平底圓筒鋼皮倉的設計和應用

Design and Application of Flat-bottom Steel Tanks

行政院國科會客座專家
國立臺灣大學客座副教授

蕭介宗

Jai-tsung Shaw

摘要

介紹目前製造業者所用的平底圓筒鋼皮倉的設計理論。分析包括屋頂、倉壁，和支架受到貯藏穀類，靜動負荷的情形。

貯藏倉自燃生熱，導致溫度上昇可利用有限差異方式預測。為移除產生的熱，通風是必需的。並且提供倉儲業使用的通風設計的實例。

當平底圓筒鋼皮倉做為乾燥機時，它必需具備整個有孔地板，穀類分配器、風機、加熱器、加强結構和循環裝置。比較五種常用乾燥倉的優缺點，並推演一次乾燥所需時間的計算公式。

Abstract

At the present time, the theory of designing flat-bottom tanks adapted by manufacturers is introduced. The analysis includes roof panels, tank shells, and stiffeners subjected to stored grain, dead and live loads.

Spontaneous heating in storage bin results in temperature rise which can be predicted by finite difference method. To remove generated heat, aeration is necessary. A practical example of designing aeration system used by grain storage industry is also provided.

When flat-bottom steel tanks are used as bin dryers, they are necessarily equipped with fully perferated floors, grain spreaders, fans, heaters, reinforced structures, and recirculating devices. Five types of common bin dryers are compared with their advantages and disadvantages. An equation is also developed for estimating the time required to dry a batch.

1. Introduction

Steel grain tanks can be prefabricated by manufacturers inside the plants. Through cold roll forming, the result of mass production and the saving of erection time can be very economic. Even if the steel tanks are imported from the United States, the price to have 39,285 bushel storage capacity set up is about 43% of reinforced concrete silo. At the present time, China Steel Corporation in Kaohsiung can produce high quality steel coil. If proper design and application information is available, we may help our domestic manufacturers to produce their steel tanks and consequently reduce the price of steel tanks further. This will help our domestic grain and feed industry to store the related agricultural produce more competitive.

The author has involved in the design and research of steel tanks for the last 10 years, and hopes this paper will be helpful for manufacturers and users who can make the most of steel tanks. The scope of this paper will be limited three major areas:

1. Analysis and design of flat-bottom steel tanks.
2. Steel tanks for storage.
3. Steel tanks for drying.

2. Analysis and Design of Flat-bottom Steel Tanks

The analysis and design of steel grain tanks is dependent on the calculation of the grain induced action on the cylindrical shell and application of these loads to the design of body sheets and vertical wall stiffeners. Many theories have been developed to modify Janssen's equation which can be used to predict the dynamic conditions such as bin loading and bin emptying (1,17,21,24,27,31,36). Although Janssen's theory is based on the behavior of stored grain at rest, the flat-bottom grain tanks are normally unloaded by a unloading auger at the center as shown in Figure 1. Emptying bin is close to a funnel flow. Therefore, there was little or no pressure increase in the wall(24,37). In other words, Janssen's equation is still valid if the flat-bottom tank is unloaded from the center and the unloading flow is close to a funnel flow.

Since both wheat and corn are most comon and heavy grains, the material density, angle of repose and coefficient of materal on wall friction of wheat are used to determine the maximum lateral pressure. Similarly, the values of corn are used to determine the maximum vertical stiffener loads. Dead load and live load are used to determine the required thickness of roof panels.

To elaborate the above analysis and design of a flat-bottom grain tanks, a 40.6 ft dimeter by 40 ft wall height tank is used for an example. All of the galvanized coil steel used in tank panels have a minimum yield strength of 33,000 psi. The bolts used are standard mild steel bolts with a design shear strength of 10,000 psi.

2.1 Design of Roof Panels

As shown in Figure 2 find the section modulas of two panel elements plus a Z-shape stiffener as follows:

$$S_1 = 2.996\,t' \quad \text{(1)}$$

$$S_2 = 10.91t' \quad \text{(2)}$$

where S_1 = section modulas of roof panel, in^3

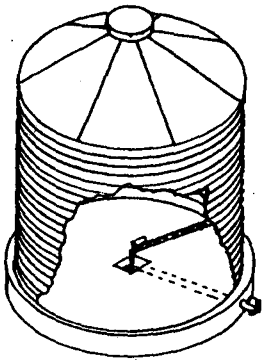
S_2 = section modulas of Z-shape stiffener, in^3

t' = thickness of roof panel or stiffener, in

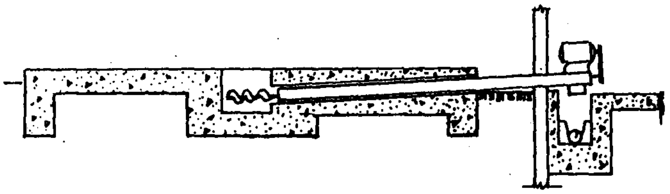
If 2 pieces of roof panels with a 0.0359-inches thickness and a 0.0598-inches-thick Z-shape stiffener as shown in Figure 3(C), the combined section modulas (S_t) can be calculated as follows and is equal to 0.76 in^3.

$$S_t = 2S_1 + S_2 \quad \text{(3)}$$

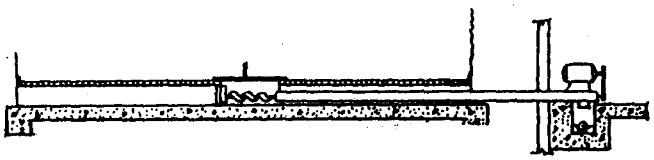
or $S_t = 2(2.996)(0.0359) + 10.91(0.0598) = 0.76$ in^3



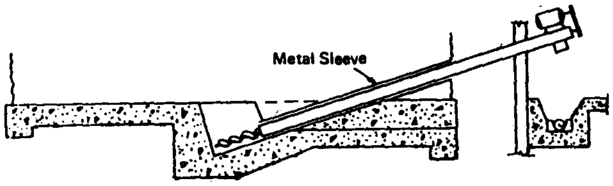
(a) Bin with under floor unloading auger and with sweep auger on the floor



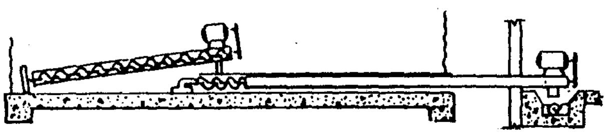
(b) Details of concrete floor bin with underfloor auger



(c) Details of false floor bin with underfloor auger

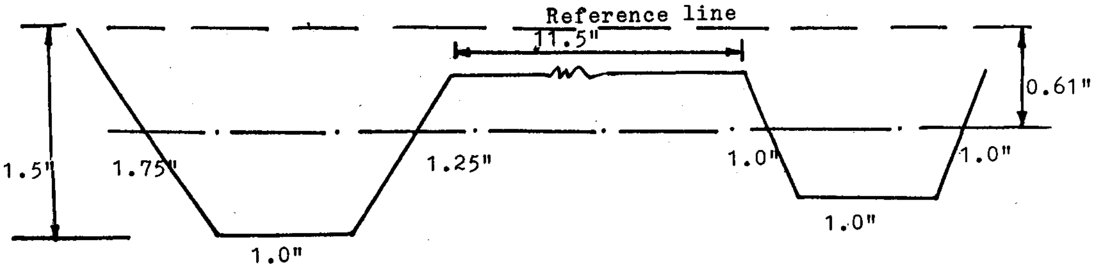


(d) Details of concrete floor bin with underfloor auger inclined above floor at bin wall and with ramp over auger tube

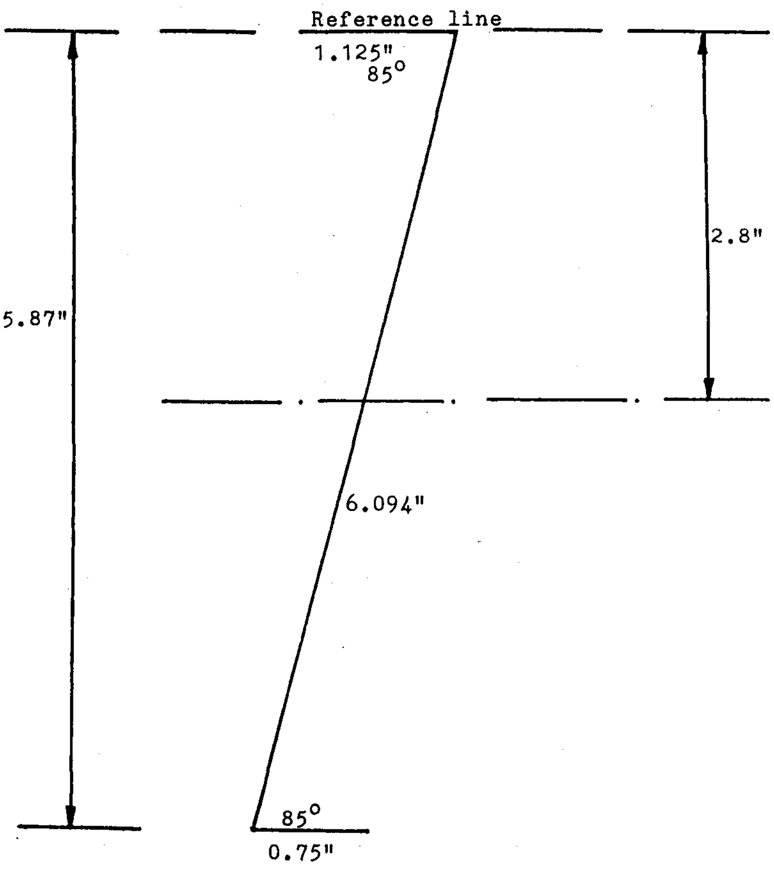


(e) Top of the floor auger with sweep auger for existing bin with no formed channel in floor

Figure 1. Unloading grain from round tanks



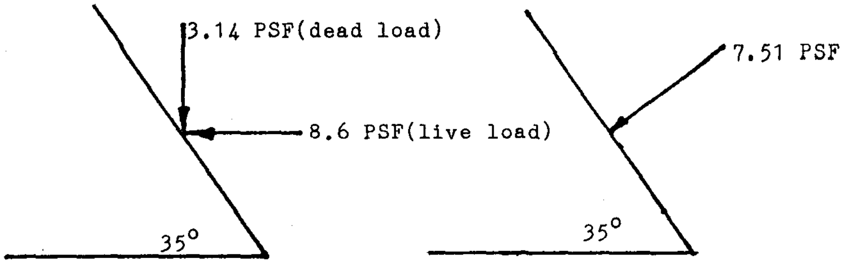
(a) Cross section of roof panel.



