DEEP BED DRYING OF MALT

by

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Table 2.1

Mean Values of Length, Width and Thickness of Malt for a Range of Moisture Content

Variety	Number of Measurements	Moisture Content % (w.b.)	Mean Length (s.d.) (mm)	Mean Width (s.d.) (mm)	Mean Thickness (s.d.) (mm)
Triumph	50	41.22	8.940 (0.278)	4.074 (0.069)	3.334 (0.044)
	50	28.56	8.432 (0.105)	3.846 (0.059)	3.278 (0.039)
	50	12.53	8.388 (0.232)	3.810 (0.067)	3.255 (0.069)
	50	9.42	8.144 (0.288)	3.762 (0.100)	3.238 (0.245)
	50	6.51	8.072 (0.162)	3.756 (0.076)	3.223 (0.109)
Sonja	50	41.66	9.172 (0.204)	4.222 (0.086)	3.494 (0.077)
	50	28.93	8.762 (0.203)	3.994 (0.037)	3.319 (0.028)
	50	12.83	8.416 (0.197)	3.734 (0.073)	3.220 (0.048)
	50	8.58	8.274 (0.229)	3.748 (0.055)	3.193 (0.042)
	50	4.80	8.366 (0.198)	3.724 (0.059)	3.174 (0.058)

Table 2.2

1000 Grain Weight of Malt for a Range of Moisture Content

Variety	Replications	Moisture Content % (w.b.)	1000 Grain Weight (s.d.) (g)
Triumph	5	41.22	60.49 (2.483)
	5	28.56	49.50 (1.116)
	5	12.53	42.05 (0.723)
	5	9.42	40.57 (1.193)
	5	6.51	39.21 (0.890)
Sonja	5	41.66	64.24 (1.246)
	5	28.93	53.18 (0.591)
	5	12.83	43.61 (0.674
	5	8.58	41.52 (0.731)
	5	4.80	39.50 (0.279)

Table 2.3 Bulk Density and Dry Bulk Density for a Range of Moisture Content

Variety	Replications	Moisture Content % (w.b.)	Bulk Density (s.d.) (kg/m³)	Dry Bulk Density (Kg/m³
Triumph	5	41.22	572.84 (2.369)	336.71
	5	28.56	544.58 (9.858)	389.04
	5	12.53	525.57 (2.264)	459.71
	5	9.42	537.00 (2.134)	486.41
	5	6.51	545.50 (1.485)	509.98
Sonja	5	41.66	603.36 (5.356)	352.00
	5	28.93	569.36 (8.072)	404.64
	5	12.83	525.73 (3.865)	458.59
	5	8.58	530.08 (4.381)	484.59
	5	4.80	540.90 (1.256)	514.93

Table 2.4 Specific Heats of Some Common Agricultural Crops

Crops	Specific Heat/Regression Equation for Specific Heat (kgJ/kg^{o}K)	Authors(s)	Remarks if any
Wheat	1.5949	Babbit (1945)	Determined indirectly
Wheat	$C_p = 1.184 + 0.03031\ M_w$ $C_p = 1.260 + 0.03068\ M_w$ $C_p = 1.205 + 0.03466\ M_w$	Pfalzner (1951)	Sample A Sample B Sample C
Wheat (soft white)	$C_p = 1.398 + 0.04080\ M_w$	Kazarian & Hall (1965)	
Wheat (hard red spring)	$C_p = 1.096 + 0.0408\ Md$	Muir & Viravanichai (1972)	
Rough Rice	$C_p = 1.109 + 0.04479\ M_w$	Haswell (1954)	
Rough Rice	$C_p = 0.921 + 0.05447\ M_w$	Wratten et al (1969)	
Rough Rice (Short grain)	$C_p = 1.269 + 0.03487\ M_w$	Morita & Singh (1979)	
Rough Rice (medium)	$C_p = 1.136 + 0.01758\ M_w$	Vemuganti & Pfost (1980)	
Corn (Yellow dent)	$C_p = 1.523 + 0.03562\ M_w$	Kazarian & Hall	Moisture content 0.91 to 30.2%
Maize grain	1.835	Matouk (1976)	Specific heat if dry matter in the temp range 0 - 15 ^{o}C
Corn dent	$C_p = 0.77 + 0.00502\ M_w$	Vemuganti & Pfost (1980)	
Soybeans	$C_p = 1.64 + 0.019\ Md$	Alam & Shove (1973)	
Barley	$C_p = 0.878 + 0.03475\ M_w$	Vemuganti & Pfost (1980)	
Barley	$C_p = 1.445 + 0.04885\ Md$	Boyce (1966)	Moisture Content 7.70 to 34.52
Malt	$C_p = 1.651 + 0.04116\ M_w$	This work	

Table 2.5

Mean Values of Specific Heat of Malt for a Range of Moisture Content

Variety	Replications	Moisture Content % (w.b.)	Mean Specific heat (s.d.) (kJ/kg K)
Triumph	5	41.22	3.343 (0.256)
	5	28.56	2.795 (0.126)
	5	12.53	2.184 (0.113)
	5	9.42	2.010 (0.149)
	5	6.51	1.889 (0.146)
Sonja	5	41.66	3.372 (0.145)
	5	28.93	-
	5	12.83	2.262 (0.049)
	5	8.58	2.039 (0.093)
	5	4.80	1.808 (0.117)

Table 2.6 Determination of Latent Heat of Malt Based on Equilibrium Moisture Content Data (Rixton & Henderson, 1981)

Moisture Content % (d.b.)	Relative Humidty %			Equilibrium Vapour Pressure x 10^3 bar			Latent Heat of Malt
	5°C	25°C	45°C	5°C	20°C	45°C	Latent Heat of Water
47.92	95.9	97.0	95.3	8.3617	30.7208	91.3498	1.0000
38.12	95.0	95.0	94.0	8.2832	30.0874	90.1037	1.0000
19.18	76.1	79.3	82.0	6.6353	25.1151	78.6011	1.0410
10.74	37.2	42.4	53.6	3.2453	13.4285	51.3782	1.1503
7.41	17.7	21.8	30.5	1.5432	6.9042	29.2357	1.2222
5.59	11.2	14.9	18.6	0.9765	4.7189	17.8290	1.2500
Saturation Vapour Pressure x 10^3 bar	-	-	-	8.7192	31.6710	95.8550	-

Table 2.7 Data on Shrinkage of Malt Bed during Drying

Run	1		2	
Initial Moisture Content % (w.b.)	42.33		42.55	
Weight of Wet Grains (g)	2770		2772	
Initial Depth of Grain Bed (cm)	28.20		27.90	
Number of Observations	$(M_{wo}-M_w)\%$	S%	$(M_{wo}-M_w)\%$	S%
1	0.00	0.00	0.00	0.00
2	0.84	1.77	0.84	1.07
3	1.71	2.48	1.71	1.97
4	2.61	3.36	2.60	2.68
5	3.53	4.96	3.52	3.94
6	4.48	6.20	4.46	5.19
7	5.47	7.44	5.44	6.27
8	6.48	8.51	6.45	7.52
9	7.53	9.20	7.49	8.24
10	8.61	9.92	8.57	8.96
11	9.73	10.46	9.68	9.31
12	10.89	10.99	10.83	9.85
13	12.08	11.52	12.03	10.39
14	13.32	12.05	12.26	10.75
15	14.61	12.58	14.54	11.11
16	15.94	12.94	15.87	11.46
17	17.32	13.12	17.02	11.82
18	18.76	13.65	18.67	12.18
19	20.25	13.82	20.15	12.54
20	21.80	14.18	21.70	12.90
21	23.41	14.71	23.30	13.26
22	25.09	15.07	24.97	13.62
23	26.85	15.24	26.72	13.97
24	28.67	15.60	28.53	14.15
25	30.58	15.95	30.43	14.69
26	32.58	16.66	32.42	15.05
27	34.66	16.84	34.49	15.23

Table 2.8 Heat Transfer Coefficient of Malt for a Range of Air Flow Rate

Run No.	Amospheric Pressure (Pascal)	Temp (^{o}C)	Air Flow Rate (kg/sec m^2)	Value of Y at			Heat Transfer Coefficient			Mean Value of h_{cv} (kJ/m^3 sec ^{o}K)
				x = 6 cm	x = 12 cm	x = 18 cm	x = 6 cm	x = 12 cm	x = 18 cm	
1	100206	50.82	0.3589	4.0	8.0	12.0	23.92	23.92	23.92	23.92
2	100260	51.29	0.4504	3.5	7.0	10.0	26.27	26.27	25.02	25.85
3	101306	51.99	0.6082	3.0	7.0	10.0	30.4	35.47	33.78	33.22
4	101466	62.57	0.3543	4.5	8.0	11.5	26.57	23.62	22.63	24.46
5	101960	63.25	0.4959	3.5	7.5	11.0	28.92	30.99	30.30	30.07
6	101653	63.48	0.6211	3.5	7.0	10.0	36.23	36.23	34.50	35.65
7	101380	69.70	0.3525	4.5	8.0	12.0	26.43	23.50	23.50	24.47
8	101786	70.82	0.5640	-	7.5	11.0	-	35.25	34.46	34.85
9	101920	70.04	0.5001	-	8.0	12.0	-	33.34	33.34	33.34

Table 3.1 Balance Accuracy Test (Weight suspended on tray with Air Flow)

Change in Weight (g)	Balance Reading in mV (increasing wt.)	Balance Reading in mV (decreasing wt.)
0	3.0050	3.0050
5	3.5000	3.5000
10	3.9950	3.9950
20	4.9850	4.9850
25	5.4849	5.4849
30	5.9800	5.9800
40	6.9700	6.9700
45	7.4650	7.4650
50	7.9650	7.9600

$$y = 3.004 + 0.0099\,x$$

$$r^2 = 0.99$$

S.E. = 0.0015 mV

= 0.015 g

Table 3.2 Experimental Data to Check the Accuracy of the Temperature Logging System

Thermometer Reading (°C)	Data Logger			Digital Voltmeter		
	Reading (mV)	Interpolated Temperature(°C)	Error	Reading (mV)	Interpolated Temperature (°C)	Error
92.10	3.950	92.960	+0.860	3.962	93.222	+1.122
88.50	3.780	89.270	+0.770	3.792	89.530	+1.030
85.80	3.640	86.220	+0.420	3.657	86.594	+0.794
82.80	3.505	83.260	+0.460	3.522	83.634	+0.834
79.90	3.370	80.290	+0.390	3.391	80.750	+0.850
76.00	3.200	76.500	+0.520	3.215	76.855	+0.855
73.00	3.060	73.400	+0.400	3.076	73.762	+0.762
69.80	2.910	70.050	+0.250	2.925	70.375	+0.575
66.10	2.750	66.430	+0.330	2.763	66.726	+0.626
62.50	2.585	62.685	+0.185	2.599	63.003	+0.503
59.90	2.470	60.060	+0.160	2.486	60.408	+0.508
57.10	2.350	57.310	+0.210	2.361	57.563	+0.463
54.10	2.220	54.310	+0.210	2.234	54.400	+0.300
51.50	2.090	51.290	-0.210	2.120	51.900	+0.490
48.50	1.970	48.490	-0.010	1.983	48.792	+0.292
46.40	1.890	46.610	+0.210	1.897	46.778	+0.378
44.30	1.795	44.329	+0.029	1.809	44.706	+0.406
43.00	1.730	42.840	-0.160	1.754	43.406	+0.406
41.40	1.670	41.420	+0.020	1.683	41.729	+0.329
40.00	1.610	39.990	-0.010	1.625	40.350	+0.350
38.60	1.550	38.560	-0.040	1.566	38.940	+0.340
35.90	1.440	35.930	+0.030	1.450	36.170	+0.270
34.20	1.360	34.010	-0.190	1.376	34.394	+0.194
33.00	1.320	33.040	+0.040	1.328	33.232	+0.232
31.90	1.270	31.830	-0.070	1.281	32.095	+0.195
30.80	1.220	30.620	-0.180	1.239	31.085	+0.285
29.40	1.160	29.160	-0.240	1.178	29.602	+0.202
27.90	1.115	28.065	+0.165	1.121	28.214	+0.314
24.70	0.960	24.270	-0.430	0.984	24.860	+0.160
18.80	0.730	18.580	-0.220	0.742	18.878	+0.078
Standard Error	s.d. = 0.3231 °C			s.d. = 0.5421°C		

Stand error of data logger compared with digital voltmeter = 0.1271°C

Table 3.3 Constants in the Single Exponential Equation

Run Number	Initial M.C. % (d.b.)	Air Temperature	RH,%	M1	k , (min^{-1})	M_{dd} % (d.b.)	M_f % (d.b.)	(s.d.)
1	71.49	70.16	4.85	66.69	0.033636	5.63	4.66	0.75
2	72.16	59.80	7.66	66.79	0.019712	5.79	6.41	1.45
3	73.31	50.55	11.90	65.66	0.009831	8.25	7.85	1.10
4	73.11	79.84	4.50	64.71	0.039910	5.62	4.27	0.97
5	73.36	65.31	8.31	66.34	0.021278	6.22	5.66	1.95
6	72.97	50.62	16.44	66.68	0.009755	8.48	7.92	1.66
7	69.33	40.93	27.15	59.06	0.004671	8.12	10.56	1.10
8	70.29	29.77	51.88	59.95	0.001832	9.85	23.56	0.88
9	71.33	69.75	10.74	66.42	0.026697	5.33	5.43	1.12

Table 3.4 Constants in the Single Exponential Equation

Run No	Initial M.C. %, (d.b.)	Air Temp., (^oC)	RH%	M1	a	k, (min^{-1})	M_{dd} % (d.b.)	M_f %, (d.b.)	(s.d.)
10	78.72	30.28	71.99	64.46	0.9695	0.001512	12.23	27.50	0.38
13	80.63	39.74	42.65	74.37	1.0257	0.004123	8.13	10.85	0.78
14	69.00	45.25	32.14	61.02	0.9996	0.006823	7.96	9.15	0.58
15	72.56	34.57	70.21	57.86	0.9860	0.002212	13.88	22.02	0.33
16	74.50	37.12	61.47	64.11	0.9968	0.002582	10.19	16.85	0.30
17	75.46	39.95	52.68	67.58	1.0205	0.003245	9.24	12.48	0.52
18	72.11	32.42	79.24	51.59	0.9868	0.001881	19.83	25.95	0.36
19	61.42	40.06	28.94	50.37	0.9657	0.005775	9.23	10.56	0.46
20	61.43	49.65	17.82	54.20	1.0059	0.011363	7.55	9.04	0.72
21	60.68	45.27	32.00	51.24	0.9702	0.007881	7.87	9.54	0.47
22	68.59	65.10	8.53	62.03	1.0033	0.028256	6.77	6.69	0.45
23	63.02	60.02	8.28	57.02	1.0149	0.021859	6.84	7.24	0.63
24	69.52	69.88	5.34	62.62	0.9864	0.031425	6.04	5.64	0.43
25	69.85	80.13	3.46	61.25	0.9607	0.043225	6.10	5.03	1.01
26	68.89	69.76	10.06	62.29	0.9966	0.031339	6.39	5.03	0.50
27	67.26	85.12	2.86	61.50	0.9846	0.061128	4.80	3.80	0.67
28	67.67	90.18	2.38	60.31	0.9577	0.062621	4.70	3.95	0.91
29	69.84	80.06	4.49	61.02	0.9580	0.040732	6.15	5.04	0.96
30	62.27	60.61	15.15	56.67	1.0354	0.022515	7.54	7.00	0.74
31	67.98	90.09	2.37	59.80	0.9540	0.062267	5.30	3.98	1.00

Table 3.5 Constants in the Page Equation

Run Number	Initial M.C. % (d.b.)	Air Temp., (^{o}C)	RH,%	M1	a	k, (min^{-1})	u	M_{dd} % (d.b.)	M_f % (d.b.)	(s.d.)
14	69.00	45.25	32.14	57.47	0.9525	0.003447	1.1285	8.69	9.15	0.39
16	74.50	37.12	61.47	62.67	0.9881	0.002165	1.0326	11.08	16.85	0.28
17	75.46	39.95	52.68	64.19	0.9944	0.001886	1.0981	10.91	12.48	0.38
18	72.11	32.42	79.24	56.70	1.0096	0.003190	0.8991	15.95	25.95	0.28
19	61.42	40.06	28.94	49.56	0.9525	0.005046	1.0242	9.39	10.56	0.42
20	61.43	49.65	17.82	49.93	0.9468	0.004895	1.1797	8.70	9.04	0.50
21	60.68	45.27	32.00	50.25	0.9542	0.006772	1.0282	8.02	9.45	0.44
22	68.59	65.10	8.53	60.51	0.9813	0.022501	1.0562	6.93	6.69	0.41
23	63.02	60.02	8.28	53.97	0.9677	0.012664	1.1282	7.25	7.24	0.48
24	69.52	69.88	5.34	63.30	0.9962	0.034772	0.9741	5.98	5.64	0.41
25	69.85	80.13	3.46	69.14	1.0727	0.096341	0.7826	5.40	5.03	0.55
26	68.89	69.76	10.06	63.03	1.0076	0.034484	0.9762	6.34	5.03	0.5
27	67.26	85.12	2.86	65.09	1.0384	0.090613	0.8824	4.58	3.80	0.55
28	67.67	90.18	2.38	69.15	1.0884	0.134229	0.7754	4.14	3.95	0.53
29	69.84	80.06	4.49	69.26	1.07563	0.091114	0.7865	5.45	5.04	0.56
30	62.27	60.61	15.15	52.96	0.9756	0.011363	0.1609	7.99	7.00	0.56
31	67.98	90.09	2.37	67.83	1.0713	0.132250	0.7744	4.67	3.98	0.58

Table 3.6 Constants in the Double Exponential Equation

Run Number	Initial M.C. % (d.b.)	Air Temp. (^{o}C)	RH, %	M1	a	k_1 (min $^{-1}$)	M_2	b	k_2 (min $^{-1}$)	M_{dd} % (d.b.)	M_f % (d.b.)	(s.d.)
10	78.72	30.28	71.99	65.76	0.9570	0.0014	3.12	0.0454	0.0423	10.01	27.50	0.23
15	72.56	34.57	70.21	57.88	0.9646	0.0021	2.51	0.0418	0.0223	12.56	22.02	0.24
18	72.11	32.42	79.24	50.45	0.9136	0.0016	4.94	0.0894	0.0075	16.89	25.95	0.27
25	69.85	80.13	3.46	48.69	0.7467	0.0642	17.10	0.2623	0.0168	4.67	5.03	0.32
27	67.26	85.12	2.86	58.10	0.9113	0.0707	6.03	0.0945	0.0120	3.48	3.80	0.34
28	67.67	90.18	2.38	50.13	0.7818	0.0879	14.12	0.2202	0.0230	3.55	3.95	0.35
29	69.84	80.06	4.49	51.81	0.7903	0.0564	13.92	0.2123	0.0129	4.29	5.04	0.32
31	67.98	90.09	2.37	49.84	0.7776	0.0884	14.14	0.2206	0.0213	3.89	3.98	0.39

Table 5.1 Grain and Air Conditions for the Deep Bed Drying Experiments

	RUN NUMBER				
	1	2	3	4	5
Initial Moisture Content %, (d.b.)	62.47	76.06	76.61	65.26	76.33
Initial Grain temperature, ^{o}C	27.74	25.57	30.48	26.49	37.74
Bed Depth, m	0.75	0.75	0.75	0.75	0.75
Bulk Density, kg/m^3	606.33	607.99	588.43	608.00	608.00
Atmospheric Pressure, bar	1.0060	1.0119	1.0223	1.0113	1.0179
Drying Air Temperature, ^{o}C	Table 5.4	Table 5.5	Table 5.6	Table 5.7	Table 5.8
Drying Air Humidity ratio	0.0142	0.0146	0.0147	0.0147	0.0145
Mass Velocity of Air, kg/m^2 s	22.2548	22.1892	22.2841	22.2384	22.2563
Shrinkage, m	0.160	0.080	0.085	0.150	0.110

Table 5.2 Changes of Mean Moisture Content during Deep Bed Drying

RUN NUMBER									
1		2		3		4		5	
Time, Min	Mean Moisture Content %^{2} (d.b.)	Time, Min	Mean Moisture Content %^{2} (d.b.)	Time, Min	Mean Moisture Content %^{2} (d.b.)	Time, Min	Mean Moisture Content %^{2} (d.b.)	Time, Min	Mean Moisture Content %^{2} (d.b.)
0.0	62.46	0.0	76.06	0.0	73.61	0.0	65.25	0.0	76.33
15.0	61.32	16.0	74.82	12.0	72.35	15.0	64.09	7.0	75.10
29.0	60.7	30.0	73.59	25.0	71.09	29.0	62.82	18.0	73.86
41.0	58.75	41.0	72.35	36.0	69.83	41.0	61.66	30.0	72.62
50.0	57.89	53.0	71.12	46.0	68.57	50.0	60.61	43.0	71.38
60.0	56.65	64.0	69.88	58.0	67.31	60.0	59.45	54.0	70.15
72.0	55.60	75.0	68.64	69.0	66.06	72.0	58.29	65.0	68.91
84.0	54.46	87.0	67.41	80.0	64.80	79.0	57.13	76.0	67.67
95.0	53.31	97.0	66.17	90.0	63.54	95.0	55.86	87.0	66.43
105.0	52.17	110.0	84.94	100.0	62.28	105.0	54.81	99.0	65.20
120.0	56.91	120.0	63.70	111.0	61.02	115.0	53.65	110.0	63.96
129.0	49.88	132.0	62.47	121.0	59.76	126.0	52.49	121.0	62.72
140.0	48.74	145.0	61.23	134.0	58.50	139.0	51.33	133.0	61.48
150.0	47.60	155.0	60.00	144.0	57.24	150.0	50.17	144.0	60.25
161.0	46.46	168.0	58.76	155.0	55.98	160.0	49.01	155.0	59.01
174.0	45.31	179.0	57.52	165.0	54.73	175.0	47.39	166.0	57.77

Table 5.2 (Cont'd)

RUN NUMBER									
1		2		3		4		5	
Time, Min	Mean Moisture Content $\%^2$ (d.b.)	Time, Min	Mean Moisture Content $\%^2$ (d.b.)	Time, Min	Mean Moisture Content $\%^2$ (d.b.)	Time, Min	Mean Moisture Content $\%^2$ (d.b.)	Time, Min	Mean Moisture Content $\%^2$ (d.b.)
185.0	44.17	190.0	56.29	175.0	53.47	182.0	46.70	179.0	56.53
195.0	43.03	202.0	55.05	187.0	52.21	195.0	45.42	190.0	55.30
209.0	41.88	214.0	53.82	197.0	50.95	206.0	44.26	204.0	54.06
219.0	40.74	226.0	52.58	209.0	49.69	216.0	43.22	214.0	52.82
231.0	39.60	237.0	51.35	220.0	48.43	231.0	41.71	225.0	51.58
244.0	38.45	250.0	50.11	230.0	47.17	239.0	40.90	236.0	50.35
255.0	37.31	261.0	48.88	242.0	45.91	250.0	39.74	248.0	49.11
266.0	36.17	273.0	47.64	253.0	44.65	265.0	38.23	264.0	47.38
278.0	35.02	285.0	46.41	260.0	43.90	274.0	37.42	274.0	46.51
290.0	33.88	296.0	45.17			285.0	36.26	283.0	45.40
302.0	32.74	309.0	43.93			296.0	35.10	296.0	44.16
315.0	31.59	321.0	42.70			308.0	33.94	307.0	42.92
326.0	30.45	334.0	41.46			320.0	32.78	318.0	41.81
340.0	29.31	347.0	40.23			332.0	31.62		
352.0	28.16	360.0	38.99			344.0	30.46		
365.0	27.02	372.0	37.76			355.0	29.30		
379.0	25.88	386.0	36.52			367.0	28.14		
391.0	24.73	398.0	35.29			380.0	26.98		
405.0	23.59	412.0	34.05			393.0	25.82		
417.0	22.45	426.0	32.82			405.0	24.66		
427.0	21.30	441.0	31.51			419.0	23.39		

Table 5.2 (Cont'd)

RUN NUMBER									
1		2		3		4		5	
Time, Min	Mean Moisture Content $\%^2$ (d.b.)	Time, Min	Mean Moisture Content $\%^2$ (d.b.)	Time, Min	Mean Moisture Content $\%^2$ (d.b.)	Time, Min	Mean Moisture Content $\%^2$ (d.b.)	Time, Min	Mean Moisture Content $\%^2$ (d.b.)
441.0	20.16					431.0	22.34		
457.0	19.02					445.0	21.18		
474.0	17.82					460.0	20.02		
490.0	16.73					474.0	18.86		
509.0	15.59					489.0	17.70		
530.0	14.44					506.0	16.54		
550.0	13.30					524.0	15.38		
574.0	12.16					542.0	14.22		
585.0	11.59					550.0	13.64		
600.0	11.02					561.0	13.06		
612.0	10.56					571.0	12.48		
						583.0	11.90		
						595.0	11.33		
						607.0	10.76		
						615.0	10.42		

Table 5.3 Moisture Content Distributions at the Termination of Drying

	RUN NUMBER				
	1	2	3	4	5
Run Time, min.	612	441	260	615	318
Position, m	Moisture Content %[2] (d.b.)	Moisture Content %[2] (d.b.)	Moisture Content %[2] (d.b.)	Moisture Content %[2] (d.b.)	Moisture Content %[2] (d.b.)
0.00	6.55	7.16	8.15	6.22	7.67
0.10	6.67	7.72	10.55	6.49	8.83
0.20	7.17	10.78	28.06	6.98	20.28
0.30	8.03	26.23	49.18	7.92	42.18
0.40	10.15	49.68	64.39	9.97	57.63
0.50	16.82	50.23	69.11	19.08	69.10
0.60	-	61.82	71.41	30.66	70.04
Off bed	26.82	62.48	70.05	30.66	67.98

Table 5.4 Changes of Temperature with Time at a Number of Different Positions (Run - 1)

Time in Min	Temperatures in ^{o}C at the Position															
	0.0 m	0.05m	0.10m	0.15m	0.20m	0.25m	0.30m	0.35m	0.40m	0.45m	0.50m	0.55m	0.60m	0.65m	0.70m	Off Bed
0	45.32															
12	57.77	50.24	35.93	28.92	28.80	28.80	28.68	28.68	28.55	28.43	28.31	28.19	28.06	27.94	27.82	27.70
42	58.68	53.84	46.96	41.30	35.08	29.78	29.78	29.78	29.78	29.78	29.78	29.78	29.78	29.78	29.78	29.65
72	58.79	55.46	49.89	44.85	40.47	36.17	31.71	29.89	29.78	29.89	29.89	29.89	29.89	29.89	29.89	29.78
102	58.68	57.00	52.45	47.90	43.67	39.99	37.01	34.25	30.50	29.78	29.78	29.78	29.89	29.89	29.89	29.78
132	58.68	58.00	54.77	50.82	46.73	42.72	39.99	37.73	34.97	31.35	29.78	29.78	29.78	29.78	29.89	29.78
162	58.79	58.45	56.72	53.72	49.89	45.44	42.84	40.59	30.08	34.97	31.59	30.38	29.78	29.78	29.89	29.78
192	58.91	58.68	57.88	56.03	52.92	48.37	45.32	43.19	40.47	37.37	34.49	32.32	30.14	29.78	29.78	29.65
222	59.01	58.79	58.33	57.42	55.34	50.94	48.02	45.79	43.08	40.23	37.01	34.85	32.19	30.50	29.78	29.53
252	58.68	58.68	58.56	58.00	56.96	53.61	50.70	48.25	45.55	42.37	39.16	36.89	34.61	32.32	29.89	29.65
282	58.56	58.79	58.68	58.33	57.77	55.88	53.49	51.29	47.90	45.55	41.77	39.28	36.29	34.37	31.35	30.01
312	58.91	58.79	58.68	58.45	58.11	57.08	55.57	53.61	50.47	47.79	43.90	41.42	38.20	36.53	32.68	31.35
342	58.79	58.68	58.68	58.56	58.33	57.77	56.96	55.69	53.03	50.12	46.61	43.90	40.71	38.68	34.01	33.77
372	58.91	58.91	58.91	58.68	58.56	58.11	57.66	56.72	54.88	52.68	49.07	46.26	43.43	40.59	35.69	36.41
402	58.79	58.79	58.91	58.79	58.68	58.33	58.00	57.42	56.26	54.65	51.63	48.84	46.14	41.30	37.96	38.68
432	58.79	58.91	58.91	58.91	58.68	58.56	58.22	57.88	57.31	56.03	53.84	51.40	48.49	44.02	39.04	37.96
462	59.02	59.02	59.02	58.91	58.79	58.56	58.45	58.22	57.77	57.19	55.57	53.84	51.17	46.02	40.11	36.17
492	58.91	58.91	58.91	58.91	58.79	58.68	58.56	58.33	58.00	57.54	56.61	55.46	53.03	48.02	41.66	44.14
522	58.79	58.91	59.02	58.91	58.79	58.56	58.56	58.33	58.11	57.88	57.31	56.61	54.88	49.64	43.19	46.61
552	58.91	58.91	59.02	58.91	58.91	58.68	58.68	58.56	58.33	58.11	57.65	57.31	56.15	51.06	43.79	49.07
582	59.02	59.02	58.91	58.79	58.68	58.68	58.56	58.56	58.33	58.22	57.88	57.65	56.84	52.68	45.91	51.99
612	58.91	58.91	58.91	58.91	58.91	58.79	58.68	58.56	58.45	58.33	58.11	57.88	57.42	53.95	47.90	53.84

Table 5.5 Changes of Temperature with Time at a Number of Different Positions (Run - 2)

Time in Min	Temperatures in ^{o}C at the Position															
	0.0 m	0.05m	0.10m	0.15m	0.20m	0.25m	0.30m	0.35m	0.40m	0.45m	0.50m	0.55m	0.60m	0.65m	0.70m	Off Bed
0	54.07															
21	58.45	49.19	41.77	30.26	29.65	29.65	29.65	29.65	29.65	29.65	29.53	29.53	29.53	29.53	29.41	29.27
51	58.91	52.10	46.73	42.13	37.01	30.62	30.01	30.01	30.01	30.14	30.01	30.01	30.14	30.14	30.14	30.14
81	58.91	53.95	49.42	45.55	41.30	36.89	31.47	30.01	30.14	30.14	30.14	30.14	30.14	30.26	30.14	30.26
111	59.14	55.80	51.75	48.25	44.14	40.35	37.01	32.80	30.14	30.14	30.14	30.14	30.14	30.14	30.14	30.26
141	59.14	57.31	53.95	50.70	46.85	42.96	39.87	36.89	33.77	30.50	30.01	30.01	30.14	30.14	30.14	30.26
171	58.91	58.45	55.92	53.26	49.42	45.79	42.60	39.63	37.13	34.61	30.86	30.01	30.01	30.01	30.14	30.26
201	59.14	58.91	57.41	55.34	51.87	48.60	45.08	42.13	39.75	37.49	34.37	31.71	30.01	30.01	30.01	30.26
231	59.02	59.02	58.33	57.08	54.07	50.94	47.44	44.61	42.13	39.99	37.37	34.97	31.47	30.14	29.89	30.26
261	59.02	59.14	58.79	58.11	56.15	53.49	50.00	47.32	44.61	42.49	39.75	37.49	34.73	32.80	30.26	30.26
291	59.02	59.25	59.02	58.56	57.54	55.46	52.22	49.66	47.20	44.85	42.01	39.87	37.25	35.57	33.28	30.26
321	58.91	59.25	59.14	58.91	58.33	56.96	54.42	51.87	49.54	47.20	44.37	42.13	39.52	37.85	35.81	30.38
351	58.91	59.37	59.25	59.14	58.79	58.00	56.38	54.19	51.75	49.54	46.49	44.37	41.89	40.11	38.20	30.38
381	59.02	59.37	59.25	59.14	58.79	58.33	57.54	55.92	53.95	51.75	49.07	46.73	44.26	42.48	40.23	30.38
411	58.91	59.37	59.37	59.25	58.91	58.68	58.22	57.19	55.57	53.61	51.29	48.60	46.26	44.49	42.37	32.44
441	58.91	59.37	59.37	59.25	59.14	58.79	58.56	57.88	56.72	55.23	53.26	50.82	48.60	46.73	44.49	34.01

Table 5.6 Changes of Temperature with Time at a Number of Different Positions (Run - 3)

Time in Min	Temperatures in ^{o}C at the Position															
	0.0 m	0.05m	0.10m	0.15m	0.20m	0.25m	0.30m	0.35m	0.40m	0.45m	0.50m	0.55m	0.60m	0.65m	0.70m	Off Bed
0	55.23															
20	58.56	47.67	40.71	30.86	29.77	29.77	29.77	27.77	29.77	29.65	29.65	29.65	29.65	29.65	29.65	29.41
50	58.68	51.29	46.61	42.25	38.44	31.83	30.01	30.01	30.14	30.14	30.14	30.14	30.14	30.14	30.14	30.14
80	58.91	53.72	49.77	45.55	42.13	38.44	34.49	30.74	30.14	30.14	30.14	30.14	30.14	30.26	30.26	30.14
110	59.02	55.92	52.80	48.72	45.32	41.66	38.44	35.69	31.11	30.26	30.14	30.14	30.14	30.14	30.14	30.26
140	58.91	57.65	55.57	51.87	48.13	44.61	41.18	38.68	35.21	33.16	30.50	30.14	30.14	30.14	30.14	30.26
170	59.02	58.56	57.65	54.88	51.29	47.32	43.79	41.30	38.08	35.81	33.77	30.74	30.01	30.01	30.01	30.26
200	59.25	58.79	58.45	56.84	54.19	50.36	46.73	43.90	40.82	38.32	35.93	33.77	31.47	30.14	30.01	30.14
230	59.14	59.02	59.02	58.00	56.38	53.15	49.19	46.73	43.19	40.59	37.96	35.69	34.01	31.95	30.14	30.14
260	59.14	59.02	59.14	58.68	57.88	55.57	52.45	49.54	45.79	42.96	39.87	37.61	35.33	33.77	31.71	30.14

Table 5.7 Changes of Temperature with Time at a Number of Different positions - (Run 4)

Time in	Temperature in ^{o}C at Position						
Min	0.0 m	0.15 m	0.25 m	0.35 m	0.45 m	0.55 m	0.65 m	Off Bed
0	54.31							
15	58.68	29.28	29.28	29.28	29.28	29.28	29.04	28.92
45	58.79	36.29	30.01	30.01	30.14	30.28	30.28	30.14
75	58.79	40.35	32.56	30.01	30.28	30.28	30.28	30.28
105	58.91	42.84	36.41	30.01	30.14	30.28	30.28	30.28
135	58.91	45.32	38.68	30.62	30.14	30.28	30.28	30.14
165	59.02	48.13	40.94	33.52	30.14	30.28	30.28	30.14
195	58.91	50.70	43.55	35.69	30.18	30.18	30.28	30.14
225	59.02	53.49	45.79	37.85	31.11	30.14	30.14	30.01
255	58.91	55.69	48.14	39.40	33.04	30.14	30.14	30.01
285	59.02	56.96	50.82	41.66	35.09	30.14	30.14	30.01
315	59.14	58.22	53.03	44.02	36.89	30.76	30.01	30.01
345	59.02	58.68	54.88	46.49	38.92	32.07	30.14	30.01
375	59.14	59.02	56.38	49.07	41.06	34.25	30.50	30.38
405	59.25	59.25	57.31	51.63	43.43	35.93	31.95	32.56
435	59.25	59.25	57.77	54.19	45.55	37.73	33.89	34.47
465	59.37	59.25	58.00	55.69	48.25	39.75	35.33	36.17
495	59.37	59.37	58.33	57.08	50.47	41.89	37.25	38.20
525	59.37	59.37	58.22	57.54	52.92	44.26	39.28	40.35
555	59.37	59.37	58.45	57.88	54.77	46.85	41.66	42.60
585	59.48	59.48	58.45	58.11	56.15	49.30	44.02	45.08
615	59.48	59.48	58.56	58.33	56.95	51.99	46.38	47.67

Table 5.8 Changes of Temperature with Time at a Number of Different Positions (Run 5)

Time in	Temperature in ^{o}C at Position							
Min	0.0 m	0.15 m	0.25 m	0.35 m	0.45 m	0.55 m	0.65 m	Off Bed
0	54.77							
18	58.45	29.76	29.53	29.53	29.41	29.53	29.28	29.28
48	58.79	33.16	30.14	30.14	30.01	30.14	30.14	30.14
78	59.14	38.80	31.59	30.14	30.14	30.26	30.26	30.26
108	59.14	41.42	35.93	30.14	30.14	30.26	30.26	30.26
138	58.91	43.55	38.08	30.26	30.01	30.26	30.26	30.14
168	59.26	45.67	40.11	30.96	30.01	30.14	30.14	30.14
198	59.26	48.02	42.01	32.32	30.01	30.14	30.14	30.14
228	59.02	50.59	44.37	34.85	30.26	30.14	30.14	30.14
258	59.26	53.03	46.73	37.01	31.11	30.01	30.01	30.14
288	59.02	55.46	49.42	39.04	34.01	30.01	30.14	30.14
318	58.91	57.19	51.99	40.94	35.57	30.01	30.01	30.01

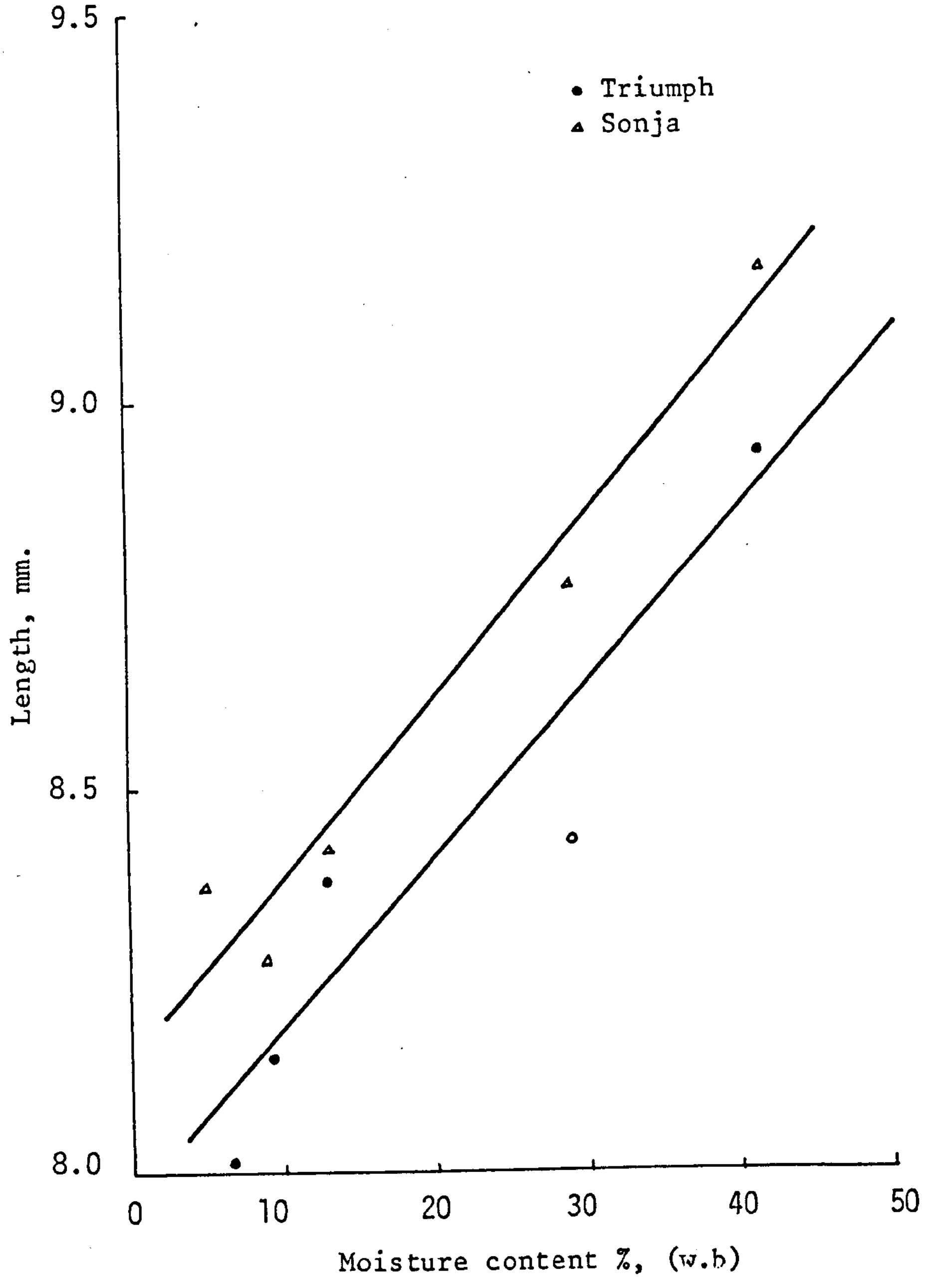


Fig. 2.1 Length of malt as a function of moisture content

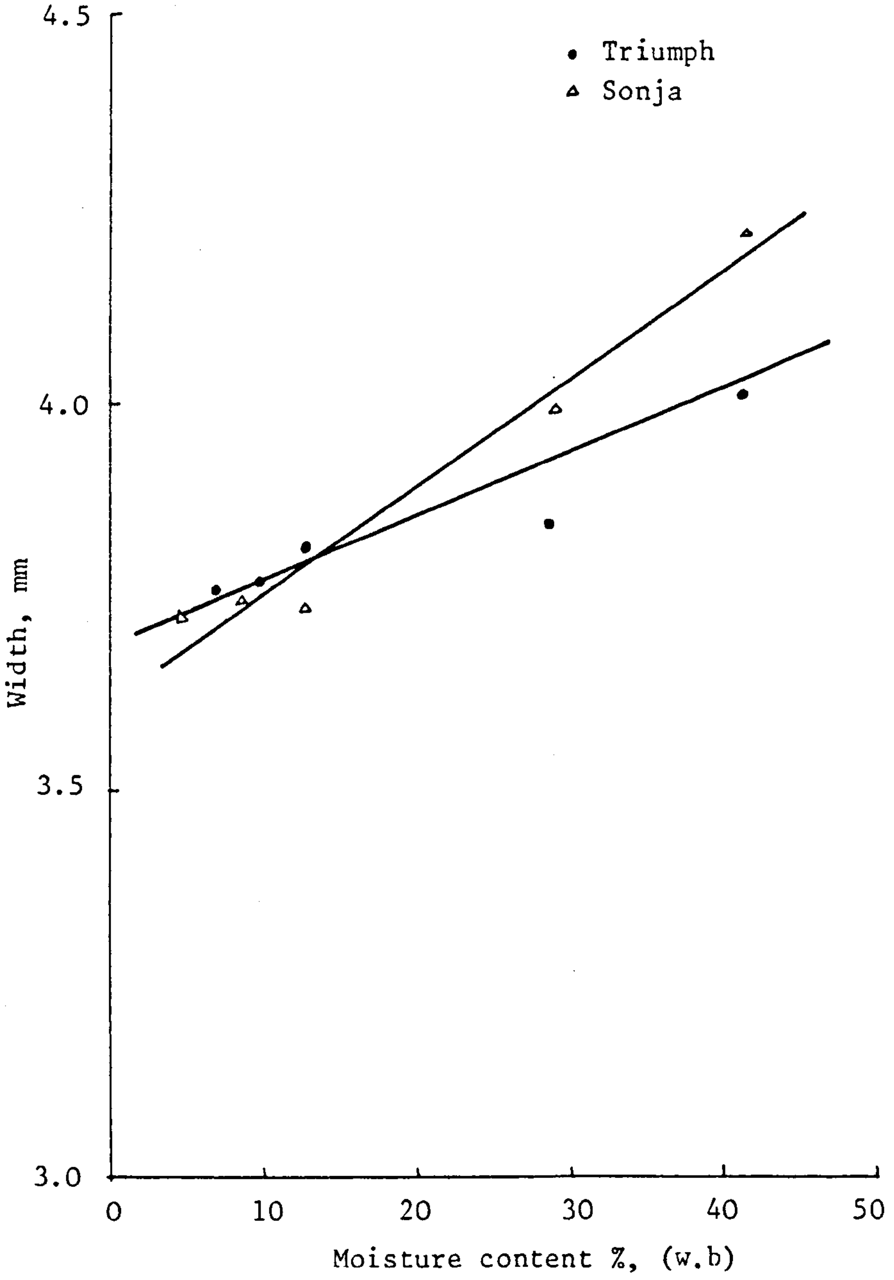


Fig. 2.2 Width of malt as a function of moisture content

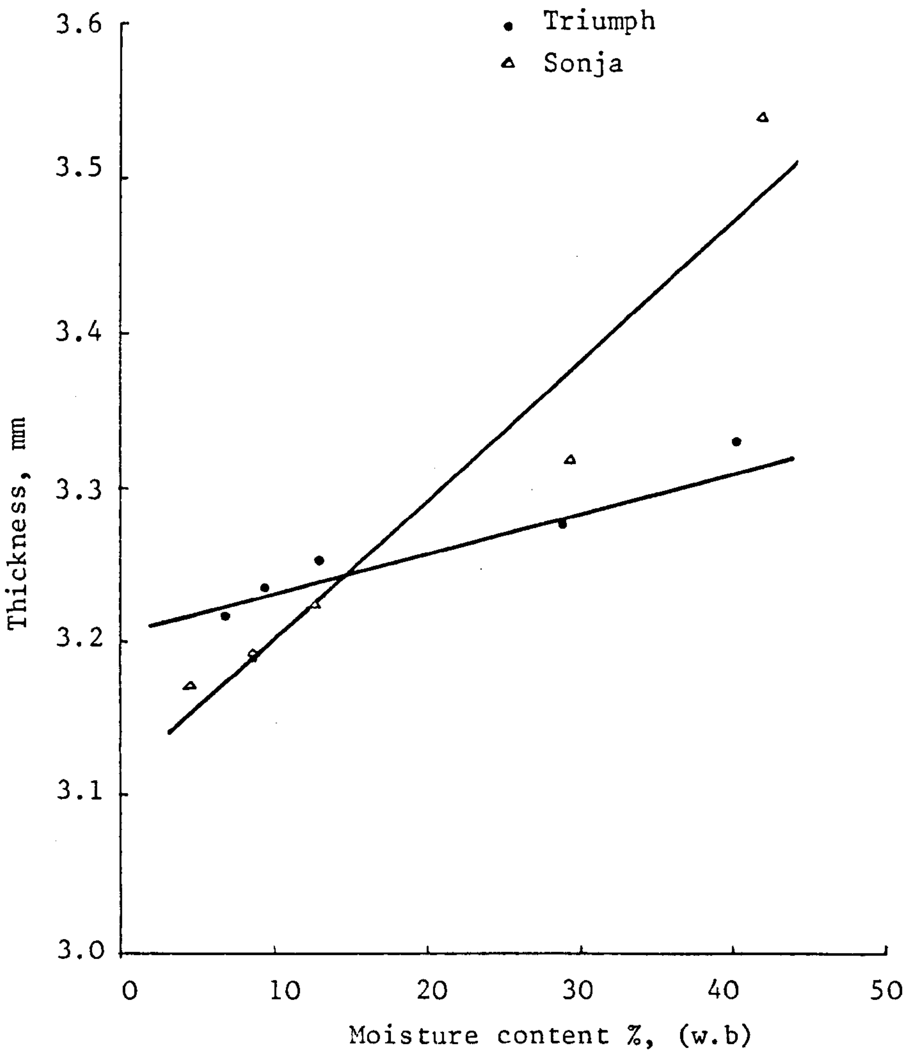


Fig. 2.3 Thickness of malt as a function of moisture content

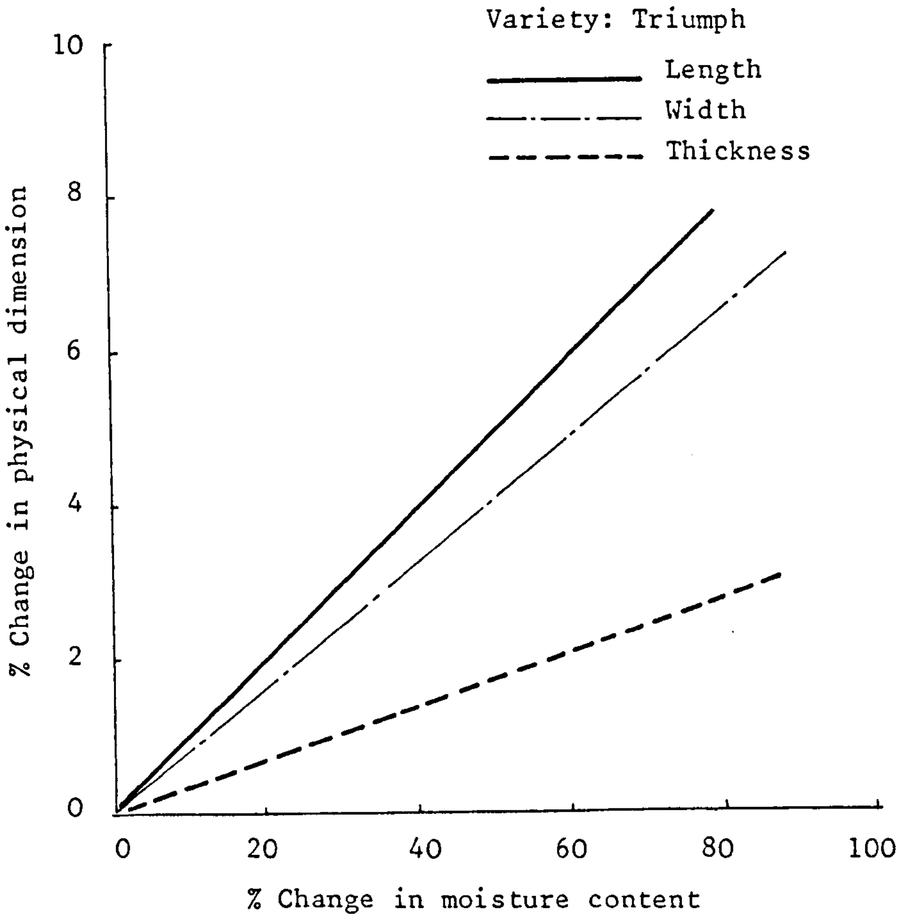


Fig. 2.4 Percentage change in physical dimensions as a function of percentage change in moisture content

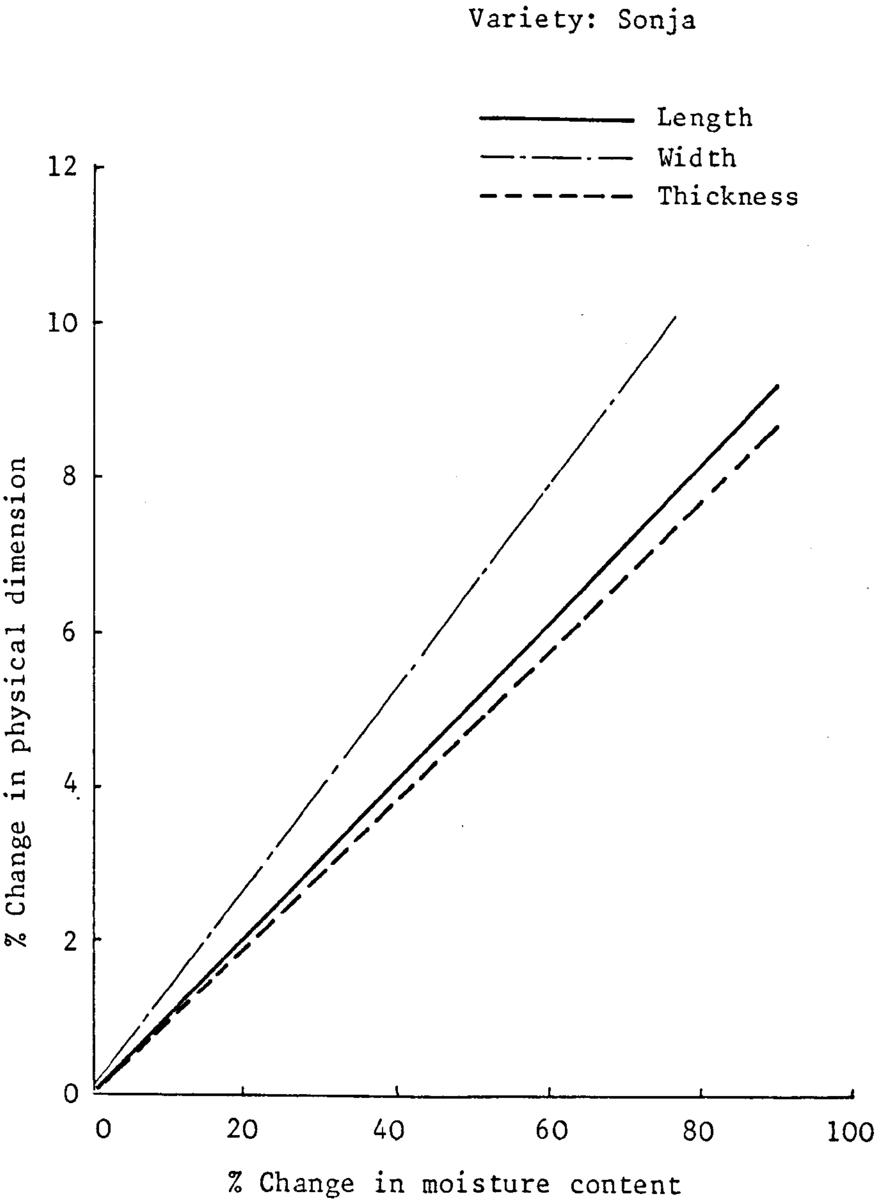


Fig. 2.5 Percentage change in physical dimensions as a function of percentage change in moisture content

