CHALLENGES RELATED TO MEASURING AND REPORTING TEMPERATURE-DEPENDENT APPARENT THERMAL CONDUCTIVITY OF INSULATION MATERIALS

CANADIAN BUILDING SCIENCE & TECHNOLOGY CONFERENCE 2017

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- Shared test results and long discussions and critiques

R-values

→ R-values are fundamental to building industry design and analysis

→ R-value = thickness / thermal conductivity

→ Promoted by Everett Schuman, Penn State's Housing Research Institute (1940s)

→ But true R-values are not simple, or single values

→ R-values depend on

- → **Time**
- → **Airflow**
- → **Thermal bridging**
- → **Temperature**

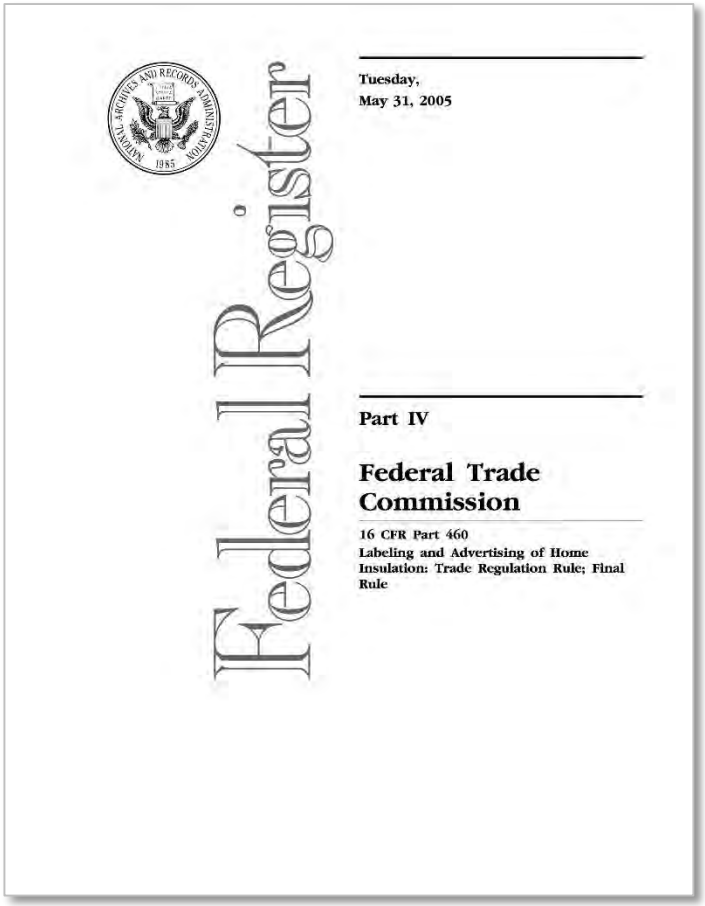
Label R-Values: what most people use

→ FTC 16 CFR Part 460

→ Federal Trade Commission

→ Title 16 – Commercial Practices Commercial Federal Regulation

→ Part 460 – Labeling and Advertising of Home Insulation Trade Regulations



Federal Register

Tuesday,
May 31, 2005

Part IV

Federal Trade Commission

16 CFR Part 460
Labeling and Advertising of Home Insulation: Trade Regulation Rule; Final Rule

http://www.ecfr.gov/cgi-bin/text-idx?SID=79485feed2653b4002a771a5b34c6cd8&node=pt16.1.460&rgn=div5

Measuring R-Values

→ Property of a layer of material or assembly

→ Measurement of resistance to heat flow

→ R-value is the reciprocal of thermal conductance

→ Methods used:
ASTM C518, ASTM C177

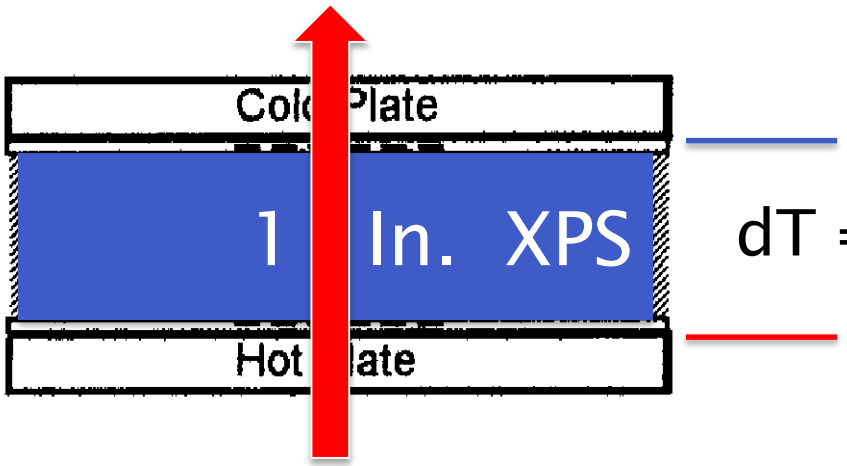
Measuring Label R-Values (ASTM C518)

1.141 Btu/hr

T_{cold}= 50.0˚F

T_{mean}= 75.2˚F

T_{hot}= 100.5˚F



dT = 50.5˚F

1. Impose temperature difference across sample
2. Measure heat flow, sample thickness and area
3. Calculate R-value

$$R = \frac{area \times temperature\ difference}{heat\ flow}$$

Measuring Label R-Values (ASTM C518)

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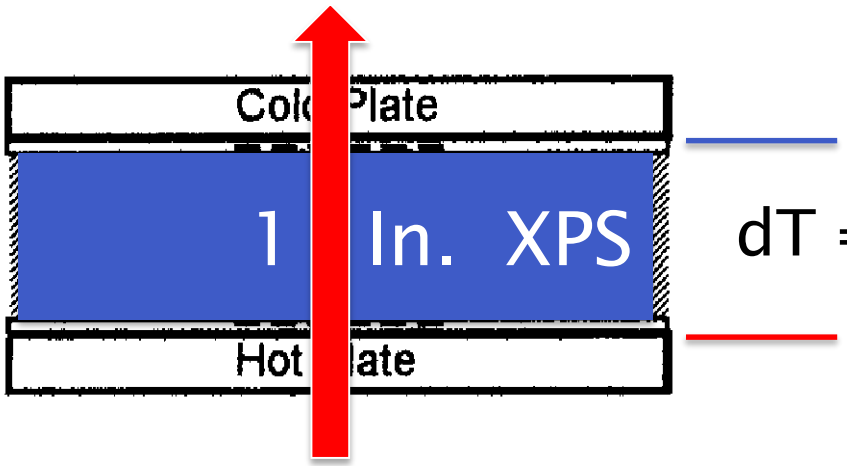


