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Effect of Temperature on Drinking Water Bottles

Siripong Malasri, Ali Pourhashemi, Robert Moats, Antoine Herve, Joseph Ferris, Asit Ray, and Ray Brown

Healthcare Packaging Consortium, Christian Brothers University, 650 East Parkway South, Memphis, TN, USA

Correspondence should be addressed to Siripong Malasri, pong@cbu.edu

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Abstract Two drinking water bottle sizes; 10 Fl. Oz. and 16.9 Fl. Oz., were crushed across a range of temperatures, from 32$^\circ F$ to 125$^\circ F$. Three sets of bottles were placed in a temperature chamber at 150$^\circ F$, in refrigerator, and in freezer for about three hours. Another set of bottles were kept at room temperature. Bottle compression strength reduced at a rate of about 0.5 and 0.3 pound per 1 $^\circ F$ increase in temperature for the 10 and 16.9 Fl. Oz. respectively. Bulging was observed at the bottom of the 16.9 Fl. Oz. bottles. It was stabilized at about 5 hours under 150$^\circ F$. However, leaks occurred shortly after the temperature was elevated to 170$^\circ F$. In addition, the strength per bottle of a 24-bottle pack was found to be about 25% more than that of single bottle strength.
Keywords *Drinking Water Bottles; High Temperature; Bulging*

1. Introduction

Bottled water has been widely consumed due to convenience and cleanliness. In 2008, bottled water sales accounted for about 8.6 billion U.S. gallons, which was about 29% of the U.S. beverage market [1]. Bottle manufacturers have reduced the materials used through thickness reduction and clever structural design of water bottles. During distribution and transport, bottled water is often placed in a high temperature environment.

In a previous study [2], the temperature inside a truck container could easily reach 150$^\circ F$ during a hot summer day based on the following heat transfer equation (Equation 1):

$$T_i - T_\infty = \left(\frac{q_s \alpha}{1.91/W^{1/4} + 2.84H^{3/4}\left(\frac{1}{W} + \frac{1}{L}\right)} \right)^{0.8} \quad \text{...... Equation 1}$$

Where T_i = interior temperature of tractor trailer (°C), T_∞ = exterior temperature (°C), q_s = sun load (1000 W/m^2), α = absorptivity of solar radiation, L = length of tractor trailer (m), H = height (m), and W = width (m). As the temperature rose, it was found that wooden pallet compression resistance weakened.

This article reports the effect of high temperatures on the compression strength and bulging of bottled water.

2. Materials and Methods

2.1. Polyethylene Terephthalate (PET)

Most of the beverage bottles, used in the USA, are manufactured using PET (polyethylene Terephthalate) and PET modified by copolymerization by the use of added co-monomer. PET is relatively strong, withstands higher temperature (has high melting point), and has good barrier properties against moisture, oxygen, CO_2, alcohol, and solvents. It can be made transparent by limiting crystallinity using copolymerization, adding fillers or controlling cooling when melt-processed during manufacture. PET bottles made for containing water are amorphous (non-crystalline) or have low crystallinity for clarity and toughness. However, one of the disadvantages of PET is its low melt strength which makes it difficult or impossible to process to make bottles by the standard extrusion blow molding. Melt strength can be improved by copolymerization using any number of co-monomers or increasing molecular weight during polymerization, i.e. when making polymer resins [3].

Hence, water bottles sold by different vendors are expected to be made from PET's having minor differences in chemical constituents - in terms of types and quantities of co-monomers added during polymerization and molecular weight (intrinsic viscosity) attained during the process. Because of this fact, the percentage of crystallinity and tendency for crystallization can vary from one set of bottles to another; hence, their responses to temperature, humidity, compressions, drops, shocks, and vibrations experienced during transportation/distribution can vary significantly. A significant factor in the growth of PET containers, in the market, is the high value and performance characteristics that it maintains even after being recycled. It has the highest recycling rate of all plastics.

The properties of PET polymer include: density of 1.33-1.38 gm/cm^3 (amorphous), transparency of 85-92%, melting point of 255-260°C, tensile strength of 58 MPa, tensile elongation of 150-300%, and processing temperature of 275-295°C [4]. Additional properties can be found on Wikipedia [5].