(b) Cross section of Z-shape roof stiffener

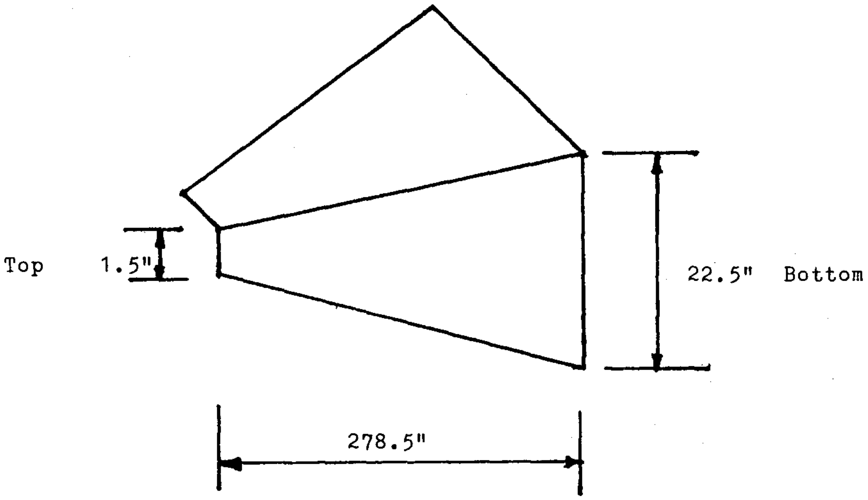
Figure 2. Cross sections of roof panel and stiffener.

The weight of above two pieces of roof panels and a Z-shape sitffener is equal to 3.14PSF. If the wind load in the vertical direction is 25PSF, take 60% of 25PSF or 15PSF per foot of vertical projection is used for a round structure(14) as shown in Figure 3(a). Resolve forces into components perpendicular to the roof equal to 7.51PSF as shown in Figure 3(b). The moment of roof panel as shown in Figure 3(d) is as follows:

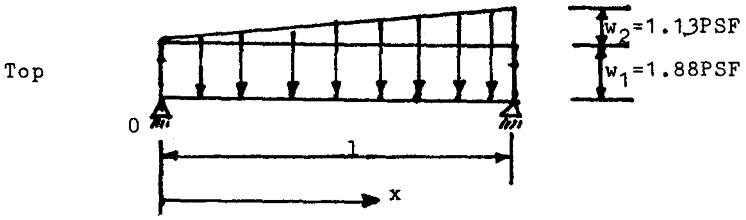


(a) Dead load and live load.

(b) Combination of dead load and live load.



(c) Dimension of roof panel.



(d) Load on the roof panel.

Figure 3 Force diagram of roof panel.

$$M_x = \frac{\omega_1 x}{2}(\ell - x) + \frac{\omega_2 x}{6}(\ell^2 - x^2) \qquad (4)$$

or $$\frac{dM_x}{dx} = \frac{-\omega_2 x^2}{2} - \omega_1 x + \frac{\omega_1 \ell}{2} + \frac{\omega_2 \ell^2}{6} \qquad (5)$$

Where the maximum moment occurs, $\frac{dM_x}{dx}$ is equal to zero or the location is at the point where x is equal to 13.19ft. Substituting x is equal to 13.19ft into Equation(4), we find the maximum moment is equal to 1,029 ft-lb or 12,348 in-lb. As we mentioned before, the yield strength of coil steel is 33,000psi or the working strength is equal to 20,000psi(29). From Equation(3), we have chosen two pieces of 0.0359-inches roof panels and a 0.0598-inches Z-shape roof sitffeners. The combined section modulas is 0.76 in^3 which is larger than 0.62 in^3 (=12,348/20,000). Therefore, the roof design will be adequate.

2.2. Tank Shell Design

The following equation was developed by Janssen for calculating grain lateral pressure on the tank wall(5,22,26).

$$P_h = \frac{\omega R}{\mu'}(1 - e^{-K\mu' H/R}) \qquad (6)$$

P_h = lateral pressure, PSF

ω = grain density, PCF

R = hydraulic radius equal to one quarter of bin diameter for round shape, ft.

K = ratio of lateral to vertical pressure $= \frac{1-\sin\phi}{1+\sin\phi}$

ϕ = angle of repose

μ' = coefficient of grain on the tank wall

H = depth of grain, ft

e = base of natural log = 2.71828

Since wheat is the most common and heavy grain, use the following values to calculate the maximum lateral pressure of 40.6 ft diameter by 40 ft wall height. The cone shape grain piled up above the eave height is calculated for the equivalent 4.7 ft height of 40 ft diameter cylinder.

ω = 50 PCF

R = 10.15 ft

ϕ = 25°

μ' = 0.34

H = 15.6, 25.6, 35.6, and 45.6 ft

Substituting the above values into Equation(6), the lateral pressure is listed in

Column(2) in terms of PSF or Column(3) in terms of psi of Table 1. If the wall panels are connected by two rows of 3/8-inch bolts at 1.5-inch spacing along the vertical seamline, the tensile stress(F*) on net section shall not exceed the value calculated by either Equation(7) or Equation(8) from cold formed steel design manual(29):

$$F^* = F_y/1.6 \quad \ldots\ldots (7)$$

$$F^* = (1.0\text{-}0.9r + 3rd/s)F^* \quad \ldots\ldots (8)$$

where F^* = design stress for bolted connection, psi

F_y = yield strength = 33,000psi

r = the force transmitted by bolt or bolts at the section considered, divided by the tensile force in the member at that section. If r is less than 0.2, it may be taken as equal to zero.

s = spacing of bolts perpendicular to line of stress, in

d = diameter of bolt, in

Let r=0.5, s=1.5 in, d=3/8 in, the design stress for bolted connection on net section is equal to 19,100psi. Normally, the hole of wall panel is punched with a 1/16 in larger than bolt diameter which is 3/8 in diameter in this case. Therefore, the allowable tension (T) between bolts can be calculated by the following equation

$$T = [1.5 - (3/8 + 1/16)](t')(F^*) \quad \ldots\ldots (9)$$

where T = allowable tension, lb

t' = thickness of wall panel, in

F^* = 19,100 psi.

With different thickness of wall panels, the allowable tension loads are calculated and listed in Column(6) of Table 1. Comparing the values of Column(6) with Column(4), the designed thickness of wall panels at various grain depth is adequate.

Table 1. Designed thickness of wall panels of 40.6-feet diameter by 40-feet sidewall of wheat tank

Grain depth	Lateral pressure		Hoop tension per 1.5 in of vertical height Col.(3)x243.6*x1.5	Designed thickness of wall panels	Allowable tension loads at designed thickness
ft	PSF	psi	lb	in	lb
15.6	284.7	1.977	722	0.0359	707
25.6	438.0	3.04	1111	0.0598	1120
35.6	572.0	3.97	1451	0.0747	1395
45.6	688.6	4.78	1747	0.0897	1690
Column No. 1	2	3	4	5	6

* Radius of tank in terms of inches

2.3 Sidewall Stiffener Design

The first step in the design of the vertical sidewall stiffeners is the determination of the maximum loading existent in each. At any given grain depth, the load per stiffener is equal to the total vertical wall load at that depth divided by the number of stiffeners around the tank. Then the stiffener may be analyzed as an axially compressed column. The cross-sectional area required for the stiffener will depend on the magnitude of axial compression, the unbraced length of the stiffener and the yield strength of the raw material. As the vertical load of stiffener increases from the top to the bottom of any tank, the required stiffener cross-section will increase in the same manner. From Janssen's formula, the vertical load on the floor can be calculated by the following equation:

$$V = P_h/K = \frac{\omega R}{\mu K} (1 - e^{-K\mu H/R}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

where V = vertical stiffener pressure, PSF

P_h, K, ω, R, μ', H and e are defined as in Equation (6) .

If a cold formed section as shown in Figure 4 is chosen for the sidewall stiffeners, the allowable load for different thickness is listed in Table 2.

Table 2. Allowable load of designed sidewall stiffener

Thickness	allowalble load
in	lb
0.0359	3091
0.0478	4766
0.0598	6573
0.0747	8896
0.0897	11018
0.1046	12783
0.1345	16982
0.1875	26148

For the maximum vertical stiffener loads, use the following values of corn:

ω = 48 PCF

$R = 10.15$ ft
$\mu = 0.447$
$\phi = 27.52^\circ$
$H = 15.6, 25.6, 35.6,$ and 45.6 ft.

Substituting the above values into Equation$^{(10)}$, the designed stiffener is listed in Table 3 at various grain depth. Comparing the allowable loads of Table 2 with stiffener loads in Column$^{(6)}$ of Table 3, the designed thickness of stiffeners in Column$^{(7)}$ of Table 3 is adequate.

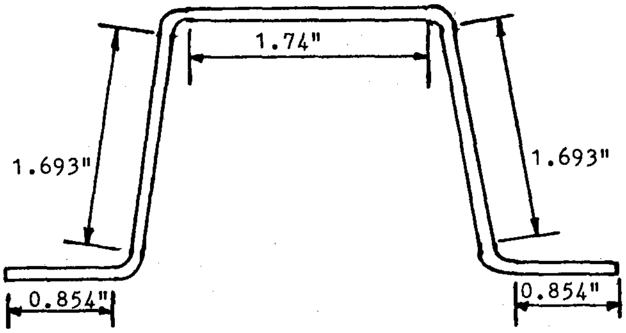


Figure 4. Cross section of wall stiffeners.

