UNDERGRADUATE REPORT

REU Report: CALCE Electronic Device Experimentation

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Summary

Semiconductor devices are categorized by the temperature limits that the device manufacturers specify. The usage of high temperature components are common in certain markets, like the military, oil and natural gas exploration, and avionics control systems. However, manufacturers are reducing and, in some cases, eliminating the production of these high temperature components, for the profitability and the market-share are dwindling. Because of this, many companies and research organizations are looking at extending the temperature ranges of the commonly produced devices. The CALCE (Computer Aided Life Cycle Engineering) organization at the University of Maryland is one such group.

CALCE has been testing multiple semiconductor devices out of their specification ranges, verifying if the components will operate successfully in temperature extremes. There is also a motive to recognize the patterns of part behavior and then be able to accurately predict behavior of similar parts in varying environments.

My role at CALCE was to analyze data on several electrical parameters. The following paper is a rigorous analysis on propagation delay times of two different semiconductor devices. Unfortunately I received results on the second part recently, and I was unable to include all the appropriate information.

The paper is not completed, but further testing will provide more results and analysis to add. Diganta Das and Margaret Jackson (both at CALCE) are extending the scope of the project and performing more experimentation. This paper will end up as a section in a larger article that will be submitted for publication, and I will be a co-author.

The importance of this project should not be understated. If markets are going to “uprate” common semiconductor devices to an expanded temperature scale, many issues will arise, like who will perform the uprating, how will it be performed on lots, what are the ramifications at the component, board, and system, levels, what are the legal issues, and many more. CALCE is a leading organization that is attempting to answer these questions as well as prove that uprating can be an efficient market-wide realization, and I am gratified that I was a part of it.

Extracting Theoretical Parameters for Electronic Part Characterization

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Extracting Theoretical Parameters for Electronic Part Characterization

1. Introduction

Understanding and characterizing electrical parameter variation at extended temperature ranges is one focus for CALCE at the University of Maryland. Significant parameters that are known to vary with temperature changes, including propagation delay times, logic voltage levels, and leakage currents, are primary concerns and thus recent areas of study. Components are marketed by temperature-specific classes, for example, commercial (0 to 70°C), industrial (-40 to 85°C), and military (-55 to 125°C) [ATMEL, 1989]. In recent years many suppliers have stopped producing parts for military temperature grades, and reduced availability of extended temperature range components is a motivation for this research. Another stimulus for CALCE investigation is government and industry demands for higher quality automotive circuitry.

Late research at CALCE has turned out experimental data, in temperature ranges surpassing the military specification range (-55 to 125°C), concerning the Texas Instruments octal buffer SN74ALS244. This paper overviews recent analysis specifically in regard to high-to-low-level output propagation delay time.

2. Problem Statement

The motivation of the analysis is to extract theoretical parameters from experimental data. This will give us greater confidence on our experimental results, as this is validating our results against theoretical models.

This report does not deal with the physics of the temperature dependency. Only experimental results are analyzed, taken over a wide temperature range, to deduce allowable theoretical parameters.

3. Approach

Propagation delay time (t_d) is a temperature-dependent electrical parameter through the temperature dependency of mobility (μ) and threshold voltage (V_t), as reflected by Equations 1 and 2. The expanded parametric definition in Equation 3 [CALCE, 1998] relates how these factors effect propagation delay time. Equations 4 and 5 [CALCE, 1998] exhibit that mobility and threshold voltage are directly related to temperature. Equations 3, 4, and 5 are the underlying basis for the analysis.

$$t_d = f(T) \qquad \text{(Eq. 1)}$$

$$t_d = f(\mu, V_t) \qquad \text{(Eq. 2)}$$

$$t_d(T) = \frac{C_L V_{DD} L_{eff}}{\mu_{eff}(T) W_{eff} C_{OX} (V_{gs} - V_t(T))^2} \qquad \text{(Eq. 3)}$$

$$\mu_{eff} = \mu_0 \left(\frac{T_0}{T} \right)^n \qquad \text{(Eq. 4)}$$

$$V_t(T) = V_{tNOM} - k(T - T_0) \qquad \text{(Eq. 5)}$$

Equations 4 and 5 prescribe the additional parameters "n" and "k," respectively. In this discussion, "n" is the exponent for mobility and "k" is the threshold voltage temperature coefficient. Certain ranges of values are reported in literature for these parameters, yet their accuracy and response to temperature changes are not fully understood. Our goal is to identify values for the two parameters via experimentation over a -55°C to 150°C temperature range and to check if they are in agreement with published values.

CALCE laboratory testing furnished data of high-to-low-level output propagation delay time (t_d) on the TI octal buffer SN74ALS244. The trend of t_d is linear with temperature. However, the driving theoretical equation, found as Eq. 8 in this paper, is not linear. This complicates the goal of extracting theoretical parameters "n" and "k" (in Eq. 8) to match the experimental data. (Data is presented as propagation delay time at a temperature versus that at a standard temperature of 293 Kelvin (20°C), since Equation 8 is defined in this manner. Because t_d is linear, t_d divided by a constant is also linear.)

Analysis began with a graphical/spreadsheet approach, which is discussed in the following section. Also a mathematical linearization of the theoretical equation was conducted as an alternative and comparative measure.

3.1 Engineering Spreadsheet Analysis

$$\frac{t_d(T)}{t_d(T_0)} = \left(\frac{T}{T_0} \right)^n \frac{(V_{gs} - V_{tNOM})^2}{[(V_{gs} - V_{tNOM}) + k(T - T_0)]^2} \qquad \text{(Eq. 8)}$$

The idea of this method of analysis is very straightforward. The ratio of $t_d(T)/t_d(T_0)$ was computed for each acceptable set of "n" and "k" values using Equation 8, taken at the same temperatures as experimental values. The exponent for mobility is considered to range from 1.3 to 1.7, while threshold voltage temperature coefficient is taken to fall between 1 to 5 mV/K [Foty, 1997]. The suitability of each calculated set with the experimental values was evaluated via the sum of percent differences at the experimental points, and then averaged over the number of experimental points in the temperature range.

Close approximations to experimental trends were found when the data was split into three temperature ranges, which are –55 to 20°C, 20 to 110°C, and 110 to 150°C. The following graph (Figure 1) illustrates these regional approximations. Figure 2 displays the three regional approximations over the entire experimental temperature scale. The loss of accuracy with respect to the experimental data outside their own region is clearly visible from Figure 2.

