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Research Article

Gel Weight Estimation for Cold-Chain Packaging

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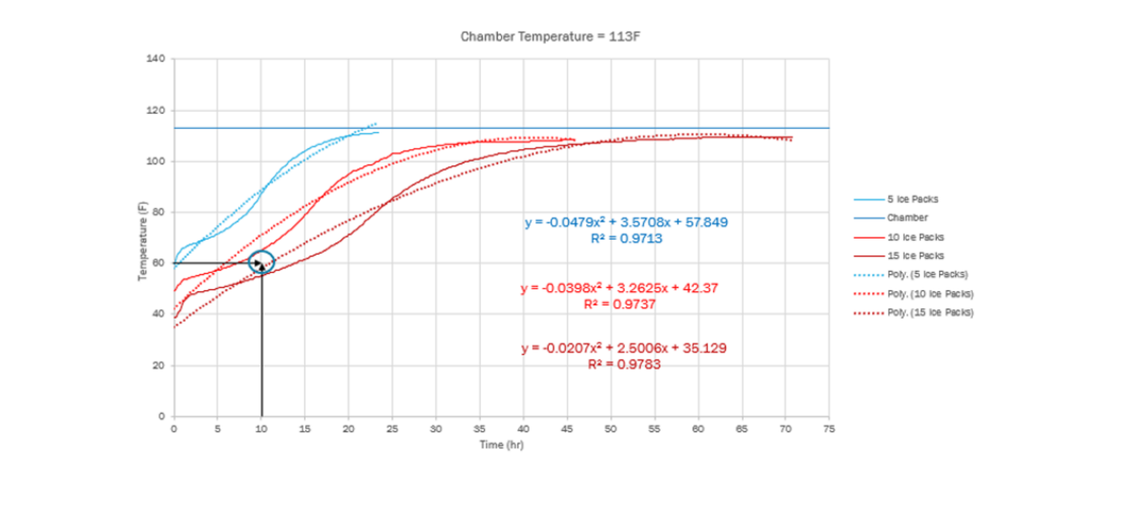
Abstract Cold-chain packaging is critical to shipments of temperature-sensitive products. The simplest practice is to put products inside an insulated shipping container with a sufficient coolant amount to maintain a certain temperature during the distribution process. In this study, a 12 x 12 x 11½" expanded polystyrene insulated container with 2" wall thickness was used along with non-toxic gel pack coolant. Temperature data was collected under exterior temperature conditions of 60F, 90F, and 113F. The data was plotted and equations were derived for estimating the amount of gel packs needed for a given trip duration, product threshold temperature, and exterior temperature. In addition, Gel Pack Estimator, an Excel application, was developed based on artificial neural network technology.

Keywords *Cold-Chain Packaging; Coolant Amount Estimation; Artificial Neural Network*

1. Introduction

A cold chain is a temperature-controlled supply chain of temperature-sensitive products, such as agriculture produce, seafood, frozen food, photographic film, chemicals, and pharmaceutical products [1]. For some temperature-sensitive products, the use of insulated shipping containers with cold gel or ice packs are adequate [2]. Expanded polystyrene shipping containers are widely used. Gel packs made from polyethene bags filled with non-mechanical refrigeration are safe for food, pharmaceutical, and other medical products [3]. The amount of coolant depends on two basic components; insulation and coolants [4]. The insulation material slows down the heat penetration while the melting of coolants absorbs heat.

In a preliminary study [5], SonocoThermoSafe Polar Packs [3] were used with a 12 x 12 x 11½" expanded polystyrene insulated container with 2" wall thickness [6] under an exterior temperature of 113F. A graph and an equation were developed for gel weight estimation as shown in Figure 1. However, the previous work was only limited to a 113F exterior temperature. As noted in [5], the 113F temperature was chosen for the study because it was the highest temperature used in the ISTA 7D test protocol [7]. The use of a graph can be prone to error and using an equation requires number crunching. These two methods were based on trendline equations instead of real collected data.



$$n = [\ y_n + 0.0615x^2 - 4.1046x - 69.1817\ ] \,/\, [\ 0.00649x^2 - 0.2554x - 5.423\ ]$$

n = Coolant weight (lb)

x = Trip duration (hr)

y = Product temperature (F)

Figure 1: *Graph and Equation for Gel Weight Estimation for 113F Exterior Temperature [5]*

This article presents a more comprehensive study to include exterior temperatures of 60F and 90F. This means the results can be used from about normal temperature at 60F to 113F of exterior temperature. In addition, a neural network was used to develop an Excel application, called Gel Pack Estimator [8]. The network derived from real collected data and the Excel application is much easier to use.