2.2. Chamber Dwell Time

Two bottle sizes commonly found in grocery stores were used in this study: 10 Fl. Oz. and 16.9 Fl. Oz. However, only the larger size was used in the bulging experiment. Sets of bottles were placed in a freezer, refrigerator, environmental chamber (set at 150$^\circ F$), and at room temperature. The dwell time in the freezer, refrigerator, and environmental chamber was about three hours, which was more than the minimum dwell time determined from a simplified form of the Fourier equation of cylindrical coordinate unsteady state heat conduction, as shown in Equation 2 [6] and backed up with experimental data:

$$t := \frac{r^2}{5.78\alpha} \ln\left[0.692 \frac{T_s - T_o}{T_s - T_f}\right] \quad \text{...... Equation 2}$$

Where t = time for water to reach equilibrium (minutes), r = liquid radius, α = thermal diffusivity = $\frac{k}{\rho C_p}$, T_s = surface temperature ($^\circ F$), T_o = initial temperature of water ($^\circ F$), T_f = final average temperature of water ($^\circ F$), k = thermal conductivity as shown in Figure 1, ρ = water density (62.4 lb/ft^3), and C_p = water heat capacity (1 BTU/lb$^\circ F$).

Based on Equation 2, the time for water to reach 95% of a chamber temperature between 80$^\circ F$ to 180$^\circ F$ was in the range of 42.6 to 48.9 minutes for T_s. This was backed up by an experiment where thermocouples were used to measure water temperature (T_f) and surface temperature (T_s) in a 16.9 Fl. Oz. bottle, as shown in Figure 2. It took about 100 minutes for the water temperature (T_f) to reach 150$^\circ F$. Thus, the 3-hour chamber dwell time at 150$^\circ F$ used in this study was more than sufficient.