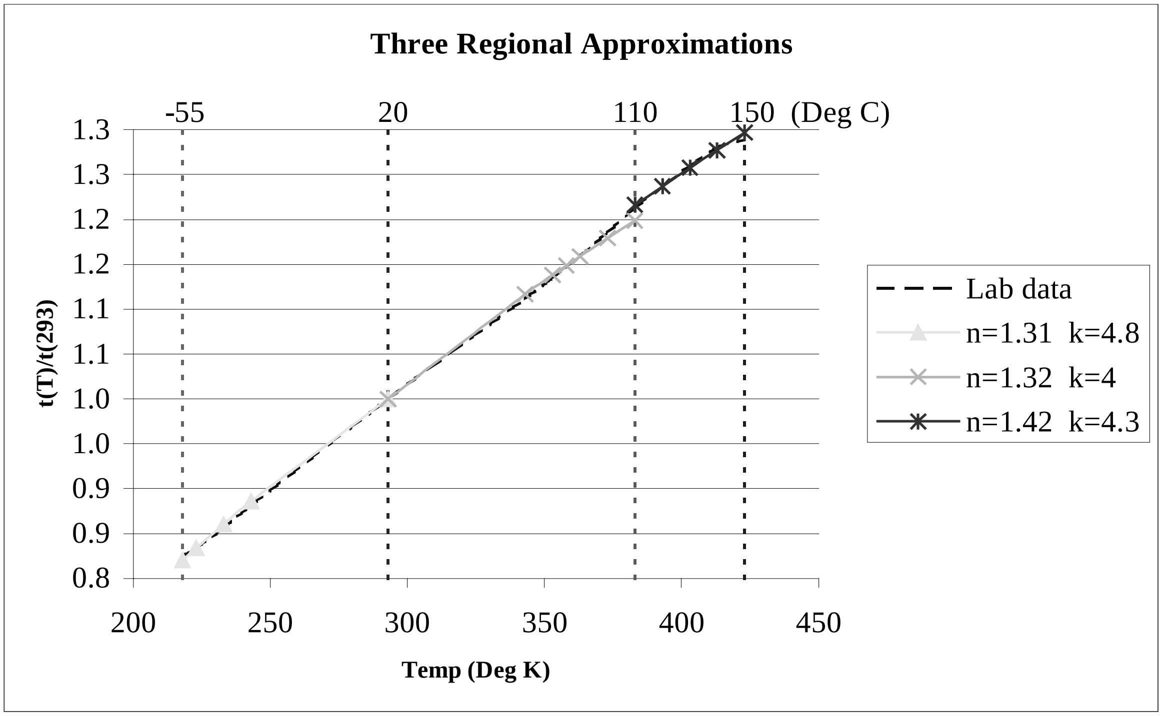

Figure 1. Curve Fitting $t_d(T)/t_d(293)$ – Three Temperature Regions

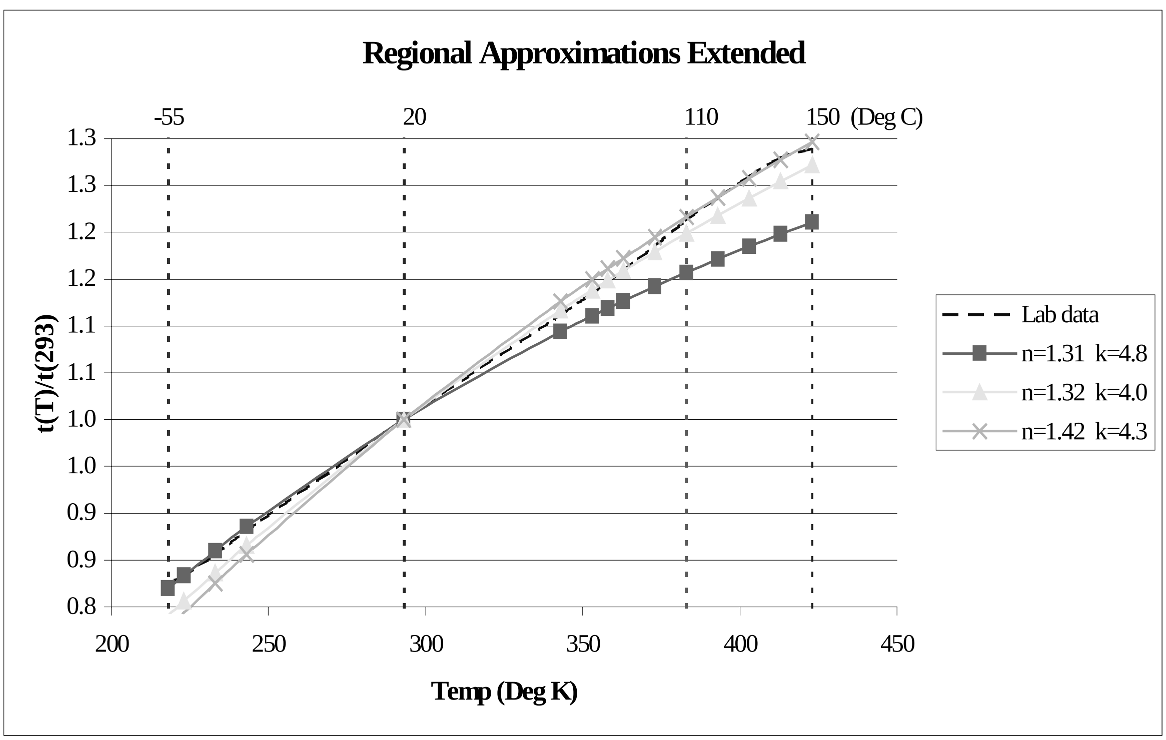

Figure 2. Curve Fitting $t_d(T)/t_d(293)$ – Regional Approximations Extended

None of the three regional approximations model the entire temperature range accurately, so the spreadsheet analysis continued over the complete temperature range. Results, shown in Table 1, turned out a large range of usable values for both the exponent for mobility and the threshold voltage temperature coefficient. The highlighted set corresponds to the best fitting values of “n” and “k” through the percent-difference method. (Percent differences are essentially the metric for goodness of fit in this analysis.) Computed percentage differences in Table 1 were fairly similar and low, considering the rejected sets of values averaged percent differences four to five times as large. The spread over the range of percent differences was fairly even. Other sets of "n" and "k" values fit comparably, yet Table 1 compiles the best fits for each "n" series only. Sets from "n" values from 1.54 and up exhibited significantly increasing average percent differences, thus not considered accurate fits and excluded from Table 1.

All Points (-55 to150°C)								
n	k	avg % diff (absolutes)	n	k	avg % diff (absolutes)	n	k	avg % diff (absolutes)
1.3	0.0037	1.3396285	1.38	0.0043	1.4104537	1.46	0.0048	1.45631304
1.31	0.0038	1.3454371	1.39	0.0043	1.4084438	1.47	0.0048	1.46714377
1.32	0.0039	1.3621599	1.4	0.0044	1.4178823	1.48	0.0049	1.46272445
1.33	0.0039	1.3641994	1.41	0.0044	1.4309738	1.49	0.005	1.47260585
1.34	0.004	1.3715762	1.42	0.0045	1.4281388	1.5	0.005	1.48283647
1.35	0.0041	1.3873002	1.43	0.0046	1.4380758	1.51	0.005	1.50748481
1.36	0.0041	1.3871341	1.44	0.0046	1.4498593	1.52	0.005	1.58453143
1.37	0.0042	1.3957201	1.45	0.0047	1.4462292	1.53	0.005	1.70799651

Table 1. Closest Fit “n” and “k” Values – Entire Temperature Range

Figure 3 displays curves for several selected sets of these acceptable values. Curves for all combinations of “n” and “k” values in Table 1 were graphed and fit almost the same. The second two regional fits are similar to “n” and “k” values resulting from the entire-range fits. The concern is now that a wide variety of the exponent for mobility and the threshold voltage temperature coefficient values appear to be fair approximations for the entire temperature range, and a few that are excellent for only specific temperature regions. Since many sets of values for the two parameters seem to fit the experimental data similarly, I hypothesize that the parameters are not unique. Trends may be identified for the acceptable “n” and “k” parameters, but additional theoretical analysis is needed to limit the already numerous possibilities.

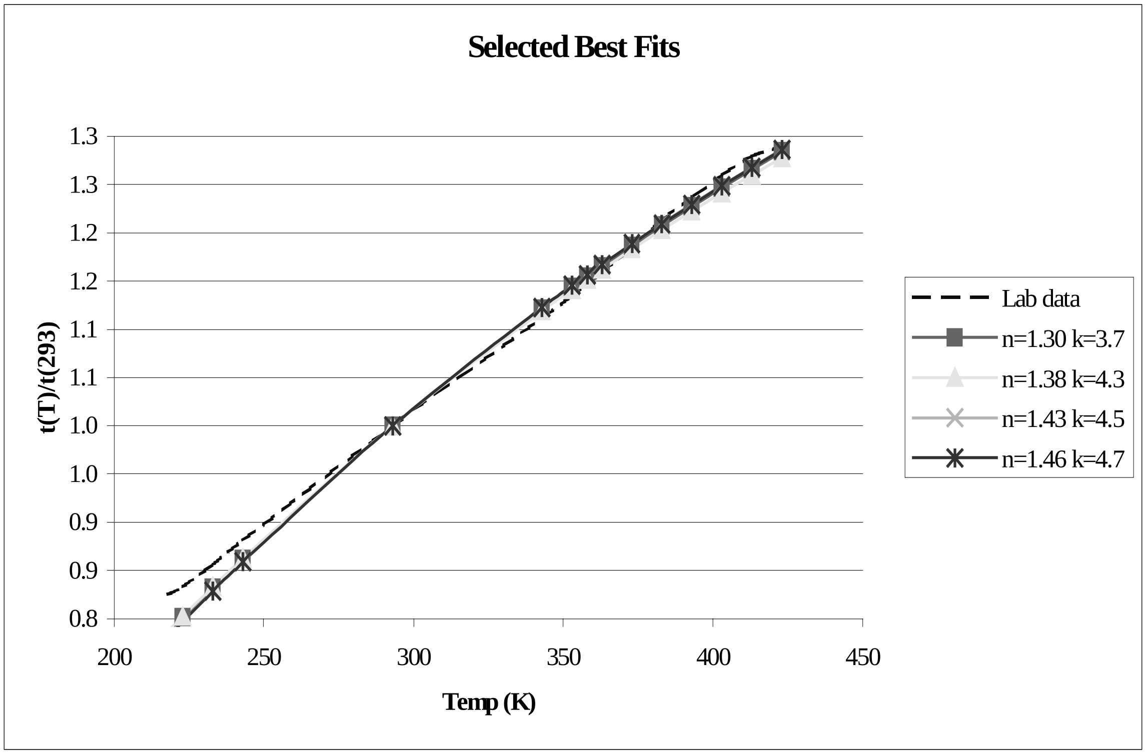

Figure 3. Curve Fitting $t_d(T)/t_d(293)$ – Several Best Fits for Entire Range

Unmentioned until this point is the significance of the bias voltage, the (V_{gs} -V_{tNOM}) factor in Equation 8. V_{tNOM} is the threshold voltage at the nominal temperature (293K) and is taken to be 1 volt in this report. V_{gs}, the gate-to-source voltage, is a fixed parameter in a given circuit setup, and for our purposes, may vary from 3 to 5 volts. Hence (V_{gs} -V_{tNOM}) ranges from 2 to 4 volts. All of the previous analysis assumed that this term was 4 volts. For thoroughness, it is logical to find bests fits assuming the (V_{gs} -V_{tNOM}) term is 2 volts, the lower end of the bias voltage range.

Table 2 summarizes best-fit values in similar fashion to Table 1, but under the assumption that the bias voltage is 2 volts instead of 4. A wide range of both the exponent for mobility and the threshold voltage temperature coefficient are included in this list, which upholds the hypothesis of non-unique parameters. The best fit, that is the set with the lowest average percent difference, is highlighted. Figure 3 plots several of the sets from Table 2. The situation of many sets fitting similarly graphically persists with the (V_{gs} -V_{tNOM})=2V assumption as well.

Trends of the values are noted again for the 2-volt assumption, but cannot be specifically and mathematically quantified from analyzing graphs. Thus I look to driving theoretical equation, Equation 8, for such information. This formula should provide insight into the relation of the exponent for mobility and the threshold voltage temperature coefficient. Section 3.2 is devoted to this approach.

All Points (-55 to150°C)								
n	k	avg % diff (absolutes)	n	k	Avg % diff (absolutes)	n	k	avg % diff (absolutes)
1.3	0.0019	1.3521337	1.44	0.0023	1.4498593	1.58	0.0028	1.50992771
1.31	0.0019	1.3454371	1.45	0.0024	1.4630395	1.59	0.0028	1.52044852
1.32	0.0019	1.3646117	1.46	0.0024	1.456313	1.6	0.0029	1.52538262
1.33	0.002	1.3782723	1.47	0.0024	1.4671438	1.61	0.0029	1.51855011
1.34	0.002	1.3715762	1.48	0.0025	1.4793477	1.62	0.0029	1.52985632
1.35	0.002	1.3883605	1.49	0.0025	1.4726059	1.63	0.003	1.53214129
1.36	0.0021	1.402419	1.5	0.0025	1.4828365	1.64	0.003	1.52527909
1.37	0.0021	1.3957201	1.51	0.0026	1.4937257	1.65	0.003	1.53771105
1.38	0.0021	1.4104777	1.52	0.0026	1.4869655	1.66	0.0031	1.53701787
1.39	0.0022	1.4245872	1.53	0.0026	1.4969461	1.67	0.0031	1.53012328
1.4	0.0022	1.4178823	1.54	0.0027	1.5061842	1.68	0.0031	1.54401905
1.41	0.0022	1.4309738	1.55	0.0027	1.4994027	1.69	0.0032	1.54002044
1.42	0.0023	1.44479	1.56	0.0027	1.5094809	1.7	0.0032	1.53309082
1.43	0.0023	1.4380758	1.57	0.0028	1.5167333			