2. Materials and Methods

The materials, temperature data collector, and chamber used in this study were the same as those used in previous preliminary work [5]. They are summarized in Figure 2. NeuroShell2 software [9], as shown in Figure 3, was used to train a neural network to recognize the temperature data pattern.

Figure 2: *Materials, Temperature Data Collector, and Chamber*

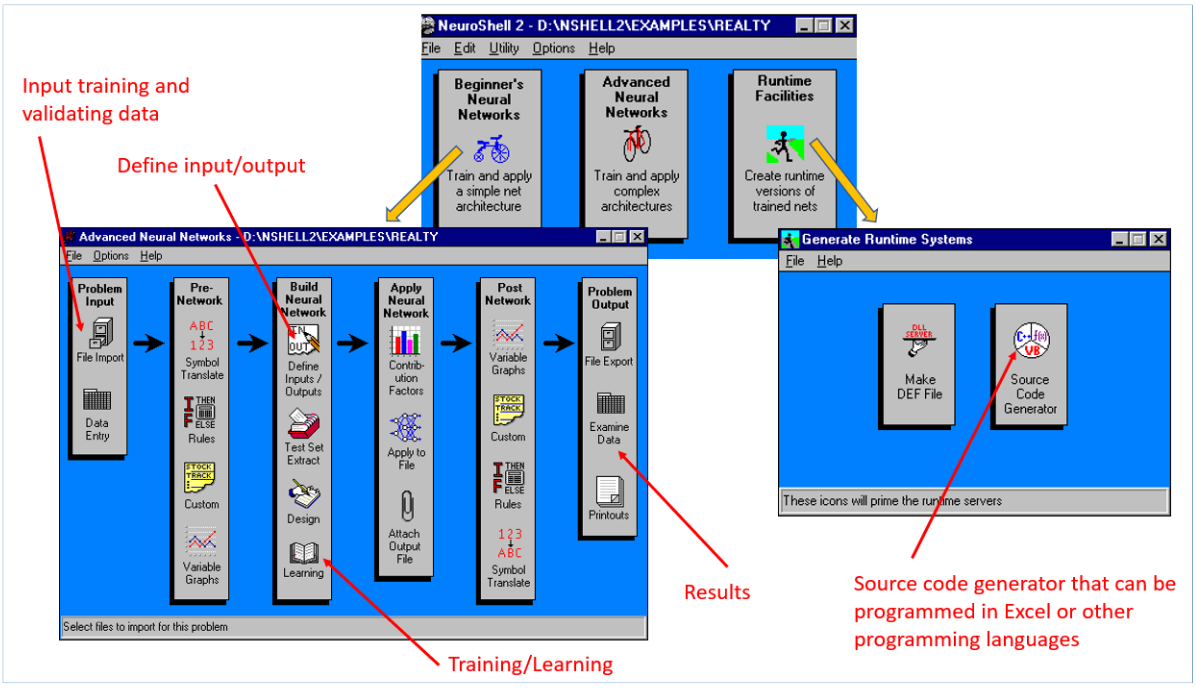


Figure 3: *NeuroShell 2 [9]*

3. Data & Results

Data Collection

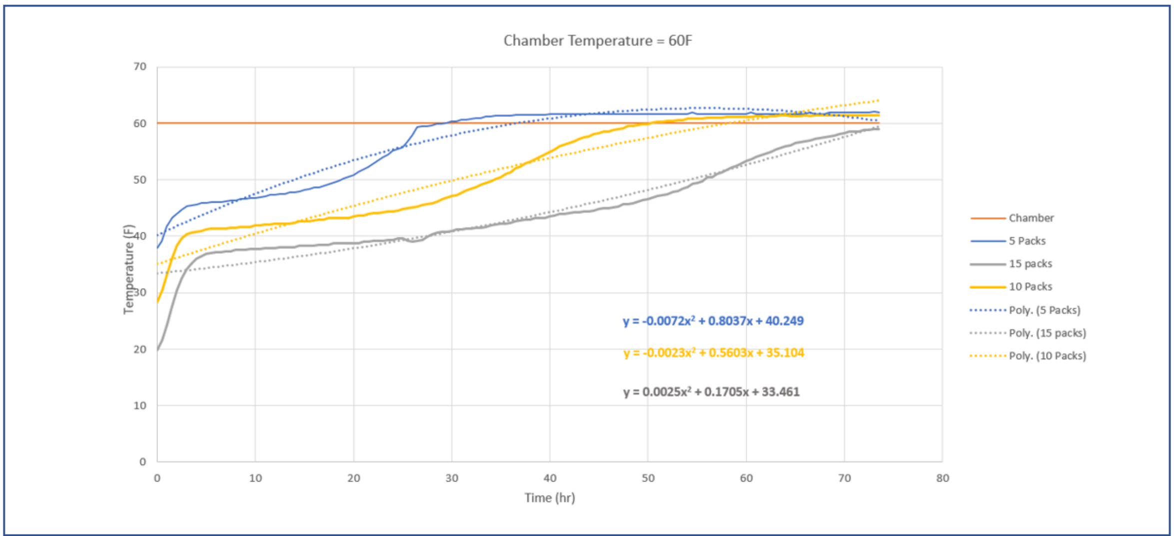
Table 1 shows part of the data collected. The data for 60F and 90F chamber temperatures were added to the data collected for 113F in the preliminary work [5].

Table 1: *Recorded Temperature Data*

Chamber Temperature (F)	Date	11/21/2019				11/25/2019				11/22/2019			
	Gel (Packs)	5				10				15			
	Gel (Kg)	0.95				1.9				2.85			
	Gel (Lb)	2.09				4.19				6.28			
	Sample	Time Data	Time (min)	Time (hr)	Temp (F)	Time Data	Time (min)	Time (hr)	Temp (F)	Time Data	Time (min)	Time (hr)	Temp (F)
113	1	13:12:16	0	0.00	60	15:05:21	0	0.00	49	11:08:22	0	0.00	39
113	2	13:22:16	10	0.17	61	15:15:21	10	0.17	50	11:18:22	10	0.17	39
113	3	13:32:16	20	0.33	63	15:25:21	20	0.33	50	11:28:22	20	0.33	39
113	4	13:42:16	30	0.50	64	15:35:21	30	0.50	51	11:38:22	30	0.50	41
113	5	13:52:16	40	0.67	65	15:45:21	40	0.67	52	11:48:22	40	0.67	42
