Temperature Prediction Software for Refrigerated Container Cargoes

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Introduction

 "Censor" software has been developed to estimate cargo temperature in refrigerated containers during normal and abnormal operation. Problems that may occur at transfer points, following power failures, during equipment malfunction or following operator error can be assessed and analysed. Thus the program may be used both as a risk assessment tool and as an aid in cargo claims work.

Container Operations

Refrigerated marine containers transport perishable cargoes over a variety of trade routes world-wide. Typically a container will undergo a pre trip inspection (PTI) to ensure that both the refrigeration unit and structural components meet with operational specifications. It is then delivered to the cargo shipper for loading. The controls will either be set at this time or have been pre-set following the PTI. Chilled or frozen cargoes should have been pre-cooled before loading into the container. Fruit cargoes for the USA, Japan and some other destinations must undergo in-transit sterilisation (USDA) to eliminate fruit fly and other pests.

To check this procedure 4 PRT temperature probes are placed in the cargo during loading. However for most cargoes and routes in transit sterilisation is not required so as far as the container reefer log is concerned only supply air and return temperatures are recorded. Reefer units that do not have digital recorders use circular chart recorders (e.g. Partlow Recorder) to record return air temperature. During normal continuous operation, when cargo has been loaded at close to the intended carriage temperature, return air temperature gives a good indication of cargo temperature. For chilled cargoes supply air temperature is controlled at the set point using refrigeration modulation methods to provide steady temperatures. Frozen cargoes are temperature controlled with respect to return air temperature and the method of control is generally compressor ON/OFF.

After a container has been stuffed, the doors are closed and the refrigeration machinery is switched on immediately power is available. This may be provided by a diesel generator mounted on the reefer unit or more usually under slung on the skeletal trailer. Delivery on active refrigeration is essential for most chilled

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cargoes but frozen loads are sometimes transported off power for a few hours, At the port, a container may be transferred directly to a vessel or held on power in a container terminal, until transfer to a vessel. On some routes the first vessel may be a feeder for a hub port, where the container will be held on a terminal or be transferred directly to another vessel, Further similar transfers may take place before the container is delivered to the consignees cold store.

During periods off power, circular chart recorders and some refrigeration unit recorder systems continue to operate on back up batteries, but unless USDA probes have been placed in contact with the cargo, the supply and return air probes merely record still air temperatures within the container plenum spaces. This may not be a true reflection of the cargo temperature when the air circulation fans are off. Where no battery back up is available there is no record for the off power period.

During evaporator coil defrosting high temperatures are recorded by the return air probe or Partlow sensor. During this process fans are off and the recorded temperature does not indicate cargo temperature..

Operational difficulties occasionally give rise to problems that cause cargo temperatures to drift outside specified limits. In addition to periods off power, a small percentage of problems will result from machinery malfunctions. Problems may also occur on feeder vessels which are outside the control of the container operator.

This program has been designed to estimate cargo temperatures in situations where product deterioration or non-conformity with carriage regulations may result in cargo loss and consequent claims.

Examples of the types of problems with which "Censor" can provide assistance are:

a) How long can a reefer container carrying frozen produce be left off power before temperature damage occurs? What is the effect of an intermittent power supply on cargo temperature?

b) Over what distance can reefer container cargoes be carried by land transport off power? What is the effect of ambient temperature?

c) How many hours can chill cargoes be off refrigeration before shippers' temperature recorders monitor temperatures out of carriage limits?

d) What are the limiting factors?

e) What will be the rate at which the cargo temperature increases?

f) Where reefer containers lose power for hours or days and are then brought back under refrigerated control:
- What will be the maximum cargo temperature attained before control recovery?
- For how long would the cargo have been outside acceptable temperature limits?
- Would this temperature be recorded by the Partlow recorder?
- Would the refrigeration unit electronic sensors have recorded this temperature?
- Would USDA probes have recorded this temperature?

Both the Partlow and refrigeration unit temperature sensors record either supply or return air temperatures. With the unit off power, the Partlow and, on units with battery backup, the supply & return air sensors will continue to operate, but will not be recording cargo temperature, merely still air in either the upper or lower refrigeration unit plenum chamber. Only recorders with battery back up and fitted with and using the USDA sensors would retain an accurate record of cargo temperature at this time. With knowledge of conditions before power loss the program will produce an estimate of core temperatures during and after the period of power loss.

Program Features

The "Censor program" models the thermal performance and properties of the combination of container refrigeration unit, container air circulation and cargo properties.
There are three versions:

1. Block stow model
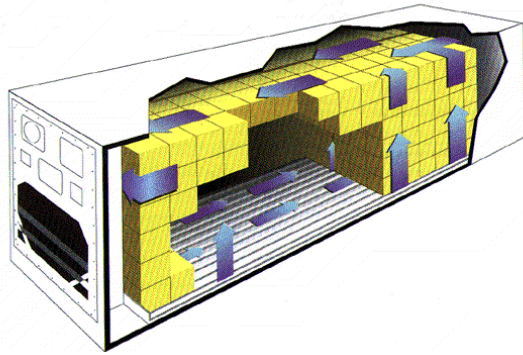Divides container cargo into 300 discrete

Figure 1 Diagrammatic view of the air flow inside a refrigerated container

nodes. These are arranged in 12 rows with 5 x 5 nodes in each row.

