Paper Towel Absorptive Properties and Measurement using a Horizontal Gravimetric Device

David Loebker, Jeffrey Sheehan
The Procter & Gamble Company

ABSTRACT
Consumers often list ability to absorb as a key attribute for paper towels. Paper towel absorbency rate and capacity were measured using a customized horizontal radial absorption instrument. This report discusses repeatability and other details of the method, as well as other similar methods using commercially available equipment. Absorptive properties of both through-air dried and conventional wet pressed papers were compared. Results show that papermaking technology and number of plies, in general, have a much larger effect on absorptive properties as compared to basis weight (within the studied range).

Background

Measurement of paper towel absorptive properties using a horizontal radial wicking apparatus is not a new proposition. Industry standardization groups, such as TAPPI and CEN, have evaluated two such devices (Sherwood Instrument's "ATS" and M/K System's "GATS") and their associated methods for quantifying towel absorption properties

In April 2008 Jeff Lundeen, Working Group Chair for TAPPI Working Group 030803.10, published an interim report regarding the development of absorbency rate methods for towel and tissue products [1]. In that report, two proposed absorbency methods were compared across labs using two different substrates (a TAD and a conventional wet pressed (CWP) product), the two available absorbency instruments (the "ATS" and the "GATS"), and three different absorbency rate calculations. The Tappi tissue subcommittee members involved concluded that both instruments could differentiate between products of differing absorbency capability but neither instrument, running either absorbency method, provided data of sufficient repeatability or reproducibility. Subsequently, the provisional GATS method (T561 pm-96) was withdrawn and the aforementioned working group was discontinued. Since then M/K Systems has continued work to improve their GATS instrument, as documented by presentations from Andy Kallmes to TAPPI tissue properties subcommittee in both May and October 2010 meetings as well as in patent US7,779.685.

There are a number of capacity methods that have been published over the years. A few that have been used to measure towel-like substrates include: Federal Specification: Towels, Paper [2] , Federal Specification: Towel, Wiping, Paper; Industrial and Institutional [3], EN ISO 12625-8 [4], ASTM D-4250 [5], and INDA Test Method IST 10.1 [6]. These can be classified as essentially "dunk and drain" capacity-only techniques, since rate is not relevantly captured. These methods, and others that are reported in patents and literature, report a "capacity" value; however, different capacities result from each method's different approach (e.g., multiple sheets, angle of sheet while draining, drain time, etc.). In this report, we will focus on capacity as measured by horizontal gravimetric wicking instrumentation.

To assist in developing a better absorbency instrumentation and methodology for making towel products, Procter & Gamble developed instrumentation to gravimetrically measure absorbency rate and capacity. Our instrument can be run in a mode that is somewhat similar to that of the Sherwood ATS and the M/K GATS, albeit with alterations to attempt to improve repeatability and reproducibility, which we will compare to that shared in Lundeen's interim report.

Experimental Approach

In our approach, a circular cut towel sample is placed on a platform which has a water supply orifice at its center, and from which radial absorption can be gravimetrically measured. It was then run in a mode similar in some ways to the GATS tester (as will be discussed later in this report).

In studying our instrument and associated techniques, we evaluated three key aspects of performance: repeatability, accuracy with respect to ranking samples, and sensitivity. For repeatability, we compared our results to the other two commercially available instruments using a market towel product and compared repeatability with that reported in TAPPI Interim Report [1]. For accuracy, we tested multiple product substrates with known relative absorbency performance and determined if the instrument appropriately ranked them. The samples were market towel products taken from each of these categories: one-ply conventional wet pressed (CWP), two-ply CWP, one-ply TAD, and two-ply TAD. For sensitivity, we chose to study the impact of basis weight on absorbency rate and capacity. The impact of basis weight on absorbency rate has not been well established in the literature and therefore seemed to be useful both to verify sensitivity as well as to add to the scientific knowledge in the area.