dT = 50.5˚F

Heat Flux Transducer Area = 16 in^2 = 0.111ft^2

Apparent R-value of aged 1 in. XPS

R 4.92

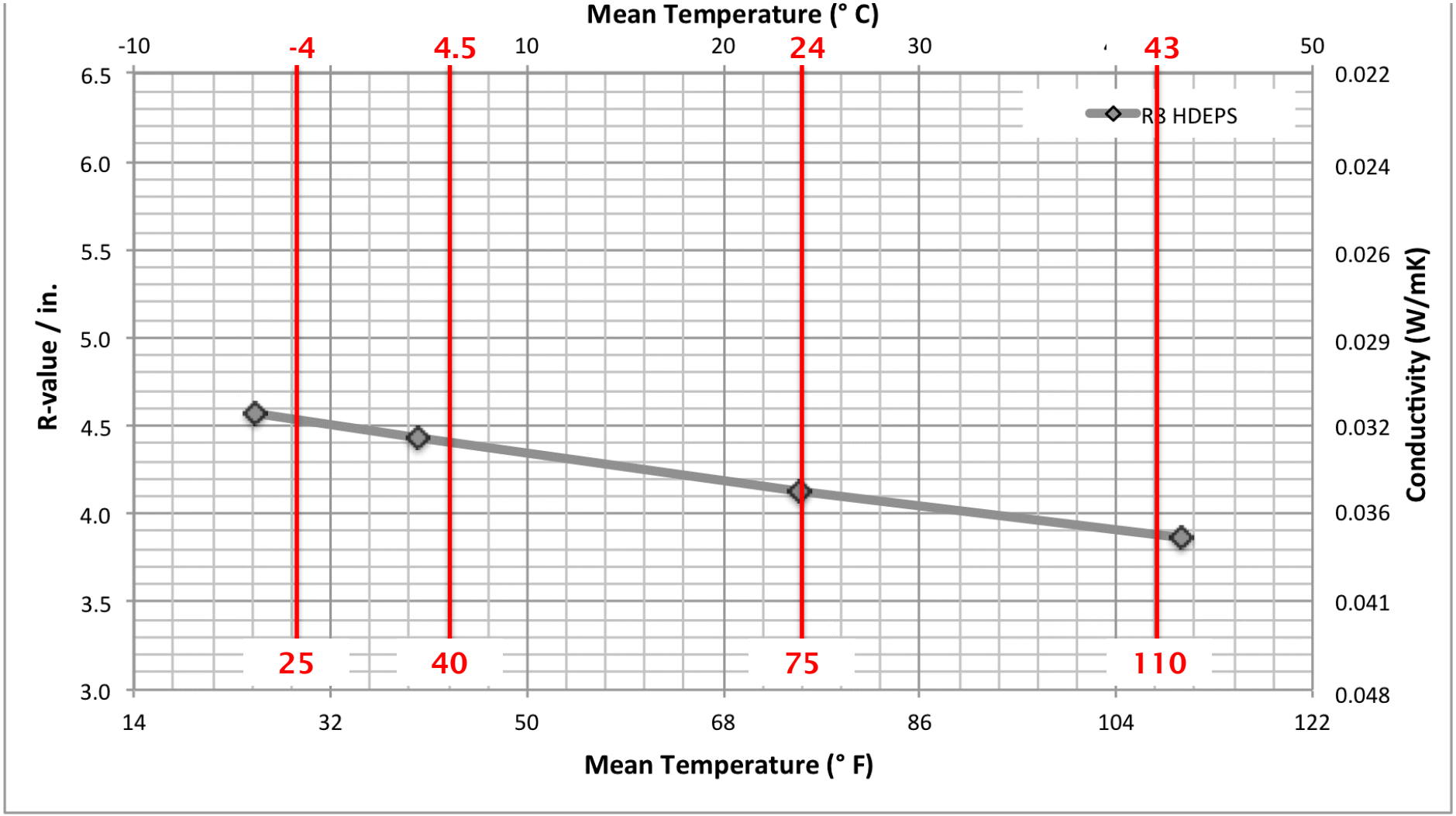
(within 2% of label R-value)

The rest of the story…

→ The ASTM C518 R-value **results change** with Mean (average) Temperature across sample

- E.g., Cold=10 C and hot=38C, mean=24 C
- E.g., Cold=50 F and hot = 100 F, mean =75F

E.g.High-Density Expanded Polystyrene

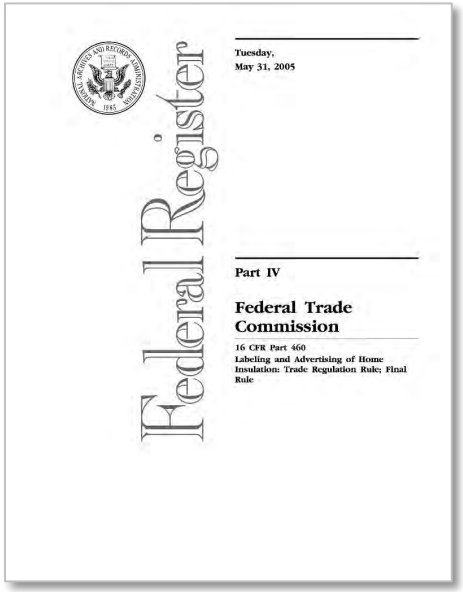


Temperature-Dependent Thermal Conductivity

Historically

→ Report and consider R-value and/or thermal conductance at a single mean temperature of 75˚F (24 ˚C)

→ FTC 16 CFR Part 460 "R-Value Rule"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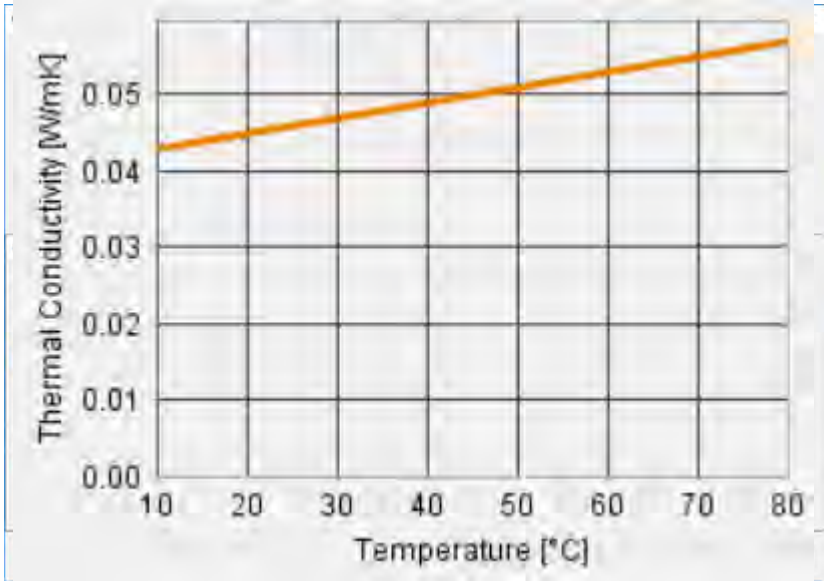
More Recently

→ Growing recognition, reporting, and application of temperature-dependent thermal performance

→ Energy and hygrothermal calculation programs



ASTM C1058 – around for decades

"Standard Practice for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation"

→Recognizes temperature dependence

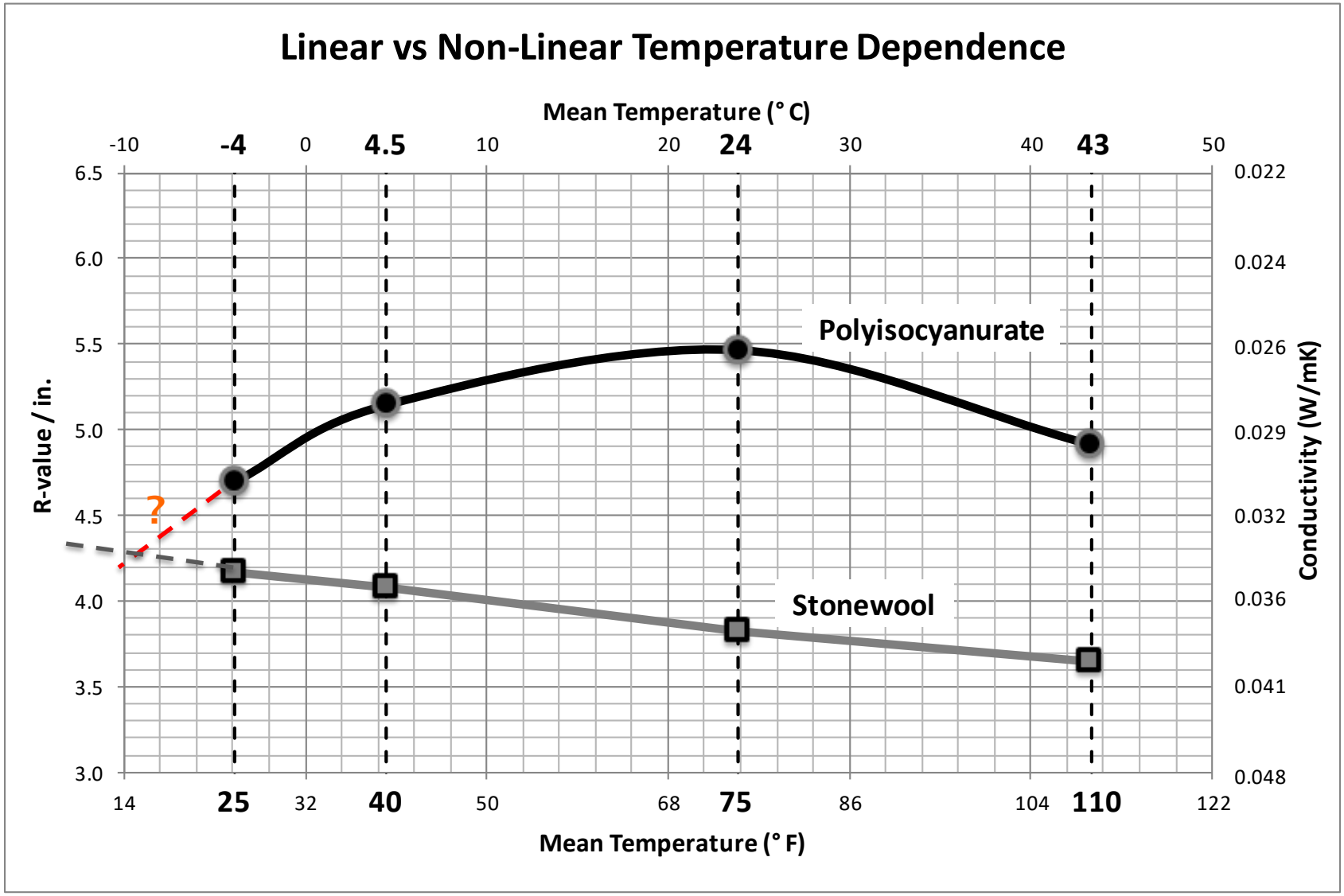
4.2 It is possible that thermal properties of a specimen will change with mean temperature, with temperature difference across the specimens, and with high temperature exposure. Data and information at standard temperatures are necessary for valid comparison of thermal properties.