Table 3. Designed thickness of wall stiffeners of 40.6 feet-diameter by 40-feet height of corn tank

Grain depth	Vertical pressure on floor		Grain weight	Steel tank weight	Stiffener load	Designed thickness
		Col. $^{(2)}$ x1295			$\frac{\text{Col.}^{(4)}+\text{Col.}^{(5)}-\text{Col.}^{(3)}}{34}$	
ft	PSF	lb	lb	lb	lb	in
15.6	662	857,290	921,888	8,820	2,159	0.0478
25.6	1,006	1,302,770	1,529,088	14,210	7,074	0.0747
35.6	1,298	1,680,910	2,135,712	20,725	13,986	0.1345
45.6	1,547	2,003,365	2,773,824	28,800	23,508	0.1875
Column No.						
1	2	3	4	5	6	7

2.4 Bolt Shear Stress

If the bolts used are standard mild steel bolts, the designed shear stress will be 10,000psi. As shown in Table 1, the load per bolt on the bottom panel is equal to 874 lb (=1747/2). For a 3/8 in bolt, the allowable shear is equal to 1104 lb which is larger than 874 lb. Therefore, the bolt shear stress for wall panel is adequate.

As shown in the Table 3, the bottom stiffener load is equal to 9,522 lb (=23,508-

13,986). For a 10 feet loang stiffener with 19 bolts attaching to sidewall, the average load per bolt is equal to 501 lb which is less than 1104 lb. Consequently, the bolt shear stress of stiffener will be strong enough.

2.5 Wind Load

The wind load on structures is the product of the design wind pressure multiplied by the projected exposed area. The design wind pressure, should be satisfactory for local building code or recommended code of standard practice (6,10,13,14). For this analysis, assume 25 PSF wind pressure which is equal to 98.8 miles per hour velocity pressure. For a round structure, use a shape factor 0.6 or the design wind pressure will be 15 PSF(14).

Since the empty tank may be the most critical condition, the load on anchor bolt to prevent overturning as shown in Figure 5. can be calculated as follows:

Area of roof = ½ (40.6)(54.2–40) = 288.3 ft^2
Wind load on roof (L_1) = 15x288.3 = 4324 lb
Area of wall = (40.6)(40) = 1624 ft^2
Wind load on wall(L_2) = 1624 x 15 = 24360 lb
Weight of steel tank (P_2) = 28,800 lb

$$\text{The tensile load on anchor bolts } (P_1) = \frac{20.3P_2 - 20L_2 - 43.55L_1}{40.6} = \frac{584{,}640 - 487{,}200 - 188{,}310}{40.6} = -2238 \text{ lb}$$

Assuming the total wind load is in shear and 34 anchor bolts are used, the shear per bolt will be 844 lb $(=\frac{4324 + 24360}{34})$. For a 5/8 inch diameter mild steel anchor bolt, the allowable load is 3068 lb $[=10{,}000\text{psi } (\frac{\pi}{4})(5/8)^2]$. Therefore, the shear stress of anchor bolt is adequate.

The allowable tensile load on the smallest stiffener is equal to the allowable design stress, 20 ksi (=33 ksi/1.65), multiplied by the smallest cross section which is equal to the blank width minus the bolt hole. The allowable tensile load can be calculated as follows:

Allowable tensile load = (20,000) [7 7/8-(3/8+1/16)] (0.0478) = 7110 lb

From the above calculation, the allowable tensile load on the smallest stiffener is larger than 2238 lb. Therefore, stiffeners for tensile load due to wind are adequate.

Following the above analysis and design procedures, the author has designed some customer built tanks as shown in Figure 6. Figure 7 shows more details of a typical steel tank.

3. Steel Tanks for Storage

To use steel tanks for storage, proper aeration is very critical. The following section will discuss the heating problem of stored rapeseed and design an aeration system to solve the problem.

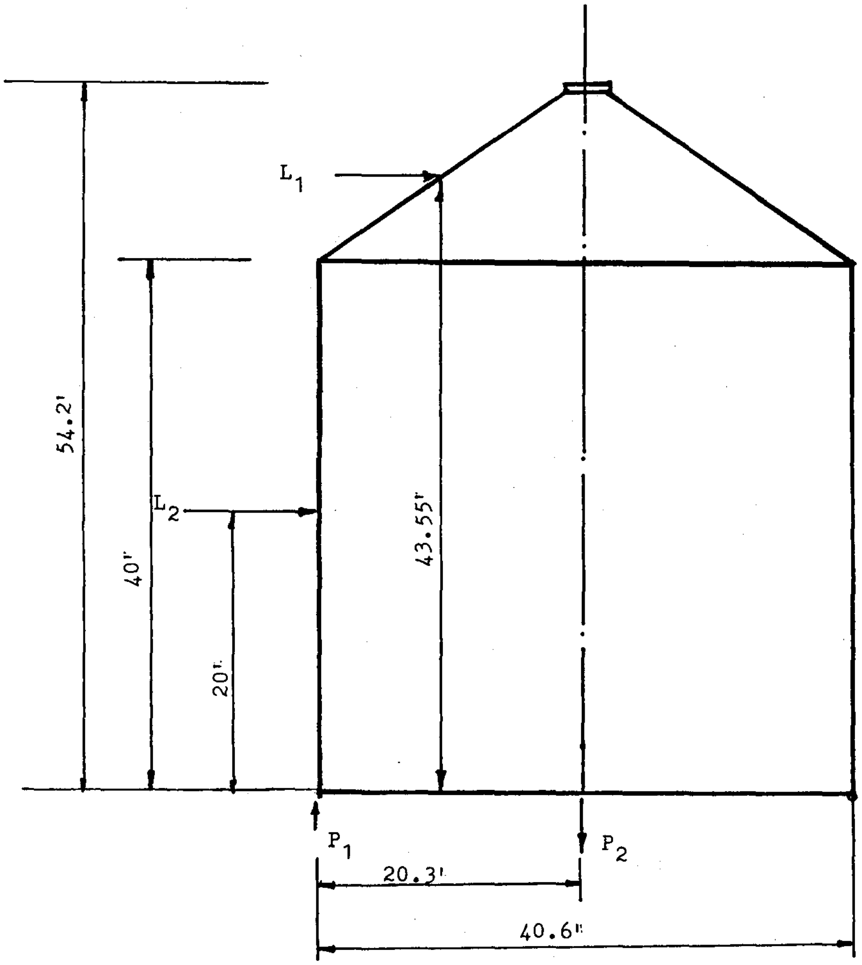


Figure 5 Wind load on the empty tank .

3.1 Spontaneous Heating of Stored Rapeseed

A 44-inch diameter by 66-in high steel bin was set up as shown in Figure 8A. Thermocouple locations and other equipment were shown in Figure 9. The bin was insulated with a 1-inch layer of fiber-glass wool insulation covered with a plastic film. A second 6-mil plastic film was mounted on a wood frame surrounding the bin providing an air space which was maintained at a constant temperature with a capillary thermostat (Type EA3 Robert Shaw-Fultan Controls Co.) controlling an electric heater and circulating fan. Humidified ventilation air was supplied to the bin through a manifold located in the bottom. Approximately 50 Bushels of rapeseed having an initial moisture content of 7.9% (wet basis). By adding water and mixing for two hours, 100-pound lots of seed were conditioned to 10.33% or 10.62% moisture content. Then the seed was removed from the mixer and allowed to stand in a covered box for three-days prior to loading into the bin(30).

The temperature rise due to spontaneous heating at different locations in the bin were listed in Table 4 and 5.

Table 4. Measured temperatures (F) versus time at different locations of 44-inch diameter bin from initial conditions of 10.62% moisture content and 97F

Time, hr t	Radial distance from the center of 44-inch bin, inches					
	0	2	7	12	17	22
0	97.71	97.28	97.02	96.58	95.23	93.01
35	100.81	100.37	100.11	99.41	97.71	94.97
72	104.16	103.90	103.46	102.46	100.15	96.54

Table 5. Measured temperatures (F) versus time at different locations of 44-inch diameter bin from initial conditions of 10.33% moisture content and 81F

Time, hr t	Radial distance from the center of 44-inch bin, inches					
	0	2	7	12	17	22
0	80.61	80.61	80.48	80.22	79.78	79.30
144	88.57	88.57	88.05	86.83	84.74	81.74
288	96.24	96.10	95.15	93.14	90.05	85.92
499	102.16	102.02	100.35	98.28	94.28	88.88

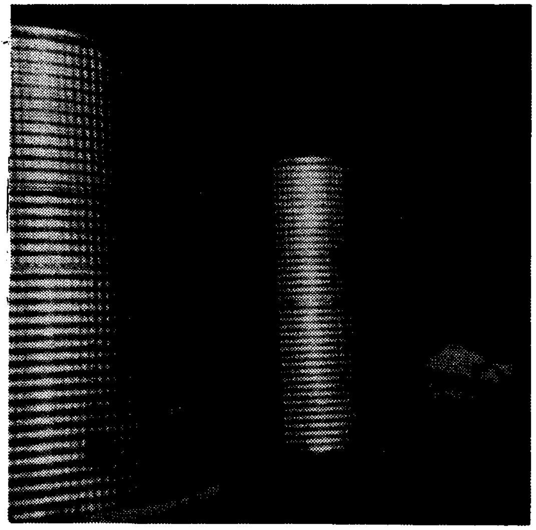


Figure 6. Exterior-view of grain tanks.

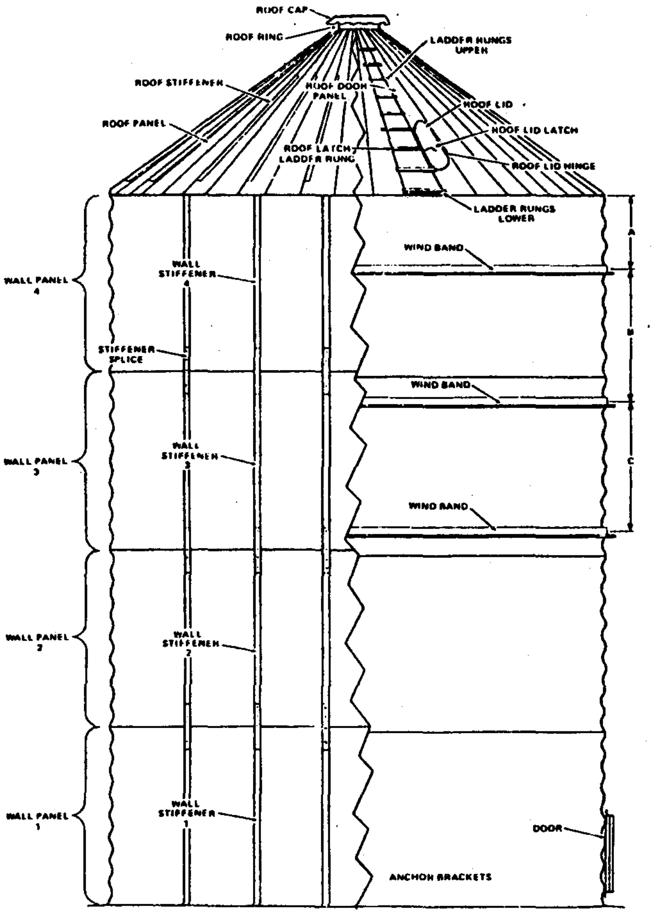


Figure 7. Details of a typical steel tank.