113	6	14:02:16	50	0.83	66	15:55:21	50	0.83	53	11:58:22	50	0.83	43
113	7	14:12:16	60	1.00	66	16:05:21	60	1.00	53	12:08:22	60	1.00	44
113	8	14:22:16	70	1.17	66	16:15:21	70	1.17	54	12:18:22	70	1.17	45
113	9	14:32:16	80	1.33	67	16:25:21	80	1.33	54	12:28:22	80	1.33	46
113	10	14:42:16	90	1.50	67	16:35:21	90	1.50	54	12:38:22	90	1.50	46
113	11	14:52:16	100	1.67	67	16:45:21	100	1.67	54	12:48:22	100	1.67	47
113	12	15:02:16	110	1.83	67	16:55:21	110	1.83	54	12:58:22	110	1.83	47
113	13	15:12:16	120	2.00	68	17:05:21	120	2.00	55	13:08:22	120	2.00	48
113	14	15:22:16	130	2.17	68	17:15:21	130	2.17	55	13:18:22	130	2.17	48
113	15	15:32:16	140	2.33	68	17:25:21	140	2.33	55	13:28:22	140	2.33	48
113	16	15:42:16	150	2.50	68	17:35:21	150	2.50	55	13:38:22	150	2.50	48
113	17	15:52:16	160	2.67	68	17:45:21	160	2.67	55	13:48:22	160	2.67	49
113	18	16:02:16	170	2.83	69	17:55:21	170	2.83	55	13:58:22	170	2.83	49
113	19	16:12:16	180	3.00	69	18:05:21	180	3.00	55	14:08:22	180	3.00	49
113	20	16:22:16	190	3.17	69	18:15:21	190	3.17	56	14:18:22	190	3.17	49
113	21	16:32:16	200	3.33	69	18:25:21	200	3.33	56	14:28:22	200	3.33	49
113	22	16:42:16	210	3.50	69	18:35:21	210	3.50	56	14:38:22	210	3.50	49
113	23	16:52:16	220	3.67	69	18:45:21	220	3.67	56	14:48:22	220	3.67	49
113	24	17:02:16	230	3.83	70	18:55:21	230	3.83	56	14:58:22	230	3.83	49