→ Provides guidance on standard conditions for testing

TABLE 1 Mean Test Temperatures for Reporting and Evaluation of Thermal Properties of Thermal Insulations

Insulation Classification	Mean Test Temperature	
	°C	[°F][A]
Building Envelopes	–4	[25]
	4	[40]
	10	[50]
	24	[75]
	38	[100]
	43	[110]

“One of these things is not like the other”

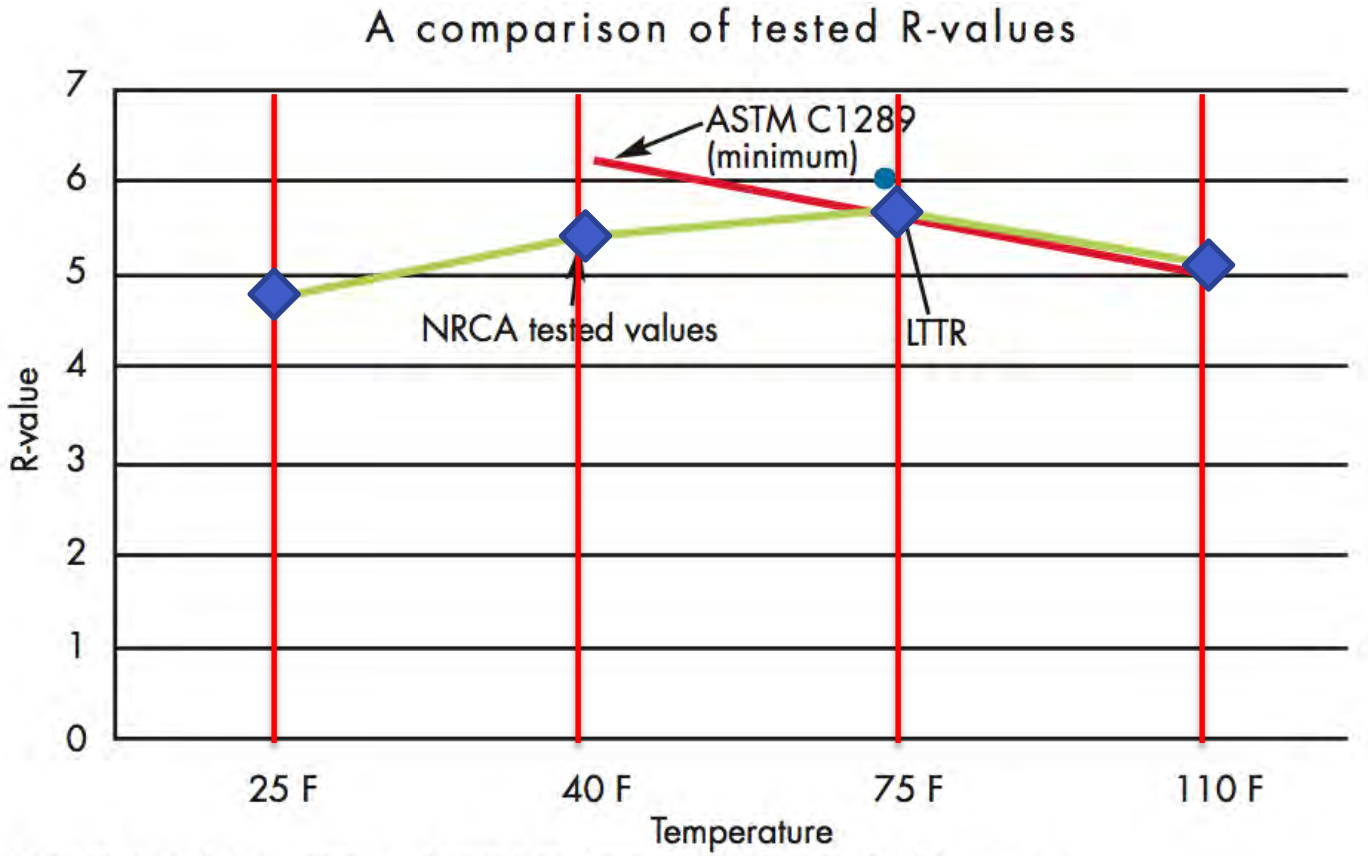


Polyisocyanurate Roof Insulation over a Range of Mean Temperatures

→ *Professional Roofing*, May 2010 – Mark Graham (NRCA)