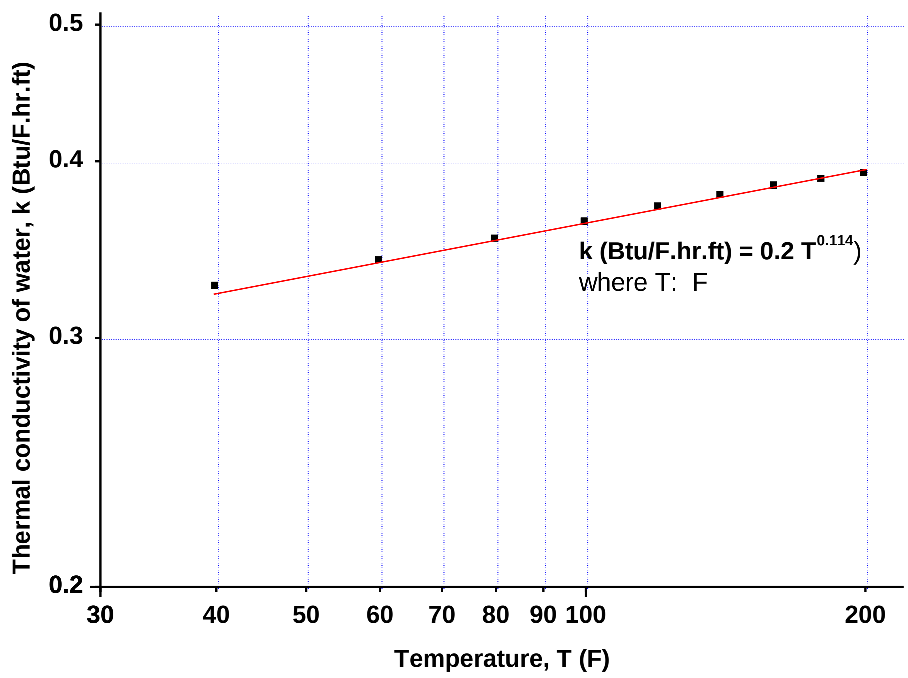

Figure 1: *Thermal Conductivity of Water as a Function of Temperature*

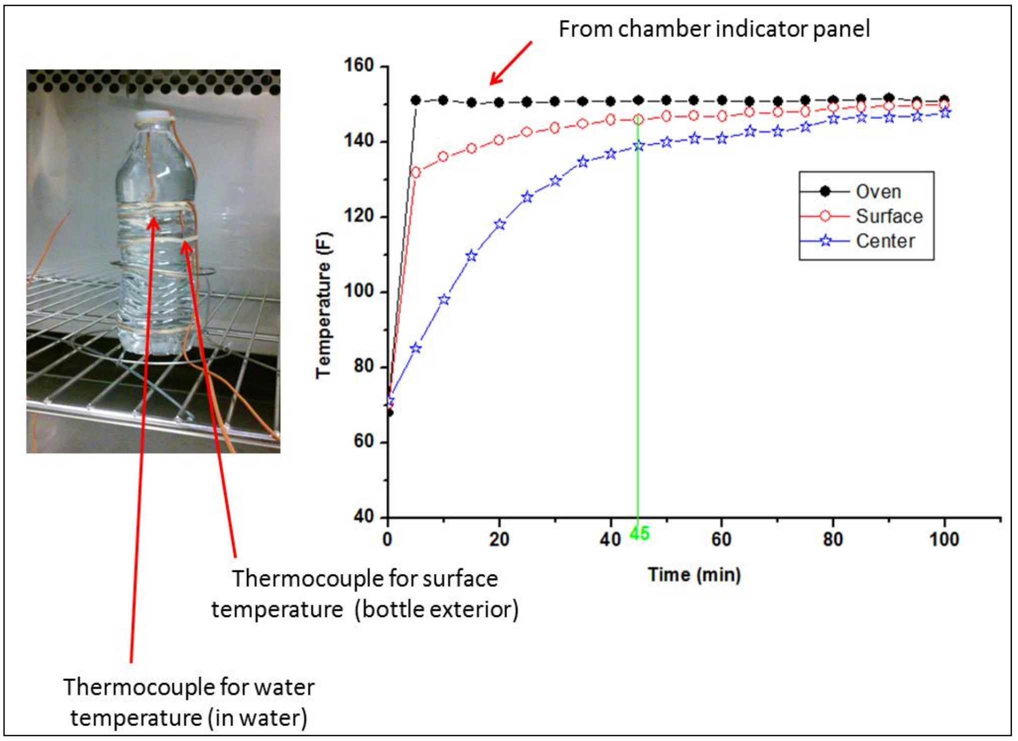

Figure 2: *Heating of Water Bottle*

2.3. Compression Test and Surface Temperature Measurement

Bottles were taken from the chamber, refrigerator, and freezer to a compression table, along with those dwelled in room temperature. A hand-held thermocouple reader was used to determine the bottle exterior temperature at the time of the compression test (Figure 3). Force was applied at the rate of 0.5 inch/minute.

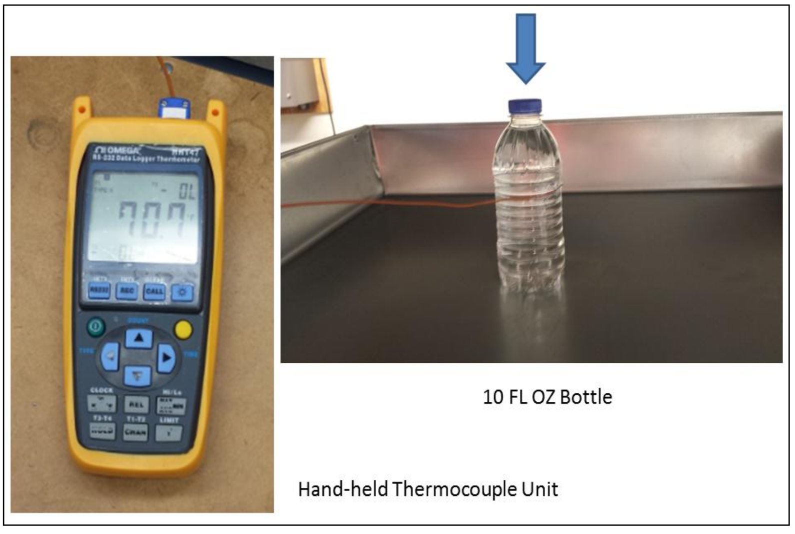

Figure 3: *Measuring Bottle Temperature at the Time of Compression Test*

The bulging at the bottom of the 16.9 Fl. Oz. bottles was much more pronounced than in the 10 Fl. Oz. bottles. Thus, it was difficult to make a bulged bottle stand vertically while being compressed. Thus, a simple supporting fixture was designed to ensure the verticalness of the bottle, as shown in Figure 4. The foam at the bottom of a corrugated box prevented the slippage while the brush on the top held the bottle vertically with a minimum of lateral force due to the flexibility of the brush hairs. Compression test data was summarized in Tables 1 and 2.