Table 2. Closest Fit "n" and "k" Values, (V_{gs} -V_{tNOM}) = 2 volts

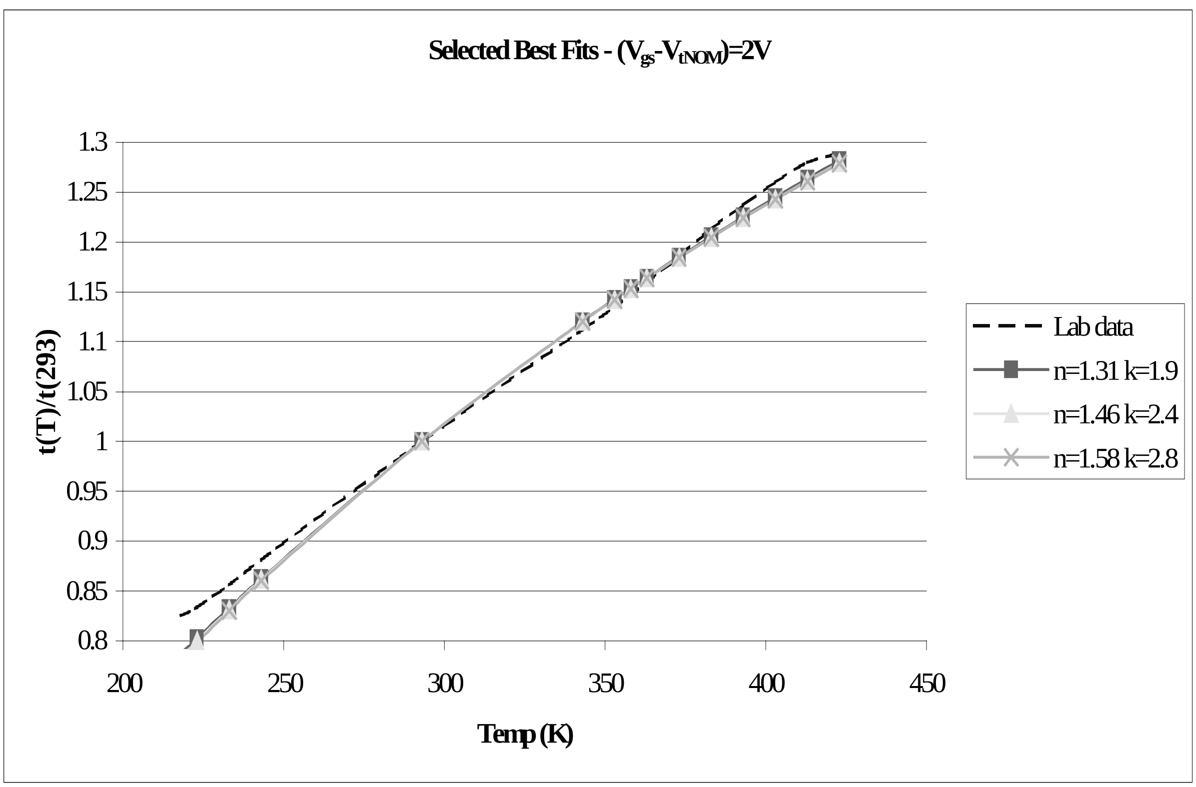

Figure 4. Curve Fitting $t_d(T)/t_d(293)$ – Several Best Fits, (V_{gs} -V_{tNOM}) = 2 volts

3.2 Linearization of the Derived Theoretical Expectation

Since the experimental data is found to be strongly linear with temperature, simplicity in examination calls for a linear theoretical equation to match it. Because Equation 8 is not linear with temperature, it must be converted to such a form. A first-order Taylor series approximation of the formula is an excellent choice, and the derivation is presented in the Appendix. The final result, Equation 13, follows.

$$\frac{t_d(T')}{t_d(0)} = 1 + \left[\frac{n}{T_0} - \frac{2k}{(V_{gs} - V_{tNOM})}\right] T' \qquad \text{(Eq. 13)}$$

Equation 13 is of the form of a straight line (y = b +mx), where the intercept (b) is unity and the slope is

$$m = \left[\frac{n}{T_0} - \frac{2k}{(V_{gs} - V_{tNOM})}\right] \qquad \text{(Eq. 14)}$$

The fact that the intercept is independent of "n" or "k" verifies the hypothesis cited in section 3.1 that these two parameters are not unique; That is, from the equation a specific value of a parameter cannot be determined without the other parameter being specified.

The next step is comparing the derived results to experimental data. The following graph depicts the experimental data along with a linear fit (via Microsoft Excel least-squares fit) versus the previously defined temperature T′. The intercept value is very close to one, which correlates well with the derived expectation of unity. This suggests that the Taylor series approximation is valid.

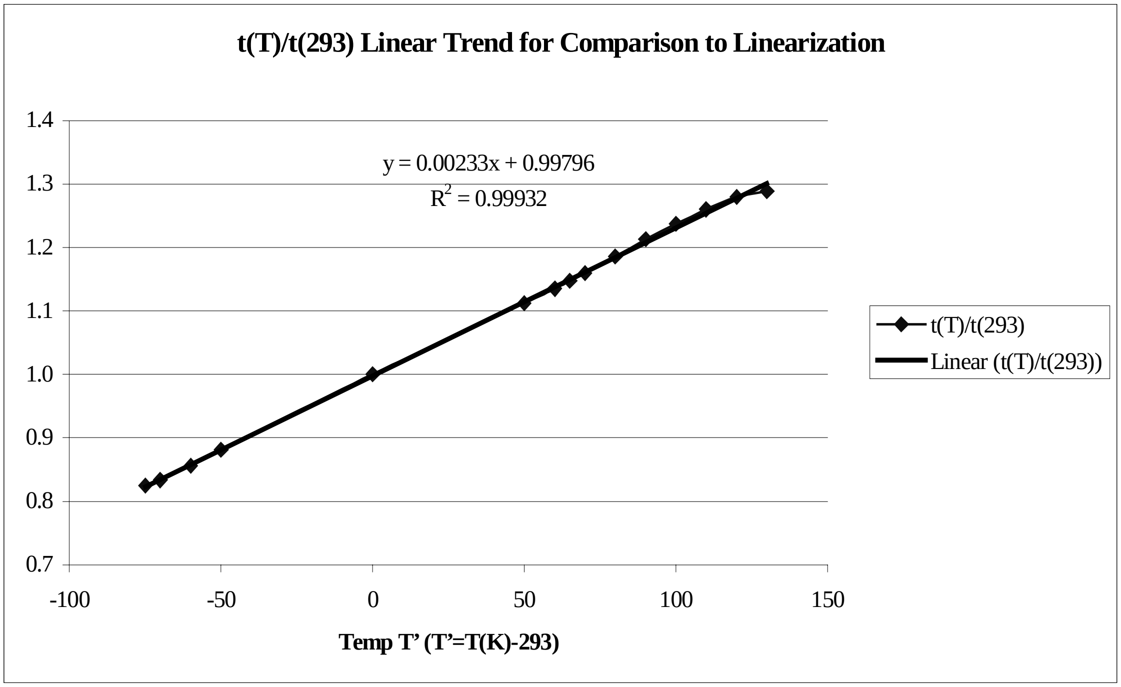

Figure 5. $t_d(T)/t_d(293)$ – Excel Linear Data Fit

The slope obtained from the linear fit to experimental data is 0.00233 (taking three significant figures). This may be equated to the slope term from the derivation, such that Equation 14 applies with m=0.00233. Knowing that T_0 is 293 K and assuming (V_{gs}-V_{tNOM}) is 4 volts, Equation 14 reduces to, solving for n,

$$n = 0.683 + 147k \qquad \text{(Eq. 15)}$$

Because certain ranges for "n" and "k" are considered acceptable, it is now reasonable to compute the matching values according to the relation above. Both methods of inputting the acceptable range of "n" to find "k" values and vice versa are found in the following tables. The highlighted cells identify the values where both parameters are in their corresponding acceptable ranges.

k=(n-.683)/147 --> n range is 1.3 to 1.7					
n	k	n	k	n	k
1.3	0.00420	1.42	0.00501	1.56	0.00597
1.31	0.00427	1.43	0.00508	1.57	0.00603
1.32	0.00433	1.44	0.00515	1.58	0.00610
1.33	0.00440	1.45	0.00522	1.59	0.00617
1.34	0.00447	1.46	0.00529	1.6	0.00624
1.35	0.00454	1.47	0.00535	1.61	0.00631
1.36	0.00461	1.48	0.00542	1.62	0.00637
1.37	0.00467	1.49	0.00549	1.63	0.00644
1.38	0.00474	1.5	0.00556	1.64	0.00651
1.39	0.00481	1.51	0.00563	1.65	0.00658
1.4	0.00488	1.52	0.00569	1.66	0.00665
1.41	0.00495	1.53	0.00576	1.67	0.00671
		1.54	0.00583	1.68	0.00678
		1.55	0.00590	1.69	0.00685
				1.7	0.00692

Table 3. Derived Relation "n" and "k'" Values – "n" Specified, (V_{gs}-V_{tNOM})=4V

n=.683+147k --> k range is 0.001V/K to 0.005V/K									
k	n	k	n	k	n	k	n	k	n
0.001	0.83	0.0019	0.96	0.0028	1.09	0.0037	1.23	0.0042	1.30
0.0011	0.84	0.002	0.98	0.0029	1.11	0.0038	1.24	0.0043	1.32
0.0012	0.86	0.0021	0.99	0.003	1.12	0.0039	1.26	0.0044	1.33
0.0013	0.87	0.0022	1.01	0.0031	1.14	0.004	1.27	0.0045	1.34
0.0014	0.89	0.0023	1.02	0.0032	1.15	0.0041	1.29	0.0046	1.36
0.0015	0.90	0.0024	1.04	0.0033	1.17			0.0047	1.37
0.0016	0.92	0.0025	1.05	0.0034	1.18			0.0048	1.39
0.0017	0.93	0.0026	1.07	0.0035	1.20			0.0049	1.40
0.0018	0.95	0.0027	1.08	0.0036	1.21			0.005	1.42

Table 4. Derived Relation “n” and “k’” Values – “k” Specified, $(V_{gs}-V_{tNOM})$=4V