→ Results from ASTM C518 testing at 4 mean temperatures

→ Presentation implies k(T) is well defined



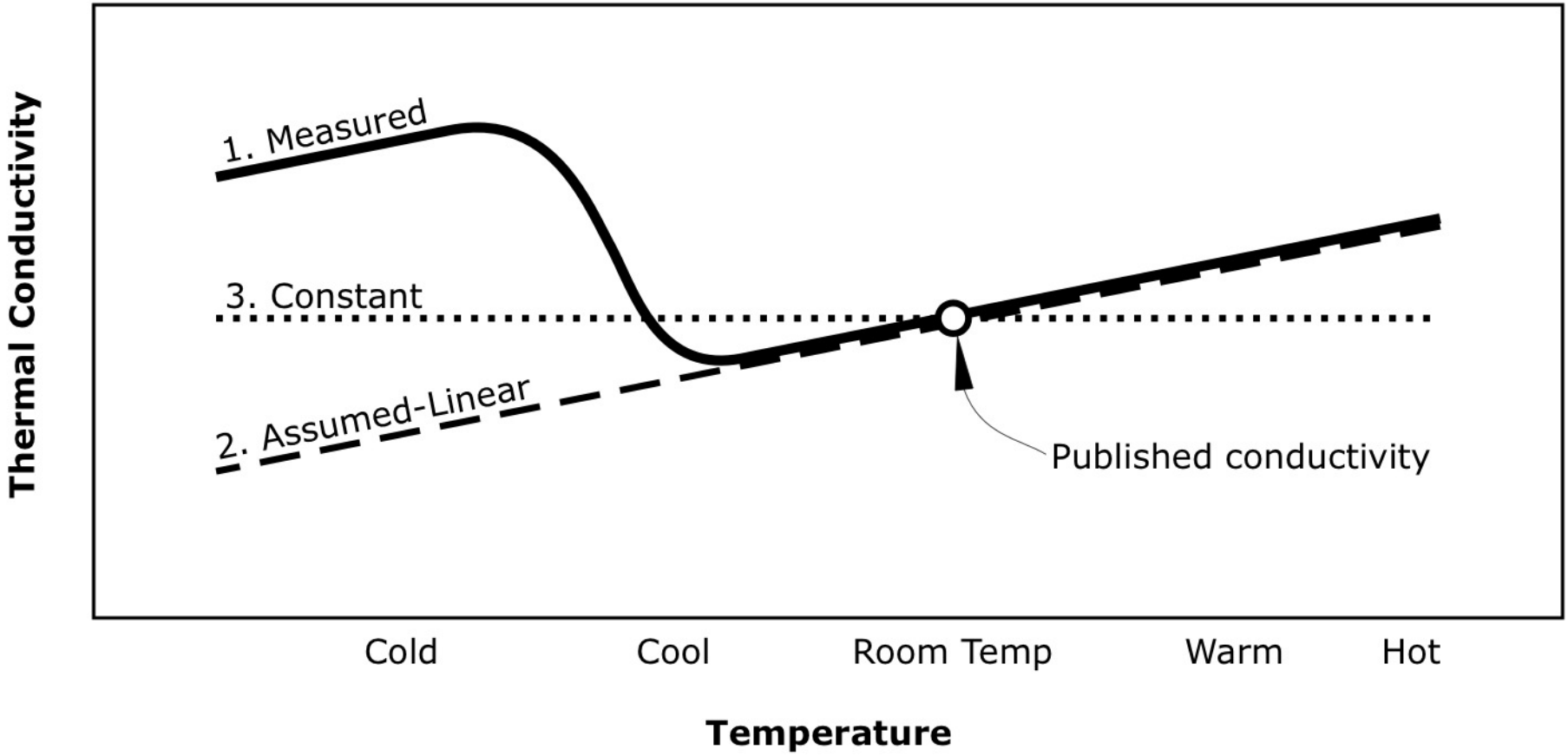
NRCA's tested data, LTTR and ASTM C1289's minimum required R-values

Shapes matter

→3. Assumed for energy modeling

→2. Assumed by scientists study heat transfer

→1. What we have measured



Short Summary to date

→ No doubt: temperature affects insulation R-value

  → Usually R-value goes up as temperature drops

→ Effect varies with insulation type

→ Most insulation exhibits linear behaviour

  → Expected because of radiation effects

→ Polyiso is one type that acts non-linearly

  → Blowing agents are assumed to be the reason

Experimental work

- → **Investigate and Compare Two Approaches to Determine k(T)**
- → Round Robin Testing between three Labs
- → Analysis and Demonstration

Followed ASTM C1045

"Standard Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions"

→ Gives method for developing k(T), the apparent thermal conductivity as a function of temperature

- → characterize material
- → comparison to specifications
- → use in calculation programs

1.3 This practice provides the method for developing the apparent thermal conductivity as a function of temperature relationship for a specimen from data generated by standard test methods at small or large temperature differences. This relationship can be used to characterize material for comparison to material specifications and for use in calculation programs such as Practice C680.

ASTM C1045

→ Provides explanation of our 1st approach to determining k(T):

Thermal Conductivity Integral (TCI) Method

6.5 *TCI Method—A Summary*—The thermal conductivity integral method of analysis is summarized in the following steps:

6.5.1 Measure several sets of λ_{exp}, T_h, and T_c over a range of temperatures.

6.5.2 Select a functional form for $\lambda(T)$ as in Eq 19, and integrate it with respect to temperature to obtain the equivalent of Eq 20.

6.5.3 Perform a least-squares fit to the experimental data of the integral of the functional form obtained in 6.5.2 to obtain the best values of the coefficients.

6.5.4 Use these coefficients to complete the $\lambda(T)$ equation as defined in 6.5.2. Remember that the thermal conductivity equation derived herein is good only over the range of temperatures encompassed by the test data. Extrapolation of the test results to a temperature range not covered by the data is not acceptable.

Hints from ASTM C1045 and C1058

→ Schumacher developed 2nd approach to determining k(T):

Decreasing Delta T Method

(limit of k(T) as the applied temperature difference approaches zero)

ASTM C1045

NOTE 9—One exception to this temperature difference conditions is testing of insulation materials exhibiting inflection points due to the change of state of insulating gases. For these materials, testing shall be conducted with sufficiently small temperature differences and at closely spaced mean temperatures. The selection of test temperatures will depend on the vapor pressure versus temperature relationship of the gases involved and the ability of the test apparatus to provide accurate measurements at low temperature differences. Another exception occurs

ASTM C1058

4.4 These conditions must be stated to describe accurately thermal properties such as thermal conductivity versus mean temperature for thermal insulating materials. Thermal insulations exhibiting inflection points due to the change of state of insulating gases (see Note 2), must be tested at sufficiently small temperature differences between (*1*) the hot and cold sides and (*2*) between mean temperatures. The test temperature differences used depend on the vapor pressure versus temperature relationship of the gases involved and the ability of the test apparatus to provide accurate measurements of low temperature differences.