2. 20' Pallet/Batten Version
375 nodes arranged in 5 groups of 3 rows of 5 x 5 nodes, to simulate 5 rows of pallets.

3. 40' Pallet/Batten Version
750 nodes arranged in 10 groups of 3 rows of 5 x 5 nodes, to simulate 10 rows of pallets.

Cargo surface and air temperatures are determined at points relative to the surface nodes.

Three dimensional differential equations determine the variation of each node temperature with time, using temperature dependent physical properties [specific heat, and thermal conductivity for all cargoes plus heat of respiration for fruit and vegetables] which are continuously updated from look tables as the computation proceeds.

Cargo temperatures may be calculated over time periods covering minutes to months.

Cargo type, dimensions, weight, etc., ambient temperatures, container and refrigeration unit performance are entered or selected from menus using an entry form selected from file.

The program can be operated on Vissim 32 v2.0k and above and on Windows 95 and above. A run time version is available on CD for operation without the full VisSim software.
Factors which Determine Rates of Temperature Change

Cargo temperatures and rates of temperature change are dependent upon the following factors:

Cargo
Thermal properties
    Thermal conductivity
    Specific heat
    Heat of respiration for fresh fruit, vegetables, flower bulbs etc.

These are temperature dependent
The values vs. temperature for each commodity are stored in look up tables

Packing density, dimensions and total weight.
Carriage temperature.
Packing or loading temperature.

Container
Dimensions, weight, U-value, specific heat
Free cargo space.
Air circulation rate
Air thermal properties vs. temperature and relative humidity.

Refrigeration Unit
Set point temperature.
Control mode.
Heat extraction rate versus evaporating and condensing temperatures.
Air Delivery Rate
Time periods: on and off power.

Ambient Conditions
Fixed or time varying ambient temperatures can be programmed
Temperatures from vessel deck logs or met office records may be stored in look up files.

Model Overview

Operating system
Censor has been assembled using VisSim software from Visual Solutions Inc, supplied by Adept Scientific of Letchworth. VisSim is a visual environment for the development of continuous, discrete, multi-rate and hybrid system models and performance of dynamic simulations. VisSim menus list commands that automate many tasks and blocks that correspond to numerous linear and non linear functions.

System Model

The system model is built up in the form of block diagrams. Each block corresponds to a specific mathematical function. VisSim simulates the model, by numerically solving the equations that define the system. To solve differential equations VisSim provides seven integration algorithms which provide a trade off between speed and accuracy. Solutions at the points of interest within the model are displayed continuously in graph format as the computations proceed. On completion these may be printed or saved.

Several displays are shown simultaneously to represent temperatures and other variables at various locations represented by the model. Data may be exported to spread sheets at discrete intervals.

Data Entry

All data may be entered or selected from menus using an input menu sheet [see Table 1].

For example, there are 17 cargo types currently

		Enter Data			
Set point temperature **[Highest operates]**	Chill Frozen	2.2 -20.0	2.2 -20		
Cargo Width m		2.28	0.456		
Cargo height m		2.23	0.446		
Cargo length m		11.568	0.386		
Cargo Density kg/m3		333.2407	333.2407		
Container internal height m		2.55	2.55	Cargo Code	
Cargo commodity	see table	17	17	butter	0
Initial Cargo temperature °C		10	10	chocolate	1
Initial roof temperature °C		20	20	haddock	2
Initial wall temperature °C		20	20	banana	3
Initial front wall temperature °C		20	20	lamb	4
Initial door Temperature °C		20	20	cod	5
Initial floor temperature °C		20	20	beef	6
Roof thickness m		0.1	0.10	shrimp (prov)	7
Wall thickness m		0.1	0.1	pork ribs	8
Front wall thickness m		0.1	0.1	herring	9
Door thickness m		0.08	0.08	white fish	10
Floor thickness m		0.07	0.07	apples	11
Roof U-value W/m2K		0.38	0.38	grapes	12
Wall U-value W/m2K		0.38	0.38	milk	13
Front U-value W/m2K		0.38	0.38	chicken	14
Doors U-value Wm2K		0.38	0.38	fruit juice con	15
Floor U- value W/m2K		0.38	0.38	Honeydew	16
Air space roof m	Calculated	0.32	0.32	Cantaloupe	17
Air space walls m	must not be zero	0.02	0.02		
Air space front m	must not be zero	0.05	0.05		
Air space doors	must not be zero	0.05	0.05		
Air space floor	must not be zero	0.076	0.076		
Pallet/batten space		0.05	0.05		
Volume Flow	m3/s	1	1		
No defrost	Select	1	1		
6 hour defrost interval	only one from	0	0		
12 hour defrost interval	this group	0	0		
24 hour defrost interval		0	0		
Timer user 1		0	0		
Timer user 2		0	0		
Reefer Unit CRR 40	Select	1	1		
Reefer Unit B	only one from	0	0		
Reefer Unit C	from	0	0		
Reefer Unit D	this group	0	0		
Reefer Unit E		0	0		

Table 1. Data Entry (continued on next page)