We obtained six different paper towel samples from the market, all made by producers other than P&G. They can be characterized as:

Table 1: Paper towels samples used in this study

Structure	# Plies	BW (lbs/3000ft^2)
CWP	1	26.1
CWP	2	30.4
TAD	1	23.6
TAD	2	25.0
TAD	2	28.7
TAD	2	32.8

Sample Preparation
All samples were preconditioned under TAPPI standard conditions of 73°± 2°F (23°± 1°C), relative humidity of 50 ± 2%. A circular sample was obtained using a 3 3/8" diameter circular die in a Thwing-Albert hydraulic precision cutter.

Instrument Description
The CRT (Capacity and Rate Tester) is a radial orifice wicking instrument (Fig. 1) in which we placed a 3 3/8" diameter sample onto a mesh support of monofilaments and centered over a water supply tube (I.D. 7.9 mm). Water is available to the sample under a controllable negative pressure, accurate within +/- 0.1 mm H_20. After the sample is hydraulically connected to the water supply, water wicks radially outward from the supply tube and the sample weight is recorded as a function of time (20 points/second) using a Mettler-Toledo three place precision balance. The sample is also weighed just before testing (dry) and after hydraulic disconnection. Distilled water was used in the instrument (conductivity < 10 uS/cm (target <5 uS/cm) @ 25 ^oC). Other parameters are shown in Table 2 below, as compared to those outlined for the New TAPPI method run on the GATS instrument described in the TAPPI interim report.

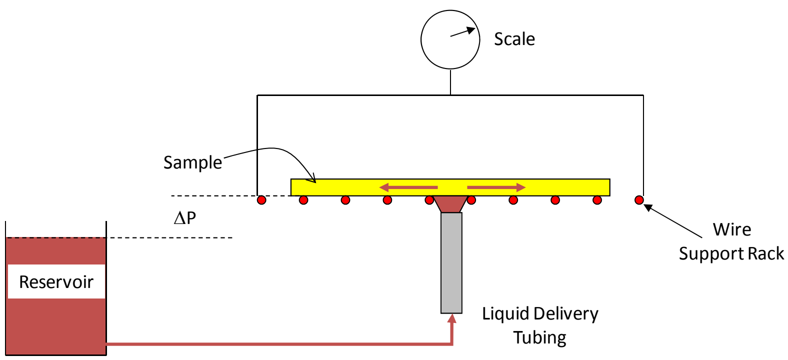

Figure 1: Schematic diagram of CRT test set-up

Table 2: Comparison of GATS method [7] and CRT method parameters as presented in this report

	GATS	CRT
Sample Diameter	2 in	3.375 in
Sheets	1	1
Support Surface	Mesh	Mesh
Top Surface	Mesh	Top Cover
Negative hydrostatic Pressure	5mm	2 mm
Orifice Diameter	3 mm	7.9mm
End Point for Capacity	5 mg / 5 sec	9 mg / 6 sec

A top cover is used in the testing to improve consistency and repeatability. The cover is designed to: 1) keep the sample from bending away from the supply tube at initiation, 2) to keep the sample flat during testing, 3) to minimize contact with the sample, and 4) to minimize air currents around the instrument that might interfere with the weight measurement.

Calculations

Capacity

The samples were allowed to take up water until the rate of uptake fell at or below 9 milligrams per 6 seconds. The six second time period helps prevents a premature end that could be caused rate fluctuations, particularly at initiation. The hydraulic connection from the water supply to the sample was then broken, and the final sample weight obtained. Absorbency Capacity was calculated by subtracting the initial dry sample weight from the final wet sample weight. The results are listed in g/in^2 and g/g.

Rate

For this study, we calculated absorbency rate in a number of ways in an attempt to better understand the behavior of consumer towel products in these types of measurements. These rate calculations can be categorized into the two groups below:

1. Cumulative rate

   Simply the mass of water taken up (from time 0) divided by the amount of time. This was calculated at 2, 5, and 10 seconds, in similar fashion as recorded in the TAPPI Interim Report [1]. These results are listed in g/sec.