Design Graphs

Two additional graphs for 60F and 90F were added to the previous graph shown in Figure 1 above. They are shown in Figures 4 and 5 along with equations to estimate the amount of gel packs.



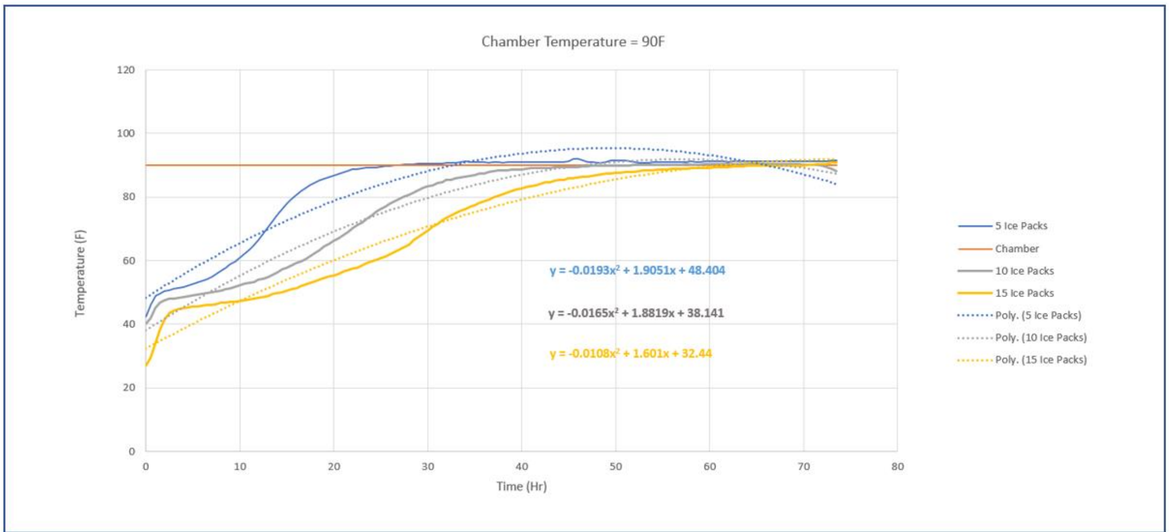
$$n = [\ y_n + 0.01204x^2 - 1.1195x - 43.6348\ ] \ / \ [\ 0.002315x^2 - 0.15112x - 1.62\ ]$$

n = Coolant weight (lb)

x = Trip duration (hr)

y = Product temperature (F)

Figure 4: *Graph and Equation for Gel Weight Estimation for 60F Exterior Temperature*



$$n = [\ y_n + 0.0235x^2 - 2.0568x - 56.3668\ ] \ / \ [\ 0.0020x^2 - 0.0726x - 3.8106\ ]$$

n = Coolant weight (lb)

x = Trip duration (hr)

y = Product temperature (F)

Figure 5: *Graph and Equation for Gel Weight Estimation for 90F Exterior Temperature*

Graphs and equations shown in Figures 1, 4, and 5 can be used to estimate the amount of gel packs needed. Linear interpolation would be needed for exterior temperatures that are not exactly 60F, 90F, or 113F. The temperature range from 60F to 113F should cover most situations.

