AIRAH SEMINAR

Refrigerating for Meat Quality.

Thursday 11th July 1996

Introduction to Refrigeration Modelling.
Typical Blast Freezer Cell Application.

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Introduction.

This paper provides an overview of the design steps necessary and methods used for designing a typical blast freezer cell for meat carton freezing duty.

The paper concentrates on the cell layout, construction and freezing application, using the MIRINZ Food Product Modeller computer program as a design aid. By using this program we can establish the freezing time, air temperature and air velocity necessary to achieve the desired end result. From this data the refrigeration plant can be designed. By utilising the model we can demonstrate the effects of variances that product type, packaging and air temperature will have on the end result.

From this presentation we hope you will obtain an understanding of the importance that must be placed on accessing the correct data before starting any design for a blast freezer that has to meet a specific time and temperature specification.

Stepping through our sample application we first of all have to obtain the customer specification.

1. Customer Information.

Meat cartons and Specification.	(You will normally be told a standard meat carton)
- Obtain a sample	(There is usually more than one construction)
- Observe construction	(There is usually more than one type)
- Observe board thickness	(There are several types and thicknesses)
- Take external dimensions	(There is usually more than one size)
- Plastic carton liners	(Plastic thickness & expected air gaps in pack)
- Determine type of product	(The product type will vary between packs)
- Determine packed weight	(The normal weight is 72.27 kG (60lb) however this can also vary.
- Desired freezing capacity	(Number of cartons per day)
- Product entering temperature	(For each carton type)
- Product leaving temperature	(For each carton type)
- Desired freezing time	(Hours product will be in the freezer)
- Loading sequence	(How often will freezer doors be open)
- Construction constraints	(Building size, height restrictions, floor ventilation)

All of this information must be obtained before you can actually start to design the freezer.

2. Freezer Layout.

- This step determines the size and loading of each freezer cell.
- As most product in this type of freezer is frozen on racks or stillages, we must layout the freezer to obtain the best possible freezing arrangement.
- Sheet 1 This shows a loading plan, nominating the number of cartons per rack shelf, number of shelves per rack, number of racks long, wide, high and number of cartons per cell.
- Sheet 2 Shows a typical section through the freezer, in this instance we have two freezer cells back to back. As the established freezing cycle is over two days, the consecutive cells are loaded on alternate days.
- Sheet 3 Provides an elevation along the cell showing the cartons placed on the freezer racks, evaporators above and false ceiling air baffle. This view gives us a picture of the carton ends exposed to the air movement.
- Sheet 4 Is an exploded view of a section of sheet three, showing the air gaps around the carton surfaces. This air gap area has to be calculated and combined with the air volume from the evaporator fans, this calculation then provides us with the air speed over the carton surfaces. As the cartons are effectively one length across the cell this is considered a rod when using the computer model, if all surfaces were touching this would then be considered a slab, creating an extended effect on the freezing time.
- Sheet 5 Is a plan view showing the evaporators, fans, air direction and false ceiling. Depending on the design specifications, the air could be directed along the room rather than across as shown in this example.
- Sheet 6 This is a plan view under the false ceiling, showing the carton and freezer rack layout.
- Sheet 7 Is an exploded plan view of one of the freezer racks showing the carton loading configuration and air gaps.
- Sheet 8 Is a summary of our calculations to date, showing the area of the air gaps, and some nominal air volume figures to set the tone for our first try at producing the computer model.

All of the steps as detailed have to be considered, and determined to be as practical as possible in relation to the customer specification, building restraints etc before producing the first freezing model.

3. Computer Model.

We have prepared a model showing three examples for the basic design, the first example is as shown starting on sheet 9

- **Example #1 Sheets 9/10**

  This example shows a typical design for a 175mm thick carton, having an air velocity over the carton of 2.5m/s at a temperature of -32c. from this the computer generated time for freezing the product from +10c to -10c is 46 hours.

- **Example #2 Sheets 11/12**

  For this example all criteria for freezing is the same as above, we have however assessed the operation and concluded the concept of a freezer operating over a 48 hour period with a constant air temperature of -32c is not practical. We therefore have imposed an air temperature change into the program. and now show this to be 12 hours at -26c and 12 hours at -32c. This would compensate for loading time, defrosting and product pull down.

  This now gives us an extended freezing time, changing from 46 to 55 hours.

- **Example #3 Sheets 13/14**

  This example is as per example #1 except that the carton thickness has been increased from 175mm to 185mm. This change extends the freezing time from 46 to 49 hours.

As can be seen the relative minor changes to the freezing pattern have a great effect on the overall freezing time. There are many variances that can be factored into the model calculation.

Some are as listed.

- Time
- Final Temperature
- Cardboard Thickness / Type
- Number of cardboard layers
- Product type/Composition
- Product wrapping
- Mean or All node temperatures
- Varying Surface Conditions
- Initial Temperature
- Carton Dimensions
- Air velocity
- Carton Construction
- Air gaps
- Stopping time
- Number of nodes
- Freezer operation

4. Conclusion.

The following charts show some typical freezer results, as can be seen the air temperature is not constant, varying during the pull down period with peaks occurring during loading and defrost times. We also see a difference between the freezing times for different carton sizes in the same freezer.

The MIRINZ Computer Model therefore provides us with a most useful tool, this enables us to examine and explore the effects and variances that can be expected in the operation of a manually loaded, batch blast freezer the type that is found in many Australian abattoirs and meat packing factories.

It is a lot more pleasant to do this examination at the computer before the project has been constructed rather than after if the freezing times and results are not as expected.

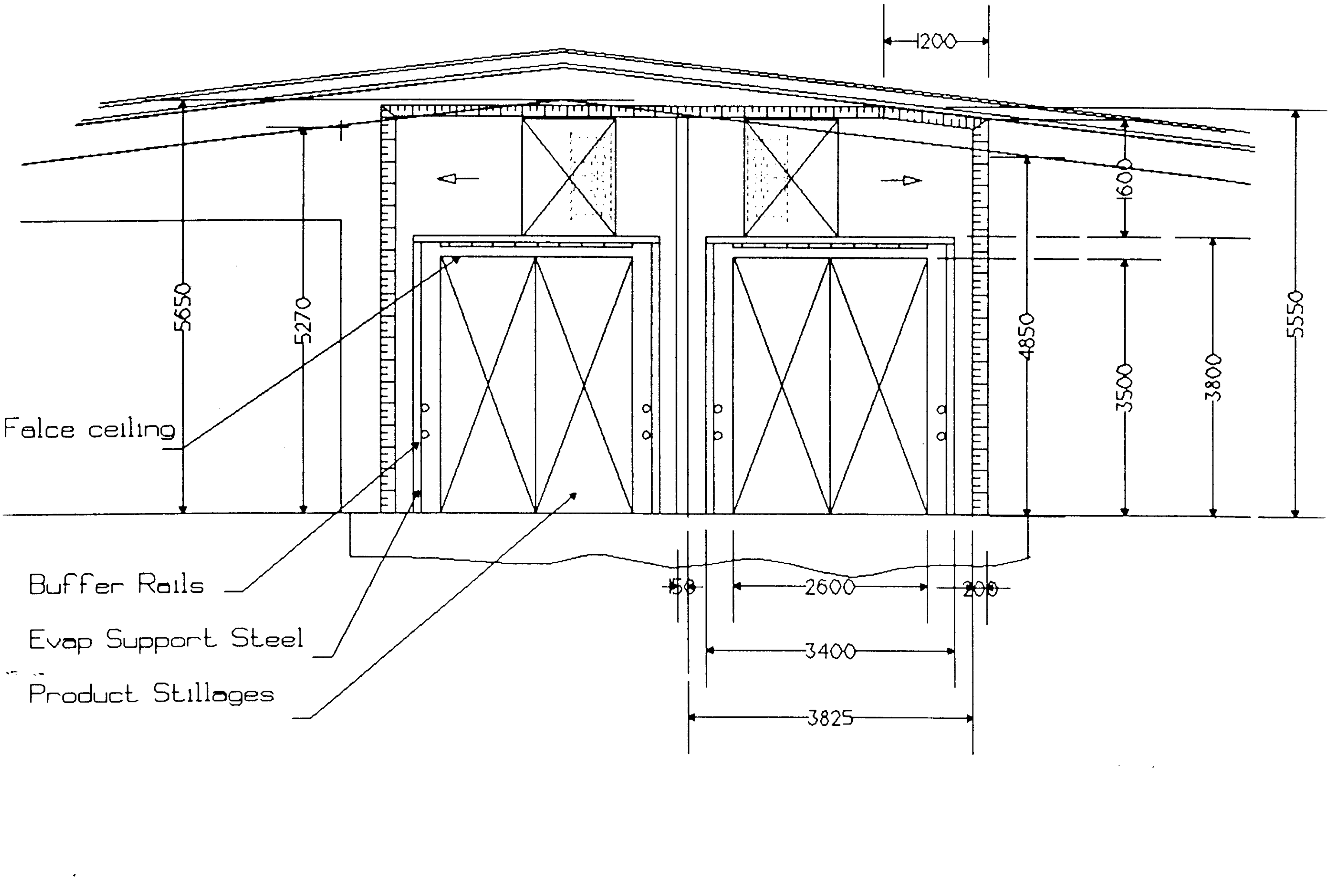
Example Freezer Tests Sheets 15/16

Sheet No 1

Freezer Cell Loading
5 x Cartons per shelf
7 x Shelves per stillage
8 x Stillages Long
2 x Stillages Wide
2 x Stillages High
Carton Capacity per Cell = 1120
Freezing Cycle 48 hours
Carton Dimensions
Type A - 360x540x160
Type B - 375x575x135
O/A Stillage Dimensions
1000W x 1300D x 1775H