2. Slope of the water uptake data vs. time

   For these measurements, we performed a linear regression on the raw data vs. linear time and vs. the square root of time. The raw data was not smoothed or altered in any fashion. We avoided the data collected during the first 2 seconds of the test, since it is often noisy from the initiation surge and can impact the rate calculations. This observation helped to define the time at the beginning of the rate calculation. For this study, we also wanted to investigate the impact of different termination times, or the time at which the rate calculation would end. This choice is one of the difficulties method developers are faced with due to the differences in behavior seen amongst products produced in different ways. The figures below help to demonstrate this.

   Figure 2 below shows the results from two of the products measured during this study: a one-ply TAD and a two-ply TAD sample. The one-ply TAD sample showed linear absorbency all the way to 20 seconds. The two-ply TAD sample showed a large decrease in rate at around 10 seconds. If you try to regress the uptake data vs. time from the early portion of the curve to any point after about 10 seconds, the linear regression of the two-ply TAD product, while having an excellent r^2, doesn't match the actual slope of the data demonstrated in the curve. As shown in Figure 2, the linear regression from 2 to 15 seconds has an r^2=0.93, but the linear fit doesn't closely match the measured rate of uptake.

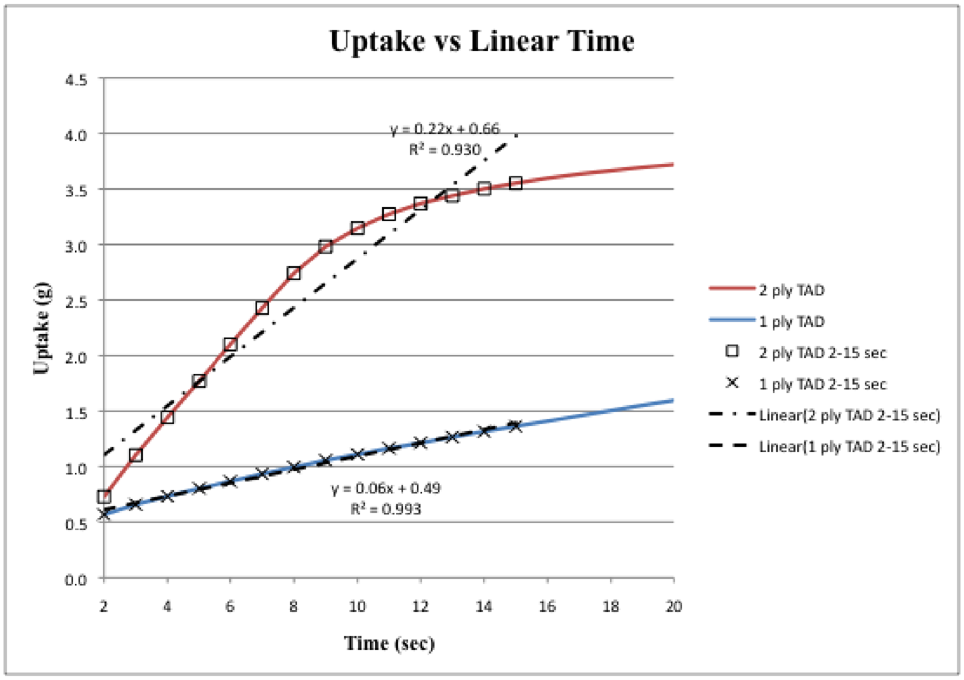

Figure 2: Uptake vs. Time for two of the test samples

The approach taken in previous TAPPI articles to avoid this problem was to focus on the early portion of the curve, when many samples show linear behavior with respect to time. Specifically, two recent publications focused on the cumulative rate at 2, 5, and10 seconds [1] and the averaged instantaneous rate between 3-5 seconds [8].