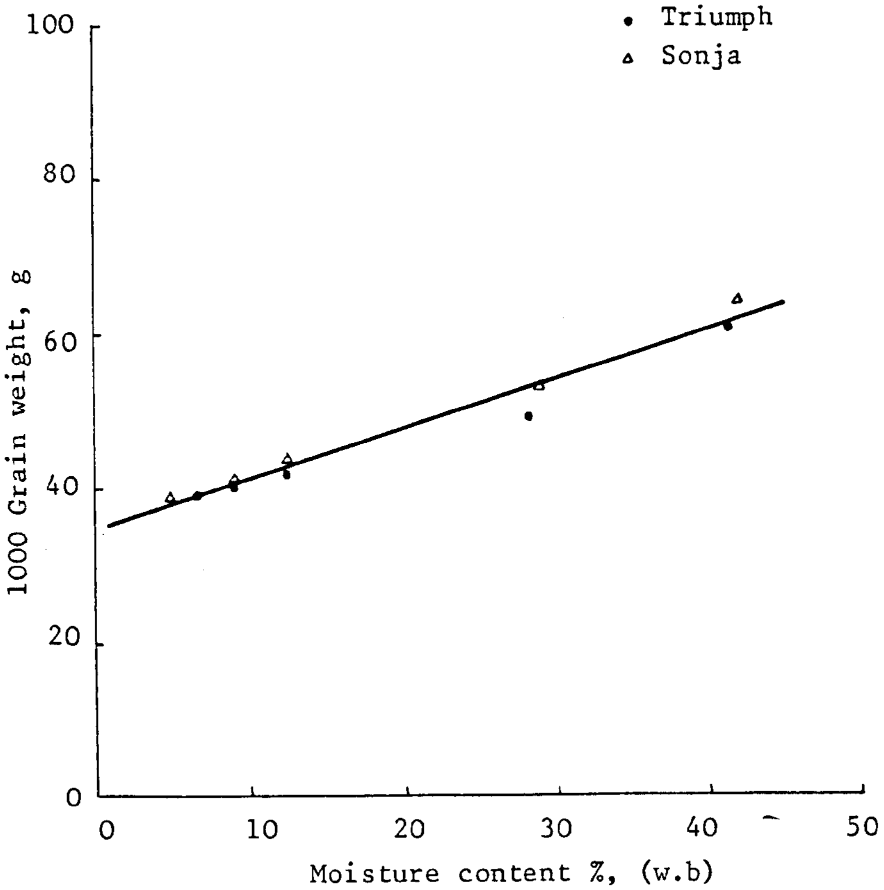


Fig. 2.6 1000 Grain weight of malt as a function of moisture content

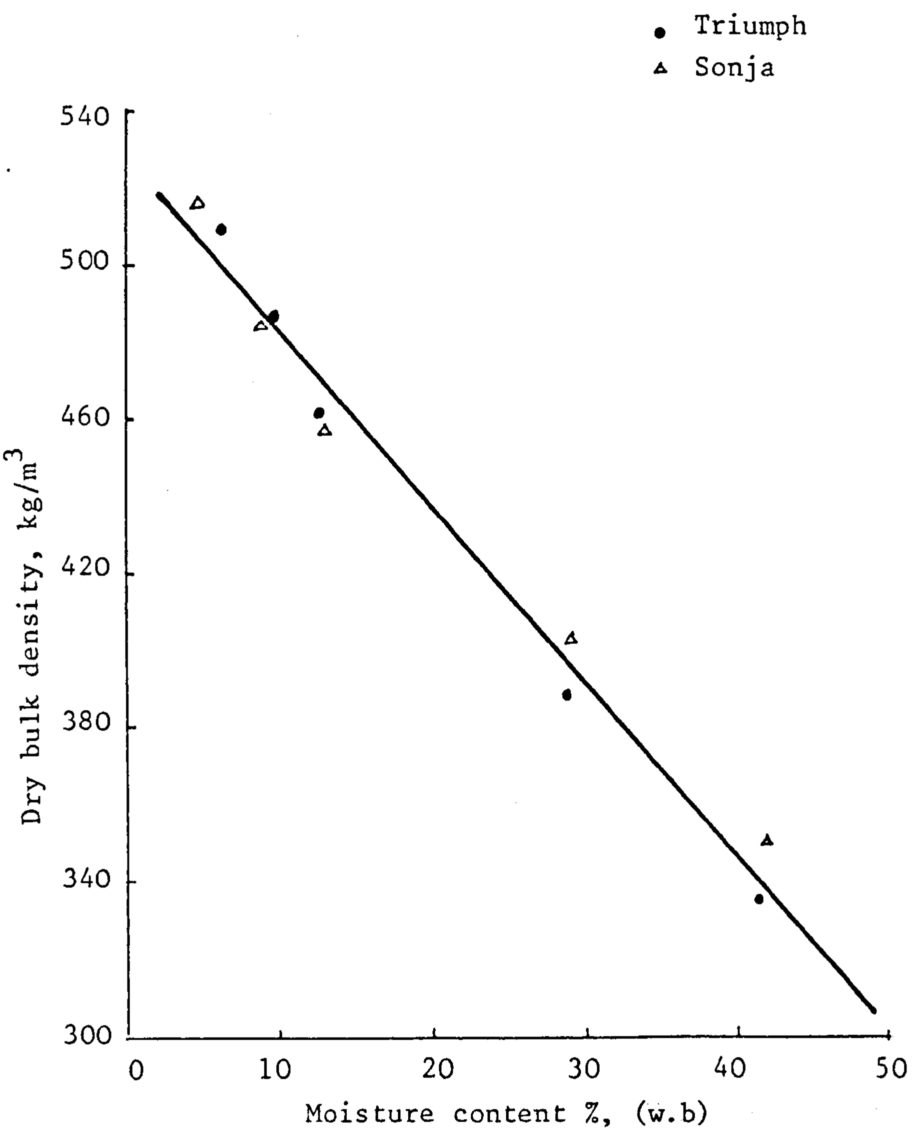


Fig. 2.7 Dry bulk density of malt as a function of moisture content

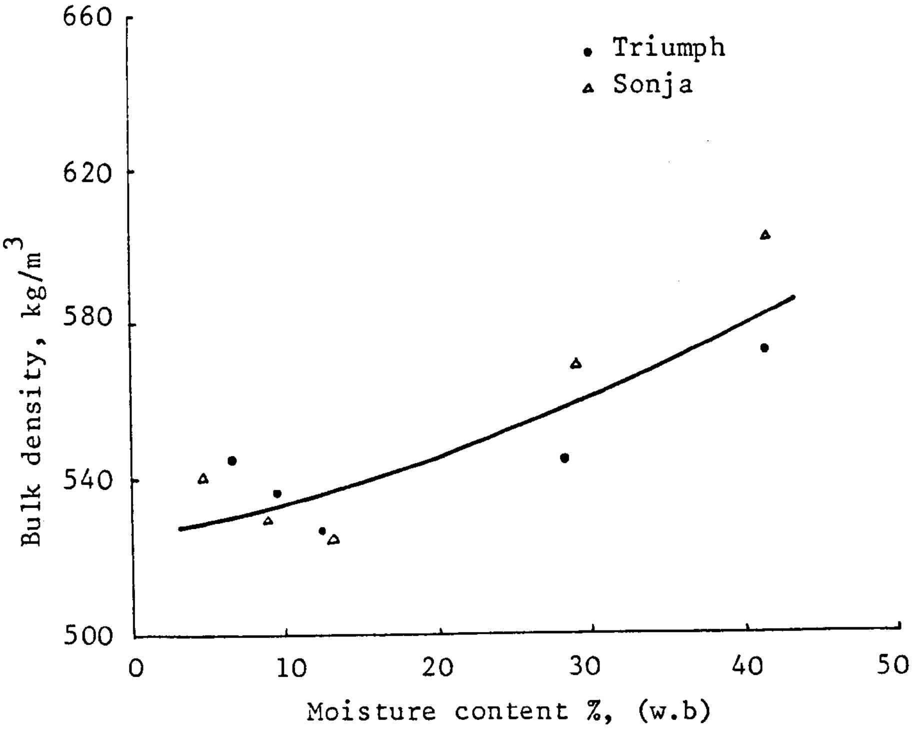


Fig. 2.8 Bulk density of malt as a function of moisture content

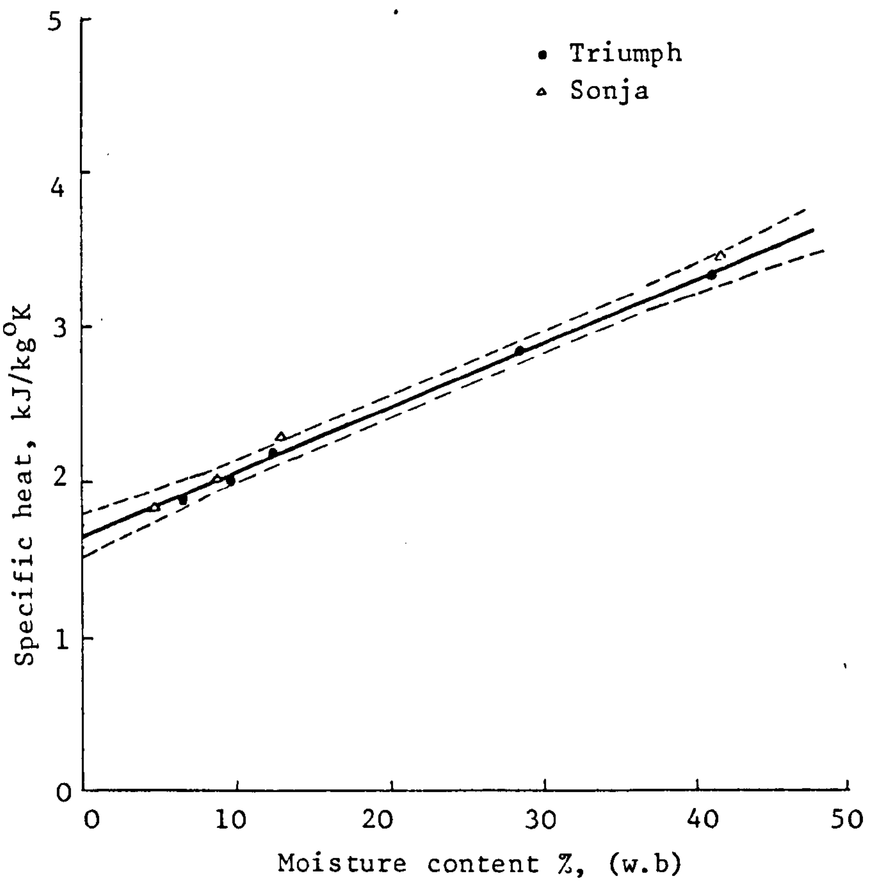


Fig. 2.9 Specific heat of malt as a function of moisture content with 95% confidence band

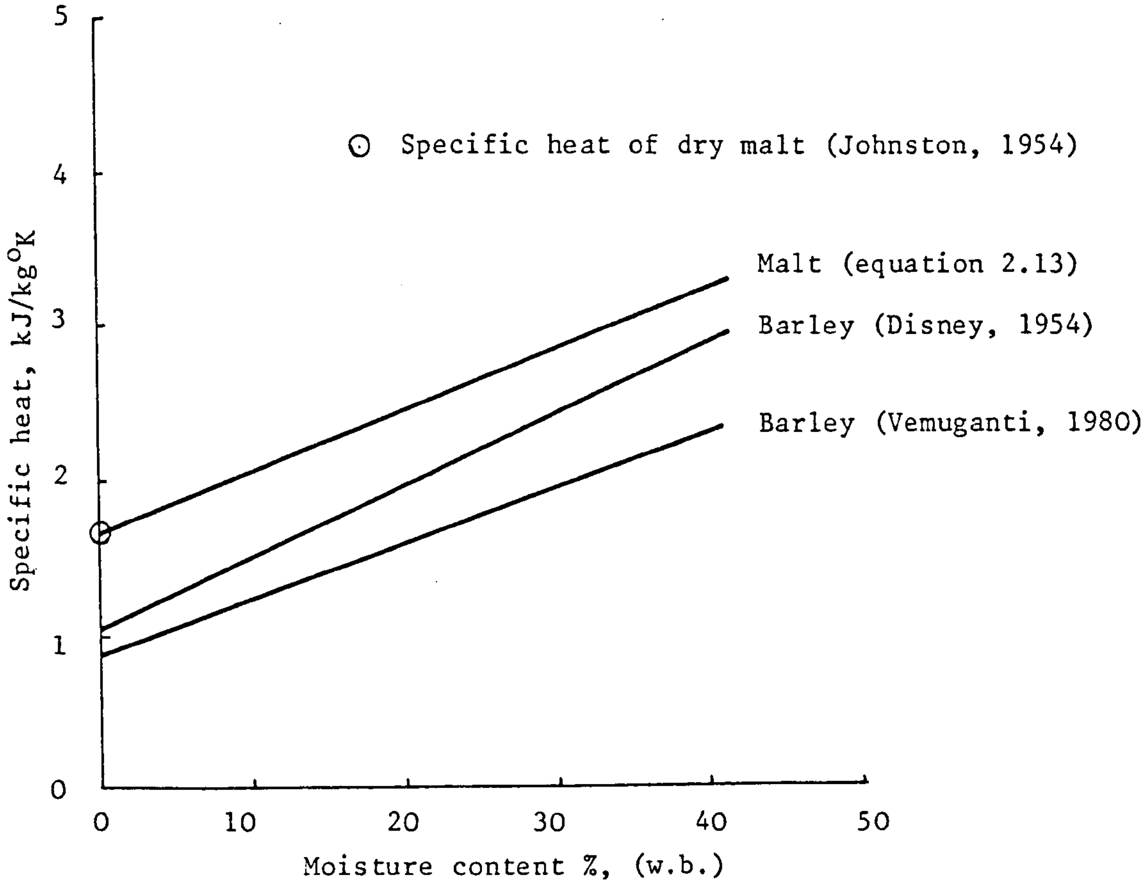


Fig. 2.10 Specific heat as a function of moisture content for barley and malt

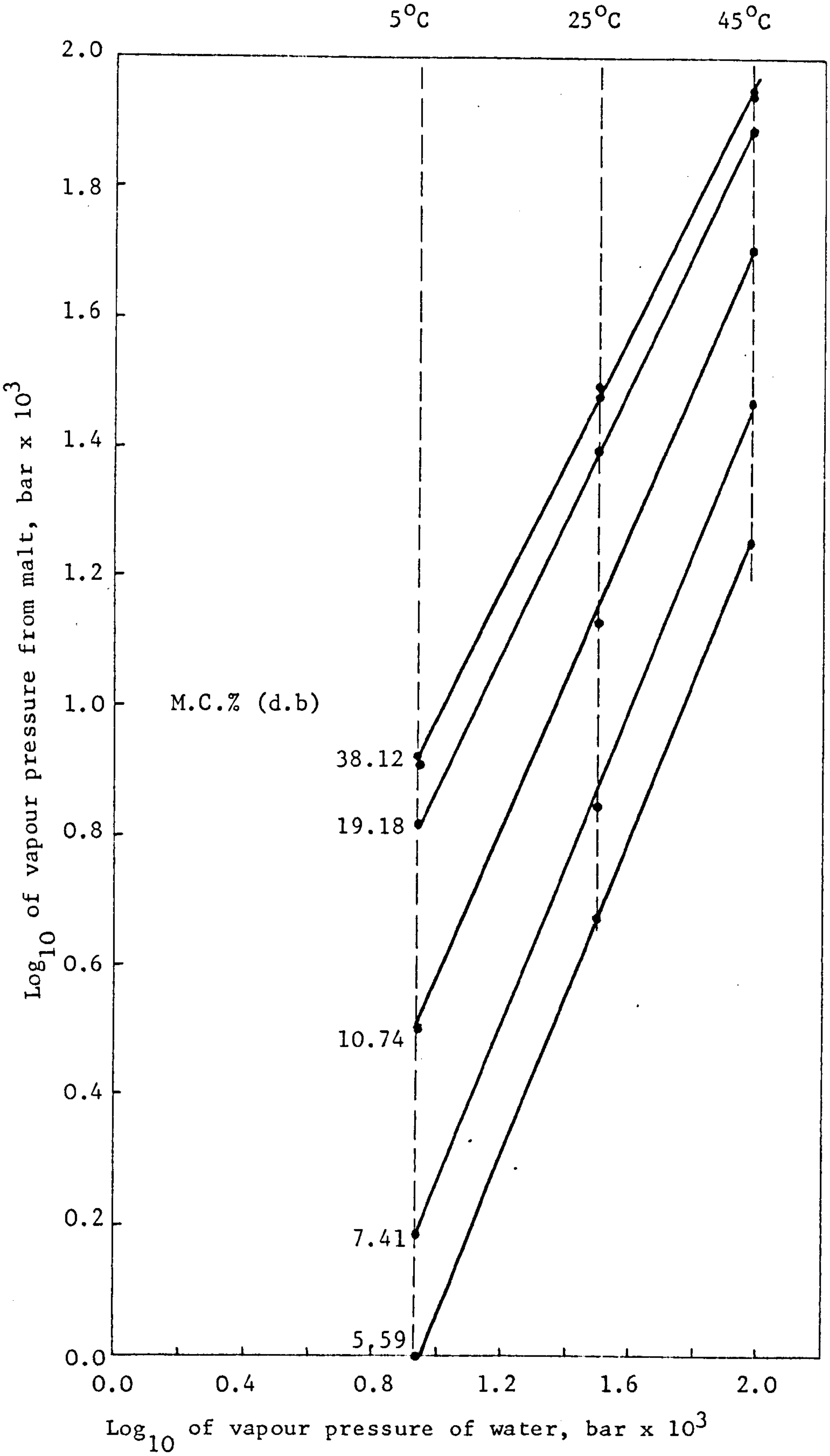


Fig. 2.11 Othmer plots for equilibrium moisture content data of malt

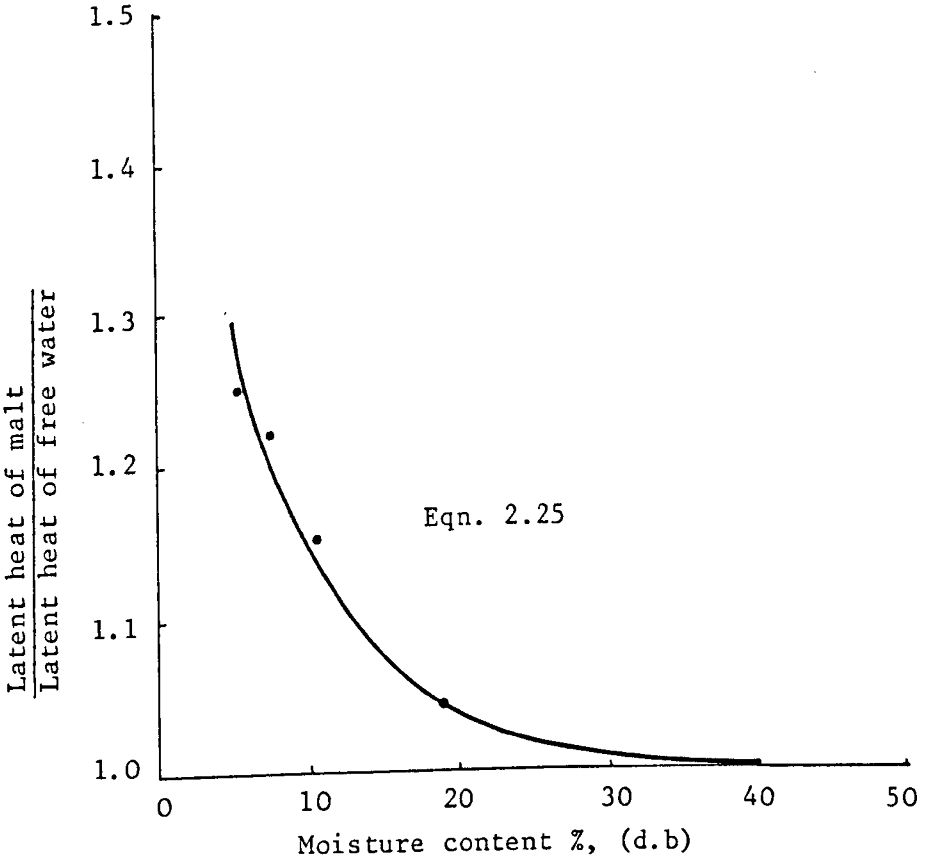


Fig. 2.12 The ratio of latent heat of malt to latent heat of free water as a function of moisture content

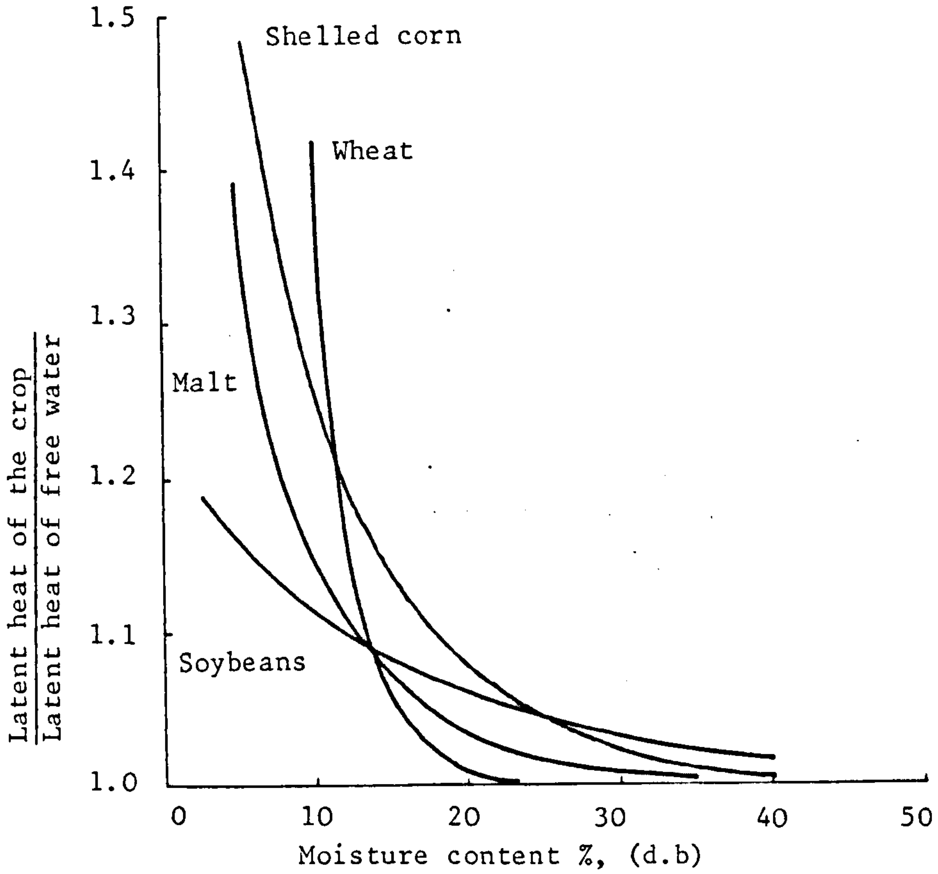


Fig. 2.13 The ratio of latent heat of the crop to latent heat of free water as a function of moisture content for shelled corn, wheat, soybeans and malt

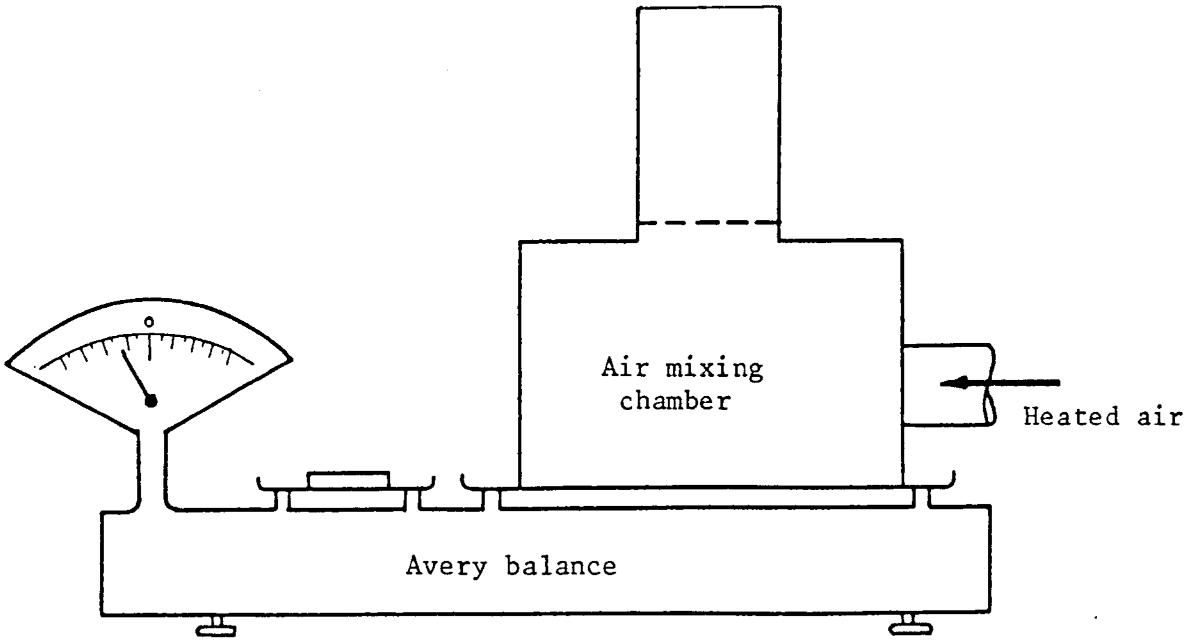


Fig. 2.14 Schematic diagram of the experimental set up for shrinkage and heat transfer coefficient experiments

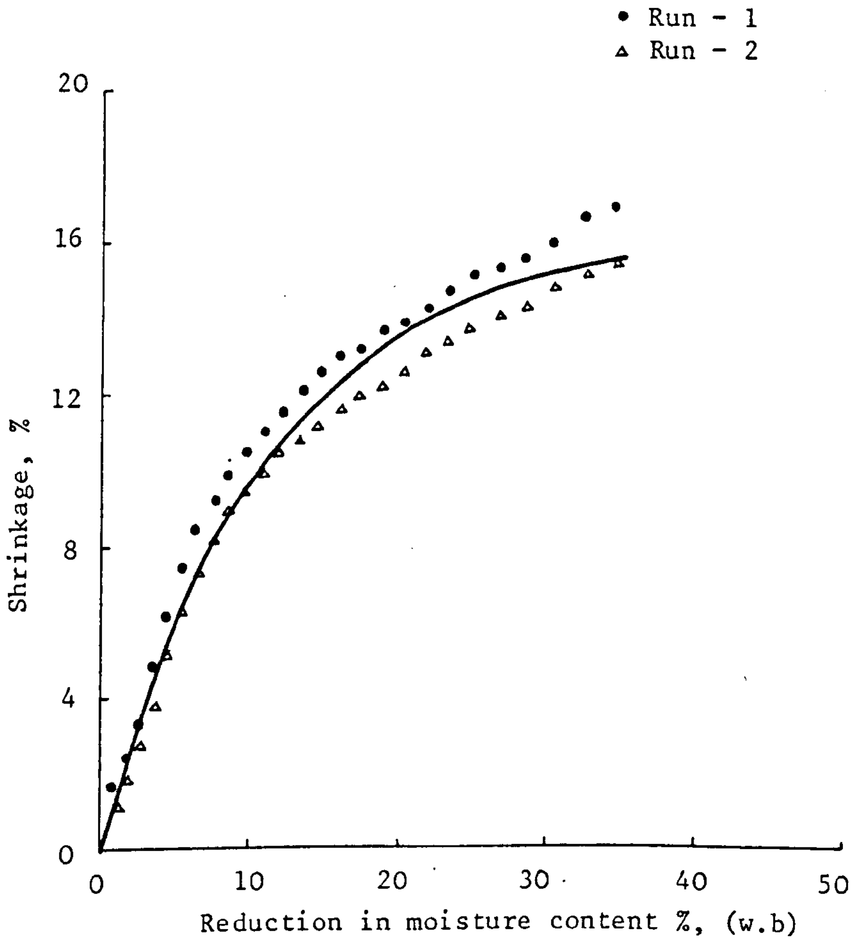
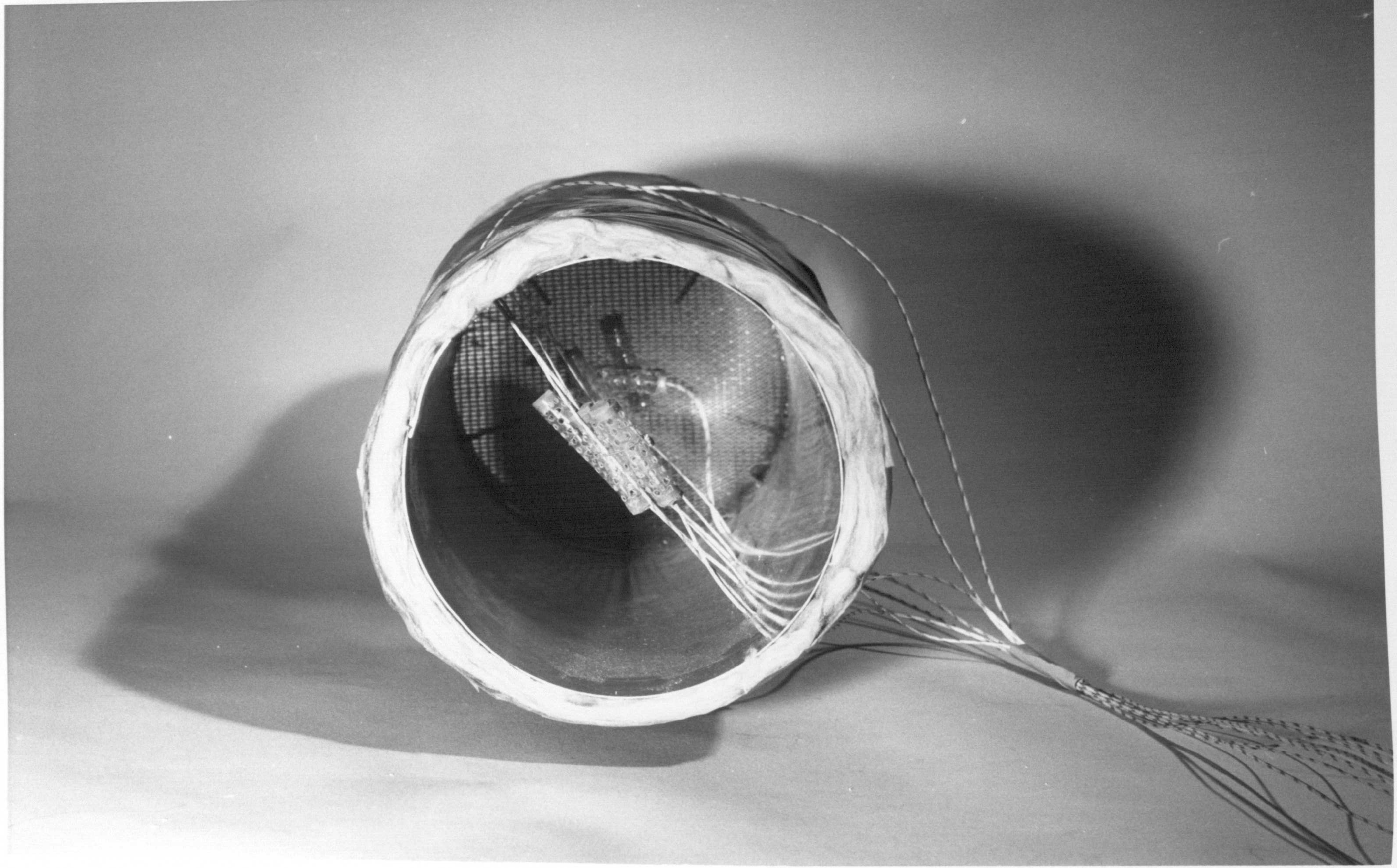