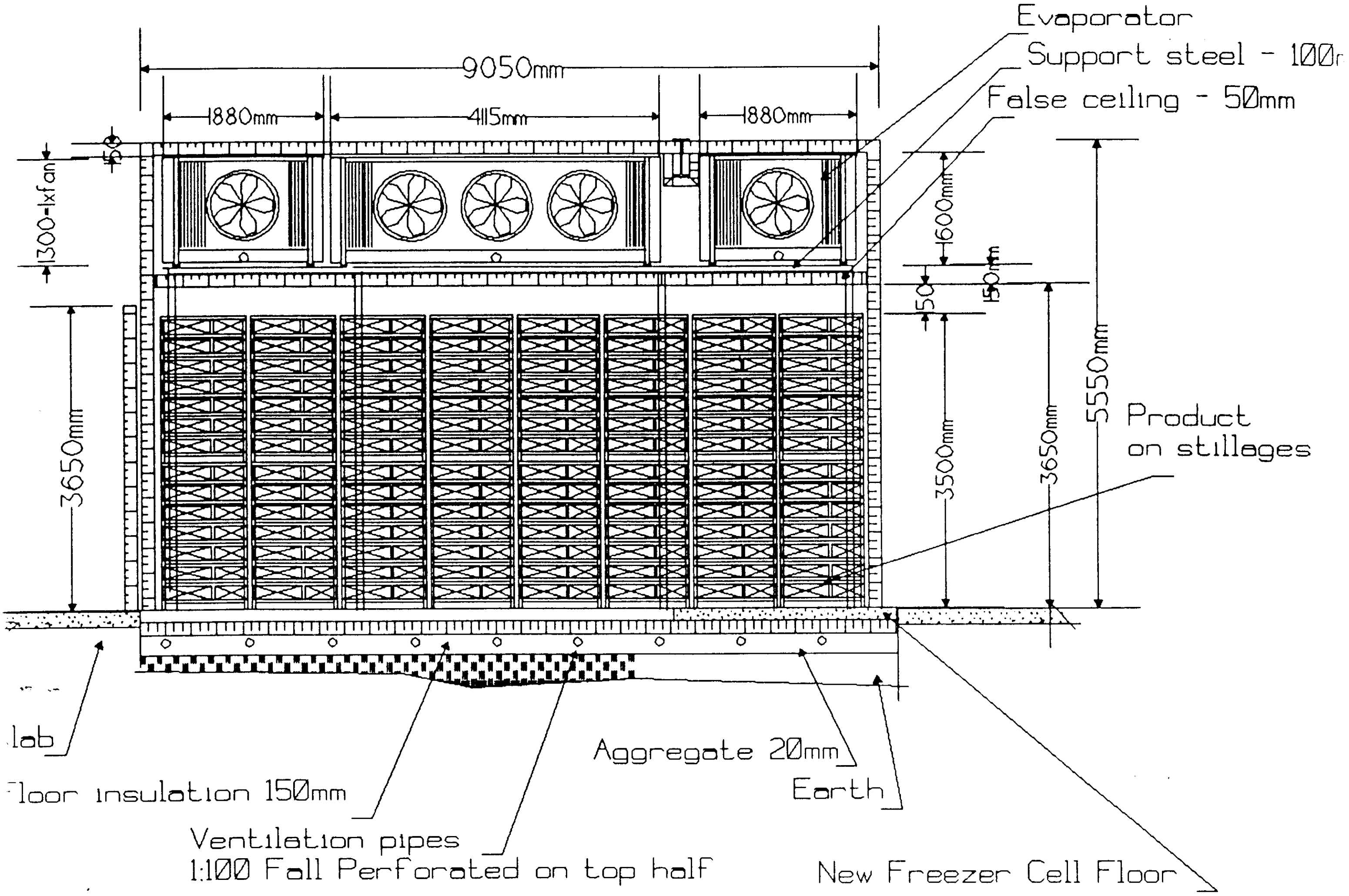
Sheet No 2

BUILDING & FREEZER SECTION A - A

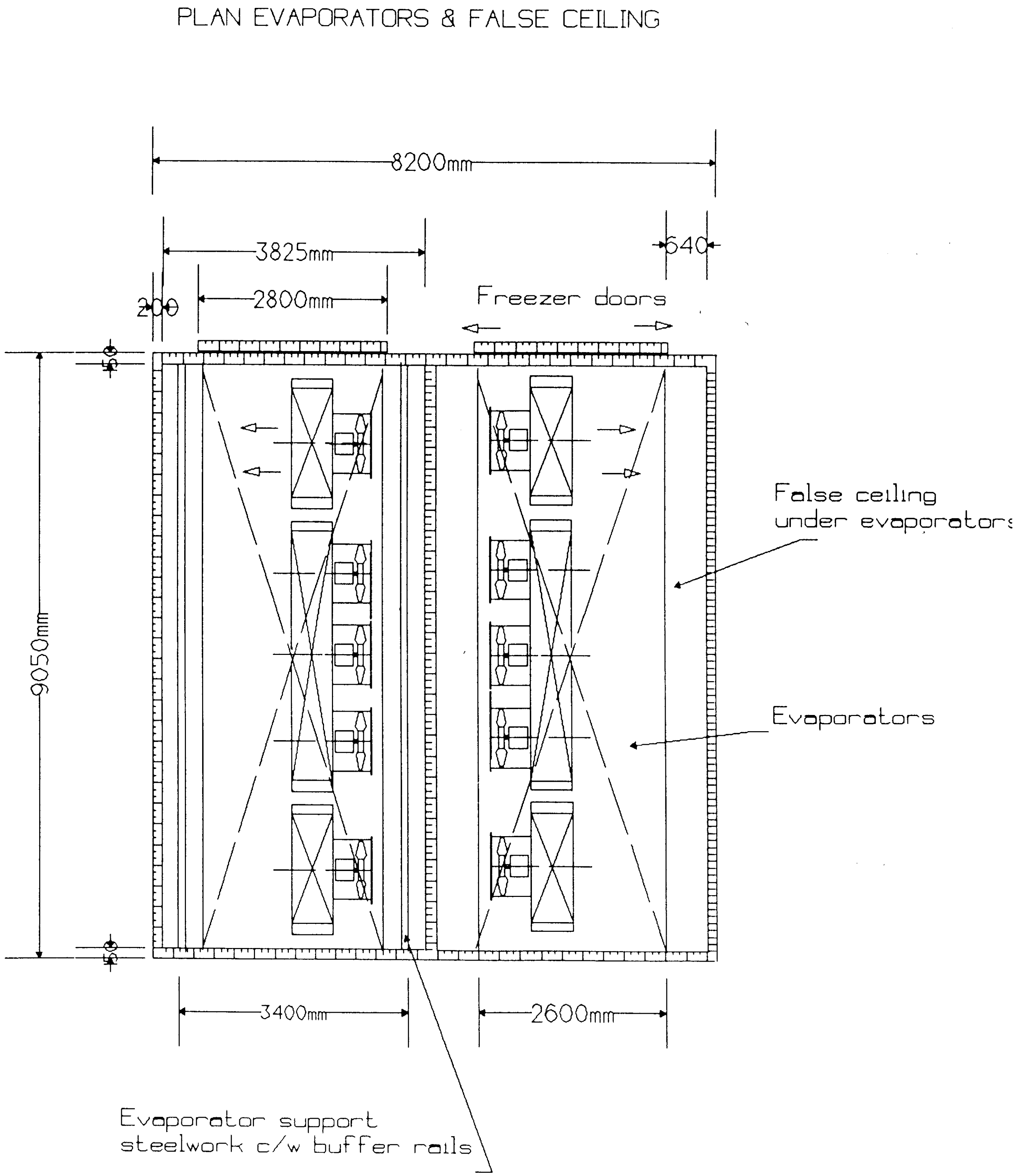


Sheet No 3

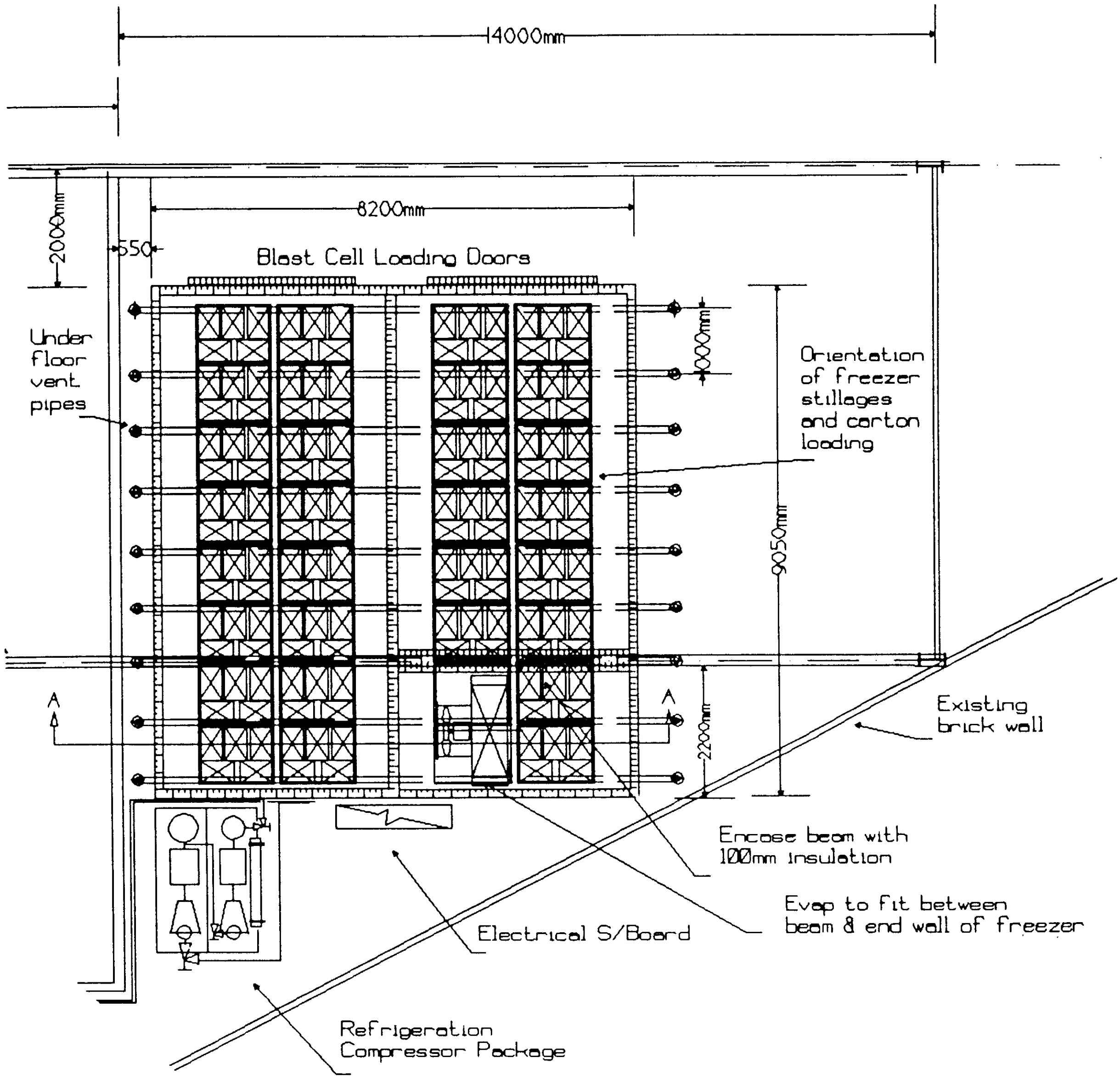
SECTION ELEVATION FREEZER CELL



Sheet No 5


PLAN EVAPORATORS & FALSE CEILING
8200mm
3825mm
640
200
2800mm
Freezer doors
50
9050mm
50
False ceiling
under evaporators
Evaporators
3400mm
2600mm
Evaporator support
steelwork c/w buffer rails

Sheet No 6


14000mm
8200mm
2000mm
550
Blast Cell Loading Doors
Under floor vent pipes
1000mm
Orientation of freezer stillages and carton loading
9050mm
A
A
2200mm
Existing brick wall
Encase beam with 100mm insulation
Evap to fit between beam & end wall of freezer
Electrical S/Board
Refrigeration Compressor Package

Sheet No 8

Refrigerating for Meat Quality
Seminar

Refrigerating for Meat Quality.						
Typical Blast Freezer Design						
Freezer Design and Loading						
	Carton blast freezer cells			2		
	Cartons per cell			1120		
	Freezing cycle hrs			48		
	Cartons on stillages			32		
	Cartons per shelf			5		
	Shelves per stillage			7		
	Cartons per stillage			35		
	Stillages placed long			8		
	Stillages places deep			2		
	Stillages high			2		
	A - Carton Size	360	540	160		
	B - Carton Size	375	575	135		
	Average carton weight kG			27.4		
	Total product kG in each cell			30,000		
Air Space and Velocity				A	B	
	Carton sides in air stream			112	112	
	Carton ends in air stream			112	112	
	Carton sides area sqm			9.7	8.7	
	Carton ends area sqm			6.5	5.7	
	Total area cartons facing air stream			16.2	14.4	
	Stillage steel frames		20%	3.2	3.2	
	Total solids area cartons & stillages			19.4	17.6	