For our investigation we wanted to study the calculation of rate over longer periods of time, to terminate at times later than 10 seconds. In order to enable this, we made two changes. First, we increased the sample size from 2" to 3.375". Second, we analyzed the data measured up to 20 seconds. We found that you can improve the estimation of rate for fast absorbing samples to times past 10 seconds by regressing the uptake data vs. the square root of time, as shown in Figure 3. In this case, regressing the data between 2 and 15 seconds, the r^2 of the 2-ply TAD sample was 0.98 and the line of regression better matched the measured data.

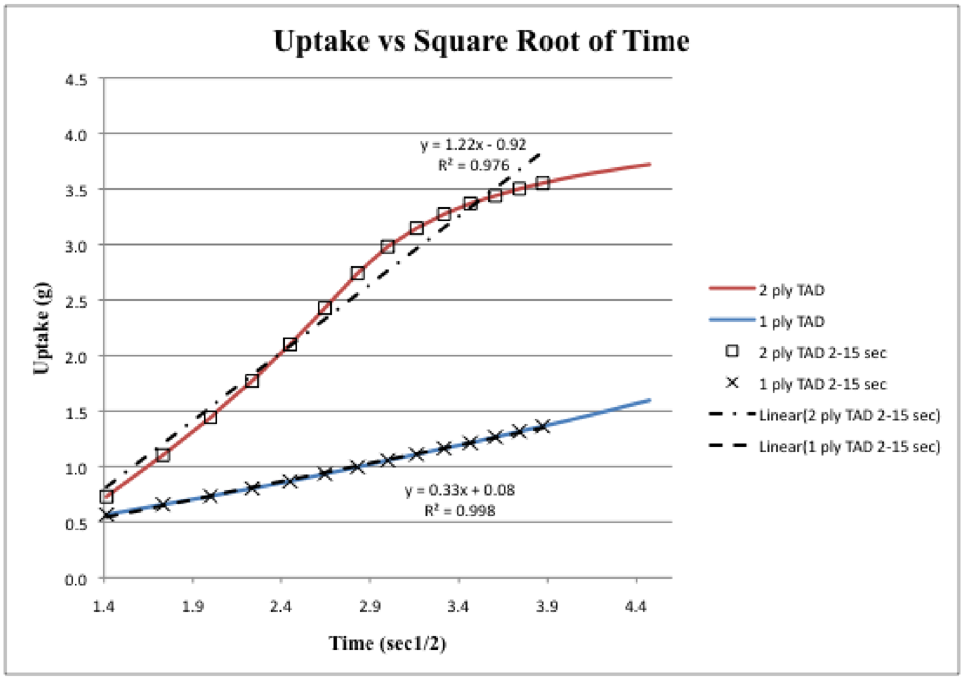

Figure 3: Uptake vs. Square Root of Time, including Regression from 2-15 seconds

It is important to note that the rate of uptake for the 2-ply TAD samples was still quite high through 15 seconds. As shown in Figure 4 below, the rate of uptake for the 2-ply TAD samples from 11-15 seconds (slope = 0.07 g/sec) was the same as that seen from 2 seconds up to 15 seconds in the 1-ply TAD (0.06 g/sec) and 2-ply CWP samples (0.07 g/sec). This suggests that towel samples can indeed be measured to longer measurement times.