Fig. 2.15 Predicted and observed shrinkage of malt

Fig. 2.16 The experimental cylinder for heat transfer coefficient experiments



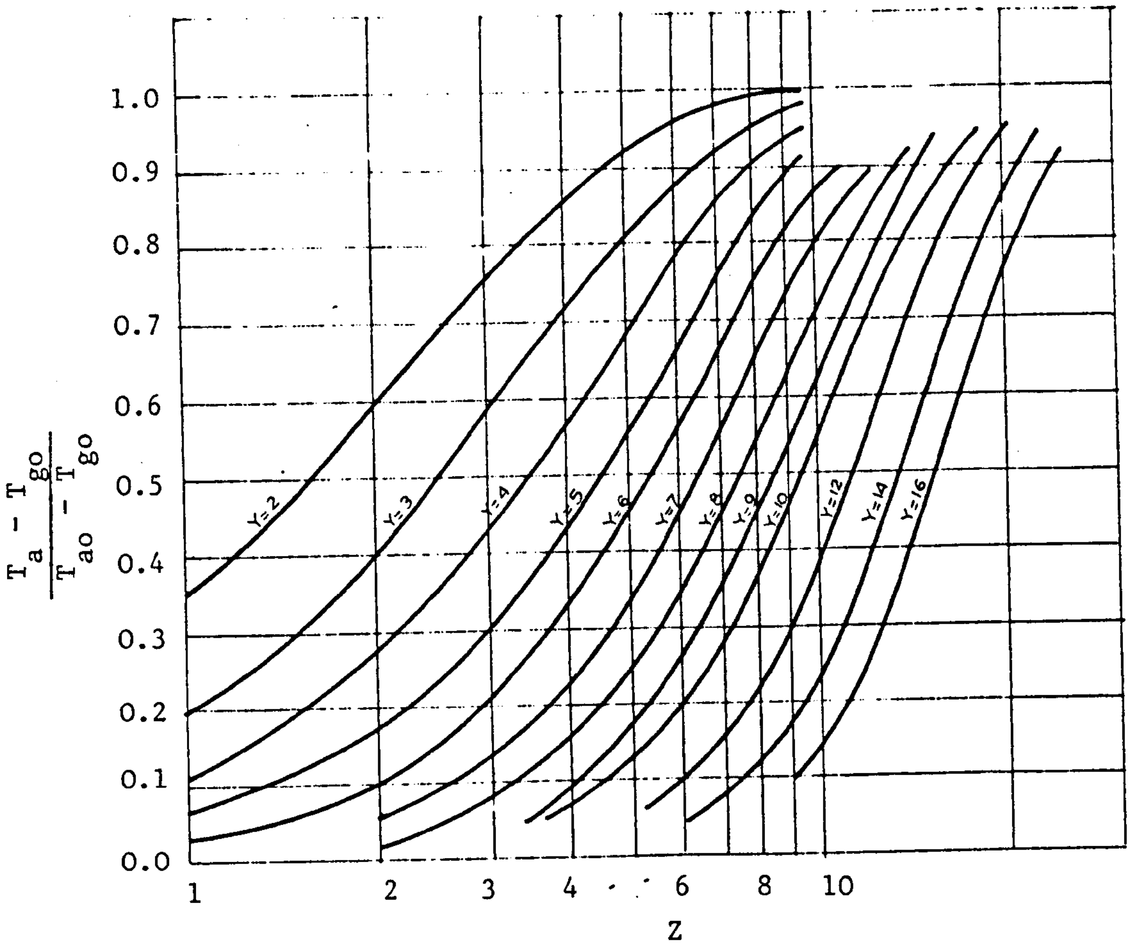


Fig. 2.17 Computed temperature history of air

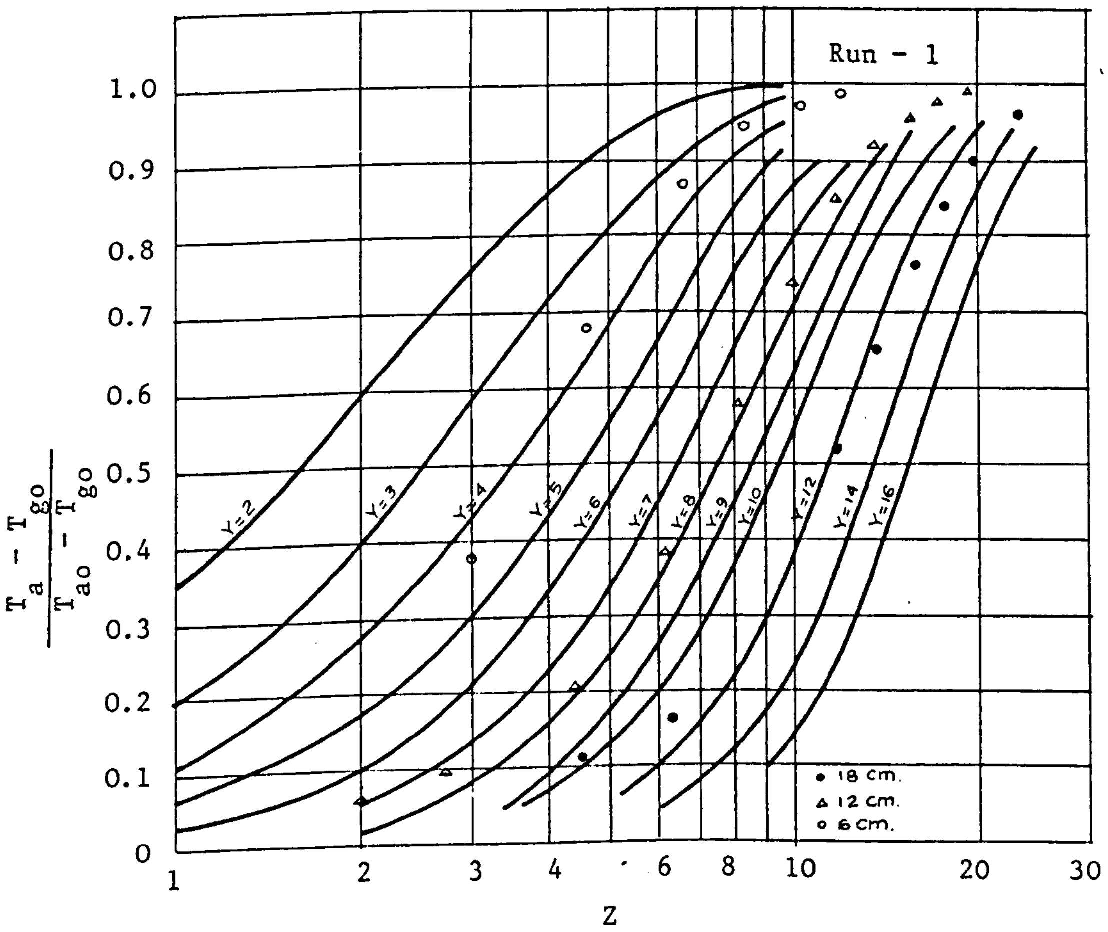


Fig. 2.18 Computed and observed temperature history of air

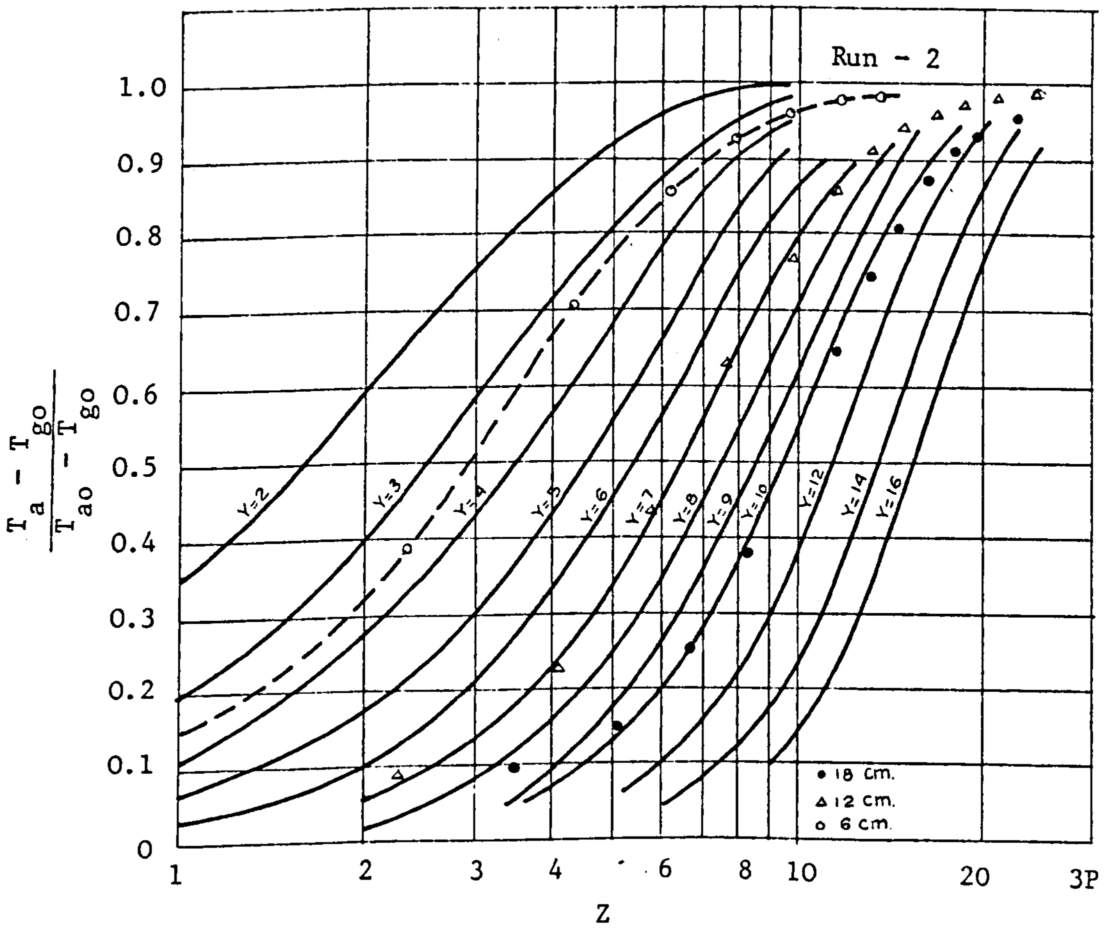


Fig. 2.19 Computed and observed temperature history of air

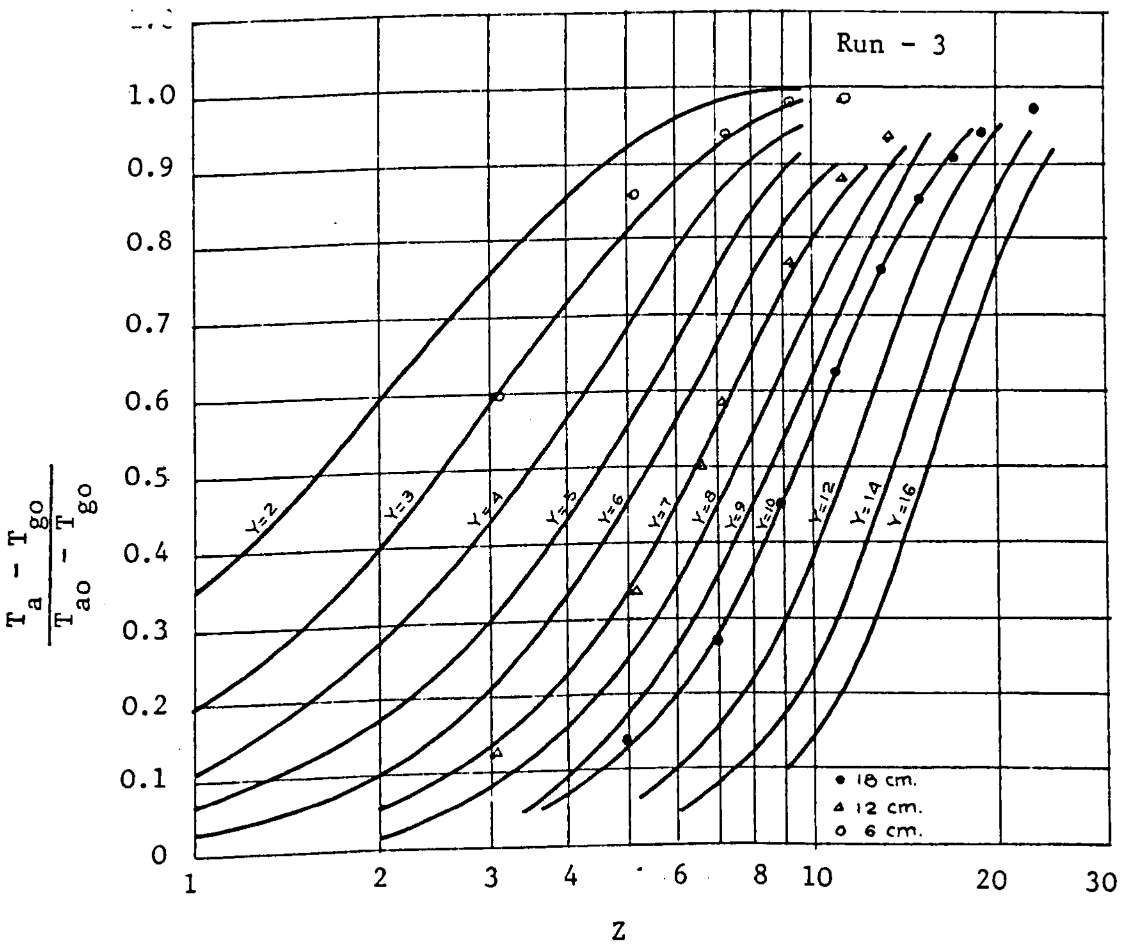


Fig. 2.20 Computed and observed temperature history of air

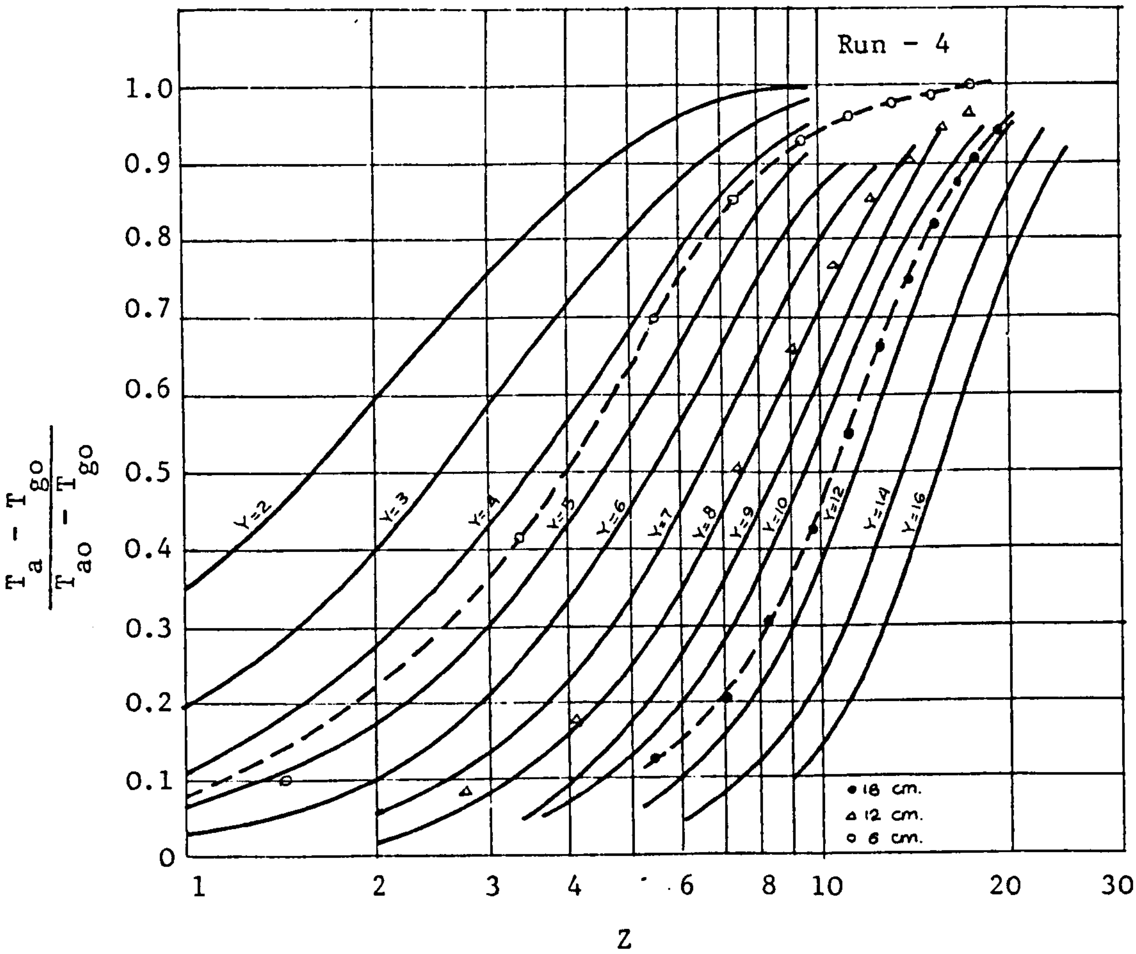


Fig. 2.21 Computed and observed temperature history of air

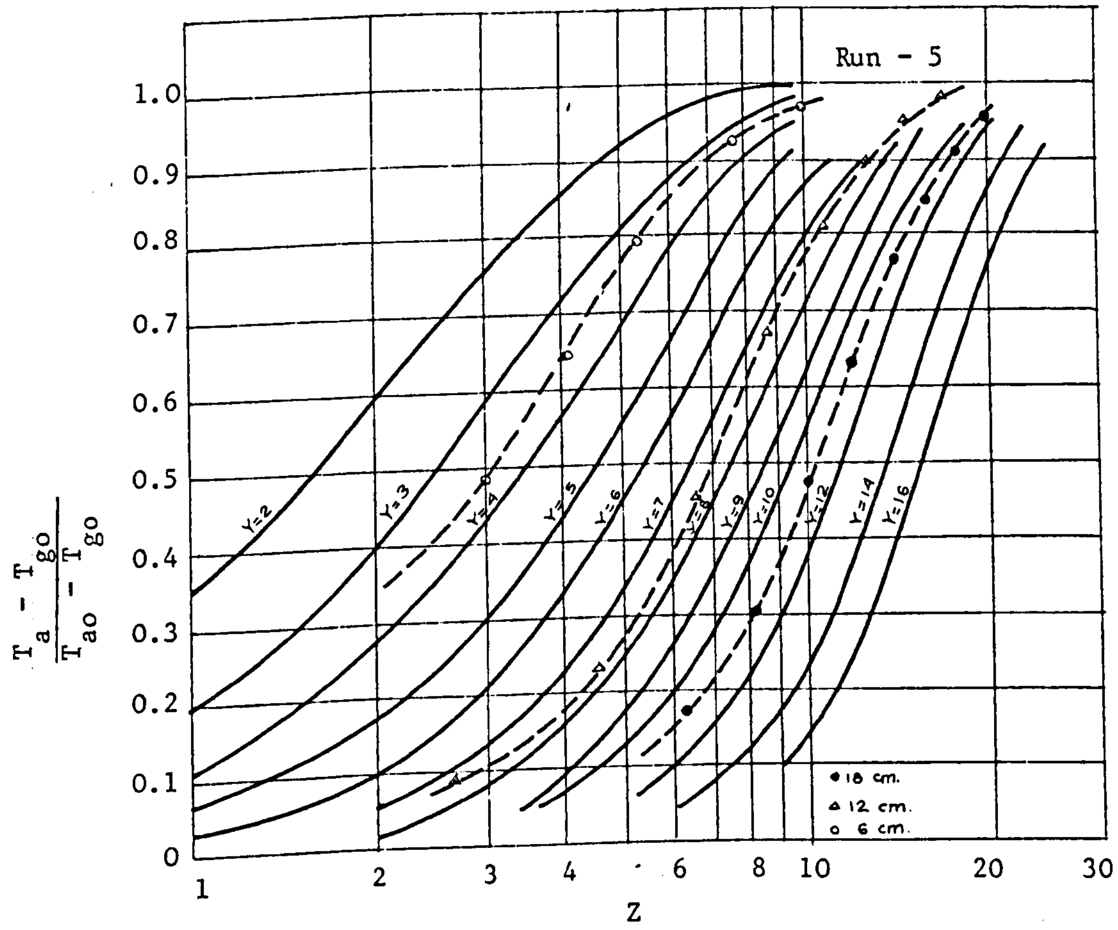


Fig. 2.22 Computed and observed temperature history of air

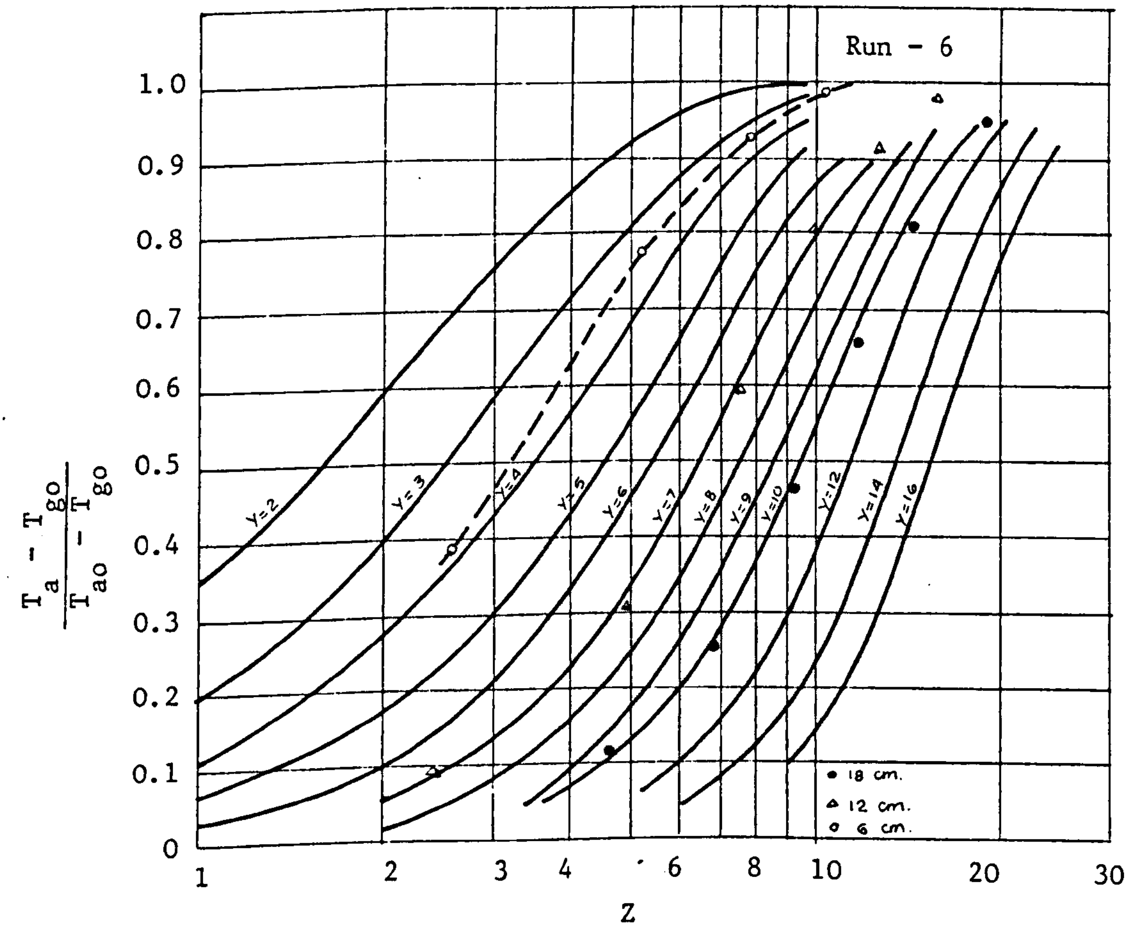


Fig. 2.23 Computed and observed temperature history of air

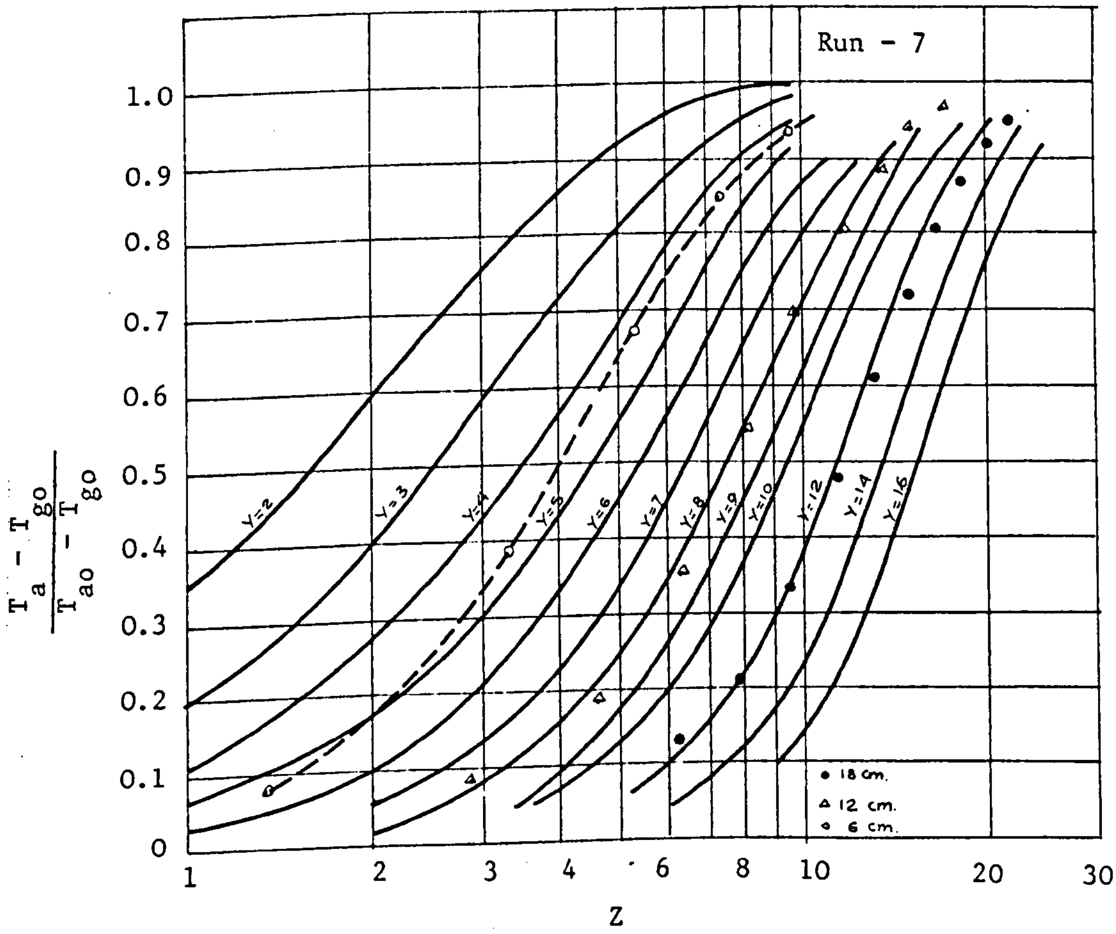


Fig. 2.24 Computed and observed temperature history of air

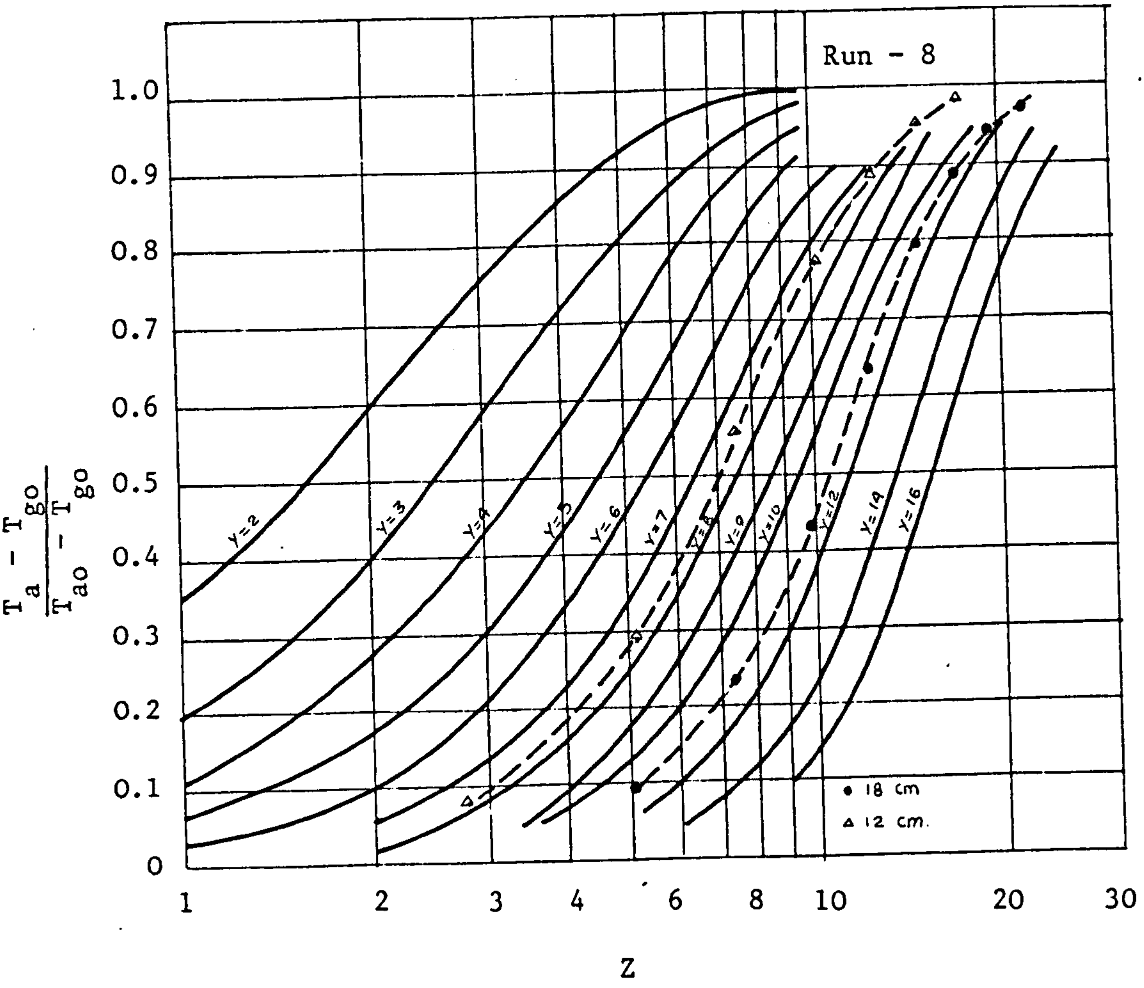


Fig. 2.25 Computed and observed temperature history of air

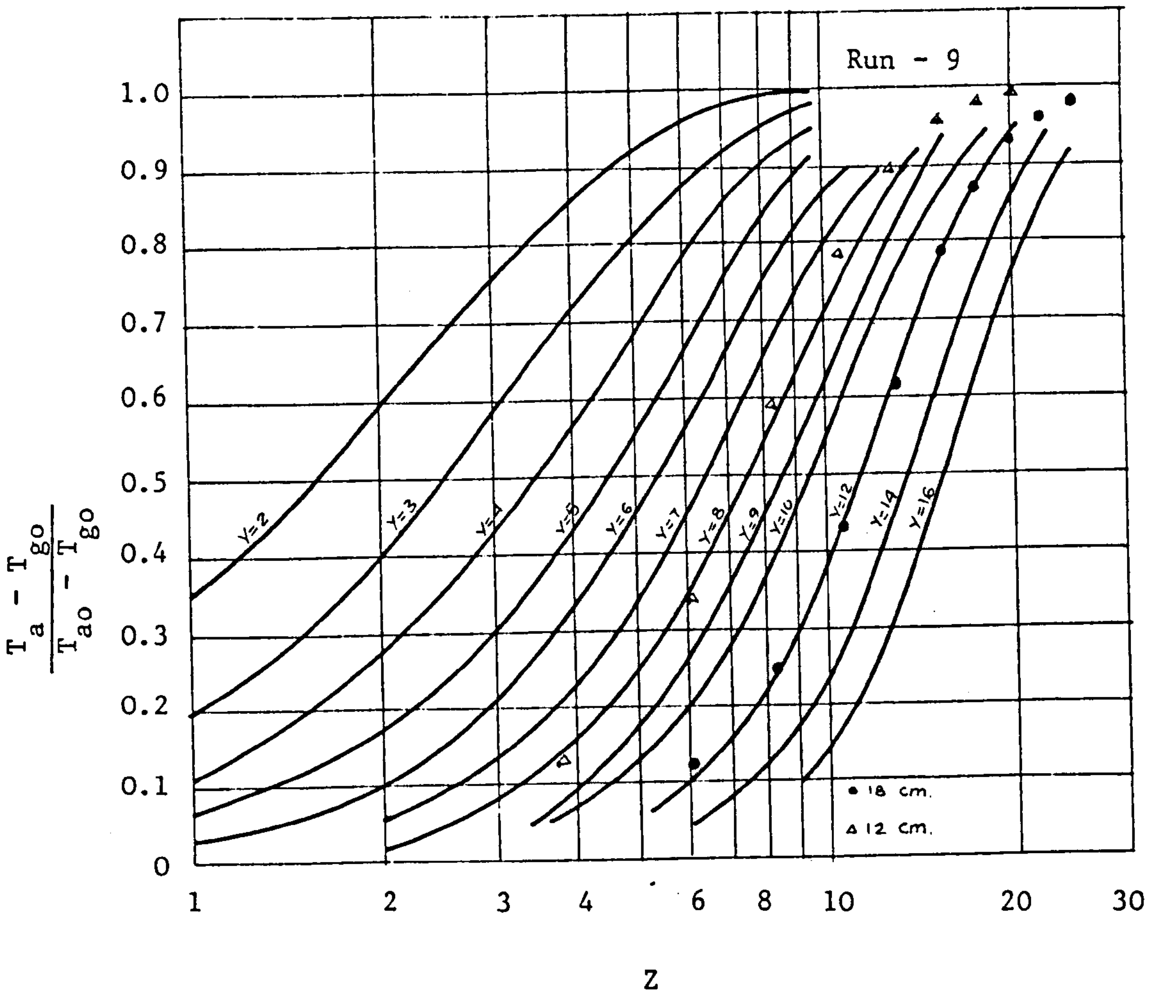


Fig. 2.26 Computed and observed temperature history of air

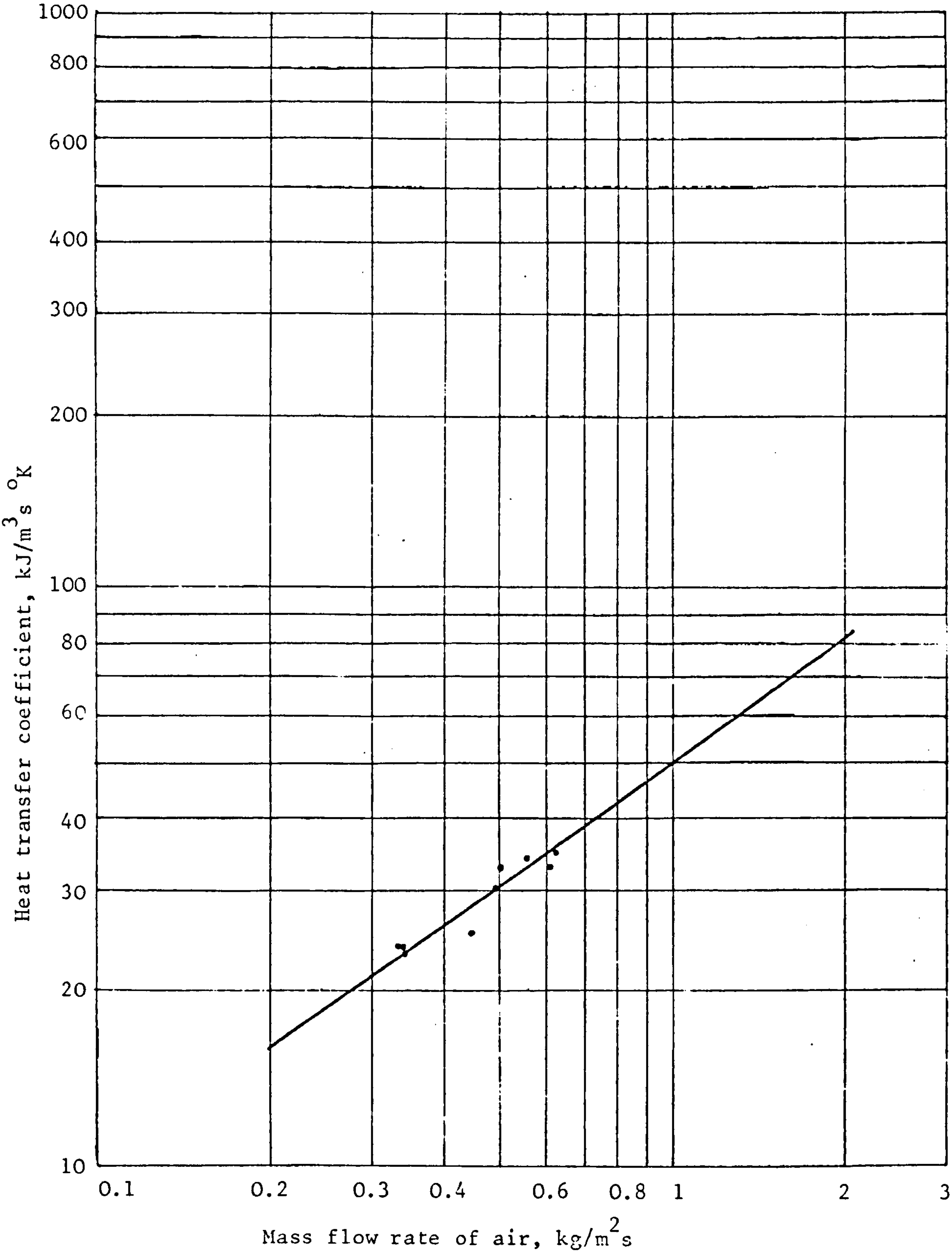


Fig. 2.27 Heat transfer coefficient as a function of air flow rate

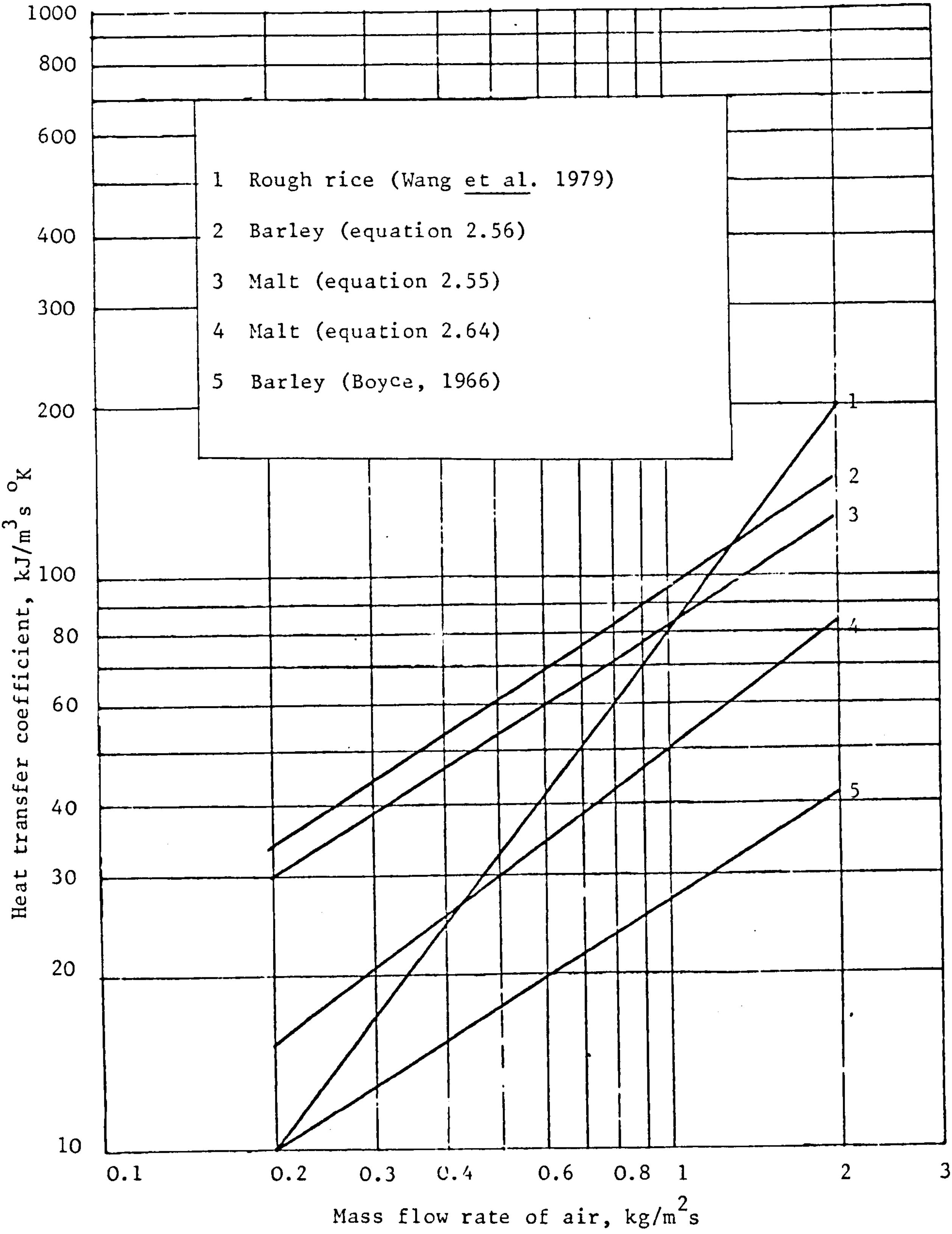


Fig. 2.28 Comparison of heat transfer coefficient of malt, barley and rough rice

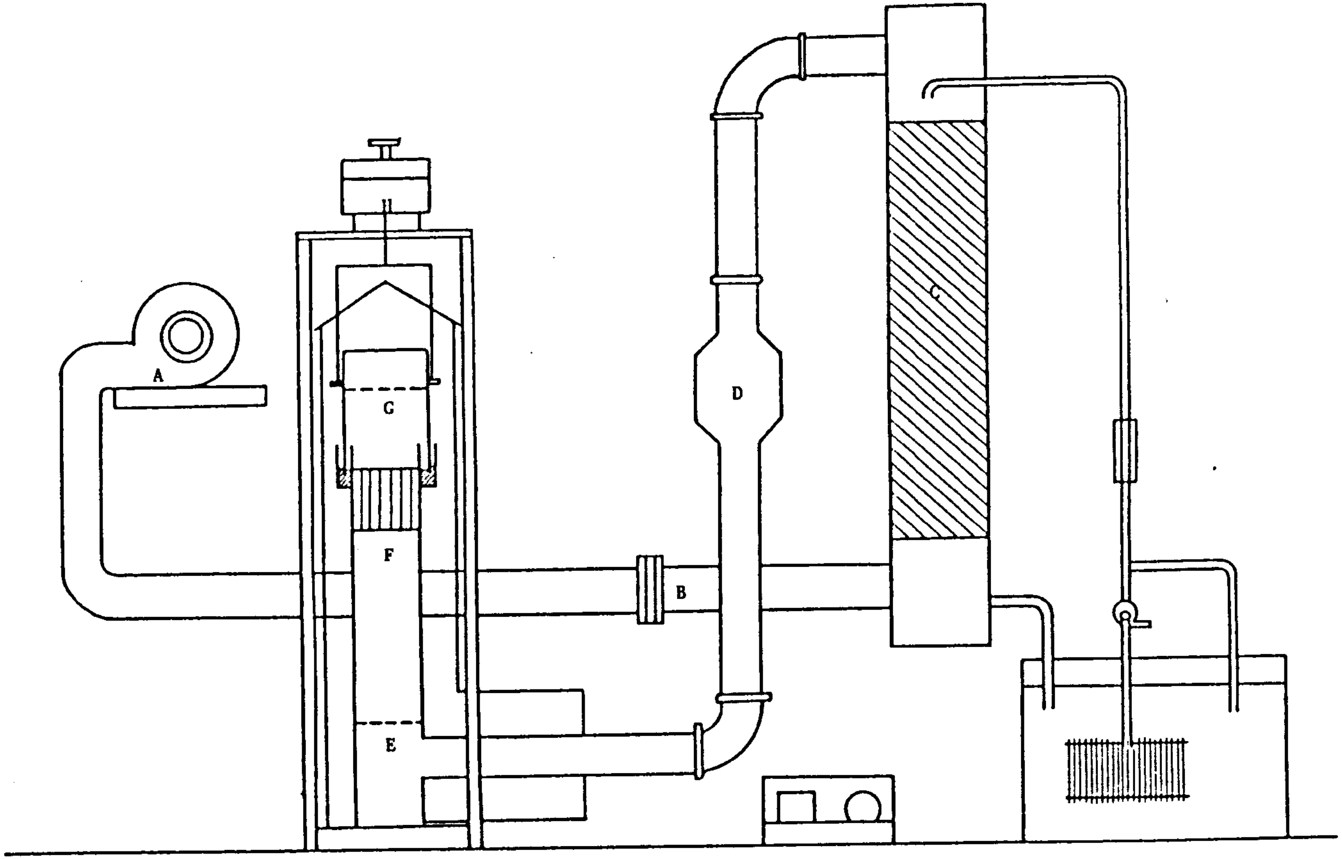


Fig. 3.1 Schematic diagram of the apparatus for thin layer drying

Fig. 3.2 The grain drier assembly

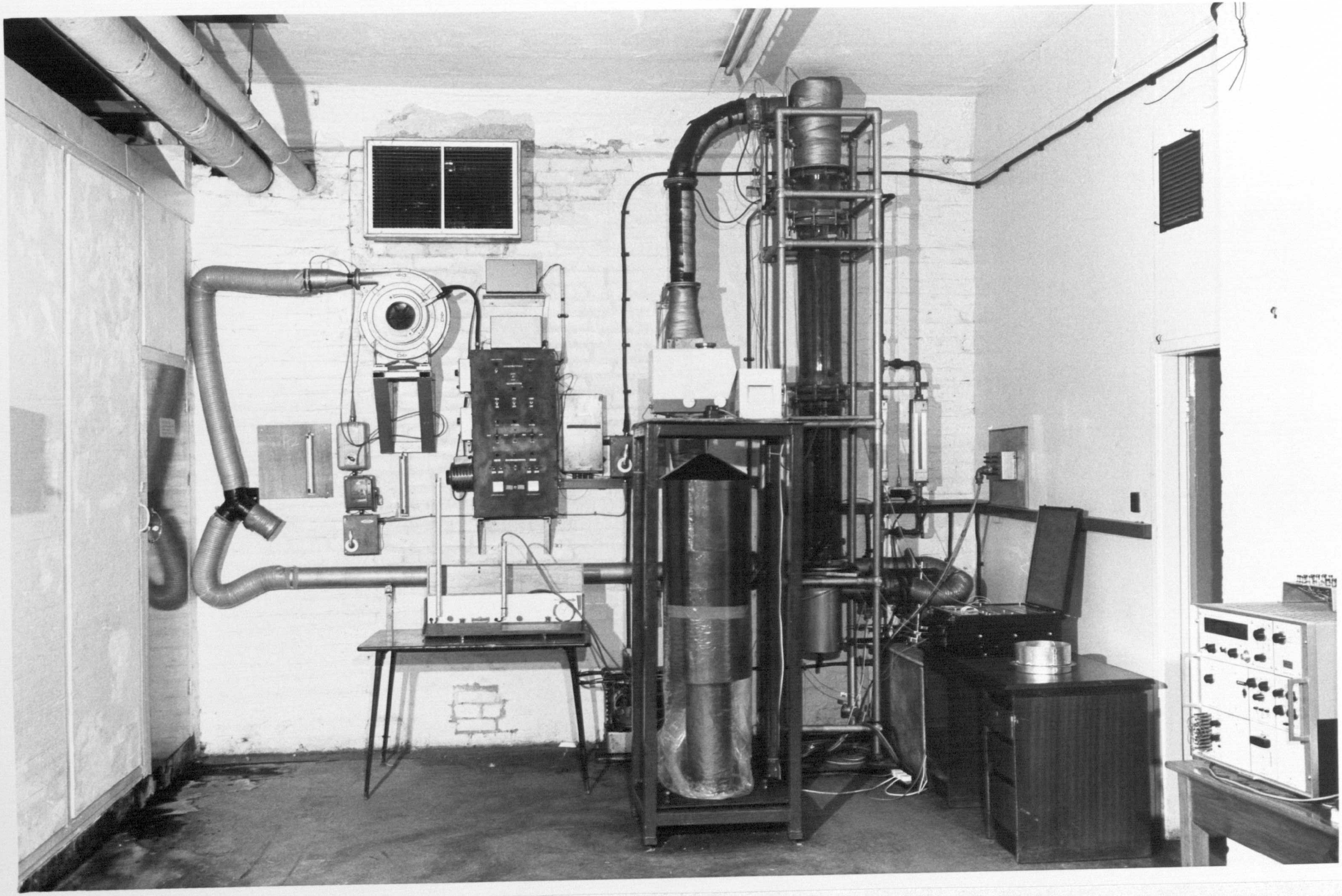


Fig. 3.3 The drying chamber

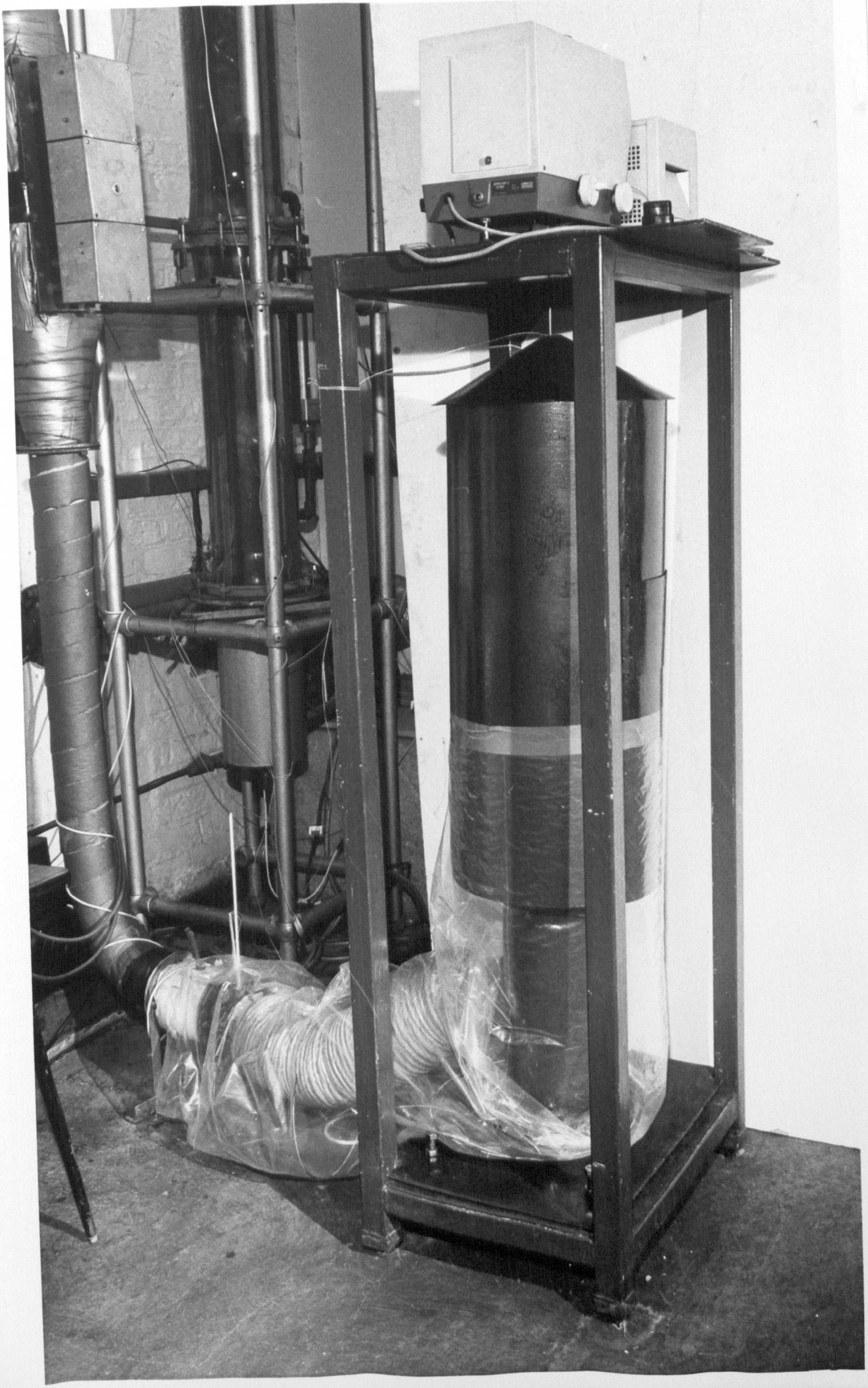


Fig. 3.4 The inner cylinder and drying tray


CREEP ROOM NO.4
Long-term Creep Tests for

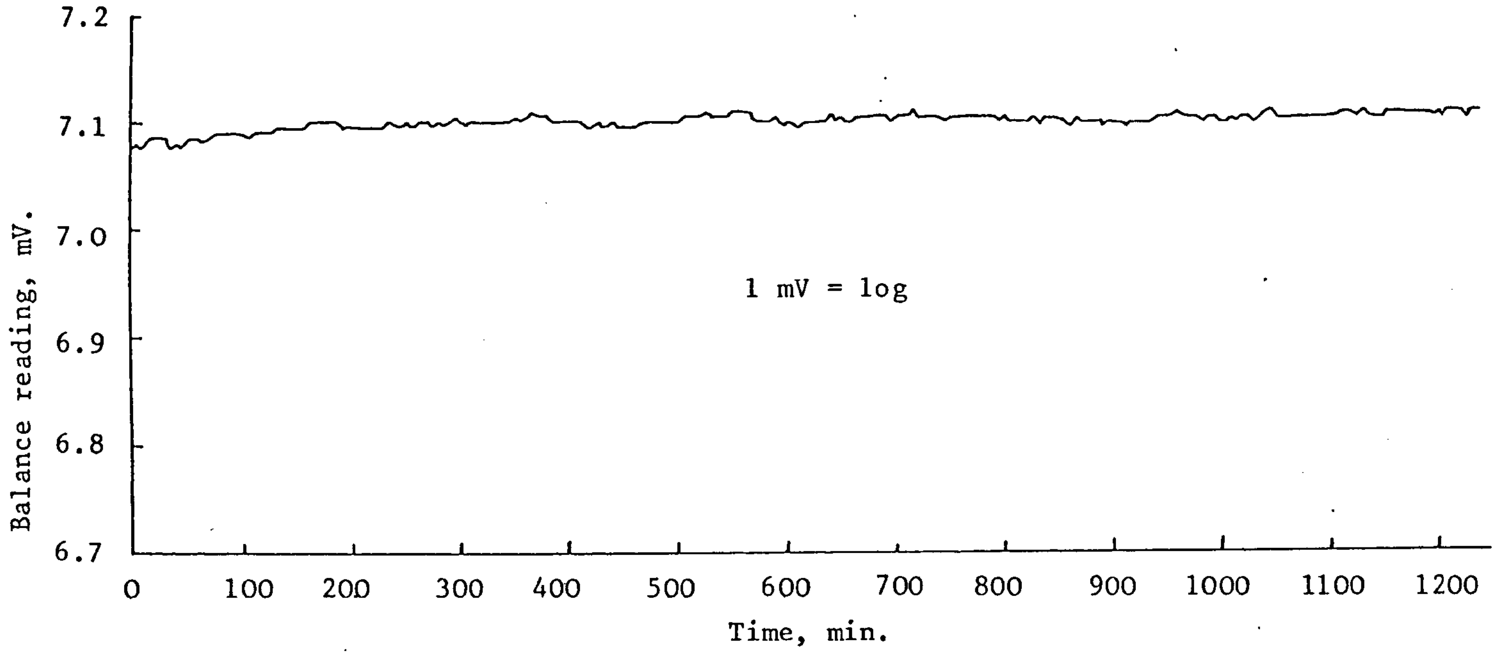


Fig. 3.5 Balance response with a constant weight suspended from the balance (no air flow)