	Freezer cell area under falce ceiling			33.25	33.25	
	Free area for air		sqm	13.85	15.65	
	Nominal Air volume from evaps		cm/sec	36	36	
	Air velocity over cartons		M/sec	2.6	2.3	
	Calculated velocity required		M/sec	2.5	2	
	Air volum required per cell		M/sec	34.6	31.3	

BLAST FREEZER EXAMPLE 1

Notes:
Carton blast freezer cells
with air flow accross the cell

Simulation data:

Geometry:
Meat Carton (slab)

Dimension	Size	# of nodes
Top-Bottom	175 mm	6

Initial Conditions:
Initial temperature: 10°C

Boundary Conditions:
Boundary: Top
Heat transfer medium: Air
Air gap: 1mm
Plastic thickness: 0.3mm
Card layer 1: B-flute

Time (hr)	Temperature (°C)
48	-32

Time (hr)	Velocity (m/s)
48	2.5

Boundary: Bottom
Heat transfer medium: Air
Plastic thickness: 0.3mm
Card layer 1: B-flute
Card layer 2: B-flute

Time (hr)	Temperature (°C)
48	-32

Time (hr)	Velocity (m/s)
48	2.5

Thermal Properties:
Food type: Meat, lean, typical*

Temperature (°C)	Enthalpy (MJ/m³)
-100.9	-93.5018
-40.9	-1.71895
-20.9	40.7068
-10.9	70.1318
-5.9	96.9509
-3.4	128.732
-2.15	168.301
-1.525	211.605
-1.2125	250.247
-0.9	316.966
39.1	469.489
199.1	1079.58

Temperature (°C)	Conductivity (W/(m.K))
-100.9	2.10199
-40.9	1.56097
-20.9	1.42845
-10.9	1.34472
-5.9	1.25259
-3.4	1.12724
-2.15	0.970374
-1.525	0.937143
-1.2125	0.776939
-0.9	0.459824
39.1	0.504472
199.1	0.676545

Temperature (°C)	Internal heating (W/m³)
-100.9	0
-40.9	0
-20.9	0
-10.9	0
-5.9	0
-3.4	0
-2.15	0
-1.525	0
-1.2125	0
-0.9	0
39.1	0
199.1	0

Computational Details:

Time step:	0.25hr
Output time step:	1hr

Output Nodes:
Tot. Enth.
Heat Flow
Mean Temp.