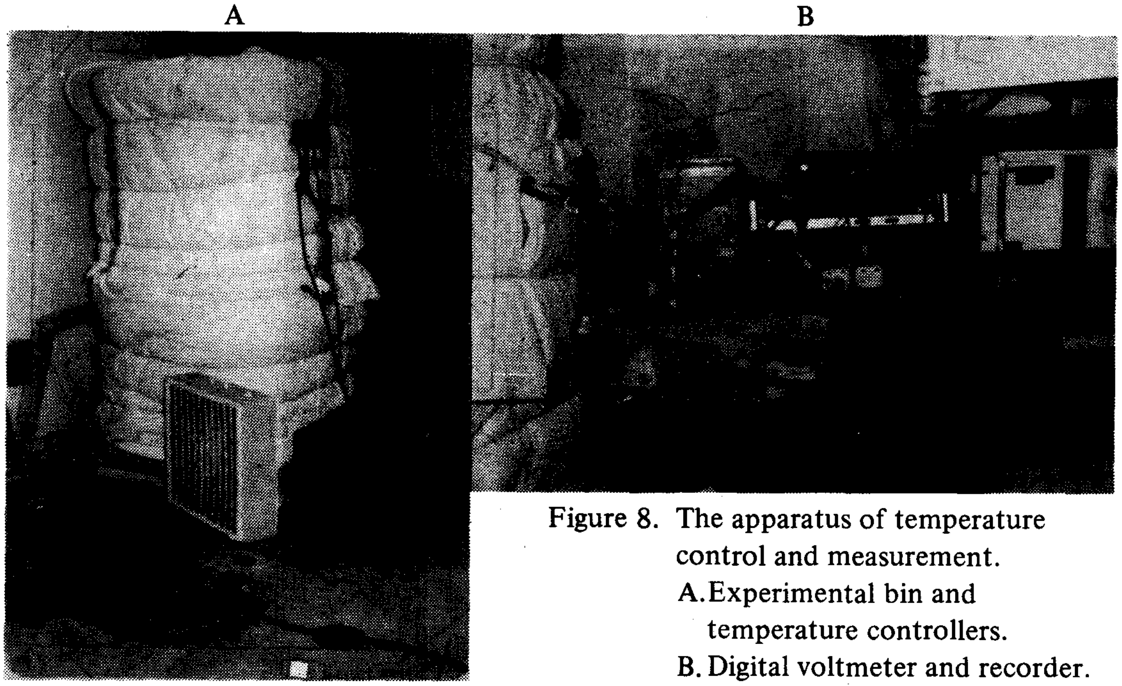


Figure 8. The apparatus of temperature control and measurement.
A. Experimental bin and temperature controllers.
B. Digital voltmeter and recorder.

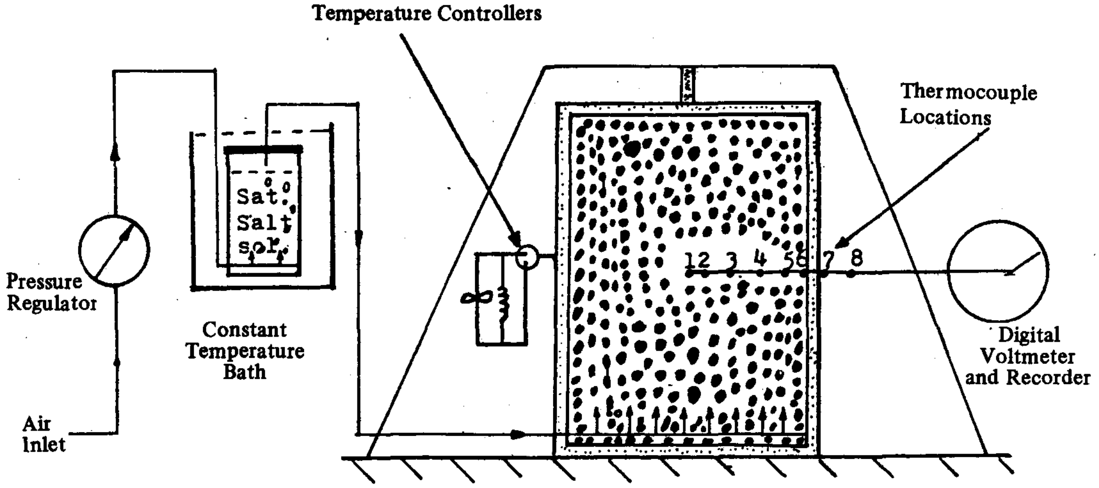


Figure 9. Diagram of temperature measurement in the 44-inch diameter bin.

To predict the temperature rise due to spontaneous heating, the author has developed the following equations based on heat balance equation and finite difference method by considering the sector of a cylindrical bin shown in Figure 10.(16,25,30,38)

$$M = \frac{c\gamma\,(\Delta r)^2}{k\Delta t} \quad \ldots\ldots\ldots\ldots \quad (11)$$

$$T'_i = \left(1 - \frac{2}{M}\right) T_i + \frac{2i-1}{2(M)\,(i)} T_{i-1} + \frac{2i+1}{2(M)\,(i)} T_{i+1} + \frac{(W)\,(\Delta t)}{(\gamma)\;(c)} \quad \ldots\ldots \quad (12)$$

$$T'_c = \frac{(W)\,(\Delta t)}{(\gamma)\;(c)} + \left(1 - \frac{4}{M}\right) T_c + \frac{4}{M}\,(T_1) \quad \ldots\ldots\ldots\ldots \quad (13)$$

$$T'_n = \frac{(8n-4)}{(4n-1)\,M} T_{n-1} + \frac{8(B_0)\,(n)}{(4n-1)\,M} T_a + \left(1 - \frac{8n-4+8B_0 n}{(4n-1)\,M}\right) T_n + \frac{(W)\,(\Delta t)}{(\gamma)\;(c)} \quad \ldots\ldots\ldots\ldots \quad (14)$$

Where k = thermal conductivity, Btu/hr-ft-F
Δr = length of radius increment, ft
i = number of spatial increment
Δz = depth of sector, ft
$\Delta \theta$ = angle of bin sector, rad.
W = generated heat, Btu/ft^3–hr
Δt = finite time period, hr
T_{i-1} = temperature of elements i–1 at time t, F
T_i = temperature of element i at time t, F
T_{i+1} = temperature of element i+1 at time t, F
T'_i = temperature of element i at time t+Δt, F
γ = density, lb/ft^3
c = specific heat, Btu/lb-F

T_c = temperature of center element at time t, F

T'_c = temperature of center element at time t+Δt, F

T_n = temperature of exterior element at time t, F

T'_n = temperature of exterior element at time t+Δt, F

$B_0 = \frac{h\,\Delta r}{K}$ = Biot number, dimensionless.

h = convective heat transfer coefficient, Btu/hr-ft^2-F

T_a = outside air temperature, F

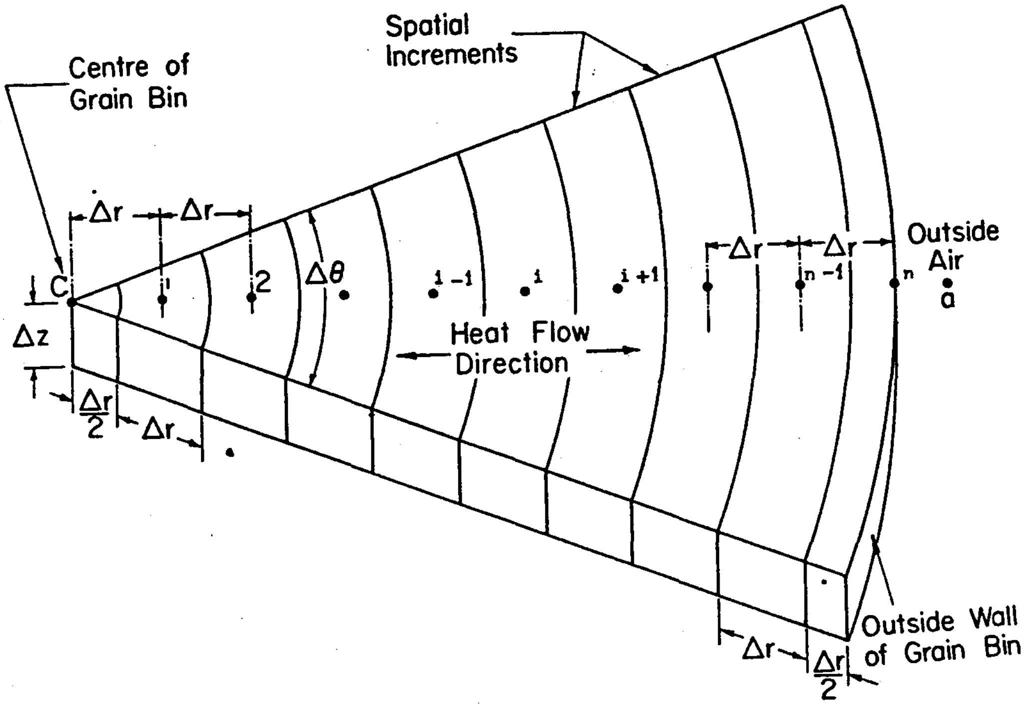


Figure 10. A sector of the grain bin.