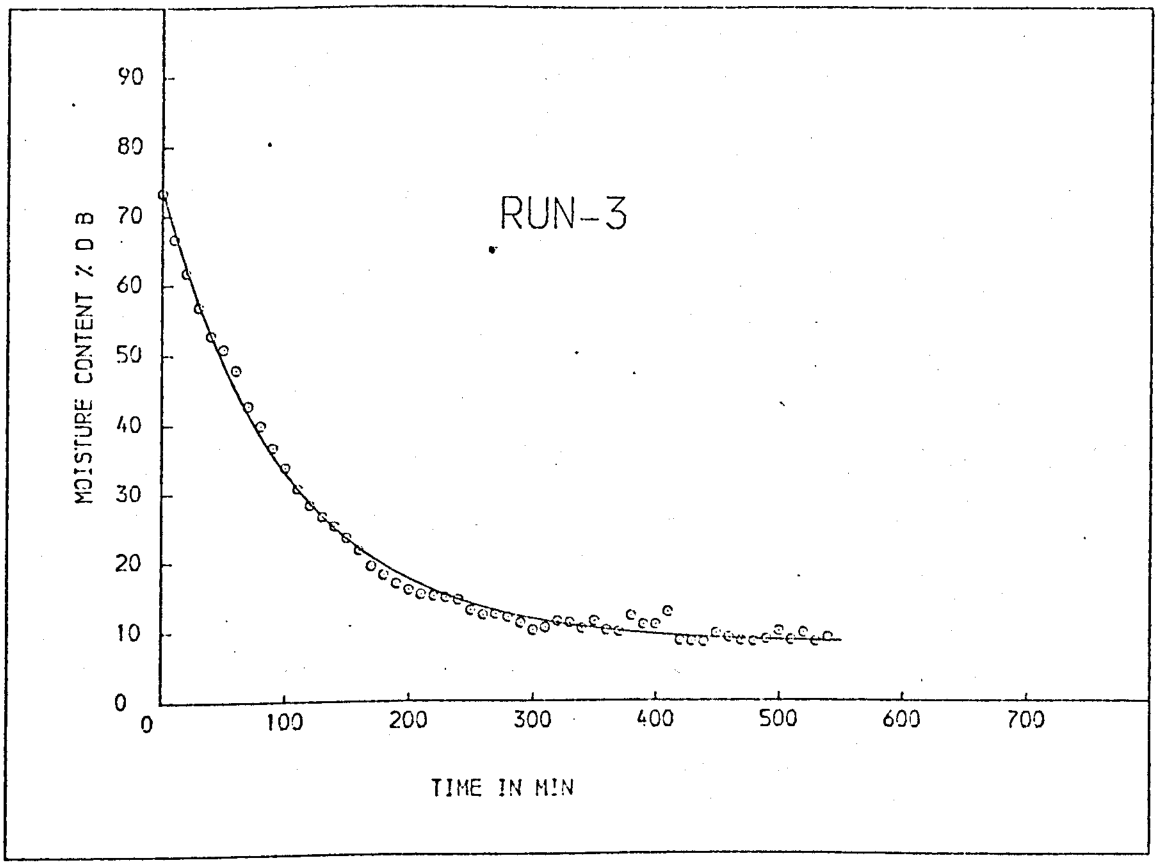


Fig. 3.6 Predicted and observed moisture contents

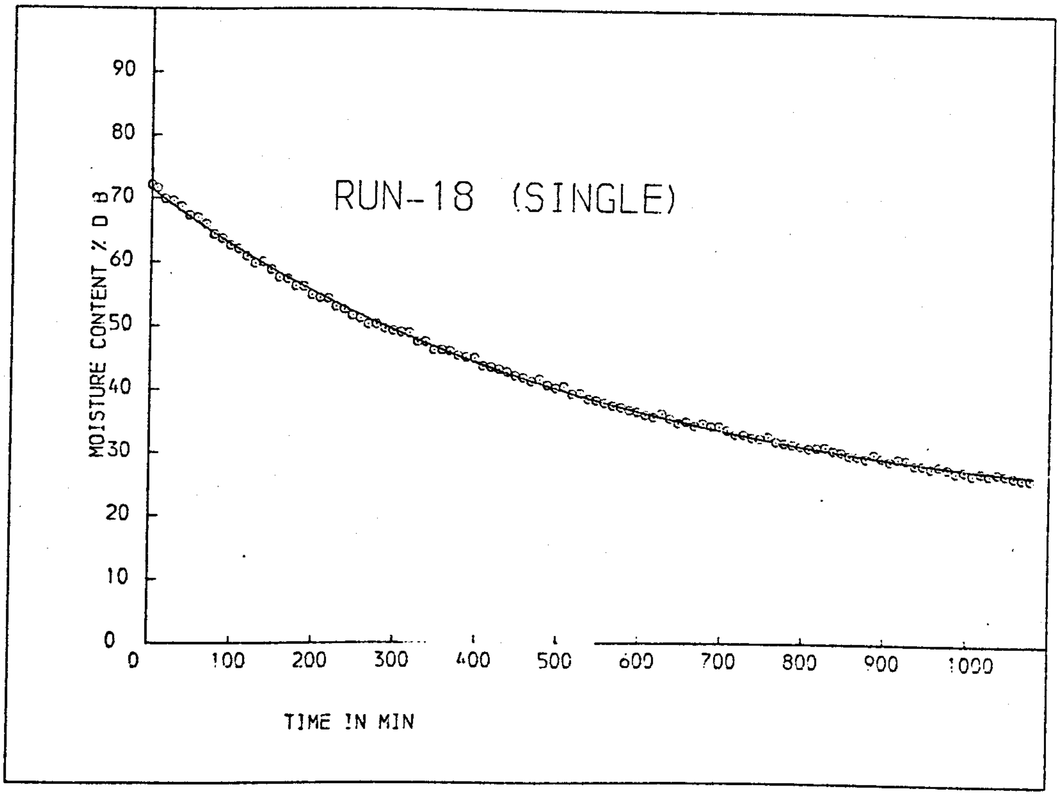


Fig. 3.7 (a) Predicted and observed moisture contents

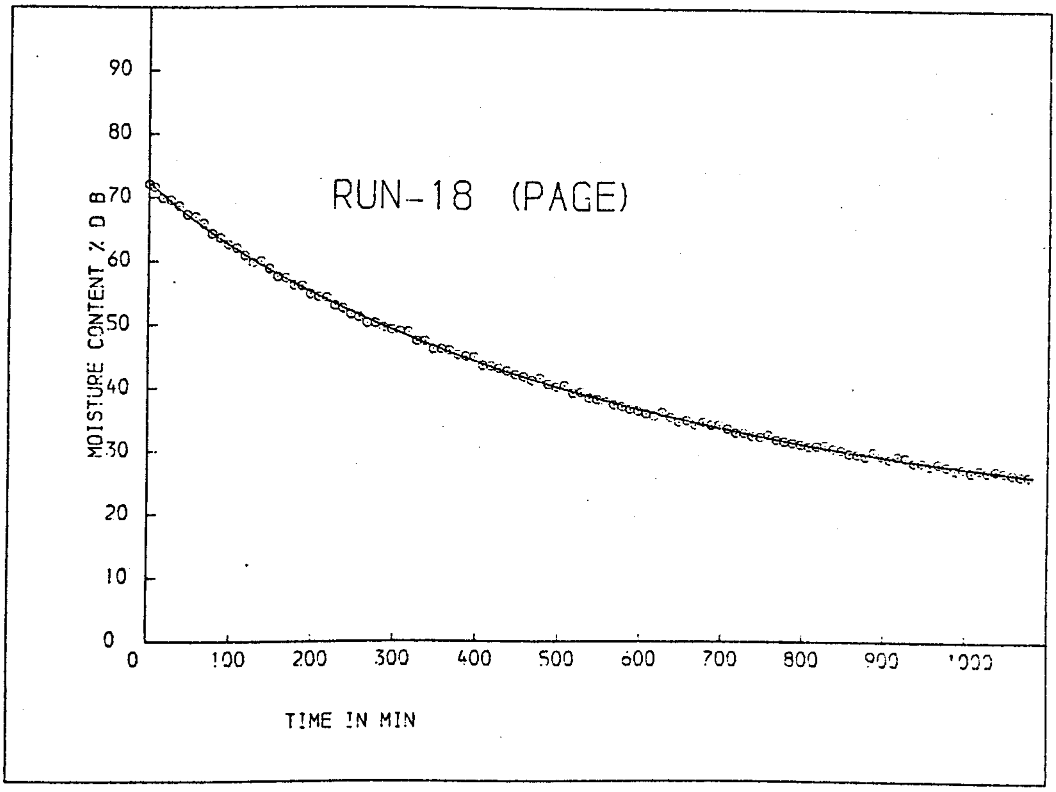


Fig. 3.7 (b) Predicted and observed moisture contents

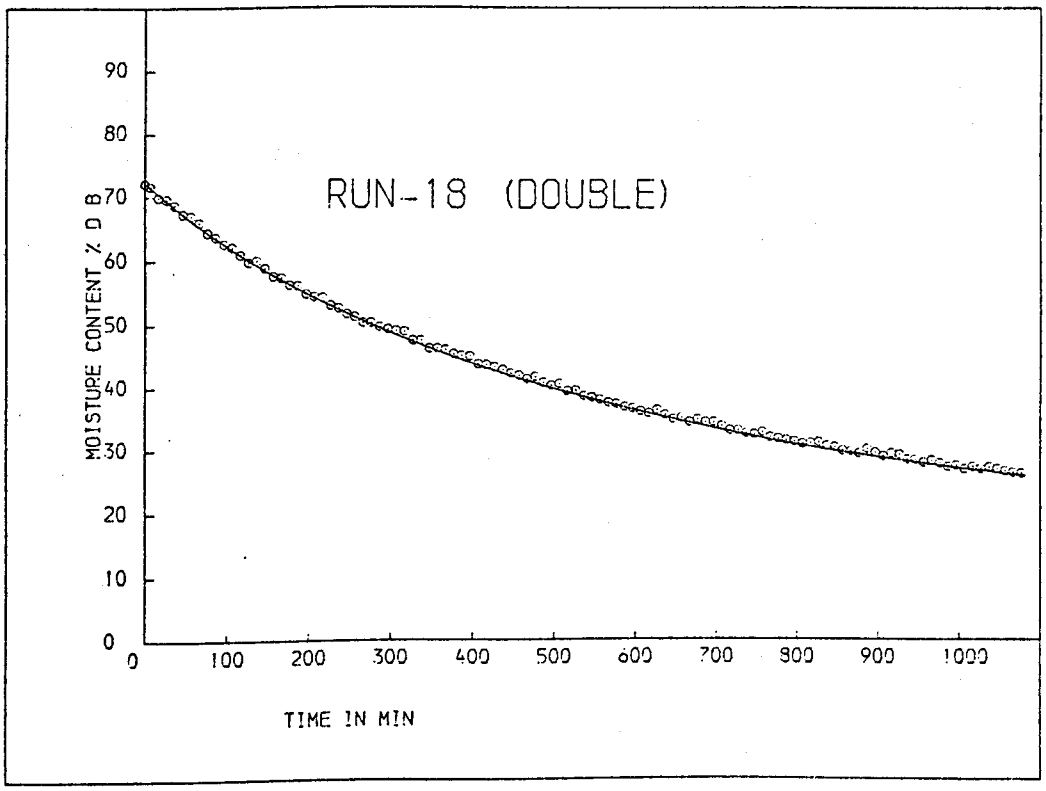


Fig. 3.7 (c) Predicted and observed moisture contents

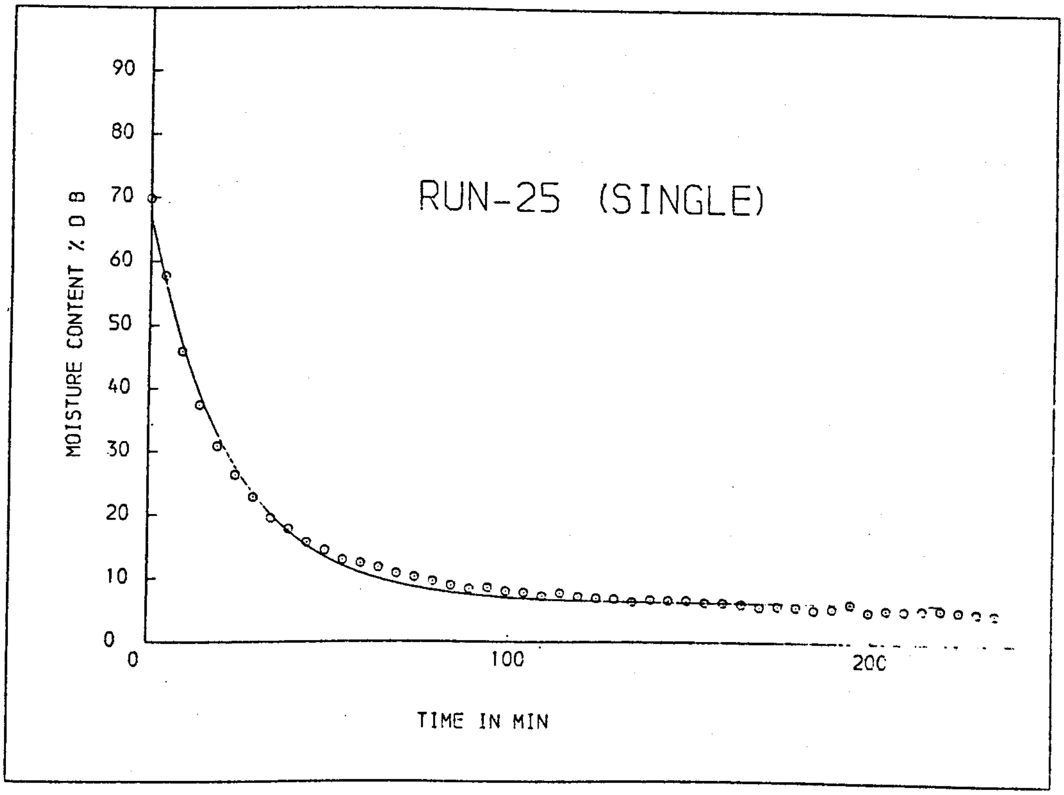


Fig. 3.8 (a) Predicted and observed moisture contents

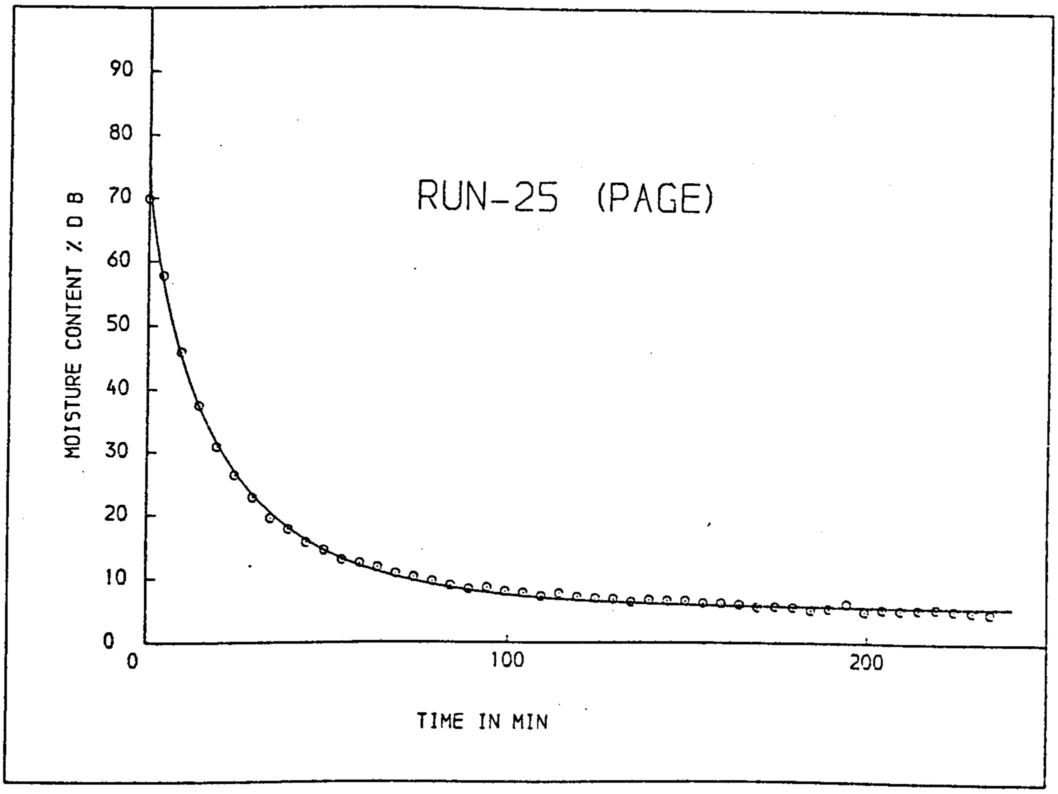


Fig. 3.8 (b) Predicted and observed moisture contents

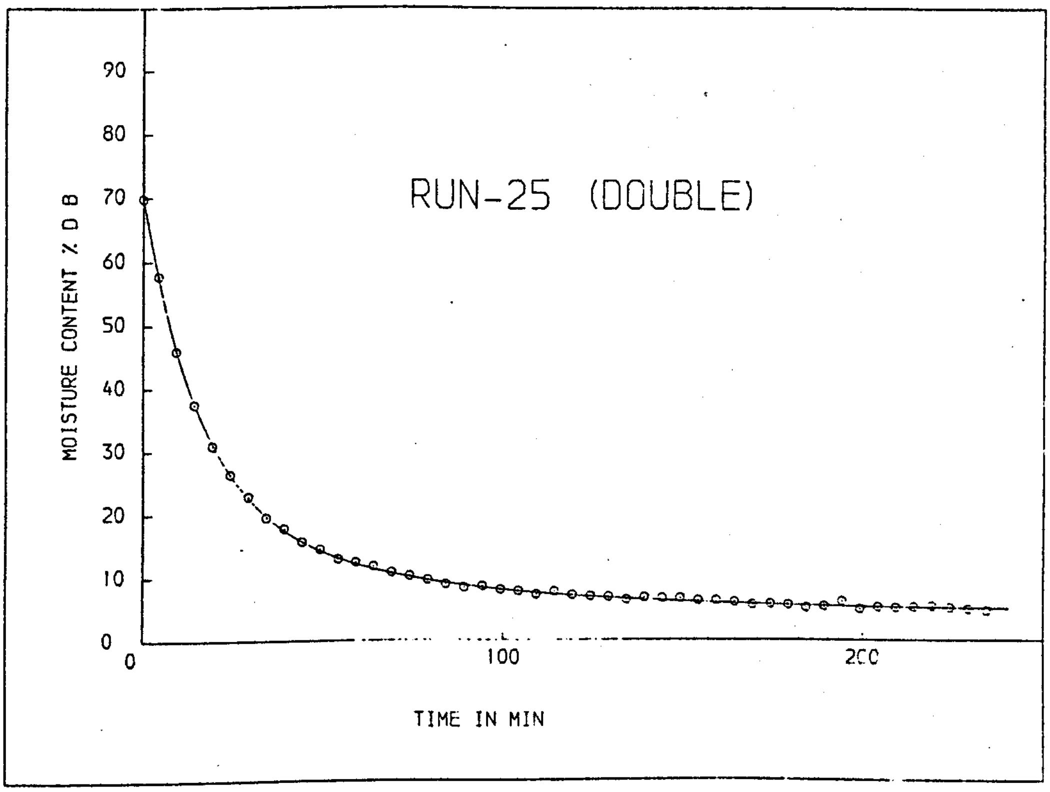


Fig. 3.8 (c) Predicted and observed moisture contents

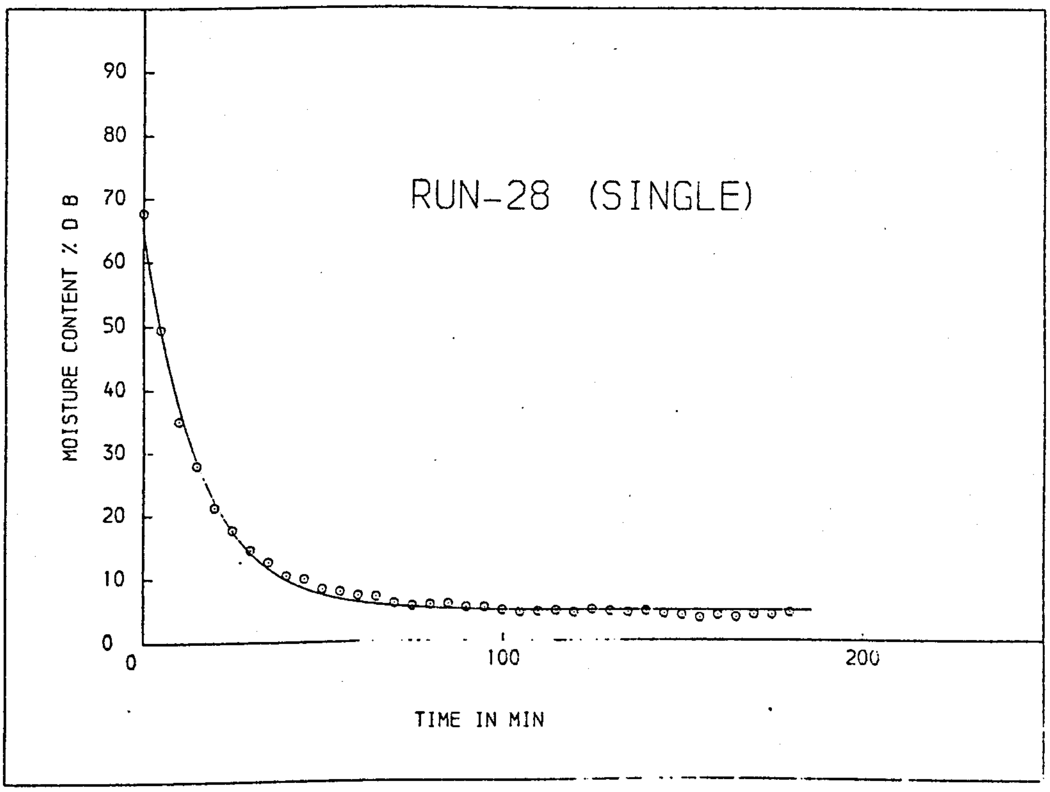


Fig. 3.9 (a) Predicted and observed moisture contents

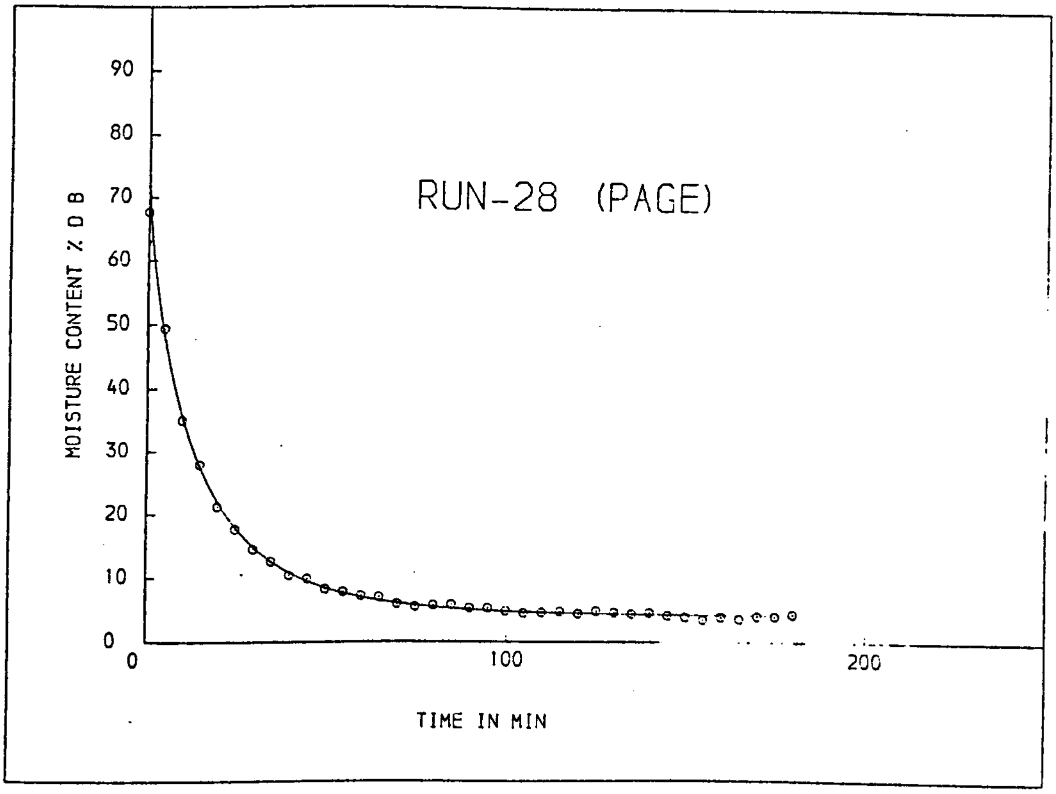


Fig. 3.9 (b) Predicted and observed moisture contents

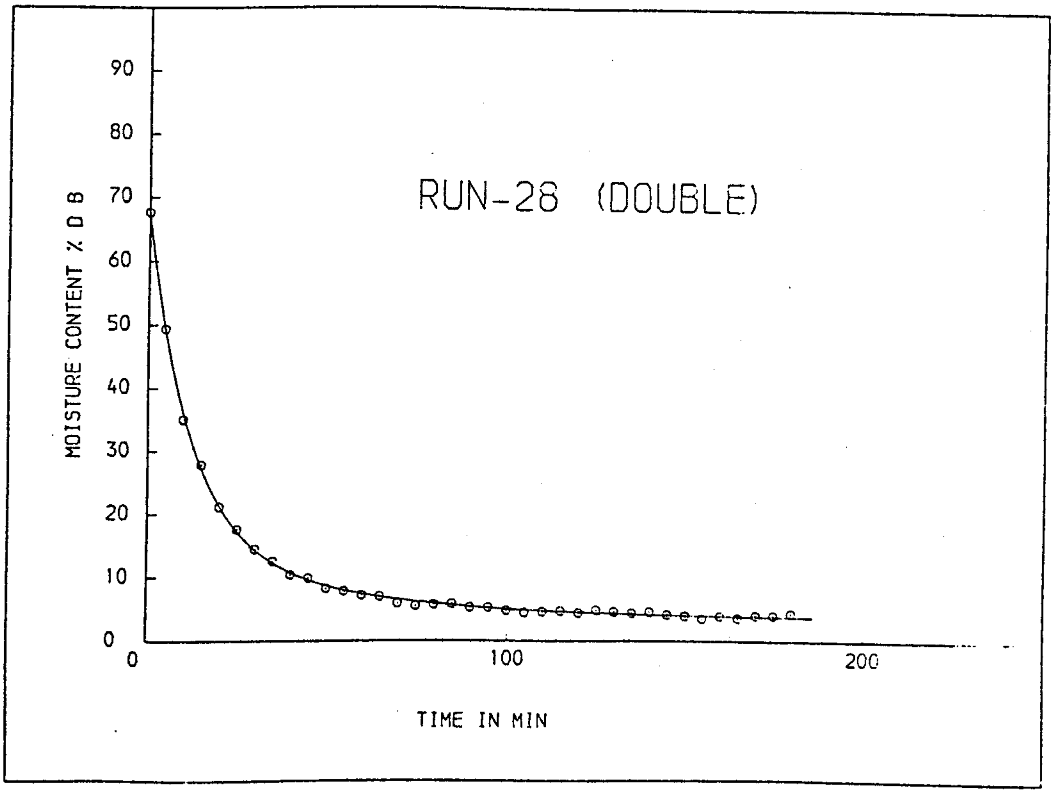


Fig. 3.9 (c) Predicted and observed moisture contents

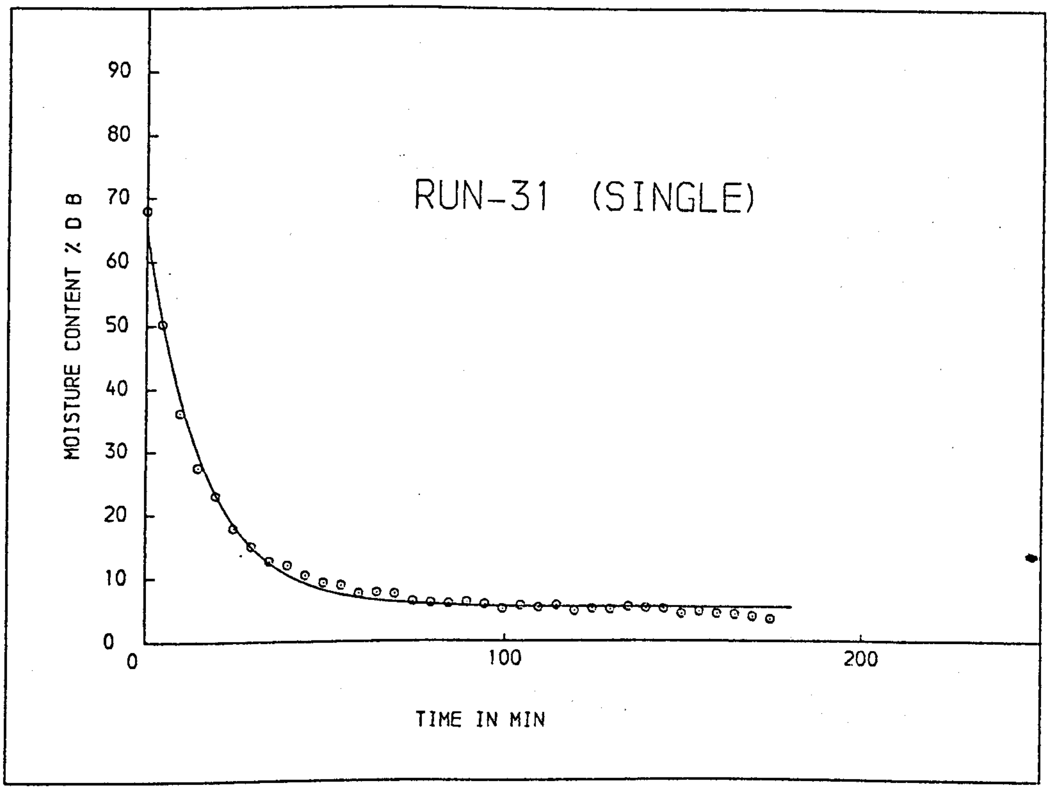


Fig. 3.10 (a) Predicted and observed moisture contents

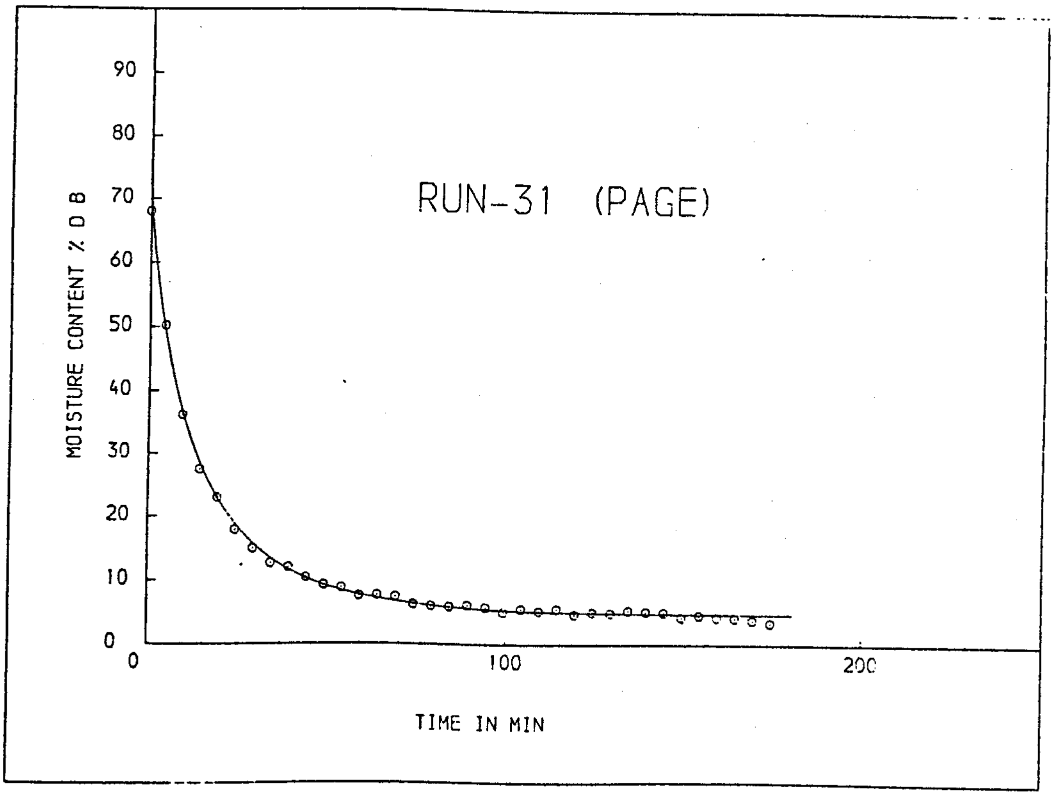


Fig. 3.10 (b) Predicted and observed moisture contents

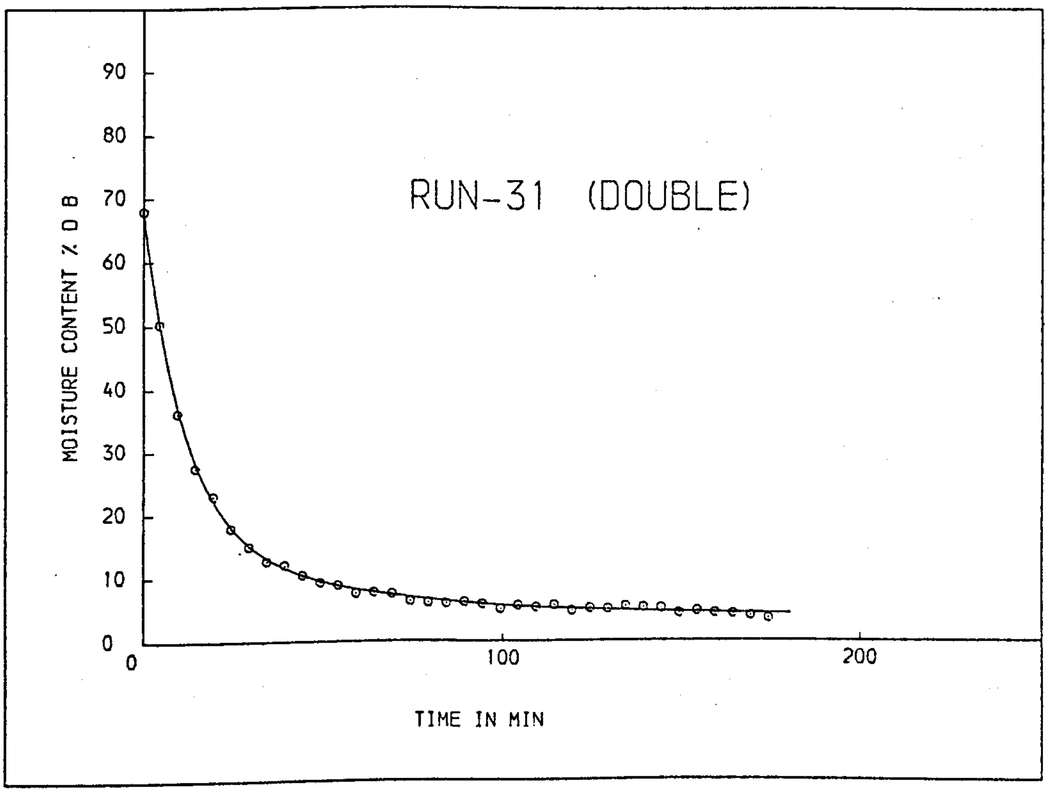


Fig. 3.10 (c) Predicted and observed moisture contents

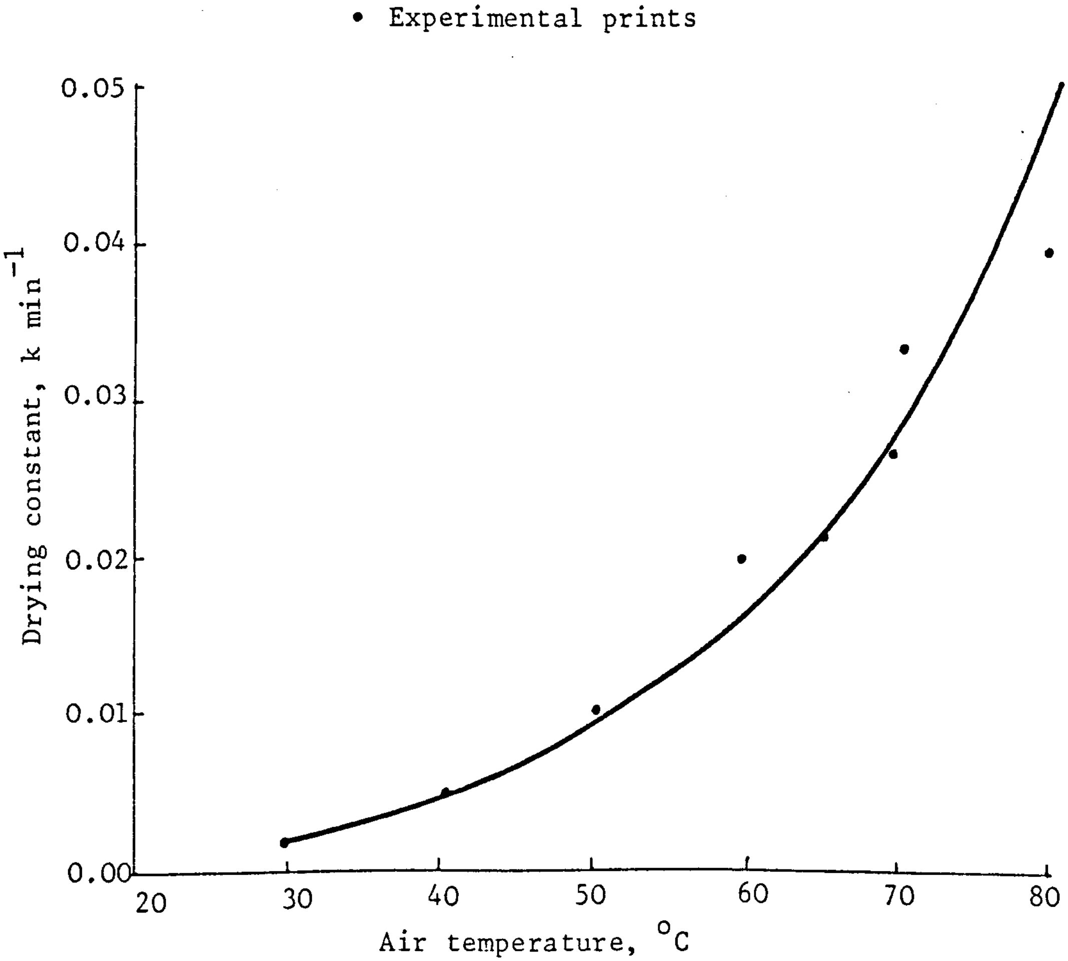


Fig. 3.11 Drying constant as a function of temperature from the fit of the single exponential equation (9 expts).

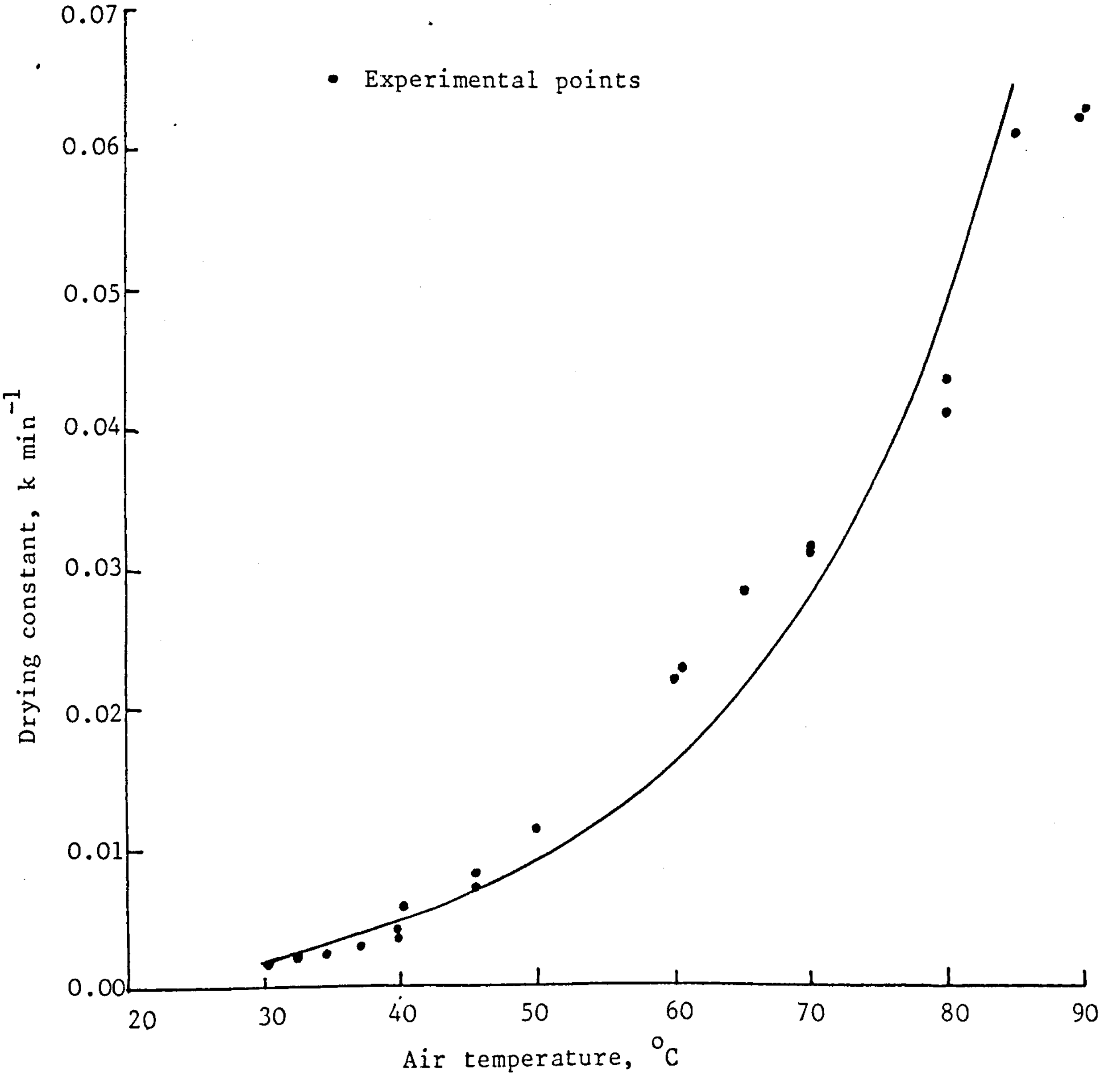


Fig. 3.12 Drying constant as a function of temperature from the fit of the single exponential equation (20 expts.)

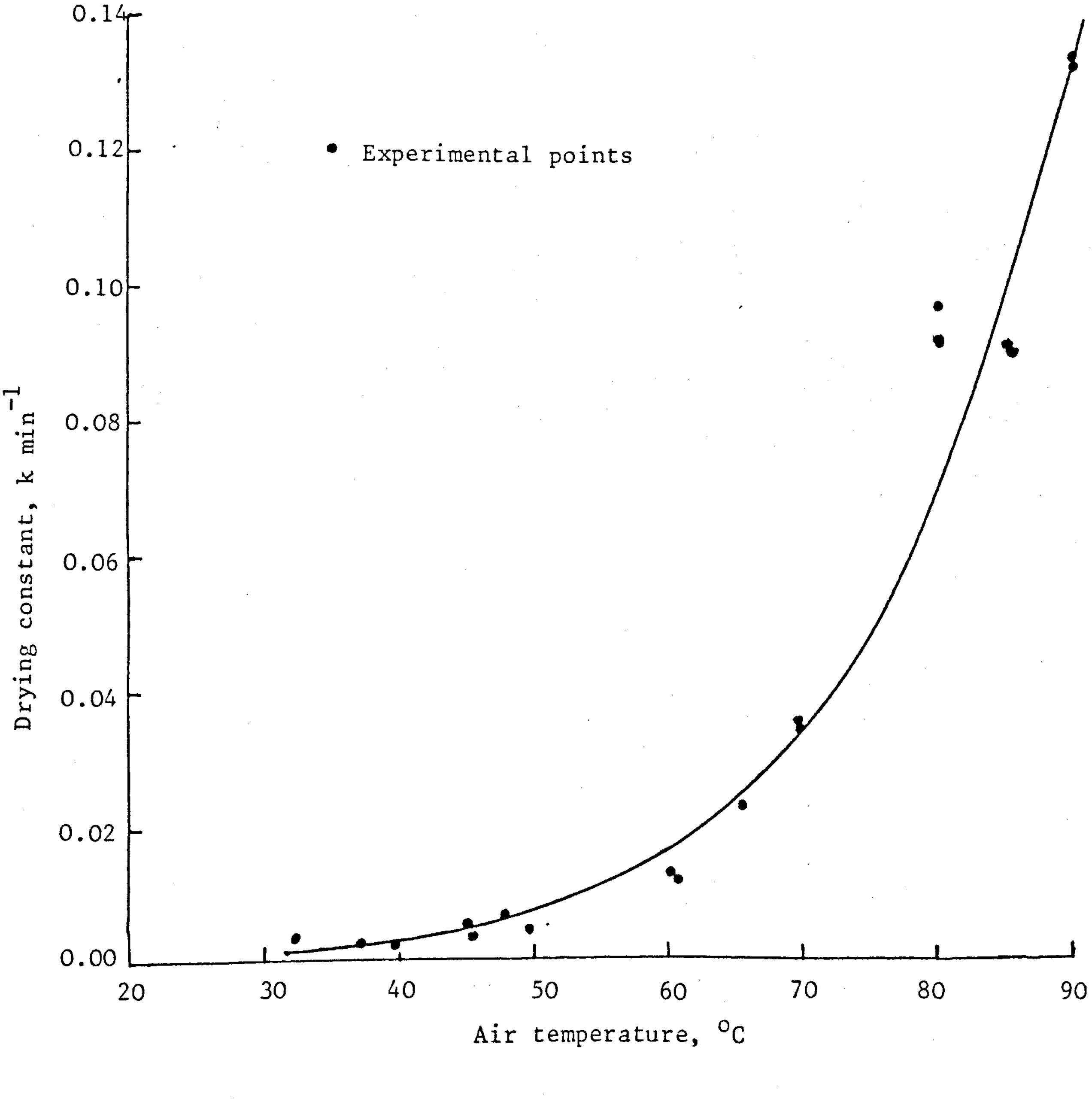


Fig. 3.13 Drying constant as a function of temperature from the fit of the Page equation

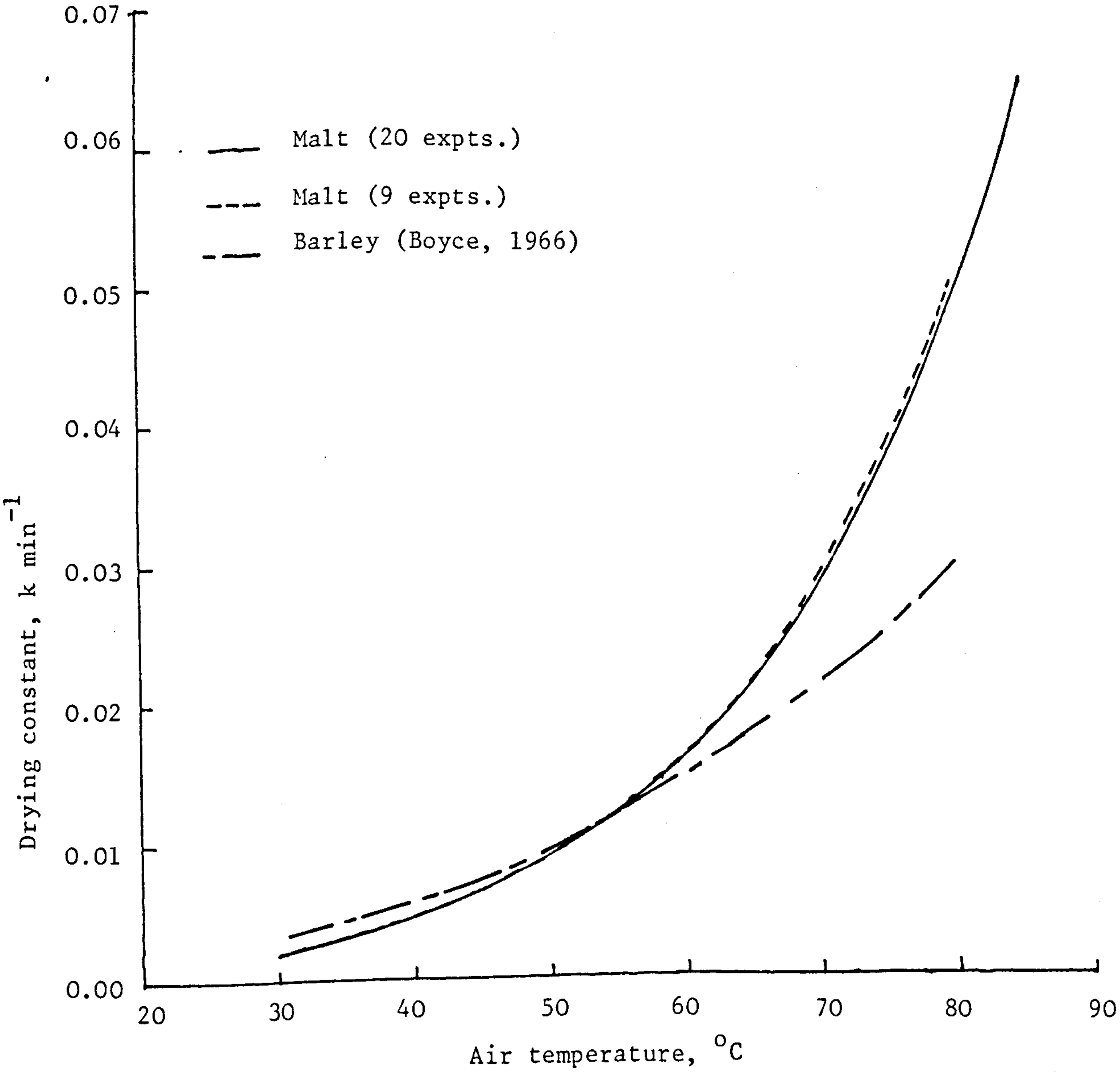


Fig. 3.14 Comparison of drying constants between malt and barley for the fit of the single exponential equation

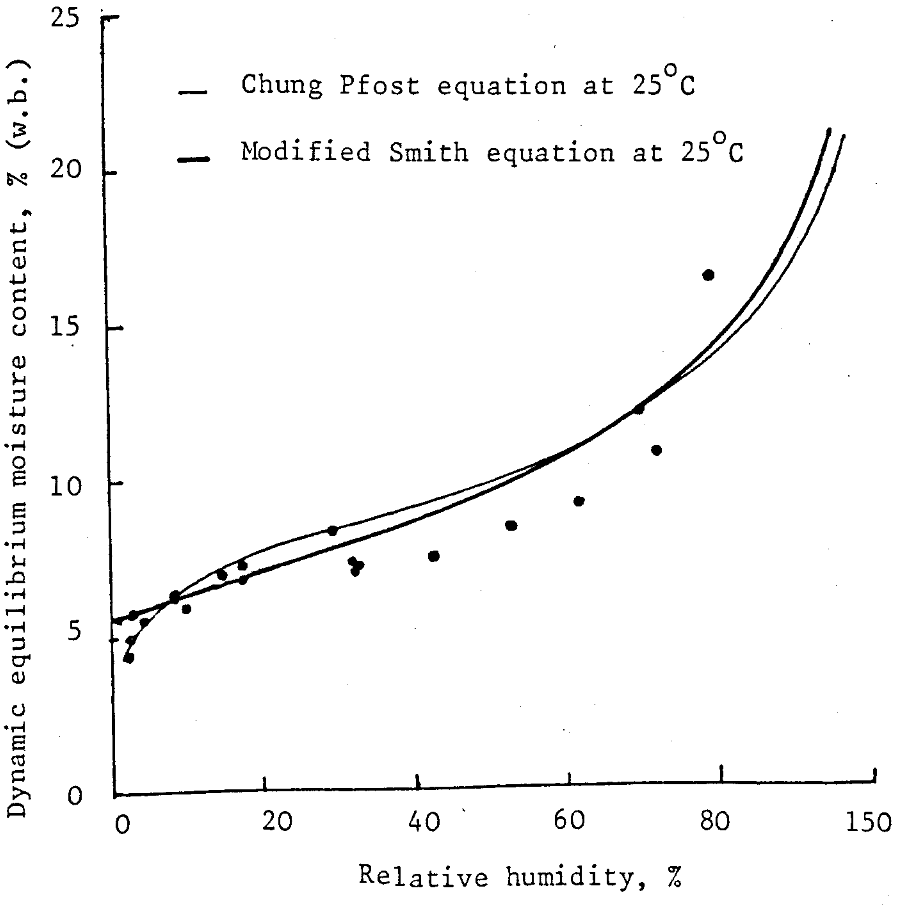


Fig. 3.15 Dynamic equilibrium moisture content derived from the fit of the single exponential equation

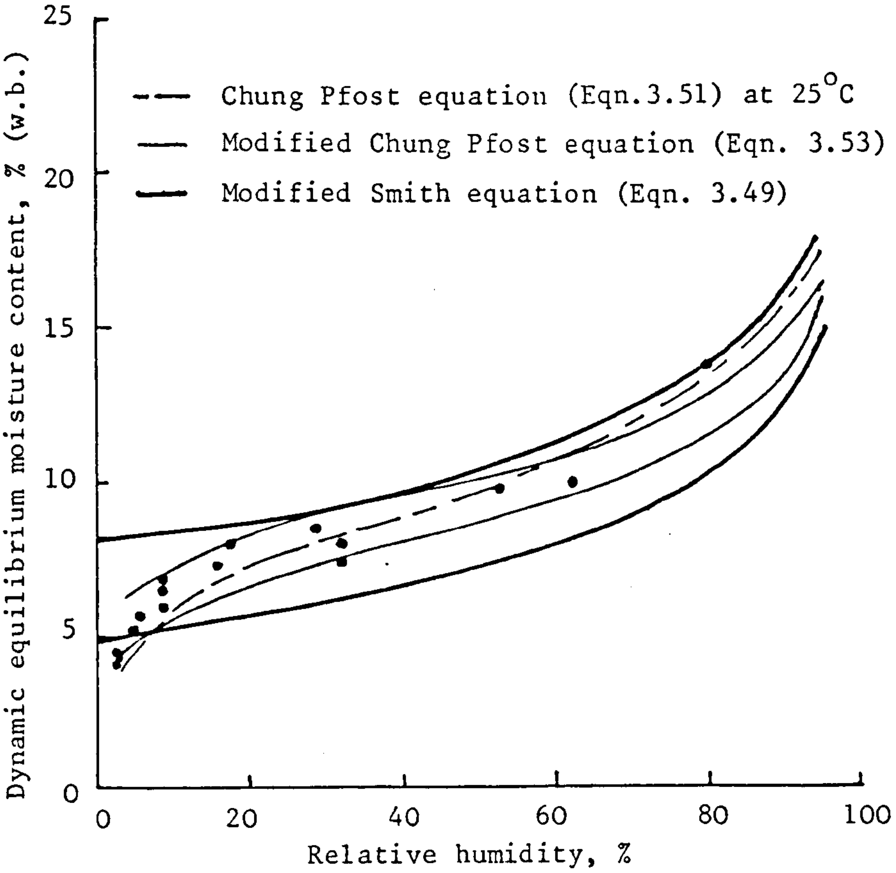


Fig. 3.16 Dynamic equilibrium moisture content derived from the fit of the Page equation (upper curves at 25°C and lower curves at 80°C)

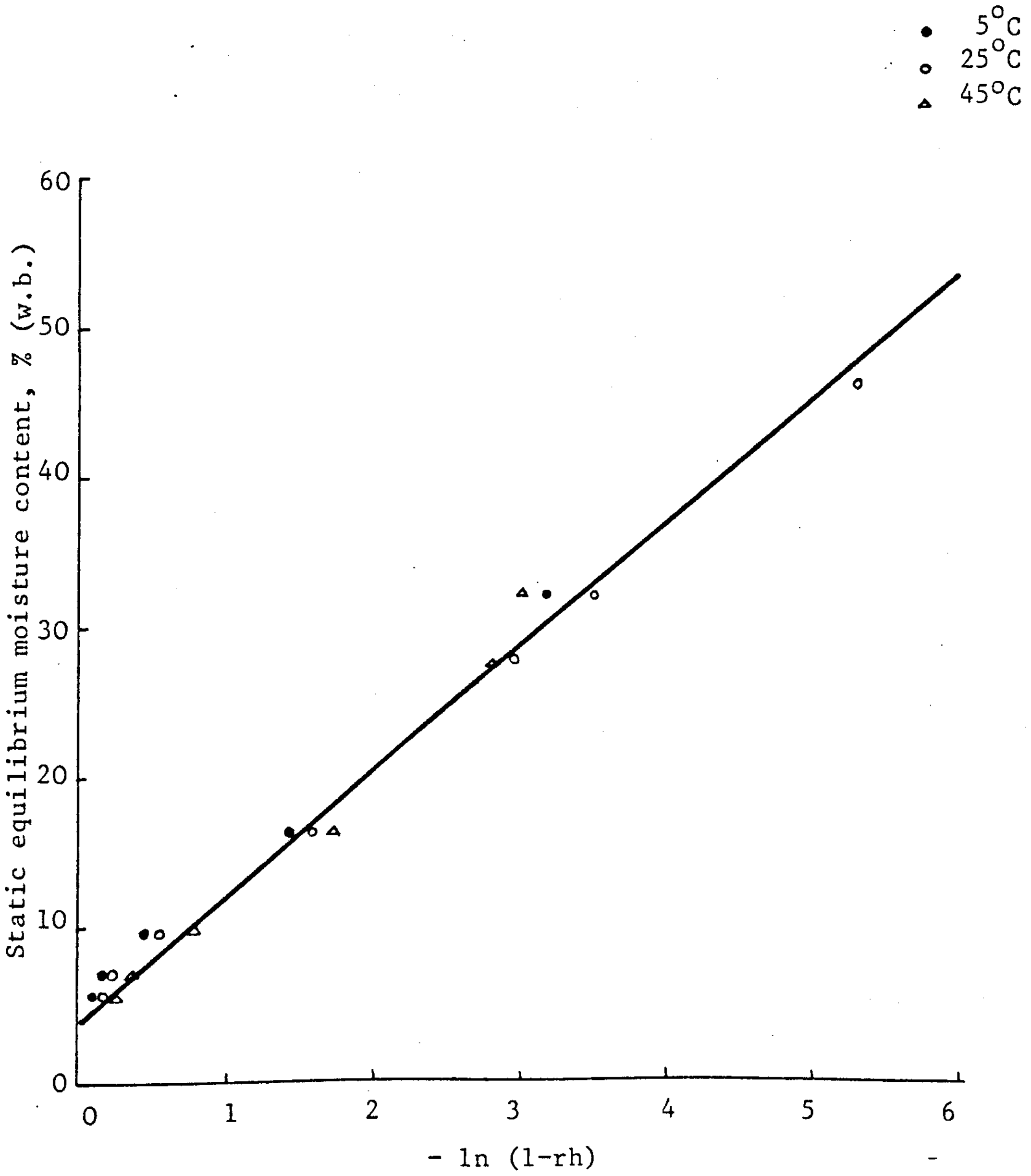


Fig. 3.17 Static equilibrium moisture content of malt as a function of -ln (1-rh) and predicted line from Smith equation at 25°C.

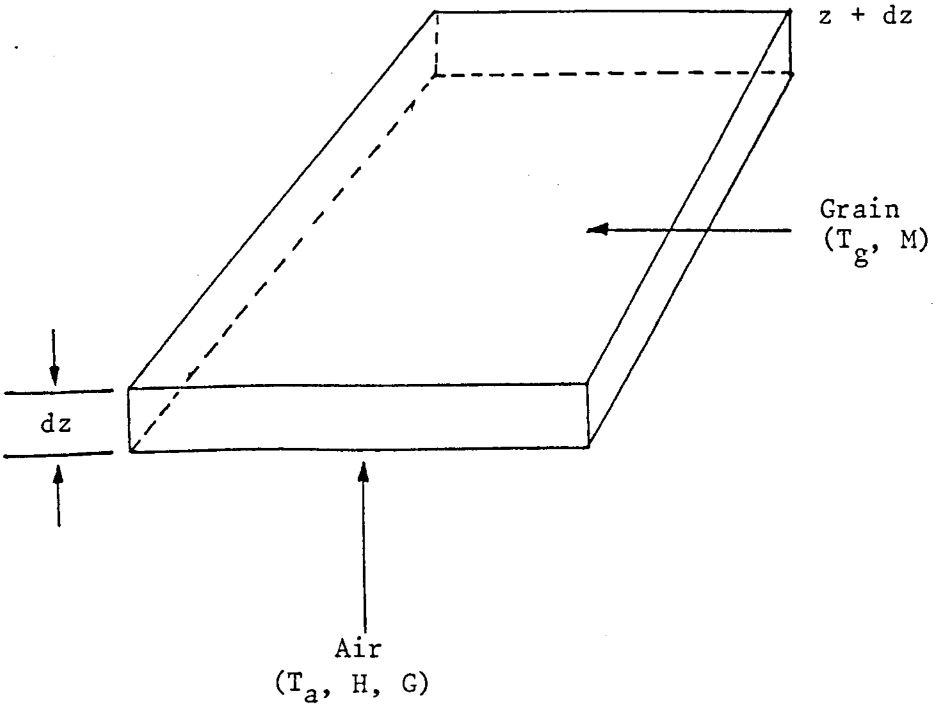


Fig. 4.1 Element of bed

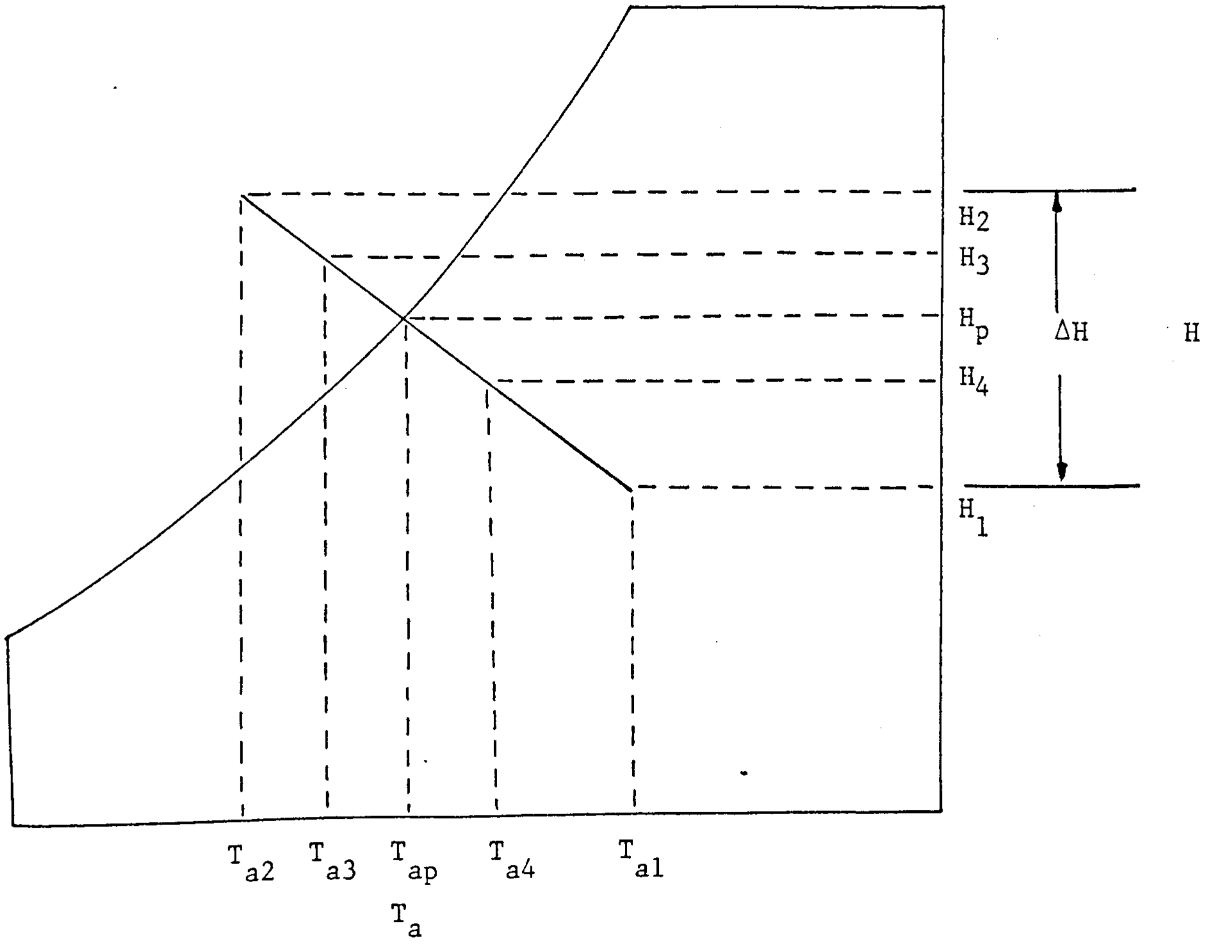


Fig. 4.2 Illustration of the principle of the condensation procedure on a skeleton psychrometric chart