Stopping criteria:
The model will stop calculating when the mean temperature has reached -10°C

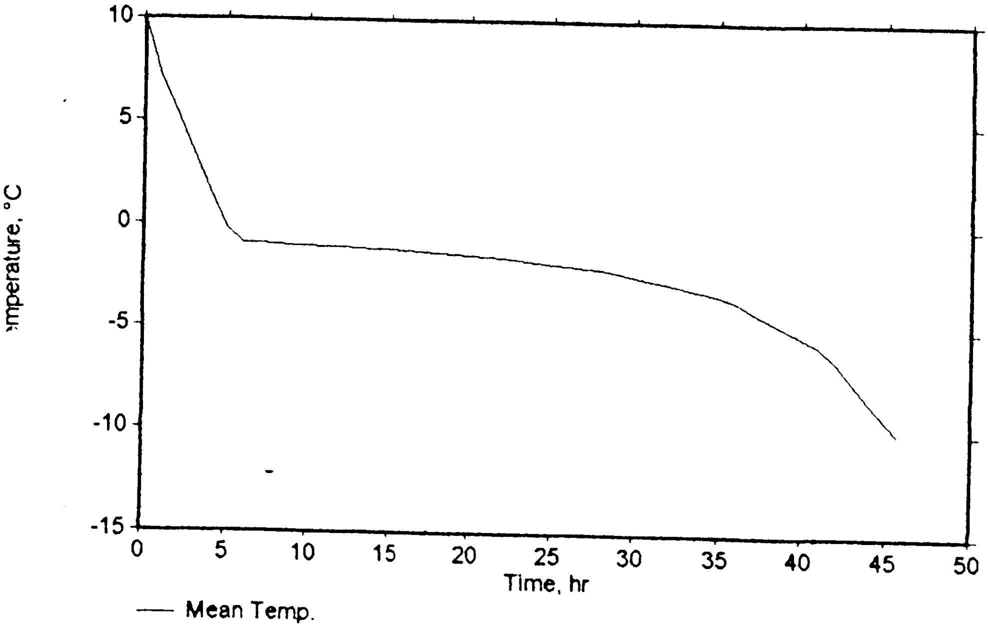
Final Values:
Finish time: 45.9857hr

Temperatures in °C:

x=	1	2	3	4	5	6
Temp.=	-11.2524	-9.49909	-8.72734	-8.95007	-10.1556	-12.2391

BLAST FREEZER EXAMPLE 1

Time hr	Heat Flow W/m³	Mean Temp. °C	Tot. Enth. MJ
0	0	10	62.7425
1	2052.93	7.19415	60.8702
2	1958.04	5.32676	59.6241
3	1956.45	3.45932	58.378
4	1950.09	1.61615	57.1481
5	1943.83	-0.221295	55.922
6	1937.52	-0.920588	54.6998
7	1931.31	-0.953192	53.4817
8	1924.4	-0.985687	52.2675
9	1916.24	-1.01805	51.0584
10	1907.22	-1.05027	49.8546
11	1895.78	-1.08231	48.6574
12	1884.28	-1.11415	47.4676
13	1865.24	-1.14573	46.2879
14	1842.06	-1.17694	45.1218
15	1820.07	-1.20777	43.97
16	1790.83	-1.25678	42.835
17	1765.69	-1.30847	41.7165
18	1742.65	-1.35943	40.6136
19	1727.12	-1.40987	39.5222
20	1716.01	-1.45995	38.4386
21	1707.55	-1.50975	37.361
22	1699.93	-1.58626	36.2882
23	1692.44	-1.67434	35.2202
24	1684.64	-1.76202	34.157
25	1675.49	-1.84927	33.0992
26	1660.1	-1.93582	32.0497
27	1646.51	-2.02163	31.0092
28	1633.72	-2.10676	29.977
29	1619.06	-2.24015	28.9534
30	1600.33	-2.42292	27.9409
31	1586.03	-2.60387	26.9385
32	1572.78	-2.78331	25.9445
33	1560.39	-2.96127	24.9586
34	1549.94	-3.13797	23.9797
35	1540.95	-3.31359	23.0069
36	1532.78	-3.61975	22.0393
37	1524.6	-4.05237	21.0769
38	1515.69	-4.48255	20.1198
39	1505.61	-4.91002	19.1688
40	1492.94	-5.33425	18.225
41	1475.11	-5.75396	17.2913
42	1452.5	-6.53482	16.3705
43	1422.18	-7.49719	15.4672
44	1387.94	-8.43765	14.5844
45	1339.03	-9.34977	13.7282
45.75	1296.95	-10.01	13.1085



Sheet No 11

BLAST FREEZER EXAMPLE 2

Notes:
Carton blast freezer cells
with air flow accross the cell

Simulation data:

Geometry:
Meat Carton (slab)

Dimension	Size	# of nodes
Top-Bottom	175 mm	6

Initial Conditions:
Initial temperature: 10°C

Boundary Conditions:
Boundary: Top
Heat transfer medium: Air
Air gap: 1mm
Plastic thickness: 0.3mm
Card layer 1: B-flute

Time (hr)	Temperature (°C)
12	-32
12	-26

Time (hr)	Velocity (m/s)
48	2.5

Boundary: Bottom
Heat transfer medium: Air
Plastic thickness: 0.3mm
Card layer 1: B-flute
Card layer 2: B-flute

Time (hr)	Temperature (°C)
12	-32
12	-26

Time (hr)	Velocity (m/s)
48	2.5

Thermal Properties:
Food type: Meat, lean, typical*

Temperature (°C)	Enthalpy (MJ/m^3)
-100.9	-93.5018
-40.9	-1.71895
-20.9	40.7068
-10.9	70.1318
-5.9	96.9509
-3.4	128.732
-2.15	168.301
-1.525	211.605
-1.2125	250.247
-0.9	316.966
39.1	469.489
199.1	1079.58

Temperature (°C)	Conductivity (W/(m.K))
-100.9	2.10199
-40.9	1.56097
-20.9	1.42845
-10.9	1.34472
-5.9	1.25259
-3.4	1.12724
-2.15	0.970374
-1.525	0.937143
-1.2125	0.776939
-0.9	0.459824
39.1	0.504472
199.1	0.676545

Temperature (°C)	Internal heating (W/m^3)
-100.9	0
-40.9	0
-20.9	0
-10.9	0
-5.9	0
-3.4	0
-2.15	0
-1.525	0
-1.2125	0
-0.9	0
39.1	0
199.1	0

Computational Details:
Time step: 0.25hr
Output time step: 1hr

Output Nodes:
Tot. Enth.
Heat Flow
Mean Temp.

Stopping criteria:
The model will stop calculating when the mean temperature has reached -10°C

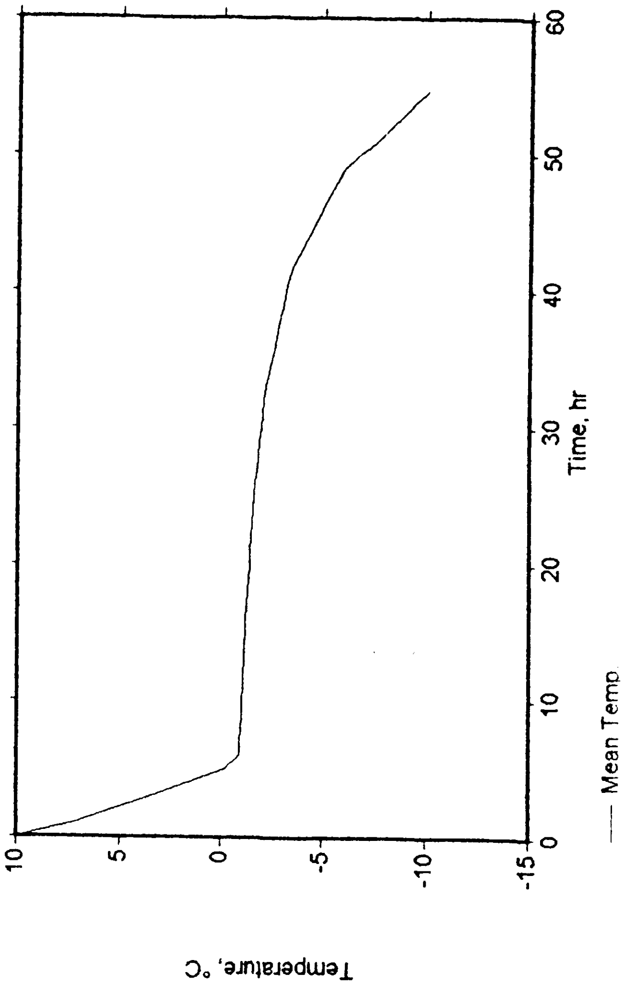
Final Values:
Finish time: 54.9441hr

Temperatures in °C:

x=	1	2	3	4	5	6
Temp.=	-10.8333	-9.66434	-9.12173	-9.25314	-10.0698	-11.5607

BLAST FREEZER EXAMPLE 2

Time hr	Heat Flow W/m³	Mean Temp. °C	Tot. Enth. MJ
0	0	10	62.7425
1	2052.93	7.19415	60.8702
2	1958.04	5.32676	59.6241
3	1956.45	3.45932	58.378
4	1950.09	1.61615	57.1481
5	1943.83	-0.221295	55.922
6	1937.52	-0.920588	54.6998
7	1931.31	-0.953192	53.4817
8	1924.4	-0.985687	52.2675
9	1916.24	-1.01805	51.0584
10	1907.22	-1.05027	49.8546
11	1895.78	-1.08231	48.6574
12	1884.28	-1.11415	47.4676
13	1489.43	-1.14056	46.4812
14	1473.75	-1.16551	45.5488
15	1458.15	-1.19019	44.6266
16	1443.94	-1.21617	43.7137
17	1426.83	-1.25792	42.8103
18	1411.09	-1.29916	41.9178
19	1398.62	-1.34002	41.0337
20	1385.12	-1.38048	40.1581
21	1375.47	-1.42063	39.2895
22	1368.18	-1.46054	38.4259
23	1362.2	-1.50026	37.5663
24	1356.65	-1.55144	36.7103
25	1351.32	-1.62176	35.8577
26	1345.81	-1.69179	35.0086
27	1339.97	-1.76153	34.163
28	1333.14	-1.83094	33.3214
29	1325.72	-1.89996	32.4845
30	1317.93	-1.9686	31.6523
31	1309.58	-2.0368	30.8253
32	1301.24	-2.10457	30.0035
33	1292.17	-2.19795	29.1871
34	1281.23	-2.34411	28.3774
35	1270.98	-2.48908	27.5743
36	1262.07	-2.63298	26.7772
37	1254.46	-2.77596	25.9852
38	1247.7	-2.91814	25.1975
39	1240.01	-3.05952	24.4143
40	1230.67	-3.19985	23.6369
41	1223.07	-3.33926	22.8647
42	1216.09	-3.59387	22.0969
43	1208.79	-3.93696	21.3336
44	1200.89	-4.27789	20.5751
45	1192.02	-4.61642	19.822
46	1182.11	-4.95224	19.0749
47	1170.71	-5.28502	18.3346
48	1156.29	-5.61411	17.6024
49	1135.89	-5.99013	16.8818
50	1111.57	-6.74261	16.1755
51	1084.21	-7.47721	15.4859
52	1053.51	-8.19233	14.8147
53	1017.83	-8.8846	14.1649
54	980.176	-9.55205	13.5383
54.75	946.656	-10.0341	13.0858



BLAST FREEZER EXAMPLE 3

Notes:
Carton blast freezer cells
with air flow accross the cell

Simulation data:

Geometry:
Meat Carton (slab)

Dimension	Size	# of nodes
Top-Bottom	185 mm	6

Initial Conditions:
Initial temperature: 10°C

Boundary Conditions:

Boundary: Top
Heat transfer medium: Air
Air gap: 1mm
Plastic thickness: 0.3mm
Card layer 1: B-flute

Time (hr)	Temperature (°C)
48	-32

Time (hr)	Velocity (m/s)
48	2.5

Boundary: Bottom
Heat transfer medium: Air
Plastic thickness: 0.3mm
Card layer 1: B-flute
Card layer 2: B-flute

Time (hr)	Temperature (°C)
48	-32

Time (hr)	Velocity (m/s)
48	2.5

Thermal Properties:
Food type: Meat, lean, typical*

Temperature (°C)	Enthalpy (MJ/m³)
-100.9	-93.5018
-40.9	-1.71895
-20.9	40.7068
-10.9	70.1318
-5.9	96.9509
-3.4	128.732
-2.15	168.301
-1.525	211.605
-1.2125	250.247
-0.9	316.966
39.1	469.489
199.1	1079.58

Temperature (°C)	Conductivity (W/(m.K))
-100.9	2.10199
-40.9	1.56097
-20.9	1.42845
-10.9	1.34472
-5.9	1.25259
-3.4	1.12724
-2.15	0.970374
-1.525	0.937143
-1.2125	0.776939
-0.9	0.459824
39.1	0.504472
199.1	0.676545

Temperature (°C)	Internal heating (W/m³)
-100.9	0
-40.9	0
-20.9	0
-10.9	0
-5.9	0
-3.4	0
-2.15	0
-1.525	0
-1.2125	0
-0.9	0
39.1	0
199.1	0

Computational Details:

Time step:	0.25hr
Output time step:	1hr

Output Nodes:
Tot. Enth.
Heat Flow
Mean Temp.

Stopping criteria:
The model will stop calculating when the mean temperature has reached -10°C

Final Values:
Finish time: 49.0313hr

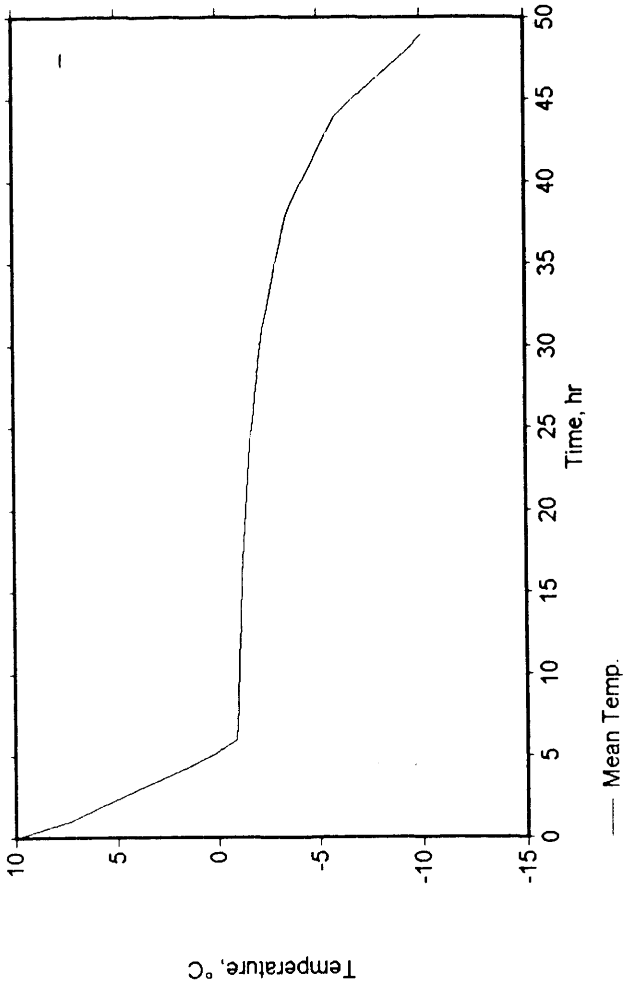
Temperatures in °C:

x=	1	2	3	4	5	6
Temp.=	-11.5692	-9.69136	-8.85954	-9.09283	-10.3562	-12.5241

Sheet No 14

BLAST FREEZER EXAMPLE 3

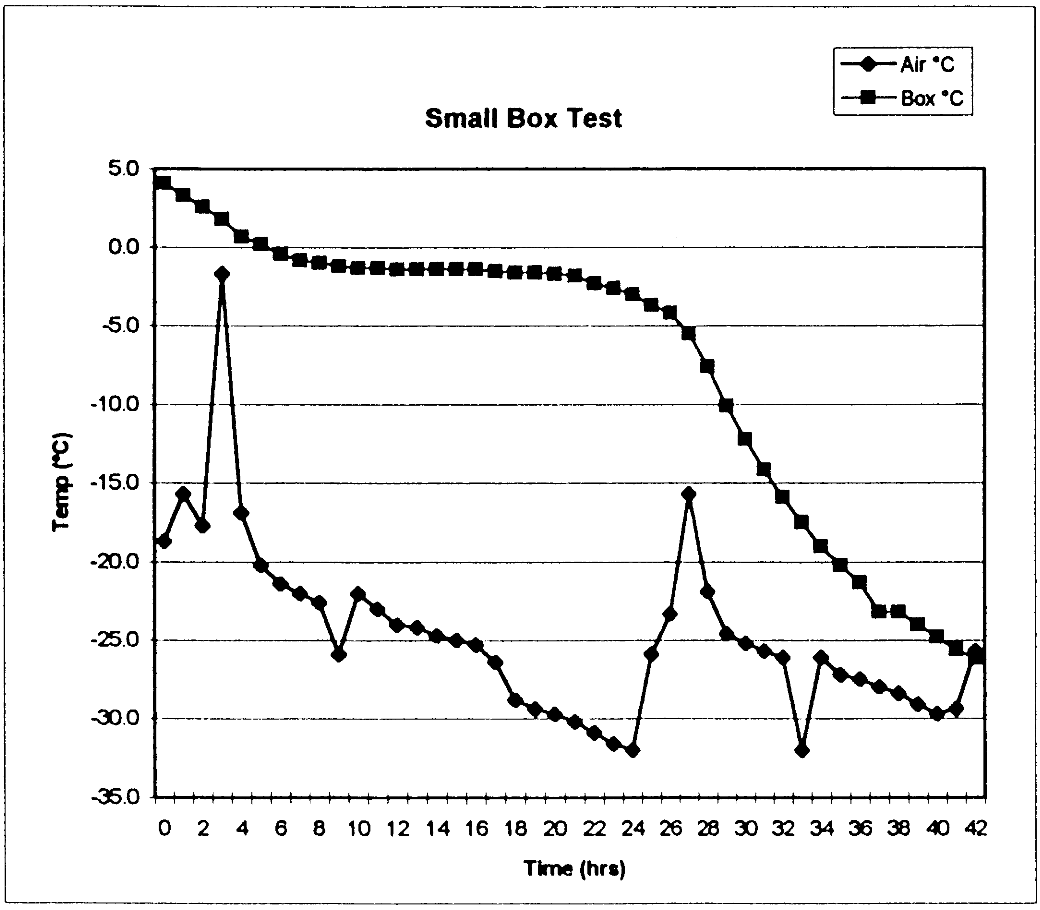
Time hr	Heat Flow W/m³	Mean Temp. °C	Tot. Enth. MJ
0	0	10	66.3278
1	1937.43	7.35929	64.465
2	1853.48	5.59659	63.2215
3	1847.59	3.82985	61.9753
4	1839.44	2.09159	60.7491
5	1833.97	0.358064	59.5262
6	1828.17	-0.908394	58.3072
7	1822.46	-0.93916	57.092
8	1816.7	-0.96983	55.8806
9	1809.61	-1.00039	54.6736
10	1802.36	-1.03083	53.4714
11	1793.33	-1.06112	52.2747
12	1782.89	-1.09125	51.0847
13	1770.59	-1.12119	49.902
14	1752.45	-1.15086	48.7303
15	1730.96	-1.18018	47.5722
16	1709.56	-1.20915	46.4279
17	1682.81	-1.25599	45.3008
18	1658.79	-1.30456	44.1898
19	1637.74	-1.35245	43.0942
20	1622.89	-1.39985	42.0099
21	1612.24	-1.4469	40.9337
22	1604.16	-1.49369	39.8634
23	1597.19	-1.55224	38.7979
24	1590.39	-1.635	37.737
25	1583.56	-1.71741	36.6807
26	1575.52	-1.79945	35.6291
27	1562.58	-1.88088	34.5853
28	1551.06	-1.9617	33.5495
29	1539.78	-2.04192	32.5211
30	1528.3	-2.12156	31.5004
31	1510.96	-2.26034	30.4896
32	1495.9	-2.43107	29.4897
33	1483.56	-2.6003	28.4987
34	1471.19	-2.76814	27.5158
35	1459.88	-2.93463	26.5408
36	1450.34	-3.09997	25.5726
37	1442.14	-3.26431	24.6101
38	1434.7	-3.4692	23.6528
39	1427.62	-3.87423	22.7002
40	1420.29	-4.27722	21.7524
41	1412.29	-4.67802	20.8098
42	1402.92	-5.07636	19.873
43	1390.12	-5.47144	18.9438
44	1374.4	-5.86238	18.0244
45	1353.83	-6.72509	17.1172
46	1327.5	-7.62284	16.2263
47	1298.04	-8.50171	15.3542
48	1254.41	-9.35493	14.5076
49	1203.53	-10.1763	13.6925