With measured thermal properties and carbon dioxide production mulitplied by a factor of 3.5 to determine heat generation, W, in the above equations, the measured and predicted temperatures are shown in Figure 11.(23,30)

3.2 Design Criteria for Aeration System

As shown in Section 3.1, the stored produce inside the steel tank could cause heating due to moisture movement within the grain bulk as shown in Figure 12 or due to localized development of fungi and insects as shown in Figure 13.(19,35)

As shown in Figures 14 and 15, structural failures can happen without having adequate roof vents for air inlet or outlet. From Figure 16, improper switch timing of pressure-vacuum aeration system can also result in bin failures. Because grain tank roofs are not designed to withstand excessive air pressure differentials as mentioned in

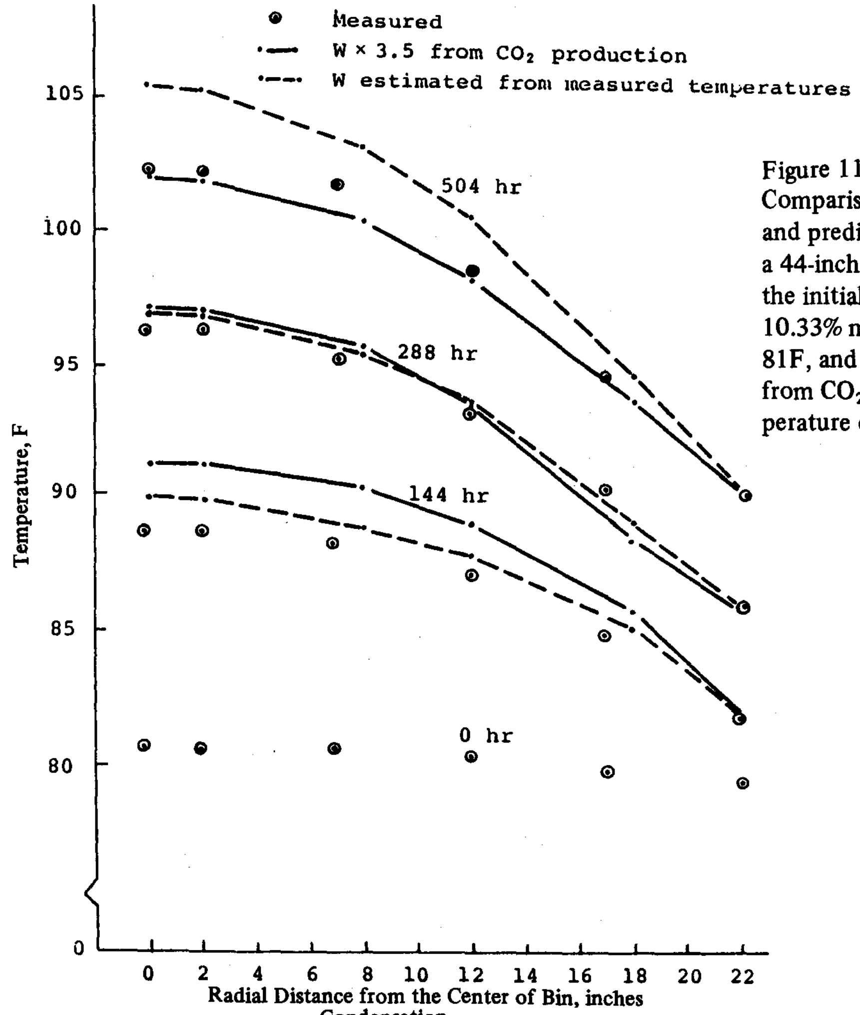


Figure 11.
Comparison between measured and predicted temperatures of a 44-inch diameter bin from the initial conditions of 10.33% moisture content and 81F, and W, heat generated from CO_2 production or temperature data.

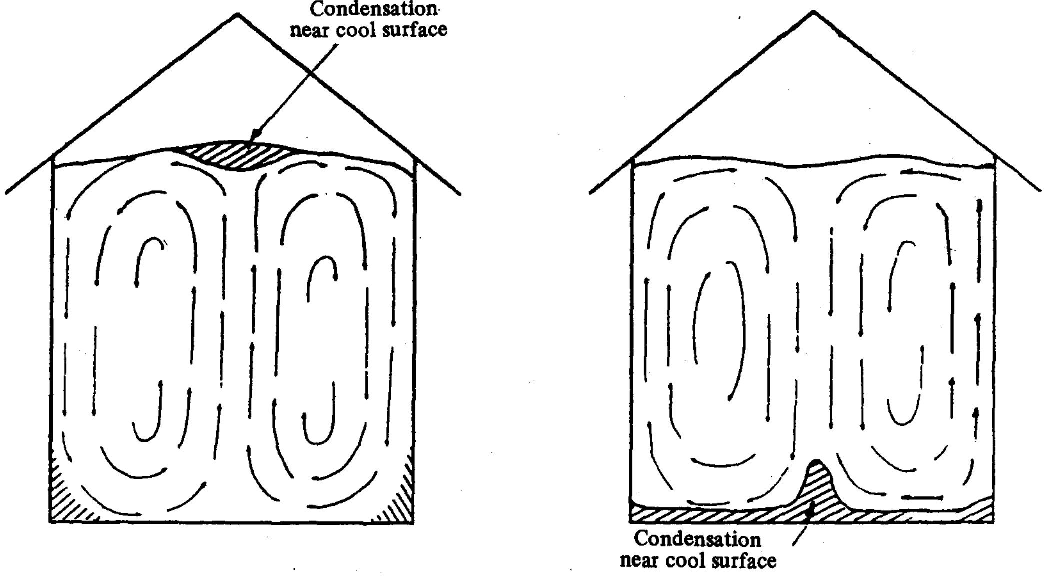


Figure 12. Mositure movement within bulk of grain due to difference between the temperature of outside air and of stored grain. Left, outside air temperature below grain temperature; right, outside air temperature above grain temperature(19,35)

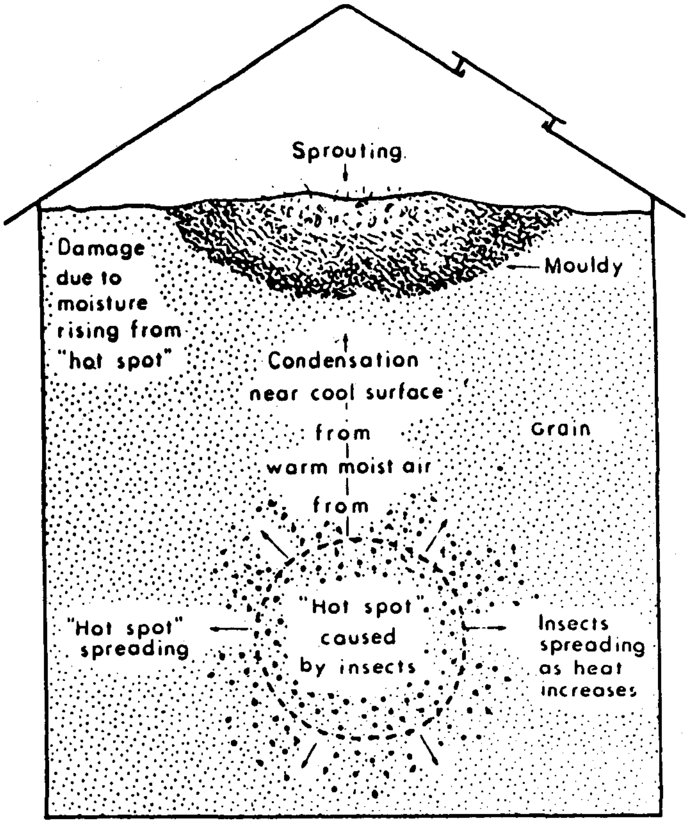


Figure 13. Spoilage of grain due to temperature gradients, movement of moisture and localized development of fungi and insects(19,35)

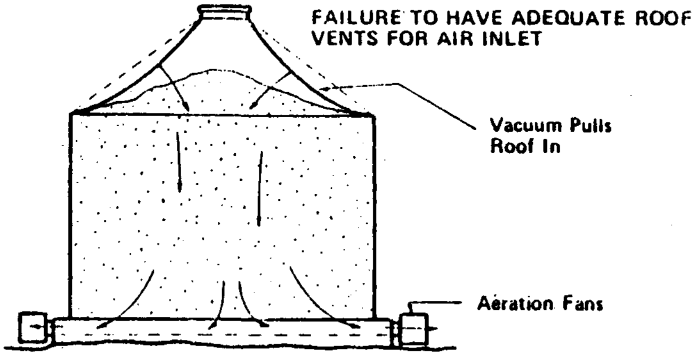


Figure 14. Bin failure due to inadequate roof vents for air inlet.

Section 2.1, general recommendations are that 125% of the cross-sectional area of the main duct.(8) Grain piled in the roof area must not block the roof vents. Therefore, the area above the surface of the grain must allow free movements of the air to the vents as shown in Figure 17.(35)

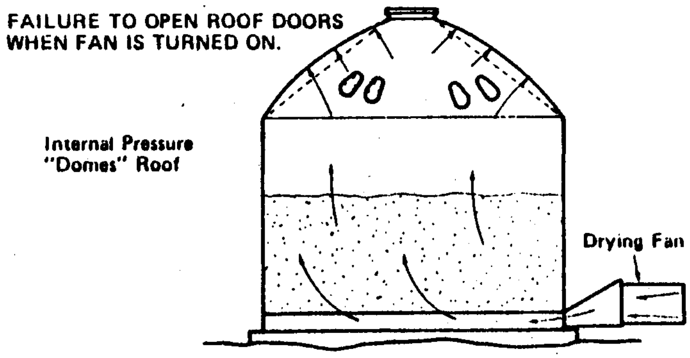


Figure 15. Bin failure due to inadequate roof openings for air outlet.

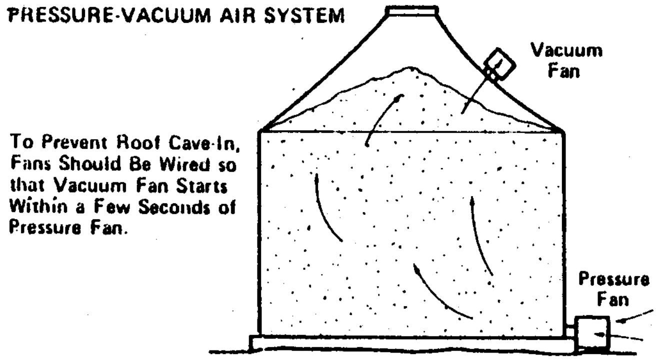


Figure 16. Bin failure due to improper switch timing.