$$\Delta H = - \Delta M \frac{\rho_d \ \Delta z}{G \ \Delta t}$$

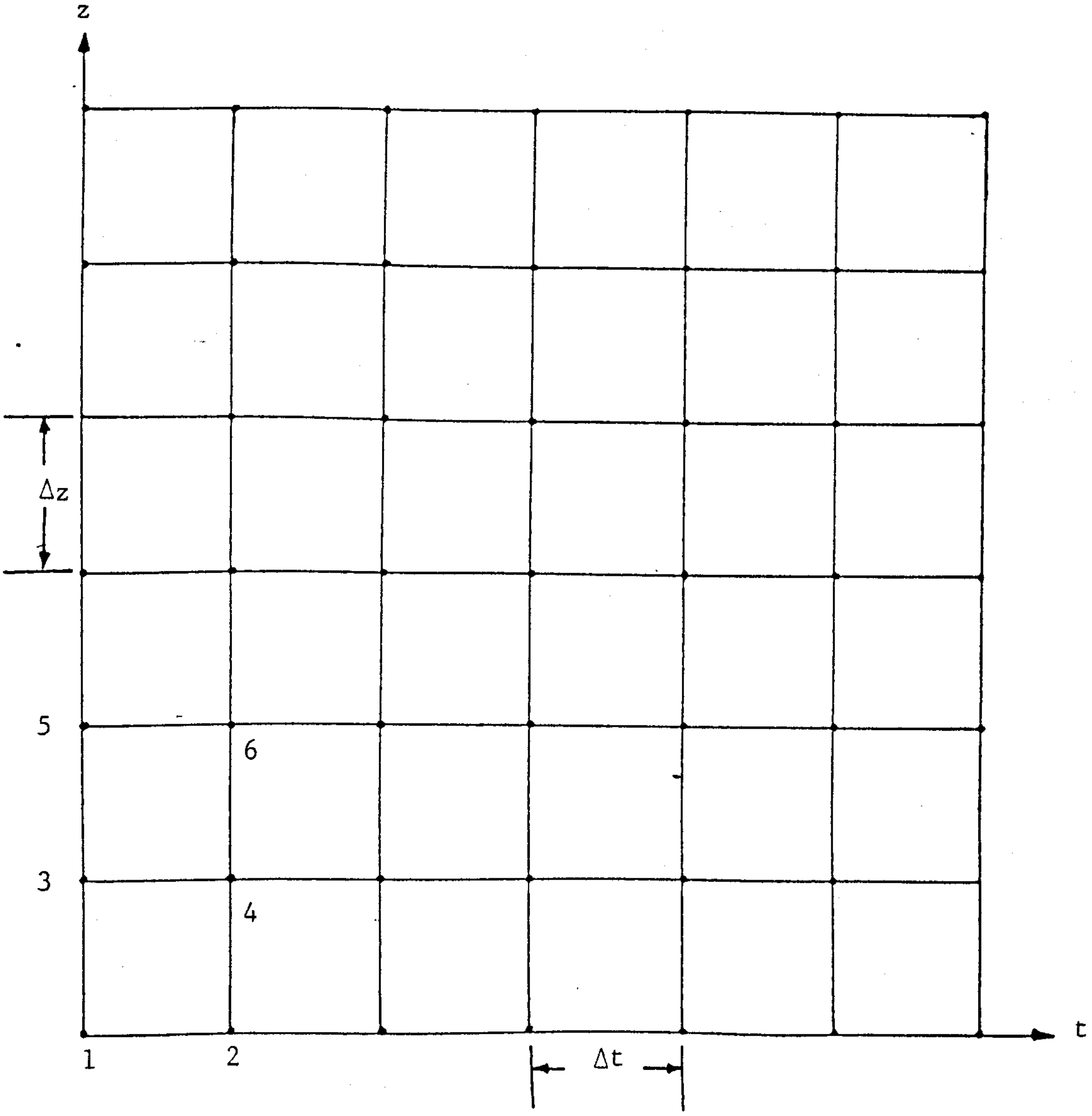


Fig. 4.3 Finite difference grid for the deep bed drying equations

Fig. 5.1   Experimental set up for deep bed drying experiments

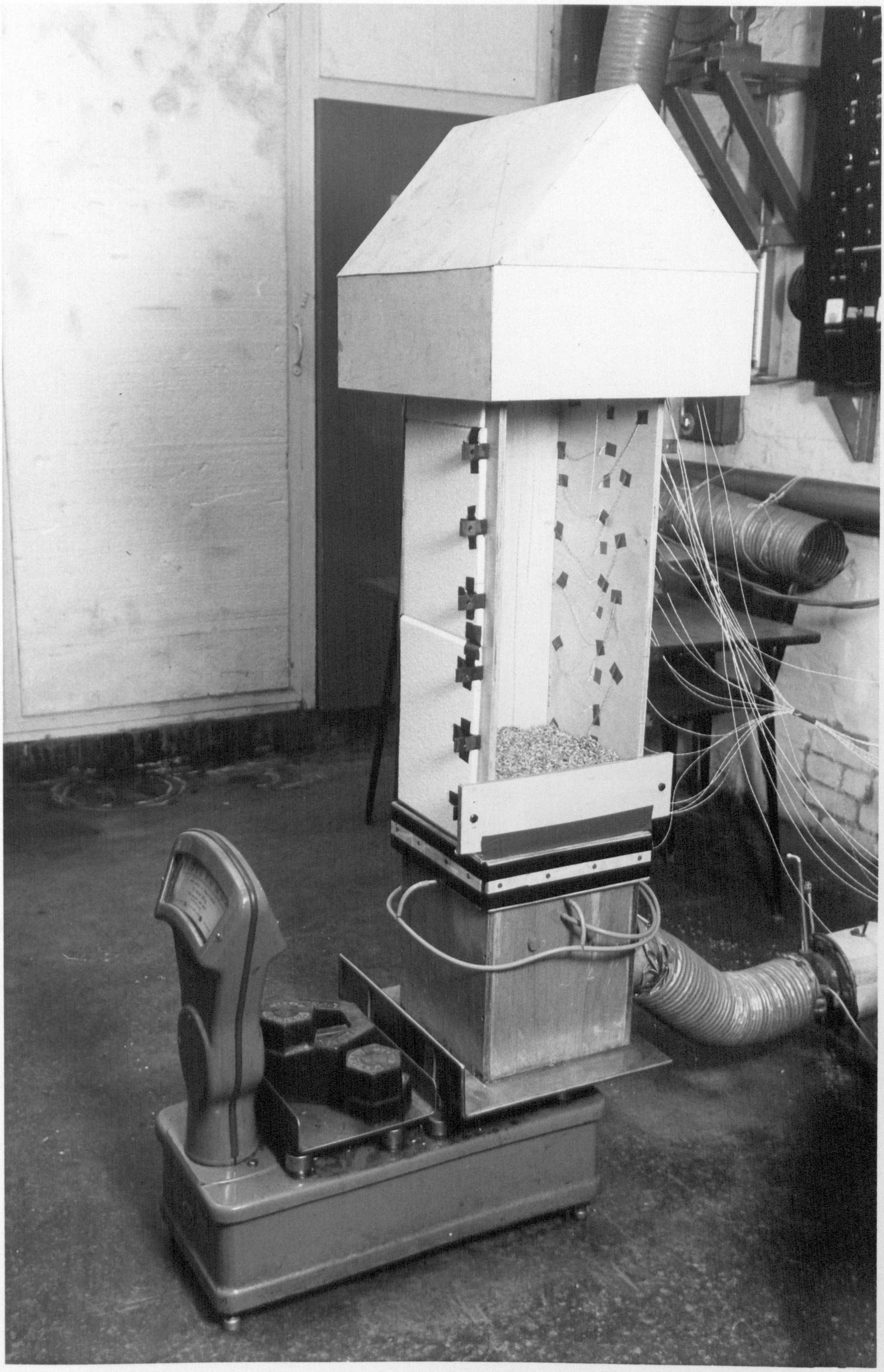
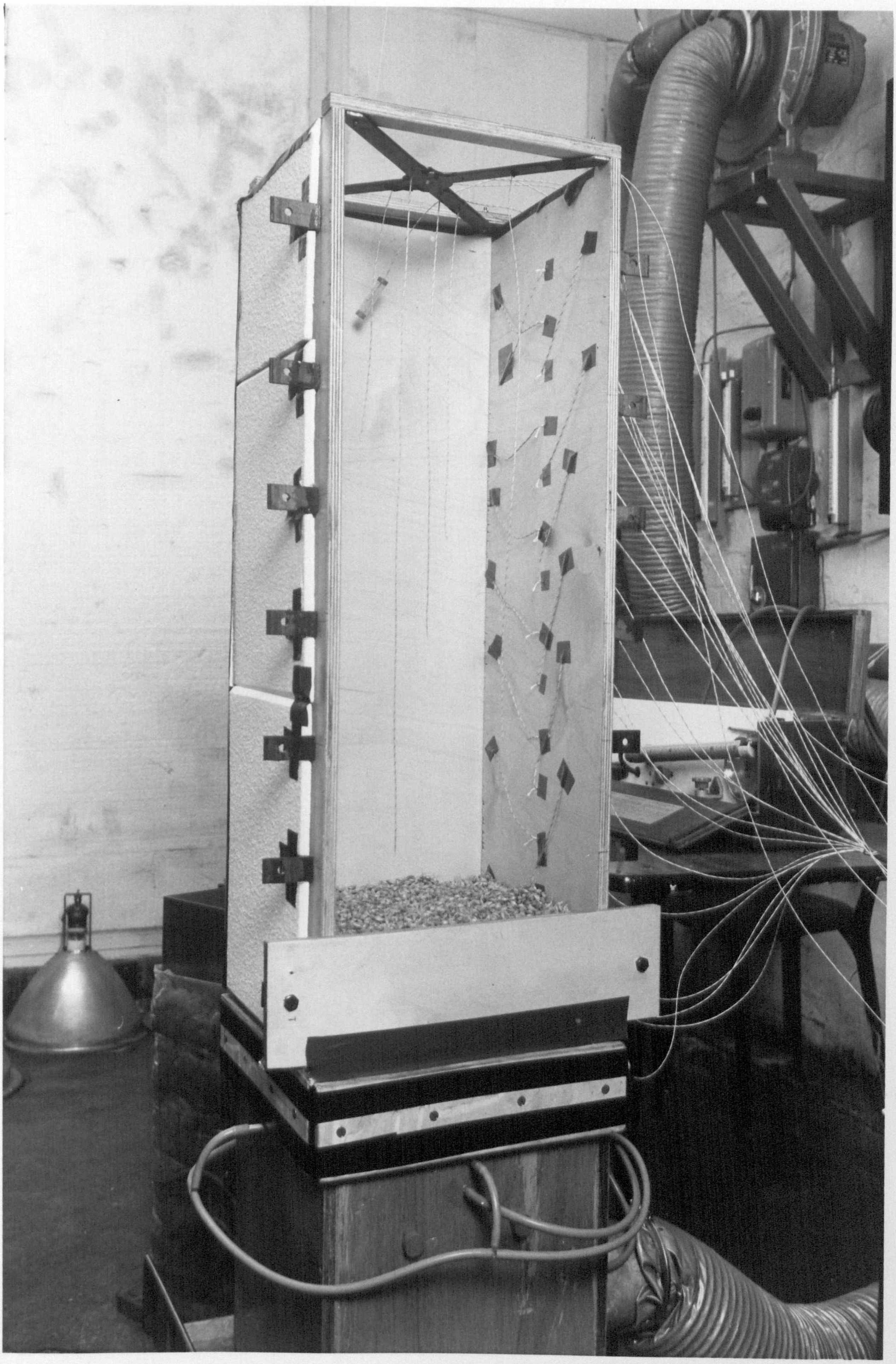


Fig. 5.2 Experimental bin with the shielded thermocouples supported by thin horizontal rods

Fig. 5.3 Experimental bin with thermocouples suspended from the 'star' shaped support



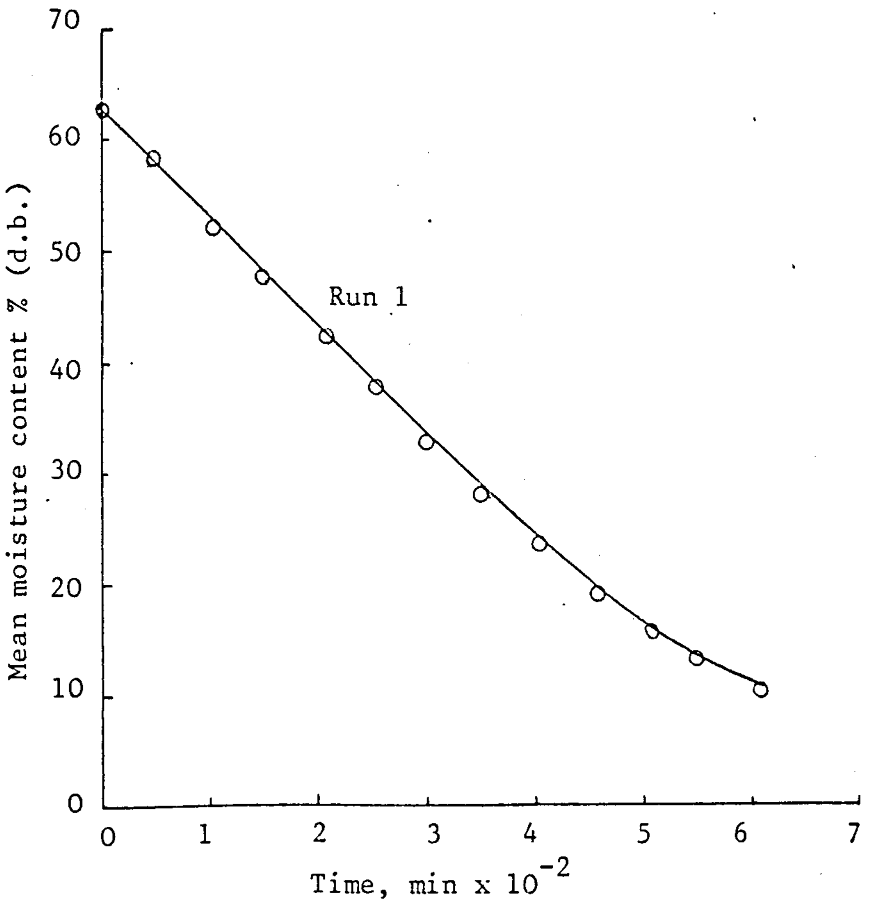


Fig. 5.4 (a) Predicted and observed mean moisture content

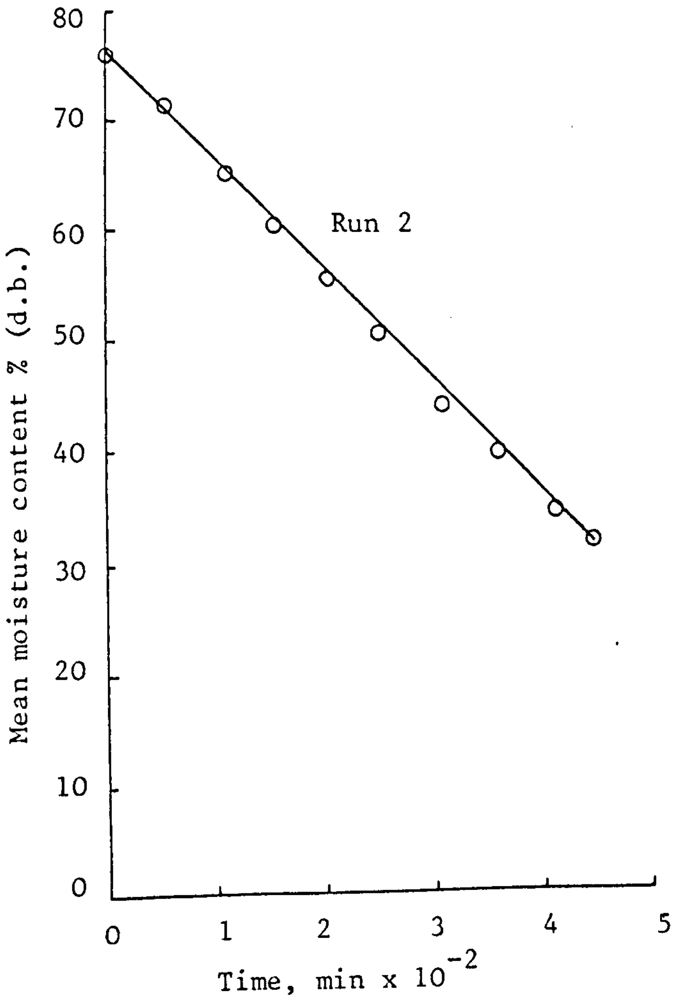


Fig. 5.4 (b) Predicted and observed mean moisture content

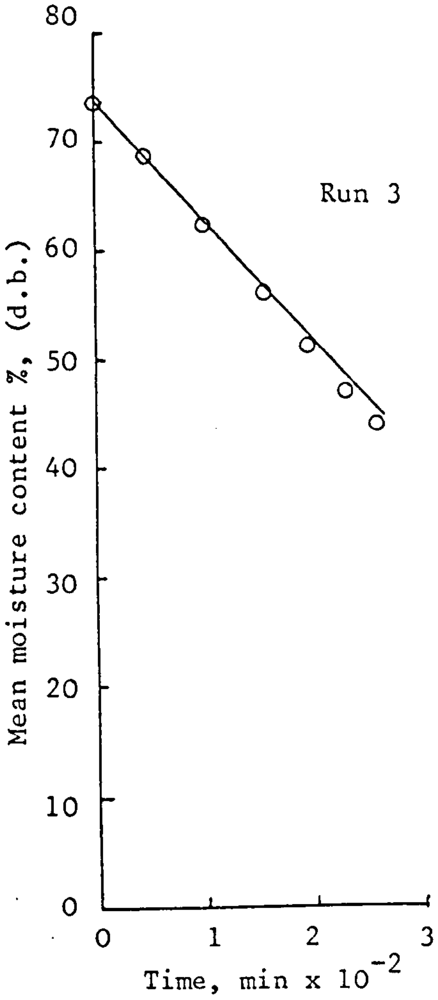


Fig. 5.4 (c) Predicted and observed mean moisture content

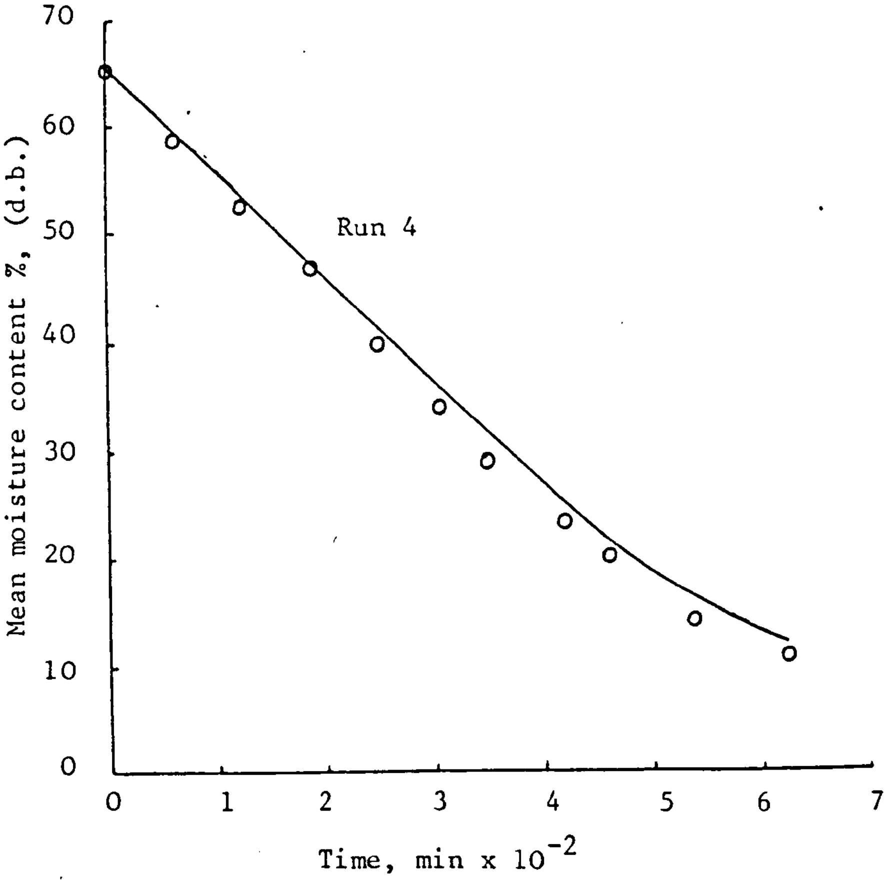


Fig. 5.4 (d) Predicted and observed mean moisture content

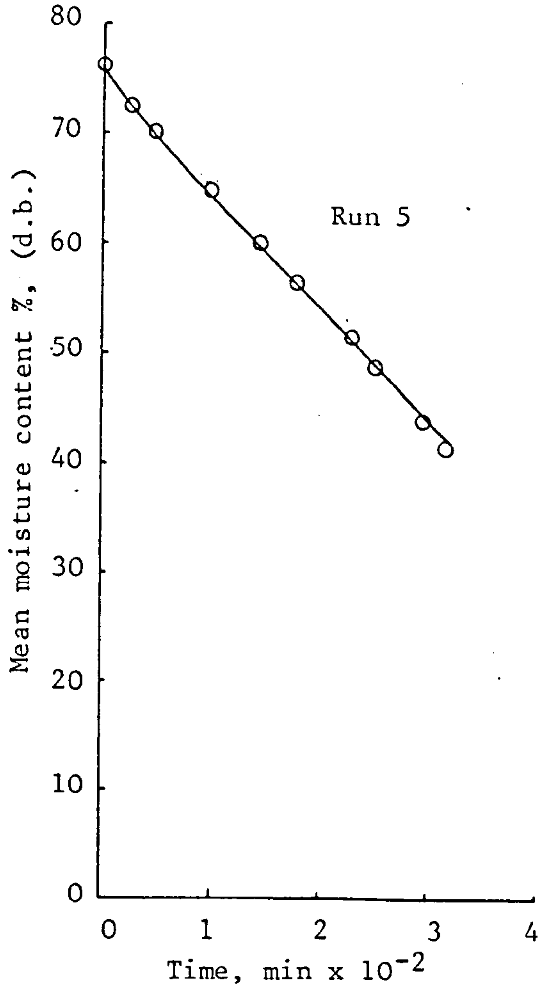


Fig. 5.4 (e) Predicted and observed mean moisture content

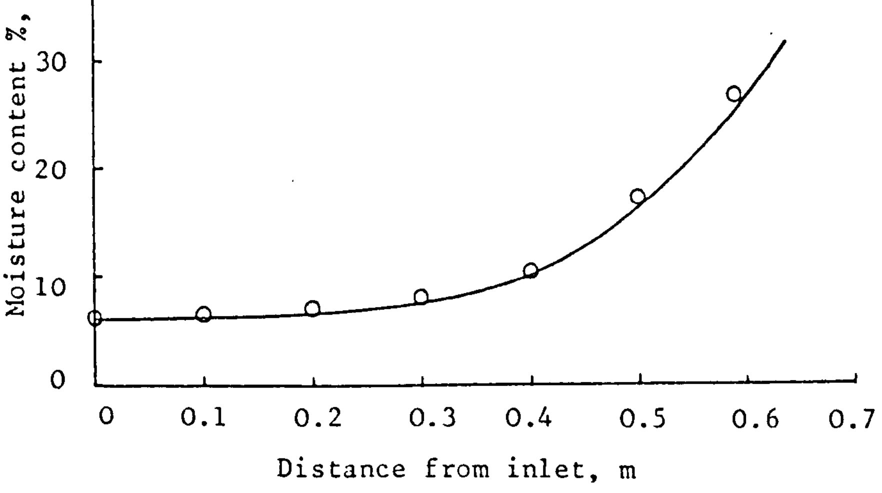


Fig. 5.5 (a) Predicted and observed moisture content distribution

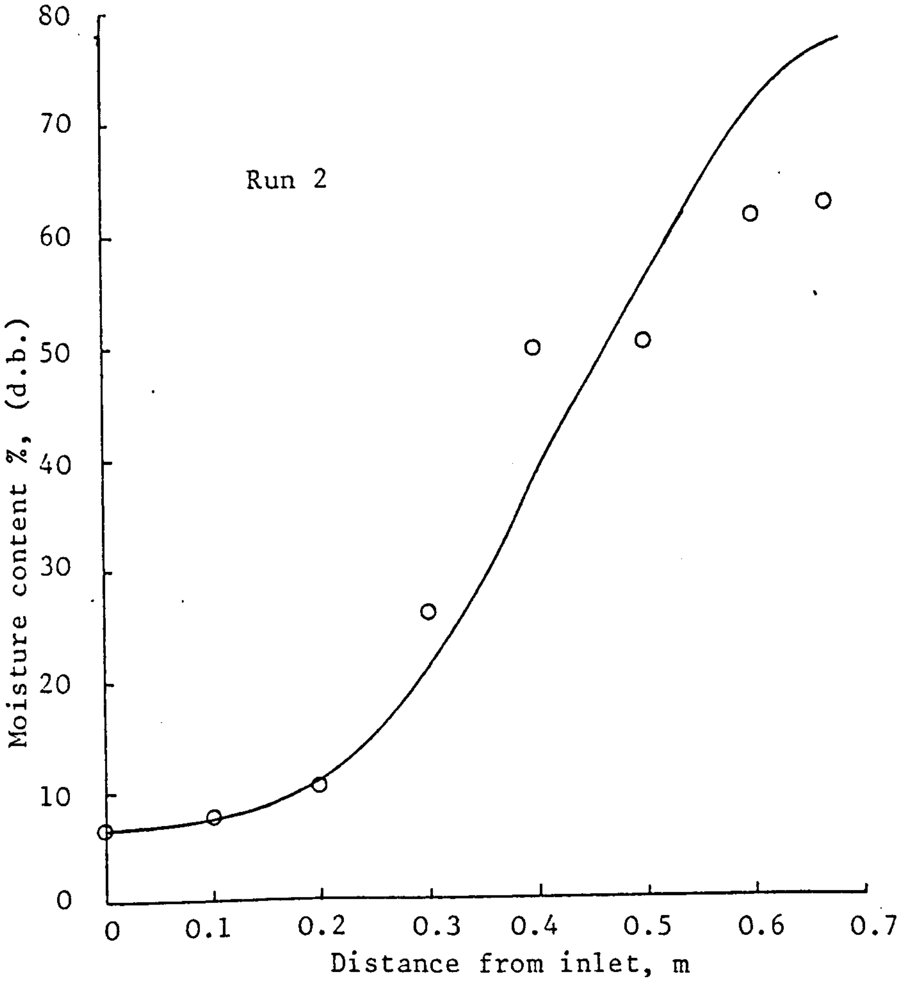


Fig. 5.5 (b) Predicted and observed moisture content distribution

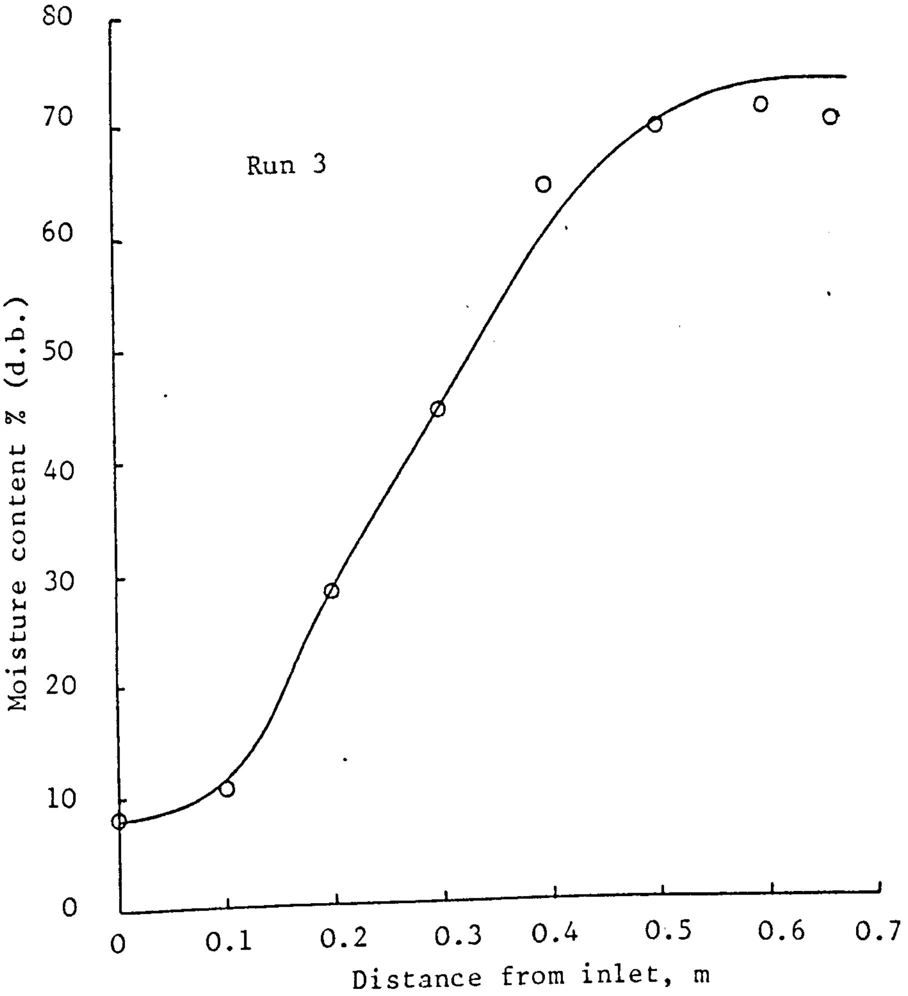


Fig. 5.5 (c) Predicted and observed moisture content distribution

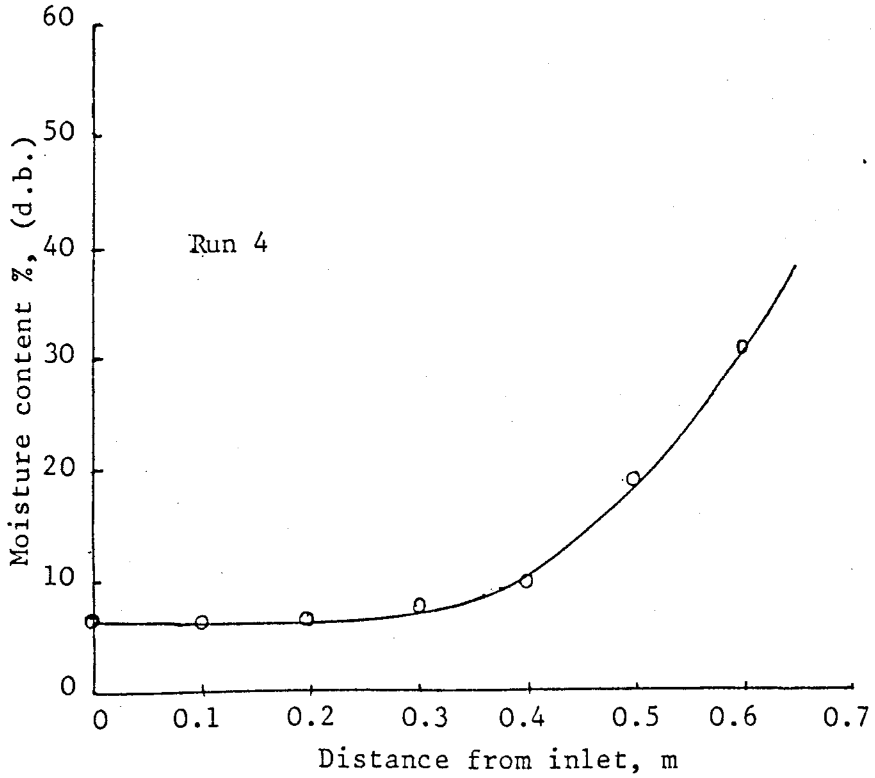


Fig. 5.5 (d) Predicted and observed moisture content distribution

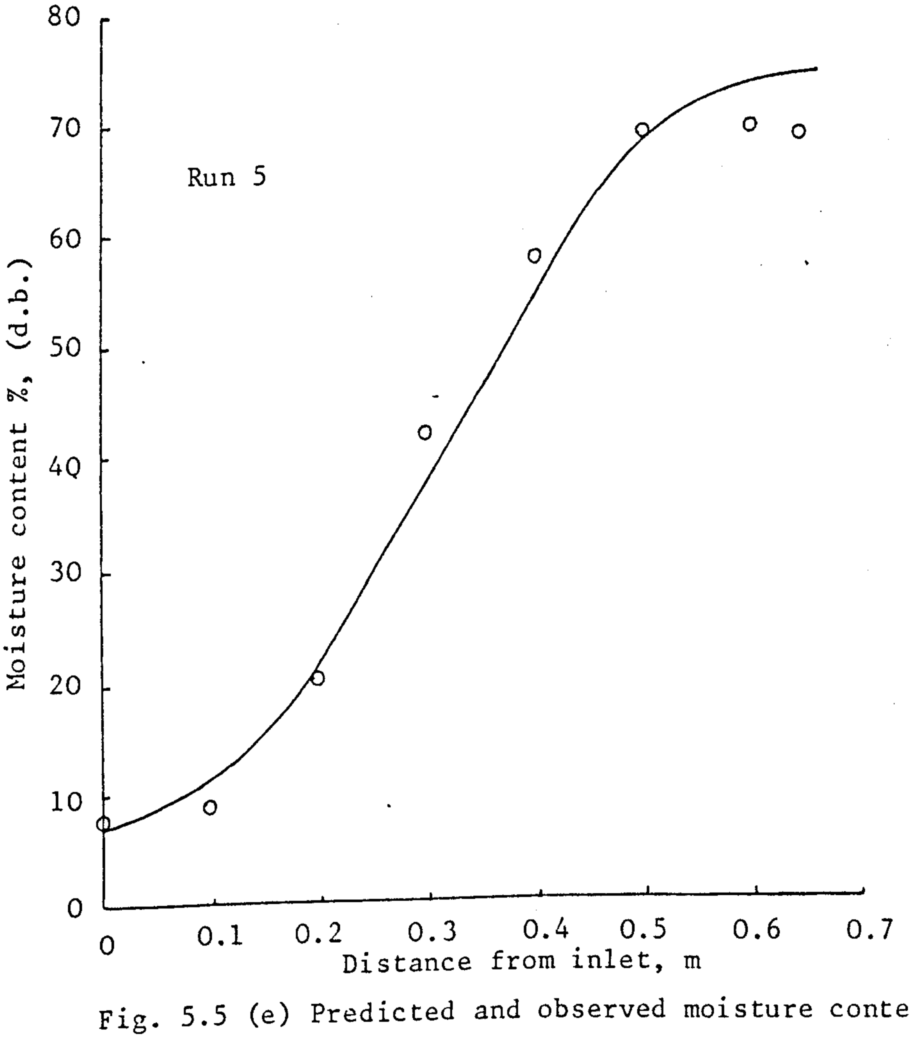


Fig. 5.5 (e) Predicted and observed moisture content distribution

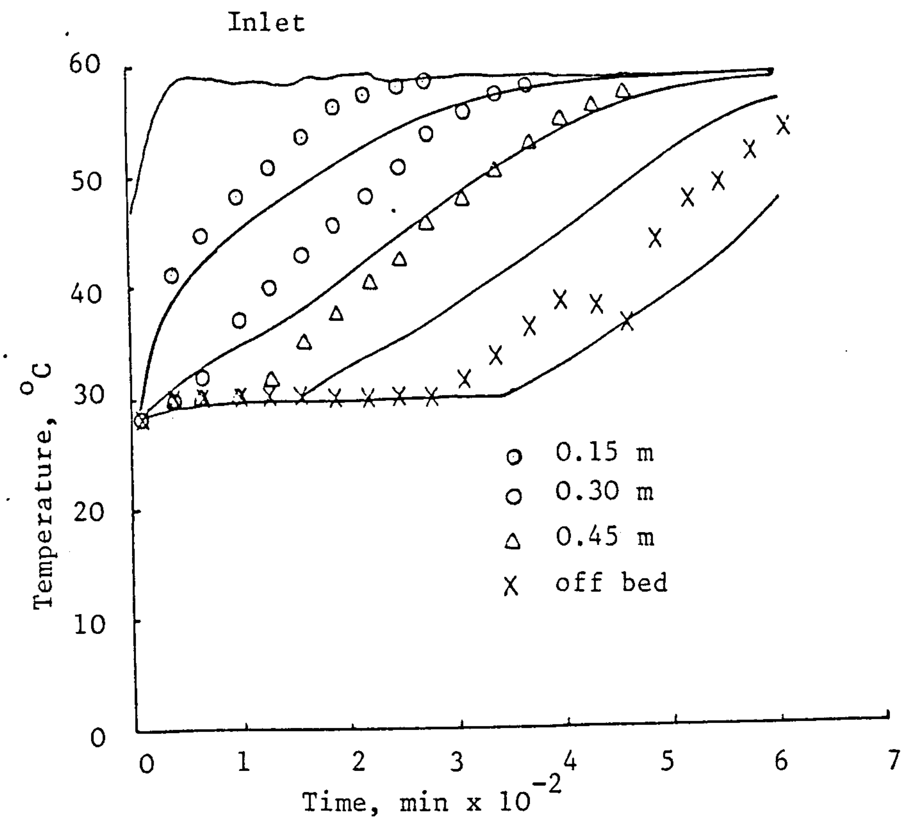


Fig. 5.6 (a) Predicted and observed temperature variation with time at a number of bed depths

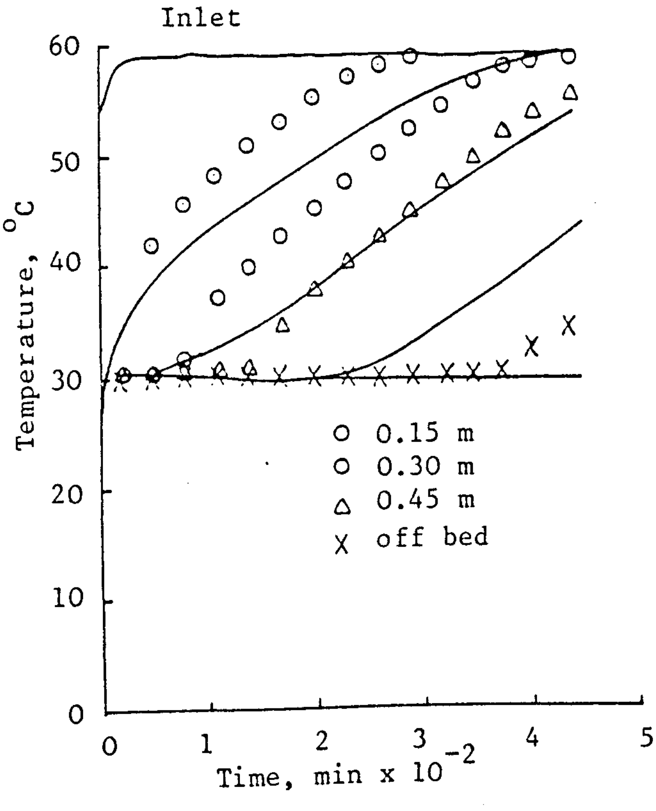


Fig. 5.6 (b) Predicted and observed temperature variation time at a number of bed depths

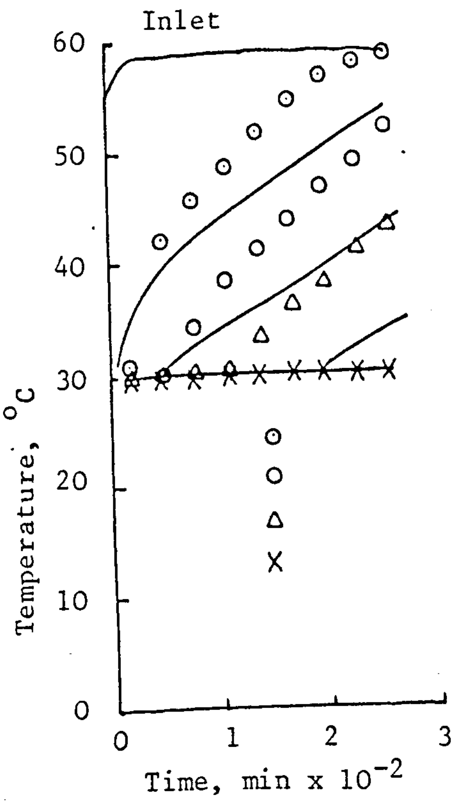


Fig. 5.6 (c) Predicted and observed temperature variation with time at a number of bed depths

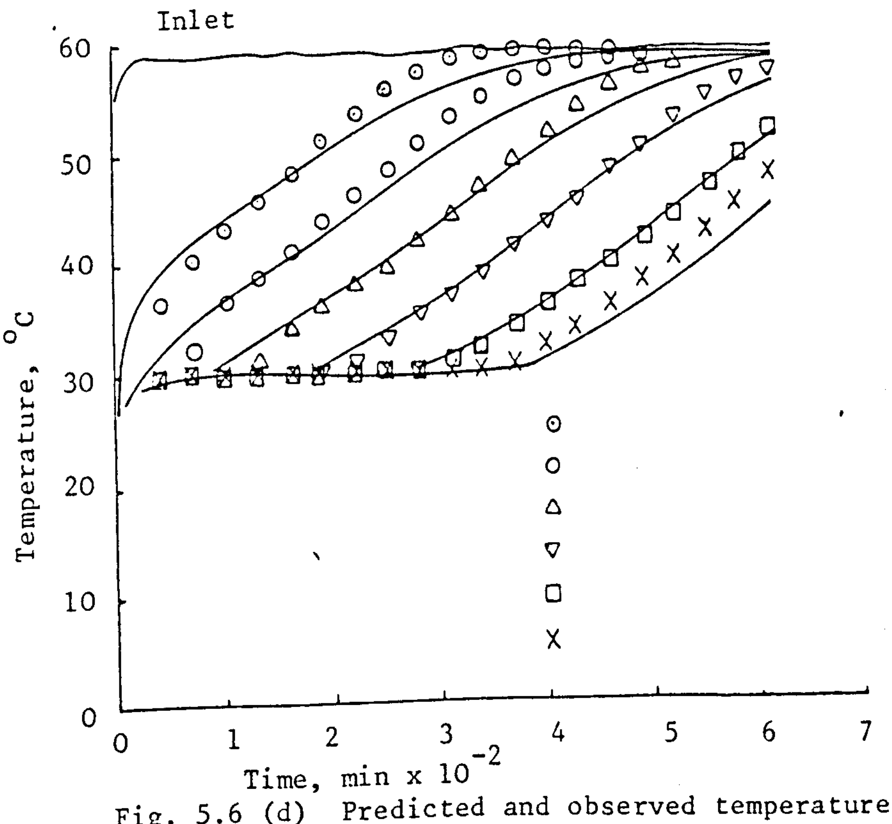


Fig. 5.6 (d) Predicted and observed temperature variation with time at a number of bed depths

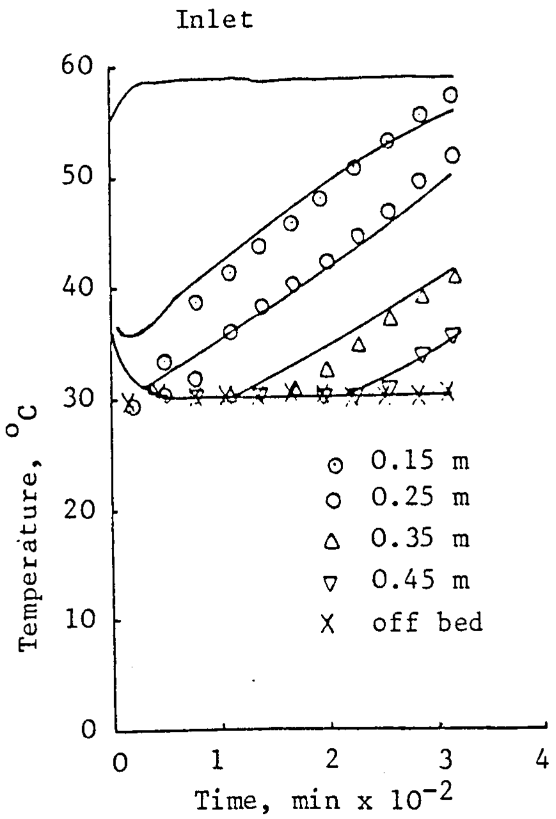


Fig. 5.6 (e) Predicted and observed temperature variation with time at a number of bed depths

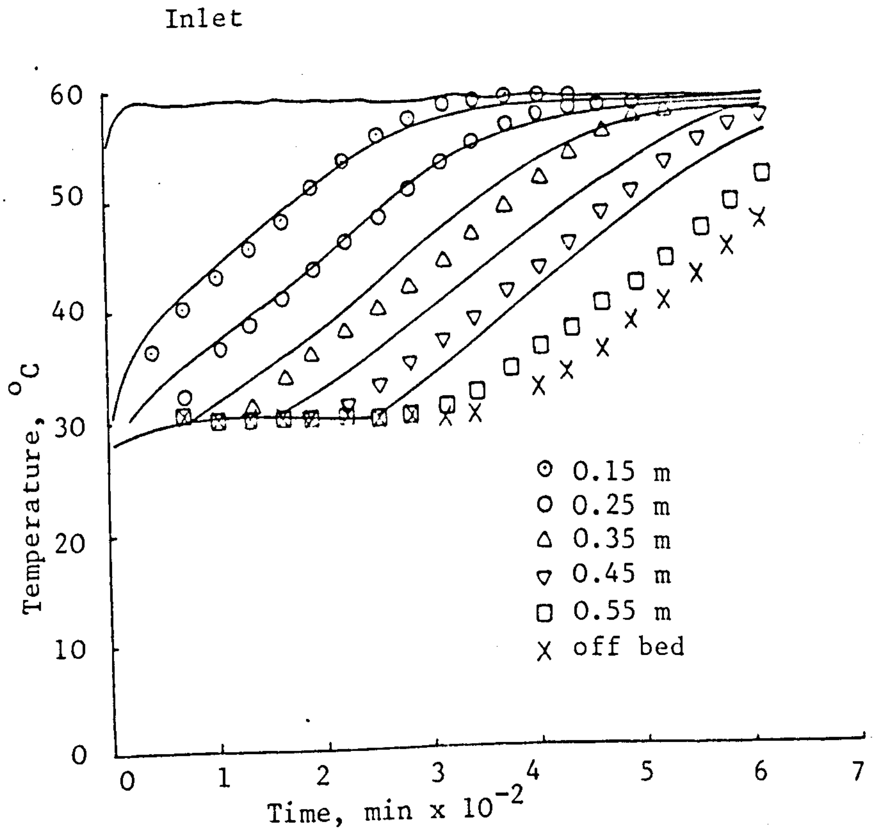


Fig. 5.7 Predicted and observed temperature variation with time at a number of bed depths without incorporating the shrinkage effect

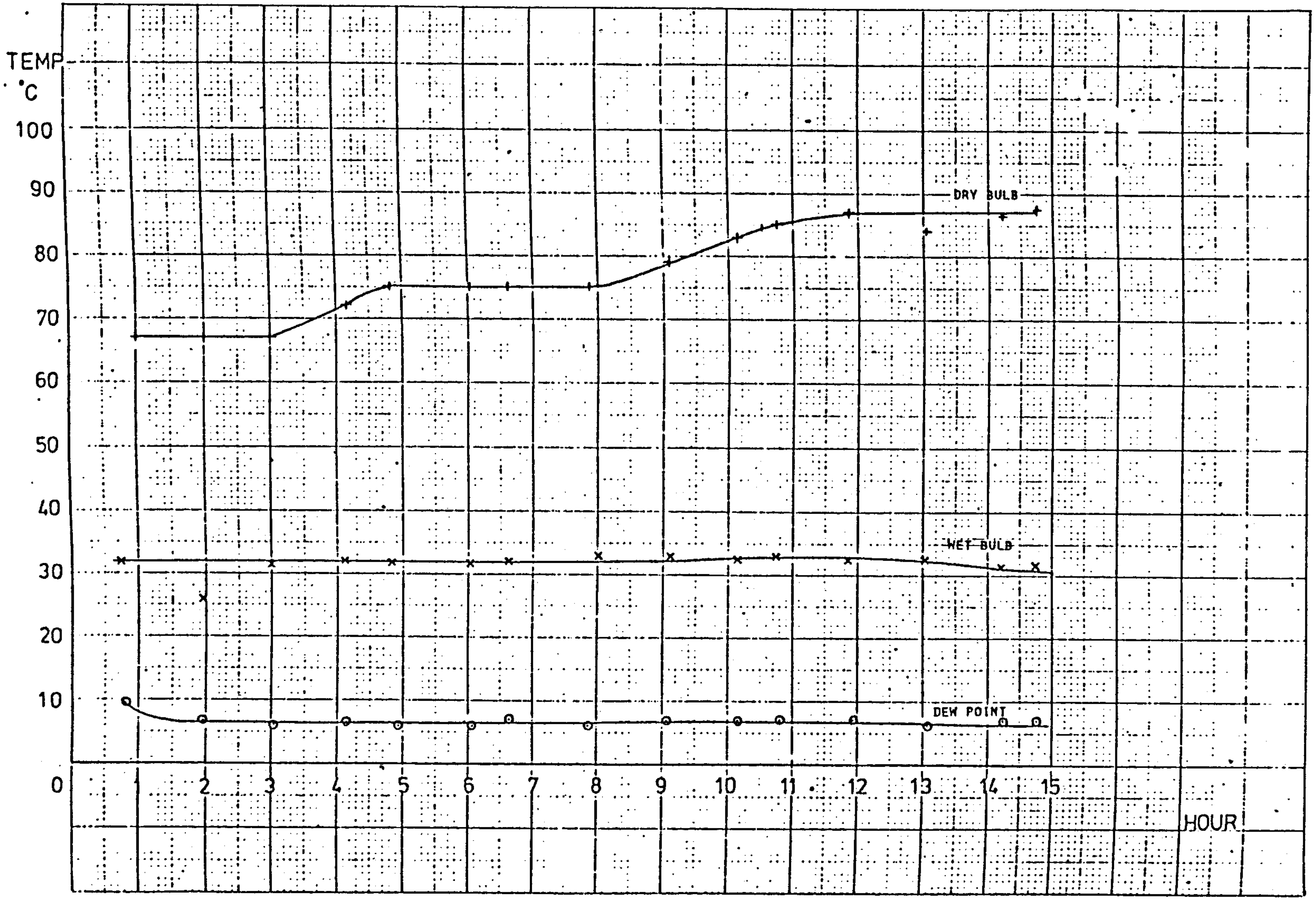


Fig. 5.8 (a) Kiln trial data for air on temperature

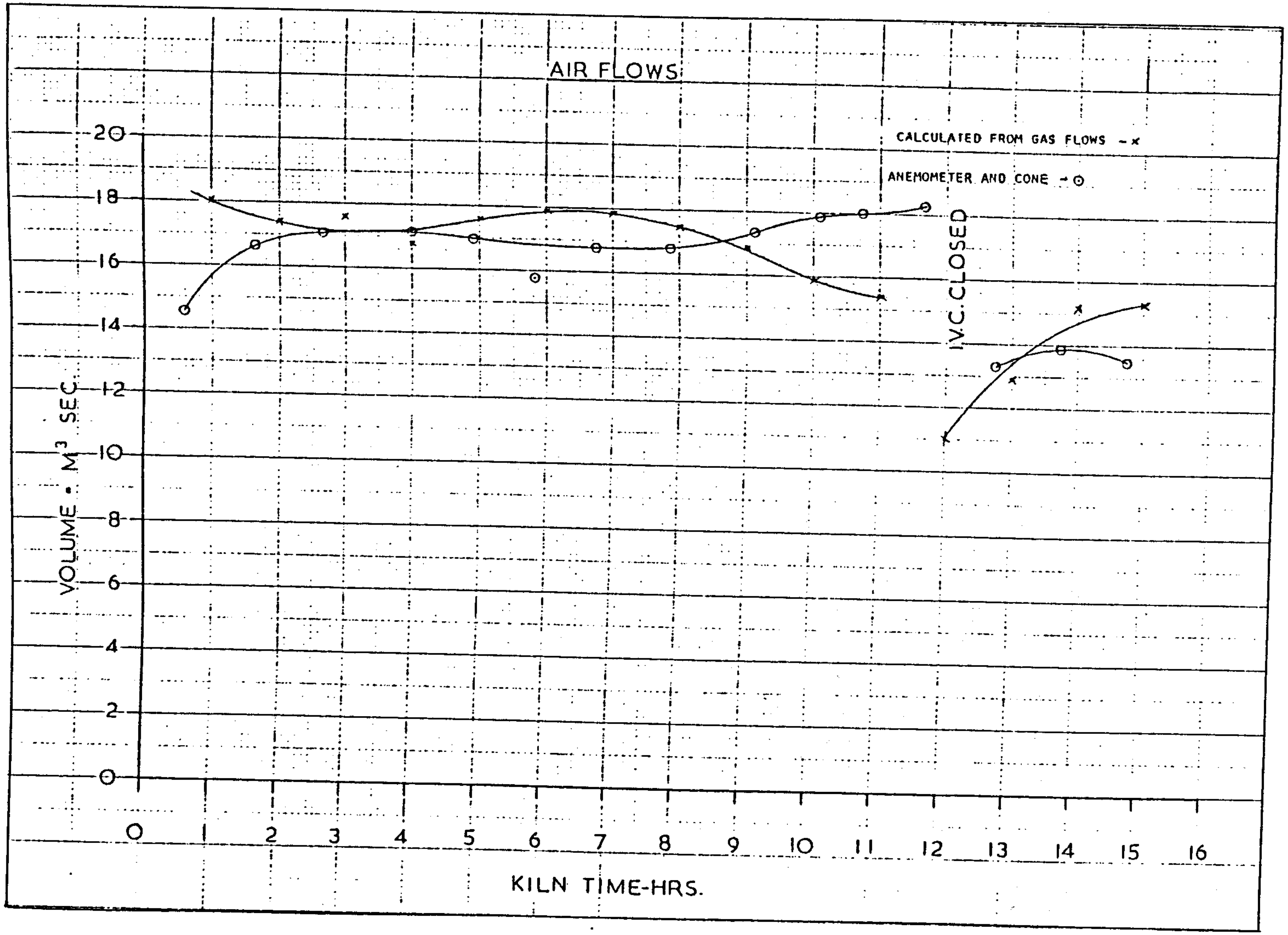


Fig. 5.8 (b) Kiln trial data on air flows

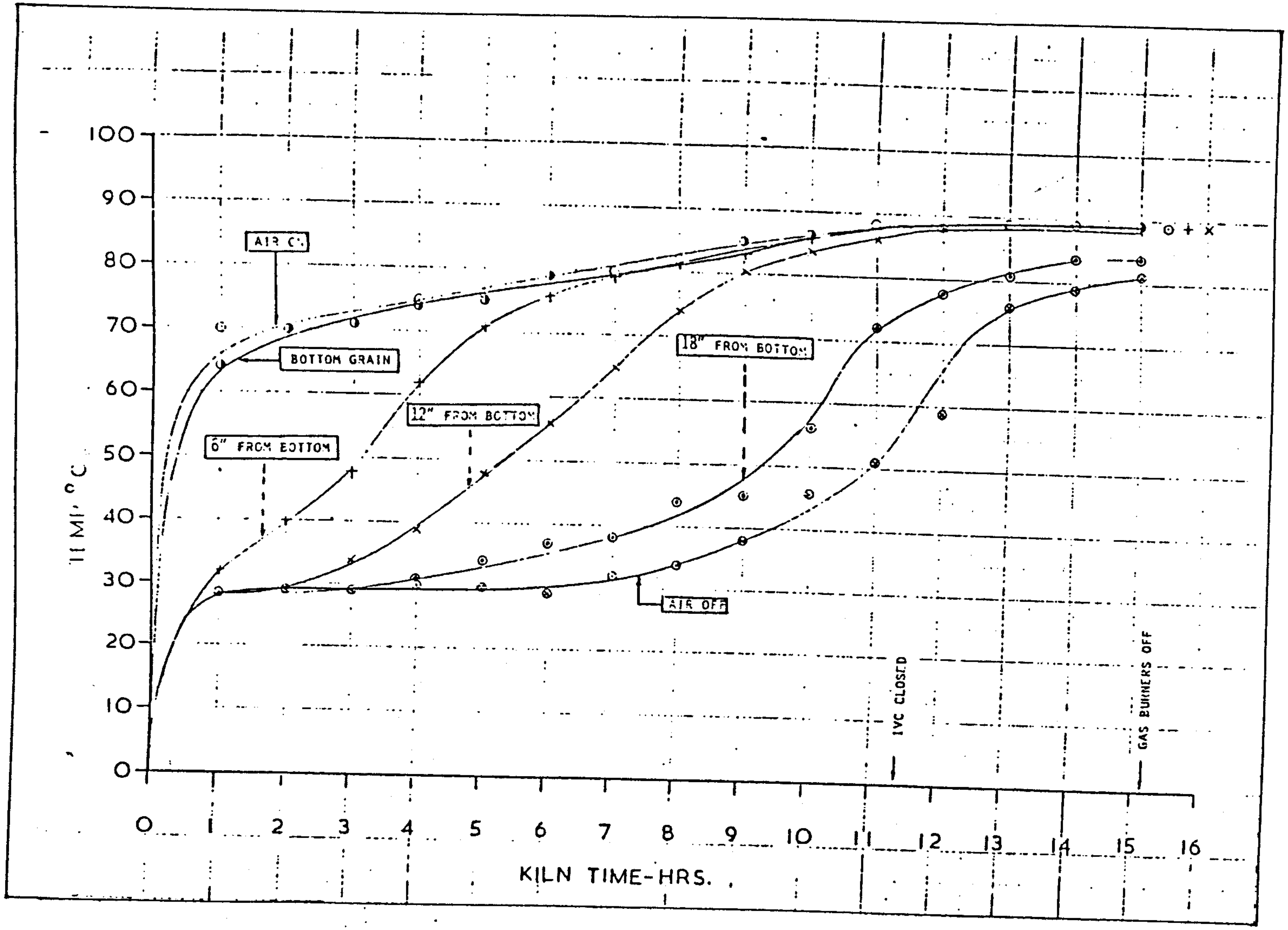


Fig. 5.8 (c) Kiln trial data on temperature variation with time at a number of depths