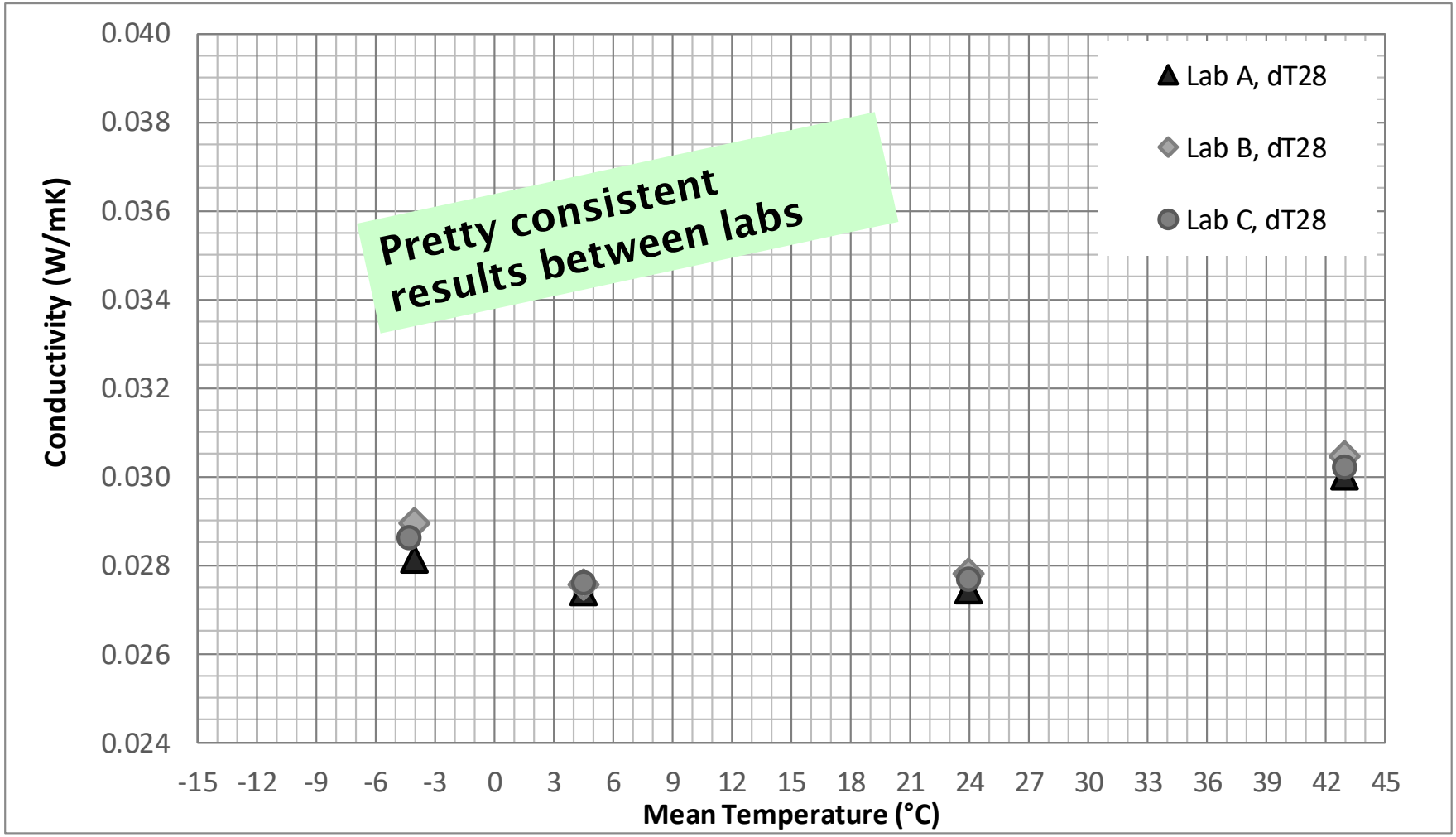
Three-Lab Round Robin

→ Two samples of 1 in. thick foil-faced polyisocyanurate insulation

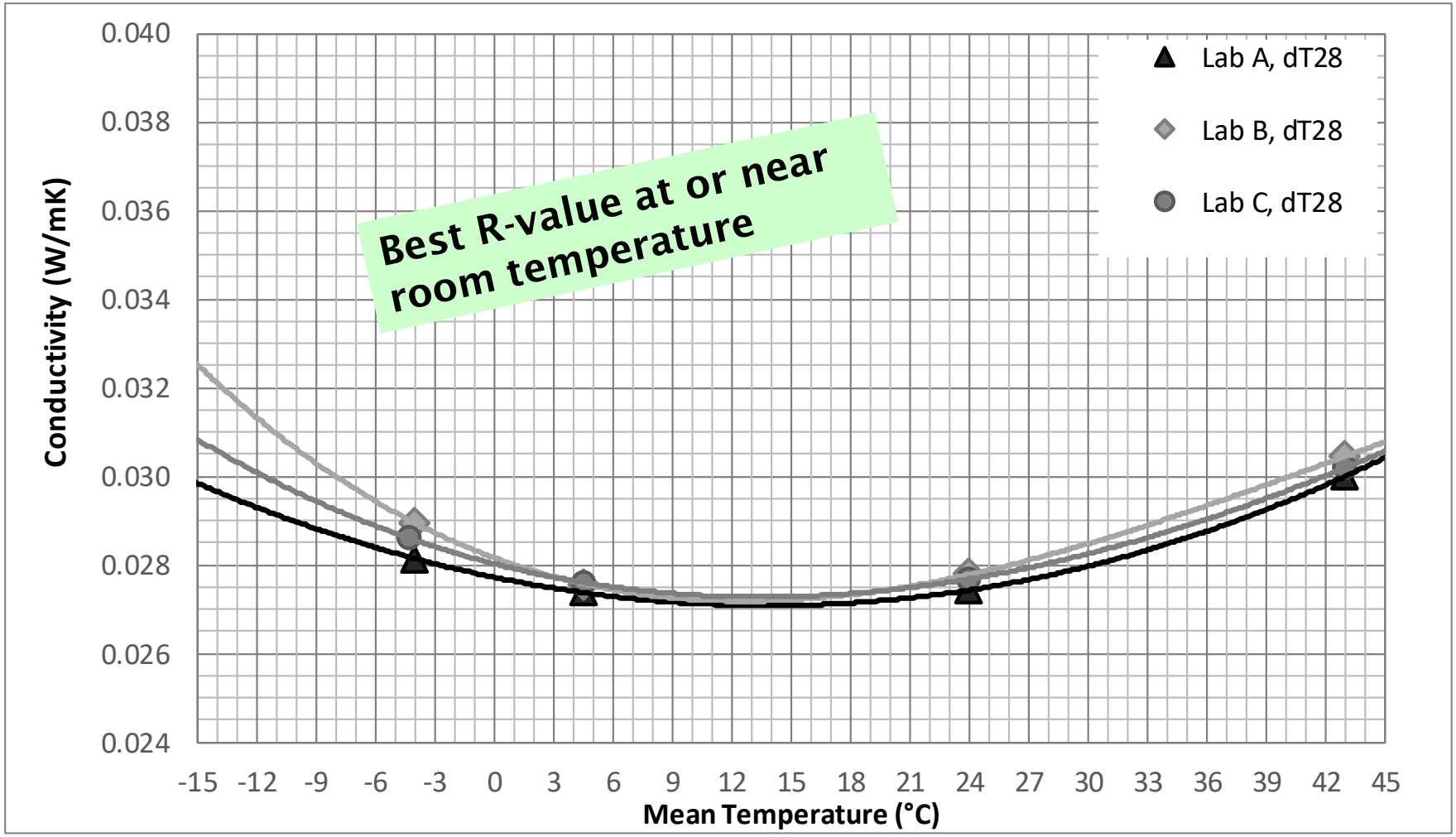
Full Data Set			Sample 1			Sample 2		
Segment	Mean Temp	Delta T	Lab A	Lab B	Lab C	Lab A	Lab B	Lab C
B1	-12	12	0.03415			0.03006		
B2	-12	9	0.03530			0.03050		
B3	-12	6	0.03699			0.03112		
B4	-12	3	0.03951			0.03226		
A1c	-4.3	28.7						0.02860
A1	-4	28	0.02958			0.02814		
A1b	-4	22		0.03080			0.02894	
A2	-4	12	0.03210	0.03282		0.0290[illegible]	[illegible]02980	
A3	-4	6	0.03445			0.0[illegible]		
B5	-4	3	0.03731					
A4	4.5	28	0.02773	0.02786			0.02757	0.02760
B6b	4.5	16					0.02827	
A5	4.5	12	0.02900	0.02961		[illegible]2775	0.02834	0.02801
B6c	4.5	8		0.03133			0.02907	
B6	4.5	6	0.03105			0.02847		0.02866
B7b	4.5	4		0.[illegible]			0.03030	
B7	4.5	3	0.03247			0.02900		0.02926
B8	10	12	0.02702	0.02[illegible]		0.02702	0.02747	0.02714
B9	10	6	0.02748	0.02824		0.02713	0.02902	0.02721
A6	24	28	0.02577	0.02593		0.02743	0.02778	0.02768
A7	24	12	0.02547	0.02547		0.02719	0.02742	0.02737
A8	43	28	0.02800	0.02814		0.03000	0.03045	0.03019
A9	43	12	0.02778	0.02770		0.02926	0.02951	0.02996

Measured a range of Mean and Delta T's

Polyiso Sample 2 Results, Delta T = 28˚C



Results, Delta T = 28˚C
Cubic Curve Fit



1. Applying Integral Method

Applying the Integral Method

→ For an equation with cubic form

$$k(T) = a + b \cdot T + c \cdot T^2 + d \cdot T^3$$

→ From test results and integrating our cubic we get

$$\begin{aligned} k_{ave} = \; & a + b \cdot [\; (1/2)(T_2^2 - T_1^2) / (T_2 - T_1) \;] \\ & + c \cdot [(1/3)(T_2^3 - T_1^3) / (T_2 - T_1) \;] \\ & + d \cdot [\; (1/4)\,(T_2^4 - T_1^4) / (T_2 - T_1) \;] \end{aligned}$$