If $(V_{gs}-V_{tNOM})$ were taken as 2 volts, Equation 14 reduces to

$$n = 0.683 + 293k \qquad \text{(Eq. 16)}$$

Following from Equation 16, Tables 5 and 6 show the breakdown of applicable exponent for mobility and the threshold voltage temperature coefficient values, again with the highlighted sets representing those in which both parameters are within their corresponding acceptable ranges. A noteworthy observation, the entire range of "n" values is included in the acceptable sets.

k=(n-.683)/293 --> n range is 1.3 to 1.7					
n	k	n	k	n	k
1.3	0.00211	1.42	0.00252	1.56	0.00299
1.31	0.00214	1.43	0.00255	1.57	0.00303
1.32	0.00217	1.44	0.00258	1.58	0.00306
1.33	0.00221	1.45	0.00262	1.59	0.00310
1.34	0.00224	1.46	0.00265	1.6	0.00313
1.35	0.00228	1.47	0.00269	1.61	0.00316
1.36	0.00231	1.48	0.00272	1.62	0.00320
1.37	0.00234	1.49	0.00275	1.63	0.00323
1.38	0.00238	1.5	0.00279	1.64	0.00327
1.39	0.00241	1.51	0.00282	1.65	0.00330
1.4	0.00245	1.52	0.00286	1.66	0.00333
1.41	0.00248	1.53	0.00289	1.67	0.00337
		1.54	0.00292	1.68	0.00340
		1.55	0.00296	1.69	0.00344
				1.7	0.00347

Table 5. Derived Relation “n” and “k’” Values – “n” Specified, $(V_{gs}-V_{tNOM})$=2V

n=.683+293k --> k range is 0.001V/K to 0.005V/K							
k	n	k	n	k	n	k	n
0.001	0.98	0.002	1.27	0.003	1.56	0.004	1.86
0.0011	1.01	0.0021	1.30	0.0031	1.59	0.0041	1.88
0.0012	1.03	0.0022	1.33	0.0032	1.62	0.0042	1.91
0.0013	1.06	0.0023	1.36	0.0033	1.65	0.0043	1.94
0.0014	1.09	0.0024	1.39	0.0034	1.68	0.0044	1.97
0.0015	1.12	0.0025	1.42	0.0035	1.71	0.0045	2.00
0.0016	1.15	0.0026	1.44	0.0036	1.74	0.0046	2.03
0.0017	1.18	0.0027	1.47	0.0037	1.77	0.0047	2.06
0.0018	1.21	0.0028	1.50	0.0038	1.80	0.0048	2.09
0.0019	1.24	0.0029	1.53	0.0039	1.83	0.0049	2.12
						0.005	2.15

Table 6. Derived Relation “n” and “k’” Values – “k” Specified, $(V_{gs}-V_{tNOM})$=2V

Because the spreadsheet data were evaluated for fitness by percent differences to the experimental data, the linearization-method data shall undergo the same analysis. Table 7 presents such manipulations with the acceptable data highlighted in Tables 5 and 6. Again the best fits according to percentage differences are highlighted.

(Vgs-V_{tNOM})=4V			**(Vgs-V_{tNOM})=2V**								
n	k	Avg of % Diff (abs)	n	k	avg of % diff (abs)	n	k	avg of % diff (abs)	n	k	avg of % diff (abs)
1.3	0.00420	1.835	1.2983	0.0021	1.857	1.36	0.00231	1.922	1.56	0.00299	2.047
1.31	0.00427	1.846	1.3276	0.0022	1.890	1.37	0.00234	1.931	1.57	0.00303	2.050
1.32	0.00433	1.857	1.3569	0.0023	1.919	1.38	0.00238	1.940	1.58	0.00306	2.053
1.33	0.00440	1.867	1.3862	0.0024	1.946	1.39	0.00241	1.949	1.59	0.0031	2.055
1.34	0.00447	1.877	1.4155	0.0025	1.970	1.4	0.00245	1.957	1.6	0.00313	2.057
1.35	0.00454	1.887	1.4448	0.0026	1.991	1.41	0.00248	1.965	1.61	0.00316	2.059
1.36	0.00461	1.896	1.4741	0.0027	2.009	1.42	0.00252	1.973	1.62	0.0032	2.060
1.37	0.00467	1.905	1.5034	0.0028	2.025	1.43	0.00255	1.980	1.63	0.00323	2.061
1.38	0.00474	1.914	1.5327	0.0029	2.038	1.44	0.00258	1.987	1.64	0.00327	2.062
1.39	0.00481	1.922	1.562	0.003	2.048	1.45	0.00262	1.994	1.65	0.0033	2.062
1.4	0.00488	1.930	1.5913	0.0031	2.055	1.46	0.00265	2.001	1.66	0.00333	2.062
1.41	0.00495	1.938	1.6206	0.0032	2.060	1.47	0.00269	2.007	1.67	0.00337	2.062
1.30	0.0042	1.835	1.6499	0.0033	2.062	1.48	0.00272	2.012	1.68	0.0034	2.061
1.32	0.0043	1.851	1.6792	0.0034	2.061	1.49	0.00275	2.018	1.69	0.00344	2.061
1.33	0.0044	1.867	1.3	0.00211	1.859	1.5	0.00279	2.023	1.7	0.00347	2.059
1.34	0.0045	1.881	1.31	0.00214	1.870	1.51	0.00282	2.028		avg->	1.999
1.36	0.0046	1.895	1.32	0.00217	1.881	1.52	0.0029	2.032			
1.37	0.0047	1.908	1.33	0.00221	1.892	1.53	0.0029	2.036			
1.39	0.0048	1.921	1.34	0.00224	1.902	1.54	0.0029	2.040			
1.40	0.0049	1.933	1.35	0.00228	1.912	1.55	0.003	2.044			
1.42	0.005	1.944			Cont. -->			Cont. -->			
	avg->	1.891									

Table 7. Acceptable Derived “n” and “k” Values – Goodness of Fit

3.3 Comparison: Spreadsheet and Linearization

3.3.1 Comparison of Data

Since the two forms of approach did not bring identical results, it is rational to compare the statistics and identify where they coincide. Table 8 maps the overlapping "n" values with both methods’ "k" numbers, for both the 2- and 4-volt assumptions.

$(Vgs-V_{tNOM})$=4V			$(Vgs-V_{tNOM})$=2V					
n	k		n	k		n	k	
Overlap	spreadsheet	linearization	Overlap	spreadsheet	linearization	Overlap	spreadsheet	linearization
1.3	0.0037	0.00420	1.3	0.0019	0.00211	1.5	0.0025	0.00279
1.31	0.0038	0.00427	1.31	0.0019	0.00214	1.51	0.0026	0.00282
1.32	0.0039	0.00433	1.32	0.0019	0.00217	1.52	0.0026	0.00286
1.33	0.0039	0.00440	1.33	0.002	0.00221	1.53	0.0026	0.00289
1.34	0.004	0.00447	1.34	0.002	0.00224	1.54	0.0027	0.00292
1.35	0.0041	0.00454	1.35	0.002	0.00228	1.55	0.0027	0.00296
1.36	0.0041	0.00461	1.36	0.0021	0.00231	1.56	0.0027	0.00299
1.37	0.0042	0.00467	1.37	0.0021	0.00234	1.57	0.0028	0.00303
1.38	0.0043	0.00474	1.38	0.0021	0.00238	1.58	0.0028	0.00306
1.39	0.0043	0.00481	1.39	0.0022	0.00241	1.59	0.0028	0.00310
1.4	0.0044	0.00488	1.4	0.0022	0.00245	1.6	0.0029	0.00313
1.41	0.0044	0.00495	1.41	0.0022	0.00248	1.61	0.0029	0.00316
1.42	0.0045	0.00500	1.42	0.0023	0.00252	1.62	0.0029	0.00320
			1.43	0.0023	0.00255	1.63	0.003	0.00323
			1.44	0.0023	0.00258	1.64	0.003	0.00327
			1.45	0.0024	0.00262	1.65	0.003	0.00330
			1.46	0.0024	0.00265	1.66	0.0031	0.00333
			1.47	0.0024	0.00269	1.67	0.0031	0.00337
			1.48	0.0025	0.00272	1.68	0.0031	0.00340
			1.49	0.0025	0.00275	1.69	0.0032	0.00344
						1.7	0.0032	0.00347

Table 8. Overlapping “n” Values with Method-Specific "k" Values

Observations of the results confirm a positive correlation between the exponent for mobility and the threshold voltage temperature coefficient. Comparing the two methods, a dominant trend is that the linearization (of the theoretical equation) approach consistently produces "k" values of about 0.5 mV/K higher than the spreadsheet approach for the 4-volt assumption, and about 0.2 mV/K higher for the 2-volt assumption. Another observation is only a lower portion of the "n" range and a mid-portion of the "k" range are considered acceptable for the 4-volt assumption. (Recall that “n” is considered to range from 1.3 to 1.7, while “k” is taken to fall between 1 to 5 mV/K.) For the 2-volt assumption, the entire "n" range applies, with only a lower to mid-portion of "k" values.

Figure 6 and 7 graph the 4-volt and 2-volt best fits from both methods against the lab data, respectively. The sets referred to as best fits result in the lowest average percentage difference in regard to the lab data, but more importantly, they represent a group of sets that fit the data similarly when graphed.