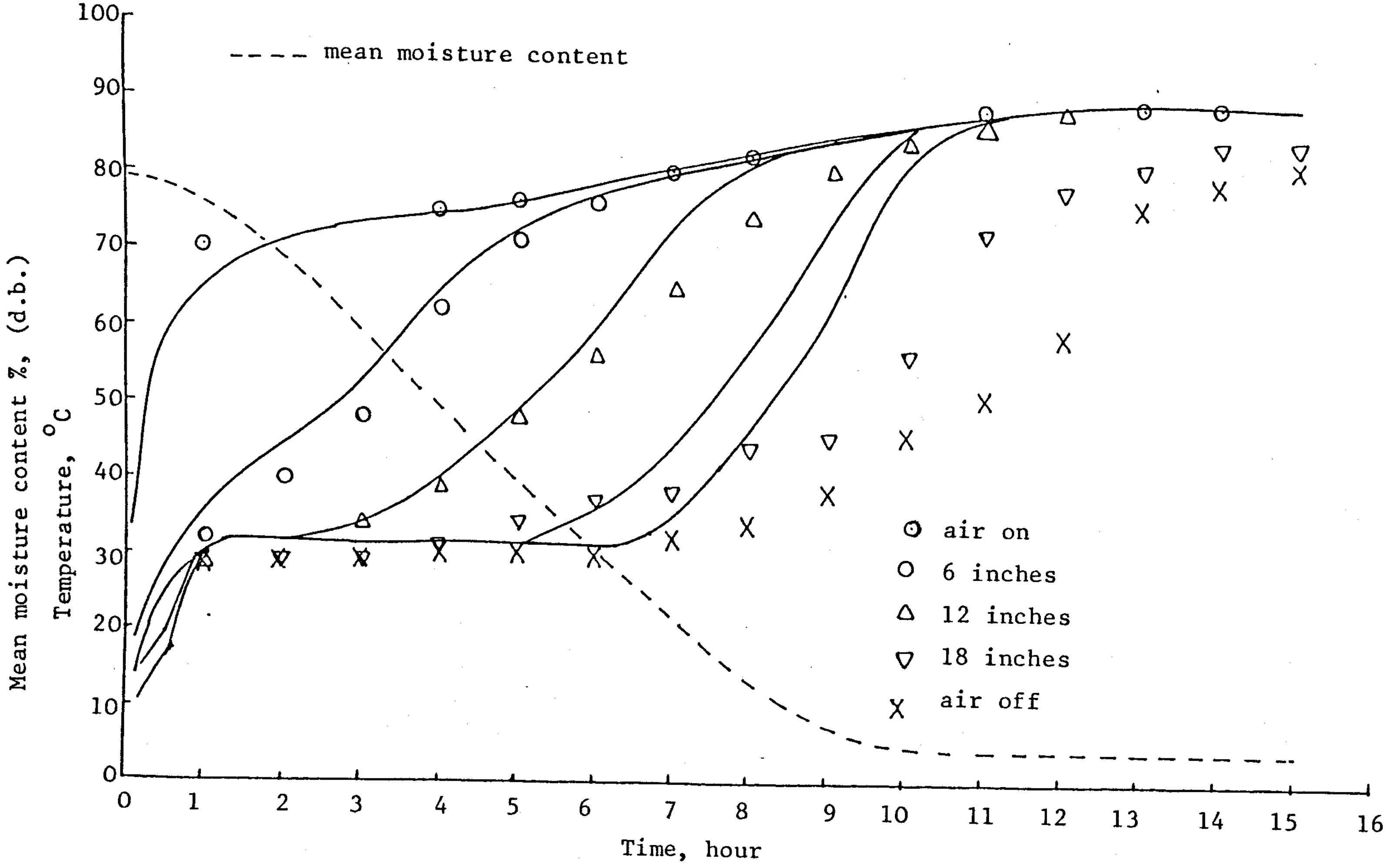


Fig. 5.9 Predicted and observed temperature profiles

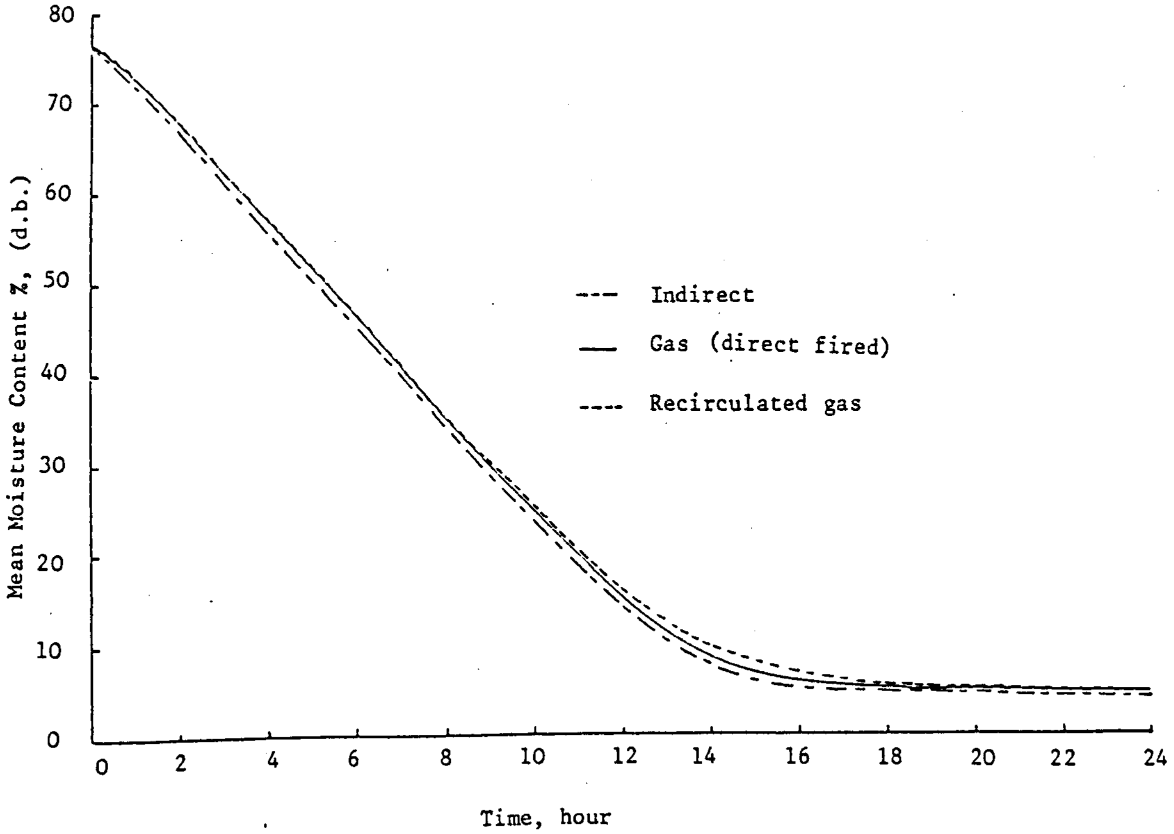


Fig. 5.10 Mean moisture content changes with time for gas fired, indirect fired and recirculated gas fired conditions for a typical commercial kilning cycle

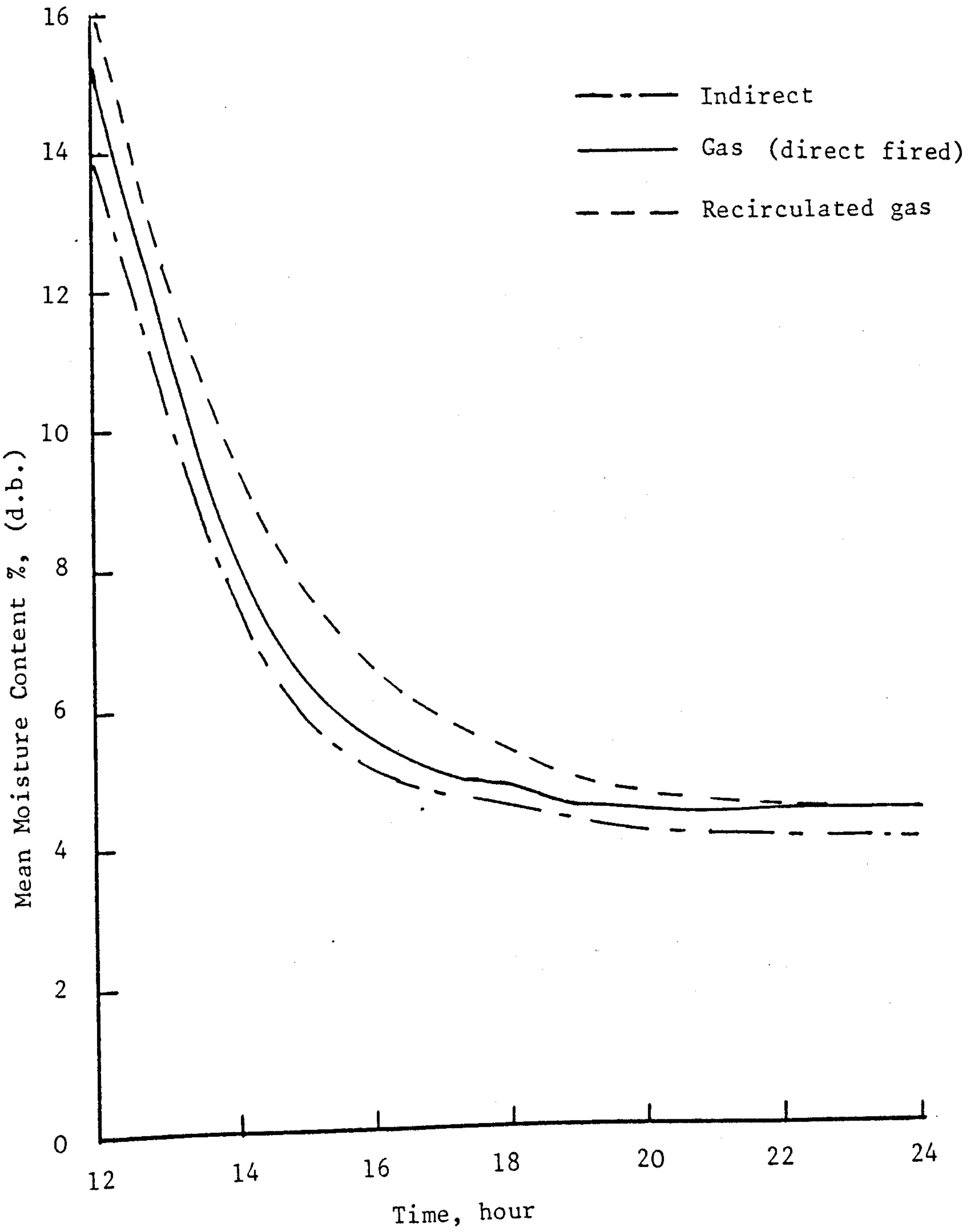


Fig. 5.11 Mean moisture content changes with time during the later stage of kilning cycle for gas fired, indirect fired and recirculated gas fired conditions

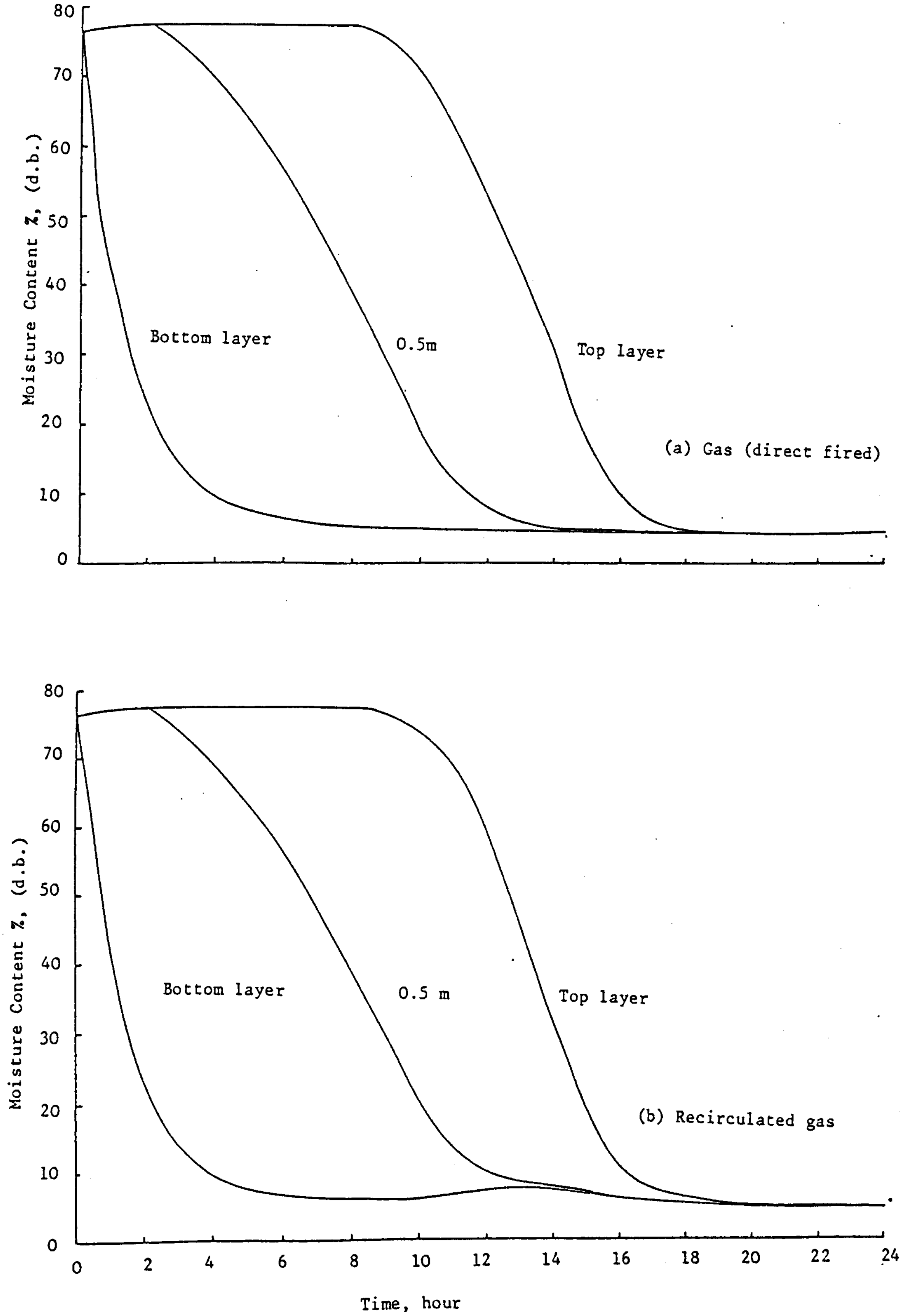


Fig. 5.12 Moisture content changes with time at the bottom layer, 0.5 m and the top layer for a typical commercial kilning cycle for (a) gas fired conditions and (b) recirculated gas fired conditions

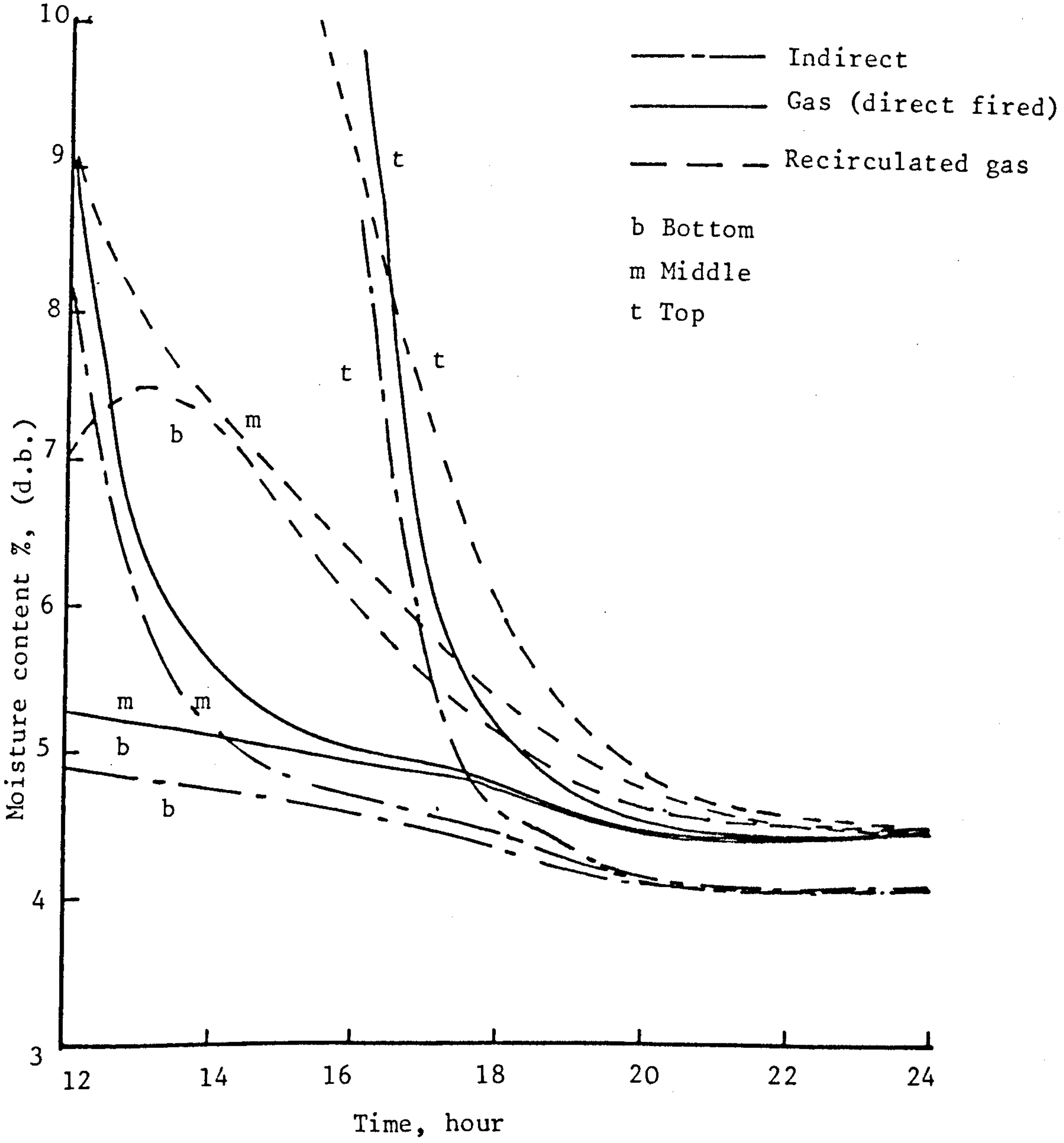


Fig. 5.13 Moisture content changes with time during the later stage of kilning cycle for gas fired, indirect fired and recirculated gas fired conditions

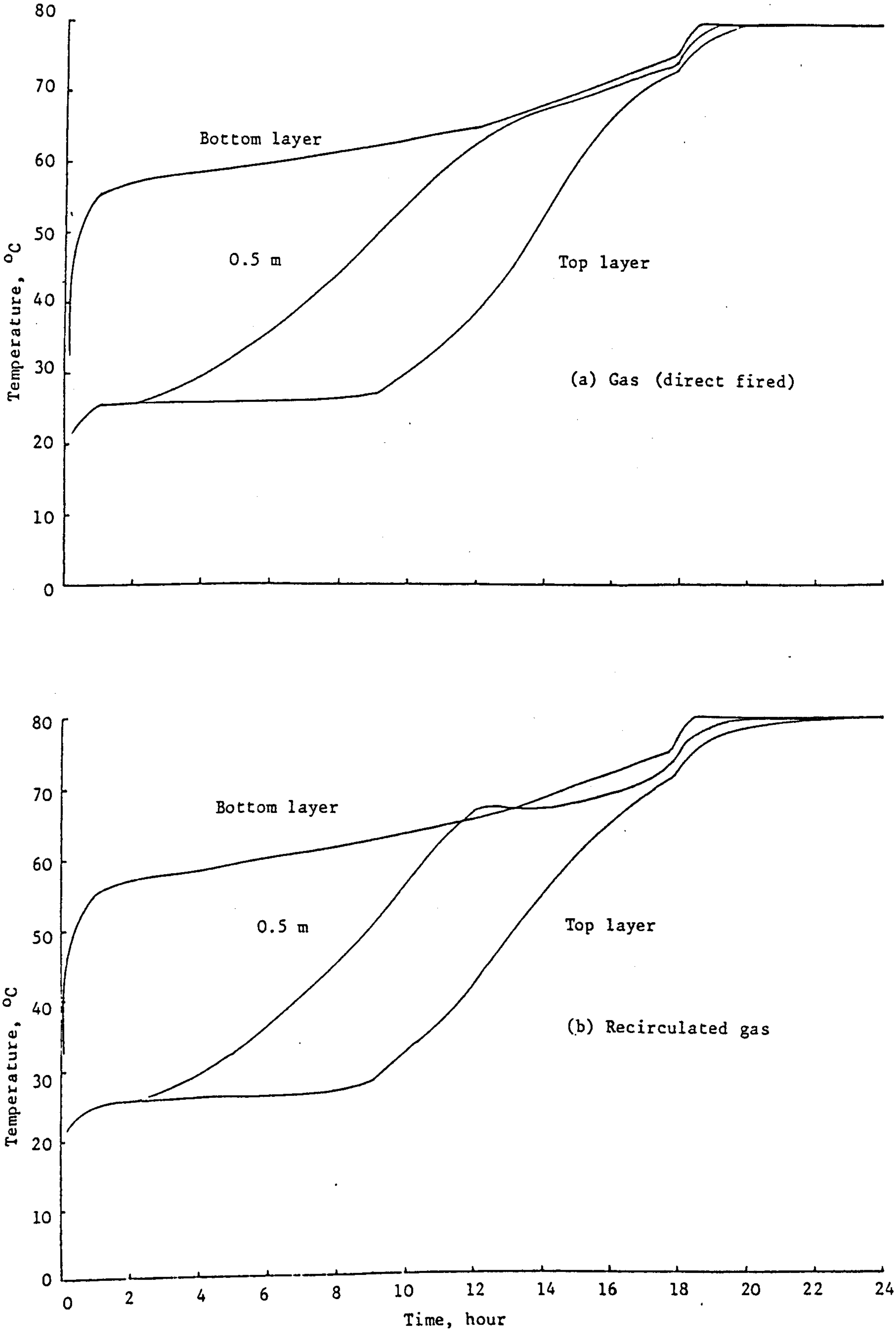


Fig. 5.14 Temperature changes with time at the bottom layer, 0.5 m and the top layer for a typical commercial kilning cycle for (a) gas fired conditions and (b) recirculated gas fired conditions

Appendix 2.1

Simplified Derivation of Schumann's Equation

The equations were derived for isomoisture heating of grains. The following assumptions were made in deriving the equations for heating a packed bed of grains

(a) The air flow is one dimensional.

(b) There is no heat loss perpendicular to the direction of air flow.

(c) Direct transfer of heat between particles is negligible.

(d) No shrinkage of bed occurs.

(e) Thermal properties are constant

(f) Contribution of $\frac{\partial T_a}{\partial t}$ is negligible

Consider an elemental layer of grain of thickness dx and unit cross-section.

The datum used for zero heat is at 0°C. Then in unit time the heat flowing into the element (x, x + dx) is

$$G\ C_{pa}\ T_a\ (x)$$

and that flowing out is

$$G\ C_{pa}\ (T_a\ (x+dx)\ )$$

The difference represents heat transferred convectively to the grain, $h_{cv}\ (T_a - T_g)\ dx$ and that accumulated in the air volume $\varepsilon \rho_a \frac{\partial T_a}{\partial t}\ dx$.

The conservation of heat flow demands that

$$G\,C_{pa}\,(T_a(x+dx) - T_a(x)\,) = -h_{cv}(T_a - T_g)\,dx - \varepsilon\rho_a \frac{\partial T_a}{\partial t}\,dx$$

Applying Taylor series expansion and ignoring $\frac{\partial T_a}{\partial t}$ gives

$$\frac{\partial T_a}{\partial x} = -\frac{h_{ev}}{G\,C_{pa}}\,(T_a - T_g)$$

Consider heat exchange for unit depth over a time increment (t+dt). At the beginning of the step the grain heat is

$$\rho_d\,C_{pg}\,T_g\,(t)$$

and at t+dt

$$\rho_d\,C_{pg}\,T_g\,(t+dt)$$

This change of heat is the result of the convective heat transfer from the air. Therefore from the principle of the conservation of heat and applying Taylor series expension over the interval dt gives

$$\frac{\partial T_g}{\partial t} = \frac{h_{ev}}{\rho_d C_{pg}}\,(T_a - T_g)$$

If the equations are normalized into the standard forms of Schumann, one gets

$$\frac{\partial T_a}{\partial Y} = T_g - T_a$$

$$\frac{\partial T_g}{\partial Z} = T_a - T_g$$

where

$$Y = \frac{h_{cv} x}{G\ C_{pa}}$$

$$Z = \frac{h_{cv} t}{\rho_d\ C_{pg}}$$

Appendix 3.1

Determination of Moisture Content

All the moisture contents were determined by the method recommended by the Institute of Brewing.

When the sample was known to contain less than 17% moisture (w.b.), a sample of 20g was ground. Before grinding the mill was set to grind finely and rinsed by grinding a small quantity of malt. About 5 g of the ground sample was transferred to each of the three tared dishes and shaken until level and closed immediately. The lid was removed and the samples were dried in an electric oven for 3 hours at 103 - 104°C. Then the lid was replaced and cooled in a dessicator for at least 20 minutes before weighing.

When the sample was known to contain over 17% moisture (w.b.), the grinding and analysis were made after pre-drying the whole grain overnight at room temperature and four 4 hours at about 45°C in an electric oven.

When pre-drying was used, the moisture content was calculated from the following equation

$$M_w = M_{w1} + M_{w2} - \frac{M_{w1} \times M_{w2}}{100}$$

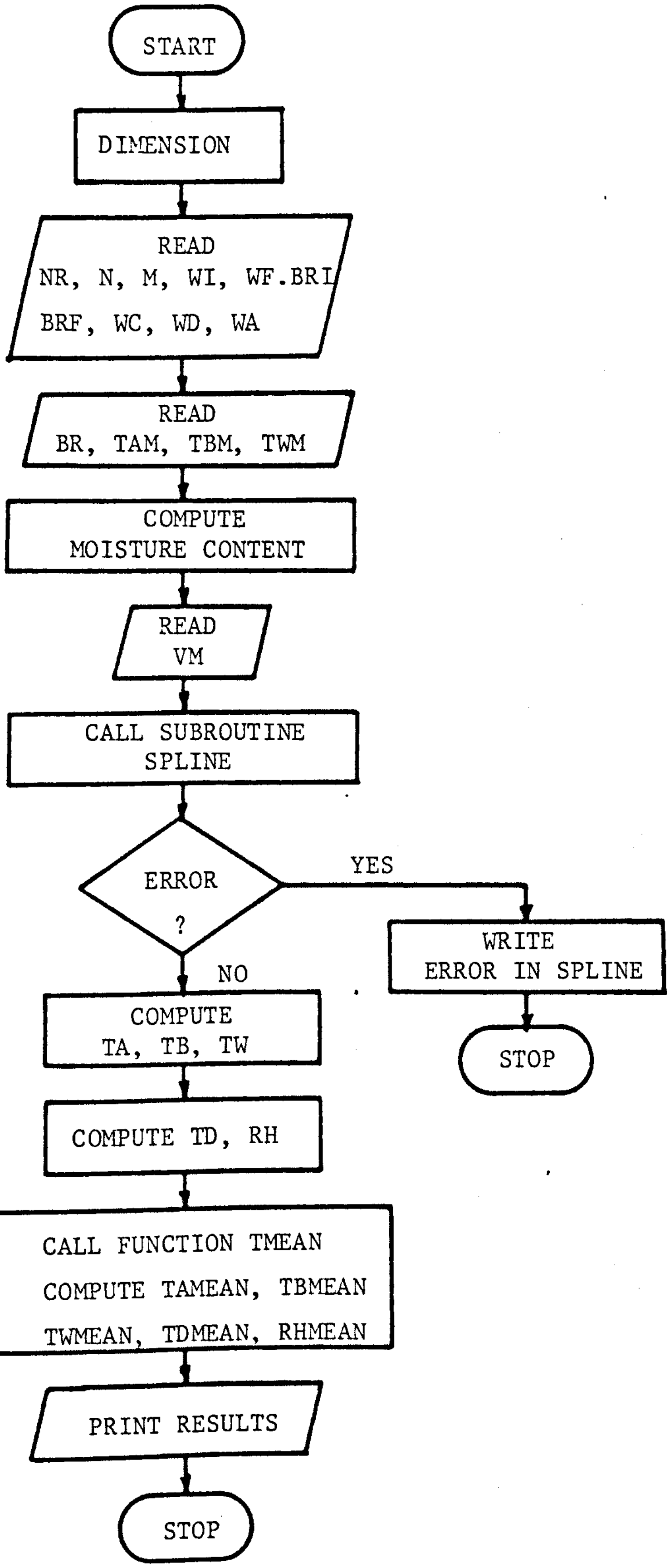
where

M_w = moisture content %, (w.b.)
M_{w1} = percentage moisture lost by pre-drying %, (w.b.)
M_{w2} = percentage moisture found in pre-dried sample %, (w.b.)

The accuracy of the balance used in the moisture content determination was 0.0001 g.

Appendix 3.2

Flow chart to convert the mV readings to temperature, relative humidity and moisture content



```
C      PROGRAM TO CONVERT THERMOCOUPLE READINGS INTO TEMPERATURES AND
C      BALANCE READING INTO MOISTURE CONTENT
C      TA=AIR TEMP
C      TB= DRY BULB TEMP
C      TW = WET BULB TEMP
C      TD = DEW POINT TEMP
C      RH=RELATIVE HUMIDITY
C      BRI=INITIAL BALANCE READING
C      BRF=FINAL BALANCE READING
C      BR(I) = BALANCE READING
C      WI=INITIAL WEIGHT OF SAMPLE
C      WF=FINAL WEIGHT OF SAMPLE
C      WD=WEIGHT OF DRY MATTER OF SAMPLE
C      WC=MOISTURE CONTENT (PERCENT)
C      WA=INITIAL MOISTURE CONTENT (DECIMAL)
C      T = TIME IN MIN
       DIMENSION BR(700),TA(300),TB(300),TW(300),TD(300),WC(700),
      1S2(150),S1(1),RH(300),PSDB(300),PSDP(300),TAM(300),TBM(300),
      2TWM(300),TEMP(300),VM(300)
       READ (5,120) NR,N,N1
  120  FORMAT(3I5)
       READ(5,103) WI,WF,BRI,BRF,WD,WC(1),WA
  103  FORMAT(7F8.4)
       READ(5,121)(BR(I),I=1,N1)
  121  FORMAT(10F6.4)
       READ(5,128)(TAM(I),TBM(I),TWM(I),I=1,N)
  128  FORMAT(3F6.4)
       SLOP=(((WI-WF)/(BRI-BRF))/WD)
       READ(1,122) (VM(I),I=1,150)
  122  FORMAT(10F5.3)
       DO 1 I=1,150
    1  TEMP(I)=I-1
       DO 2 I=2,N1
    2  WC(I)=(WA-SLOP*(BRI-BR(I)))*100.
       DO 3 I=1,N
       CALL SPLINE(VM,TEMP,S2,150,TAM(I),TA(I),S1,1,&999)
       CALL SPLINE(VM,TEMP,S2,150,TBM(I),TB(I),S1,1,&999)
       CALL SPLINE(VM,TEMP,S2,150,TWM(I),TW(I),S1,1,&999)
       TD(I)=(TB(I)+TW(I))/2.
    3  CONTINUE
       A=-0.274055E5
       B=0.541896E2
       C=-0.451370E-1
       D=0.215321E-4
       E=-0.462027E-8
       F=0.241613E1
       G=0.121547E-2
       R=0.320618E4
       DO 6 I=1,N
       TT=TA(I)*1.8+491.59
       TP=A+TT*(B+TT*(C+TT*(D+TT*E)))
       TQ=(TT*(F-G*TT))
       TP=TP/TQ
       PSDB(I)=EXP(TP)*R*6894.76
       TT=TD(I)*1.8+491.69
       TP=A+TT*(B+TT*(C+TT*(D+TT*E)))
       TQ=(TT*(F-G*TT))
       TP=TP/TQ
       PSDP(I)=EXP(TP)*R*6894.76
    6  RH(I)=(PSDP(I)/PSDB(I))*100.

       TAMEAN=TMEAN(TA,N)
       TBMEAN=TMEAN(TB,N)
       TWMEAN=TMEAN(TW,N)
       TDMEAN=TMEAN(TD,N)
       RHMEAN=TMEAN(RH,N)
       WRITE (6,123)NR
  123  FORMAT (////,60X,'RUN-',I3/60X,7(1H-))
       WRITE (6,124) WC(1),WC(N1),TAMEAN,RHMEAN,TDMEAN
  124  FORMAT (20X,'MI=',F6.2,6X,'MF=',F6.2,6X,'TA=',F6.2,6X,'RH=',
      9F5.2,5X,'TD=',
      4F6.2,/15X,90(1H-)/15X,'TIME',5X,'BALANCE',5X,'AIR',5X,'DRY-BULB',
      53X,'WET BULB',5X,'DEW POINT',5X,'RELATIVE',5X,'MOISTURE'/
      615X,'MIN',5X,'READING',5X,'TEMP',7X,'TEMP',8X,'TEMP',10X,
      7'TEMP',7X,
      7'HUMIDITY',5X,'CONTENT'/15X,90(1H-))
```

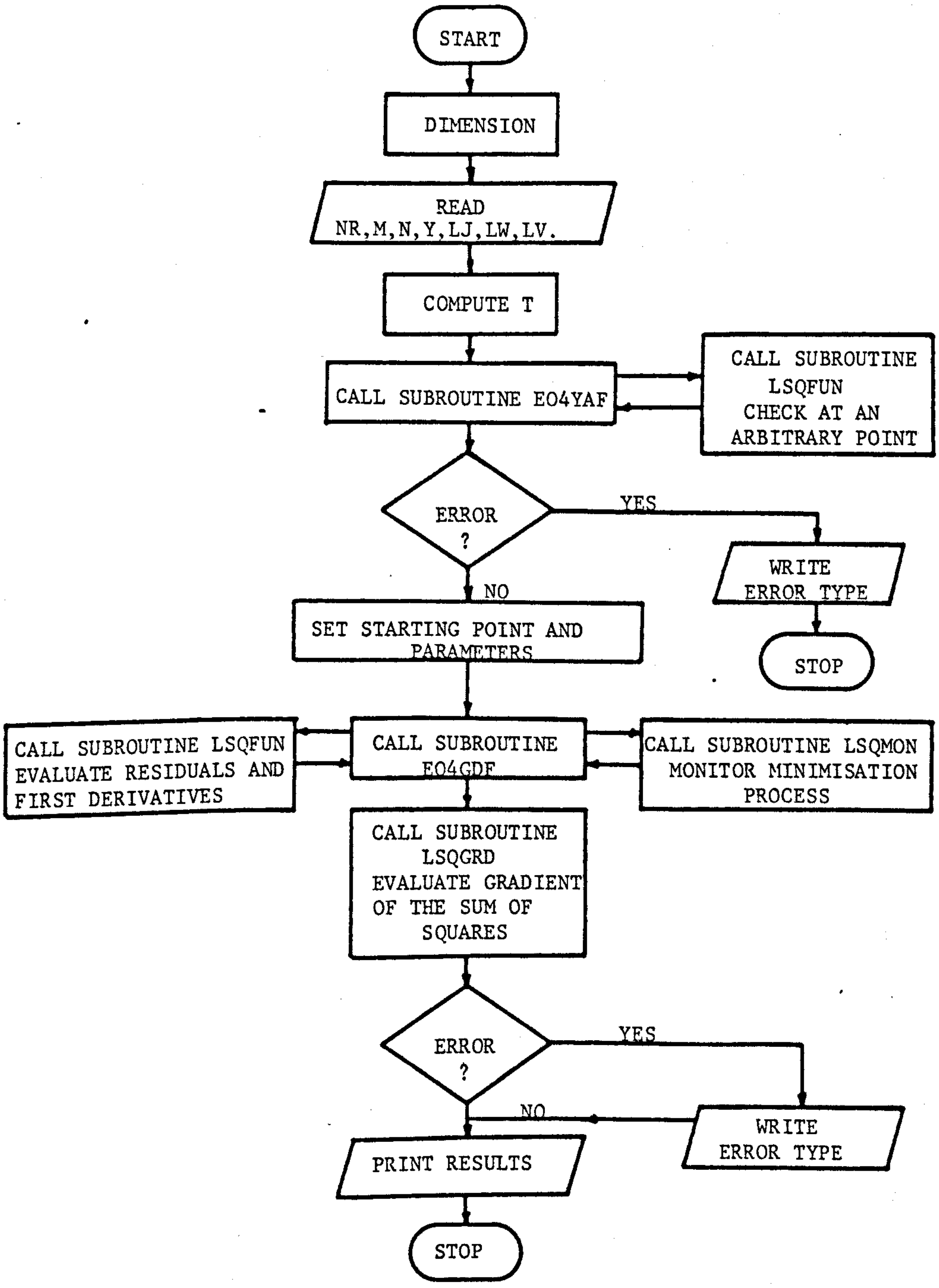
```
      DO 127 I=2,N1,2
      J=I-2
      BK=1.5+(I-2.0)*5.0
      K=(J/2)+1
      WRITE (6,125) BK,BR(I),TA(K),TB(K),TW(K),TD(K),RH(K),WC(I)
  127 CONTINUE
  125 FORMAT (11X,F7.2,6X,F6.3,7X,F6.2,5X,F6.2,6X,F6.2,6X,F6.2,7X,F6.2,
     97X,F6.2)
      WRITE (8,140) (WC(I),I=1,N1)
  140 FORMAT (12F6.3)
      GO TO 500
  999 WRITE(6,126)
  126 FORMAT('ERROR IN SPLINE')
  500 STOP
      END
      FUNCTION TMEAN(SUM,NO)
      DIMENSION SUM(NO)
      TSUM=0.0
      DO 7 I=1,NO
      TSUM=TSUM+SUM(I)
    7 CONTINUE
      TMEAN=TSUM/NO
      RETURN
      END
      SUBROUTINE SPLINE (X,Y,S2,N,T,S,S1,M,*)
      DIMENSION DX(199),DY(199),OFDIAG(199),RHS(198),
     1X(N),Y(N),S2(N),S(M),S1(M),T(M)
      IF(N.LT.3.OR.N.GT.200)RETURN 1
      NM1=N-1
      DO 4 I=1,NM1
      IF(X(I).GE.X(I+1))RETURN 1
    4 CONTINUE
      IF(M.EQ.0)GOTO 8
      IF(T(1).LT.X(1).OR.T(M).GT.X(N))RETURN 1
      IF(M.EQ.1)GOTO 8
      J=M-1
      DO 6 I=1,J
      IF(T(I).GT.T(I+1))RETURN 1
    6 CONTINUE
    8 NM2=NM1-1
      DO 10 I=1,NM1
      IP1=I+1
      DX(I)=X(IP1)-X(I)
   10 DY(I)=(Y(IP1)-Y(I))/DX(I)
      S2(1)=0.0

      S2(N)=0.0
      DO 15 I=2,NM1
   15 S2(I)=6.0*(DY(I)-DY(I-1))
      Z=0.5/(DX(1)+DX(2))
      OFDIAG(1)=-DX(2)*Z
      RHS(1)=S2(2)*Z
      IF(N-3)17,22,17
   17 K=1
      DO 20 I=2,NM2
      IP1=I+1
      Z=1.0/(2.0*(DX(I)+DX(IP1))+DX(I)*OFDIAG(K))
      OFDIAG(I)=-DX(IP1)*Z
      RHS(I)=(S2(IP1)-DX(I)*RHS(K))*Z
   20 K=I
   22 S2(NM1)=RHS(NM2)
      IF(N-3)23,100,23
   23 I=NM2
   25 K=I-1
      S2(I)=OFDIAG(K)*S2(I+1)+RHS(K)
      I=I-1
      IF(I.GE.2)GOTO 25
  100 IF(M.LE.0)RETURN
      DO 105 I=1,NM1
  105 OFDIAG(I)=(S2(I+1)-S2(I))/DX(I)
      I=2
      K=1
      DO 150 J=1,M
  110 IF(T(J).LE.X(I))GOTO 120
      K=I
      I=I+1
      GOTO 110
  120 H1=T(J)-X(K)
      H2=T(J)-X(I)
      H3=H1*H2
      H4=S2(K)+H1*OFDIAG(K)
      Z=(S2(I)+S2(K)+H4)/6.0
      S(J)=Y(K)+H1*DY(K)+H3*Z
      S1(J)=DY(K)+Z*(H1+H2)+H3*OFDIAG(K)/6.0
  150 CONTINUE
      RETURN
      END
```

```
                                                   RUN- 18
                                                   -------
      MI= 72.11        MF= 25.95        TA= 32.42          RH=79.24        TD= 28.35
--------------------------------------------------------------------------------------------------
  TIME      BALANCE      AIR     DRY-BULB     WET BULB      DEW POINT     RELATIVE     MOISTURE
   MIN      READING      TEMP      TEMP         TEMP          TEMP        HUMIDITY     CONTENT
--------------------------------------------------------------------------------------------------
   1.50      8.215      32.14     28.27        28.27         28.27         80.09        72.00
  11.50      8.180      32.39     28.27        28.27         28.27         79.00        71.19
  21.50      8.115      32.39     28.27        28.27         28.27         79.00        69.70
  31.50      8.060      32.39     28.39        28.27         28.33         79.28        68.44
  41.50      8.035      32.39     28.39        28.27         28.33         79.28        67.87
  51.50      7.980      32.39     28.39        28.27         28.33         79.28        66.61
  61.50      7.950      32.51     28.51        28.39         28.45         79.30        65.92
  71.50      7.925      32.51     28.39        28.39         28.39         79.02        65.35
  81.50      7.850      32.39     28.39        28.39         28.39         79.56        63.63
  91.50      7.830      32.39     28.39        28.39         28.39         79.56        63.17
 101.50      7.775      32.39     28.51        28.39         28.45         79.84        61.91
 111.50      7.755      32.51     28.51        28.39         28.45         79.30        61.45
 121.50      7.710      32.39     28.51        28.39         28.45         79.84        60.43
 131.50      7.695      32.51     28.39        28.39         28.39         79.02        60.08
 141.50      7.655      32.51     28.39        28.39         28.39         79.02        59.17
 151.50      7.605      32.51     28.51        28.39         28.45         79.30        58.02
 161.50      7.595      32.51     28.51        28.39         28.45         79.30        57.79
 171.50      7.540      32.51     28.39        28.39         28.39         79.02        56.53
 181.50      7.540      32.51     28.51        28.39         28.45         79.30        56.53
 191.50      7.500      32.51     28.39        28.39         28.39         79.02        55.61
 201.50      7.445      32.51     28.39        28.39         28.39         79.02        54.35
 211.50      7.420      32.51     28.39        28.39         28.39         79.02        53.78
 221.50      7.415      32.51     28.39        28.39         28.39         79.02        53.67
 231.50      7.405      32.51     28.51        28.39         28.45         79.30        53.44
 241.50      7.360      32.51     28.39        28.39         28.39         79.02        52.41
 251.50      7.325      32.51     28.39        28.39         28.39         79.02        51.61
 261.50      7.290      32.39     28.39        28.27         28.33         79.28        50.80
 271.50      7.270      32.39     28.39        28.27         28.33         79.28        50.35
 281.50      7.260      32.39     28.39        28.39         28.39         79.56        50.11
 291.50      7.230      32.51     28.51        28.39         28.45         79.30        49.43
 301.50      7.215      32.39     28.51        28.39         28.45         79.84        49.09
 311.50      7.210      32.39     28.39        28.39         28.39         79.56        48.97
 321.50      7.160      32.39     28.51        28.39         28.45         79.84        47.83
 331.50      7.145      32.39     28.51        28.39         28.45         79.84        47.48
 341.50      7.125      32.39     28.39        28.39         28.39         79.56        47.02
 351.50      7.100      32.39     28.51        28.39         28.45         79.84        46.45
 361.50      7.095      32.39     28.51        28.39         28.45         79.84        46.34
 371.50      7.075      32.39     28.51        28.39         28.45         79.84        45.88
 381.50      7.055      32.39     28.51        28.39         28.45         79.84        45.42
 391.50      7.035      32.51     28.51        28.39         28.45         79.30        44.96
 401.50      6.985      32.39     28.51        28.39         28.45         79.84        43.81
 411.50      6.980      32.51     28.51        28.39         28.45         79.30        43.70
 421.50      6.935      32.51     28.51        28.39         28.45         79.30        42.67
 431.50      6.930      32.51     28.51        28.39         28.45         79.30        42.56
 441.50      6.910      32.51     28.51        28.51         28.51         79.58        42.10
 451.50      6.910      32.51     28.51        28.39         28.45         79.30        42.10
 461.50      6.880      32.39     28.51        28.39         28.45         79.84        41.41
 471.50      6.860      32.51     28.51        28.51         28.51         79.58        40.95
 481.50      6.860      32.51     28.51        28.39         28.45         79.30        40.95
```

```
 491.50   6.845   32.51   28.51   28.39   28.45   79.30   40.61
 501.50   6.820   32.51   28.39   28.27   28.33   78.74   40.03
 511.50   6.800   32.39   28.39   28.39   28.39   79.56   39.58
 521.50   6.795   32.39   28.39   28.27   28.33   79.28   39.46
 531.50   6.780   32.39   28.39   28.27   28.33   79.28   39.12
 541.50   6.780   32.39   28.39   28.27   28.33   79.28   39.12
 551.50   6.760   32.39   28.39   28.27   28.33   79.28   38.66
 561.50   6.715   32.39   28.39   28.27   28.33   79.28   37.63
 571.50   6.710   32.39   28.39   28.27   28.33   79.28   37.52
 581.50   6.675   32.39   28.39   28.27   28.33   79.28   36.71
 591.50   6.665   32.39   28.39   28.27   28.33   79.28   36.48
 601.50   6.665   32.39   28.39   28.27   28.33   79.28   36.48
 611.50   6.640   32.39   28.27   28.15   28.21   78.72   35.91
 621.50   6.645   32.39   28.27   28.27   28.27   79.00   36.03
 631.50   6.640   32.39   28.39   28.27   28.33   79.28   35.91
 641.50   6.625   32.39   28.39   28.27   28.33   79.28   35.57
 651.50   6.615   32.39   28.39   28.27   28.33   79.28   35.34
 661.50   6.595   32.39   28.39   28.27   28.33   79.28   34.83
 671.50   6.585   32.39   28.39   28.27   28.33   79.28   34.65
 681.50   6.575   32.39   28.39   28.27   28.33   79.28   34.42
 691.50   6.570   32.39   28.39   28.27   28.33   79.28   34.31
 701.50   6.535   32.39   28.39   28.27   28.33   79.28   33.51
 711.50   6.545   32.51   28.39   28.27   28.33   78.74   33.74
 721.50   6.530   32.39   28.39   28.27   28.33   79.28   33.39
 731.50   6.530   32.39   28.39   28.27   28.33   79.28   33.39
 741.50   6.500   32.39   28.39   28.27   28.33   79.28   32.70
 751.50   6.480   32.39   28.39   28.39   28.39   79.56   32.25
 761.50   6.490   32.39   28.39   28.27   28.33   79.28   32.48
 771.50   6.470   32.51   28.39   28.39   28.39   79.02   32.02
 781.50   6.460   32.39   28.39   28.39   28.39   79.56   31.79
 791.50   6.440   32.39   28.39   28.39   28.39   79.56   31.33
 801.50   6.440   32.39   28.39   28.39   28.39   79.56   31.33
 811.50   6.450   32.39   28.39   28.39   28.39   79.56   31.56
 821.50   6.420   32.39   28.39   28.39   28.39   79.56   30.87
 831.50   6.405   32.39   28.51   28.39   28.45   79.84   30.53
 841.50   6.405   32.39   28.39   28.39   28.39   79.56   30.53
 851.50   6.410   32.39   28.39   28.27   28.33   79.28   30.64
 861.50   6.390   32.39   28.27   28.27   28.27   79.00   30.18
 871.50   6.370   32.39   28.27   28.27   28.27   79.00   29.72
 881.50   6.370   32.39   28.27   28.15   28.21   78.72   29.72
 891.50   6.350   32.39   28.27   28.15   28.21   78.72   29.27
 901.50   6.355   32.39   28.27   28.15   28.21   78.72   29.38
 911.50   6.355   32.39   28.27   28.15   28.21   78.72   29.38
 921.50   6.335   32.39   28.27   28.15   28.21   78.72   28.92
 931.50   6.315   32.39   28.27   28.15   28.21   78.72   28.46
 941.50   6.330   32.39   28.27   28.15   28.21   78.72   28.81
 951.50   6.315   32.39   28.27   28.15   28.21   78.72   28.46
 961.50   6.285   32.39   28.27   28.15   28.21   78.72   27.78
 971.50   6.300   32.39   28.27   28.15   28.21   78.72   28.12
 981.50   6.275   32.39   28.27   28.15   28.21   78.72   27.55
 991.50   6.280   32.39   28.27   28.15   28.21   78.72   27.66
1001.50   6.270   32.39   28.27   28.15   28.21   78.72   27.43
1011.50   6.250   32.39   28.27   28.15   28.21   78.72   26.97
1021.50   6.255   32.39   28.27   28.27   28.27   79.00   27.09
1031.50   6.240   32.39   28.27   28.15   28.21   78.72   26.75
1041.50   6.245   32.39   28.27   28.27   28.27   79.00   26.86
1051.50   6.230   32.39   28.27   28.27   28.27   79.00   26.52
1061.50   6.250   32.39   28.27   28.27   28.27   79.00   26.97
1071.50   6.225   32.39   28.27   28.27   28.27   79.00   26.40
1081.50   6.205   32.51   28.39   28.27   28.33   78.74   25.95
```