→ Simplify and determine W, X, Y, and Z from the tests

$$W = a + bX + cY + dZ$$

→ Finally, determine a, b, c, d from a least squares fit

Sample 2 Results, dT = 28˚C
Applying the Integral Method

→ From measured round robin data for Sample 2, at dT=28˚C

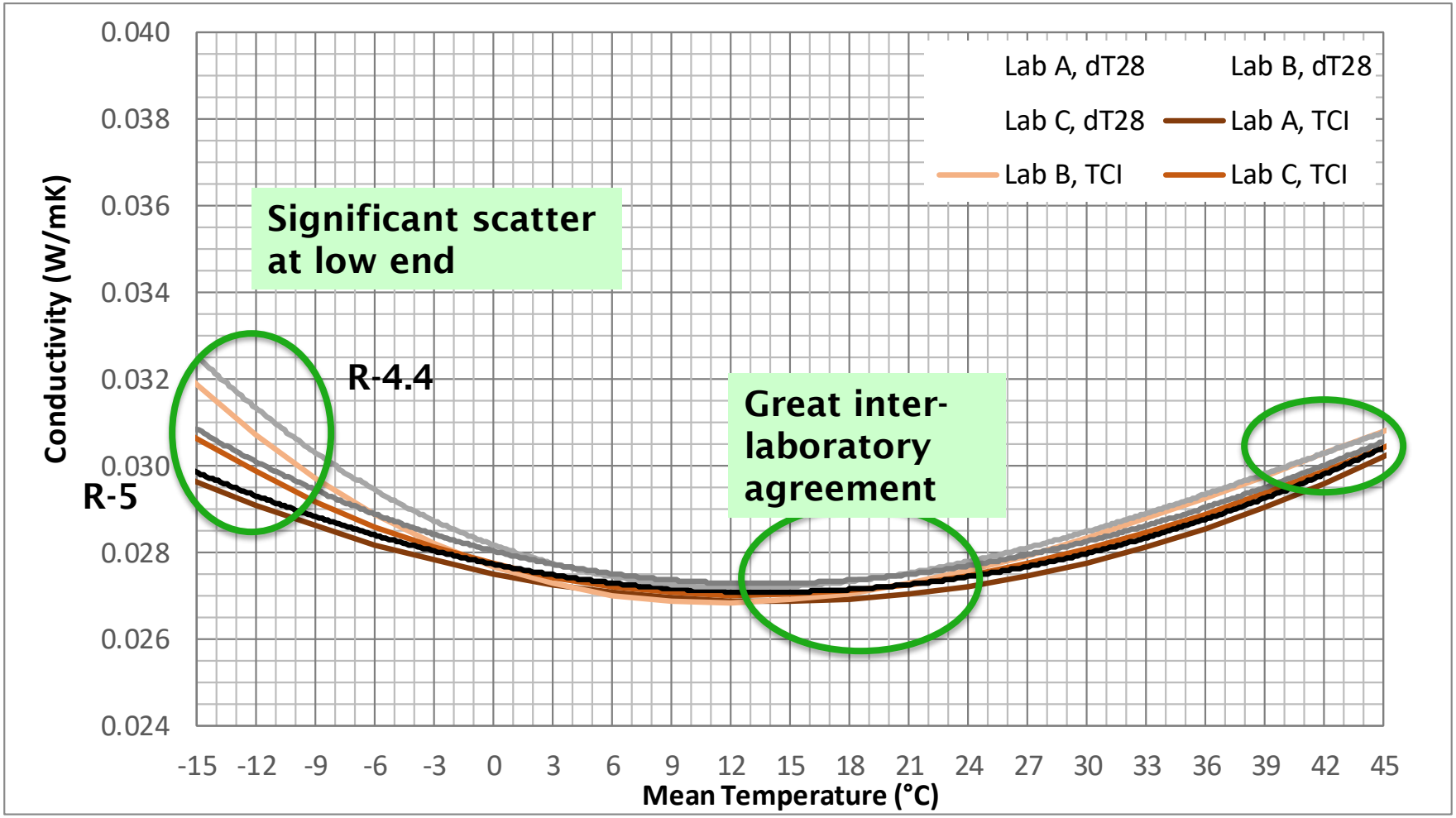
						Lab A		Lab B		Lab C	
						a	2.7503E-02	a	2.7664E-02	a	2.7723E-02
						b	-9.2640E-05	b	-1.5234E-04	b	-1.1542E-04
						c	3.2992E-06	c	7.5852E-06	c	4.8817E-06
						d	1.8771E-09	d	-5.8949E-08	d	-2.1776E-08
						R2	1.0000	R2	1.0000	R2	1.0000
Tmean	T1 (cold)	T2 (hot)	X	Y	Z	k avg	k integral	k avg	k integral	k avg	k integral
-4	-18	10	-4.0	81.3	-848.0	0.02814	0.02793	0.02894	0.02840	0.02860	0.02826
4.5	-9.5	18.5	4.5	85.6	973.1	0.02737	0.02715	0.02757	0.02713	0.02760	0.02730
24	10	38	24.0	641.3	18528.0	0.02743	0.02721	0.02778	0.02756	0.02768	0.02746
43	29	57	43.0	1914.3	87935.0	0.03000	0.02977	0.03045	0.03045	0.03019	0.03005

$$k(T) = a + b \cdot T + c \cdot T^2 + d \cdot T^3$$

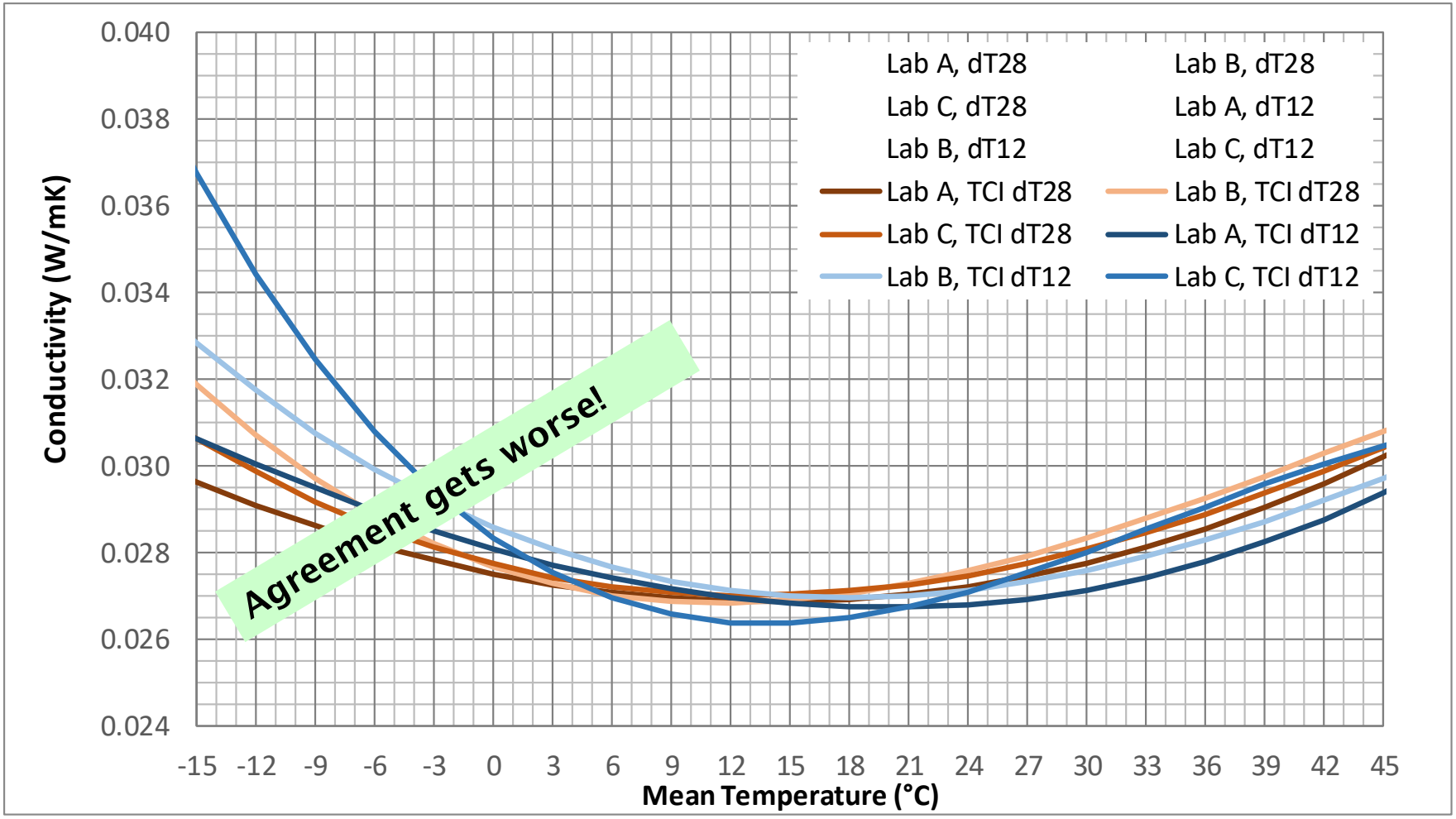
$$k_{ave} = a + b \cdot [\ (1/2)(T_2^2 - T_1^2)/(T_2 - T_1)\ ] + c \cdot [(1/3)(T_2^3 - T_1^3)/(T_2 - T_1)\ ] + d \cdot [\ (1/4)(T_2^4 - T_1^4)/(T_2 - T_1)\ ]$$