Fan Power	Watts	850	850
Power on at Time 1	HOURS	0	0
Power off at Time 2	HOURS	11.18333	40260
Power on at Time 3	HOURS	18.36667	66120
Power off at Time 4	HOURS	23.71667	85380
Power on at Time 5	HOURS	24.53333	88320
Power off at Time 6	HOURS	81.58333	293700
Power on at Time 7	HOURS	82.53333	297120
Power off at Time 8	HOURS	150.1333	540480
Power on at Time 9	HOURS	150.8333	543000
Power off at Time 10	HOURS	151.1833	544260
Power on at Time 11	HOURS	154.5	556200
Power off at Time 12	HOURS	441.2833	1588620
Power on at Time 13	HOURS	441.9333	1590960
Power off at Time 14	HOURS	485.3667	1747320
Power on at Time 15	HOURS	492.0667	1771440
Power off at Time 16	HOURS	500.7	1802520
Power on at Time 17	HOURS	506.35	1822860
Power off at Time 18	HOURS	549.7	1978920
Power on at Time 19	HOURS	563.4333	2028360
Power off at Time 20	HOURS	565.7333	2036640
Ambient User 1	1 to select	0	0
Ambient User 2	1 to select	1	1
Ambient User 3	1 to select	0	0
Ambient User 4	1 to select	0	0
Fixed Ambient	1 to select	0	0
Ambient Roof	Enter value	30	30
Ambient	Enter value	30	30
Estimated Relative humidity	Enter value	95	95

Table 1. Data Entry (continued)

available on menu. Selection of a given cargo causes the program to automatically enter the relevant cargo properties. Refrigeration unit model, and hence performance, may be se-lected. The properties of unlisted cargoes and refrigeration units may be added as and when required.
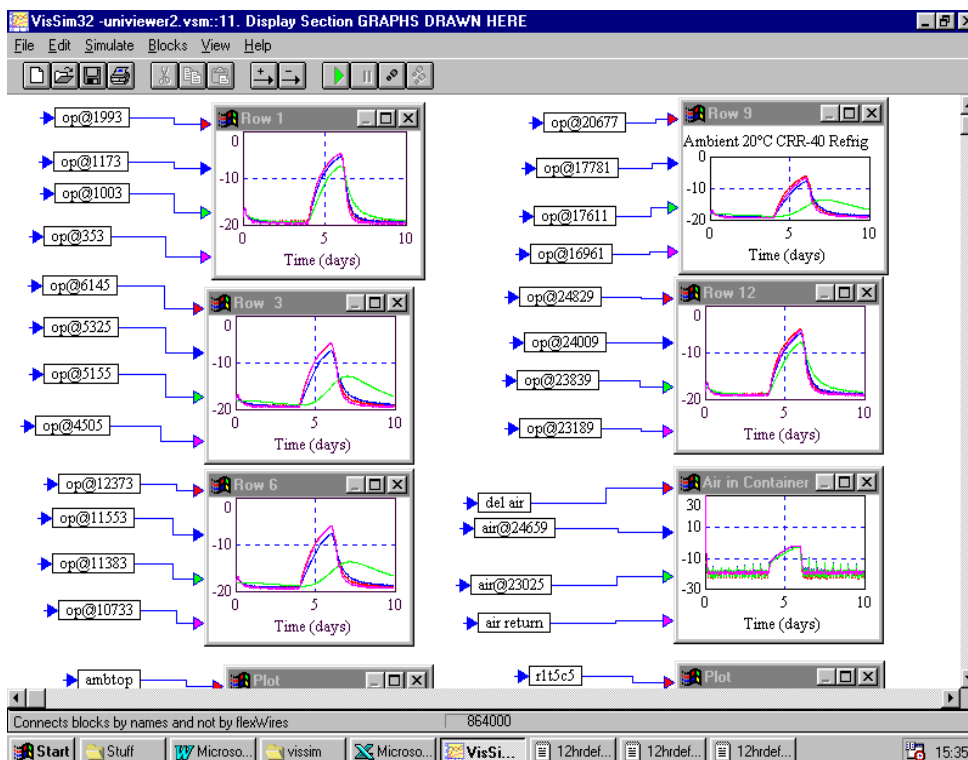

Figure 2. Full screen display

Data Display

Calculated values are presented on a series of graphs, each which can be displayed full screen and or printed out full page. Data may also be transferred directly to spreadsheets. Several graphs may be displayed on the screen and each maybe maximised for full screen display

Examples of simulated displays
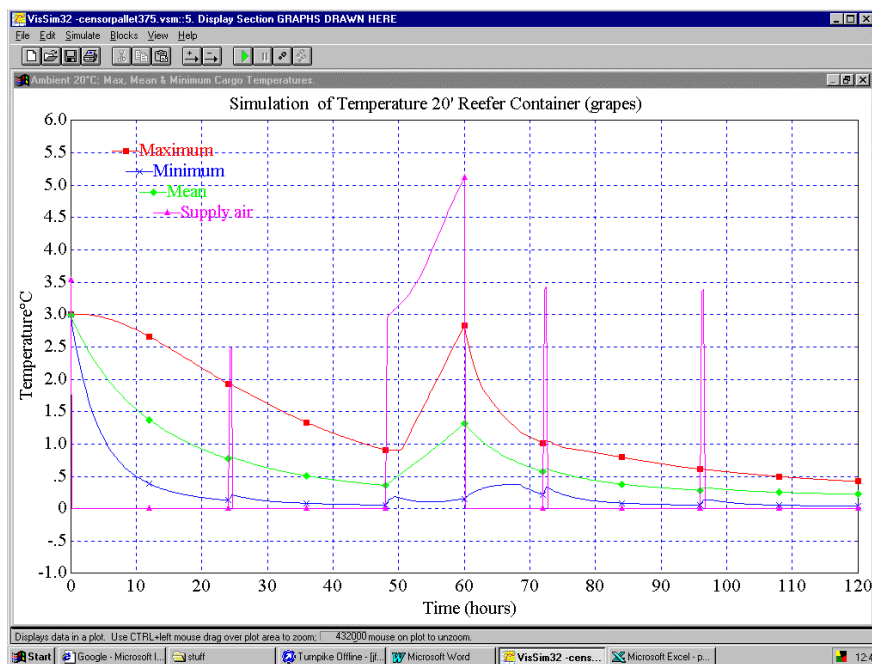Simulation outputs showing temperature changes in both frozen and chilled cargoes are shown on the appended graphs:

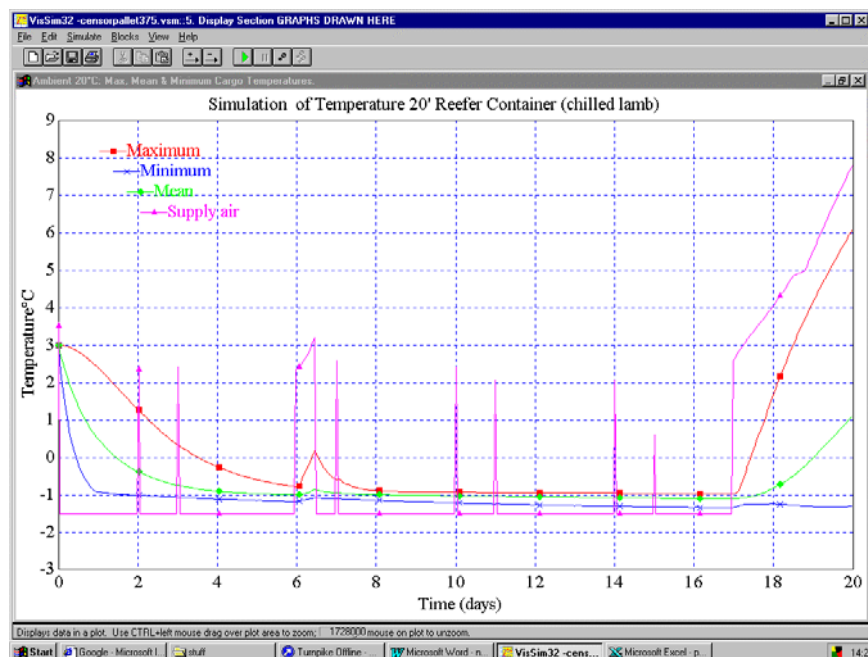*Figure 3 Grapes loaded warm, off power after 2 days for 12 hours*

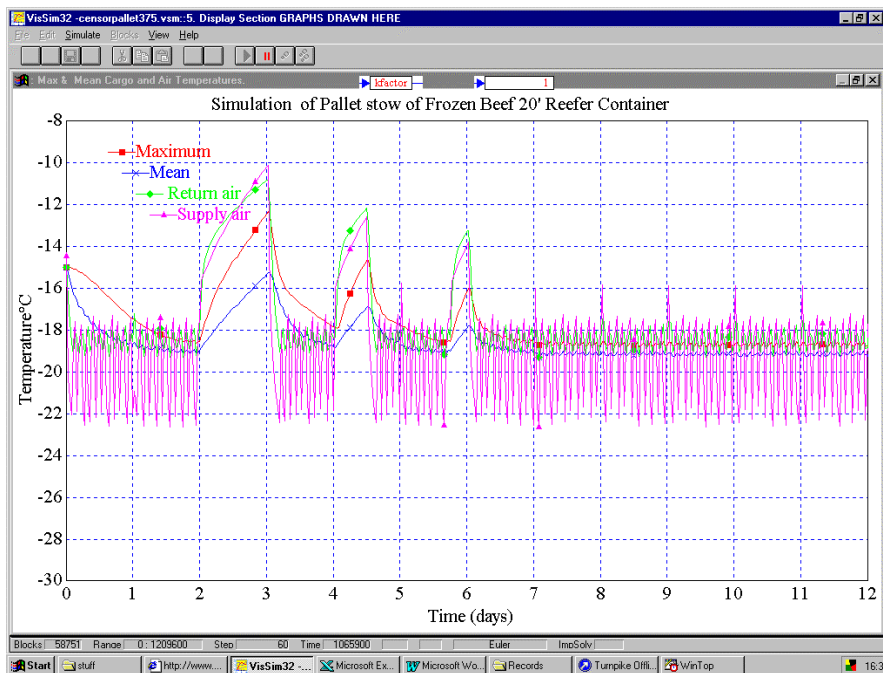*Figure 4 Chilled Lamb loaded warm, off power after 6 days for 12 hours*