Appendix 3.3

Flow chart of the curve fitting program



```
C      PROGRAM TO FIT SINGLE TERM EXPONENTIAL CURVE TO THE THIN LAYER
C      DRYING DATA
C      Y=MOISTURE CONTENT
C      X(I)=VARIABLES OF LEAST SQURE ESTIMATE
C      T=TIME IN MIN
       IMPLICIT REAL*8(A-H,O-Z)
       DIMENSION T(218),Y(218),FJAC(218,3),FVEC(218),G(3),
      1S(3),V(3,3),W(4000),X(3),IW(1),YE(218)
       EXTERNAL LSQFUN,LSQMON
       COMMON Y,T
       NR=19
       WRITE(6,122) NR
  122  FORMAT(////,27X,'RUN -',I3)
       WRITE (6,123)
  123  FORMAT (/,20X,'SINGLE EXPONENTIAL FIT'/20X,22(1H-)//)
       N=3
       M=218
       LJ=218
       LW=4000
       LV=3
       LIW=1
       READ (5,124) (YE(I), I=1,M)
  124  FORMAT (12F6.3)
       DO 20 I=1,M
       Y(I)=YE(I)*0.01
   20  CONTINUE
       T(1)=0.0D0
       DO 12 J=2,M
       T(J)=1.50D0+(J-2.0D0)*5.0D0
   12  CONTINUE
       X(1)=0.5D0
       X(2)=0.008D0
       X(3)=0.09D0
       IFAIL=0
       CALL E04YAF(M,N,LSQFUN,X,FVEC,FJAC,LJ,IW,
      2LIW,W,LW,IFAIL)
       IPRINT=1
       MAXCAL=80*N
       ETA=0.9D0
       XTOL=10.0*DSQRT(X02AAF(XTOL))
       STEPMX=2.0D0
       X(1)=0.70D0
       X(2)=0.0080D0
       X(3)=0.20D0
       IFAIL=1
       CALL E04GDF(M,N,LSQFUN,LSQMON,IPRINT,MAXCAL,
      3ETA,XTOL,STEPMX,X,FSUMSQ,FVEC,FJAC,LJ,S,
      4V,LV,NITER,NF,IW,LIW,W,LW,IFAIL)
       IF (IFAIL.NE.0) WRITE (6,125) IFAIL
       IF (IFAIL.EQ.1) GO TO 60
       WRITE (6,126) FSUMSQ
       WRITE (6,127) (X(J),J=1,N)
       CALL LSQGRD(M,N,FVEC,FJAC,LJ,G)
       WRITE (6,128) (G(J),J=1,N)
       WRITE (6,129)
       DO 40 I=1,M
       WRITE (6,130) FVEC(I)
   40  CONTINUE
   60  WRITE (6,131)
       STOP

  125  FORMAT (///15H ERROR EXIT TYPE, I3, 22H - SEE ROUTINE DOCUMEN
      5, 1HT)
  126  FORMAT (///31H ON EXIT,THE SUM OF SQUARES IS ,F12.6)
  127  FORMAT (13H AT THE POINT, 3F12.6)
  128  FORMAT (30H THE CORRESPONDING GRADIENT IS,1P3E12.3)
  129  FORMAT (22H AND THE RESIDUALS ARE)
  130  FORMAT (1H ,1PE9.1)
  131  FORMAT (6A4, 1A3)
       END
```

```
      SUBROUTINE LSQFUN(IFLAG,M,N,XC,FVECC,FJACC,LJC,
     1IW,LIW,W,LW)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION FJACC(LJC,N),FVECC(M),W(LW),XC(N),
     2IW(LIW),T(218),Y(218)
      COMMON Y,T
      DO 20 I=1,M
      IF (IFLAG.EQ.2) FVECC(I)=XC(1)*DEXP(-XC(2)*T(I))
     3+XC(3)-Y(I)
      FJACC(I,1)=DEXP(-XC(2)*T(I))
      FJACC(I,2)=-(XC(1)*T(I)*DEXP(-XC(2)*T(I)))
      FJACC(I,3)=1.0D0
   20 CONTINUE
      RETURN
      END
      SUBROUTINE LSQMON(M,N,XC,FVECC,FJACC,LJC,S,IGRADE,
     4NITER,NF,IW,LIW,W,LW)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION FJACC(LJC,N),FVECC(M),S(N),W(LW),XC(N),
     5IW(LIW),G(50)
      FSUMSQ=F01DEF(FVECC,FVECC,M)
      CALL LSQGRD(M,N,FVECC,FJACC,LJC,G)
      GTG=F01DEF(G,G,N)
      WRITE (6,132) NITER,NF,FSUMSQ,GTG,IGRADE
      WRITE (6,133)
      DO 20 J=1,N
      WRITE (6,134) XC(J),G(J),S(J)
   20 CONTINUE
      RETURN
  132 FORMAT (///6H ITNS ,4X, 7HF EVALS, 10X, 5HSUMSQ, 13X, 3HGTG,
     6 8X, 5HGRADE/1H , I4, 6X,I5,6X, 1PE13.5, 6X,1PE9.1, 6X, I3)
  133 FORMAT (/8X, 1HX, 20X, 1HG, 11X, 15HSINGULAR VALUES)
  134 FORMAT (1H ,1PE13.5, 10X, 1PE9.1, 10X, 1PE9.1)
      END
      SUBROUTINE LSQGRD(M,N,FVECC,FJACC,LJC,G)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION FJACC(LJC,N),FVECC(M),G(N)
      DO 40 J=1,N
      SUM=0.0E+0
      DO 20 I=1,M
      SUM=SUM+FJACC(I,J)*FVECC(I)
   20 CONTINUE
      G(J)=SUM+SUM
   40 CONTINUE
      RETURN
      END
```

```
                              RUN - 18

                      SINGLE EXPONENTIAL FIT
                      ----------------------


  ITNS        F EVALS          SUMSQ                    GTG             GRADE
   0               1        5.33206E+00              5.0E+05              3

          X                      G                SINGULAR VALUES
    7.00000E-01             -2.9E+00                   2.2E+02
    8.00000E-03              7.0E+02                   1.1E+01
    2.00000E-01             -5.9E+01                   2.7E+00


  ITNS        F EVALS          SUMSQ                    GTG             GRADE
   1               2        7.58849E-01              1.1E+06              3

          X                      G                SINGULAR VALUES
    3.37051E-01              2.6E+00                   7.8E+02
    1.95504E-03             -1.1E+03                   6.1E+00
    3.19052E-01              1.7E+01                   1.8E+00


  ITNS        F EVALS          SUMSQ                    GTG             GRADE
   2               3        6.29430E-03              1.6E+04              3

          X                      G                SINGULAR VALUES
    5.15543E-01              5.4E-01                   1.3E+03
    1.84481E-03             -1.3E+02                   6.3E+00
    1.98820E-01              1.4E+00                   1.6E+00


  ITNS        F EVALS          SUMSQ                    GTG             GRADE
   3               4        2.82500E-03              1.4E+00              3

          X                      G                SINGULAR VALUES
    5.15943E-01              3.4E-03                   1.2E+03
    1.89013E-03             -1.2E+00                   6.2E+00
    1.98336E-01              1.2E-02                   1.7E+00


  ITNS        F EVALS          SUMSQ                    GTG             GRADE
   4               7        2.82475E-03              5.1E-06              1

          X                      G                SINGULAR VALUES
    5.15593E-01              1.1E-06                   1.2E+03
    1.88093E-03             -2.3E-03                   6.2E+00
    1.98356E-01              4.0E-06                   1.7E+00


  ITNS        F EVALS          SUMSQ                    GTG             GRADE
   5              11        2.82475E-03              2.1E-09              0

          X                      G                SINGULAR VALUES
    5.15563E-01              2.0E-07                   1.2E+03
    1.88091E-03             -4.6E-05                   6.2E+00
    1.98358E-01              5.3E-07                   1.7E+00


  ITNS        F EVALS          SUMSQ                    GTG             GRADE
   6              12        2.82475E-03              5.3E-25              0

          X                      G                SINGULAR VALUES
    5.15568E-01              6.8E-16                   1.2E+03
    1.88091E-03             -7.3E-13                   6.2E+00
    1.98359E-01              2.3E-15                   1.7E+00


ON EXIT,THE SUM OF SQUARES IS      0.002825
AT THE POINT      0.515568      0.001881      0.198358
THE CORRESPONDING GRADIENT IS    6.837E-16   -7.293E-13    2.276E-15
```

```
C       PROGRAM TO FIT PAGE EQUATION TO THE THIN LAYER
C       DRYING DATA
C       Y=MOISTURE CONTENT
C       X(I)=VARIABLES OF LEAST SQURE ESTIMATE
C       T=TIME IN MIN
        IMPLICIT REAL*8(A-H,O-Z)
        DIMENSION T(217),Y(217),FJAC(217,4),FVEC(217),G(4),
       1S(4),V(4,4),W(4000),X(4),IW(1),YE(218)
        EXTERNAL LSQFUN,LSQMON
        COMMON Y,T
        NR=18
        WRITE(6,122) NR
  122   FORMAT(////,25X,'RUN -',I3)
        WRITE (6,123)
  123   FORMAT (/,20X,'PAGE EQUATION FIT'/20X,17(1H-)//)
        N=4
        M=217
        LJ=217
        LW=4000
        LV=4
        LIW=1
        READ (5,124) (YE(I), I=1,218)
  124   FORMAT (12F6.3)
        DO 20 I=1,M
        J=I+1
        Y(I)=YE(J)*0.01
        T(I)=1.50D0+(I-1.0D0)*5.0D0
   20   CONTINUE
        X(1)=0.03D0
        X(2)=0.8D0
        X(3)=0.04D0
        X(4)=1.5D0
        IFAIL=0
        CALL E04YAF(M,N,LSQFUN,X,FVEC,FJAC,LJ,IW,
       2LIW,W,LW,IFAIL)
        IPRINT=1
        MAXCAL=50*N
        ETA=0.9D0
        XTOL=10.0*DSQRT(X02AAF(XTOL))
        STEPMX=100000.0D0
        X(1)=0.20D0
        X(2)=0.650D0
        X(3)=0.008020D0
        X(4)=0.990D0
        IFAIL=1
        CALL E04GDF(M,N,LSQFUN,LSQMON,IPRINT,MAXCAL,
       3ETA,XTOL,STEPMX,X,FSUMSQ,FVEC,FJAC,LJ,S,
       4V,LV,NITER,NF,IW,LIW,W,LW,IFAIL)
        IF (IFAIL.NE.0) WRITE (6,125) IFAIL
        IF (IFAIL.EQ.1) GO TO 60
        WRITE (6,126) FSUMSQ
        WRITE (6,127) (X(J),J=1,N)
        CALL LSQGRD(M,N,FVEC,FJAC,LJ,G)
        WRITE (6,128) (G(J),J=1,N)
        WRITE (6,129)
        DO 40 I=1,M
        WRITE (6,130) FVEC(I)
   40   CONTINUE
   60   WRITE (6,131)
        STOP

  125   FORMAT (///16H ERROR EXIT TYPE, I3, 22H - SEE ROUTINE DOCUMEN
       5, 1HT)
  126   FORMAT (///31H ON EXIT.THE SUM OF SQUARES IS ,F12.6)
  127   FORMAT (13H AT THE POINT, 4F12.6)
  128   FORMAT (30H THE CORRESPONDING GRADIENT IS,1P4E12.3)
  129   FORMAT (22H AND THE RESIDUALS ARE)
  130   FORMAT (1H ,1PE9.1)
  131   FORMAT (5A4, 1A3)
        END
```

```
      SUBROUTINE LSQFUN(IFLAG,M,N,XC,FVECC,FJACC,LJC,
     1IW,LIW,W,LW)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION FJACC(LJC,N),FVECC(M),W(LW),XC(N),
     2IW(LIW),T(217),Y(217)
      COMMON Y,T
      DO 20 I=1,M
      IF (IFLAG.EQ.2) FVECC(I)=XC(1)+XC(2)*
     3DEXP(-XC(3)*(T(I)**XC(4)))-Y(I)
      FJACC(I,1)=1.0D0
      FJACC(I,2)=DEXP(-XC(3)*(T(I)**XC(4)))
      FJACC(I,3)=-(XC(2)*(T(I)**XC(4)))*FJACC(I,2)
      FJACC(I,4)=-XC(2)*FJACC(I,2)*XC(3)*(T(I)**XC(4))*
     6DLOG(T(I))
   20 CONTINUE
      RETURN
      END
      SUBROUTINE LSQMON(M,N,XC,FVECC,FJACC,LJC,S,IGRADE,
     4NITER,NF,IW,LIW,W,LW)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION FJACC(LJC,N),FVECC(M),S(N),W(LW),XC(N),
     5IW(LIW),G(50)
      FSUMSQ=F01DEF(FVECC,FVECC,M)
      CALL LSQGRD(M,N,FVECC,FJACC,LJC,G)
      GTG=F01DEF(G,G,N)
      WRITE (6,132) NITER,NF,FSUMSQ,GTG,IGRADE
      WRITE (6,133)
      DO 20 J=1,N
      WRITE (6,134) XC(J),G(J),S(J)
   20 CONTINUE
      RETURN
  132 FORMAT (///6H ITNS ,4X, 7HF EVALS, 10X, 5HSUMSQ, 13X, 3HGTG,
     6 8X, 5HGRADE/1H , I4, 6X,I5,6X, 1PE13.5, 6X,1PE9.1, 6X, I3)
  133 FORMAT (/8X, 1HX, 20X, 1HG, 11X, 15HSINGULAR VALUES)
  134 FORMAT (1H ,1PE13.5, 10X, 1PE9.1, 10X, 1PE9.1)
      END
      SUBROUTINE LSQGRD(M,N,FVECC,FJACC,LJC,G)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION FJACC(LJC,N),FVECC(M),G(N)
      DO 40 J=1,N
      SUM=0.0E+0
      DO 20 I=1,M
      SUM=SUM+FJACC(I,J)*FVECC(I)
   20 CONTINUE
      G(J)=SUM+SUM
   40 CONTINUE
      RETURN
      END
```

RUN - 18

PAGE EQUATION FIT

```
ITNS        F EVALS          SUMSQ               GTG            GRADE
  0               1       5.15104E+00          5.2E+05            4

      X                        G               SINGULAR VALUES
 2.00000E-01              -6.0E+01                 2.1E+02
 5.60000E-01              -4.4E+00                 1.1E+01
 9.00000E-03               7.2E+02                 2.7E+00
 7.90000E-01               3.2E+01                 5.5E-01

ITNS        F EVALS          SUMSQ               GTG            GRADE
  1               3       3.01735E-01          2.1E+04            4

      X                        G               SINGULAR VALUES
 2.43733E-01              -1.1E+01                 1.6E+02
 5.92720E-01              -2.2E+00                 4.0E+00
 1.51424E-02               1.4E+02                 3.5E+00
 7.53573E-01               1.3E+01                 4.2E-01

ITNS        F EVALS          SUMSQ               GTG            GRADE
  2               5       4.59576E-02          1.6E+01            4

      X                        G               SINGULAR VALUES
 2.05934E-01               3.6E-01                 2.4E+02
 5.71591E-01              -3.9E-01                 4.7E+00
 1.10959E-02               4.0E+00                 1.9E+00
 7.41673E-01              -1.9E-01                 2.9E-01

ITNS        F EVALS          SUMSQ               GTG            GRADE
  3               9       3.38501E-02          7.7E+02            4

      X                        G               SINGULAR VALUES
 1.95191E-01               1.7E+00                 3.0E+02
 5.73021E-01               1.6E-01                 5.0E+00
 9.13420E-03              -2.8E+01                 1.7E+00
 7.60531E-01              -2.0E+00                 2.7E-01

ITNS        F EVALS          SUMSQ               GTG            GRADE
  4              13       2.79931E-02          2.2E+03            4

      X                        G               SINGULAR VALUES
 1.87904E-01               2.2E+00                 3.5E+02
 5.73453E-01               4.3E-01                 5.2E+00
 7.93954E-03              -4.7E+01                 1.7E+00
 7.73474E-01              -2.7E+00                 2.6E-01

ITNS        F EVALS          SUMSQ               GTG            GRADE
  5              17       2.37919E-02          3.8E+03            4

      X                        G               SINGULAR VALUES
 1.82533E-01               2.4E+00                 3.9E+02
 5.71433E-01               5.9E-01                 5.3E+00
 7.03143E-03              -6.2E+01                 1.6E+00
 7.95901E-01              -3.0E+00                 2.5E-01

ITNS        F EVALS          SUMSQ               GTG            GRADE
  6              20       2.09799E-02          7.8E+03            4

      X                        G               SINGULAR VALUES
 1.73471E-01               2.9E+00                 4.6E+02
 5.72991E-01               8.4E-01                 5.5E+00
 5.95867E-03              -8.8E+01                 1.5E+00
 8.10193E-01              -3.5E+00                 2.5E-01
```

```
ITNS        F EVALS            SUMSQ                  GTG            GRADE
  7              23         1.76907E-02             1.0E+04            4

       X                         G                SINGULAR VALUES
   1.72523E-01               2.9E+00                   5.1E+02
   5.72193E-01               9.1E-01                   5.7E+00
   5.23340E-03              -1.0E+02                   1.5E+00
   8.23004E-01              -3.5E+00                   2.4E-01

ITNS        F EVALS            SUMSQ                  GTG            GRADE
  8              26         1.43149E-02             1.1E+04            4

       X                         G                SINGULAR VALUES
   1.69353E-01               2.7E+00                   5.7E+02
   5.71230E-01               9.0E-01                   5.8E+00
   4.73047E-03              -1.1E+02                   1.5E+00
   8.40903E-01              -3.3E+00                   2.4E-01

ITNS        F EVALS            SUMSQ                  GTG            GRADE
  9              28         1.19007E-02             1.6E+04            4

       X                         G                SINGULAR VALUES
   1.64550E-01               2.7E+00                   6.8E+02
   5.63477E-01               9.9E-01                   5.9E+00
   3.95135E-03              -1.3E+02                   1.4E+00
   8.64711E-01              -3.3E+00                   2.4E-01

ITNS        F EVALS            SUMSQ                  GTG            GRADE
 10              29         7.41810E-03             1.7E+04            4

       X                         G                SINGULAR VALUES
   1.58815E-01               2.1E+00                   8.6E+02
   5.65447E-01               8.8E-01                   6.2E+00
   3.03029E-03              -1.3E+02                   1.4E+00
   8.93747E-01              -2.5E+00                   2.4E-01

ITNS        F EVALS            SUMSQ                  GTG            GRADE
 11              30         1.76508E-03             5.3E+00            4

       X                         G                SINGULAR VALUES
   1.59601E-01               3.8E-02                   8.3E+02
   5.65953E-01               1.3E-02                   6.1E+00
   3.13597E-03              -2.3E+00                   1.5E+00
   8.93933E-01              -4.8E-02                   2.5E-01

ITNS        F EVALS            SUMSQ                  GTG            GRADE
 12              34         1.76297E-03             1.5E-05            1

       X                         G                SINGULAR VALUES
   1.59534E-01               6.7E-05                   8.3E+02
   5.67012E-01               2.7E-05                   6.1E+00
   3.19570E-03              -3.9E-03                   1.5E+00
   8.99133E-01              -7.8E-05                   2.5E-01

ITNS        F EVALS            SUMSQ                  GTG            GRADE
 13              39         1.76297E-03             4.4E-13            0

       X                         G                SINGULAR VALUES
   1.59533E-01               9.9E-09                   8.3E+02
   5.67013E-01               3.7E-09                   6.1E+00
   3.19573E-03              -6.6E-07                   1.5E+00
   8.99183E-01              -1.2E-08                   2.5E-01

ITNS        F EVALS            SUMSQ                  GTG            GRADE
 14              40         1.76297E-03             2.3E-23            0

       X                         G                SINGULAR VALUES
   1.59533E-01               8.1E-14                   8.3E+02
   5.67013E-01               3.2E-14                   6.1E+00
   3.19579E-03              -4.8E-12                   1.5E+00
   8.99183E-01              -9.7E-14                   2.5E-01

ON EXIT,THE SUM OF SQUARES IS      0.001763
AT THE POINT     0.159532     0.567015     0.003190     0.899183

THE CORRESPONDING GRADIENT IS   8.094E-14    3.180E-14   -4.823E-12   -9.697E-14
```

```
C     PROGRAM TO FIT TWO TERM EXPONENTIAL CURVE TO THE THIN LAYER
C     DRYING DATA
C     Y=MOISTURE CONTENT
C     X(I)=VARIABLES OF LEAST SQURE ESTIMATE
C     T=TIME IN MIN
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION T(218),Y(218),FJAC(218,5),FVEC(218),G(5),
     1S(5),V(5,5),W(4500),X(5),IW(1),YE(218)
      EXTERNAL LSQFUN,LSQMON
      COMMON Y,T
      NR=18
      WRITE(6,122) NR
  122 FORMAT(////,27X,'RUN -',I3)
      WRITE (6,123)
  123 FORMAT (/,20X,'DOUBLE EXPONENTIAL FIT'/20X,22(1H-)//)
      N=5
      M=218
      LJ=218
      LW=4500
      LV=5
      LIW=1
      READ (5,124) (YE(I), I=1,M)
  124 FORMAT (12F6.3)
      DO 20 I=1,M
      Y(I)=YE(I)*0.01
   20 CONTINUE
      T(1)=0.0D0
      DO 12 J=2,M
      T(J)=1.50D0+(J-2)*5.0D0
   12 CONTINUE
      X(1)=0.30D0
      X(2)=-0.03D0
      X(3)=0.320D0
      X(4)=0.02D0
      X(5)=0.040D0
      IFAIL=0
      CALL E04YAF(M,N,LSQFUN,X,FVEC,FJAC,LJ,IW,
     2LIW,W,LW,IFAIL)
      IPRINT=1
      MAXCAL=50*N
      ETA=0.50D0
      XTOL=10.0D0*DSQRT(X02AAF(XTOL))
      STEPMX=1.50D0
      X(1)=0.120D0
      X(2)=0.02D0
      X(3)=0.550D0
      X(4)=0.0010D0
      X(5)=0.190D0
      IFAIL=1
      CALL E04GDF(M,N,LSQFUN,LSQMON,IPRINT,MAXCAL,
     3ETA,XTOL,STEPMX,X,FSUMSQ,FVEC,FJAC,LJ,S,
     4V,LV,NITER,NF,IW,LIW,W,LW,IFAIL)
      IF (IFAIL.NE.0) WRITE (6,125) IFAIL
      IF (IFAIL.EQ.1) GO TO 60
      WRITE (6,126) FSUMSQ
      WRITE (6,127) (X(J),J=1,N)
      CALL LSQGRD(M,N,FVEC,FJAC,LJ,G)
      WRITE (6,128) (G(J),J=1,N)
      WRITE (6,129)
      DO 40 I=1,M

      WRITE (6,130) FVEC(I)
   40 CONTINUE
   60 WRITE (6,131)
      STOP
  125 FORMAT (///16H ERROR EXIT TYPE, I3, 22H - SEE ROUTINE DOCUMEN
     5, 1HT)
  126 FORMAT (///31H ON EXIT,THE SUM OF SQUARES IS ,F12.4)
  127 FORMAT (13H AT THE POINT, 5F12.4)
  128 FORMAT (30H THE CORRESPONDING GRADIENT IS,1P5E12.3)
  129 FORMAT (22H AND THE RESIDUALS ARE)
  130 FORMAT (1H ,1PE9.1)
  131 FORMAT (5A4, 1A3)
      END
```

```
      SUBROUTINE LSQFUN(IFLAG,M,N,XC,FVECC,FJACC,LJC,
     1IW,LIW,W,LW)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION FJACC(LJC,N),FVECC(M),W(LW),XC(N),
     2IW(LIW),T(218),Y(218)
      COMMON Y,T
      DO 20 I=1,M
      IF (IFLAG.EQ.2) FVECC(I)=XC(1)*DEXP(-XC(2)*T(I))
     3+XC(3)*DEXP(-XC(4)*T(I))+XC(5)-Y(I)
      FJACC(I,1)=DEXP(-XC(2)*T(I))
      FJACC(I,2)=-(XC(1)*T(I)*DEXP(-XC(2)*T(I)))
      FJACC(I,3)=DEXP(-XC(4)*T(I))
      FJACC(I,4)=-(XC(3)*T(I)*DEXP(-XC(4)*T(I)))
      FJACC(I,5)=1.0D0
   20 CONTINUE
      RETURN
      END
      SUBROUTINE LSQMON(M,N,XC,FVECC,FJACC,LJC,S,IGRADE,
     4NITER,NF,IW,LIW,W,LW)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION FJACC(LJC,N),FVECC(M),S(N),W(LW),XC(N),
     5IW(LIW),G(50)
      FSUMSQ=F01DEF(FVECC,FVECC,M)
      CALL LSQGRD(M,N,FVECC,FJACC,LJC,G)
      GTG=F01DEF(G,G,N)
      WRITE (6,132) NITER,NF,FSUMSQ,GTG,IGRADE
      WRITE (6,133)
      DO 20 J=1,N
      WRITE (6,134) XC(J),G(J),S(J)
   20 CONTINUE
      RETURN
  132 FORMAT (///6H ITNS ,4X, 7HF EVALS, 10X, 5HSUMSQ, 13X, 3HGTG,
     6 8X, 5HGRADE/1H , I4, 6X,I5,6X, 1PE13.5, 6X,1PE9.1, 6X, I3)
  133 FORMAT (/8X, 1HX, 20X, 1HG, 11X, 15HSINGULAR VALUES)
  134 FORMAT (1H ,1PE13.5, 10X, 1PE9.1, 10X, 1PE9.1)
      END
      SUBROUTINE LSQGRD(M,N,FVECC,FJACC,LJC,G)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION FJACC(LJC,N),FVECC(M),G(N)
      DO 40 J=1,N
      SUM=0.0D0
      DO 20 I=1,M
      SUM=SUM+FJACC(I,J)*FVECC(I)
   20 CONTINUE
      G(J)=SUM+SUM
   40 CONTINUE
      RETURN

      END
```

```
                                   RUN - 18

                           DOUBLE EXPONENTIAL FIT
                           ----------------------


ITNS       F EVALS              SUMSQ              GTG           GRADE
  0              1          2.82757E+00         5.8E+07            5

       X                          G            SINGULAR VALUES
  1.20000E-01                 2.3E+00              2.4E+03
  2.00000E-02                -1.1E+01              1.2E+01
  3.50000E-01                 2.9E+01              3.5E+00
  1.00000E-03                -7.6E+03              1.7E+00
  1.90000E-01                 4.9E+01              3.0E-01


ITNS       F EVALS              SUMSQ              GTG           GRADE
  1              2          3.94191E-01         1.9E+06            5

       X                          G            SINGULAR VALUES
  3.50427E-02                 1.8E-02              1.2E+03
  1.45171E-02                -4.8E-01              8.0E+00
  1.27435E-01                 5.4E+00              2.1E+00
  1.69923E-03                -1.4E+03              1.4E+00
  2.57603E-01                 1.6E+01              5.9E-01


ITNS       F EVALS              SUMSQ              GTG           GRADE
  2              3          4.48607E-03         1.6E+04            5

       X                          G            SINGULAR VALUES
  3.61394E-02                 2.4E-01              1.5E+03
  5.33617E-03                -1.6E+00              1.4E+01
  3.11273E-01                 7.5E-01              4.5E+00
  1.60435E-03                -1.3E+02              8.2E-01
  1.71003E-01                 1.4E+00              9.2E-02


ITNS       F EVALS              SUMSQ              GTG           GRADE
  3              4          1.73974E-03         4.6E+01            5

       X                          G            SINGULAR VALUES
  4.43393E-02                -1.2E-02              1.5E+03
  3.31299E-03                 2.0E-02              1.3E+01
  3.07937E-01                 6.1E-03              3.9E+00
  1.57409E-03                -6.7E+00              9.6E-01
  1.69903E-01                 4.3E-02              2.1E-01


ITNS       F EVALS              SUMSQ              GTG           GRADE
  4             10          1.72792E-03         1.4E+01            1

       X                          G            SINGULAR VALUES
  4.79451E-02                 1.4E-03              1.5E+03
  7.63923E-03                -3.0E-02              1.5E+01
  3.03732E-01                 1.7E-02              4.2E+00
  1.55373E-03                -3.8E+00              9.1E-01
  1.63193E-01                 3.5E-02              1.7E-01


ITNS       F EVALS              SUMSQ              GTG           GRADE
  5             16          1.72568E-03         5.4E-04            0

       X                          G            SINGULAR VALUES
  4.83991E-02                 2.3E-05              1.5E+03
  7.61249E-03                 4.3E-04              1.5E+01
  3.03123E-01                 1.6E-04              4.2E+00
  1.55411E-03                -2.3E-02              9.0E-01
  1.63347E-01                 2.3E-04              1.7E-01
```

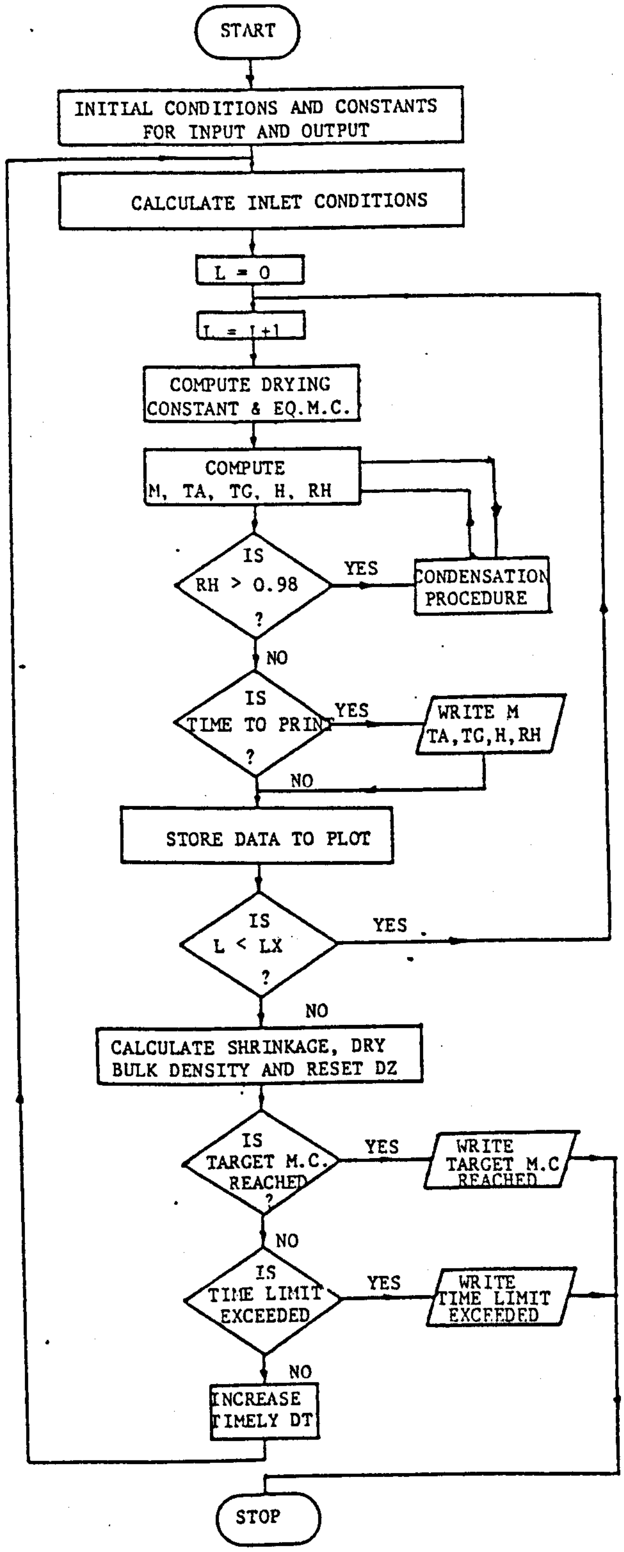
```
ITNS       F EVALS           SUMSQ              GTG          GRADE
  6            22          1.72564E-03        2.0E-02          0

      X                       G              SINGULAR VALUES
  4.93557E-02              2.9E-04              1.5E+03
  7.51910E-03             -2.2E-03              1.6E+01
  5.04577E-01              9.9E-04              4.2E+00
  1.55955E-03             -1.4E-01              8.9E-01
  1.69573E-01              1.6E-03              1.6E-01


ITNS       F EVALS           SUMSQ              GTG          GRADE
  7            28          1.72563E-03        5.9E-09          0

      X                       G              SINGULAR VALUES
  4.94001E-02              8.1E-08              1.5E+03
  7.51543E-03              1.8E-06              1.6E+01
  5.04590E-01              4.9E-07              4.2E+00
  1.55941E-03             -7.7E-05              8.9E-01
  1.69833E-01              9.5E-07              1.6E-01


ITNS       F EVALS           SUMSQ              GTG          GRADE
  8            34          1.72563E-03        1.2E-11          0

      X                       G              SINGULAR VALUES
  4.94051E-02              7.0E-09              1.5E+03
  7.51593E-03             -5.2E-08              1.6E+01
  5.04543E-01              2.4E-08              4.2E+00
  1.55941E-03             -3.5E-06              8.9E-01
  1.69852E-01              4.0E-08              1.6E-01


ITNS       F EVALS           SUMSQ              GTG          GRADE
  9            35          1.72563E-03        3.2E-26          0

      X                       G              SINGULAR VALUES
  4.94051E-02             -6.1E-16              1.5E+03
  7.51593E-03              4.1E-15              1.6E+01
  5.04543E-01             -1.3E-15              4.2E+00
  1.55941E-03              1.8E-13              8.9E-01
  1.69852E-01             -2.1E-15              1.6E-01


ON EXIT,THE SUM OF SQUARES IS        0.0017
AT THE POINT        0.0494        0.0075        0.5045        0.0016        0.1689
THE CORRESPONDING GRADIENT IS  -6.075E-16   4.144E-15  -1.310E-15   1.785E-13  -2.092E-15
```

Appendix 3.4

```
C       PROGRAM TO PLOT CURVE
C       Y=MOISTURE CONTENT
C       T=TIME IN MIN
        DIMENSION T(700),YE(700),YS(700),
       1Y(700),TE(700)
        N=132
        READ(5,121) ( Y(I),I=1,N)
   121  FORMAT(12F6.3)
        READ(5,122) AS,BS,CS,DS,ES
   122  FORMAT(5F8.5)
        T(1)=0.0
        DO 1  I=2,N
     1  T(I)=(I-2.0)+0.42
        M=N/5
        TE(1)=T(1)
        YE(1)=Y(1)
        DO 3  I=2,M
        J=(I-1)*5+1
        TE(I)=T(J)
     3  YE(I)=Y(J)
        DO 2  I=1,N
     2  YS(I)=AS+(BS)*EXP(-(CS)*T(I))+(DS)*EXP(-(ES)*T(I))
        CALL PAPER(1)
        CALL PSPACE(0.15.0.9,0.15,0.7)
        CALL MAP(0.0,250.0,0.0,100.0)
        CALL CSPACE(0.15.0.9.0.15,0.7)
        CALL CTRSET(5)
        CALL CTRMAG(20)
        CALL PLOTCS(100.0,75.0,'RUN-31 (DOUBLE)',15)
        CALL CTRSET(1)
        CALL CTRMAG(10)
        CALL PLOTCS(100.0,7.5,'TIME IN MIN',11)
        CALL BORDER
        CALL PSPACE(0.25.0.9,0.25,0.7)
        CALL MAP(0.0.250.0.0.0,100.0)
        CALL AXESSI(100.,10.)
        CALL CTRORI(1.0)
        CALL PLOTCS(-20.0,30.0,'MOISTURE CONTENT % D B',22)
        CALL CTRSET(4)
        CALL PTPLOT(TE,YE,1,M,54)
        CALL FULL
        CALL NSCURV(T,YS,1,N)
        CALL GREND
        STOP
        END
```

Appendix 4.1

Simplified flow chart of the computer programme for model 1



```
C       PROGRAM TO SIMULATE DEEP BED DRYING OF MALT (MODEL-1)
C       AD=INITIAL MOISTURE CONTENT, RATIO,D.B.
C       AED=MOISTURE CONTENT, RATIO,D.B.
C       EMC=EQUILIBRIUM MOISTURE CONTENT, RATIO,D.B.
C       DK=DRYING CONSTANT (1/MIN.)
C       TAG=AIR TEMPERATURE, DEG C
C       TG=GRAIN TEMPERATURE, DEG C
C       RH=RELATIVE HUMIDITY, RATIO
C       ERH=EQUILIBRIUM RELATIVE HUMIDITY, RATIO
C       HUM=HUMIDITY, KG/KG
C       PV=VPOR PRESSURE, N/M**2
C       PVS=SATURATED VAPOR PRESSURE, N/M**2
C       APR=ATMOSPHERIC PRESSURE, N/M**2
C       ROM=DRY BULK DENSITY OF MALT, KG/M**3
C       CPG=SPECIFIC HEAT OF MALT, KJ/KGK
C       CPL=SPECIFIC HEAT OF LIQUID, KJ/KGK
C       CPW=SPECIFIC HEAT OF VAPOR, KJ/KGK
C       CPA=SPECIFIC HEAT OF AIR, KJ/KGK
C       ALA=LATENT HEAT OF VAPORIZATION, KJ/KGK
C       HT=VOLUMETRIC HEAT TRANSFER COEF.,KJ/(M**3)MIN.K
C       RT=DRYING RATE
C       GA=MASS FLOW RATE OF AIR(DRY),KG/(M**2)MIN.
C       DWA=DRY WEIGHT PER UNIT AREA,KG/(M**2)
C       XD=INCREMENT FOR MOISTURE CONTENT CHANGE REDUCTION
C       DTPR=PRINTING INTERVAL,MIN.
C       TIME=TIME, MIN.
C       TML=RUN TIME, HOUR
C       Z=DEPTH, METERS
C       DZ=INCREMENT IN DEPTH, METER
C       DT=INCREMENT IN TIME, MIN.
C       IT=ITERATION
        DIMENSION AED(200),TAG(200),TG(200),HUM(200),RH(200),
       1RT(200)
        COMMON TIM(200),TAM(200)
        EXTERNAL SPR
        CALL TIME(0)
C       DATA ON PHYSICAL AND THERMAL PROPERTIES
        READ(5,101) APR,GA,CPG,CPW,CPL,CPA,RAMEAN,ROM,DWA
   101  FORMAT(9F7.3)
C       RUN TIME,DEPTH,NO.OF LAYERS,TIME STEP AND DEPTH STEP
        READ(5,103) TML,Z,LX,DT,DZ,ZL
   103  FORMAT(2F6.3,I3,3F6.3)
C       CRITERION
        READ(5,104) EPSI,EPS,RHP
   104  FORMAT(3F8.5)
C       INITIAL GRAIN TEMP. AND MOISTURE CONTENT
        READ(5,105) TGN,AD
   105  FORMAT(2F6.3)
C       INPUT DATA FOR INLET CONDITIONS
        READ(5,106) (TIM(I),TAM(I),I=1,22)
   106  FORMAT(2F6.2)
        WRITE(6,201) Z,LX,DZ,TML,DT,AD,TGN,CPG,ROM,GA
   201  FORMAT(//40X,'DEEP BED DRYING OF MALT'///20X,'BED DEPTH',
       122X,'=',F10.4,2X,'METERS'/20X,'NO. OF LAYERS',13X,'=',I10/20X,
       2'DEPTH OF LAYER',16X,'=',F10.4,2X,'METER'/20X,'RUN TIME OF SIMULAT
       3ION','=',F10.4,2X,'HOUR.'/20X,'TIME STEP',16X,'=',F10.4,'MIN.'/,
       420X,'INITIAL MOISTURE CONTENT(D.B.)',1X,'=',F10.4,2X,'DECIMAL'/
       520X,'INITIAL TEMP. OF MALT',10X,'=',F10.4,2X,'DEG C'/20X,
       6'SPECIFIC HEAT OF MALT',10X,'=',F10.4,2X,'KJ/KGK'/20X,
       7'DENSITY OF DRY MALT',12X,'=',F10.4,2X,'KG/M**3'/20X,'AIR FLOW RA

       8TE',13X,'=',F10.4,2X,'KG/MIN.(M**2)')
        APR=APR*1000.0
C       INITIAL CONDITIONS OF THE LAYERS
        REL=ERH(AD,TGN)
        PVS=SPR(TGN)
        PV=REL*PVS
        HUMN=(0.622*PV)/(APR-PV)
        DO 8 L=1,LX
        RH(L)=REL
        AED(L)=AD
        TG(L)=TGN
        TAG(L)=TGN
        RT(L)=0.0
        HUM(L)=HUMN
      8 CONTINUE
        AMEAN=AD
        AI=(AMEAN/(1.0+AMEAN))*100.0
```

```
C     LOOP TO ITERATE IN TIME
      BTIME=0.0
      WRITE(6,240) BTIME,AMEAN
  240 FORMAT(//33X,'TIME=',F10.4,'MIN.'/
     330X,'MEAN MOISTURE CONTENT=',F6.3)
      WRITE(6,242)
  242 FORMAT(//2X,'POSITION',8X,'M.C.',8X,'AIR',9X,'GRAIN',3X,
     1'AIR',9X,'AIR',3X,'DRYING'/2X,'LAYER',11X,'DRY',7X,'TEMP',
     29X,'TEMP',6X,'HUMIDITY',3X,'RELATIVE',3X,'RATE'/2X,'NUMBER
     3',2X,'BASIS',7X,'DEGC',7X,'DEGC',9X,'KG/KG',6X,'HUMIDITY',4X,
     4'1/MIN.')
      DO 11 I=1,LX
   11 WRITE(6,245) I,AED(I),TAG(I),TG(I),HUM(I),RH(I),RT(I)
  245 FORMAT(2X,I3,5X,6(6X,F7.4))
      TIMA=BTIME/60.0
       ZX=0.75
      DTPR=30.0
      TPR=DTPR
    9 CONTINUE
      BTIME=BTIME+DT
      AMEAN=0.0
C     VARIABLE INLET CONDITIONS
      CALL INLET(BTIME,TAIN)
      TA=TAIN
      HUMN=0.0147
      GA=22.2334
      PVS=SPR(TA)
      PV=(HUMN*APR)/(0.622+HUMN)
      RHX=PV/PVS
C     LOOP TO ITERATE IN LAYERS
      DO 45 L=1,LX
      DK=DRK(TA)
      IF(RHX.GT.0.98) RHX=0.98
      ECC=EOMC(TA,RHX)
      EMC=(ECC/(1.0-ECC))
      DM=DMT(AED(L),DK,EMC,DT)
      A=2.0*(TA-TG(L))
      B=CPG+CPL*AED(L)
      F=CPW*TA+2501.61-TG(L)*CPL
C     EFFECT OF MASS FLOW RATE OF AIR ON HEAT TRANSFER COEF.
      HT=175.07*((GA)**0.6906)
C     EFFECT OF M.C. ON LATENT HEAT
      ALG=2501.61*(1.0+0.5704*EXP(-13.67*AED(L)))

      YY=CPA*TA+ALG-CPL*TG(L)
   53 E=CPA+CPW*(HUMN-(DM*ROM*DZ/(GA*DT)))
      GE=GA*E
      TOP=(ROM/DT)*DM
      TOP=A+(TOP*((2.0*YY/HT)+(F*DZ/GE)))
      BB=B+CPL*DM
      BOT=1.0+((ROM/DT)*(2.0*B/HT+DZ*BB/GE))
      DTG=TOP/BOT
      DTA=-(ROM*DZ/((GA*DT)*E))*((DTG*BB)-(DM*F))
      T=TA+DTA
      PS=SPR(T)
      H=HUMN-(DM*ROM*DZ/(GA*DT))
      P=(H*APR)/(0.622+H)
      RHX=P/PS
      FXX=RHX-RHP
      IF(ABS(FXX).LE.EPS) GO TO 47
      IF(FXX) 47,47,49
C     CONDENSATION PROCEDURE
C     INCRENMENTAL SEARCH METHOD
   49 XD=0.0006
      IT=0
      CX=DM
      FX=RHX-RHP
   56 CXX=CX+XD
      E=CPA+CPW*(HUMN-(CXX*ROM*DZ/(GA*DT)))
      GE=GA*E
      TOP=(ROM/DT)*CXX
      TOP=A+(TOP*((2.0*YY/HT)+(F*DZ/GE)))
      BB=B+CPL*CXX
      BOT=1.0+((ROM/DT)*(2.0*B/HT+DZ*BB/GE))
      DTG=TOP/BOT
      DTA=-(ROM*DZ/((GA*DT)*E))*((DTG*BB)-(CXX*F))
      T=TA+DTA
      PS=SPR(T)
      H=HUMN-(CXX*ROM*DZ/(GA*DT))
      P=(H*APR)/(0.622+H)
      RHX=P/PS
      FXX=RHX-RHP
      IF((FX)*(FXX)) 55,77,57
   57 CX=CX+XD
      FX=FXX
      IT=IT+1
      IF(IT-30) 56,56,67
   67 WRITE(6,309) IT
  309 FORMAT(20X,'SEARCH FAILED AND IT=',I4)
      GO TO 85
C     BISECTION METHOD
```

```
   55 CONTINUE
      DO 53 N=1,5
      XAV=(CX+CXX)/2.0
      E=CPA+CPW*(HUMN-(XAV*ROM*DZ/(GA*DT)))
      GE=GA*E
      TOP=(ROM/DT)*XAV
      TOP=A+(TOP*((2.0*YY/HT)+(F*DZ/GE)))
      BB=B+CPL*XAV
      BOT=1.0+((ROM/DT)*(2.0*B/HT+DZ*BB/GE))
      DTG=TOP/BOT
      DTA=-(ROM*DZ/((GA*DT)*E))*((DTG*BB)-(XAV*F))
      T=TA+DTA
      PS=SPR(T)

      H=HUMN-(XAV*ROM*DZ/(GA*DT))
      P=(H*APR)/(0.622+H)
      RHX=P/PS
      FAV=RHX-RHP
      IF(FX*FAV) 54,46,59
   59 CX=XAV
      FX=FAV
      GO TO 63
   54 CXX=XAV
      FXX=FAV
      IT=IT+1
   63 CONTINUE
C     SECANT METHOD
   49 XAV=(CX*FXX-CXX*FX)/(FXX-FX)
      E=CPA+CPW*(HUMN-(XAV*ROM*DZ/(GA*DT)))
      GE=GA*E
      TOP=(ROM/DT)*XAV
      TOP=A+(TOP*((2.0*YY/HT)+(F*DZ/GE)))
      BB=B+CPL*XAV
      BOT=1.0+((ROM/DT)*(2.0*B/HT+DZ*BB/GE))
      DTG=TOP/BOT
      DTA=-(ROM*DZ/((GA*DT)*E))*((DTG*BB)-(XAV*F))
      T=TA+DTA
      PS=SPR(T)
      H=HUMN-(XAV*ROM*DZ/(GA*DT))
      P=(H*APR)/(0.622+H)
      RHX=P/PS
      FAV=RHX-RHP
      IT=IT+1
      IF(IT.GT.50) GO TO 77
      IF(ABS(FAV).LE.EPS) GO TO 46
      IF(FX*FAV) 43,46,44
   44 CX=XAV
      FX=FAV
      GO TO 49
   43 CXX=XAV
      FXX=FAV
   46 CONTINUE
      CXX=XAV
   77 CONTINUE
      DM=CXX
      GO TO 53
   47 TG(L)=TG(L)+DTG
      TA=TA+DTA
      TAG(L)=TA
      AED(L)=AED(L)+DM
      RH(L)=RHX
      HUMN=H
      HUM(L)=HUMN
      RT(L)=DM/DT
      IF((TG(L)-TA).LT.20.0) GO TO 64
      WRITE(6,254) L,TAG(L),TG(L)
  254 FORMAT(/32X,'AIR TEMPERATURE BELOW 20 DEGC'/20X,
     1'LAYER NO.=',I10,'AIR TEMP=',F10.4,'GRAIN TEMP=',F10.4)
   64 AMEAN=AMEAN+AED(L)*DZ
   45 CONTINUE
C       END OF BED
      AMEAN=AMEAN/ZX
      TIMA=BTIME/60.0
      IF(ABS(TIMA-TML).LE.EPSI) GO TO 72

      IF(ABS(BTIME-TPR)-EPSI) 72,72,73
   72 WRITE(6,207) BTIME,AMEAN,DZ
  207 FORMAT(//38X,'TIME=',F10.4,'MIN'/30X,
     3'MEAN MOISTURE CONTENT=',F6.3,5X,'DZ=',F6.4)
      DO 12 KK=1,LX
   12 WRITE(6,206) KK,AED(KK),TAG(KK),TG(KK),HUM(KK),RH(KK),RT(KK)
  206 FORMAT(2X,I3,6(6X,F7.4))
      TPR=TPR+DTPR
   73 CONTINUE
      IF((AMEAN-RAMEAN).LE.0.0) GO TO 65
      IF(TIMA.GE.TML) GO TO 76
C     ADVANCE IN TIME STEP
      WMEAN=(AMEAN/(1.0+AMEAN))*100.0
```

```
C       EFFECT OF M.C. ON SHRINKAGE
        DZ2=ZL*0.1596*(1.0-EXP(-0.0366*(AI-WMEAN)))
        ZX=ZL-DZ2
        ROM=DWA/ZX
        DZ=ZX/150.0
        GO TO 3
   76   WRITE(6,225)
  225   FORMAT(//32X,'TIME LIMIT EXCEEDED')
        GO TO 85
   65   WRITE(6,230)
  230   FORMAT(//32X,'TARGET MOISTURE CONTENT REACHED')
   85   CONTINUE
        CALL TIME(1,-1,ITIME)
        STOP
        END
        FUNCTION ERH(AA,GT)
C       FUNCTION TO CALCULATE INITIAL RELATIVE HUMIDITY WITHIN LAYER
        AW=(AA/(1+AA))
        A=-37357.912
        B=-29.9857
        R=8.315
        ERH=EXP((A/(R*(GT+273.15)))*EXP(B*AW))
        RETURN
        END
        FUNCTION SPR(TT)
C       FUNCTION TO CALCULATE SATURATED VAPOR PRESSURE
        A=-0.274055E5
        B=0.541896E2
        C=-0.451370E-1
        D=0.215321E-4
        E=-0.462027E-8
        F=0.241613E1
        G=0.121547E-2
        R=0.220619E4
        T=TT*1.8+491.69
        TP=A+T*(B+T*(C+T*(D+T*E)))
        TO=(T*(F-G*T))
        TP=TP/TO
        SPR=EXP(TP)*R*6894.76
        RETURN
        END
        FUNCTION DRK(TA)
C       FUNCTION TO CALCULATE DRYING CONSTANT
        A=11061456.0
        B=-6317.5249
        DRK=A*EXP(B/(273.16+TA))
        RETURN

        END
        FUNCTION EQMC(TA,RH)
C       FUNCTION TO CALCULATE EQUILIBRIUM MOISTURE CONTENT
        A=10.5283
        B=29.9357
        R=8.315
        EQMC=(A-ALOG(-R*(TA+273.15)*ALOG(RH)))/B
        RETURN
        END
        FUNCTION DMT(AA,DK,EMC,DT)
C       FUNCTION TO CALCULATE THE CHANGE IN MOISTURE CONTENT
        DMT=-(DK*DT)*(AA-EMC)/(1.0+(DK*DT*0.5))
        RETURN
        END
        SUBROUTINE INLET(BTIME,TC)
C       SUBROUTINE TO INTERPOLATE INLET CONDITION FROM GIVEN DATA
        COMMON TIM(200),TAM(200)
        N=21
        B=BTIME
        DO 1 I=1,N
        IF(B.GE.(TIM(I)).AND.B.LT.TIM(I+1)) GO TO 2
    1   CONTINUE
        TC=TAM(N+1)
        GO TO 3
    2   A=(B-TIM(I))/(TIM(I+1)-TIM(I))
        TC=TAM(I)+(TAM(I+1)-TAM(I))*A
    3   RETURN
        END
```

```
                        DEEP BED DRYING OF MALT
           BED DEPTH                              =    0.7500  METERS
           NO. OF LAYERS                          =       150
           DEPTH OF LAYER                        =   0.0050  METER
           RUN TIME OF SIMULATION=    10.2500  HOUR.
           TIME STEP                       =   1.0000MIN.
           INITIAL MOISTURE CONTENT(D.B.) =      0.6520  DECIMAL
           INITIAL TEMP. OF MALT                  =   26.4960  DEG C
           SPECIFIC HEAT OF MALT                  =    1.6510  KJ/KGK
           DENSITY OF DRY MALT                    =  367.9270  KG/M**3
           AIR FLOW RA TE                  =   22.2380  KG/MIN.(M**2)


                            TIME=   600.0000MIN
                  MEAN MOISTURE CONTENT= 0.129      DZ=0.0043


POSITION        M.C.        AIR        GRAIN        AIR         AIR        DRYING

LAYER           DRY         TEMP        TEMP      HUMIDITY    RELATIVE    RATE
NUMBER          BASIS       DEGC       DEGC         KG/KG      HUMIDITY     1/MIN.


    1         0.0660      59.4795     59.4774     0.0147      0.1201      -0.0000
    2         0.0660      59.4789     59.4767     0.0147      0.1201      -0.0000
    3         0.0660      59.4783     59.4759     0.0147      0.1201      -0.0000
    4         0.0661      59.4776     59.4751     0.0147      0.1201      -0.0000
    5         0.0661      59.4769     59.4742     0.0147      0.1201      -0.0000
    6         0.0661      59.4762     59.4733     0.0147      0.1201      -0.0000
    7         0.0661      59.4754     59.4723     0.0147      0.1201      -0.0000
    8         0.0661      59.4745     59.4712     0.0147      0.1201      -0.0000
    9         0.0662      59.4736     59.4700     0.0147      0.1202      -0.0000
   10         0.0662      59.4726     59.4688     0.0147      0.1202      -0.0000
   11         0.0662      59.4715     59.4674     0.0147      0.1202      -0.0000
   12         0.0662      59.4704     59.4660     0.0147      0.1202      -0.0000
   13         0.0663      59.4691     59.4645     0.0147      0.1202      -0.0000
   14         0.0663      59.4678     59.4629     0.0147      0.1202      -0.0000
   15         0.0663      59.4664     59.4611     0.0147      0.1202      -0.0000
   16         0.0664      59.4649     59.4592     0.0147      0.1202      -0.0000
   17         0.0664      59.4633     59.4573     0.0147      0.1202      -0.0000
   18         0.0664      59.4616     59.4552     0.0147      0.1203      -0.0000
   19         0.0665      59.4598     59.4529     0.0147      0.1203      -0.0000
   20         0.0665      59.4579     59.4505     0.0147      0.1203      -0.0000
```

