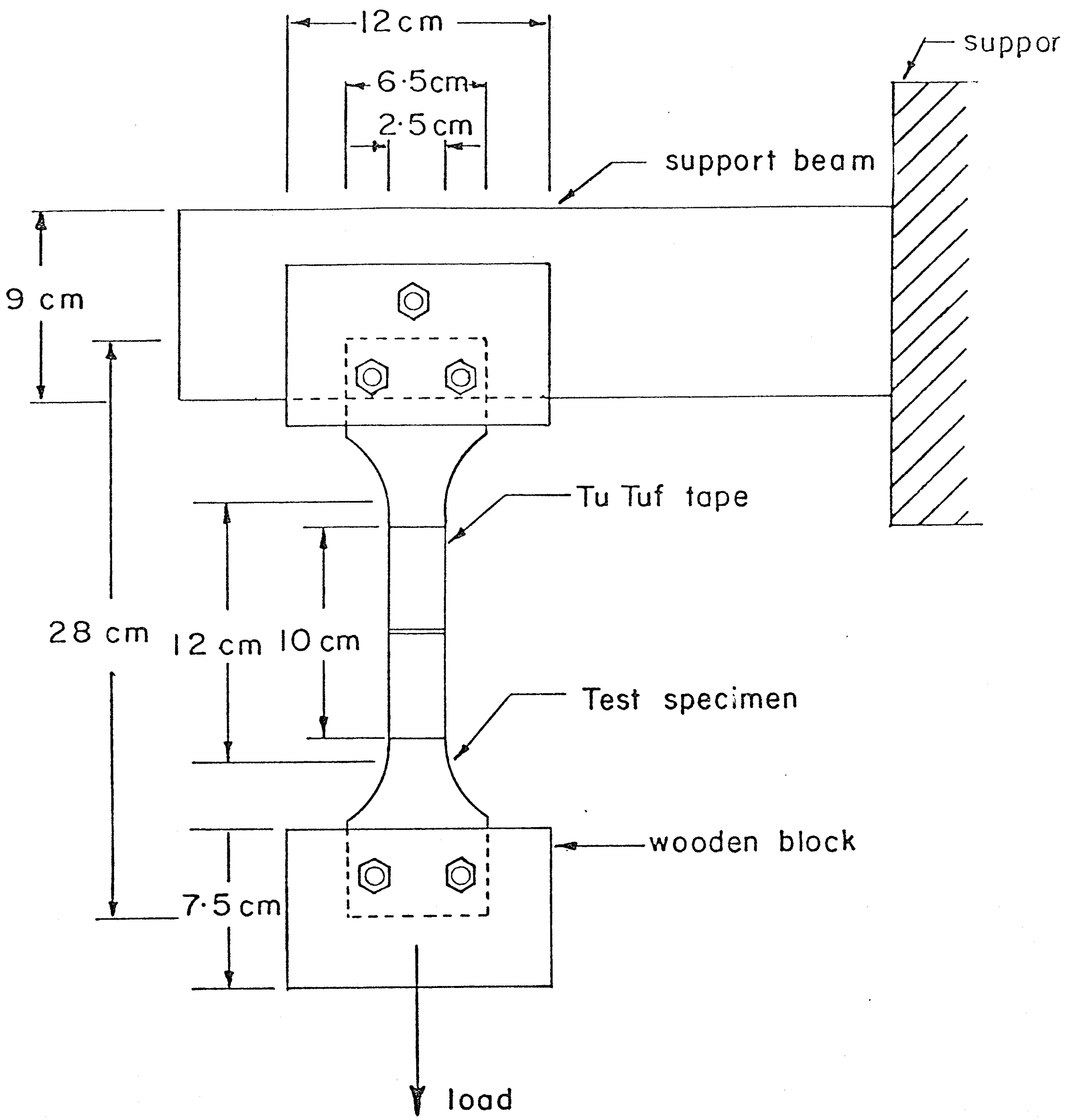



Fig. 6.1 Testing of sample in laboratory.

# 7. RESULTS

## 7.1 Condition of the Bin Material

The Fabrene-wall bin underwent excessive elongation and filling had to be stopped when it was approximately 2/3 full. Excessive elongation of the Fabrene resulted in failure of the temporary wall support system. The four Tu-Tuf bins were easily erected, filled and emptied. Some problem was experienced with bin 5 in keeping the Poly-Fastener floor-to-wall seam in line above the ground level. During filling, no problem of eccentricity was experienced.

Fastening of the roof-to-wall joint was a problem. Grain running through this joint was difficult to check during taping. The grain rolled over the wall sheeting which was in the same plane as the grain surface. Once the joint was taped this overflow problem was checked.

Because the roofs were placed after filling, the gap between the roof and the grain bulk was negligible. Moreover, the roofs of bins 2 and 5 were restrained by sto-downs and fish netting, respectively. Hence no roof flapping was evident in bins 2 and 5 during the storage tests. The other roofs flapped slightly in the wind but it was not a serious problem. A few pin holes (15 to 20) developed in the black roofs by the end of the storage period. Apparently the type of roof restraining materials did not affect the development of holes in the roof. Almost no holes were found in the white roofs.

The bins withstood the grain loads during the storage period. Weathering effects on the steel mesh and wall membranes of the test bins appeared to be negligible. The wire mesh could probably be reused a number of times.

The Tu-Tuf tape used to join the roof-to-wall joint in bin 4 did not stick well to the Fabrene. The joint started failing after about one month, indicating that this tape is not a good fastening material for Fabrene. The roof was tied to wooden pegs with sto-downs and covered with a small piece of fish netting. Some rubber tires were put on the roof to prevent it flapping.

Tape used for the roof-to-wall joint in the other bins also deteriorated probably due to ultraviolet radiation. To prevent the roofs flapping in the wind, rubber tires were put on the roofs when the snow started melting. The joints were retaped at the end of March and at the beginning of May. The 5-cm tape deteriorated more rapidly than 10-cm tape. Flapping of the roof and ultraviolet radiation loosened the roof membrane joints on bins 1 and 3. The joints were retaped at the end of March. No such problem was found in bins 2, 4 and 5 which did not have flapping roofs. All other taped joints seemed to be satisfactory during the storage period.