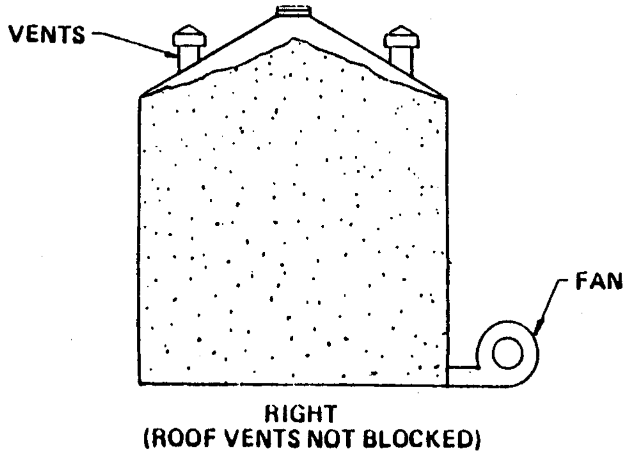


Figure 17. Proper roof vents installation.

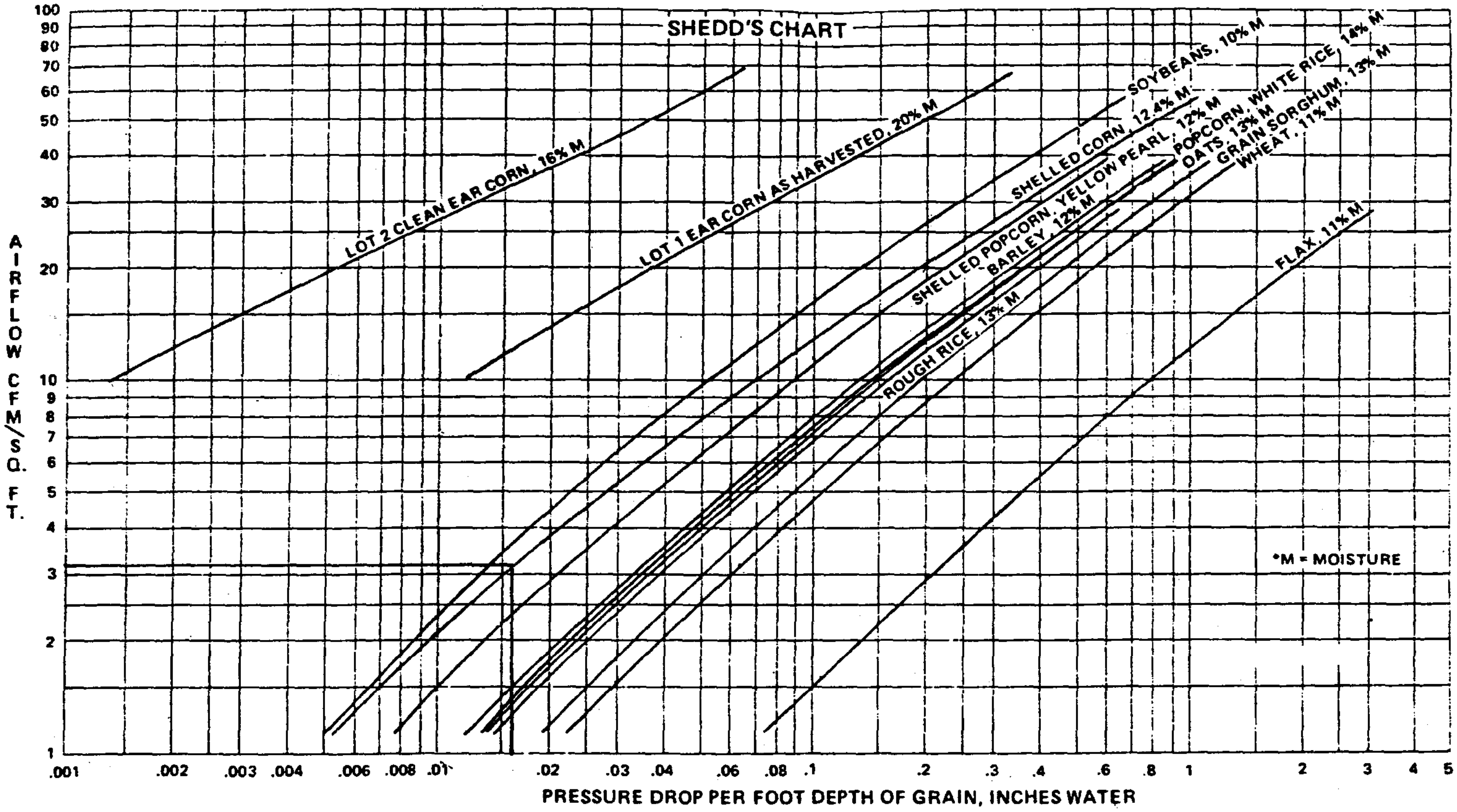


Figure 18. Resistance of loose-filled clean grains and seeds to different air flow.(11)

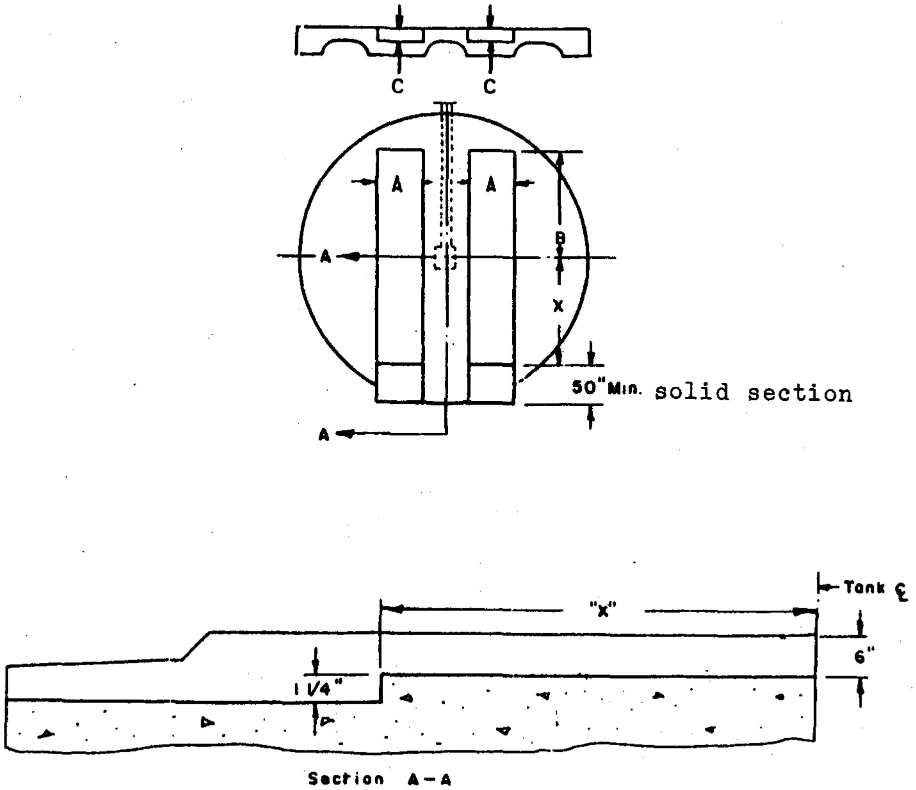
Table 6. Fan performance of axial vane and centrifugal fans(4,32)

	Axial vane aeration and crop drying fans										Centrifugal Fans			
H.P.	½	1½	3	5	10-13	7½	15	20	25	40	5	10	20	30
R.P.M.	3,450	3,450	3,450	3,450	3,450	1,750	1,750	1,750	1,750	1,750	1,750	1,750	1,750	1,750
SWP	AIR FLOW VOLUME – FAN RATING CUBIC FEET PER MINUTE													
¼"	1,907	4,169	5,850	12,100	24,750	18,300	26,300	29,100	32,700	47,000				
½"	1,630	3,812	5,450	11,100	24,400	17,900	25,700	28,450	32,400	46,000				
¾"	1,360	3,440	5,070	10,000	24,050	17,350	25,100	27,700	31,700	45,000				
1"	1,130	3,083	4,700	9,300	23,600	16,850	24,370	27,100	31,100	43,950	7,600	12,600	19,000	20,500
1¼"	950	2,800	4,350	8,700	23,250	16,150	23,700	26,400	30,300	42,900				
1½"	780	2,522	4,000	8,200	22,700	15,650	23,000	25,800	29,600	41,800				
1¾"	610	2,270	3,650	7,670	22,200	15,050	22,300	25,100	28,850	40,650				
2"	462	1,990	3,350	7,102	21,500	14,480	21,600	24,400	28,100	39,500	7,200	11,800	18,000	19,800
2¼"	330	1,760	3,050	6,720	20,800	13,800	20,850	23,600	27,300	38,350				
2½"	200	1,532	2,730	5,685	20,100	13,060	19,900	22,800	26,250	37,150				
2¾"		1,310	2,420	5,100	19,250	12,200	18,900	21,900	24,800	35,850				
3"'		1,023	2,070	4,569	18,300	11,300	17,800	20,700	22,300	34,500	6,500	10,800	17,000	19,100
3¼"		620	1,720	3,980	17,300	10,100	16,600	19,300	20,400	33,100				
3½"			1,360	3,517	16,200	9,300	15,300	17,850	18,800	31,600				
3¾"			850	3,000	15,050	8,200	14,200	16,500	17,100	30,000				
4"'			520	2,518	13,800	7,320	13,000	15,300	15,700	28,250	5,800	9,800	16,000	18,300
4¼"				1,800	12,500	6,300	11,700	14,100	14,400	26,500				
4½"				800	10,000	5,550	10,500	12,750	13,000	24,900				
4¾"					9,450	4,700	9,200	11,300	11,400	23,450				
5"'					8,800	4,120	7,900	9,850	10,000	22,000	4,700	8,800	14,900	17,500
5¼"					8,200	3,200	6,800	8,300	8,500	20,450				
5½"					7,500	2,520	5,700	6,900	7,300	18,900				
5¾"					6,800	2,000	4,800	5,600	6,100	17,250				
6"					6,100	1,480	3,850	4,550	4,900	15,600		7,800	13,200	16,600
6¼"					5,300		2,900	3,500	3,900	14,100				
6½"					4,400		2,100	2,700	3,000	12,600				
6¾"					3,500		1,300	1,850	2,000	11,100				
7"					2,600		500	1,000	1,100	9,500		6,600	11,000	15,800
8"												4,900	7,800	15,000
9"														14,100
10"														13,000
11"														12,000
12"														10,700
13"														8,800

To keep uniform temperature and moisture content of stored grain inside the steel tank, 0.1 CFM per bushel (= 1.25 ft^3) aeration rate is recommended.(2,33) As shown in Figure 18, the resistance of loose-filled grains and seeds to different airflow can be used to choose proper fan. For a 40-ft diameter by 40-ft height steel tank used for corn storage, the pressure drop per foot of corn will be 0.016 in water/ft or total pressure drop in corn bulk will be 0.64 in water (= 0.016 x40). Adding 50% for compaction and system resistance, the total static pressure for a fan will be 0.97-inch water. As shown in Table 6, choose two 1.5 HP axial vane fans at 1" static pressure to deliver about 6166 CFM or approximately 0.15 CFM per bushel which is more than adequate.