Neural Net

A neural network is used to recognize the temperature data collected above. It consists of 6 input cells, 17 hidden cells, and 1 output cell as shown in Figures 6, 6(a), 7, and 8.

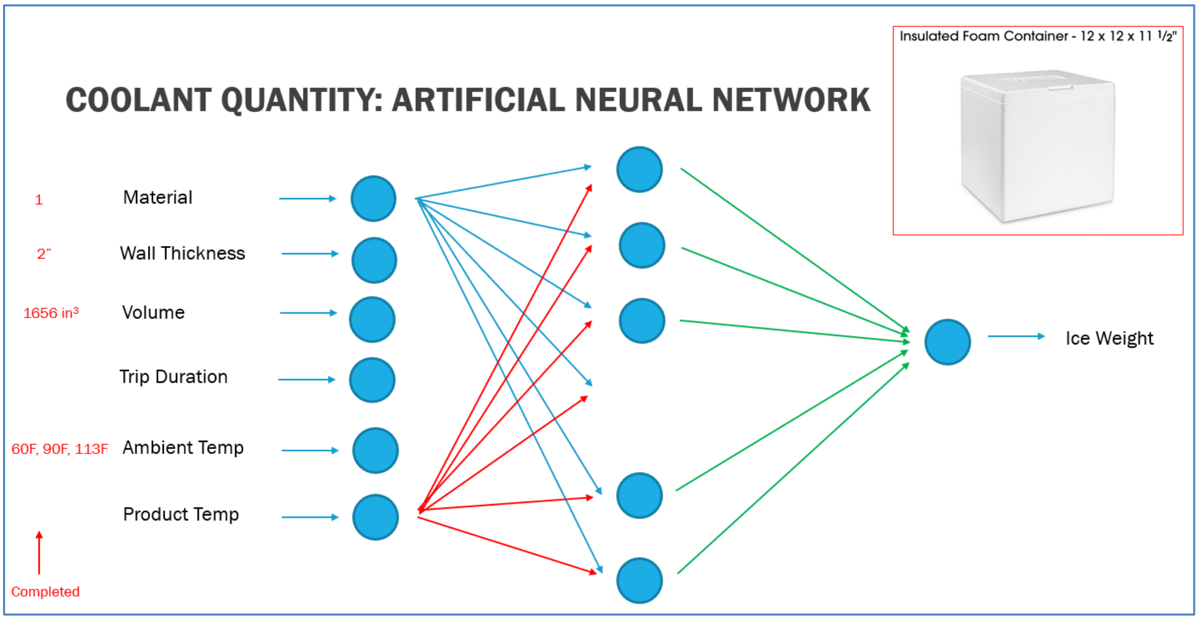


Figure 6: *Neural Network Configuration*

	A	B	C	D	E	F	G	H
1	MT	VL	TH	AT	PT	TD	IW	MARK
2	1	1656	2	113	65	40	2.09	T
3	1	1656	2	113	67	90	2.09	T
4	1	1656	2	113	68	140	2.09	T
5	1	1656	2	113	69	190	2.09	T
6	1	1656	2	113	70	240	2.09	V
7	1	1656	2	113	71	290	2.09	T
8	1	1656	2	113	73	340	2.09	T
9	1	1656	2	113	75	390	2.09	T
10	1	1656	2	113	77	440	2.09	T
11	1	1656	2	113	79	490	2.09	V
12	1	1656	2	113	82	540	2.09	T
13	1	1656	2	113	86	590	2.09	T
14	1	1656	2	113	90	640	2.09	T
15	1	1656	2	113	94	690	2.09	T
16	1	1656	2	113	97	740	2.09	V
17	1	1656	2	113	100	790	2.09	T
18	1	1656	2	113	102	840	2.09	T
19	1	1656	2	113	104	890	2.09	T
20	1	1656	2	113	105	940	2.09	T
21	1	1656	2	113	107	990	2.09	V
22	1	1656	2	113	108	1040	2.09	T
23	1	1656	2	113	109	1090	2.09	T
24	1	1656	2	113	109	1140	2.09	T
25	1	1656	2	113	110	1190	2.09	T
26	1	1656	2	113	110	1240	2.09	V