A few sto-downs (5 out of 16) were found to be broken at the end of May probably due to over-tightening of the support line. The fish netting was still in good condition at the termination of the storage period. The main problem with fish netting was the difficulty in forming a circular shape and then tying it over the roof.

A few pin holes and other larger holes (less than 4 mm in diameter) were observed in the floors of the emergency bins which did not have the extra polyethelene sheet. The holes were likely caused by debris under the bins which punctured the floors. Bin 1 had a few small holes in the outer Tu-Tuf floor but the upper polyethelene sheet was punctured only at two or three places.

During winter, some snow blew into the plywood bin and steel bin around the roof cap. The snow piled up on the peak of the grain bulk, about 5-cm thick and 40-cm in diameter in the plywood bin and about 7-cm thick and 60-cm in diameter in the steel bin. Some snow blew in through the vent of bin 1 because some spoiled grain was found at the peak during unloading. No such problem was evident in bin 2 which had a polyethelene cap.

Mouse holes in the sides of bins 1 to 4 were found during spring. The mice lived under the snow that piled up on the north side of the bins during winter. When the snow melted, the holes allowed snow water to enter the bottom 5 to 10 cm of wheat which caused rotting of the grain. There were no holes in bin 5 which had less snow piled around it.

### 7.2 Temperature

During filling, average temperature of the grain in each bin ranged between $14^{o}C$ to $18^{o}C$. As the average temperature of the ambient air (average of the mean daily temperatures over a 15-day span taken at Winnipeg International Airport) decreased during the storage period, the temperature at each thermocouple location also decreased. Since the roof and wall thermocouples were attached to the bin structural material, these temperatures were most noticably affected by changes in the ambient temperature. Temperatures of the bottom thermocouples were more slowly affected by the ambient temperature because the thermocouples were attached to the bin floors and they were affected more by the soil and grain temperatures. In the plywood bin and steel bin, air passed underneath the bin floor and affected floor temperatures. The temperatures of the centre thermocouple were only slowly affected by the ambient temperatures. Three bins, 3, 5 and 7 were selected to represent the temperatures behavior (Fig. 7.1). (Bin 3 in which water entered through holes chewed by mice which resulted in grain spoilage on the floor, bin 5 in which no holes were found and bin 7 which was a steel bin used to compared with the emergency bins).

Until the end of March 1976, the temperature measurements did not indicate any grain spoilage in any of the seven bins. By the second week of April, however, a rapid increase in the temperatures of the bottom thermocouples of bins 2, 3 and 4 and the northwest thermocouple of bin 1 indicated the presence of hot spots (Fig. 7.2). No similar signs of grain deterioration were noticed in the other bins. The hot spots in bins 1 to 4 developed after the snow melted and water entered the bins through holes chewed by mice. Unloading of the bins confirmed that grain rotting had occurred on the floors of these bins. No other hot spots were noticed at any other location in any of the bins.

Hourly measurement of the roof temperatures indicated that Tu-Tuf black sheeting was rapidly affected by solar radiation (Fig. 7.3). Tu-Tuf white sheeting reached a maximum temperature abut $10^{\circ}C$ lower than the maximum temperature of Tu-Tuf black sheeting. The plywood bin and steel bin were more slowly affected by solar radiation.