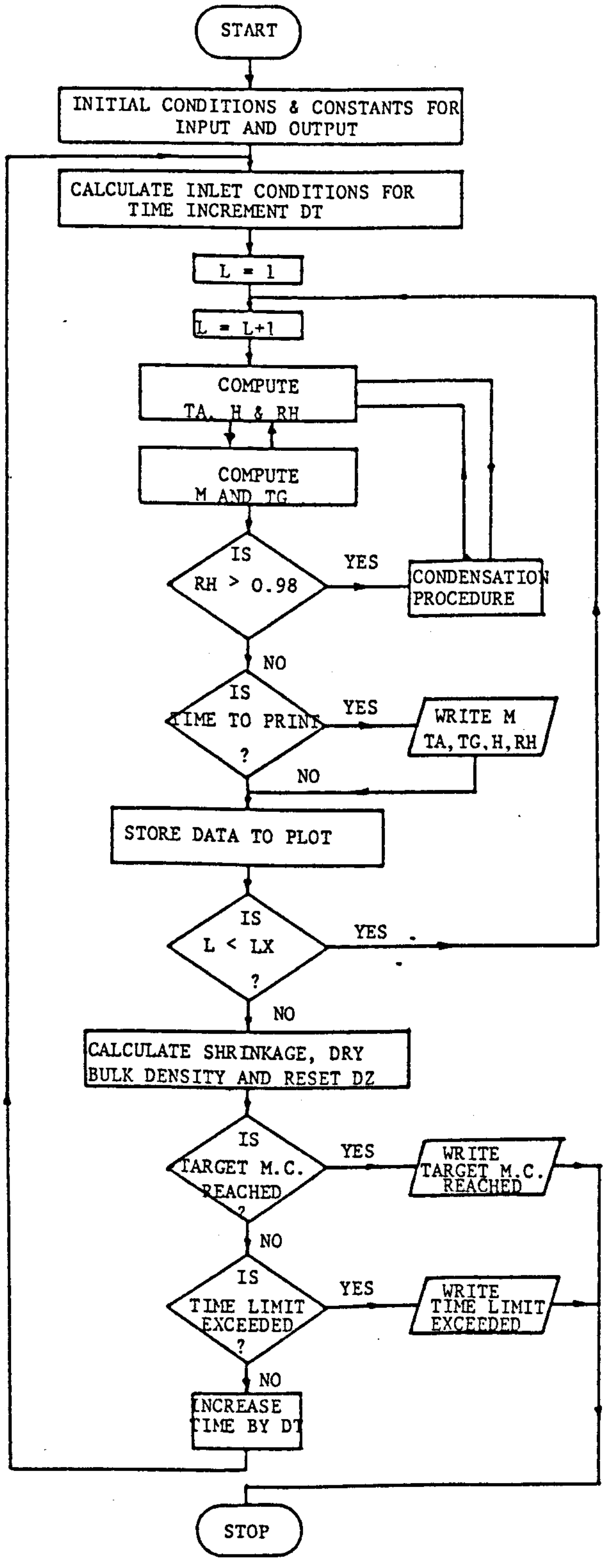
```
21    0.0666    59.4558    59.4480    0.0147    0.1203    -0.0000
22    0.0666    59.4536    59.4453    0.0147    0.1203    -0.0000
23    0.0667    59.4513    59.4424    0.0147    0.1204    -0.0000
24    0.0667    59.4488    59.4394    0.0147    0.1204    -0.0000
25    0.0668    59.4462    59.4362    0.0147    0.1204    -0.0000
26    0.0668    59.4434    59.4327    0.0147    0.1204    -0.0000
27    0.0669    59.4404    59.4291    0.0147    0.1205    -0.0000
28    0.0670    59.4372    59.4252    0.0147    0.1205    -0.0000
29    0.0670    59.4339    59.4211    0.0147    0.1205    -0.0000
30    0.0671    59.4303    59.4167    0.0147    0.1205    -0.0000
31    0.0672    59.4265    59.4121    0.0147    0.1206    -0.0000
32    0.0673    59.4224    59.4072    0.0147    0.1206    -0.0000
33    0.0674    59.4182    59.4021    0.0147    0.1207    -0.0000
34    0.0674    59.4136    59.3966    0.0147    0.1207    -0.0000
35    0.0675    59.4088    59.3907    0.0147    0.1207    -0.0000
36    0.0677    59.4037    59.3846    0.0147    0.1208    -0.0000
37    0.0678    59.3983    59.3780    0.0147    0.1208    -0.0000
38    0.0679    59.3926    59.3711    0.0147    0.1209    -0.0000

39    0.0680    59.3866    59.3638    0.0147    0.1209    -0.0000
40    0.0681    59.3801    59.3561    0.0147    0.1210    -0.0000
41    0.0683    59.3734    59.3479    0.0147    0.1211    -0.0000
42    0.0684    59.3662    59.3392    0.0147    0.1211    -0.0000
43    0.0686    59.3586    59.3301    0.0148    0.1212    -0.0000
44    0.0687    59.3505    59.3205    0.0148    0.1213    -0.0000
45    0.0689    59.3421    59.3103    0.0148    0.1213    -0.0000
46    0.0691    59.3331    59.2996    0.0148    0.1214    -0.0000
47    0.0692    59.3236    59.2882    0.0148    0.1215    -0.0000
48    0.0694    59.3136    59.2762    0.0148    0.1216    -0.0001
49    0.0696    59.3030    59.2636    0.0148    0.1217    -0.0001
50    0.0699    59.2919    59.2503    0.0148    0.1218    -0.0001
51    0.0701    59.2801    59.2362    0.0148    0.1219    -0.0001
52    0.0703    59.2676    59.2214    0.0148    0.1220    -0.0001
53    0.0706    59.2545    59.2058    0.0148    0.1221    -0.0001
54    0.0708    59.2407    59.1894    0.0148    0.1222    -0.0001
55    0.0711    59.2261    59.1721    0.0148    0.1224    -0.0001
56    0.0714    59.2108    59.1539    0.0148    0.1225    -0.0001
57    0.0717    59.1945    59.1346    0.0148    0.1227    -0.0001
58    0.0720    59.1775    59.1144    0.0148    0.1228    -0.0001
59    0.0724    59.1595    59.0931    0.0148    0.1230    -0.0001
60    0.0727    59.1405    59.0707    0.0148    0.1232    -0.0001
61    0.0731    59.1206    59.0471    0.0148    0.1233    -0.0001
62    0.0735    59.0995    59.0222    0.0149    0.1235    -0.0001
63    0.0740    59.0774    58.9960    0.0149    0.1237    -0.0001
64    0.0744    59.0540    58.9684    0.0149    0.1239    -0.0001
65    0.0749    59.0294    58.9394    0.0149    0.1242    -0.0001
```

66	0.0754	59.0035	58.9087	0.0149	0.1244	-0.0001
67	0.0759	58.9762	58.8764	0.0149	0.1247	-0.0001
68	0.0765	58.9473	58.8423	0.0149	0.1249	-0.0001
69	0.0771	58.9170	58.8065	0.0149	0.1252	-0.0002
70	0.0777	58.8850	58.7688	0.0149	0.1255	-0.0002
71	0.0784	58.8513	58.7291	0.0150	0.1258	-0.0002
72	0.0791	58.8158	58.6873	0.0150	0.1261	-0.0002
73	0.0798	58.7784	58.6434	0.0150	0.1265	-0.0002
74	0.0806	58.7390	58.5972	0.0150	0.1269	-0.0002
75	0.0814	58.6976	58.5486	0.0150	0.1272	-0.0002
76	0.0822	58.6540	58.4976	0.0150	0.1277	-0.0002
77	0.0831	58.6081	58.4440	0.0151	0.1281	-0.0002
78	0.0841	58.5599	58.3877	0.0151	0.1285	-0.0002
79	0.0851	58.5092	58.3286	0.0151	0.1290	-0.0003
80	0.0861	58.4559	58.2665	0.0151	0.1295	-0.0003
81	0.0872	58.3999	58.2015	0.0151	0.1301	-0.0003
82	0.0884	58.3410	58.1332	0.0152	0.1306	-0.0003
83	0.0896	58.2793	58.0618	0.0152	0.1312	-0.0003
84	0.0909	58.2145	57.9869	0.0152	0.1319	-0.0003
85	0.0922	58.1465	57.9084	0.0153	0.1325	-0.0003
86	0.0936	58.0752	57.8264	0.0153	0.1332	-0.0004
87	0.0951	58.0005	57.7405	0.0153	0.1339	-0.0004
88	0.0966	57.9222	57.6507	0.0153	0.1347	-0.0004
89	0.0982	57.8402	57.5569	0.0154	0.1355	-0.0004
90	0.0999	57.7544	57.4588	0.0154	0.1364	-0.0004
91	0.1017	57.6646	57.3565	0.0155	0.1373	-0.0004
92	0.1035	57.5707	57.2497	0.0155	0.1382	-0.0005
93	0.1055	57.4726	57.1384	0.0155	0.1392	-0.0005
94	0.1075	57.3701	57.0224	0.0156	0.1403	-0.0005
95	0.1096	57.2631	56.9016	0.0156	0.1414	-0.0005
96	0.1118	57.1515	56.7758	0.0157	0.1425	-0.0006
97	0.1141	57.0351	56.6449	0.0157	0.1437	-0.0006
98	0.1165	56.9139	56.5090	0.0158	0.1450	-0.0006
99	0.1190	56.7877	56.3680	0.0158	0.1464	-0.0006
100	0.1216	56.6563	56.2214	0.0159	0.1478	-0.0007
101	0.1243	56.5198	56.0695	0.0159	0.1492	-0.0007
102	0.1271	56.3780	55.9120	0.0160	0.1508	-0.0007
103	0.1300	56.2307	55.7491	0.0160	0.1524	-0.0007
104	0.1330	56.0780	55.5804	0.0161	0.1541	-0.0008
105	0.1361	55.9197	55.4051	0.0162	0.1559	-0.0008
106	0.1394	55.7557	55.2260	0.0162	0.1578	-0.0008
107	0.1427	55.5860	55.0400	0.0163	0.1597	-0.0008
108	0.1462	55.4105	54.8430	0.0164	0.1617	-0.0009
109	0.1498	55.2292	54.6505	0.0165	0.1639	-0.0009
110	0.1535	55.0421	54.4470	0.0165	0.1661	-0.0009

111	0.1574	54.8491	54.2377	0.0166	0.1684	-0.0010
112	0.1613	54.6502	54.0226	0.0167	0.1709	-0.0010
113	0.1654	54.4455	53.8017	0.0168	0.1734	-0.0010
114	0.1696	54.2350	53.5752	0.0169	0.1761	-0.0011
115	0.1739	54.0186	53.3430	0.0170	0.1788	-0.0011
116	0.1783	53.7966	53.1054	0.0171	0.1817	-0.0011
117	0.1828	53.5689	52.8623	0.0171	0.1847	-0.0011
118	0.1874	53.3357	52.6140	0.0172	0.1878	-0.0012
119	0.1922	53.0969	52.3604	0.0173	0.1911	-0.0012
120	0.1970	52.8528	52.1017	0.0174	0.1944	-0.0012
121	0.2020	52.6034	51.8380	0.0175	0.1979	-0.0012
122	0.2071	52.3489	51.5696	0.0177	0.2016	-0.0013
123	0.2123	52.0893	51.2965	0.0178	0.2053	-0.0013
124	0.2176	51.8249	51.0189	0.0179	0.2093	-0.0013
125	0.2230	51.5557	50.7369	0.0180	0.2133	-0.0013
126	0.2284	51.2821	50.4512	0.0181	0.2175	-0.0014
127	0.2340	51.0041	50.1615	0.0182	0.2219	-0.0014
128	0.2396	50.7220	49.8681	0.0183	0.2264	-0.0014
129	0.2454	50.4359	49.5714	0.0184	0.2310	-0.0014
130	0.2512	50.1461	49.2715	0.0186	0.2358	-0.0014
131	0.2570	49.8523	48.9687	0.0187	0.2408	-0.0015
132	0.2630	49.5562	48.6631	0.0188	0.2459	-0.0015
133	0.2690	49.2565	48.3550	0.0189	0.2512	-0.0015
134	0.2751	48.9539	48.0444	0.0190	0.2566	-0.0015
135	0.2812	48.6408	47.7322	0.0192	0.2623	-0.0015
136	0.2873	48.3412	47.4181	0.0193	0.2680	-0.0015
137	0.2935	48.0315	47.1026	0.0194	0.2740	-0.0015
138	0.2998	47.7199	46.7857	0.0196	0.2801	-0.0015
139	0.3060	47.4067	46.4678	0.0197	0.2863	-0.0015
140	0.3123	47.0919	46.1489	0.0198	0.2928	-0.0016
141	0.3186	46.7759	45.8295	0.0199	0.2994	-0.0016
142	0.3249	46.4589	45.5095	0.0201	0.3062	-0.0016
143	0.3313	46.1410	45.1893	0.0202	0.3131	-0.0016
144	0.3377	45.8225	44.8689	0.0203	0.3202	-0.0016
145	0.3441	45.5035	44.5486	0.0205	0.3275	-0.0016
146	0.3505	45.1842	44.2285	0.0206	0.3350	-0.0016
147	0.3569	44.8643	43.9088	0.0207	0.3426	-0.0016
148	0.3634	44.5455	43.5894	0.0208	0.3504	-0.0016
149	0.3698	44.2265	43.2712	0.0210	0.3584	-0.0016
150	0.3762	43.9079	42.9538	0.0211	0.3665	-0.0016

Appendix 4.2

Simplified flow chart of the computer programme for model 2



```
C     PROGRAM TO SIMULATE DEEP BED DRYING OF MALT (MODEL-2)
C     AD=INITIAL MOISTURE CONTENT, RATIO,D.B.
C     AED=MOISTURE CONTENT, RATIO,D.B.
C     EMC=EQUILIBRIUM MOISTURE CONTENT, RATIO,D.B.
C     DK=DRYING CONSTANT (1/MIN.)
C     TAG=AIR TEMPERATURE, DEG C
C     TG=GRAIN TEMPERATURE, DEG C
C     RH=RELATIVE HUMIDITY, RATIO
C     ERH=EQUILIBRIUM RELATIVE HUMIDITY, RATIO
C     HUM=HUMIDITY, KG/KG
C     PV=VPOR PRESSURE, N/M**2
C     PVS=SATURATED VAPOR PRESSURE, N/M**3
C     APR=ATMOSPHERIC PRESSURE, N/M**2
C     ROM=DRY BULK DENSITY OF MALT, KG/M**3
C     CPG=SPECIFIC HEAT OF MALT, KJ/KGK
C     CPL=SPECIFIC HEAT OF LIQUID, KJ/KGK
C     CPW=SPECIFIC HEAT OF VAPOR, KJ/KGK
C     CPA=SPECIFIC HEAT OF AIR, KJ/KGK
C     ALA=LATENT HEAT OF VAPORIZATION, KJ/KGK
C     HT=VOLUMETRIC HEAT TRANSFER COEF.,KJ/(M**3)MIN.K
C     RT=DRYING RATE
C     GA=MASS FLOW RATE OF AIR(DRY),KG/(M**2)MIN.
C     DWA=DRY WEIGHT PER UNIT AREA,KG/(M**2)
C     XD=INCREMENT FOR MOISTURE CONTENT CHANGE REDUCTION
C     DTPR=PRINTING INTERVAL,MIN.
C     TIME=TIME, MIN.
C     TML=RUN TIME, HOUR
C     Z=DEPTH, METERS
C     DZ=INCREMENT IN DEPTH, METER
C     DT=INCREMENT IN TIME, MIN.
C     IT=ITERATION
      DIMENSION AED(200),TAG(200),TG(200),HUM(200),RH(200),X(200),
     1RT(200),TGI(200),AEI(200),RTI(200),TAI(200),RHI(200)
      COMMON TIM(200),TAM(200)
      EXTERNAL SPR
      CALL TIME(0)
C     DATA ON PHYSICAL AND THERMAL PROPERTIES
      READ(5,101) APR,GA,CPG,CPW,CPL,CPA,RAMEAN,ROM,DWA
  101 FORMAT(9F7.3)
C     RUN TIME,DEPTH,NO.OF LAYERS,TIME STEP AND DEPTH STEP
      READ(5,103) TML,Z,LX,DT,DZ,ZL
  103 FORMAT(2F6.3,I3,3F6.3)
C     CRITERION
      READ(5,104) EPSI,EPS,RHP,PNM
  104 FORMAT(4F8.5)
C     INITIAL GRAIN TEMP. AND MOISTURE CONTENT
      READ(5,105) TGN,AD
  105 FORMAT(2F6.3)
C     INPUT DATA FOR INLET CONDITIONS
      READ(5,106)(TIM(I),TAM(I),I=1,22)
  106 FORMAT(2F6.2)
      WRITE(6,201) Z,LX,DZ,TML,DT,AD,TGN,CPG,ROM,GA
  201 FORMAT(//40X,'DEEP BED DRYING OF MALT'///20X,'BED DEPTH',
     122X,'=',F10.4,2X,'METERS'/20X,'NO. OF LAYERS',13X,'=',I10/20X,
     2'DEPTH OF LAYER',16X,'=',F10.4,2X,'METER'/20X,'RUN TIME OF SIMULAT
     3ION','=',F10.4,2X,'HOUR.'/20X,'TIME STEP',18X,'=',F10.4,'MIN.'/,
     420X,'INITIAL MOISTURE CONTENT(D.B.)',1X,'=',F10.4,2X,'DECIMAL'/
     520X,'INITIAL TEMP. OF MALT',10X,'=',F10.4,2X,'DEG C'/20X,
     6'SPECIFIC HEAT OF MALT',10X,'=',F10.4,2X,'KJ/KGK'/20X,
     7'DENSITY OF DRY MALT',12X,'=',F10.4,2X,'KG/M**3'/20X,'AIR FLOW RA

     8TE',13X,'=',F10.4,2X,'KG/MIN.(M**2)')
      APP=APR*1000.0
C     INITIAL CONDITIONS OF THE LAYERS
      REL=ERH(AD,TGN)
      PVS=SPR(TGN)
      PV=REL*PVS
      HUMN=(0.622*PV)/(APR-PV)
      LX=LX+1
      DO 8 L=1,LX
      X(L)=FLOAT(L-1)*DZ
      RH(L)=REL
      AED(L)=AD
      TG(L)=TGN
      TAG(L)=TGN
      RT(L)=0.0
      HUM(L)=HUMN
    8 CONTINUE
      AMEAN=AD
      AI=(AMEAN/(1.0+AMEAN))*100.0
C     LOOP TO ITERATE IN TIME
      STIME=0.0
      WRITE(6,240) STIME,AMEAN
  240 FORMAT(//30X,'TIME=',F10.4,'MIN.'/
     330X,'MEAN MOISTURE CONTENT=',F6.3)
```

```
      WRITE(6,242)
  242 FORMAT(//2X,'POSITION',8X,'M.C.',9X,'AIR',8X,'GRAIN',8X,
     1'AIR',3X,'AIR',8X,'DRYING'/2X,'DEPTH',11X,'DRY',9X,'TEMP',
     28X,'TEMP',6X,'HUMIDITY',3X,'RELATIVE',3X,'RATE'/2X,'METER
     3',2X,'BASIS',7X,'DEGC',7X,'DEGC',9X,'KG/KG',6X,'HUMIDITY',4X,
     4'1/MIN.')
      DO 11 K=1,LX
   11 WRITE(6,245) X(K),AED(K),TAG(K),TG(K),HUM(K),RH(K),RT(K)
  245 FORMAT(2X,F6.4,2X,6(6X,F7.4))
      TIMA=BTIME/60.0
      ZX=0.75
      DTPR=30.0
      TPR=DTPR
    3 CONTINUE
      BTIME=BTIME+DT
      AMEAN=0.0
C     VARIABLE INLET CONDITIONS
      CALL INLET(BTIME,TAIN)
      TA=TAIN
      HUMN=0.0147
      GA=22.2334
      PVS=SPR(TA)
      PV=(HUMN*APR)/(0.622+HUMN)
      RHX=PV/PVS
C     GRAIN CONDITION AT THE INLET
      TAI(1)=TAG(1)
      TGI(1)=TG(1)
      AEI(1)=AED(1)
      RTI(1)=RT(1)
      RHI(1)=RH(1)
      TGL=TG(1)
      RTL=RT(1)
      AEL=AED(1)
      TB=(TAI(1)+TA)*0.50
      TBL=TB
      RAC=(RHI(1)+RHX)*0.50

      DK=DRK(TB)
      ECC=EQMC(TB,RAC)
      EMC=(ECC/(1.0-ECC))
      AAX=AED(1)*EXP(-DK*DT)+EMC*(1.0-EXP(-DK*DT))
      ABX=(AED(1)+AAX)*0.5
      PT=(ROM*(CPG+CPL*ABX))
      HT=175.07*(GA**0.5906)
      PTG=-HT/PT
      ALG=2501.61*(1.0+0.5904*EXP(-13.67*ABX))
      DMDT=-DK*(AAX-EMC)
      FTG=(ALG+(CPW-CPL)*TG(1))*(ROM*(RT(1)+DMDT)*0.5)/PT
      TG(1)=TG(1)*EXP(PTG*DT)+((FTG*TB-FTG)*
     1(1.0-EXP(FTG*DT))/FTG)
      TAG(1)=TA
      RH(1)=RHX
      HUM(1)=HUMN
      DM=AAX-AED(1)
      AED(1)=AAX
      RT(1)=DMDT
      RTP=DMDT
C     LOOP TO ITERATE IN LAYERS
      LX=LX+1
      NOD=1
      DO 45 L=2,LX
      J=L-1
      TGA=TG(J)
      IF(L.EQ.152) GO TO 53
      TAI(L)=TAG(L)
      TGI(L)=TG(L)
      AEI(L)=AED(L)
      RTI(L)=RT(L)
      RHI(L)=RH(L)
      NOD=MAX0(1,NOD/4)
      JOD=-1
   30 CONTINUE
      IPH=0
      JOD=JOD+1
   32 DZ1=DZ/FLOAT(NOD)
      DNOD=NOD
      DJOD=JOD+1
C     INTERPOLATION FOR CURRENT POSITION
      TGB=((DNOD-DJOD)*TGI(J)+DJOD*TGI(L))/DNOD
      AEM=((DNOD-DJOD)*AEI(J)+DJOD*AEI(L))/DNOD
      RTN=((DNOD-DJOD)*RTI(J)+DJOD*RTI(L))/DNOD
      TAC=((DNOD-DJOD)*TAI(J)+DJOD*TAI(L))/DNOD
      RAC=((DNOD-DJOD)*RHI(J)+DJOD*RHI(L))/DNOD
C     EFFECT OF MASS FLOW RATE OF AIR ON HEAT TRANSFER COEF.
      HT=175.07*((GA)**0.5906)
   53 PTA=-(HT-ROM*CPW*(DMDT))/(GA*(CPA+CPW*HUMN))
      T=TA*EXP(PTA*DZ1)+TGA*(1.0-EXP(PTA*DZ1))
```

```
      TB=(TAC+T)*0.5
      PS=SPR(T)
      H=HUMN-(DMDT*RCM*DZ1/GA)
      P=(H*APR)/(0.622+H)
      RHX=P/PS
      FXX=RHX-RHP
      IF(ABS(FXX).LE.EPS .AND. L.GT.151) GO TO 45
      IF(ABS(FXX).LE.EPS) GO TO 33
      IF(FXX) 33,33,48
   33 DK=DRK(TB)

      RAP=(RAC+RHX)*0.5
      IF(RAP.GT.0.98) RAP=0.98
      ECC=EQMC(TB,RAP)
      EMC=(ECC/(1.0-ECC))
      AAX=AEM*EXP(-DK*DT)+EMC*(1.0-EXP(-DK*DT))
      DM=AAX-AEM
      DMDT=-DK*(AAX-EMC)
      PT=(ROM*(CPG+CPL*(AEM+AAX)*0.5))
      PTG=-HT/PT
C     EFFECT OF M.C. ON LATENT HEAT
      ALG=2501.61*(1.0+0.5904*EXP(-13.67*(AEM+AAX)*0.5))
      RTX=(RTN+(DMDT))*0.5
      FTG=(ALG+(CPW-CPL)*TGB)*(RCM*RTX)/PT
      TGG=TGB*EXP(PTG*DT)+((PTG*TB-FTG)*
     2(1.0-EXP(PTG*DT))/PTG)
      IF(IRH.EQ.1) GO TO 47
      HUMN=(HUMN+H)*0.5
      PTA=-(HT-RCM*CPW*(RTP+(DMDT))*0.5)/
     1(GA*(CPA+CPW*HUMN))
      TGA=(TGA+TGG)*0.5
      T=TA*EXP(PTA*DZ1)+TGA*(1.0-EXP(PTA*DZ1))
      PS=SPR(T)
      P=(H*APR)/(0.622+H)
      RHX=P/PS
      TB=(TAC+T)*0.5
      DK=DRK(TB)
      RAC=(RAC+RHX)*0.5
      IF(RAC.GT.0.98) RAC=0.98
      ECC=EQMC(TB,RAC)
      EMC=(ECC/(1.0-ECC))
      AAX=AEM*EXP(-DK*DT)+EMC*(1.0-EXP(-DK*DT))
      DM=AAX-AEM
      DMDT=-DK*(AAX-EMC)
      PT=(ROM*(CPG+CPL*(AEM+AAX)*0.5))
      PTG=-HT/PT
C     EFFECT OF M.C. ON LATENT HEAT
      ALG=2501.61*(1.0+0.5904*EXP(-13.67*(AEM+AAX)*0.5))
      RTX=(RTN+(DMDT))*0.5
      FTG=(ALG+(CPW-CPL)*TGB)*(RCM*RTX)/PT
      TGG=TGB*EXP(PTG*DT)+((PTG*TB-FTG)*
     2(1.0-EXP(PTG*DT))/PTG)
      FXX=RHX-RHP
      IF(ABS(FXX).LE.EPS) GO TO 47
      IF(FXX) 47,47,48
C     CONDENSATION PROCEDURE
C     INCREMENTAL SEARCH METHOD
   48 XD=0.0006
      IT=0
      CX=DM
      BX=DM
      FX=RHX-RHP
   56 CXX=CX+XD
      RTX=CXX/DT
      PT=(ROM*(CPG+CPL*(AEL+CXX*0.5)))
      PTG=-HT/PT
      ALG=2501.61*(1.0+0.5904*EXP(-13.67*(AEL+CXX*0.5)))
      FTG=(ALG+(CPW-CPL)*TGL)*(RCM*RTX)/PT
      TGG=TGL*EXP(PTG*DT)+((PTG*TBL-FTG)*
     1(1.0-EXP(PTG*DT))/PTG)
      TGA=TGG

      PTA=-(HT-(ROM*CPW*CXX/DT))/(GA*(CPA+CPW*HUMN))
      T=TA*EXP(PTA*DZ1)+TGA*(1.0-EXP(PTA*DZ1))
      PS=SPR(T)
      H=HUMN-(CXX*RCM*DZ1/(GA*DT))
      P=(H*APR)/(0.622+H)
      RHX=P/PS
      FXX=RHX-RHP
      IF((FX)*(FXX)) 55,77,57
   57 CX=CX+XD
      FX=FXX
      IT=IT+1
      IF(IT-30)56,56,67
   67 WRITE(6,309) IT
  309 FORMAT(20X,'SEARCH FAILED AND IT=',I4)
      GO TO 85
C     BISECTION METHOD
```

```
   55 CONTINUE
      DO 63 N=1,5
      XAV=(CX+CXX)*0.5
      RTX=XAV/DT
      PT=(ROM*(CPG+CPL*(AEL+XAV*0.5)))
      PTG=-HT/PT
      ALG=2501.61*(1.0+0.5904*EXP(-13.67*(AEL+XAV*0.5)))
      FTG=(ALG+(CPW-CPL)*TGL)*(ROM*RTX)/PT
      TGG=TGL*EXP(PTG*DT)+((PTG*TBL-FTG)*
     2(1.0-EXP(PTG*DT))/PTG)
      TGA=TGG
      PTA=-(HT-(ROM*CPW*XAV/DT))/(GA*(CPA+CPW*HUMN))
      T=TA*EXP(PTA*DZ1)+TGA*(1.0-EXP(PTA*DZ1))
      PS=SPR(T)
      H=HUMN-(XAV*ROM*DZ1/(GA*DT))
      P=(H*APR)/(0.622+H)
      RHX=P/PS
      FAV=RHX-RHP
      IF(FX*FAV) 54,46,59
   59 CX=XAV
      FX=FAV
      GO TO 63
   54 CXX=XAV
      FXX=FAV
      IT=IT+1
   63 CONTINUE
C     SECANT METHOD
   49 XAV=(CX*FXX-CXX*FX)/(FXX-FX)
      RTX=XAV/DT
      PT=(ROM*(CPG+CPL*(AEL+XAV*0.5)))
      PTG=-HT/PT
      ALG=2501.61*(1.0+0.5904*EXP(-13.67*(AEL+XAV*0.5)))
      FTG=(ALG+(CPW-CPL)*TGL)*(ROM*RTX)/PT
      TGG=TGL*EXP(PTG*DT)+((PTG*TBL-FTG)*
     3(1.0-EXP(PTG*DT))/PTG)
      TGA=TGG
      PTA=-(HT-(ROM*CPW*XAV/DT))/(GA*(CPA+CPW*HUMN))
      T=TA*EXP(PTA*DZ1)+TGA*(1.0-EXP(PTA*DZ1))
      PS=SPR(T)
      H=HUMN-(XAV*ROM*DZ1/(GA*DT))
      P=(H*APR)/(0.622+H)
      RHX=P/PS
      FAV=RHX-RHP
      IT=IT+1

      IF(IT.GT.50) GO TO 77
      IF(ABS(FAV).LE.EPS) GO TO 46
      IF(FX*FAV) 43,46,44
   44 CX=XAV
      FX=FAV
      GO TO 49
   43 CXX=XAV
      FXX=FAV
      GO TO 49
   46 CONTINUE
      CXX=XAV
   77 CONTINUE
      DM=CXX
      DMDT=DM/DT
      AMEAN=(AMEAN+(CXX-BX)*0.5*DZ1)
      AED(J)=AED(J)+(CXX-BX)
      TG(J)=TGG
      RT(J)=DMDT
      IF(L.GT.151) GO TO 45
      IPH=1
      GO TO 53
   47 CONTINUE
      CHANGE=ABS(TA-T)
      IF(CHANGE.LT.PNM.OR.NOD.EQ.128) GO TO 93
      NOD=NOD*2
      JOD=JOD*2
      GO TO 92
   93 CONTINUE
      AMEAN=AMEAN+(AED(J)+AAX)*0.5*DZ1
      IF(JOD+1.EQ.NOD) GO TO 91
      TGA=TGG
      TA=T
      TGL=TGB
      RTL=RTN
      RTP=DMDT
      AEL=AEM
      TBL=TB
      HUMN=H
      GO TO 90
   91 TA=T
      TAG(L)=TA
```

```
      TG(L)=TGG
      HUMN=H
      HUM(L)=HUMN
      RH(L)=RHX
      AED(L)=AEM+DM
      RT(L)=DMDT
      RTP=DMDT
      TGL=TGB
      RTL=RTN
      AEL=AEM
      TBL=TB
   45 CONTINUE
C       END OF BED
      LX=LX-1
      AMEAN=AMEAN/ZX
      TIMA=BTIME/60.0
      IF(ABS(TIMA-TML).LE.EPSI) GO TO 72
      IF(ABS(BTIME-TPR)-EPSI) 72,72,73
   72 WRITE(6,207) BTIME,AMEAN

  207 FORMAT(//38X,'TIME=',F10.4,'MIN'/30X,
     3'MEAN MOISTURE CONTENT=',F6.3)
      DO 12 KK=1,LX
   12 WRITE(6,206) X(KK),AED(KK),TAG(KK),TG(KK),HUM(KK),RH(KK),RT(KK)
  206 FORMAT(2X,F6.4,2X,6(5X,F7.4))
      TPR=TPR+DTPR
   73 CONTINUE
      IF((AMEAN-RAMEAN).LE.0.0) GO TO 65
      IF(TIMA.GE.TNL) GO TO 76
C     ADVANCE IN TIME STEP
      WMEAN=(AMEAN/(1.0+AMEAN))*100.0
C     EFFECT OF M.C. ON SHRINKAGE
      DZ2=ZL*0.1596*(1.0-EXP(-0.0966*(AI-WMEAN)))
      ZX=ZL-DZ2
      DZ=ZX/150.0
      RCM=DWA/ZX
      DO 60 N=1,LX
   60 X(N)=FLOAT(N-1)*DZ
      GO TO 9
   76 WRITE(6,225)
  225 FORMAT(//32X,'TIME LIMIT EXCEEDED')
      GO TO 85
   65 WRITE(6,230)
  230 FORMAT(//32X,'TARGET MOISTURE CONTENT REACHED')
   85 CONTINUE
      CALL TIME(1,-1,ITIME)
      STOP
      END
      FUNCTION ERH(AA,GT)
C     FUNCTION TO CALCULATE INITIAL RELATIVE HUMIDITY WITHIN LAYER
      AW=(AA/(1+AA))
      A=-37357.912
      B=-23.9857
      R=8.315
      ERH=EXP((A/(R*(GT+273.15)))*EXP(B*AW))
      RETURN
      END
      FUNCTION SPR(TT)
C     FUNCTION TO CALCULATE SATURATED VAPOR PRESSURE
      A=-0.274055E3
      B=0.541836E2
      C=-0.451370E-1
      D=0.215321E-4
      E=-0.462027E-8
      F=0.241613E1
      G=0.121547E-2
      R=0.32061854
      T=TT*1.8+491.69
      TP=A+T*(B+T*(C+T*(D+T*E)))
      TQ=(T*(F-G*T))
      TP=TP/TQ
      SPR=EXP(TP)*R*6894.76
      RETURN
      END
      FUNCTION DRK(TA)
C     FUNCTION TO CALCULATE DRYING CONSTANT
      A=11961436.0
      B=-6819.3249
      DRK=A*EXP(B/(273.16+TA))
      RETURN
```

```
      END
      FUNCTION EQMC(TA,RH)
C     FUNCTION TO CALCULATE EQUILIBRIUM MOISTURE CONTENT
      A=10.5293
      B=23.9357
      R=8.315
      EQMC=(A-ALOG(-R*(TA+273.15)*ALOG(RH)))/B
      RETURN
      END
      SUBROUTINE INLET(ETIME,TC)
C     SUBROUTINE TO INTERPOLATE INLET CONDITION FROM GIVEN DATA
      COMMON TIM(200),TAM(200)
      N=21
      B=ETIME
      DO 1 I=1,N
      IF(B.GE.(TIM(I)).AND.B.LT.TIM(I+1)) GO TO 2
    1 CONTINUE
      TC=TAM(N+1)
      GO TO 3
    2 A=(B-TIM(I))/(TIM(I+1)-TIM(I))
      TC=TAM(I)+(TAM(I+1)-TAM(I))*A
    3 RETURN
      END
```

```
                                DEEP BED DRYING OF MALT

                 BED DEPTH                                  =      0.7500   METERS
                 NO. OF LAYERS                              =         150
                 DEPTH OF LAYER                            =     0.0050   METER
                 RUN TIME OF SIMULATION=      10.2500  HOUR.
                 TIME STEP                               =       1.0000MIN.
                 INITIAL MOISTURE CONTENT(D.B.) =        0.6520   DECIMAL
                 INITIAL TEMP. OF MALT                      =     26.4960   DEG C
                 SPECIFIC HEAT OF MALT                      =      1.6510   KJ/KGK
                 DENSITY OF DRY MALT                        =    367.9270   KG/M**3
                 AIR FLOW RA TE                         =    22.2380   KG/MIN.(M**2)


                               TIME=   600.0000MIN
                        MEAN MOISTURE CONTENT= 0.134


                                                                                      DRYING
                                                                      AIR           RATE
POSITION          M.C.          AIR          GRAIN          AIR           RELATIVE        1/MIN.
DEPTH             DRY           TEMP          TEMP        HUMIDITY         HUMIDITY
METER             BASIS         DEGC          DEGC          KG/KG

0.0              0.0660       59.4800       59.4776       0.0147        0.1201        -0.0000
0.0043           0.0660       59.4793       59.4767       0.0147        0.1201        -0.0000
0.0085           0.0660       59.4785       59.4758       0.0147        0.1201        -0.0000
0.0128           0.0661       59.4778       59.4748       0.0147        0.1201        -0.0000
0.0170           0.0661       59.4769       59.4737       0.0147        0.1201        -0.0000
0.0213           0.0661       59.4760       59.4725       0.0147        0.1201        -0.0000
0.0255           0.0661       59.4750       59.4712       0.0147        0.1201        -0.0000
0.0298           0.0661       59.4739       59.4699       0.0147        0.1201        -0.0000
0.0341           0.0662       59.4727       59.4684       0.0147        0.1202        -0.0000
0.0383           0.0662       59.4715       59.4669       0.0147        0.1202        -0.0000
0.0426           0.0662       59.4702       59.4653       0.0147        0.1202        -0.0000
0.0468           0.0662       59.4687       59.4635       0.0147        0.1202        -0.0000
0.0511           0.0663       59.4672       59.4616       0.0147        0.1202        -0.0000
0.0553           0.0663       59.4656       59.4595       0.0147        0.1202        -0.0000
0.0596           0.0663       59.4639       59.4574       0.0147        0.1202        -0.0000
0.0639           0.0664       59.4620       59.4550       0.0147        0.1202        -0.0000
0.0681           0.0664       59.4600       59.4526       0.0147        0.1203        -0.0000
0.0724           0.0665       59.4579       59.4499       0.0147        0.1203        -0.0000
0.0766           0.0665       59.4556       59.4471       0.0147        0.1203        -0.0000
0.0809           0.0666       59.4532       59.4441       0.0147        0.1203        -0.0000
```

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0.0852    0.0666    59.4506    59.4409    0.0147    0.1203    -0.0000
0.0894    0.0667    59.4478    59.4375    0.0147    0.1204    -0.0000
0.0937    0.0667    59.4448    59.4338    0.0147    0.1204    -0.0000
0.0979    0.0668    59.4417    59.4299    0.0147    0.1204    -0.0000
0.1022    0.0668    59.4383    59.4258    0.0147    0.1204    -0.0000
0.1064    0.0669    59.4348    59.4214    0.0147    0.1205    -0.0000
0.1107    0.0670    59.4310    59.4168    0.0147    0.1205    -0.0000
0.1150    0.0670    59.4269    59.4118    0.0147    0.1205    -0.0000
0.1192    0.0671    59.4226    59.4066    0.0147    0.1206    -0.0000
0.1235    0.0672    59.4181    59.4010    0.0147    0.1206    -0.0000
0.1277    0.0673    59.4132    59.3951    0.0147    0.1206    -0.0000
0.1320    0.0674    59.4081    59.3888    0.0147    0.1207    -0.0000
0.1362    0.0675    59.4026    59.3822    0.0147    0.1207    -0.0000
0.1405    0.0676    59.3968    59.3752    0.0147    0.1208    -0.0000
0.1448    0.0677    59.3906    59.3677    0.0147    0.1208    -0.0000
0.1490    0.0678    59.3841    59.3597    0.0147    0.1209    -0.0000
0.1533    0.0679    59.3772    59.3513    0.0147    0.1209    -0.0000
0.1575    0.0681    59.3698    59.3424    0.0147    0.1210    -0.0000
0.1618    0.0682    59.3620    59.3329    0.0147    0.1211    -0.0000
0.1660    0.0683    59.3538    59.3230    0.0147    0.1211    -0.0000
0.1703    0.0685    59.3451    59.3124    0.0147    0.1212    -0.0000
0.1746    0.0686    59.3358    59.3013    0.0147    0.1213    -0.0000
0.1788    0.0688    59.3260    59.2894    0.0148    0.1214    -0.0000
0.1831    0.0690    59.3157    59.2770    0.0148    0.1215    -0.0000
0.1873    0.0692    59.3047    59.2638    0.0148    0.1215    -0.0000
0.1916    0.0694    59.2931    59.2499    0.0148    0.1216    -0.0000
0.1958    0.0696    59.2809    59.2353    0.0148    0.1217    -0.0001
0.2001    0.0698    59.2680    59.2197    0.0148    0.1219    -0.0001
0.2044    0.0700    59.2543    59.2034    0.0148    0.1220    -0.0001
0.2086    0.0703    59.2399    59.1862    0.0148    0.1221    -0.0001
0.2129    0.0705    59.2247    59.1680    0.0148    0.1222    -0.0001
0.2171    0.0708    59.2087    59.1488    0.0148    0.1223    -0.0001
0.2214    0.0711    59.1918    59.1287    0.0148    0.1225    -0.0001
0.2256    0.0714    59.1740    59.1074    0.0148    0.1226    -0.0001
0.2299    0.0717    59.1552    59.0851    0.0148    0.1228    -0.0001
0.2342    0.0720    59.1354    59.0615    0.0148    0.1230    -0.0001
0.2384    0.0723    59.1145    59.0367    0.0148    0.1231    -0.0001
0.2427    0.0727    59.0926    59.0107    0.0148    0.1233    -0.0001
0.2469    0.0731    59.0695    58.9832    0.0148    0.1235    -0.0001
0.2512    0.0735    59.0452    58.9545    0.0148    0.1237    -0.0001
0.2555    0.0739    59.0196    58.9241    0.0149    0.1239    -0.0001
0.2597    0.0743    58.9927    58.8923    0.0149    0.1242    -0.0001
0.2640    0.0748    58.9644    58.8589    0.0149    0.1244    -0.0001
0.2682    0.0753    58.9346    58.8237    0.0149    0.1247    -0.0001
0.2725    0.0758    58.9034    58.7867    0.0149    0.1249    -0.0001
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0.2767     0.0764     58.8705     58.7479     0.0149     0.1252     -0.0001
0.2810     0.0769     58.8359     58.7070     0.0149     0.1255     -0.0001
0.2853     0.0776     58.7996     58.6640     0.0149     0.1258     -0.0002
0.2895     0.0782     58.7614     58.6188     0.0149     0.1262     -0.0002
0.2938     0.0789     58.7212     58.5715     0.0150     0.1265     -0.0002
0.2980     0.0796     58.6790     58.5216     0.0150     0.1269     -0.0002
0.3023     0.0804     58.6347     58.4694     0.0150     0.1273     -0.0002
0.3065     0.0812     58.5882     58.4146     0.0150     0.1277     -0.0002
0.3108     0.0820     58.5393     58.3572     0.0150     0.1281     -0.0002
0.3151     0.0829     58.4881     58.2970     0.0150     0.1286     -0.0002
0.3193     0.0838     58.4343     58.2339     0.0151     0.1290     -0.0002
0.3236     0.0848     58.3779     58.1679     0.0151     0.1295     -0.0002
0.3278     0.0859     58.3199     58.0989     0.0151     0.1301     -0.0003
0.3321     0.0869     58.2570     58.0266     0.0151     0.1306     -0.0003
0.3363     0.0881     58.1923     57.9510     0.0151     0.1312     -0.0003

0.3406     0.0892     58.1245     57.8722     0.0152     0.1318     -0.0003
0.3449     0.0905     58.0536     57.7897     0.0152     0.1325     -0.0003
0.3491     0.0918     57.9795     57.7037     0.0152     0.1332     -0.0003
0.3534     0.0932     57.9021     57.6140     0.0152     0.1339     -0.0003
0.3576     0.0946     57.8213     57.5205     0.0153     0.1346     -0.0004
0.3619     0.0961     57.7369     57.4231     0.0153     0.1354     -0.0004
0.3661     0.0977     57.6489     57.3217     0.0153     0.1363     -0.0004
0.3704     0.0993     57.5572     57.2162     0.0154     0.1371     -0.0004
0.3747     0.1010     57.4617     57.1065     0.0154     0.1380     -0.0004
0.3789     0.1028     57.3622     56.9926     0.0154     0.1390     -0.0004
0.3832     0.1046     57.2587     56.8743     0.0155     0.1400     -0.0005
0.3874     0.1066     57.1511     56.7515     0.0155     0.1411     -0.0005
0.3917     0.1086     57.0393     56.6242     0.0155     0.1422     -0.0005
0.3959     0.1107     56.9232     56.4922     0.0156     0.1433     -0.0005
0.4002     0.1129     56.8027     56.3556     0.0156     0.1445     -0.0006
0.4045     0.1152     56.6778     56.2142     0.0157     0.1458     -0.0006
0.4087     0.1176     56.5484     56.0681     0.0157     0.1471     -0.0006
0.4130     0.1201     56.4143     55.9171     0.0158     0.1485     -0.0006
0.4172     0.1227     56.2756     55.7612     0.0158     0.1500     -0.0006
0.4215     0.1253     56.1321     55.6004     0.0159     0.1515     -0.0007
0.4258     0.1281     55.9839     55.4347     0.0159     0.1531     -0.0007
0.4300     0.1310     55.8309     55.2640     0.0160     0.1548     -0.0007
0.4343     0.1340     55.6730     55.0884     0.0160     0.1565     -0.0007
0.4385     0.1370     55.5103     54.9077     0.0161     0.1583     -0.0008
0.4428     0.1402     55.3426     54.7222     0.0162     0.1602     -0.0008
0.4470     0.1435     55.1701     54.5316     0.0162     0.1622     -0.0008
0.4513     0.1469     54.9926     54.3360     0.0163     0.1642     -0.0008
0.4556     0.1504     54.8102     54.1355     0.0164     0.1663     -0.0009
0.4598     0.1540     54.6228     53.9301     0.0164     0.1686     -0.0009
0.4641     0.1577     54.4306     53.7198     0.0165     0.1709     -0.0009
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0.4683      0.1615      54.2334      53.5047      0.0166      0.1733      -0.0009
0.4726      0.1655      54.0313      53.2848      0.0167      0.1758      -0.0010
0.4768      0.1695      53.8244      53.0602      0.0168      0.1784      -0.0010
0.4811      0.1737      53.6128      52.8311      0.0168      0.1811      -0.0010
0.4854      0.1779      53.3964      52.5975      0.0169      0.1839      -0.0011
0.4896      0.1823      53.1753      52.3595      0.0170      0.1868      -0.0011
0.4939      0.1867      52.9497      52.1172      0.0171      0.1898      -0.0011
0.4981      0.1913      52.7196      51.8707      0.0172      0.1929      -0.0011
0.5024      0.1959      52.4851      51.6202      0.0173      0.1962      -0.0012
0.5066      0.2006      52.2463      51.3658      0.0174      0.1996      -0.0012
0.5109      0.2055      52.0034      51.1075      0.0175      0.2030      -0.0012
0.5152      0.2104      51.7563      50.8456      0.0176      0.2066      -0.0012
0.5194      0.2154      51.5053      50.5801      0.0177      0.2104      -0.0012
0.5237      0.2206      51.2504      50.3112      0.0178      0.2142      -0.0013
0.5279      0.2258      50.9918      50.0391      0.0179      0.2182      -0.0013
0.5322      0.2310      50.7296      49.7638      0.0180      0.2223      -0.0013
0.5364      0.2365      50.4639      49.4853      0.0181      0.2266      -0.0013
0.5407      0.2419      50.1949      49.2044      0.0182      0.2309      -0.0013
0.5450      0.2474      49.9227      48.9208      0.0183      0.2355      -0.0014
0.5492      0.2530      49.6476      48.6347      0.0184      0.2401      -0.0014
0.5535      0.2587      49.3676      48.3464      0.0185      0.2449      -0.0014
0.5577      0.2644      49.0889      48.0560      0.0187      0.2499      -0.0014
0.5620      0.2701      48.8057      47.7638      0.0188      0.2550      -0.0014
0.5663      0.2760      48.5202      47.4698      0.0189      0.2602      -0.0014
0.5705      0.2819      48.2325      47.1740      0.0190      0.2656      -0.0014
0.5748      0.2878      47.9420      46.8771      0.0191      0.2711      -0.0014
0.5790      0.2938      47.6512      46.5790      0.0192      0.2768      -0.0015
0.5833      0.2997      47.3580      46.2798      0.0194      0.2826      -0.0015
0.5875      0.3055      47.0634      45.9799      0.0195      0.2886      -0.0015
0.5918      0.3113      46.7674      45.6793      0.0196      0.2947      -0.0015

0.5961      0.3177      46.4704      45.3782      0.0197      0.3010      -0.0015
0.6003      0.3239      46.1723      45.0767      0.0199      0.3075      -0.0015
0.6046      0.3301      45.8735      44.7751      0.0200      0.3141      -0.0015
0.6088      0.3362      45.5741      44.4734      0.0201      0.3208      -0.0015
0.6131      0.3423      45.2742      44.1718      0.0202      0.3277      -0.0015
0.6173      0.3485      44.9740      43.8704      0.0203      0.3348      -0.0015
0.6216      0.3547      44.6735      43.5690      0.0205      0.3420      -0.0015
0.6259      0.3608      44.3730      43.2685      0.0206      0.3494      -0.0015
0.6301      0.3670      44.0726      42.9684      0.0207      0.3570      -0.0015
0.6344      0.3732      43.7724      42.6691      0.0208      0.3647      -0.0015
0.6386      0.3794      43.4725      42.3705      0.0210      0.3725      -0.0015
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