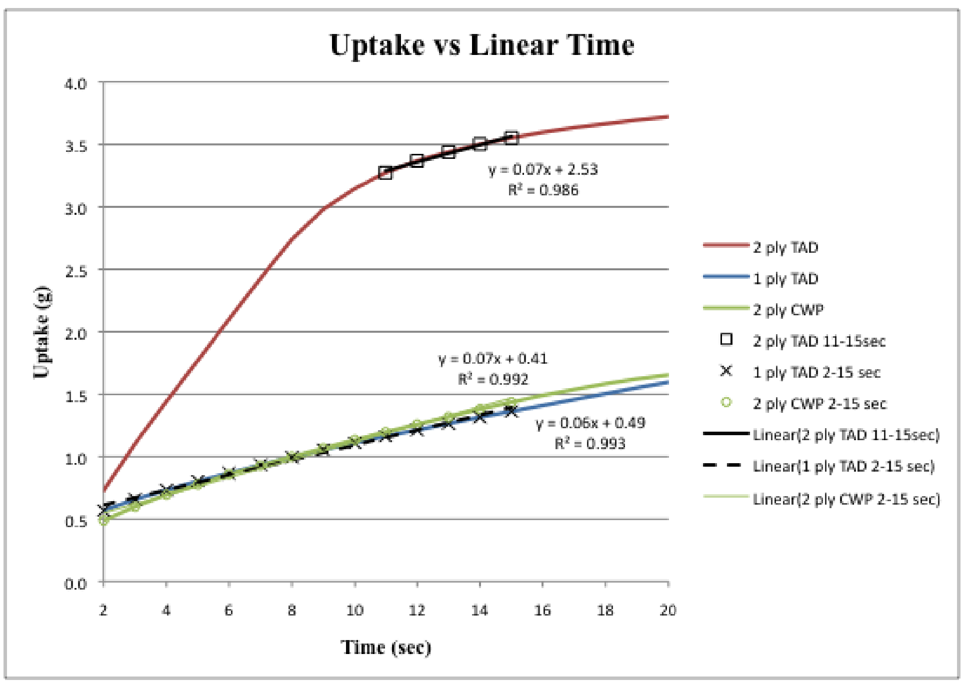

Figure 4: Comparison of Absorbency Rate – 2-ply TAD from 11-15 seconds vs. 1-ply TAD from 2-15 seconds.

In this report, in order to measure absorbency rate over a longer period of time, absorbency rate data was calculated by taking the slope of the uptake data vs. the square root of time between 2 and 15 seconds. This measurement is referred to as SST (2-15) in this document. Units for this measurement are g/sec$^{1/2}$. For rate estimates in the early portion of the curve we calculated the slope of the raw data vs. linear time between 3 and 5 seconds, similar to the calculation reported by Beuther [4]. This is referred to as 3-5 second tangent rate in this document. Units for this are g/sec.

RESULTS

Method Repeatability

One of the major themes in the development of previous absorbency methods has been the analysis of repeatability within the measurement and the instrument. For this study we took one of the market 2-ply TAD samples and measured it 20 times. From this data we calculated the average, standard deviation, and coefficient of variability (COV, which is simply the standard deviation/average * 100 with values listed in %). The results are summarized in Table 3:

Table 3: Method Results for Various Absorbency Rate and Capacity Calculations

	SST 2-15 (g/sec$^{1/2}$)	3-5 sec tangent rate (g/sec)	Cumulative 2 sec (g/sec)	Cumulative 5 sec (g/sec)	Cumulative 10 sec (g/sec)	Detached Capacity (g/g)	Detached Capacity (g/in2)
Average	1.263	0.362	0.389	0.381	0.331	16.425	0.331
Std.Dev.	0.023	0.012	0.016	0.013	0.005	0.176	0.005
COV	1.5%	3.5%	3.4%	3.4%	1.6%	0.9%	0.9%

- In general, our instrument provided COV of 4% or less. For many of our data calculations, the COV was 1-2%.
- These results compare favorably to the work previously reported in the TAPPI Interim Report, which is summarized below in Table 4.

Table 4: Method repeatability (coeff. of variation) for GATS, ATS, (from TAPPI Interim Report [7]) & CRT

COV (%)	Cum.Rate (g/s) 2 seconds		Cum.Rate (g/s) 5 seconds		Cum.Rate (g/s) 10 seconds		Capacity (g/g)	
	TAD	CWP	TAD	CWP	TAD	CWP	TAD	CWP
GATS	12.5%	19.0%	8.7%	13.3%	2.7%	10.0%	7.3%	1.6%
ATS	13.7%	27.8%	7.6%	17.2%	4.8%	11.9%	6.0%	8.1%
CRT	3.4%	-	3.4%	-	1.6%	-	0.9%	-

Accuracy – Ability to Rank Samples

In a conversation about accuracy, it is necessary to define the context of the use of the term. In this case we are referring to the ability of a method to produce an expected result. For this study we took four marketed products and measured their performance. Those products included a two-ply TAD sample, a one-ply TAD sample, a two-ply conventional sample, and a one-ply conventional sample.