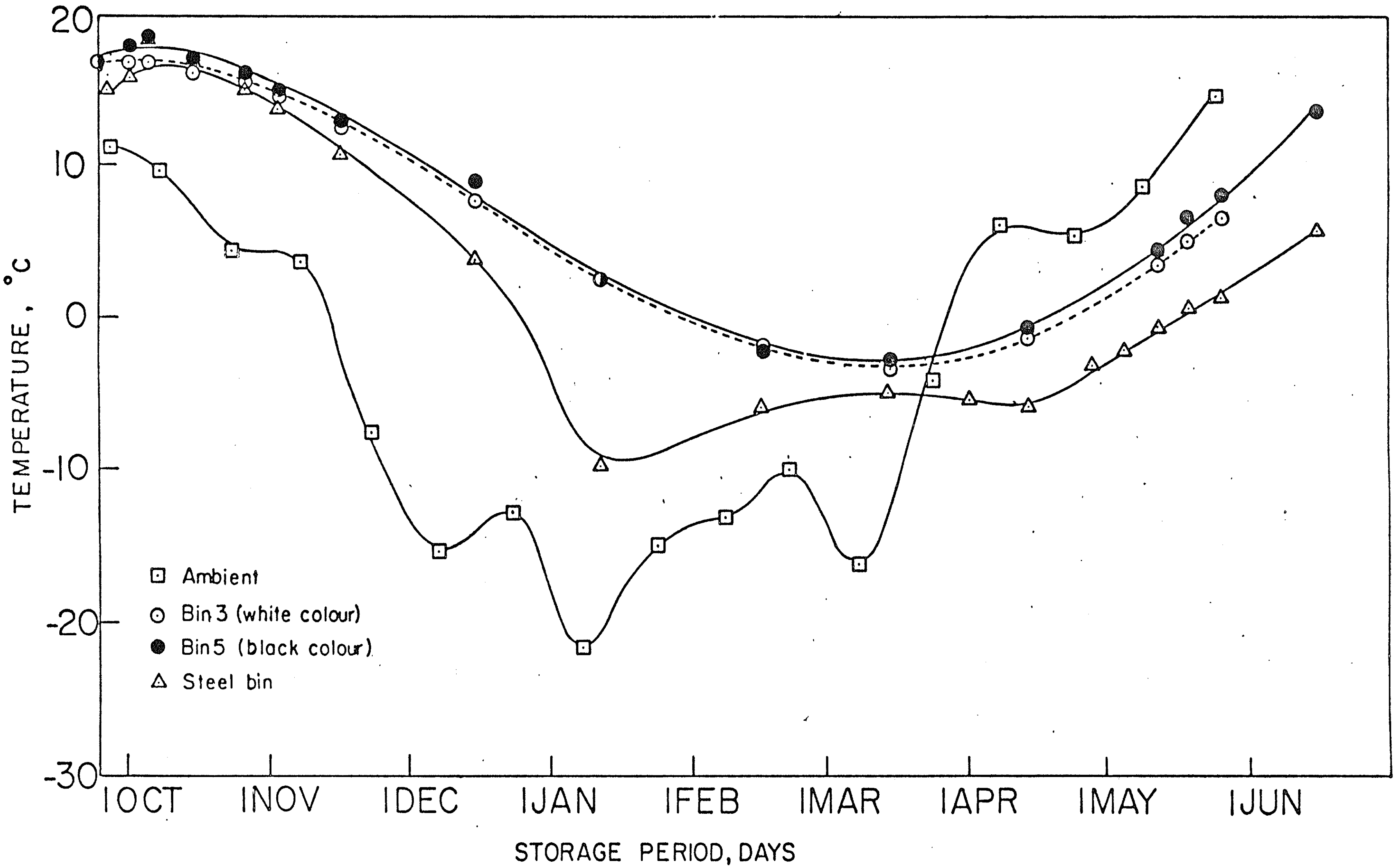



Fig. 7.1 Temperature at bin centre (C2).

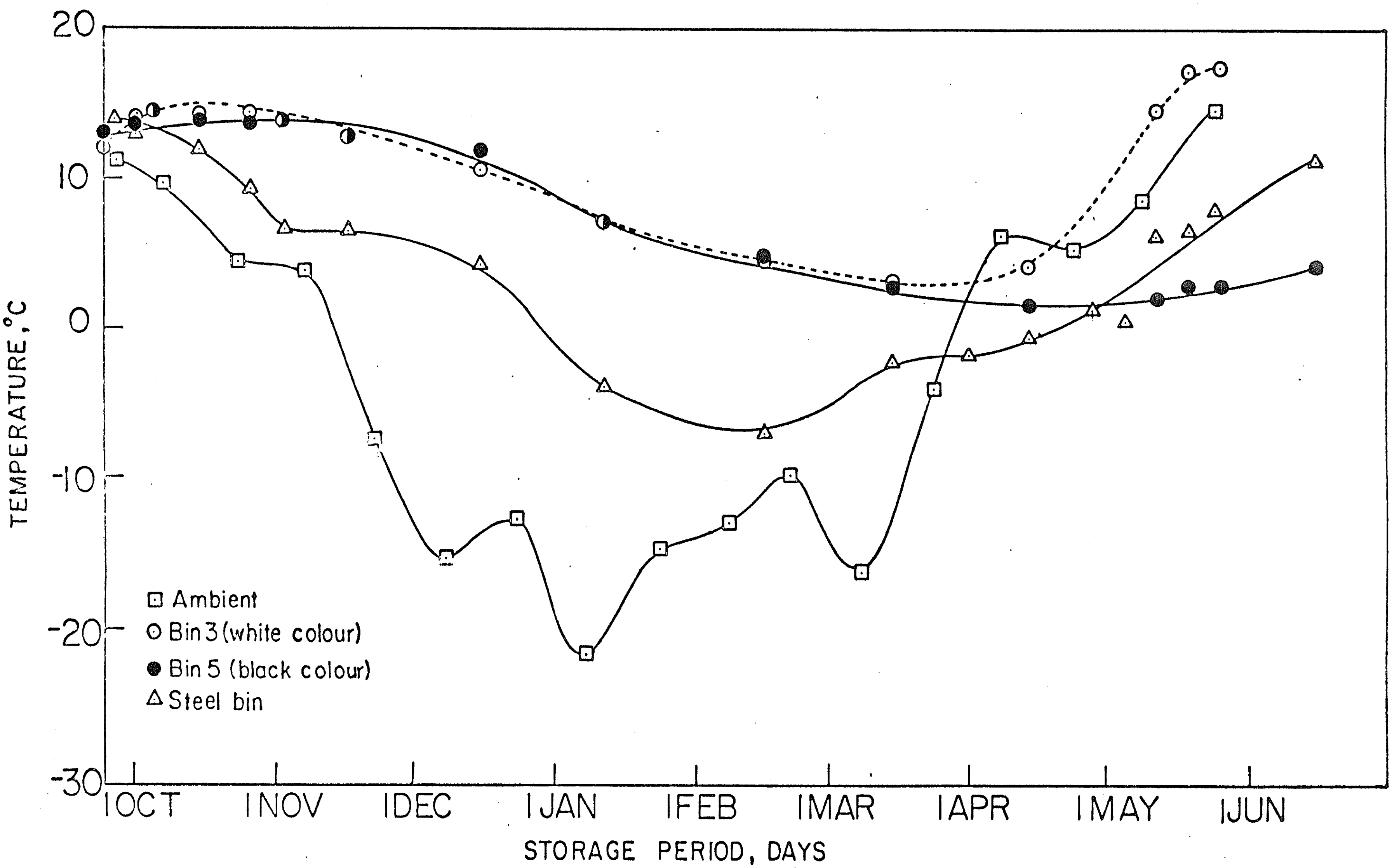



Fig. 7.2 Temperature at bottom centre (B1).