$$W = a + bX + cY + dZ$$

Sample 2 Results, dT = 28˚C
Applying the Integral Method



Sample 2 Results, dT = 28˚C and dT=12˚C Applying the Integral Method



2. Applying Decreasing Delta T Method

Applying the Decreasing Delta T Method

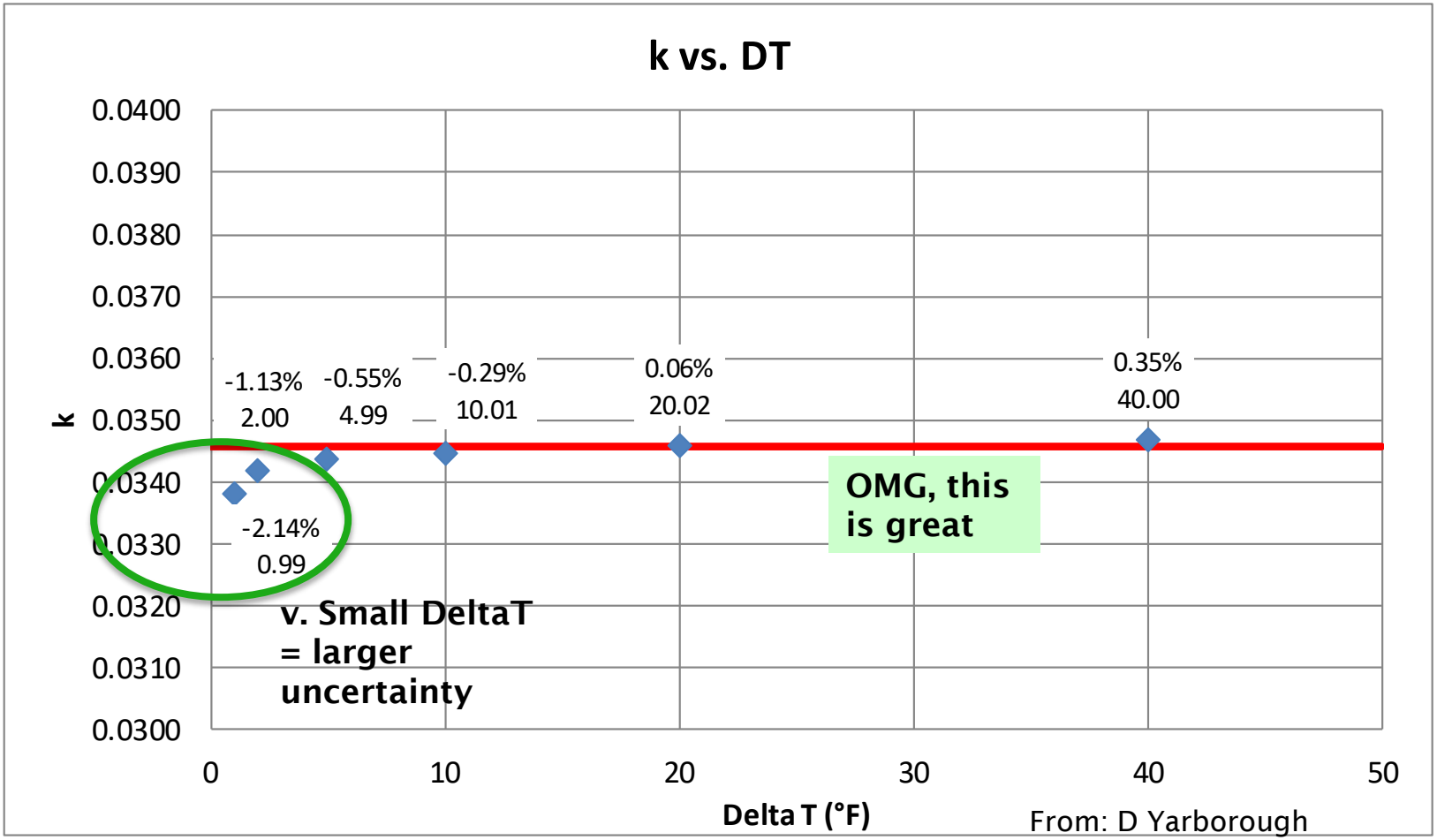
→ Perform a series of conductivity measurements at a given mean temperature, each with decreasing delta T

→ Practical issues

- → Use small sample thickness to maximize signal at low deltaT
- → Problem: Increasing uncertainty as delta T gets small and heat flow is small