It is generally understood that two-ply paper has higher absorptive rate and capacity than one-ply paper. When two or more plies of absorbent paper are laminated together "lamellar flow channels are created between the plies, which considerably reduces the viscous flow resistance" [9]. This causes absorptive rate to increase. This space also increases absorbent capacity: "The absorbent capacity gained by adding an additional ply is in general greater than absorbent capacity held within the added ply. The difference is due, at least in part, to the inter-ply storage space created by the addition of an extra ply" [10].

It is also generally understood that structured paper has higher absorptive rate and capacity than conventional, wet pressed (CWP) paper [11,12,13]. A desirable absorbency instrument and method should yield results consistent with these relationships.

Based on this understanding, the result we expected to see was that the two-ply products had higher absorptive rate and capacity than the one-ply products of the same process, and that the TAD products had higher absorptive rate and capacity than the conventional, wet pressed products with the same number of plies. The results of the measurements made for this study are shown below in Table 5, and graphically represented below in Figure 5.

Table 5: Absorbency Rate and Capacity Results

Product	BW (#/3000ft^2)	SST 2-15 (g/sec$^{1/2}$)	3-5 sec tangent rate (g/sec)	Cumulative 2 sec (g/sec)	Cumulative 5 sec (g/sec)	Cumulative 10 sec (g/sec)	Detached Capacity g/g	Detached Capacity g/in^2
2-ply TAD	25.0	1.243	0.334	0.364	0.354	0.315	16.2	0.42
1-ply TAD	23.6	0.327	0.074	0.284	0.161	0.111	13.8	0.34
2-ply CWP	30.4	0.387	0.089	0.244	0.155	0.113	6.6	0.21
1-ply CWP	26.1	0.005	0.000	0.147	0.058	0.034	0.66	0.018

- The instrument was accurate in its measurements (in terms of ranking the products):
  - The two-ply samples showed faster rate and higher capacity than the one-ply samples across all of the rate and capacity measures reported.
  - The TAD samples showed faster rate and higher capacity than the conventional, wet pressed samples across all of the rate and capacity measures reported.