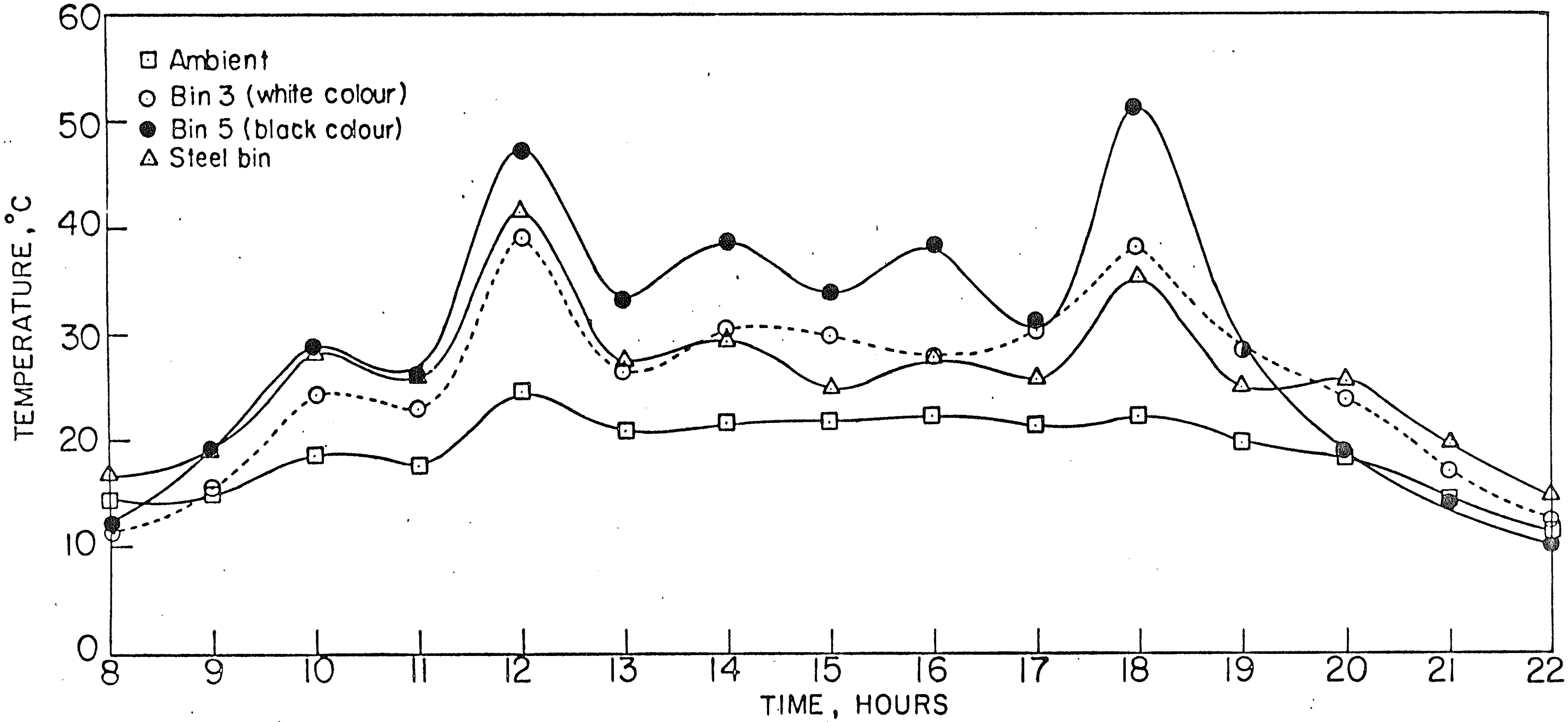



Fig. 7.3 Hourly temperature variation of the southwest side of the roofs.

## 7.3 Moisture Content

The moisture contents taken by ovendrying were about 1% lower than the moisture contents taken by the Halross moisture meter. Since only check samples were analyzed by oven drying, the moisture contents taken by moisture meter were used in the study.

Spring sampling of the stored wheat, on March 22, 1976, indicated that the moisture contents at the peaks of the two bins with vents increased to about 17% from an initial moisture content of 13.8% (Table 7.1). The grain at the peak in bin 1 did not dry during early summer. In bin 2, the grain had dried to 13.8% moisture content by unloading time. In the remaining three emergency bins without vents, the average moisture content at the peaks increased to 15.1% by March 22, 1976 and then decreased to 13.4% when unloaded. The moisture contents at the peaks increased to 22.3% in the plywood bin and 24.3% in the steel bin when sampled during spring. However by June 17, 1976, the grain had dried to 13.6% and 13.1% in the plywood bin and the steel bin, respectively. The moisture contents at 20 cm below the top of each bin increased during spring probably due to moisture migration and remained almost constant until unloading time (Table 7.1). High moisture contents at this location in bins 6 and 7 were probably due to moisture accumulation after the snow at the peak melted.

During unloading, a layer of high moisture content grain approximately 8-cm thick was found on the floors of bins 2 and 3 and approximately 3-cm thick in many areas on the floors of bins 1 and 4, because the water entered through holes chewed by mice. Moisture contents in the range of 14.5% to 54.0% were measured in bins 2, 3 and 4. In bin 1,

Table 7.1

Moisture content at different locations in each bin, % wet basis.