MT = Material
VL = Container Interior Volume (in^3)
TH = Container Wall Thickness (in)
AT = Ambient Temperature (F)
PT = Product Temperature (F)
TD = Trip Duration (mins)
IW = Ice Weight (lb)
MARK = T for training and V for validation

Figure 6(a): *Neural Network Input and Output*

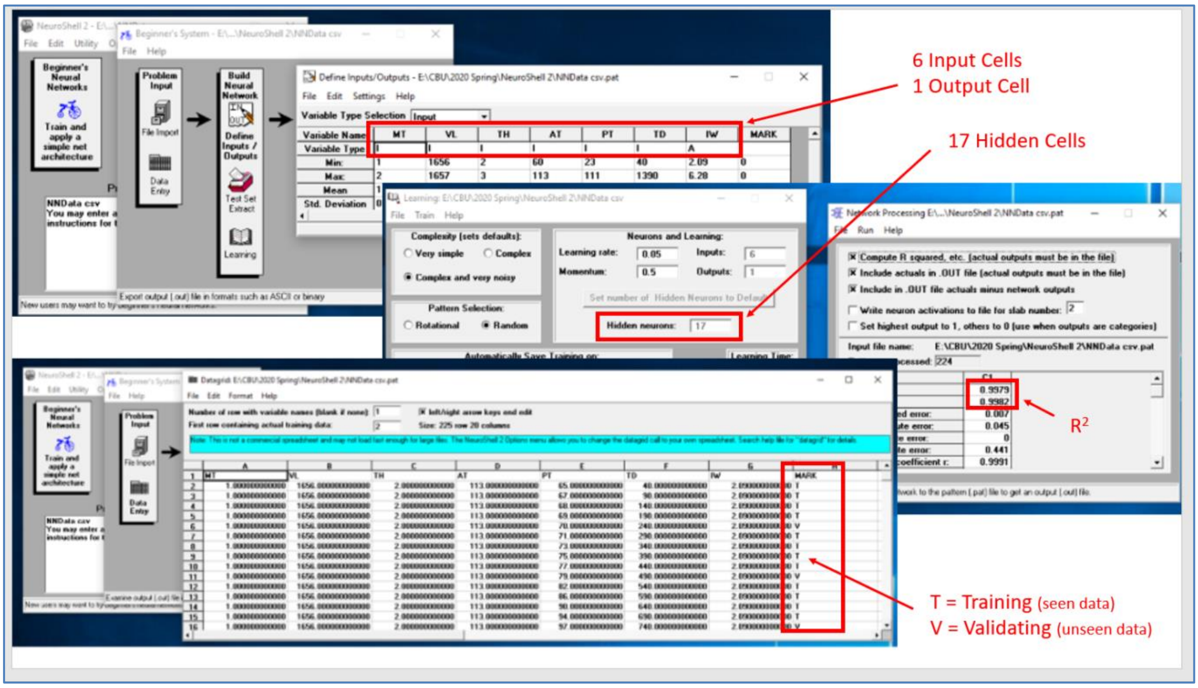


Figure 7: *Neural Network Training Details*

Figure 7 also shows some more details used in neural network training. A “MARK” column was added to the training data to inform the network which data to be used for training (T) and which for validating. The network only “sees” those used for training. Thus, this set is called “seen” data. Those not used by the network during training is called “unseen” data. A total of 224 examples were used with 180 seen samples and 44 unseen samples.

Neural network performance was summarized in Figure 8 with an average of -0.93% error and an error range of -16.09% to 7.41%. The 16% error figure seems large. However, Figure 9 shows that 93.75% of all samples were within 5% error. If 10% error is used, 98.66% of cases are within 10% error. Only 1.34% of these cases yields more than 10% error. Similar findings of error were found in “seen” and “unseen” data sets. The network performance is considered excellent.