Figure 4: *Supporting Fixture to Hold Bottle Vertically During Compression Test*

Table 1: *Compression Test Data for 10 Fl. Oz. Bottles*

Sample	Temperature ($^\circ F$)	Maximum Load (lb)
1	123.8	38
2	119.2	58
3	118.0	48
4	112.2	46
5	111.4	59
6	110.1	30
7	109.8	57
8	105.8	57
9	104.0	55
10	66.4	70
11	66.4	78
12	47.2	72
13	44.7	81
14	40.9	86
15	39.2	103

Table 2: *Compression Test Data for 16.9 Fl. Oz. Bottles*

Sample	Temperature ($^\circ F$)	Maximum Load (lb)
1	125.2	10
2	121.6	73
3	117.7	13
4	116.5	24
5	115.4	61
6	112.7	63
7	112.5	59
8	111.3	59
9	108.9	76
10	102.9	63
11	64.0	45
12	63.4	60
13	62.3	73
14	51.2	83
15	51.2	76
16	51.2	72
17	40.0	67
18	39.9	47
19	37.0	70
20	32.0	72
21	31.5	84

2.4. Bulging Experiment

Bulging (extrusion at the bottom of bottle) was observed after 16.9 Fl. Oz. bottles dwelled in the chamber at 150$^\circ F$ for three hours. Thus, an experiment was set to measure the elongation of the bottle. A dial gage with 0.001 inch accuracy was used to measure the elongation. A webcam was used so elongation could be read without having to open the chamber. Another similar bottle was also used to monitor the temperature using thermocouples. The setup is shown in Figure 5. The expansion of the wooden base was negligible, thus it was ignored. Bulging data was summarized in Table 3.