Sheet No 15

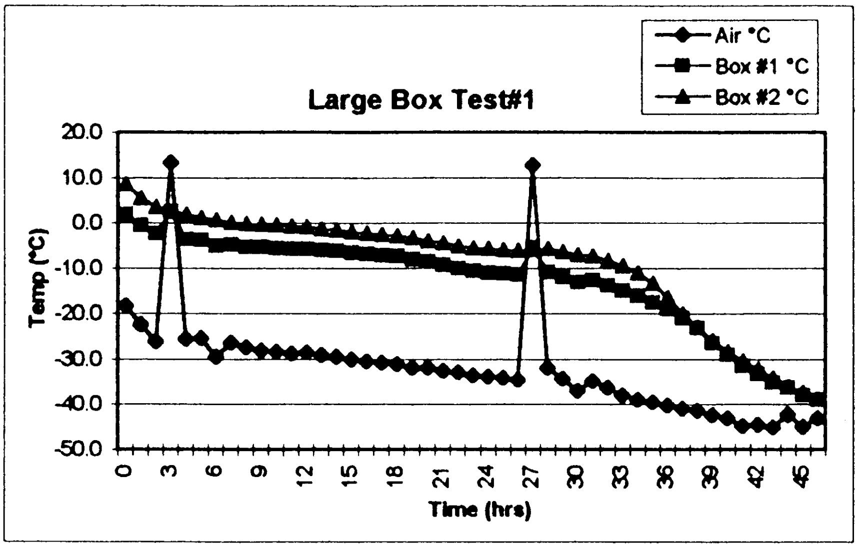
SMALL BOX TEST

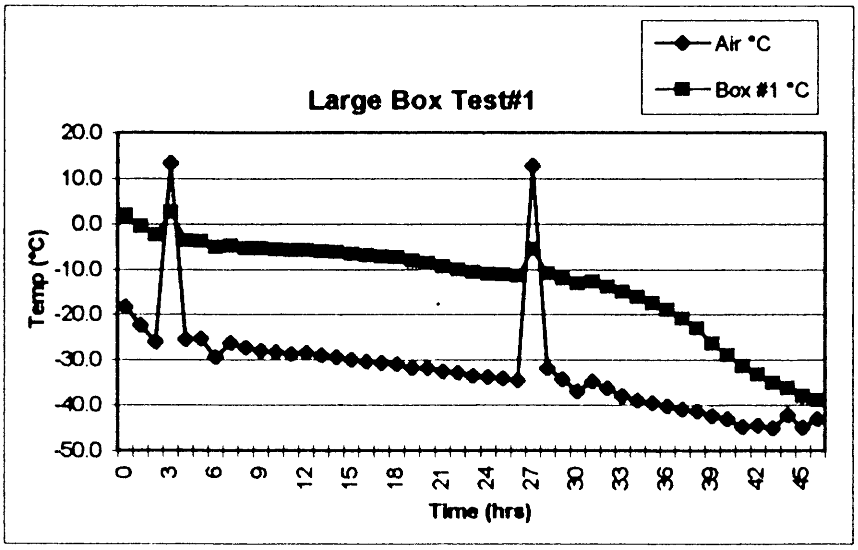
Time (hrs)	Air °C	Box °C
0	-18.7	4.1
1	-15.7	3.3
2	-17.7	2.6
3	-1.7	1.8
4	-16.9	0.7
5	-20.2	0.2
6	-21.4	-0.4
7	-22.0	-0.8
8	-22.6	-1.0
9	-25.9	-1.2
10	-22.0	-1.3
11	-23.0	-1.3
12	-24.0	-1.4
13	-24.2	-1.4
14	-24.7	-1.4
15	-25.0	-1.4
16	-25.3	-1.4
17	-26.4	-1.5
18	-28.8	-1.6
19	-29.4	-1.6
20	-29.7	-1.7
21	-30.2	-1.8
22	-30.9	-2.3
23	-31.6	-2.6
24	-32.0	-3.0
25	-25.9	-3.7
26	-23.3	-4.2
27	-15.7	-5.5
28	-21.9	-7.6
29	-24.6	-10.1
30	-25.2	-12.2
31	-25.7	-14.2
32	-26.1	-15.9
33	-32.0	-17.5
34	-26.1	-19.0
35	-27.2	-20.2
36	-27.5	-21.3
37	-28.0	-23.2
38	-28.4	-23.2
39	-29.1	-24.0
40	-29.7	-24.8
41	-29.4	-25.6
42	-25.7	-26.2