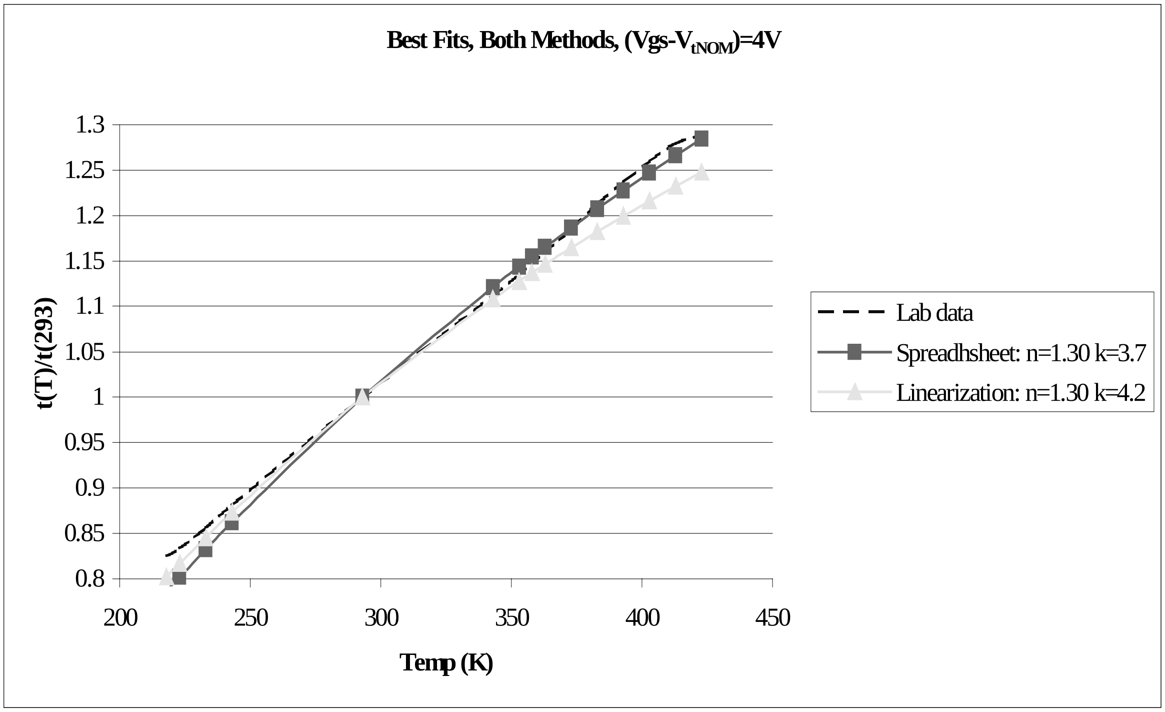

Figure 6. $t_d(T)/t_d(293)$ – Best Fits, Method Comparison, $(V_{gs}\text{-}V_{tNOM})$=4V

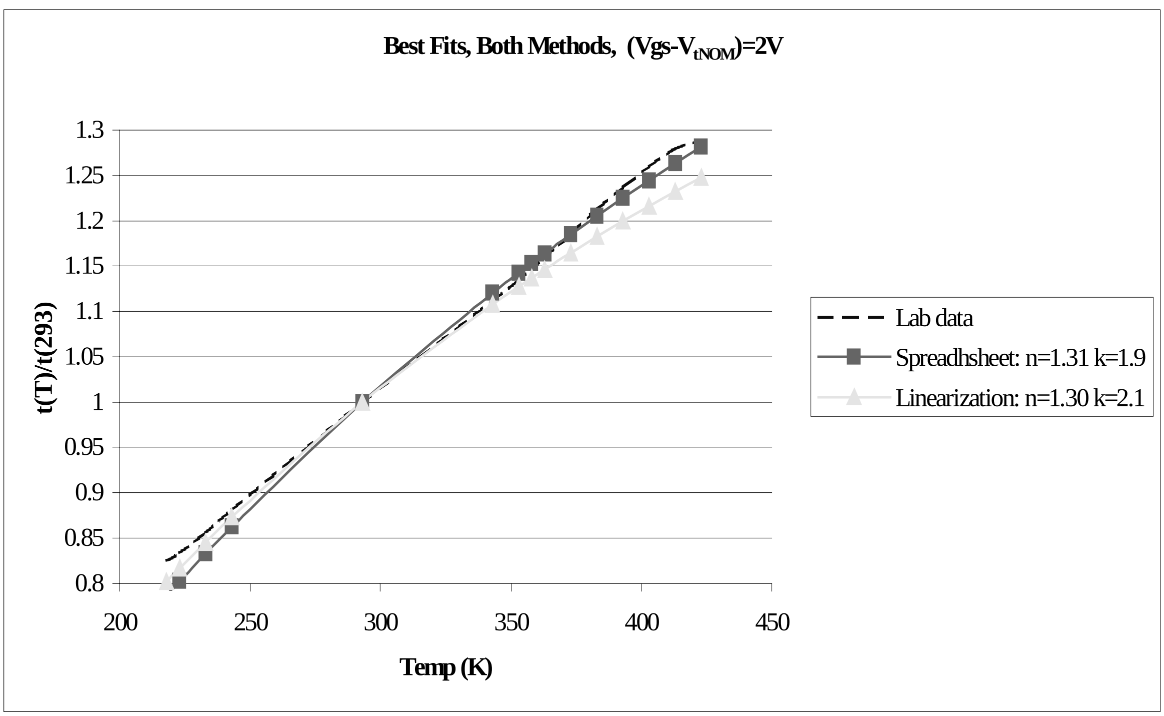

Figure 7. $t_d(T)/t_d(293)$ – Best Fits, Method Comparison, $(V_{gs}\text{-}V_{tNOM})$=2V

The spreadsheet selections are known to have lower percentage difference values, but they do not strictly follow the derived theoretical relation described in Equation 13. The acceptable sets from the linearization method appear to fit well graphically, especially at the lower end of the temperature scale, but are slightly less accurate than the spreadsheet selections when comparing percentage differences. Values for both the exponent for mobility and the threshold voltage temperature coefficient do vary to a degree in comparing the two approaches, but both reflect a positive moving trend between sets of values. In other words, when looking at best fit values, as "n" increases, so does "k" in set proportions.

Forms of experimental error must also be considered. Data was manipulated without error ranges, though experimental data, prepared and presented by Juergan Flicker, are displayed with error bars. This fact may have ramifications on the parameter values found in this analysis to match the experimental data, and thus must be thoroughly be considered before rashly stating that a very strict set of values of parameters characterizes the high-to-low-level output propagation delay time for the component under study. In retrospect, the addition of error ranges would have made the analysis unnecessarily complicated without any further significant insight on parameter behavior.

3.3.2 Comparison of Methodologies

The spreadsheet analysis is a convenient method for matching a known range of the parameters through a theoretical equation to experimental values. The task is comparable to a random search, yet the evaluation of percentage differences helps to identify which are going to be better fits. Other mathematical metrics for goodness of fit could have been chosen as well, but percent differences are acceptable for making point comparisons. After narrowing the possibilities, graphical operations give another perspective, but still left a wide range of both parameters in this analysis. Computations with new data are simplified now that several spreadsheets have been constructed. However if the new data is taken at previously untested temperatures, spreadsheets will have to be significantly expanded.

The Taylor series linearization approach narrows the field of possibilities in one action. The derivation is general in nature, for all factors are parametrized. Data values and possible ranges come into play only after a generalized relation is established. This method was faster to operate once Equation 13 was identified, and it also proved the non-uniqueness of the parameters. The only drawback of the linearization approach was that the parameter values computed did not fit quite as accurately as the spreadsheet method results. The metric for goodness of fit was percent differences. Yet percent differences were computed for only specific points in the temperature range, while Equation 13 is valid continuously over the entire range. Hence the small degree to which the evaluation claims the values found by the spreadsheet approach fit better than those from the linearization approach may not at all be significant. In fact, I consider the spreadsheet results work to validate the findings of the linearization approach.

4. Conclusion

It is known that the exponent for mobility and the threshold voltage temperature coefficient are not unique for the given data, but they follow a definite trend. Via a Taylor series approximation, a relation was found for the parameters that led to values that model results from experimentation fairly well. Spreadsheet analysis cited similar and new values that model experimental data just as efficiently, sometimes slightly better. The method chosen for the assessment of efficiency of fit, percentage differences, might not be ideal, for evaluation was only at specific points in the temperature range. Graphical examination did help to alleviate this problem to a degree. Regardless, sets of values were identified to give good approximations.

This type of analysis of parameter expectations versus observations is valuable in predicting electrical behavior of components, whether at use in the moderate temperature range of 0 to 70°C, or in extremes like the CALCE experimentation range of 55 to 150°C. It is also a learning experience as well as a stepping stone for dealing with characteristics involving more than one parameter. At CALCE, future testing will involve cases of three or more parameters to data that is not simply linear. Data was taken to be linear for this high-to-low-level output propagation delay time, but data on other characteristics may not. For example, low-to-high-level output propagation delay time data reflected a polynomial curve, and at best, was piece-wise linear. The analysis approach may have to be altered for the mathematically more complex cases, but this experience provides a framework for what trends to look for, what methods may work to give indications of parameter behavior, and a general plan of attack. This analysis builds on the evolving knowledge base of CALCE's expanding research of electrical parameter characterization.

5. Acknowledgements

This CALCE project is under the direction of Dr. Michael Pecht and Margaret Jackson. In a recent meeting with Chrish Wilkinson of Smiths UK Aerospace, notions of analyzing the data in terms of expectations along with ranges of acceptable parameters were identified and considered worthwhile. His approval led to this work. I must extend thanks to Diganta Das for his editing and general guidance and support, as well as to Juergan Flicker, who was at the helm during experimental procedures and data acquisition.

6. Appendix: Mathematical Derivation and Linearization of Theoretical Equation (Eq. 8)

Given:

$$t_d(T) = \frac{C_L V_{DD} L_{eff}}{\mu_{eff}(T) W_{eff} C_{OX} (V_{gs} - V_t(T))^2} \qquad \text{(Eq. 3)}$$

$$\mu_{eff} = \mu_0 \left(\frac{T_0}{T}\right)^n \qquad \text{(Eq. 4)}$$

$$V_t(T) = V_{tNOM} - k(T - T_0) \qquad \text{(Eq. 5)}$$

Simplifications:

Letting $X = \frac{C_L V_{DD} L_{eff}}{W_{eff} C_{OX}}$, (Eq. 6)

then $t_d(T) = X\left(\frac{T}{T_0}\right)^n \frac{1}{\mu_0} \frac{1}{(V_{gs} - V_{tNOM} + k(T - T_0))^2}$ (Eq. 7)

Ratio of $\frac{t_d(T)}{t_d(T_0)} = \left(\frac{T}{T_0}\right)^n \frac{(V_{gs} - V_{tNOM})^2}{[(V_{gs} - V_{tNOM}) + k(T - T_0)]^2}$ (Eq. 8)

Proof: First-order (Linear) Taylor series approximation about T′ = T-T$_o$, using point T′ = 0.

$$\frac{t_d(T')}{t_d(0)} = t(T')\Big|_{T'=0} + \frac{\partial t}{\partial T'}\Big|_{T'=0} T' + \text{(higher order terms)} \qquad \text{(Eq. 9)}$$

where $\frac{t_d(T' = T - T_0)}{t_d(T' = 0, T = T_0)} = \left(\frac{T' + T_0}{T_0}\right)^n \frac{(V_{gs} - V_{tNOM})^2}{[(V_{gs} - V_{tNOM}) + kT']^2}$ (Eq. 10)

Computing, applying the chain rule of differentiation… (Eq. 11)

$$\frac{t_d(T')}{t_d(0)} = \left(\frac{0 + T_0}{T_0}\right)^n \frac{(V_{gs} - V_{tNOM})^2}{[(V_{gs} - V_{tNOM}) + 0]^2} + \left[\left(\frac{0 + T_0}{T_0}\right)^{n-1} n \frac{1}{T_0} \frac{(V_{gs} - V_{tNOM})^2}{[(V_{gs} - V_{tNOM}) + 0]^2} + \left(\frac{0 + T_0}{T_0}\right)^n \frac{(-2)k(V_{gs} - V_{tNOM})^2}{[(V_{gs} - V_{tNOM}) + 0]^3}\right] T'$$

$$\frac{t_d(T')}{t_d(0)} = (1)^n 1 + \left[(1)^{n-1} n \frac{1}{T_0} 1 + (1)^n \frac{-2k}{(V_{gs} - V_{tNOM})}\right] T' \qquad \text{(Eq. 12)}$$

$$\therefore \frac{t_d(T')}{t_d(0)} = 1 + \left[\frac{n}{T_0} - \frac{2k}{(V_{gs} - V_{tNOM})}\right] T' \qquad \text{(Eq. 13)}$$

7. References

ATMEL, *Databook*, San Jose, CA, 1989.