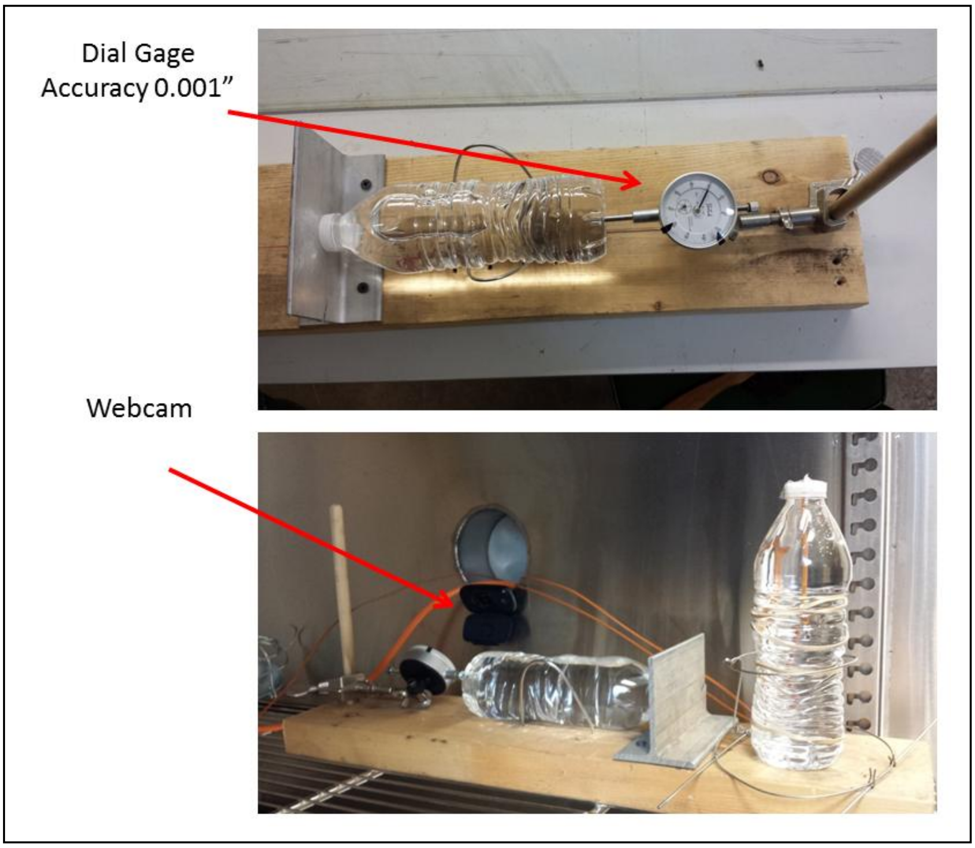

Figure 5: *Bulging Experiment Setup*

Table 3: *Bulging Data of 16.9 Fl. Oz. Bottle*

Day	Time (min)	Elongation (in)	Chamber RH (%)	Set Temperature ($^{\circ}F$)
1	0	0	6	150
1	9	0.026	6	150
1	19	0.053	6	150
1	29	0.081	6	150
1	39	0.110	6	150
1	49	0.151	6	150
1	59	0.200	6	150
1	69	0.270	6	150
1	79	0.378	6	150
1	89	0.425	6	150
1	99	0.445	6	150
1	109	0.461	6	150
1	129	0.482	6	150
1	159	0.496	6	150
1	189	0.510	6	150
1	219	0.516	6	150
1	249	0.520	6	150
1	279	0.523	6	150

1	309	0.525	6	150
2	1198	0.533	6	150
2	1208	0.535	6	150
2	1295	0.536	6	170
2	1308	0.543	6	170
2	1318	0.549	6	170
2	1328	0.554	7	170
2	1338	0.553	7	170
2	1358	0.548	7	170
2	1368	0.550	7	170
2	1378	0.550	12.4	170
2	1388	0.538	12.7	170
2	1398	0.526	13.1	170
2	1408	0.514	13.6	170

3. Results and Discussion

3.1. Effect of Temperature to Bottle Compression Strength

Data from Tables 1 and 2 were plotted in Figures 6 and 7. Even though a fixture was introduced to stabilize the 16.9 Fl. Oz. bottles during the test from the bulging, the data obtained was not as consistent as those from 10 Fl. Oz. bottles, i.e. R^2 of 0.2592 versus 0.7756. However, the trends of both bottle sizes were the same. As temperature increased, the compression strength decreased at the rate of 0.30 lb/$^\circ F$ and 0.52 lb/$^\circ F$ for 16.9 Fl. Oz. and 10 Fl. Oz. bottles, respectively.