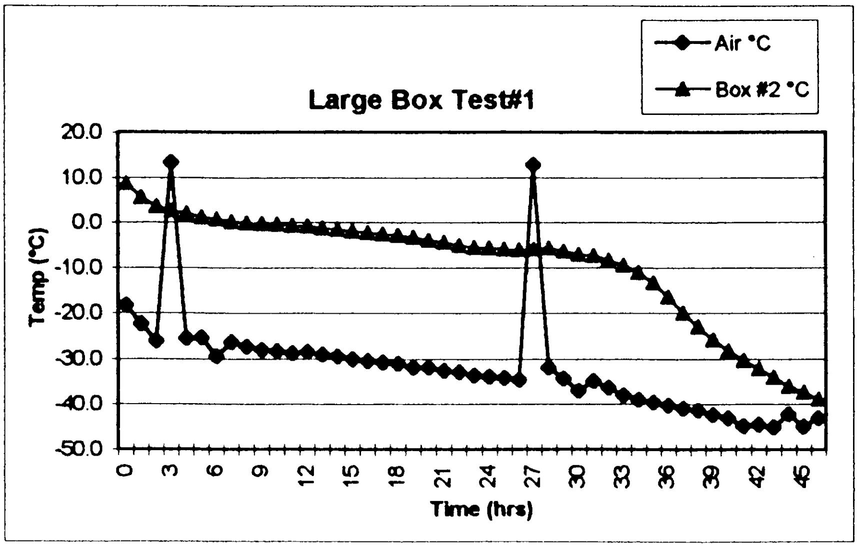


LARGE BOX TEST#1

Time (hrs)	Air °C	Box #1 °C	Box #2 °C
0	-18.2	1.9	8.6
1	-22.4	-0.6	5.6
2	-26.1	-2.4	3.5
3	13.4	2.6	2.6
4	-25.5	-3.7	2.0
5	-25.3	-3.8	1.2
6	-29.4	-5.1	0.7
7	-26.3	-4.8	0.2
8	-27.3	-5.4	-0.1
9	-28.0	-5.4	-0.3
10	-28.3	-5.6	-0.4
11	-28.8	-5.8	-0.7
12	-28.5	-5.8	-0.9
13	-29.0	-6.1	-1.2
14	-29.4	-6.2	-1.5
15	-30.0	-6.6	-1.9
16	-30.4	-6.9	-2.3
17	-30.7	-7.2	-2.6
18	-31.0	-7.3	-2.8
19	-31.8	-8.1	-3.3
20	-31.8	-8.6	-4.0
21	-32.5	-9.3	-4.4
22	-32.8	-10.0	-5.1
23	-33.6	-10.6	-5.5
24	-33.9	-11.0	-5.7
25	-34.2	-11.2	-5.9
26	-34.5	-11.4	-6.1
27	12.8	-5.5	-5.9
28	-31.8	-10.9	-5.6
29	-34.3	-12.0	-6.3
30	-37.0	-13.2	-7.0
31	-34.9	-12.8	-7.4
32	-36.3	-13.9	-8.3
33	-37.9	-15.0	-9.5
34	-39.0	-16.1	-11.0
35	-39.5	-17.5	-13.3
36	-40.2	-18.9	-16.4
37	-41.0	-20.9	-20.0
38	-41.3	-23.1	-22.9
39	-42.3	-26.5	-25.7
40	-43.0	-29.0	-28.2
41	-44.8	-31.5	-30.3
42	-44.5	-33.3	-32.1
43	-45.1	-35.1	-34.0
44	-42.2	-36.2	-36.0
45	-44.9	-37.9	-37.2
46	-43.1	-39.0	-38.8







Introduction to refrigeration modelling, chilling and freezing

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Introduction

In this paper, we will look at the modelling techniques that are applied to refrigeration processes and technologies. We will consider what makes a model, why you would choose to develop or use one, the sorts of models that can be developed and the ways in which they can be applied to real life problems. As well as being important for understanding refrigeration modelling, this is also useful for developing improved design and decision-making procedures.

What is modelling?

A model is a "simplified description of a system etc. to assist in calculations and predictions" (Concise Oxford Dictionary, 1991), and modelling is the act of developing (or perhaps using) a model. We often think of models as being a little exotic or abstruse, and it is certainly true that they can be both exotic and abstruse, but in fact, modelling is something that we all do every day, although we don't necessarily think of it that way.

For example, if you fill a glass with water, you don't necessarily have to look at it to decide when it is full. You can make a pretty good guess just from the weight of the glass. You can make this guess because you quickly develop a mental model of how the weight of the glass varies with the height of water, and you can then predict how heavy it will be when the glass has filled to the level that you want. This is a relatively simple model.

When you drive from one place to another, you can estimate your arrival time. This involves developing quite a sophisticated mental model of your driving skill, the traffic conditions, achievable speeds, and the length of the route that you will travel. Indeed, you may choose an alternative, perhaps longer, route if you come to the conclusion that your speed on that route will be quicker and you will reach your destination sooner.

In the refrigeration field, most people have developed a mental model of chilling and freezing times for situations with which they are familiar. Given small variations away from those situations, they can predict how the chilling or freezing time will change. This sort of mental model, based on experience and straightforward reasoning, shows that no great sophistication is necessary to develop or use a useful model in the refrigeration field.

So far, we have looked at mental models, but there are really several different sorts of models that we can build:

Qualitative models

Qualitative models are of the form "A and B affect C", or "as A gets bigger, D gets bigger". They tell you that things are related to one another, but not how they are related. To consider the driving example, you can say that the acceleration of a car is affected by the weight of the passengers. Beyond that, it gets more complicated: you might say that as the weight gets higher, the power-to-weight ratio gets smaller, and therefore the acceleration rate would be smaller. On the other hand, you could say that as the weight gets higher, the contact between the tires and the road becomes better, there is less chance of wheel-spin, and therefore the acceleration rate would be greater.

We cannot decide which is the correct point of view from a qualitative model because deciding whether traction or power-to-weight ratio is more important in a particular circumstance would require us to quantify the effects involved.

In fact, it is generally difficult to draw firm conclusions from qualitative models, though they may point you in the right direction.

Quantitative models

A model can also be expressed as one or more mathematical equations that indicate how one thing affects another. In this case, the model is quantitative. Quantitative models come in many levels of detail, and they must generally become more complicated to become more accurate. Note that the reverse is not always true. While an accurate model is often complicated, a complicated model is not necessarily accurate.

Quantitative models are subject to assumptions about factors that can be ignored, or things that are important or unimportant. The added complexity of more complicated models often comes from removing these assumptions. To continue the example of the accelerating car, the rate of acceleration a can be described quantitatively by the equation:

$$a = \frac{f}{M} \tag{1}$$

... where f is the force applied to the car by its engine and M is the mass of the car. This equation is therefore a simple quantitative model of an accelerating car. As well as the assumption that we have perfect traction (as mentioned before), this model also assumes that there is no friction, no air resistance, and that many other minor effects are unimportant.

The level of detail that a quantitative model includes should be appropriate to the problem in hand and the accuracy required. In some cases, the simple acceleration model would be all that is required, but if a car manufacturer was designing a new sports car, then he would want to include all the complexities of aerodynamics, drag and so on. Naturally, the model would become more complicated in that case.

Mental models

The mental models that we looked at to start with are something of a mixture of qualitative and quantitative models. They rely on a combination of simple calculations and experience to give you an answer. They are often very accurate for cases where you have experience, and less accurate as your experience of the situation becomes less.

For example, a slab of meat cartons in a batch blast freezer might take 47.9 hours to freeze to -12 °C with an air temperature of -30 °C. If you find that it takes 51.5 hours to freeze if the air temperature is -28 °C, that is a 3.6 hour increase in freezing time for a two degree increase in air temperature.

You might use a mental model of the freezing process to estimate that another two degree increase in temperature might cause an additional 3.6 hour increase in freezing time (to 55.1 hours). You could then run a test, and you might find that the freezing time with an air temperature of -26 °C is 55.8 hours. Thus, your mental model (that freezing time changes by 1.8 hours per degree Celsius temperature change) is relatively accurate for this case.

The dangerous part of using a mental model, however, is that it is only accurate over a limited range of conditions. Once the conditions are outside those for which you have experience, the model can be wildly inaccurate. For example, the model predicts that if the air temperature was -10 °C, the freezing time to -12 °C would be 83.9 hours. Of course, in this case the product would never freeze below -10 °C, so the model's predictions are completely wrong. This is always a risk of using simple models outside their ranges of applicability.

Nevertheless, we can see that whether we are using qualitative models, quantitative models, or combinations of the two, models are always an important part of the decision-making process.

Choosing a model

Given that we are always going to use models in making decisions, what sort of models should we use for the different sorts of decisions that we must make?

When to use a mental model

When you have enough experience of a situation to have developed an accurate mental model, then that is a good choice. It is quick and inexpensive to use a mental model. Mental models can also be more reliable than quantitative models because every decision that you make with a mental model is tempered by experience. There is always the risk with quantitative models — particularly computer-based models — that they are believed even when they produce silly results. Because you understand the reasoning behind any model that exists inside your own mind, you can have an appropriate level of confidence in any results that you obtain by using that model.

When to use a qualitative model

Where you don't have any experience, it is important to start off with a qualitative model to identify the factors that will affect your decision. The process of building a qualitative model is quite straightforward: it is a matter of thinking about the situation for a while and listing all the interesting things that are going on. Having done that, you can indicate which things are related to which other things, and your qualitative model is complete.

When to use a quantitative model

Once you have identified the factors that are important, a quantitative model will give you answers of variable accuracy, depending on the number of assumptions made and the complexity of the model. Quantitative models can be divided into two groups and a mixture of the two:

Theoretical models are based on fundamental physical principles, laws of physics, thermodynamics, etc. They may not necessarily be accurate because the theory may not be sophisticated enough to deal with all the complexities of the real world, but they will behave in approximately the right way and be better as the situation becomes less complex.

Empirical, or statistical, models, are developed by fitting equations to measured data. These equations can be made to fit the data with more and more precision by adding more and more parameters to the equations. Empirical models can therefore be very accurate, but they can only be trusted within the range of the data that they are fitted to. Outside that range, an empirical model can make quite silly predictions that have no basis in reality.

Theoretical models with fitted parameters

These are theoretical models where some of the parameters have been fitted to some measured data. In many cases, these sorts of models combine the best of both theoretical and empirical models. The empirical parameter fitting makes them accurate, even in the presence of real-world complexities, while the theoretical structure means that they may be less accurate away from the range of measured data to which they were fitted, but they will nevertheless predict sensible results. Most of the models used in refrigeration process modelling are of this type.