MARK	Actual(1)	Network(1)	Act-Net(1)	Error
T	2.09	2.089999914	0	0.00
T	2.09	2.131083727	-0.041083813	-1.97
T	2.09	2.147223711	-0.057223797	-2.74
T	2.09	2.138481379	-0.048481464	-2.32
V	2.09	2.1308918	-0.040891886	-1.96
T	2.09	2.134369612	-0.044369698	-2.12
T	2.09	2.095000267	-0.005000353	-0.24
T	2.09	2.089999914	0	0.00
T	2.09	2.089999914	0	0.00
V	2.09	2.117774487	-0.027774572	-1.33
T	2.09	2.12607646	-0.036076546	-1.73
T	2.09	2.114197493	-0.024197578	-1.16
T	2.09	2.108807325	-0.018807411	-0.90
T	2.09	2.095750093	-0.005750179	-0.28
V	2.09	2.105157852	-0.015157938	-0.73
T	2.09	2.096237898	-0.006237984	-0.30
T	2.09	2.111040354	-0.02104044	-1.01
T	2.09	2.106604338	-0.016604424	-0.79
T	2.09	2.137220383	-0.047220469	-2.26
V	2.09	2.091647387	-0.001647472	-0.08
T	2.09	2.089999914	0	0.00

Data

- Total 224 samples
- 180 seen samples (80%)
- 44 unseen samples (20%)