The maximum recommended duct air velocities are up to 1750 ft/min.(2,15,34,35) Then the cross section area of aeration duct is 1.76 ft^2 (= 3083/1750). If the dimension of C as shown in Figure 19 is 6", then the size of A is equal to 3'-6". Figure 20 shows a side view of aeration system.

The recommended duct surface area can be determined by a rule of thumb based on experience(2,34,35) which is 1 ft^2 per 30 CFM. Therefore, the required duct surface area with at least 10 percent perforations will be 103 ft^2 (= 3083/30). After the size of A is



Notes: A = 3'- 6"
B = 14'- 8"
C = 6"
X = 14' - 9"

Figure 19. Aeration duct design for the flush concrete floor of 40-feet diameter by 40-feet eave height steel tank.

Figure 20. Side view of aeration system

calculated, the required duct length is equal to 29.4 ft (= 103/3.5) which is equal to the sum of B and X. A 50" solid section of aeration duct near the aeration fan could avoid the air escaping from the short-cut such as openings near the fan.

4. Steel Tanks Used as Bin Dryers

Bin dryers are available in many sizes and capacities, and can be operated in different ways as shown from Figure 21 to Figure 25. Comparing drying tanks with storage tanks as mentioned above, the following conditions are different:

1. Drying tanks with a fully perforated floor are required for uniform air distribution.
2. Drying tanks are equipped with grain spreaders for uniform grain depth.
3. Stirring augers or recirculating augers are required for deep batch dryers.
4. Fans with heaters are required except natural air drying process.
5. Tanks should be reinforced to take extra loads from wet grains and stirring action.

4.1 In-Bin Shallow Batch Dryers

As shown in Figure 21, a layer of grain up to 3.5 feet depth is placed in the bin, dried overnight with continuous heat, then cooled and moved into a different storage unit.

Use about 20 CFM per bushel air flow rate and about 120°F drying temperature for best results(8). For this system, the energy required to dry corn from 25% moisture content (W.B.) to 15% moisture content (W.B.) is about 2000 BTU per pound of water removed.(8) Heat of vaporization of corn at 70°F and 16.7% moisture content (W.B) is about 1160 BTU per pound of water removed.(15,20) Therefore, the estimated drying efficiency is about 58%.

Based on heat balance equation and 58% drying efficiency, the following equation is developed by the author to estimate the time required to dry a batch of shelled corn:

$$\text{Drying time (hrs)} = \frac{0.38\ (A)}{(B)\ (C)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

Where A = pounds of water per bushel to be removed
B = air flow, CFM/bushel
C = pound of water removed per pound of air (refer to the humidity rato of pychrometric chart)

For example, use 27-feet diameter tank with 10-13 fan (Table 6), 2.5 million BTU/hr heater to dry corn from 25% to 15% moisture content (W.B), 2-feet grain, ambient temperature 60°F, relative humidity 60%, and with a drying temperature 120°F. Substituting A is equal to 7.42, B is equal to 25, and C is equal to 0.0106 into Equation(15), the estimated drying time of this batch is equal to 10.6 hours.

Usually the heater can be turned off when the drying front is about 6 inches from the surface.(18) Following the cooling process, some moisture between 1 and 2% can be removed if the weather condition is fovorable.(18)

An alternate heating and cooling cycle may be used to reduce the moisture differential between the top and bottom of the batch. A cycle time of 3 or 4 minutes with 75% of the time spent in heating and 25% in cooling, will result in less than 0.5% moisture differential in 3.3 feet depth of grain.(18)

4.2 Bin Dryer with Stirring Device

As shown in Figure 22, vertical stirring augers can be added to a bin dryer to increase the allowable depth of grain to about 8ft.(7) The action of stirring on an intermittent basis can mix the grain before it becomes overdried at the bottom of the bin.

The disadvantage of stirring action tends to loosen a column of grain around the auger. This, in turn, creates an air column or "air leak". Consequently, the heated air is exhausted at the auger points without being fully saturated. This, of course, leads to a loss of heat energy and increased operation cost.

To use standard storage tanks for drying, additional wall stiffeners and floor supports may be required to overcome the additional force due to stirring. To prevent bin failure, don't start up with screws near bin wall and have screws free prior to start up.(3)

4.3 Bin Dryer with Overhead Drying Floor

As shown in Figure 23, bin dryers use an overhead con-shaped drying floor supported about 3.3 feet below the roof(12). The heater and fan unit is mounted just below the drying floor. When the grain is dried it is dropped to a perforated floor below where an aeration fan is used to cool the grain while the next batch is loaded on the drying floor above. Additional batches are dropped on the top of the cooled grain until the bin is filled to the level of the heater unit. Then the dired grain is transferred to another storage bin.

4.4 Recirculating Batch Bin Dryer

As shown in Figure 24, a bin dryer equipped as a recirculating batch dryer(18). The hoppered perforated floor can use the gravity flow into a central chamber where it is picked up by a vertical auger and delivered to the top of the grain bin. The grain is mixed continuously as it dried, and the drying is more uniform than a non-recirculating batch dryer as shown in Figure 21. During the drying, it may be also less air leaking through the open screws as shown in Figure 22.

Figure 26 shows the moisture profile from bin bottom to top at 5 times in a typical drying cycle when a recirculator is used(15,18). After one complete cycle, the moisture differential is very small.

4.5 Continuous-Flow Bin Dryer

Figure 25 shows the dried grain near the full perforated floor is moved to the bin center by a sweep auger, and then picked by a vertical auger to recirculate the grain or carried to a cooling bin. The operation of the sweep auger is controlled by a thermostat. When the unit is operated as a continuous-flow dryer, the grain is removed from the drying bin at about 120°F and 1 to 2% above the safe storage moisture content, and is transferred to a cooling bin(9). In effect the grain steeps in the cooling bin, creating a slow cooling aeration process, similar to dryeration. The extra drying is nearly free – the only cost being the electric power to run a small aeration fan for two to three days(9).

The heat energy efficiency is excellent about half the energy that may be expended to remove a comparable amount of moisture from corn in a drying bin equipped with a

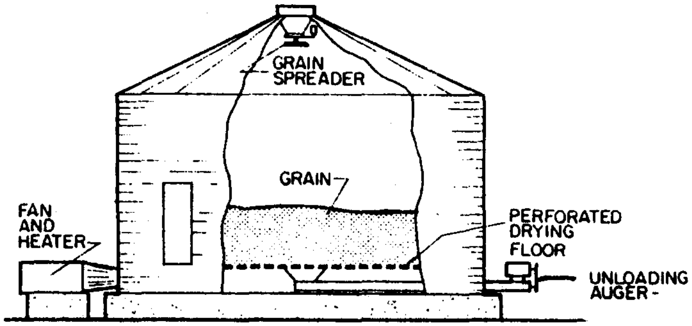


Figure 21. Typical batch dryer bin

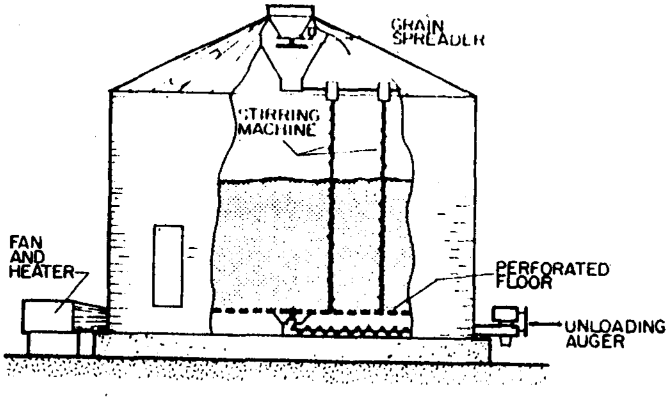


Figure 22. Bin dryer with auger stirring device

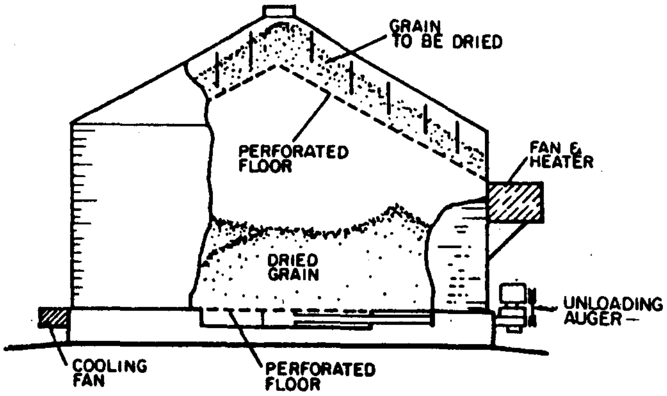


Figure 23. Bin dryer with overhead drying floor.

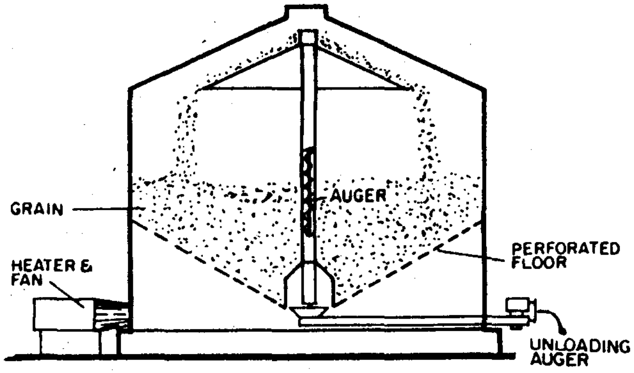


Figure 24. Recirculating batch bin dryer.