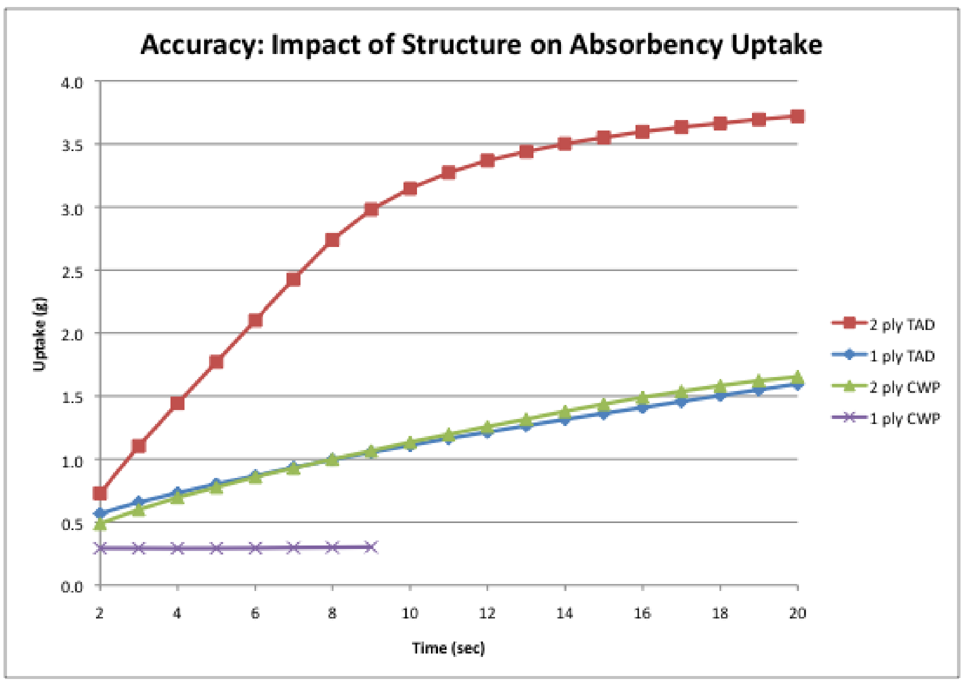

Figure 5: Uptake Data vs. Time Showing the Relative Performance Differences of the Studied Structures

Sensitivity – Effect of Basis Weight

To check the sensitivity of the new instrument and the absorbency methods of interest, we measured three two-ply products available on the market. To minimize potential differences in their mode of manufacture, we picked products from the same manufacturer, made at the same production facility, made with similar fiber mixes, all made with the TAD process. The predominant difference between the products was that each was made at a different basis weight.

Table 6: Impact of Basis Weight on Calculated Absorbency Rates and Capacity

BW	SST 2-15 ($g/sec^{1/2}$)	3-5 sec tangent rate (g/sec)	Cumulative 2 sec (g/sec)	Cumulative 5 sec (g/sec)	Cumulative 10 sec (g/sec)	Detached Capacity (g/g)	Detached Capacity (g/in^2)
25.0	1.24	[0.33]	0.36	0.35	[0.31]	17.2	0.424
28.7	1.19	[0.32]	0.41	0.37	[0.31]	15.4	0.439
32.8	1.09	0.24	0.44	0.33	0.27	14.7	0.487

- The instrument was sensitive in distinguishing rate and capacity differences in the three products.
- All results shown in Table 6 were significantly different (95% confidence) except for those bracketed.
- The effect of basis weight is much smaller than the effects measured above for 1 vs. 2-ply and TAD vs. conventional drying. This is graphically demonstrated in Figure 6 below.

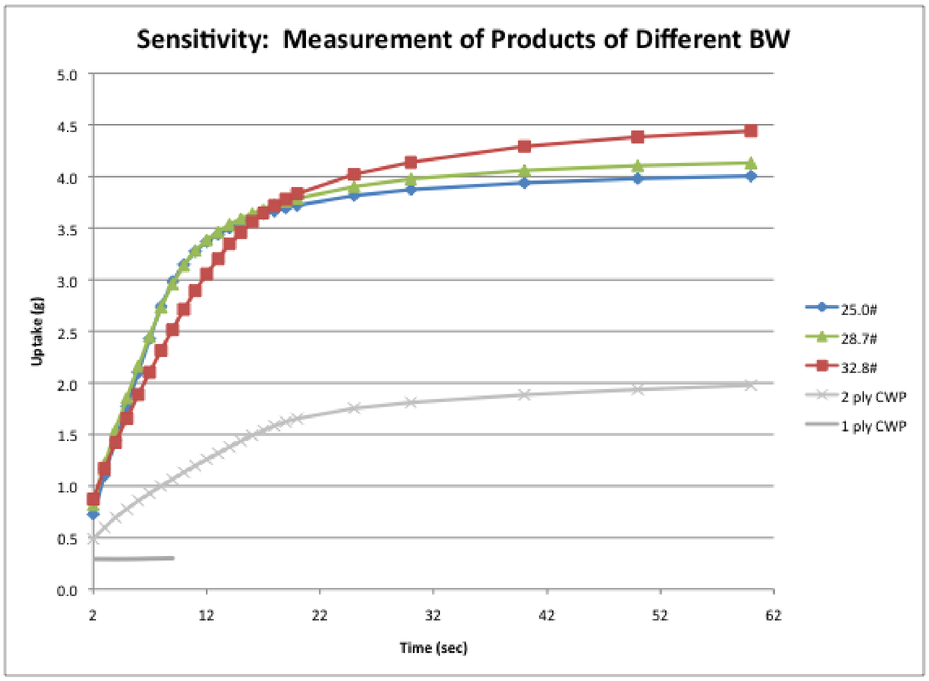

Figure 6: Uptake vs. Time for the Studied TAD Products at Three Different Basis Weights in Comparison to the Uptake Curves for Products of Different Structure