| Location | September, 1975 | March 22, 1976 | April 29, 1976 | June, 1976 |
|---|---|---|---|---|
| 1B1 | 13.9 | - | - | 14.9 |
| 1C2 | 13.9 | 14.0 | 14.6 | 15.1 |
| 1C1 | 13.9 | 14.7 | 16.8 | 16.2 |
| 1R1 | 13.6 | 16.6 | 16.1 | 16.4 |
| 1R2 | 13.5 | 13.7 | - | 11.5 |
| 1W1 | 13.9 | - | - | 11.8 |
| 1Com* | 13.8 | - | - | 14.3 |
| 2B1 | 13.8 | - | - | 31.2 |
| 2C2 | 14.0 | 14.4 | 14.7 | 14.8 |
| 2C1 | 14.3 | 15.7 | 15.8 | 15.3 |
| 2R1 | 13.9 | 17.3 | 12.8 | 13.8 |
| 2R2 | 13.7 | 13.4 | - | 10.7 |
| 2W1 | 14.1 | - | - | 13.4 |
| 2Com* | 13.8 | - | - | 14.9 |
| 3B1 | 14.2 | - | - | 48.5 |
| 3C2 | 14.3 | 14.6 | 14.9 | 15.1 |
| 3C1 | 14.3 | 14.9 | 15.6 | 15.8 |
| 3R1 | 14.1 | 15.8 | 14.4 | 12.9 |
| 3R2 | 14.3 | 13.9 | - | 11.2 |
| 3W1 | 14.3 | - | - | 14.1 |
| 3Com* | 14.3 | - | - | 14.8 |
| 4B1 | 13.8 | - | - | 41.2 |
| 4C2 | 13.9 | 14.0 | 14.4 | 14.5 |
| 4C1 | 13.8 | 14.4 | 15.1 | 15.0 |
| 4R1 | 13.6 | 15.1 | 14.8 | 13.8 |
| 4R2 | 13.6 | 13.7 | - | 11.8 |
| 4W1 | 13.7 | - | - | 12.2 |
| 4Com* | 13.9 | - | - | 14.5 |
| 5B1 | 13.6 | - | - | 14.4 |
| 5C2 | 13.5 | 13.9 | 14.1 | 14.7 |
| 5C1 | 14.1 | 14.5 | 15.0 | 15.6 |
| 5R1 | 13.9 | 14.5 | 14.4 | 13.5 |
| 5R2 | 13.7 | 14.5 | - | 11.6 |
| 5W1 | 13.5 | - | - | 11.7 |
| 5Com* | 13.9 | - | - | 14.4 |
| 6B1 | 13.7 | - | - | 13.9 |
| 6C2 | 14.2 | 14.1 | - | 14.9 |
| 6C1 | 14.4 | 16.0 | - | 17.1 |
| 6S1 | 14.3 | 22.3 | - | 13.6 |
| 6S2 | 14.0 | 16.6 | - | 13.5 |
| 6W1 | 14.2 | - | - | 14.5 |
| 6com* | 14.2 | - | - | 15.4 |
| 7B1 | 13.8 | - | - | 15.8 |
| 7C2 | 14.3 | 13.8 | - | 14.7 |
| 7C1 | 13.9 | 15.6 | - | 17.7 |
| 7S1 | 14.0 | 24.3 | - | 13.1 |
| 7S2 | 13.8 | 16.9 | - | 13.3 |
| 7W1 | 14.4 | - | - | 15.1 |
| 7Com* | 14.1 | - | - | 14.7 |

First numerical value in column 1 indicate the bin number.
* Composite sample.

the grain rotted at the northwest side of the floor with a moisture content of 44%. The moisture contents at other floor locations of bin 1 and all floor locations of bin 5 were in the range of 13.6% to 14.9%. A small amount of high moisture content grain was found at isolated locations in a layer of approximately 1 cm thick on the floors of bins 5 and 7. No such high moisture content grain was found in bin 6.

## 7.4 Grain Condition

Commercial grade of the wheat in each bin did not change during storage (Table 7.2). Dockage of stored grain at loading and unloading the bins were almost the same except for bin 6 (Table 7.2).

The total shortage in quantity and commercial value of the grain stored for nine months was estimated (Table 7.3). (The commercial value is based on the total final price received by Canadian farmers for the crop year ending July 31, 1975). The grain losses in bin 6 and 7 could not be separated because the grain was combined into one large bin before being weighed. The total grain shortage included grain spoilage during storage and grain (around 52 kg per bin) taken off from each bin during gtain sampling. However, the weight increase during storage due to the moisture content increase of the grain was not subtracted from the amount of grain unloaded. (The total increase in weight was estimated to be in the order of 135 kg in bins 1, 3 and 5, 297 kg in bin 2, 108 kg in bin 4, 324 kg in bin 6 and 162 kg in bin 7).

## 7.5 Laboratory Tests

Results on the tensile strength of Tu-Tuf sheeting indicated that white Tu-Tuf was stronger than black Tu-Tuf (Table 7.4). Tensile

Table 7.2

Commercial grade and dockage of stored grain during filling and emptying the bins.*

| Bin | September, 1975 | | June, 1975 | |
|---|---|---|---|---|
| | Canada Western Red Spring grade | Dockage % | Canada Western Red Spring grade | Dockage % |
| Bin 1 | 2 | 4.00 | 2 | 4.25 |
| Bin 2 | 2 | 3.50 | 2 | 3.00 |
| Bin 3 | 1 | 2.50 | 1 | 2.25 |
| Bin 4 | 2 | 2.25 | 2 | 2.50 |
| Bin 5 | 1 | 2.00 | 1 | 2.50 |
| Bin 6 | 1 | 8.25 | 1 | 3.00 |
| Bin 7 | 2 | 2.50 | 2 | 2.50 |

* Mean of 4 composite samples from each bin.

Table 7.3

Loss in grain quantity and commercial value of grain stored for 9 mo.

<table>
<tr><th>Bin</th><th>Amount of grain stored<br>t</th><th>Amount of grain unloaded<br>t</th><th>Shortage<br>t</th><th>Dollar value of shortage</th><th>Percent shortage<br>%</th></tr>
<tr><td>Bin 1*</td><td>27.30</td><td>27.02</td><td>0.28</td><td>44.24</td><td>1.0</td></tr>
<tr><td>Bin 2*</td><td>27.30</td><td>26.41</td><td>0.89</td><td>140.62</td><td>3.2</td></tr>
<tr><td>Bin 3</td><td>27.30</td><td>26.68</td><td>0.62</td><td>101.68</td><td>2.3</td></tr>
<tr><td>Bin 4*</td><td>18.62</td><td>18.43</td><td>0.19</td><td>30.02</td><td>1.0</td></tr>
<tr><td>Bin 5</td><td>27.32</td><td>27.20</td><td>0.12</td><td>19.68</td><td>0.4</td></tr>
<tr><td>Bin 6</td><td>27.30</td><td rowspan="2">54.42</td><td rowspan="2">0.19</td><td rowspan="2">30.59</td><td rowspan="2">0.3</td></tr>
<tr><td>Bin 7*</td><td>27.31</td></tr>
</table>

* Grade 2 wheat value at $ 158/t.
In remaining bins grade 1 wheat was stored at $ 164/t.

strength of both white and black sheeting appeared to be slightly affected by 45 days exposure to outside temperatures ranging from $-30^{o}$C to $2^{o}$C. Black Tu-Tuf deteriorated considerably when exposed for 75 days.