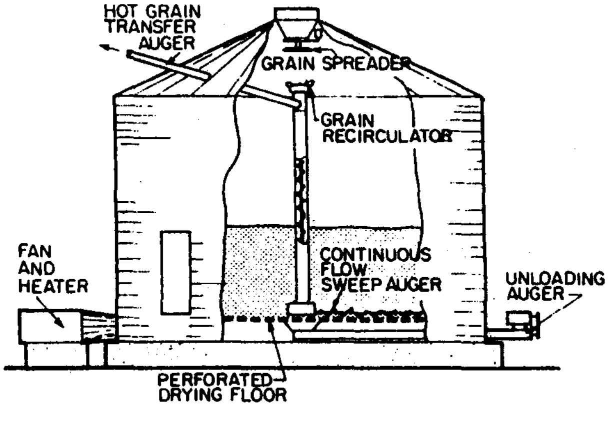


Figure 25. Continuous-flow or recirculating drying bin equipment

stirring device(9). If the heat efficiency is approximately 1400 BTU per lb of water removed(8), the drying efficiency is about 43% higher than that of batch bin dryer.

The disadvantage of this system is that the sweep auger on the floor will accumulate fines toward the bin center so that the floor must be periodically cleaned(15).

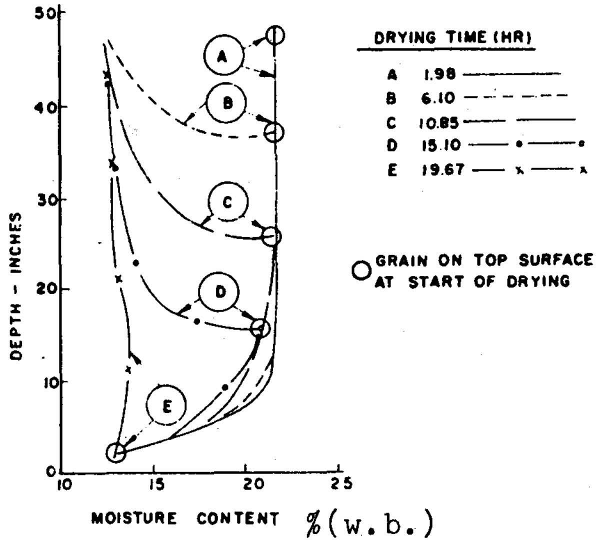


Figure 26. Moisture changes during recirculation drying

5. Conclusion

Based on the foregoing sections, the following conclusions are made:

1. To design a flat-bottom steel tanks, Janssen's equation is still valid if the flat-bottom tank is unloaded from the center and the unloading flow is close to a funnel flow.
2. A series of flat-bottom tanks is designed by applying the analysis mentioned in Section 2.1 through Section 2.5 However, the results are satisfactory.
3. Spontaneous heating of a 44-inch diameter by 66-inch high steel bin was set up to measure the temperature rise which was compared with the predicted temperature by a finite difference method. Based on the data collected, reasonable temperature prediction is possible, if the heat production from CO_2 production rate is multiplied by a factor of 3.5.
4. To solve the heating problem, an aeration system is required for steel tanks used for storage.
5. A practical example was used to demonstrate the design procedures of aeration system for steel tanks.
6. Extra equipment is required to change storage tanks into drying tanks such as fully perforated floors, grain spreaders, stirring or recirculating augers, big fans with heaters, and extra reinforcement.
7. An equation was developed for estimating a batch drying time for in-bin shallow batch dryers.
8. Bin dryer with stirring device would increase allowable drying depth and also increase operation cost.
9. Continuous bin dryer would be about 43% higher efficiency than that of batch bin dryer.

References

1. _____, 1977. ACI 313-77, Recommended Practice for Design and Construction of Concrete Bins, Silos, and Bunkers for Storing Granular Materials, American Concrete Institute.
2. _____, 1957. Aeration of Grain in Commercial Storages. Marketing Research Report No. 178., Agricultural Marketing Service, Washington 25, D.C.
3. _____, 1976. Assembly Instructions of Grain Storage Tanks, Technical Information 0021117, Behlen-wickes Company Limited, Brandon, Manitoba, Canada.
4. _____, 1978. Behlen Planning Manual for Grain Handling and Storage Systems. Behlen-wickes Company Limited, Brandon, Manitoba, Canada.
5. _____, 1975. Canadian Farm Building Code. NRCC No. 13992. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, Canada.
6. _____, 1975, Commentaries on Part 4 of National Building Code of Canada, National Research Council of Canada, Ottawa, Canada.
7. _____, ______, Foreway II, Sukup Manufacturing Company, Sheffield, Iowa 50475, USA
8. _____, Grain Conditoining Technology (31 Pages), AD-14644M, Behlen Manufacturing Company, Columbus, Nebraska 68601, USA.
9. _____, ______. How Shivvers' Circulator Conserves Energy through Efficiency, Shivvers Corporation, P.O. Box 305, Hutsonville, IL. 62433. USA.
10. _____, 1974. Metal Building Systems Manual. Metal Building Manufacturers Association, 2130 Keith Building, Cleveland, Ohio 44115. USA.
11. _____, 1983. Resistance of Airflow through Grains, Seeds, and Perforated Metal Sheets. ASAE Data: ASAE D272•1. Agricultural Engineers Yearbook of Standards. American Society of Agricultural Engineers.
12. _____, ______. Stormor-Ezee-Dry Grain Conditioning Systems, Stormor Inc., Fremont, NE 68025, USA.
13. _____, 1961. Wind Forces on Structures, Transactions of American Society of Civil Engineers. Vol. 126: 1124-1198, 345 East 47th Street, New York 10017. N.Y. USA.
14. Bouland, H.D., 1966. Locating, Designing and Building Country Grain Elevators. Agriculture Information Bulletin No. 310., United States Department of Agriculture.
15. Brooker, D.B., F.W. Bakker-Arkema, and C.W. Hall, 1974. Drying Cereal Grains. The AVI Publishing Company, Inc. Westport, Connecticut, USA.
16. Dusinberre, G.M., 1961. Heat-transfer Calculations by Finite Differences. International Textbook Company, Scranton, Pennsylvania, USA.
17. Frakhauser, C.D., 1977. Analysis and Design of Corrugated Grain Tanks. ASAE Paper No. 77-4502. American Society of Agricultural Engineers. St. Joseph, Michigan 49085.
18. Friesen, O.H. 1980. Heated-air Grain Dryers. Publication 1700. Information Servicess, Agriculture Canada, Ottawa KIA OC7 Canada.
19. Hall, D.W. 1970. Handling and Storage of Food Grains in Tropical and Subtropical Areas. FAO Agricultural Development Paper No. 90. Food and Agriculture Organization of the United Nations, Rome.

20. Haynes, B.C. 1961. Vapor Pressure Determination of Seed Hygroscopicity. Tech. Bull. 1229, ARS, USDA. Washington, D.C.
21. Jaky, J. 1948. Pressure in Silos. Proceeding 2nd International Conference Soil Mechanics and Foundations. 1: 103-108.
22. Ketchum, M.S. 1919. The Design of Walls, Bins, and Grain Elevators. 3rd Edition. McGraw-Hill Book Company, Inc. New York, U.S.A.
23. Moysey, E.B., J-T. Shaw, and W.P. Lampman, 1977. The Effect to Temperature and Moisture on the Thermal Properties of Rapeseed. Transactions of the ASAE: 461-464.American Association of Agricultural Engineers.
24. Moysey, E.B. 1979. Active and Passive Pressures in Deep Grain Bain. Transactions of the ASAE: 1409-1413. American Association of Agricultural Engineers.
25. Muir, W.E., 1970. Temperatures in Grain Bins. Canadian Agricultural Engineering 12: 21-24.
26. Neubauer, L.W. and H.B. Walker. 1961. Farm Building Design. Prentice-hall, Inc. Englewood Cliffs, N.J. U.S.A.
27. Reisner, W. 1971. Bins and Bunkers for Handling Bulk Materials. Trans Tech Publications, P.O. Box 2981, Cleveland, Ohio 44116 USA.
28. Roberts, D.E., 1972. Grain Drying with a Recirculator. Unpublished Ph.D. Thesis. University of Missouri, USA.
29. Schuster, R.M. 1975. Cold Formed Steel Design Manual. Solid Mechanics Division, University of Waterloo, Ontario, Canada.
30. Shaw, J.-T. 1977. Spontaneous Heating of Stored Rapeseed. Ph.D. Dissertation University of Saskatchewan, Saskatoon, Saskatchwan, Canada.
31. Shaw, J.-T., 1980. A Proposal for New Design of Model 12 and Model 16 Grain Tanks. Internal Report (12 Pages). Behlen-Wickes Company Ltd., Brandon, Manitoba, Canada.
32. Shaw, J.-T. 1981. A Laboratory Report of Modified Behlen Three Horsepower Axial Fans. Internal Report, Behlen-wickes Company Limited, Brandon, Manitoba, Canada.
33. Shaw, J.-T. 1982. Guidelines on Planning and Designing Grain Handling, Conditioning and Storage Systems. Journal of Chinese Agricultural Engineering, Vol. 28(4): 28-32.
34. Shaw, J.-T., 1983. A Study on Improving the Rice Storage Systems for Taiwan. Journal of Chinese Agricultural Engineering, Vol. 29(4): 68-77.
35. Shaw, J.-T. 1984. A Study on Improving the Rice Storage System for Taiwan. Paper Presented for Workshop on Post-harvest Technology of Agricultural Produce Sponsored by CCSSC and the U.S. National Academy of Science. January 9-14, 1984, Taipei, Taiwan.
36. Turitzin, A.M. 1963, Dynamic Pressure of Granular Material in Deep Bins. Proceedings ASCE 89 No. ST2: 49-73.
37. Tyson, A.W. and H.B. Manbeck. 1980. Interaction Between Bin Wall Stiffness and Emptying Pressures. ASAE Paper No. 80-4502. St. Joseph, Michigan 49085, USA.
38. Yaciuk, G., W.E. Muir, and R.N. Sinha, 1975. A Simulation Model of Temperatures in Stored Grain. J. Agri. Engng. Res. 20: 245-258.