CONCLUSIONS:

1. The CRT instrument and methods described in this report have been shown to have better repeatability for rate and capacity measurements as compared to ATS and GATS as documented in TAPPI Interim Report on Absorbency [1].
2. The rate and capacity measurements discussed in this report appear to accurately rank the products by technology (i.e., TAD > CWP) and number of plies (2-ply > 1-ply).
3. The CRT instrument and methods described in this report showed sensitivity to differences in product design. The instrument and methods were sensitive to changes in basis weight and showed that the effect of basis weight *within* a product technology (2-ply TAD) was significantly smaller than the absorbency differences measured *between* technologies (TAD vs. CWP) and number of plies (2 vs. 1).
4. Though measurable differences were observed, the overall effect of basis weight on absorbency rate requires more study. The samples included this study, though as similar as we could find in the market, might include other important differences in manufacture that could affect the measured absorbency rate and capacity.

ACKNOWLEDGEMENT
This work was sponsored by The Procter & Gamble Company.

References/Literature Cited

[1] Lundeen, Jeff, "Intrinsic Absorbency Rate and Capacity of Bibulous Paper Products", Interim Report of TAPPI Working Group 030803.10, April 3, 2008.

[2] Federal Specification: Towels, Paper: Standard UU-T-591d.

[3] Federal Specification: Towel, Wiping, Paper; Industrial and Institutional: Standard UU-T-495c.

[4] EN ISO 12625-8 ,"Tissue paper and tissue products --- Part 8: Water-absorption time and water –absorption capacity, basket immersion test method."

[5] ASTM D-4250 "Standard Test Method for Water-Holding Capacity of Bibulous Fibrous Products" (Withdrawn 2009)

[6] INDA Test method IST 101, "Method for Absorption of Water"

[7] Lundeen, Jeff, "Intrinsic Absorbency Rate and Capacity of Bibulous Paper Products", Interim Report of TAPPI Working Group 030803.10, April 3, 2008, Table 1, "New TAPPI" method, page 5, using the mesh cover.

[8] Beuther, Paul and Michael Veith, "Sources of Variability in Testing Absorptive Rate of Tissue Paper", TAPPI Engineering, Pulping, & Environmental Conference Proceedings, October 11-14, 2009, pg. 11.

[9] Hollmark, Holgar: "Absorbency of Tissue and Toweling", *Handbook of Physical and Mechanical Testing of Paper and Paperboard*, Volume 2, ed. by Richard E. Mark, Chapter 20, pg. 155, 1984.

[10] US5,830,558, Column 1, lines 61-65. In the same patent a similar comment is made at Column 1, lines 46-49, "It is generally understood that a multiple ply structure can have an absorbent capacity greater than the sum of the absorbent capacities of the individual single plies which make up the multiple ply structure".

[11] Lundeen, Jeff, "Intrinsic Absorbency Rate and Capacity of Bibulous Paper Products", Interim Report of TAPPI Working Group 030803.10, April 3, 2008, page 27.

[12] US3,301,746. This patent was the original TAD patent and described a paper sheet with had substantially lower density, substantially higher absorbent capacity, and relatively high absorbency rates compared to the creped, wet pressed papers known before. These benefits come from molding into a textured fabric and drying the sheet with hot air instead of pressing the majority of the water out.

[13] US5,048,589. Paper designed to contain "high levels of absorbent capacity, absorbent rate, strength, and softness", Column 2, lines 42-43, paper produced by avoiding the pressing and creping processes found in conventional, wet pressed tissue making.