Black Tu-Tuf with 5 and 10 cm wide taped joints had the same initial strength as an unjoined black sheet but white Tu-Tuf with taped joints had less initial strength than an unjoined white sheet. The strength of taped joints reduced to about 80% of their initial strength within 10 days of outside exposure but afterwards the rate of reduction in the strength decreased.

At low temperature ($-21^{o}$C), the tensile strength of sheeting and taped joints increased to about 120% of their initial strength.

Tensile strength tests on samples of sheeting and taped joints cut from storage bins 1 and 2 indicated that black Tu-Tuf used for the roof and white Tu-Tuf used for the wall did not deteriorate. Their tensile strength after nine months of weathering was almost the same as the initial tensile strength. Tensile strength of white Tu-Tuf used for the floor decreased by around 18%. Tu-Tuf tape joints exposed to solar radiation deteriorated and their tensile strength decreased by 37%. Tensile strength of unexposed tape joints reduced by only 10%.

The tensile strength tests imply only qualitative testing and do not claim statistical reliability. These tests show the trend of tensile strength of Tu-Tuf sheeting and taped joints and do not predict the actual tensile strength.

Table 7.4

Tensile strength of Tu-Tuf sheetings and Tu-Tuf taped joints, N/m.

| Exposure to weathering d | White Tu-Tuf | Black Tu-Tuf | White Tu-Tuf with 10 cm wide tape | Black Tu-Tuf with 10 cm tape | White Tu-Tuf with 5 cm tape | Black Tu-Tuf with 5 cm tape |
|---|---|---|---|---|---|---|
| 0 | 5 190 | 3 920 | 4 290 | 3 830 | 4 010 | 4 165 |
| 10 | 5 120 | 4 230 | 3 490 | 3 440 | 3 250 | 3 170 |
| 22 | 5 220 | 4 230 | 3 250 | 3 340 | 3 220 | 3 250 |
| 44 | 5 180 | 4 170 | 3 410 | 3 190 | 3 030 | 3 290 |
| 76 | 4 940 | 3 330 | 3 440 | 3 250 | 2 810 | 3 080 |

# 8. COST ANALYSIS

## 8.1 Emergency Bins

The farm price of an emergency Tu-Tuf bin, capacity 36 $m^3$, would probably be \$200.80 which is less than 5% of the value of the wheat that can be stored in it. This price includes material costs, fabrication labour, utilities, rents, taxes, advertizing, manufacturer's profit and other overhead costs (Table 8.1). (These last items of cost were estimated by Forever Industries Ltd., Winnipeg).

Total yearly costs are estimated by summing the fixed costs and variable costs (Appendix A). Annual fixed costs amount to \$5.83/$m^3$ and annual variable costs are estimated to be \$0.09/$m^3$. Hence, the annual storage cost amounts to \$5.92/$m^3$. If the bin can be used twice, the annual storage cost reduces to \$3.26/$m^3$ (Table 8.2).

The price of a bin with a galvanized steel metal strip, 0.40 mm thick and 15-cm wide, placed around the bin base to protect the polyethelene from mouse damage, would be about \$214.80. Annual cost based on one year life for the bin is estimated to be \$6.13/$m^3$ which reduces to \$3.42 if the bin can be used twice (Table 8.3).

The price of Tu-Tuf bin, with a capacity of 65 $m^3$, is estimated at \$263.20 which increases to \$280.10 when the metal strip cost is included (Appendix B and Table 8.3).

## 8.2 Permanent Structures

Comparable annual costs of a steel bin, with a capacity of 60 $m^3$, and a plywood bin, with a capacity of 51.6 $m^3$, used every year are \$2.57/$m^3$ and \$2.53/$m^3$, respectively (Appendix C). (The life of a steel bin is assumed to be 30 yr and the life of a plywood bin is assumed to be 10 yr). If the bins are used only one year out of three years for storing surplus grain, the fixed costs increase by a factor of three. Hence, the storage costs increase to $\$7.07/m^3$ for a steel bin and $\$6.85/m^3$ for a plywood bin, assuming variable costs remain the same for each year of storage.

Table 8.1

Bin materials and costs (36-$m^3$ capacity)

| | | |
|---|---|---|
| **Tu-Tuf-4 white sheeting** | | |
| Floor - 6.1 m X 6.1 m<br>Wall - 1.8 m X 17.3 m<br>Roof - 6.1 m X 6.1 m | 105.5 $m^2$ @ 48.4 ¢/$m^2$ (including 22% duty and 5% transportation charges) | $ 51.10 |
| **Wire mesh** | | |
| 1.5 m X 17.3 m @ 74 ¢/$m^2$ | | 17.80 |
| **Sto-downs** | | |
| 16 | | 2.00 |
| **Tu-Tuf tape** | | |
| (10-cm wide) | | 5.00 |
| Wooden pegs and miscellaneous | | 5.00 |
| **Fabrication labour cost** | | |
| 5 h @ $ 12.50/h | | 62.50 |
| TOTAL | | $ 143.40 |
| Profit and overhead costs | | 57.40 |
| TOTAL | | $ 200.80 |

Table 8.2

Total yearly cost of emergency bin

| | | |
|---|---|---|
| Initial cost | = $ 200.80 | |
| capacity | = 36.0 $m^3$ | |
| Interest rate | = 11% | |
| Annuity factor | = 1.11 | (Appendix A) |
| End use value | = Wire mesh value after 1 yr use | |
| | Wire mesh initial cost = $ 17.80 | |
| | Assuming, wire mesh life= 5 yr | |
| | Annuity factor = 0.2706 | |
| | Annual charge = $ 4.82 | |
| End use value | = $ 12.98 | |
| Fixed costs | = $ 209.90 | (Assuming insurance cost is negligible) |
| Variable costs | = $ 3.50 | (Assuming repair cost for first year is $ 1.00 and insurance on grain is $ 2.50) |
| Total yearly cost | = $ 213.40 | |
| Total yearly cost/$m^3$ | = $ 5.92 | |