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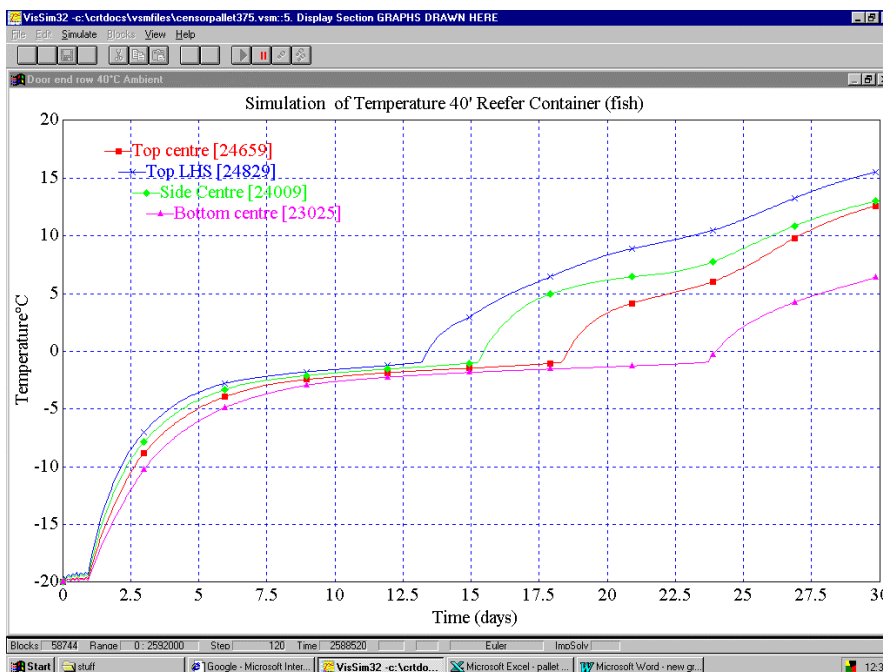*Figure 5 Frozen beef with periods off power*

Figure 6 Container of Frozen fish off power in 40°C ambient.

Explanation of the Basic Features and Factors used in the Model.

Data Entry
Three-dimensional finite element analysis is used to predict time dependent temperatures under varying control regimes and ambient conditions from starting points which are specified in the set up list. The data is entered using an excel tabular format. When the program is run, the data is transferred to the Vissim via a DDE interface. A copy of a data entry table is shown in Table 1.

Control Temperature
This is entered in the input table. Either modulated supply air temperature control (chill temperatures) or on/off return air temperature control can be selected.

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Cargo commodity
Selected from list, The commodity list may be updated and supplemented using Windows "note pad".

Cargo Dimensions
Cargo width, height, and length. The data entry table determines the element dimensions.

Cargo packing density
Entered directly or calculated on the entry sheet from cargo weight and dimensions.
i.e. packing density = total cargo weight/ volume

Cargo thermal conductivity
Determined from published values for the cargo type relative to node temperature and operational k ratio (see note). The published values, for a given commodity, are entered in a look up table with reference to temperature.

Note: Cargo Stow Thermal Conductivity (use is optional):
This depends upon the k value of the commodity, packaging and air spaces within the packs. Heat transfer within the load increases when air is circulated through the load during normal refrigerated air circulation. Thus the effective k value of the load may increase when air is being circulated at a high rate around and through the load. With this in mind, k factors may be estimated in order to take into account increased transfer of heat during period on power. During the simulation, the thermal conductivity of the cargo is determined by reference to a two-dimensional "look up" table from which the effective thermal conductivity value is determined by the local temperature and operational state of the refrigeration unit.

Cargo specific heat:
Determined from published values relative to node temperature. The published values, for a given commodity, are entered in a "look up" table with reference to temperature.

Cargo Heat of Respiration (fruit & vegetables)
Determined for the particular variety from published values, which are stored in a file relative to temperature and the respiratory heat, is determined in each node relative to the current temperature.

Container internal height
This is compared with cargo height to determine head space over the load.

Initial container structure temperatures.
These may be typed in or determined from initial cargo and ambient temperatures.

Container wall, roof, floor and door thickness.
Used in equations that determine mean wall temperatures.

Container Heat Leakage
U-values for roof, wall, front, doors and floor are typed in. Censor adjusts the U-value entered for the roof to account for additional heat leakage from the sides, above the cargo. This is done because the model assumes that all heat leakage, above the cargo, is through the roof.

Ambient temperature
Constant or varying values can be programmed.

Solar heat
Varying effects of solar heat on sides and roof can be taken into account.

Volume Air Flow Rate
Determined from refrigeration unit specifications, used to determine linear flow rates and air temperature change at the evaporator.

Linear Air Speed and Surface Heat Transfer in the Container
The linear air speed at any point within the container is dependent upon the volume airflow rate and the relative distribution of air throughout the load and free spaces to the sides, floor, front, roof and doors [and between batten or inter pallet or batten spaces on the 375 and 750 node model]. Air to surface heat transfer coefficient is calculated at each segment with reference to the local linear air velocity.

Air flow patterns
The following flow patterns have been assumed:
Front: airflow ascending vertically and parallel
Floor: air flow horizontal and parallel, front to rear, gradually reducing toward the rear as a

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proportion is deflected vertically at each segment.

Sides: a proportion of floor airflow is deflected at each segment and ascends vertically.

Between pallets: airflow ascending vertically and parallel

Doors: airflow ascending vertically and parallel.

Roof: air flow rear to front with side airflow merging at each node section.