CALCE (Computer Aided Life Cycle Engineering), "Proposed Approach to Silicon-CMOS Integrated Circuit Performance Derating," University of Maryland, College Park, MD, 1998.

Unfinished…

Part II: Additional Experimental Data

1. Introduction

Testing in late July at CALCE has produced data on high-to-low-level output propagation delay time as well as low-to-high-level output propagation delay time for the Texas Instruments octal buffer 74HC244N. This data includes results for one low-temperature run and two high-temperature runs. Each run (and for both delay parameters) was analyzed separately.

The process of analysis involves both a spreadsheet approach and a linearization approach, like the analysis for the first portion of this paper. The driving theoretical equation, Equation 8, still holds for this analysis. Thus the slope equation, Equation 14, will be applied for the linearization approach. The metric for goodness of fit is again percentage difference. Data follows.

2. Low-Temperature Run Results

2.1 High-To-Low-Level Output Propagation Delay Time (t_{PHL})

		Avg % diff			Avg % diff			Avg % diff
n	k	(pts 1-6)	n	k	(pts 1-6)	n	k	(pts 1-6)
1.3	0.0018	0.917099	1.43	0.0023	0.931678	1.56	0.0028	0.949107
1.31	0.0019	0.884199	1.44	0.0023	0.954771	1.57	0.0028	0.95162
1.32	0.0019	0.907498	1.45	0.0024	0.918521	1.58	0.0028	0.974713
1.33	0.0019	0.93061	1.46	0.0024	0.941757	1.59	0.0029	0.943899
1.34	0.002	0.897131	1.47	0.0024	0.964807	1.6	0.0029	0.958009
1.35	0.002	0.920373	1.48	0.0025	0.927912	1.61	0.0029	0.981074
1.36	0.0021	0.921107	1.49	0.0025	0.951108	1.62	0.003	0.940401
1.37	0.0021	0.909358	1.5	0.0026	0.961298	1.63	0.003	0.963629
1.38	0.0021	0.932548	1.51	0.0026	0.936564	1.64	0.003	0.986669
1.39	0.0022	0.91182	1.52	0.0026	0.959722	1.65	0.0031	0.945263
1.4	0.0022	0.920876	1.53	0.0027	0.954907	1.66	0.0031	0.968469
1.41	0.0022	0.944016	1.54	0.0027	0.944469	1.67	0.0031	0.991488
1.42	0.0022	0.966969	1.55	0.0027	0.967593	1.68	0.0032	0.949335
						1.69	0.0032	0.972523
						1.7	0.0032	0.995524

Table 9. Spreadsheet Method, Closest Fit "n" and "k" Values, (V_{gs} -V_{tNOM}) = 2 volts

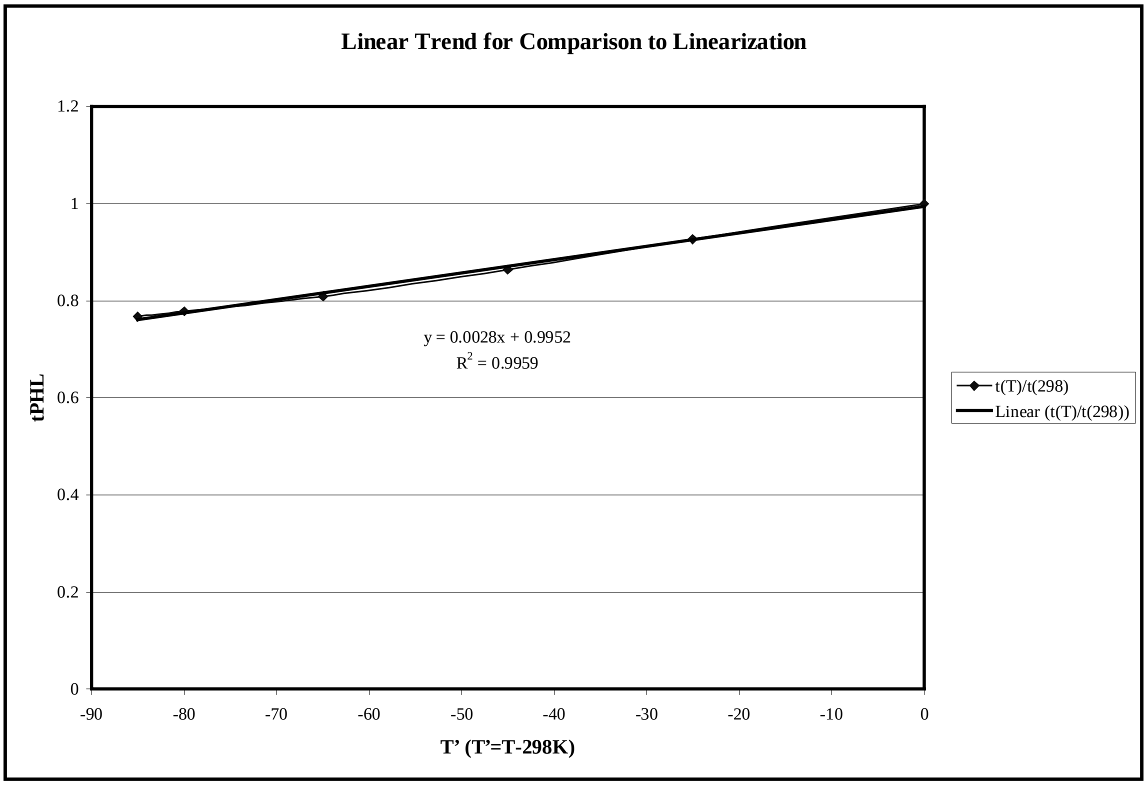

Figure 8. $t_{PHL}(T)/t_{PHL}(298)$ – Excel Linear Data Fit, $(V_{gs} - V_{tNOM}) = 2$ volts

$$n = 0.8334 + 298k \qquad \text{(Eq. 17)}$$

	Spreadsheet	Linearization			Spreadsheet	Linearization	
n	k	k	difference	n	k	k	difference
1.3	0.0018	0.00156	0.00024	1.5	0.0026	0.00223	0.00037
1.31	0.0019	0.00160	0.00030	1.51	0.0026	0.00227	0.00033
1.32	0.0019	0.00163	0.00027	1.52	0.0026	0.00230	0.00030
1.33	0.0019	0.00166	0.00024	1.53	0.0027	0.00233	0.00037
1.34	0.002	0.00170	0.00030	1.54	0.0027	0.00237	0.00033
1.35	0.002	0.00173	0.00027	1.55	0.0027	0.00240	0.00030
1.36	0.0021	0.00176	0.00034	1.56	0.0028	0.00243	0.00037
1.37	0.0021	0.00180	0.00030	1.57	0.0028	0.00247	0.00033
1.38	0.0021	0.00183	0.00027	1.58	0.0028	0.00250	0.00030
1.39	0.0022	0.00186	0.00034	1.59	0.0029	0.00254	0.00036
1.4	0.0022	0.00190	0.00030	1.6	0.0029	0.00257	0.00033
1.41	0.0022	0.00193	0.00027	1.61	0.0029	0.00260	0.00030
1.42	0.0022	0.00197	0.00023	1.62	0.003	0.00264	0.00036
1.43	0.0023	0.00200	0.00030	1.63	0.003	0.00267	0.00033
1.44	0.0023	0.00203	0.00027	1.64	0.003	0.00270	0.00030
1.45	0.0024	0.00207	0.00033	1.65	0.0031	0.00274	0.00036
1.46	0.0024	0.00210	0.00030	1.66	0.0031	0.00277	0.00033
1.47	0.0024	0.00213	0.00027	1.67	0.0031	0.00280	0.00030
1.48	0.0025	0.00217	0.00033	1.68	0.0032	0.00284	0.00036
1.49	0.0025	0.00220	0.00030	1.69	0.0032	0.00287	0.00033
				1.7	0.0032	0.00290	0.00030
			more ->			avg->	0.00029

Table 10. Overlapping “n” Values with Method-Specific "k" Values, (V_{gs} -V_{tNOM}) = 2 volts