Based on 2 yr life

| | | |
|---|---|---|
| End use value | = $ 8.16 | |
| Annuity factor | = 0.5839 | |
| Fixed costs | = $ 113.50 | |
| Variable costs | = $ 4.00 | (Assuming repair cost for for second year is $ 2.00) |
| Total yearly cost/$m^3$ | = $ 3.26 | |

Table 8.3

Cost analysis of storage bins.

| Bin Type / Cost | Emergency Tu-Tuf bins | | | | | | | | Permanent bins | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 36-m$^3$ capacity | | | | 65-m$^3$ capacity | | | | Plywood 51.6-m$^3$ capacity | Steel 60-m$^3$ capacity |
| | 1 yr life | | 2 yr life | | 1 yr life | | 2 yr life | | | |
| | Without metal strip | With metal strip | Without metal strip | With metal strip | Without metal strip | With metal strip | Without metal strip | With metal strip | | |
| Capital cost of bin, $ | 200.80 | 214.80 | 200.80 | 214.80 | 263.20 | 280.10 | 263.20 | 280.10 | 665.00 | 1070.00 |
| Annual cost (if structure is used every year), $/m$^3$ | 5.92 | 6.13 | 3.26 | 3.42 | 4.25 | 4.41 | 2.36 | 2.47 | 2.53 | 2.57 |

# 9. DISCUSSION

Experience with the Fabrene-wall bin showed that a permanent-wall-supporting system was required to support the sidewall instead of using temporary wooden stakes. Because the cost of Fabrene TM was twice that of Tu-Tuf-4 sheeting, it was not economical to use a permanent supporting system for the Fabrene-wall bin. The Tu-Tuf bin withstood the grain loads during nine months of storage with only a slight reduction in the tensile strength of Tu-Tuf sheeting. Hence, the bins can probably be reused for another storage after repairing the floor-to-wall and wall joints and any holes caused by shovelling or mice. The empty bins which are to be used for next storage should be stored in a mouse-proof location because grain remaining in the bin attracts mice.

No distinction could be made between the performance of Tu-Tuf-3 and Tu-Tuf-4 sheeting. Tu-Tuf-3 sheeting was not tested in the laboratory, therefore the tensile strength of the two materials can not be compared.

White Tu-Tuf-4 would probably be better than black Tu-Tuf-4 because it was stronger and maintained its strength based on laboratory tests. During storage no holes in any of the white roofs were observed which indicated that it was more resistant to weathering than the black Tu-Tuf. Moreover, condensation would be less in white material because it was not as rapidly affected by solar radiation as black material.

The rate of deterioration of 5-cm and 10-cm Tu-Tuf tape was almost the same when tested in the laboratory, but 5-cm Tu-Tuf tape deteriorated more rapidly during the storage test. This indicated that 10-cm Tu-Tuf tape would be better to use as a fastening material.

The grain adjacent to the Poly-Fastener joint in bin 5 spoiled, indicating that moisture entered through the joint. Moisture could not enter through the Poly-Fastener joint in bin 3 because the joint was secured by Tu-Tuf tape on both inside and outside the bin. The floor-to-wall joint made with Tu-Tuf tape did not allow moisture entrance through the joint in any of the bins, indicating that Tu-Tuf tape is a better fastening material for these bins than Poly-Fastener. The floor-to-wall joint exposed to solar radiation deteriorated after nine months of storage but it can be retaped if the bin is to be used again.

Since water entered through holes chewed by mice in bins 1 to 4, the performance of the extra polyethelene sheet on the floor in bin 1 could not be compared with the single Tu-Tuf sheet in the remaining bins. The small amount of grain spoiled on the floor of bin 5 which did not have any extra sheet might indicate that an extra sheet on the floor is unnecessary. Spoilage in bin 5 was probably due to moisture entrance through the floor-to-wall Poly-Fastener joint.

Tu-Tuf tape used for the roof-to wall joint deteriorated more rapidly than other taped joints, probably due to solar radiation and the slight flapping of the roof. It may be possible to use only sto-downs and rubber tires to restrain the roof and taping may not be necessary. Broken sto-downs can be easily replaced. Although the fish netting was in good condition after nine months of storage, tying it over the roof was a problem. Moreover, it was not as economical as sto-downs.

Results of the storage tests indicated that a vent in a bin was not advantageous during winter. Snow blew into the bin through the vent and grain spoilage resulted. The vent increased the fabrication cost. Performance of the vent during spring could not be determined.

The problem of holes caused by mice might be eliminated by placing the bins in the open instead of beside trees. In the open the snow will probably drift around the bin and not pile on the sides. The problem could also be eliminated by placing a metal strip around the bin base.

Increases in the moisture content of the stored grain at the peaks during spring sampling indicated that some moisture migration had occurred in the emergency bins without vents. In the two bins with vents, the high moisture content of the grain at the peak was probably due to snow blowing in through the vents. The increases in the steel bin and plywood bin were due to snow that blew into the bins around the roof cap. During unloading, reduction in moisture contents at the peaks indicated that the grain dried in each bin except bin 1. The cardboard vent in bin 1 probably did not function properly. Drying of the grain in the non-vented bins was probably due to occurrence of high temperatures at the surface of the roof.

The commercial grade of the grain during the nine months of storage did not change, indicating the effectiveness of the bins in preserving the grain quality. The high level of dockage in the stored grain of bin 6 during filling was probably due to measurement error or bias in sampling.

The small amount of spoiled grain in undamaged bin 5 indicated that emergency bins could store grain safely without reduction in quality. The amount of spoilage in this bin was almost the same as that in the permanent bins. Spoilage would probably have been even less if Tu-Tuf tape had been used for the floor-to-wall joint instead of Poly-Fastener.