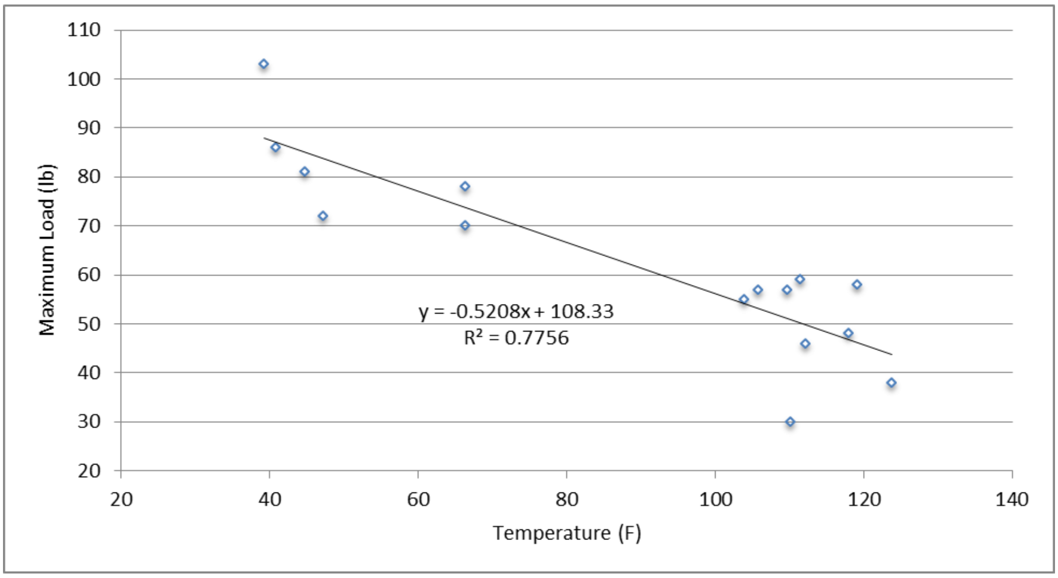

Figure 6: *Compression Strength vs Temperature for 10 Fl. Oz. Bottles*

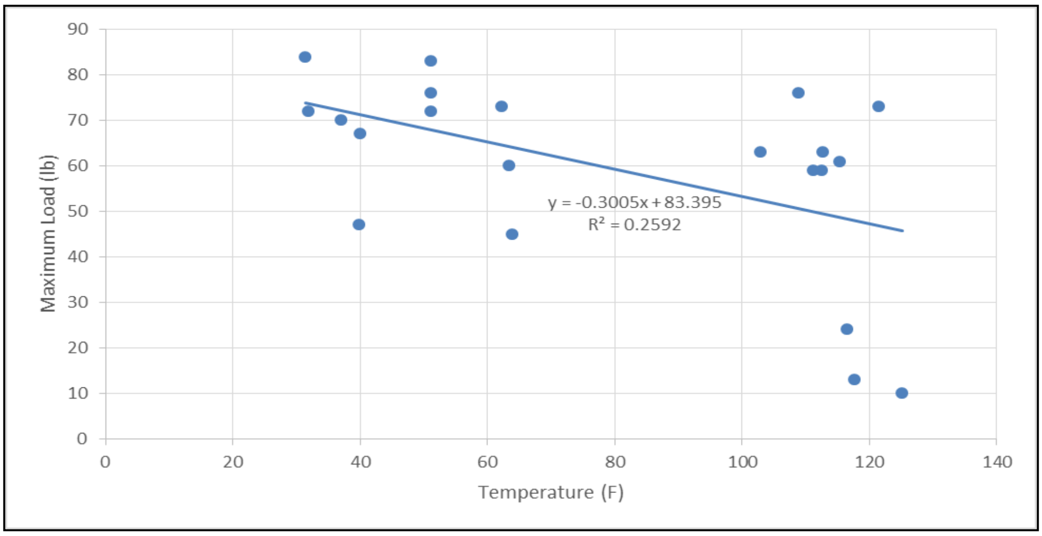

Figure 7: *Compression Strength vs Temperature for 16.9 Fl. Oz. Bottles*

3.2. Bulging

Data from Table 3 was plotted in Figure 8. The elongation was superimposed with the temperature data in Figure 9. Under 150 $^{\circ}F$ the bulging stopped at around 0.55 inch. However, when the chamber temperature was increased to 170 $^{\circ}F$, leak occurred at 1378 minutes. During the data collection, indicators of leak were an increase in chamber relative humidity from 7% to 12.4% and a drop in elongation afterward due to the release of internal pressure. Leaks were later observed at the end of the experiment, as shown in Figure 10.