The model uses a matrix of nodes 5 x 5 x 12, 15, or 30 enabling the temperatures at 300, 375 or 750 points within a container load to be estimated. The differential equation for each finite segment uses gains calculated and continually updated from the following

Heat Flow Equations

Model Division
For a total volume, the cargo is divided into 300, 375 or 750 finite blocks each of height dy, width dx and length dz where
dy = stow height/5
dx = stow width/5
dz = stow length/n where n = 12, 15 or 30 [depending on model].

Equations

The following equations form the basis of the dynamic model

Airflow around and between cartons and container

dx = finite segment width	m
dy = finite segment height	m
dz = finite segment length	m
dt = distance across flow path	m
v = volume flow past finite segment	m^3/s
L = linear flow rate	m/s

where

$v_f = L \, dt_f \, dx$ for vertical front flow m^3/s

$v_b = L \, dt_b \, dx$ for horizontal base flow m^3/s

$v_s = L \, dt_s \, dz$ for vertical side flow m^3/s

$v_r = L \, dt_r \, dx$ for horizontal roof flow m^3/s

$v_d = L \, dt_d \, dx$ for vertical door flow m^3/s

hw = heat transfer through walls W/m^2 K

Combining air to product surface and product thermal conductivity [h_p]

for front $h_p = 2kh/(2k+dz \, h)$ W/m^2 K

for base $h_p = 2kh/(2k+dy \, h)$ W/m^2 K

for sides $h_p = 2kh/(2k+dx \, h)$ W/m^2 K

for roof $h_p = 2kh/(2k+dy \, h)$ W/m^2 K

for door end $h_p = 2kh/(2k+dz \, h)$ W/m^2 K
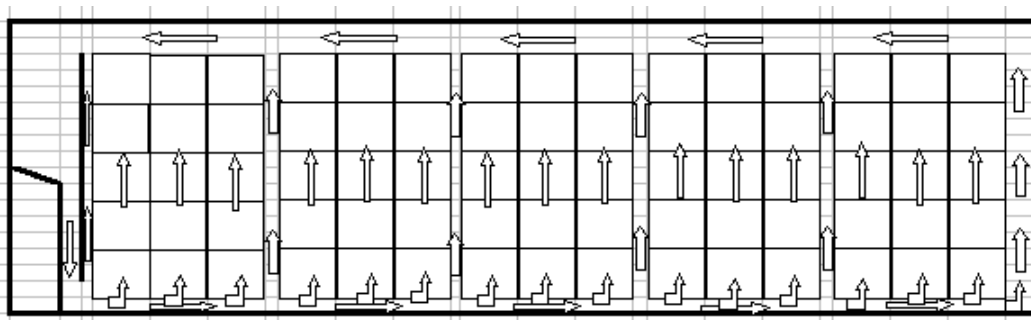
where   k = cargo thermal conductivity

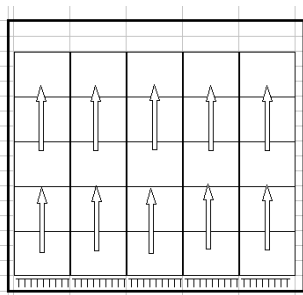*Figure 7 Air flow, side elevation, 375 node model*
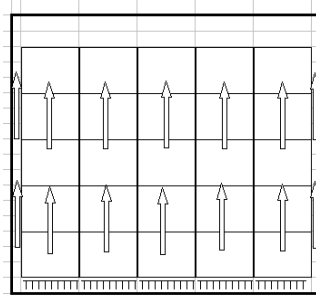

Fig. 8. Air flow at the front   *Fig.9. Air flow between pallets etc*   *Fig. 10. Air flow at the door end*
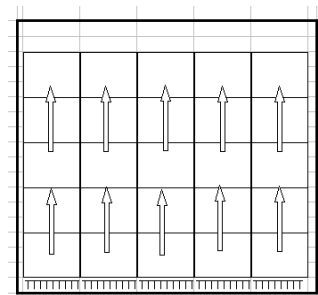
h is determined from air speed V where:
$$h = 3.9V + 5.62 \qquad W/m^2\,K$$
(Ref. 1)

In general heat content of air leaving a section = heat content of air entering the section + heat transfer to and from walls and cargo.

Front and doors

$\Theta_{out}c\rho L.dt.dx = \Theta_{in}c\rho L.dt.dx + h_p dxdy[\Theta_p - (\Theta_{out} + \Theta_{in})/2] - 2h_w dxdy[(\Theta_{out} + \Theta_{in})/2 - \Theta_{wall}]$

Hence

$\Theta_{out} = \Theta_{in}[c\rho L.dt - h_p dy/2 - h_w dy] + h_p dy\Theta_p + 2h_w dy\,\Theta_{wall}] / [c\rho L.dt. + h_p dy/2 + h_w dy]$

If flow = 0 then

$\Theta_{out} = [- h_p dy/2 - h_w dy]\,\Theta_{in} + h_p dy\Theta_p + 2h_w dy\,\Theta_{wall}] / [h_p dy/2 + h_w dy]$

Sides

$\Theta_{out}c\rho L.dt.dz = \Theta_{in}c\rho L.dt.dz + h_p dzdy[\Theta_p - (\Theta_{out} + \Theta_{in})/2] - 2h_w dzdy[(\Theta_{out} + \Theta_{in})/2 - \Theta_{wall}]$

Hence

$\Theta_{out} = \Theta_{in}[c\rho L.dt - h_p dy/2 - h_w dy] + h_p dy\Theta_p + 2h_w dy\,\Theta_{wall}] / [c\rho L.dt. + h_p dy/2 + h_w dy]$