Since everyone already has experience with mental models, and most people have developed rough qualitative models of most of the situations that they would be involved in through their work, we will look in more detail at quantitative models.

Quantitative models

Model development

As we have seen, quantitative models are usually expressed in mathematical form. This means that developing them requires some skill with mathematics and can be quite time-consuming.

Simpler sorts of quantitative models require limited amounts of time and can be developed quickly and easily, but more complex models can require powerful mathematics and can be very time-consuming to develop. Since the more complex models are often the most valuable (frequently being more accurate, for example) it is important for models that are developed by one person to be made available to others. This not only saves most people the time and effort required to develop the model, but it also improves the reliability of the model because many people have the opportunity to use it in many different situations.

Model validation

Once a model has been developed, it is important to validate it before use. The validation process compares the model predictions with reality to indicate the accuracy of the model and the situations to which it applies.

If a model has been based on measured data (that is, it is an empirical model or a combination empirical/theoretical model rather than a purely theoretical model), it is important to validate it against data that was not used to develop the model in the first place. Comparing a model against data to which it has been fitted can generate false confidence in the accuracy of the model.

Using a model

Having developed and validated a model, it can be put to use. To do this, we have to first solve the model for the practical situation of interest and then display and analyse the results in a way that allows us to draw useful conclusions.

For a simple model, solving it could be as straightforward as inserting some numbers into a formula. For instance, given the force applied to a car and its mass, we can immediately calculate the acceleration using the model that we considered before. For a more complex model, the solution procedures could be very complicated and impractical to carry out by hand.

What do we want to model in the refrigeration process?

We can apply all these sorts of models to many aspects of the refrigeration process, but there are particular cases where a modelling approach is useful.

Chilling

Mathematical models of the chilling process have been developed by many people, starting with Sir Isaac Newton, who developed an equation known as "Newton's law of cooling":

$$Q = U\,A\left(T_{surf} - T_a\right) \tag{2}$$

where:

Q is the rate of heat released from the cooling body (W)
U is the overall surface heat transfer coefficient (W m^{-2} K^{-1})
A is the surface area of the body (m^2)
T_{surf} is the surface temperature of the body (°C)
T_a is the temperature of the body's surroundings (e.g. air) (°C)

Newton's law lets us calculate the heat load placed on a refrigeration system by the product at any given moment. Unfortunately, it depends on T_{surf}, which we rarely know, and cannot readily predict unless the cooling body is so small that T_{surf} is very close to the average temperature of the body. This can be true for chilling and freezing peas, but it is not true for large pieces of meat like beef sides.

There are more sophisticated models that we can use to predict chilling heat loads, chilling times, and meat temperatures during the chilling process, but they are too complicated to go into detail about here. Many of them are impractical to use without a computer to do the calculations for us.

Freezing

One way in which we can model the freezing process is by picturing freezing as the movement of a frozen layer, the "freezing front", from the surface of the freezing body towards the centre. This model is illustrated in Figure 1.

This notion of a "freezing front" model has a lot of value. For instance, we can say that the meat is frozen when the freezing front reaches the centre of the object. We can characterise the rate of freezing by saying that the freezing front is moving at so many millimetres per hour. Finally, we can predict the amount of heat that the refrigeration system must take out of the freezing meat product between one moment and the next by multiplying the meat's latent heat of freezing by the volume of meat through which the freezing front has passed during that period.

The mathematical equations used to represent this model are not quite as complicated as for the chilling model, but they are nevertheless more conveniently used as part of a computer program.

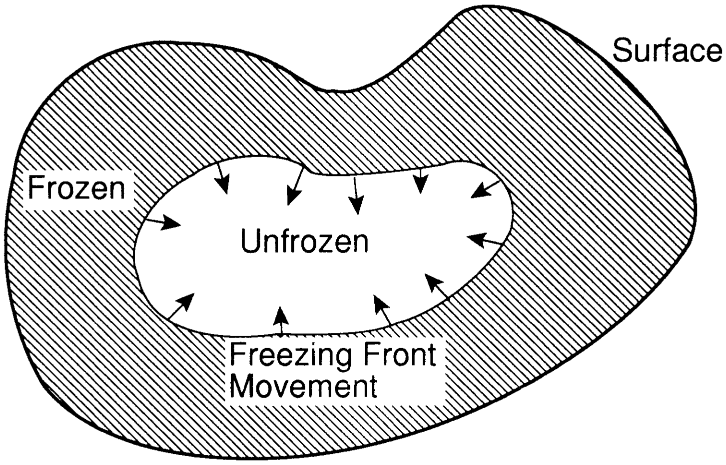

Figure 1 Movement of the freezing front inside a piece of meat.

Refrigeration cycles and equipment

Other mathematical models can be used to represent pieces of refrigeration equipment, refrigerated rooms, the refrigeration cycle, and the refrigerants themselves. Again, we will only consider a simple one. Equation (3) is a mathematical model that represents the rate of heat flow through an insulated wall:

$$Q = \frac{k\ A}{X}\left(T_{outside} - T_{inside}\right) \qquad (3)$$

where:

Q is the rate of heat passing through the wall (W)

k	is the thermal conductivity of the wall (W m^{-1} K^{-1}), e.g. polystyrene panel is approximately 0.03 W m^{-1} K^{-1}.
A	is the surface area of the wall (m^2)
X	is the thickness of the wall (m)
$T_{outside}$	is the temperature outside the wall (°C)
T_{inside}	is the temperature inside the wall (°C)

Equation (3) represents the flow of heat through an insulated wall very well, but it is nevertheless a simplified representation, as discussed above. For instance, it does not consider the rates at which heat might be transferred to the outside of the wall or away from the inside, but implicitly assumes that the resistances to heat flow in those places are much smaller than the resistance due to the insulated wall.

This is satisfactory for an insulated wall, but if you were to use this equation for a (closed) glass window, you would find that it would overestimate the heat flowing through the window. Because glass has a relatively high thermal conductivity and it is thin, the resistances to heat flow at its surfaces may be as high or higher than the resistance offered by the glass itself. Again, these sorts of complications can be taken into account by computer implementations of these models.

Meat Quality

Since the objective of this seminar is to "refrigerate for meat quality", it would be nice to have one or more models that can tell us how the refrigeration process affects meat quality.

Figure 2 is a qualitative model of the effects refrigeration has on meat products that was developed early in a project on modelling the hot-boning process that MIRINZ carried out for the Meat Research Corporation.

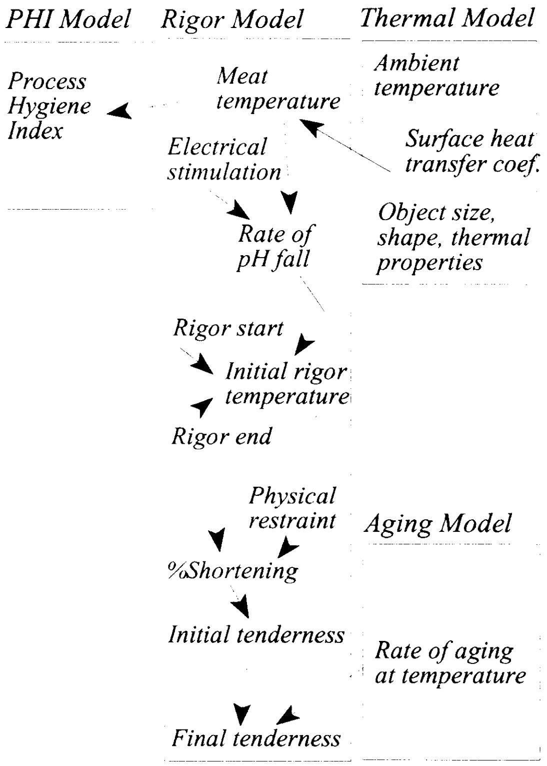

Figure 2 Outline qualitative model of how the refrigeration process affects meat quality.

Starting with Figure 2, MIRINZ researchers developed a quantitative model of the hot-boning process that can (approximately) predict the tenderness and microbial quality of hot-boned meat from the chilling conditions and a few other pieces of information. As with the other sophisticated models discussed above, this one was implemented as a computer program. More information on this project and its outcomes can be obtained through the MRC.

Why a refrigeration modelling toolkit?

Because the process of model development and validation is very time-consuming, it is desirable to have models that can be developed once and be used by many people. Ideally, we should not require the model users to necessarily understand the models in all their details, and it should be possible for the users to solve the models and obtain answers automatically, without having to carry out the computations themselves.

When a set of models is packaged together, along with methods for solving them and analysing the results, these models form a set of tools that people can use to help them with their work.

A modelling toolkit is particularly appropriate where the models are complex and cannot be readily handled without automation. We have seen in the examples above that most of the quantitative models that are useful to the meat industry come into this category.