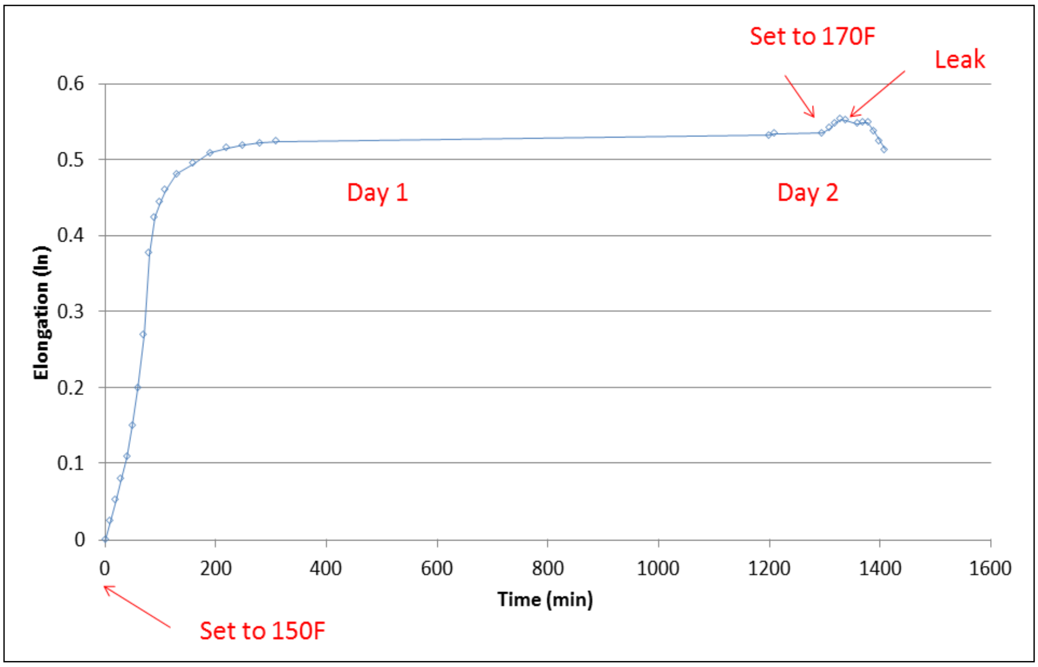

Figure 8: *Bulging Elongation with Time*

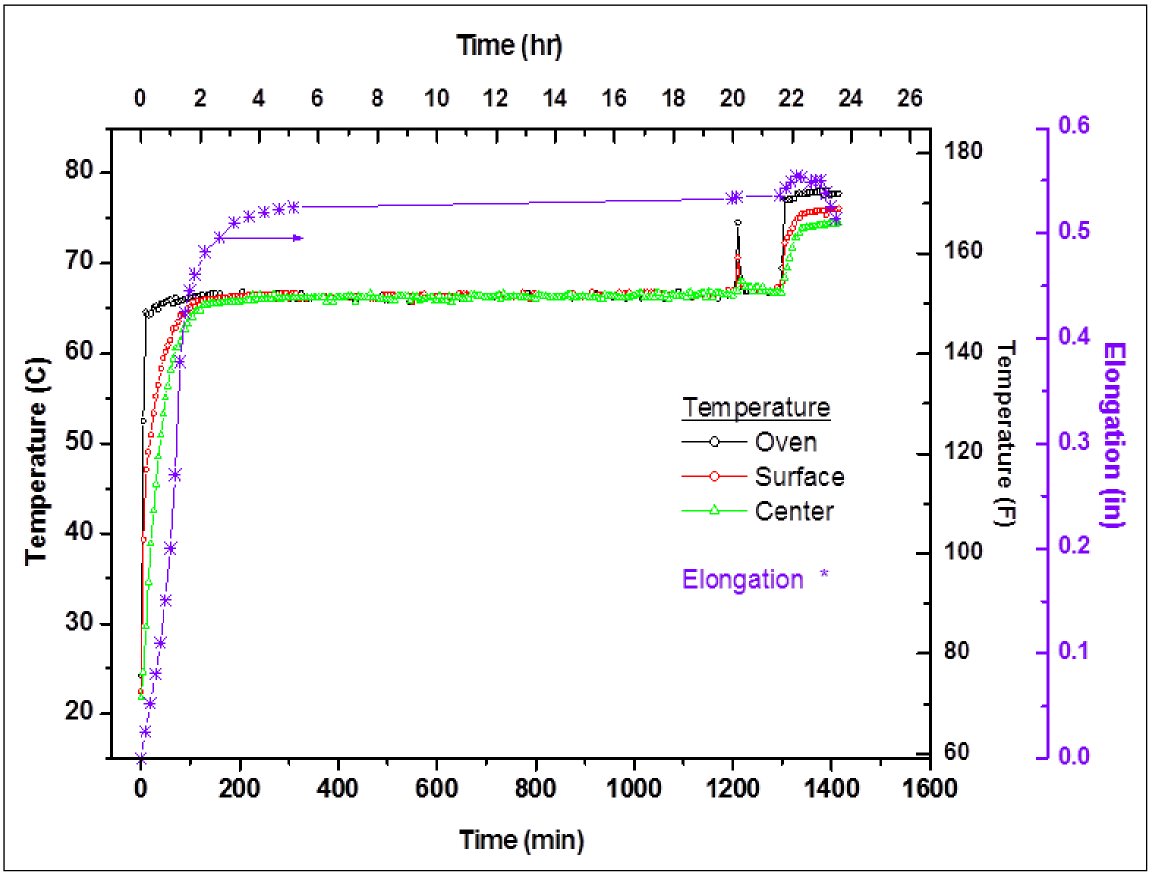

Figure 9: *Elongation with Temperature Information*

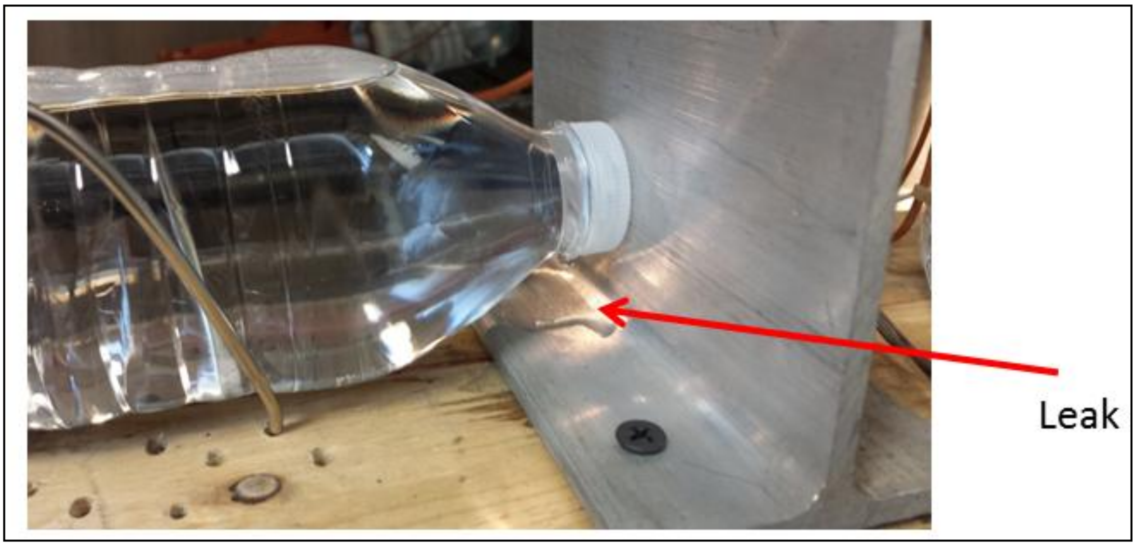

Figure 10: *Leak at Cap*

3.3. Effect of Multi-Bottle Pack

Bulging affects the stability of single bottles. However, multi-bottle packs are used during distribution. The stability of these multi-bottle packs improves significantly. It is more complex to study the effect of temperature on a multi-bottle pack. The temperature of the bottles on the pack exterior will be different from those in the pack interior. Thus, in this study 24-bottle packs of 16.9 Fl. Oz. bottles were used. An average maximum load of ten single bottles was found to be 40.20 lb, while an average maximum load of five 24-bottle packs was found to be 1,211.33 lb or 50.47 lb/bottle. Thus, the 24-bottle pack capacity per bottle was 25.55% more than single-bottle capacity. A bottle provides lateral support to its adjacent bottles. In addition, the plastic wrap that holds the bottles together increases the pack's load bearing capacity.

4. Conclusion

The compression strength of water bottles reduces as temperature increases. Different bottle design and chemical constituents of material used will affect the strength reduction and bulging rates. However, the same trends are expected. As the bottled water industry is moving toward sustainability with thinner, thus weaker bottles, the effect from high temperature becomes more pronounced. The chamber temperatures of 150$^{\circ}F$ and 170$^{\circ}F$ used in this study are not uncommon in distribution environments. The three-hour chamber dwell time is also not uncommon in truck containers on a hot summer afternoon. Bulging at the bottom affects the functionality of bottles. It should also be noted that the bulging remains after the bottles cool down. Thus, a creative design is needed to reduce the bulging effect.

Acknowledgement

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