If flow = 0 then

$\Theta_{out} = [- h_p dy/2 - h_w dy]\,\Theta_{in} + h_p dy\Theta_p + 2h_w dy\,\Theta_{wall}] / [h_p dy/2 + h_w dy]$

Transverse batten or pallet spaces

$\Theta_{out}c\rho L.dt.dx = \Theta_{in}c\rho L.dt.dx + h_{pn} dxdy[\Theta_{pn} - (\Theta_{out} + \Theta_{in})/2] + h_{pn+1} dxdy[\Theta_{pn+1} - (\Theta_{out} + \Theta_{in})/2]$

Etc

Floor and Roof

$\Theta_{out}c\rho L.dt.dx = \Theta_{in}c\rho L.dt.dx + h_p dzdx[\Theta_p - (\Theta_{out} + \Theta_{in})/2] - 2h_w dzdx[(\Theta_{out} + \Theta_{in})/2 - \Theta_{wall}]$

hence

$\Theta_{out} = \Theta_{in}[c\rho L.dt - h_p dz/2 - h_w dz] + h_p dz\Theta_p + 2h_w dz\,\Theta_{wall}] / [c\rho L.dt. + h_p dz/2 + h_w dz]$

If flow = 0 then

$\Theta_{out} = [- h_p dz/2 - h_w dz]\,\Theta_{in} + h_p dz\Theta_p + 2h_w dz\,\Theta_{wall}] / [h_p dz/2 + h_w dz]$

Volume Flow at the floor = v_{fn}
Volume flow at the sides = v_{sn}
Where v_{f1} = [Delivery air flow] –

[Front air flow]
$$v_{f2} = v_{f1} - 2v_{s1}$$
$$v_{s1} = v_{f1} \times [\text{side flow factor}]$$
The side flow factor must either be estimated or possibly be determined from measured flow rates.
For the return air over the top of the stow
$\Theta_{in} = a.\Theta_{In-1} + b.\Theta_{left} + c.\Theta_{right}$

$a + b + c = 1$ and are determined from the relative volume flow rates at each air flow node point.

Product temperatures
In general the node temperature is Θ_{xyz}, where
$d\Theta_{xyz}/dt = k/c\rho dx^2(\Theta_{x-1yz} - 2\Theta_{xyz} + \Theta_{x+1yz})$
$+ k/c\rho dy^2(\Theta_{xy-1z} - 2\Theta_{xyz} + \Theta_{xy+1z})$
$+ k/c\rho dz^2(\Theta_{xyz-1} - 2\Theta_{xyz} + \Theta_{xyz+1}). + h_{res}/1000c$

k = thermal conductivity of cargo including effects of packaging and inter cargo air flow
c = specific heat of the product
ρ = packing density of the cargo (total weight/ volume)
h_{res} = heat of respiration of fruit and vegetable cargoes W/Tonne

k, c and h_{res} all may vary with product temperature. These variations are mapped within the software.

Refrigeration Unit
At the heat exchanger
Supply air $\Theta_{del} = \Theta_{ret} - h_{ext}/vc_{air}\,\rho_{air}$
v = volume air flow through heat exchanger m^3/s
c_{air} = specific heat of air at constant volume
ρ_{air} = air density

Comparison of Measured and Simulated Temperatures.
Test measurements on fully instumented cargoes are expensive and difficult to arrange. Some published data is available for comparison and validation tests and an example is the work carried out at CRT (then known as SRCRA) by Robin Scrine and Jim Mansfield [ref 2] who measured temperature changes in frozen herrings stowed in a 20' insulated container. The tests were carried out in a test chamber where the ambient air was controlled at specified temperatures. 24 thermocouples were distributed within the

load. Following pre-cooling to approximately –25°C for each test. Cargo temperatures were monitored in constant ambient temperatures of –0.4°C, 10.3°C, 19.6°C , 30°C and a further test changing from 25°C to 41°C to 15°C. The tests have been simulated and the estimated and measured results are compared on the following tables. The temperatures at the start of each of the warming tests were not uniform, whereas a uniform cargo temperature was programmed for each of the simulations. Thus there are initial differences between estimated and measured temperatures.

	Measured	Measured	Measured	Censor	Censor	Censor	Surface	Error			
Hr	Min	Mean	Max	Min	Mean	Max	Max	Min	Mean	Max	Surface
°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
0.0	-24.6	-24.6	-23.0	-24.5	-24.5	-24.5	-24.5	0.1	0.1	-1.5	-1.5
10.0	-24.8	-24.0	-20.5	-24.8	-23.8	-22.3	-21.0	0.0	0.3	-1.8	-0.5
20.0	-24.6	-23.2	-18.5	-24.5	-22.8	-20.8	-19.5	0.1	0.4	-2.3	-1.0
30.0	-24.4	-22.5	-17.2	-24.3	-22.0	-19.5	-18.6	0.1	0.5	-2.3	-1.4
40.0	-24.2	-22.0	-16.1	-24.3	-21.5	-18.5	-17.5	-0.1	0.5	-2.4	-1.4
50.0	-24.0	-21.5	-15.3	-24.2	-20.8	-17.3	-16.7	-0.2	0.7	-2.0	-1.4
60.0	-23.9	-21.1	-14.9	-23.6	-20.3	-16.7	-16.0	0.3	0.8	-1.8	-1.1
70.0	-23.8	-20.8	-14.5	-23.3	-19.5	-16.0	-15.3	0.5	1.3	-1.5	-0.8