% Error

- Range: -16.09% to 7.41%
- Average: -0.93%

Figure 8: *Network Performance Summary*

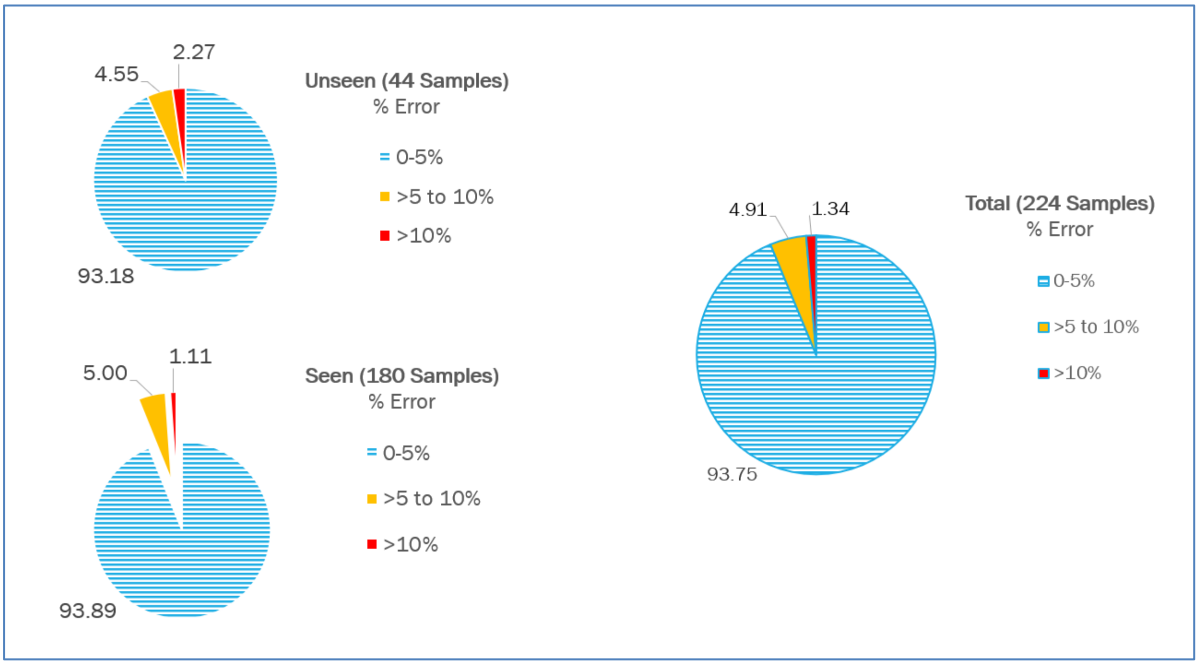


Figure 9: *Network Performance by Category*

As show in Figure 3, NeuroShell 2 software has a "Source Code Generator" module. It generates a source code so the trained network can be programmed in Excel or other programming languages. Thus, the end users can use the developed application without having to acquire a full version of NeuroShell 2 software. A part of the code generated for this work is shown in Figure 10. The code starts from row 8 and ends in row 218, a total of 211 lines of code including some blank rows for readability. The Gel Pack Estimator [8] was then developed using Excel spreadsheet as shown in Figure 11. Since the collected date for this work is limited to a specific material type (MT), container volume (VL), and container thickness (TH), default values for these input variables are given. The user would only enter the remaining three input variables; ambient temperature (AT), product threshold temperature (PT), and trip duration (TD). The network then outputs the ice/gel weight (IW).

```
netsum
feature2(17)

Note - the following are names of inputs and outputs:
Note - inp(1) is MT
Note - inp(2) is VL
Note - inp(3) is TH
Note - inp(4) is AT
Note - inp(5) is PT
Note - inp(6) is TD
Note - outp(1) is IW

if (inp(1)<1) then inp(1) = 1
if (inp(1)>2) then inp(1) = 2
inp(1) = (inp(1) - 1)

if (inp(2)<1656) then inp(2) = 1656
if (inp(2)>1657) then inp(2) = 1657
inp(2) = (inp(2) - 1656)

if (inp(3)<2) then inp(3) = 2
if (inp(3)>3) then inp(3) = 3
inp(3) = (inp(3) - 2)


netsum = 1.086496
netsum = netsum + feature2(1) * 4.687042
netsum = netsum + feature2(2) * 4.242756
netsum = netsum + feature2(3) * 2.320607
netsum = netsum + feature2(4) * 1.134749
netsum = netsum + feature2(5) * -1.106494
netsum = netsum + feature2(6) * 5.551099
netsum = netsum + feature2(7) * -8.095733
netsum = netsum + feature2(8) * -5.694211
netsum = netsum + feature2(9) * -4.557061
netsum = netsum + feature2(10) * 0.4984904
netsum = netsum + feature2(11) * 5.464834
netsum = netsum + feature2(12) * -6.262721
netsum = netsum + feature2(13) * 8.505028
netsum = netsum + feature2(14) * -3.490235
netsum = netsum + feature2(15) * 1.663898
netsum = netsum + feature2(16) * 0.1031915
netsum = netsum + feature2(17) * -6.402617
outp(1) = 1 / (1 + exp(-netsum))


outp(1) = 4.190001 * (outp(1) - .1) / .8 + 2.09
```

Figure 10: *Source Code for Application Development*

MT - Material Type	inp(1) =	1
VL - Container Volume (in^3)	inp(2) =	1656
TH - Container Thickness (in)	inp(3) =	2
AT - Ambient Temperature (F)	inp(4) =	60
PT - Product Threshold Temp (F)	inp(5) =	38
TD - Trip Duration (hr)	inp(6) =	540
IW - Ice/Gel Weight (lb)	outp(1) =	6.224963702

Figure 11: *Gel Pack Estimator Excel App*

4. Discussion & Conclusion

This work provides three methods of estimating the gel coolant amount needed to maintain a certain product threshold temperature for a given trip duration under a certain ambient temperature. The three methods are graph, equation, and Excel application software. The graph method is error prone while the equation method requires number crunching. The Excel application solution is the most practical.

The current work is limited to a 12 x 12 x 11½" expanded polystyrene insulated container with 2" wall thickness. In the future, different sizes of containers with different wall thicknesses can be included in training data for the neural network. The same is true for the inclusion of additional types of materials for insulated containers.

Even though the solutions provided in this work are limited to a specific container, the methodology can be used to develop similar solutions for other types of containers. However, collecting data experimentally is time consuming. The solutions provided in this work can be used as the first estimate and adjustments can be made accordingly from experience. Common sense can also be used in adjusting gel pack weight. For example, a thicker wall of about the same interior container volume means better insulation. Thus, the gel coolant amount needed would be less for the same shipping conditions. Bigger containers would need more gel packs due to the cooling of a larger interior volume. A container material with better insulation properties would require less gel coolant.

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