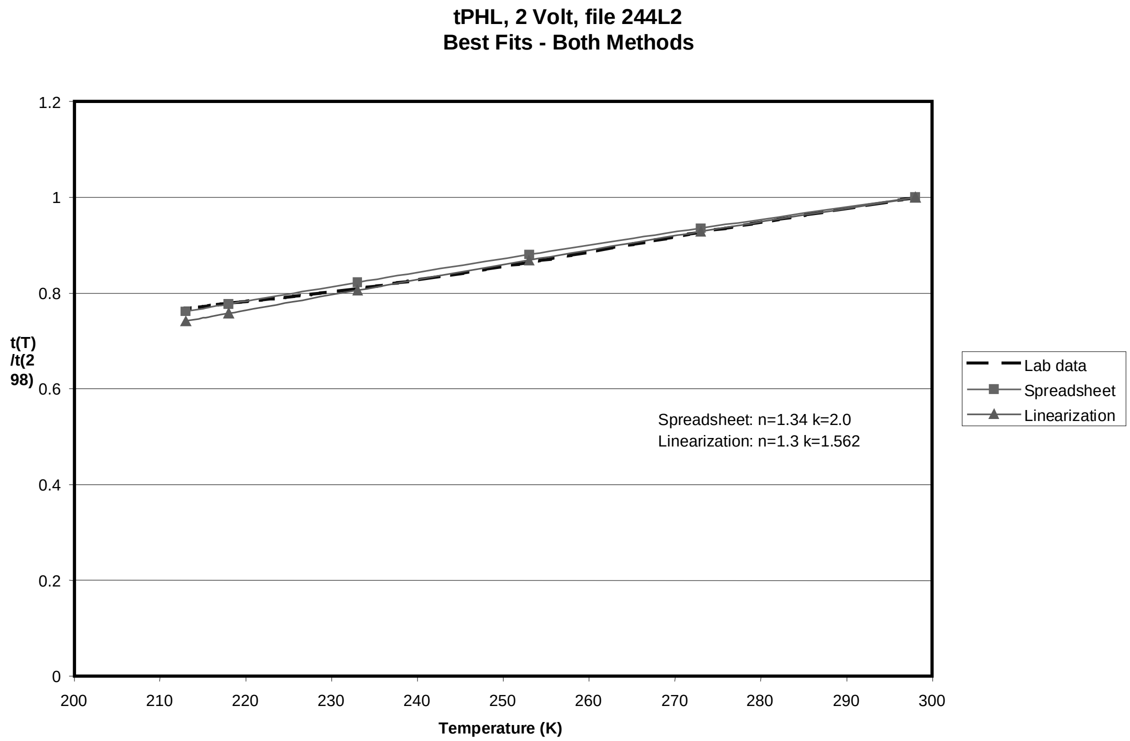

Figure 9. $t_{PHL}(T)/t_{PHL}(298)$ – Best Fits, Method Comparison, $(V_{gs}-V_{tNOM})$=2V

$(V_{gs} - V_{tNOM})$ = 4 volts

n	k	Avg % diff (pts 1-6)	n	k	Avg % diff (pts 1-6)
1.3	0.0037	0.889159	1.41	0.0045	0.914738
1.31	0.0038	0.884199	1.42	0.0046	0.908397
1.32	0.0039	0.8957	1.43	0.0046	0.931678
1.33	0.0039	0.902411	1.44	0.0047	0.925203
1.34	0.004	0.897131	1.45	0.0048	0.918521
1.35	0.0041	0.891654	1.46	0.0049	0.931539
1.36	0.0041	0.914964	1.47	0.0049	0.93494
1.37	0.0042	0.909358	1.48	0.005	0.927912
1.38	0.0043	0.903554	1.49	0.005	0.951108
1.39	0.0044	0.91182	1.5	0.005	0.974116
1.4	0.0044	0.920876	1.51	0.005	0.996938

Table 11. Spreadsheet Method, Closest Fit "n" and "k" Values, $(V_{gs} - V_{tNOM})$ = 4 volts

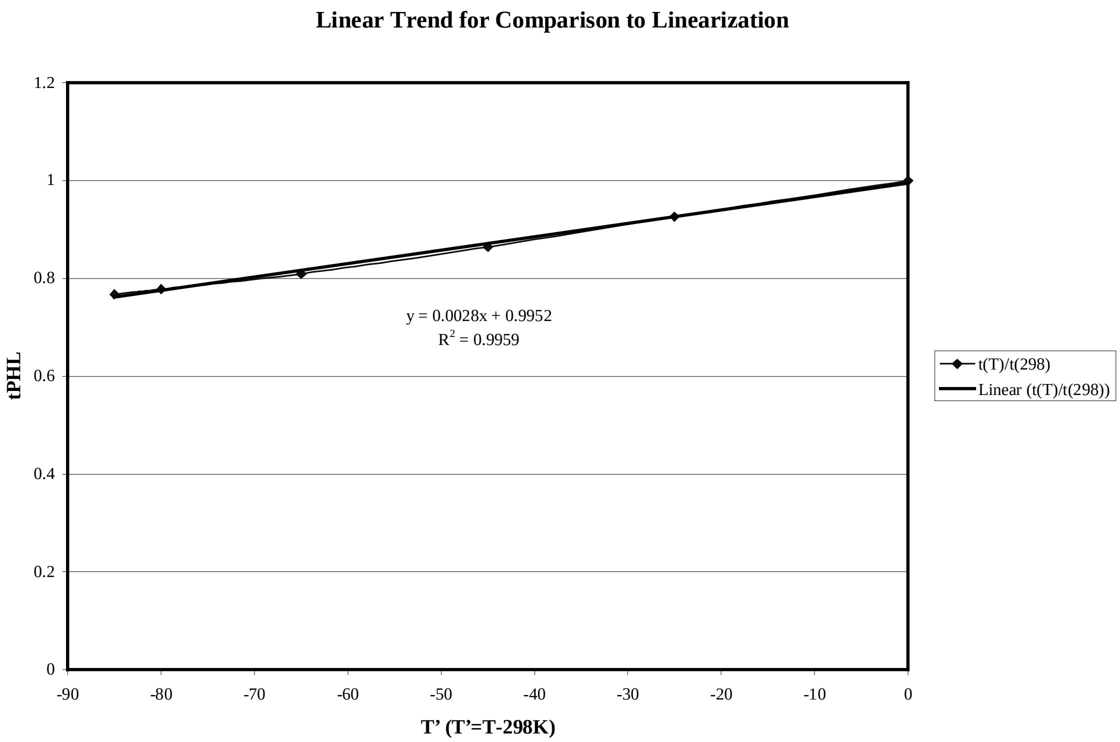

Figure 10. $t_{PHL}(T)/t_{PHL}(298)$ – Excel Linear Data Fit, $(V_{gs} - V_{tNOM})$ = 4 volts

$$n = 0.8334 + 149k \qquad \text{(Eq. 18)}$$

	spreadsheet	linearization			spreadsheet	linearization	
n	k	k	difference	n	k	k	difference
1.3	0.0037	0.00312	0.00058	1.45	0.0048	0.00413	0.00067
1.31	0.0038	0.00319	0.00061	1.46	0.0049	0.00420	0.00070
1.32	0.0039	0.00326	0.00064	1.47	0.0049	0.00427	0.00063
1.33	0.0039	0.00333	0.00057	1.48	0.005	0.00433	0.00067
1.34	0.004	0.00339	0.00061	1.49	(out of range)	0.00440	NA
1.35	0.0041	0.00346	0.00064	1.5	"	0.00447	NA
1.36	0.0041	0.00353	0.00057	1.51	"	0.00453	NA
1.37	0.0042	0.00359	0.00061	1.52	"	0.00460	NA
1.38	0.0043	0.00366	0.00064	1.53	"	0.00467	NA
1.39	0.0044	0.00373	0.00067	1.54	"	0.00474	NA
1.4	0.0044	0.00380	0.00060	1.55	"	0.00480	NA
1.41	0.0045	0.00386	0.00064	1.56	"	0.00487	NA
1.42	0.0046	0.00393	0.00067	1.57	"	0.00494	NA
1.43	0.0046	0.00400	0.00060			avg ->	0.00062
1.44	0.0047	0.00406	0.00064				

Table 12. Overlapping "n" Values with Method-Specific "k" Values, (V_{gs} - V_{tNOM}) = 4 volts

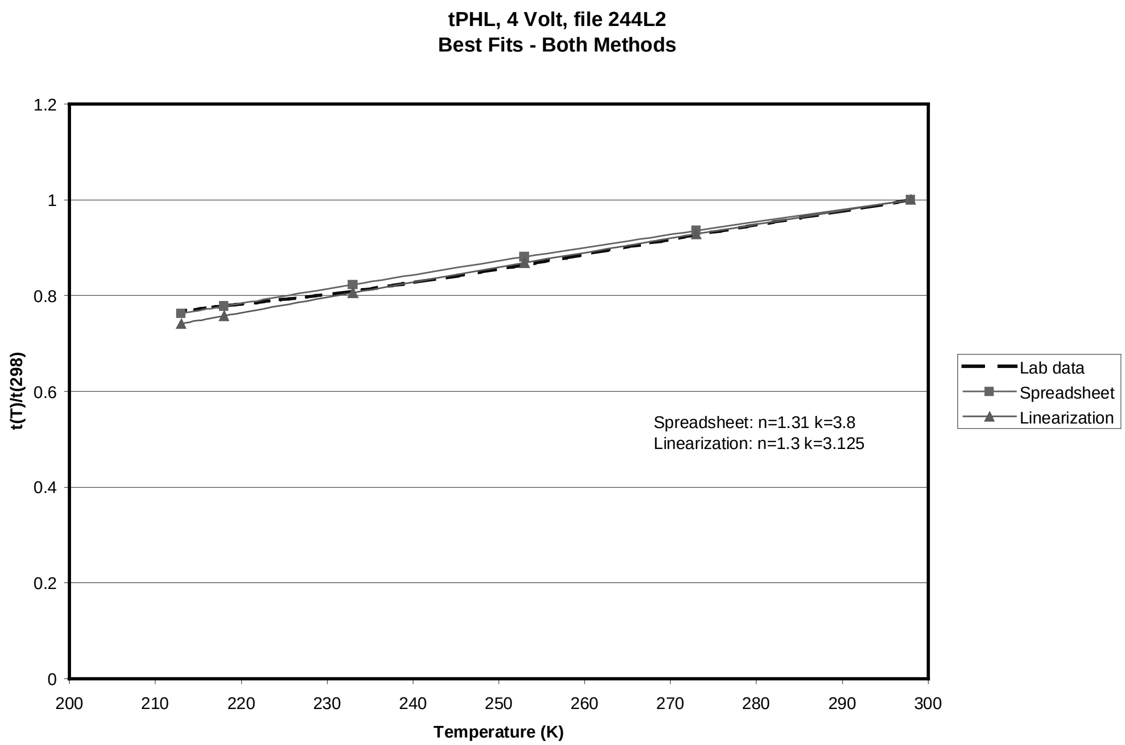

Figure 11. $t_{PHL}(T)/t_{PHL}(298)$ – Best Fits, Method Comparison, (V_{gs}-V_{tNOM})=4V