Table 1. Ambient –0.4°C

	Measured	Measured	Measured	Censor	Censor	Censor	Surface	Error			
Hr	Min	Mean	Max	Min	Mean	Max	Max	Min	Mean	Max	Surface
°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
0.0	-26.3	-25.4	-25.4	-25.5	-25.5	-25.5	-25.5	0.8	-0.1	-0.1	-0.1
10.0	-26.3	-23.8	-20.3	-25.8	-24.3	-22.3	-20.3	0.5	-0.5	-2.0	0.0
20.0	-26.3	-22.8	-18.0	-25.5	-23.2	-20.0	-18.4	0.8	-0.4	-2.0	-0.4
30.0	-26.2	-22.0	-16.5	-25.4	-22.0	-18.2	-16.7	0.8	0.0	-1.7	-0.2
40.0	-26.2	-21.4	-15.3	-25.1	-20.9	-16.6	-15.2	1.1	0.5	-1.3	0.1
50.0	-26.0	-20.9	-14.4	-24.7	-20.0	-15.3	-14.0	1.3	0.9	-0.9	0.4
60.0	-25.7	-20.5	-13.7	-24.2	-19.2	-14.1	-13.0	1.5	1.3	-0.4	0.7
70.0	-25.2	-19.8	-13.2	-23.7	-18.3	-13.0	-11.9	1.5	1.5	0.2	1.3

Table 2. Ambient 10.3°C

	Measured	Measured	Measured	Censor	Censor	Censor	Surface	Error			
Hr	Min	Mean	Max	Min	Mean	Max	Max	Min	Mean	Max	Surface
°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
0.0	-27.3	-26.3	-26.4	-26.5	-26.5	-26.5	-26.5	0.8	-0.2	-0.1	-0.1
10.0	-26.4	-23.3	-19.2	-26.8	-24.8	-22.5	-19.8	-0.4	-1.5	-3.3	-0.6
20.0	-26.2	-21.8	-15.5	-26.5	-23.5	-19.4	-17.4	-0.3	-1.7	-3.9	-1.9
30.0	-26.1	-21.0	-13.7	-26.3	-22.0	-17.2	-15.3	-0.2	-1.0	-3.5	-1.6
40.0	-25.8	-20.3	-12.2	-25.8	-20.6	-15.2	-13.5	0.0	-0.3	-3.0	-1.3
50.0	-25.4	-19.4	-10.9	-25.5	-19.5	-13.5	-11.8	-0.1	-0.1	-2.6	-0.9

Table 3. Ambient 19.6°C

	Measured	Measured	Measured	Censor	Censor	Censor	Surface	Error			
Hr	Min	Mean	Max	Min	Mean	Max	Max	Min	Mean	Max	Surface
°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
0.0	-26.4	-25.8	-25.6	-25.5	-25.5	-25.5	-25.5	0.9	0.3	0.1	0.1
10.0	-26.1	-22.7	-17.7	-26.0	-23.5	-20.5	-17.6	0.1	-0.8	-2.8	0.1
20.0	-26.0	-21.6	-13.8	-25.5	-21.8	-17.2	-14.6	0.5	-0.2	-3.4	-0.8
30.0	-25.8	-20.6	-11.7	-25.3	-20.3	-14.5	-12.2	0.5	0.3	-2.8	-0.5

Table 4 ambient 30°C

Measured	Measured	Measured	Measured	Censor	Censor	Censor	Surface	Error			
Amb°C	Min	Mean	Max	Min	Mean	Max	Max	Min	Mean	Max	Surface
25.0	-26.5	-25.6	-25.5	-25.5	-25.5	-25.5	-25.5	1.0	0.1	0.0	0.0
35.0	-26.2	-23.4	-19.6	-26.0	-24.3	-22.8	-19.6	0.2	-0.9	-3.2	0.0
38.1	-25.8	-21.8	-14.7	-26.0	-23.5	-20.2	-17.6	-0.2	-1.7	-5.5	-2.9
41.0	-25.9	-20.6	-13.0	-25.5	-22.0	-17.5	-14.2	0.4	-1.4	-4.5	-1.2
30.0	-26.0	-20.6	-12.9	-25.5	-21.7	-17.2	-14.1	0.5	-1.1	-4.3	-1.2
14.6	-26.3	-20.8	-12.8	-25.5	-21.0	-15.8	-13.4	0.8	-0.2	-3.1	-0.7
14.2	-26.3	-20.8	-12.9	-25.3	-20.2	-14.5	-12.5	1.0	0.6	-1.6	0.4
14.6	-26.2	-20.6	-12.8	-25.2	-19.5	-13.5	-11.8	1.0	1.1	-0.8	0.9
14.6	-25.9	-20.3	-12.2	-24.8	-18.5	-12.5	-11.3	1.1	1.8	-0.3	0.9

Table 5. Varying ambient

References

Ref. 1 ASHRAE Handbook of Fundamentals: Equations for Forced Convection p 3.14.

Ref. 2 Trials with Packaged Frozen Herrings G.R. Scrine & J.E. Mansfield SRCRA 1977