Emergency bins will not provide economical storage for grain every year because the annual storage cost of emergency bins is more than permanent bins. They will be an economical method of storing surplus grain that occurs one out of three years or less frequently.

# 10. CONCLUSION

Tests during summer and fall 1975 indicated that the cross-laminated polyethelene bin, permanently supported by wire mesh, performed satisfactorily. The polyolefin woven fabric-wall bin, temporarily supported by wooden stakes, failed during filling due to high elongation of the polyolefin woven fabric and could not be filled to the design capacity. The cross-laminated polyethelene withstood the grain loads during the storage period and only a slight reduction in the tensile strength of the sheeting was noticed after nine months of exposure to weathering. The tape used to fasten the roof-to-wall joint deteriorated and had to be retaped twice during storage. This problem could probably be eliminated by using sto-downs and not taping the joint at all. Mice lived under the snow that piled up around the bins and chewed holes in the sides of four bins. The holes allowed water to enter the bins and resulted in grain spoilage on the floor. The bin damage could be eliminated by placing a metal strip around the bin base or by placing the bins in an open site to reduce snow piling on the sides.

A vent in the peak of the bin did not seem of any advantage. Snow blew through the vents causing spoilage at the peaks. There might not be any need of extra sheeting on the floor to prevent the entrance of surface water because only a small amount of grain spoilage occurred on the floor of undamaged bin which did not have extra sheeting. Cross-laminated polyethelene white sheeting for bin construction, wire mesh as a reinforcing material and 10-cm wide adhesive tape as a fastening material performed satisfactorily.

Even if there had been no holes in bins 1, 2, 3 and 4, there would certainly have been a small amount of grain spoilage on the floors. The grade of the grain remained constant throughout the storage period, indicating that bins, both emergency and permanent, were effective in maintaining grain quality during a storage period of nine months (except for the poor quality grain from each bin that was thrown away and was not graded).

As expected, emergency bins can not compete economically with permanent bins in a year of average crop production. They will be an economical method of storing grain surpluses that occur in one out of three years or less frequently. Because the emergency bins can be erected by two or three people on an unprepared site in about 1/2 to 1 h, they can be readily used for the emergency storage of the grain.

## 11. SUGGESTIONS FOR FURTHER STUDY

The Tu-Tuf tape used to fasten the roof-to-wall joint deteriorated due to weathering during 1975-1976 storage tests and had to be retaped twice during nine months of storage. A bin using only sto-downs for the roof-to-wall joint and not taping the joint at all should be tested in storage tests. The bins to be tested should be erected in an open site to lessen the snow piling around the bins. If a suitable site is not available, then a 15-cm wide metal strip should be placed around the bin base to observe the effectiveness of such a strip in preventing mouse activity.

A bag structure (similar to the structure tested during 1975 summer tests, described in Sec. 4.2) without a shaped floor (so as to reduce fabrication labour cost) and inside a wire mesh should be tested again. Some modifications are required in tying the roof.

A larger capacity bin (around 65-$m^3$ capacity), which would reduce the annual storage cost per $m^3$ (refer Table 8.3), should be tested structurally. To reduce the fabrication labour cost in painting the concentric circles on the floor, a bin should be loaded eccentrically to observe the degree to which the bins can be eccenticically loaded before failure occurs.

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## APPENDIX A

Annuity approach to bin costs.

Total yearly cost = Fixed costs + Variable costs

where:

Fixed costs = Annual charge for capital recovery (depreciation) and interest + Insurance on structure

Variable costs = Grain spoilage + Repairs + Insurance on grain (Grain spoilage could not be estimated and therefore is neglected here)

The annual charge for capital recovery and interest can be calculated by an Annuity method (Smith and Oliver, 1974).

Accordingly:

Fixed costs = R (Initial structure cost - End use value) + End use value X I + Insurance on structure

Annuity factor for each dollar to be recovered can be calculated by:

$$R = A / \frac{\left[1 - (1 + I)^{-N}\right]}{I}$$

where:

R = annuity factor

A = amount to be recovered, ($1.00)

I = interest rate, %

N = recovery period, yr

APPENDIX B

Bin materials and costs (65-$m^3$ capacity)

| | | |
|---|---|---|
| Tu-Tuf-4 white sheeting | | |
| Floor - 7.3 m X 7.3 m<br>Wall - 1.8 m X 21.0 m<br>Roof - 7.3 m X 7.3 m | 144.8 @ 48.4 ¢/$m^2$ ............ | $ 69.90 |
| Wire mesh<br>1.8 m X 21.0 m @ 74.0 ¢/$m^2$ | ........................... | 28.00 |
| Tu-Tuf tape<br>(10-cm wide) | ........................................ | 6.60 |
| Sto-downs<br>20 | ................................................. | 2.50 |
| Wooden pegs and miscellaneous | ................................ | 6.00 |
| Fabrication labour cost<br>6 h @ $ 12.50/h | ..................................... | 75.00 |
| TOTAL | ........................................................ | $ 188.00 |
| Profit and overhead costs<br>40% of the direct cost | .......................... | 75.20 |
| TOTAL | .................................................... | $ 263.20 |

## APPENDIX C

Total yearly cost of permanent bins

Steel bin

Initial cost = $ 1070.00

Capacity = 60 $m^3$

Estimated life = 20 yr

Annuity factor = 0.1256

End use value = $ 107.00 (10% of the initial cost)

Fixed costs = $ 135.22 (Assuming insurance cost is $ 2.50)

Variable costs = $ 19.00 (Assuming repair cost each year is $ 15.00 and insurance on grain is $ 4.00)

Total yearly cost/$m^3$ = $ 2.57

Plywood bin

Initial cost = $ 665.00

Capacity = 51.6 $m^3$

Estimated life = 10 yr

Annuity factor = 0.1698

Fixed costs = $ 111.45

Variable costs = $ 18.50

Total yearly cost/$m^3$ = $ 2.53