2.2 Low-To-High-Level Output Propagation Delay Time (t_{PLH})

		Avg % diff			Avg % diff
n	k	(pts 1-6)	n	k	(pts 1-6)
1.3	0.002	0.67751	1.5	0.0027	0.69061
1.31	0.0021	0.675866	1.51	0.0028	0.659143
1.32	0.0021	0.590891	1.52	0.0028	0.596508
1.33	0.0021	0.698304	1.53	0.0028	0.702908
1.34	0.0022	0.648683	1.54	0.0029	0.643954
1.35	0.0022	0.610553	1.55	0.0029	0.606618
1.36	0.0022	0.717904	1.56	0.0029	0.713946
1.37	0.0023	0.623184	1.57	0.003	0.630544
1.38	0.0023	0.62901	1.58	0.003	0.616416
1.39	0.0023	0.736302	1.59	0.003	0.723714
1.4	0.0024	0.599378	1.6	0.0031	0.618927
1.41	0.0024	0.646252	1.61	0.0031	0.624931
1.42	0.0025	0.715246	1.62	0.0031	0.732202
1.43	0.0025	0.586035	1.63	0.0032	0.60912
1.44	0.0025	0.662273	1.64	0.0032	0.63215
1.45	0.0026	0.694802	1.65	0.0033	0.739168
1.46	0.0026	0.583675	1.66	0.0033	0.601137
1.47	0.0026	0.677061	1.67	0.0033	0.638063
1.48	0.0027	0.676097	1.68	0.0034	0.733005
1.49	0.0027	0.58549	1.69	0.0034	0.598028
			1.7	0.0034	0.642657

Table 13. Spreadsheet Method, Closest Fit “n” and “k” Values, (V_{gs} -V_{tNOM}) = 2 volts

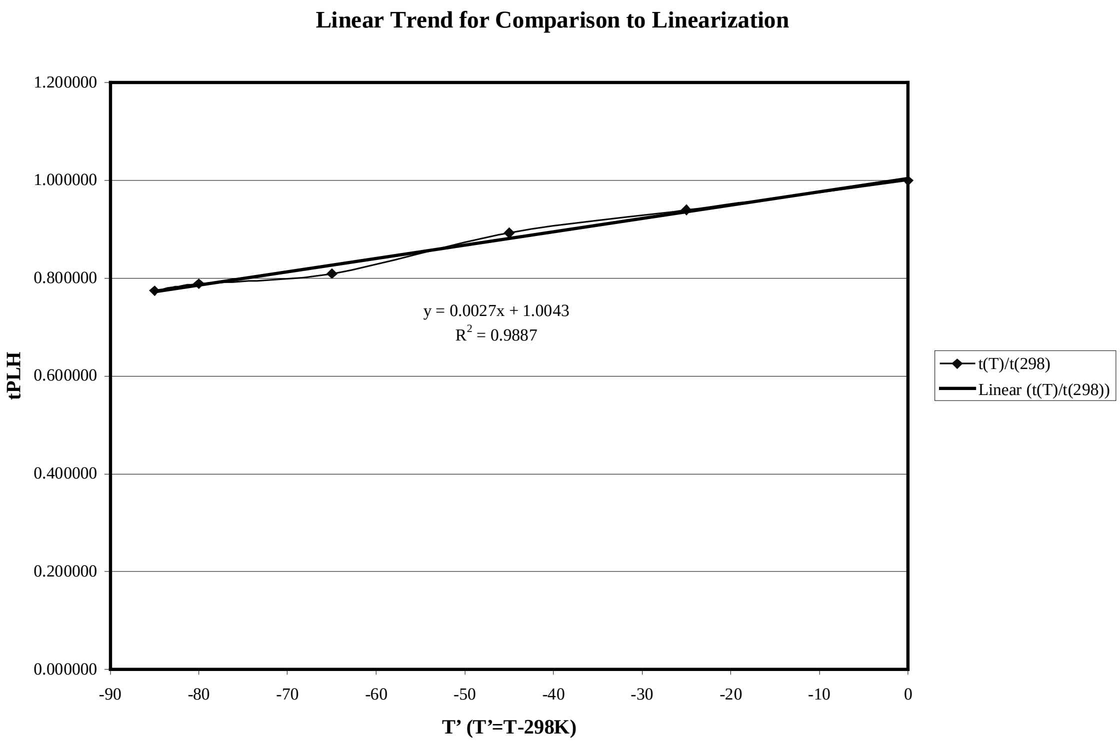

Figure 12. $t_{PLH}(T)/t_{PLH}(298)$ – Excel Linear Data Fit, $(V_{gs} - V_{tNOM})$ = 2 volts

$$n = 0.8046 + 298k \qquad \text{(Eq. 19)}$$

	Spreadsheet	Linearization			Spreadsheet	Linearization	
n	k	k	Difference	n	k	k	Difference
1.3	0.002	0.00166	0.00034	1.51	0.0028	0.00237	0.00043
1.31	0.0021	0.00170	0.00040	1.52	0.0028	0.00240	0.00040
1.32	0.0021	0.00173	0.00037	1.53	0.0028	0.00243	0.00037
1.33	0.0021	0.00176	0.00034	1.54	0.0029	0.00247	0.00043
1.34	0.0022	0.00180	0.00040	1.55	0.0029	0.00250	0.00040
1.35	0.0022	0.00183	0.00037	1.56	0.0029	0.00253	0.00037
1.36	0.0022	0.00186	0.00034	1.57	0.003	0.00257	0.00043
1.37	0.0023	0.00190	0.00040	1.58	0.003	0.00260	0.00040
1.38	0.0023	0.00193	0.00037	1.59	0.003	0.00264	0.00036
1.39	0.0023	0.00196	0.00034	1.6	0.0031	0.00267	0.00043
1.4	0.0024	0.00200	0.00040	1.61	0.0031	0.00270	0.00040
1.41	0.0024	0.00203	0.00037	1.62	0.0031	0.00274	0.00036
1.42	0.0025	0.00207	0.00043	1.63	0.0032	0.00277	0.00043
1.43	0.0025	0.00210	0.00040	1.64	0.0032	0.00280	0.00040
1.44	0.0025	0.00213	0.00037	1.65	0.0033	0.00284	0.00046
1.45	0.0026	0.00217	0.00043	1.66	0.0033	0.00287	0.00043
1.46	0.0026	0.00220	0.00040	1.67	0.0033	0.00290	0.00040
1.47	0.0026	0.00223	0.00037	1.68	0.0034	0.00294	0.00046
1.48	0.0027	0.00227	0.00043	1.69	0.0034	0.00297	0.00043
1.49	0.0027	0.00230	0.00040	1.7	0.0034	0.00300	0.00040
1.5	0.0027	0.00233	0.00037			avg ->	0.00038

Table 14. Overlapping “n” Values with Method-Specific "k" Values, (V_{gs} -V_{tNOM}) = 2 volts

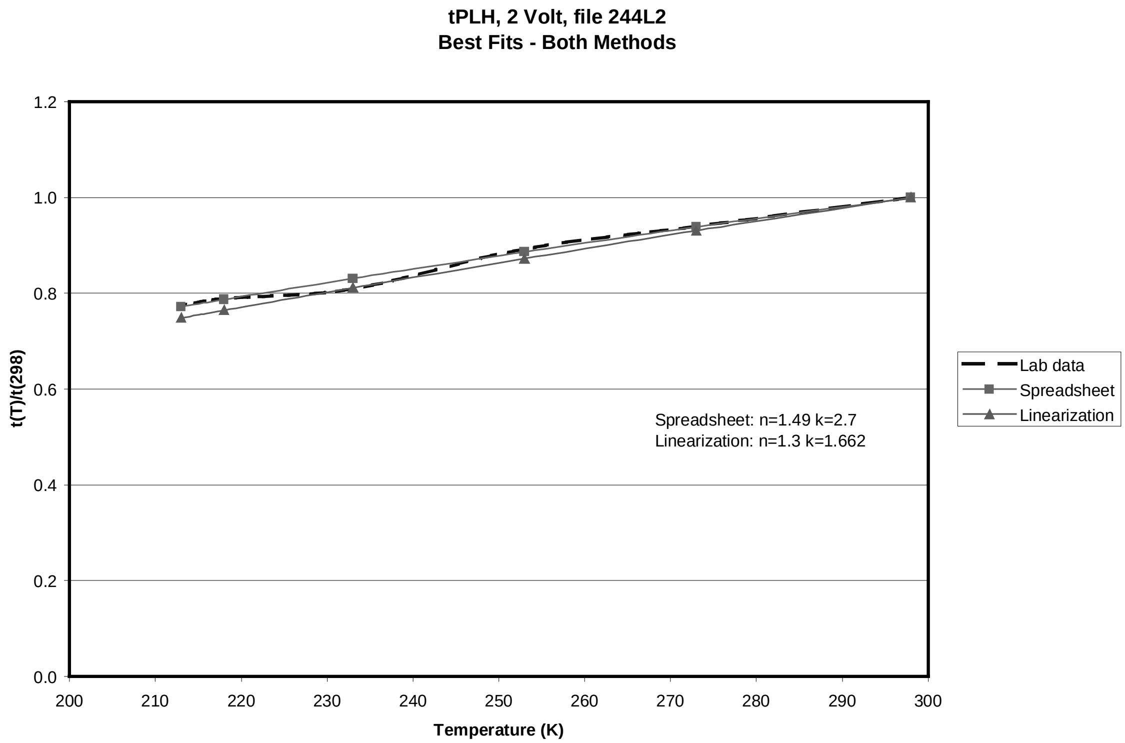

Figure 13. $t_{PLH}(T)/t_{PLH}(298)$ – Best Fits, Method Comparison, $(V_{gs}-V_{tNOM})$=2V

3. High-Temperature Run 1

3.1 High-To-Low-Level Output Propagation Delay Time (t_{PHL})

3.2 Low-To-High-Level Output Propagation Delay Time (t_{PLH})

4. High-Temperature Run 2

4.1 High-To-Low-Level Output Propagation Delay Time (t_{PHL})

4.2 Low-To-High-Level Output Propagation Delay Time (t_{PLH})