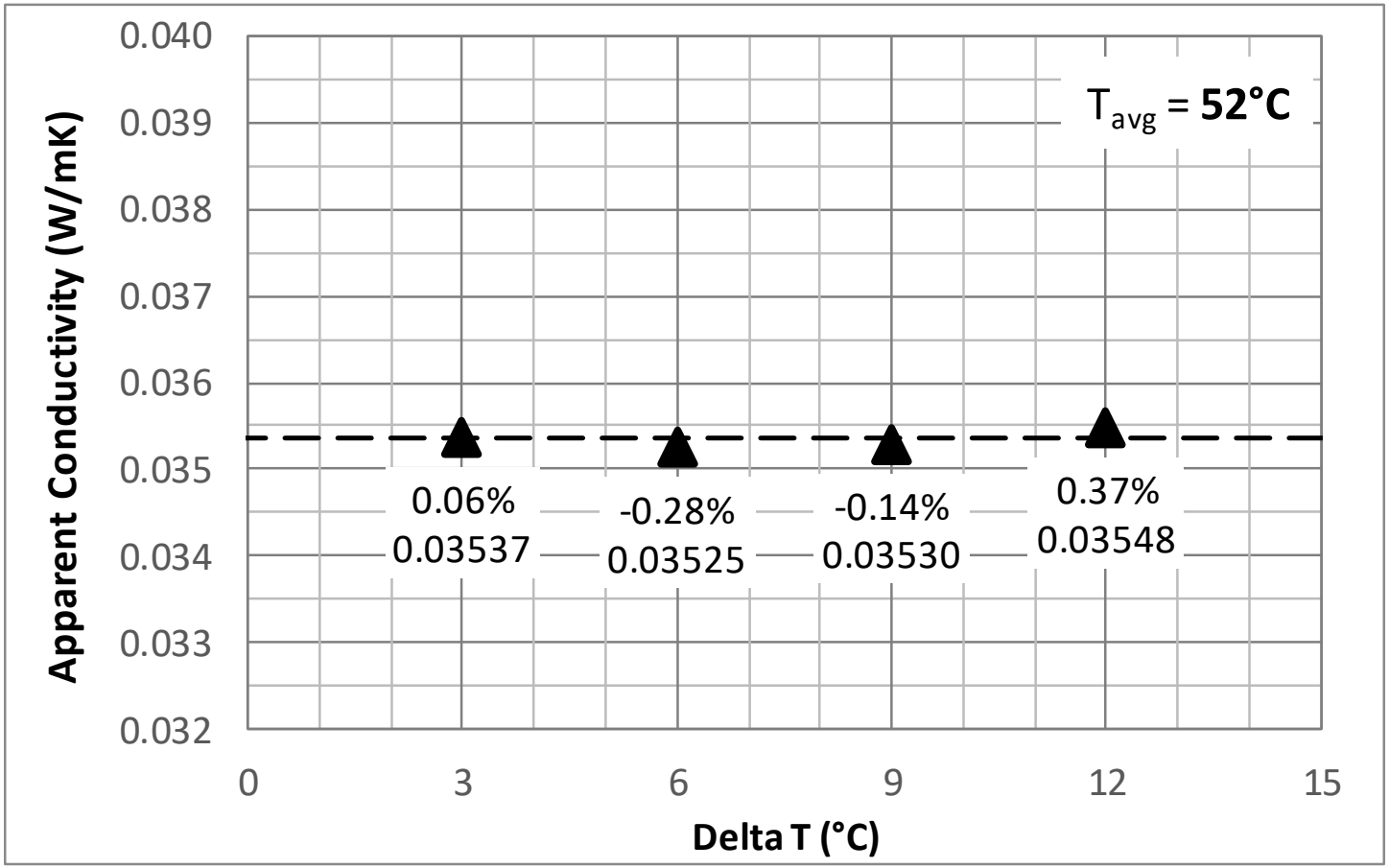
Check Measurements at Small Delta Ts

→ 1 in. thick EPS Calibration Standard



Applying Decreasing Delta T method to fiberglass

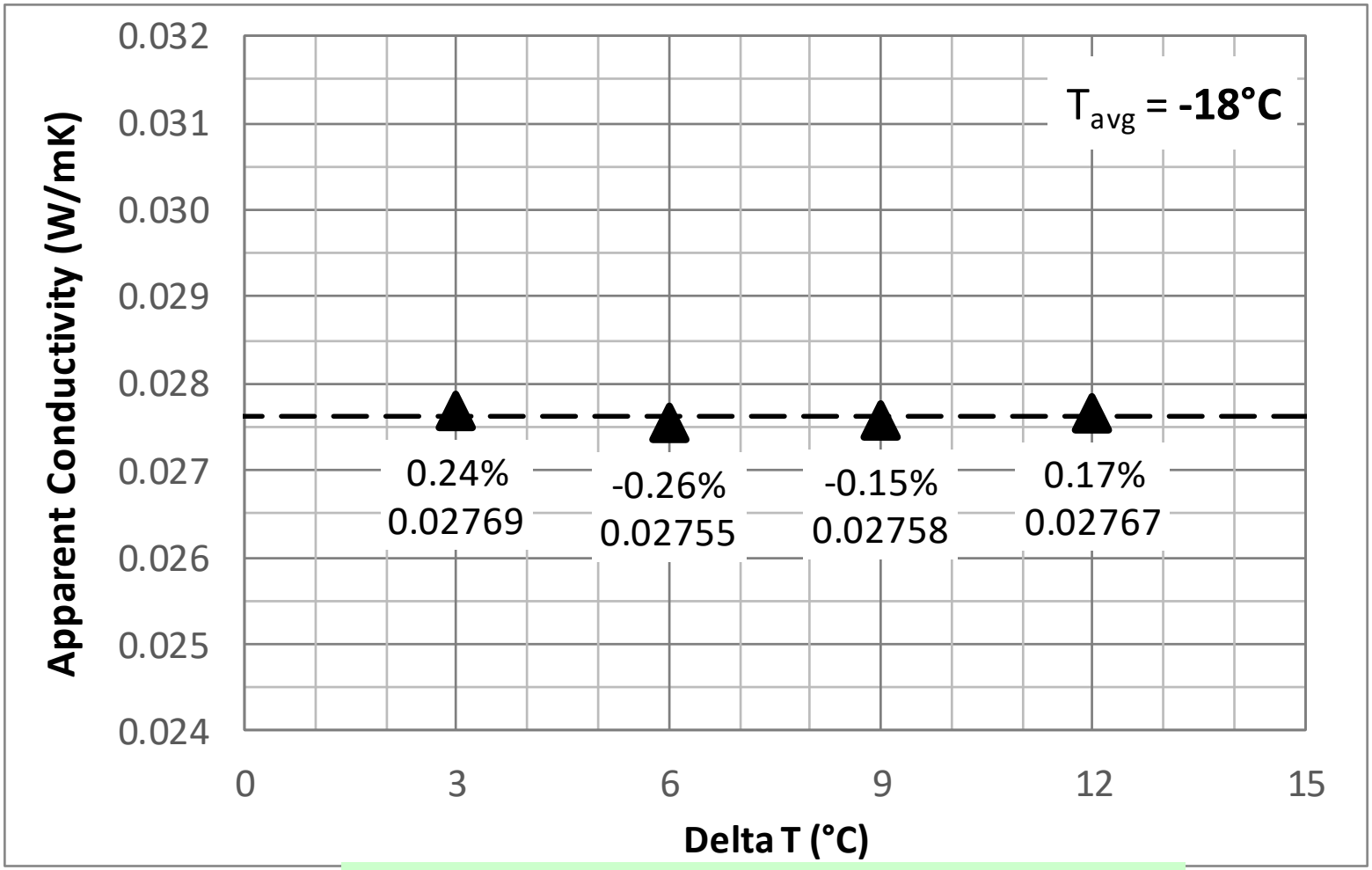
→ 2 in. thick semi-rigid fiberglass (duct board) at ~6 pcf



As expected, this method gives the same answer with decreasing Delta T

Decreasing Delta T : consistent results

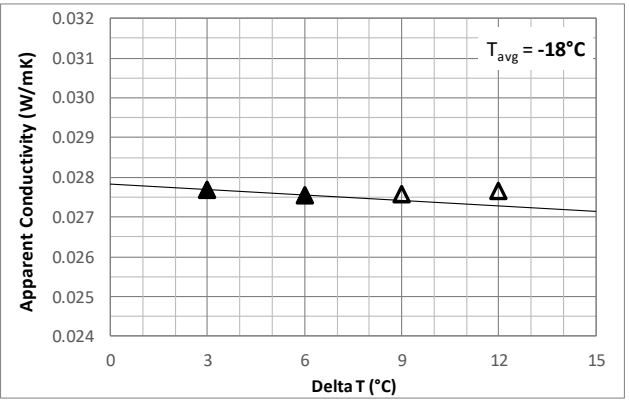
→ 2 in. thick semi-rigid fiberglass (duct board) at ~6 pcf



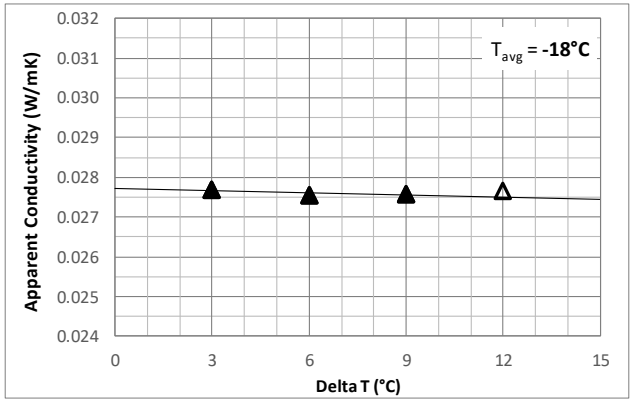
This equipment, and method, *works* for linear insulation response

Now, Estimate Conductivity as Delta T → 0

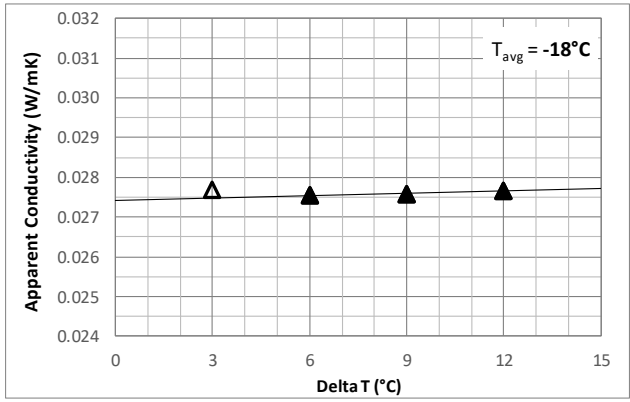
→ Final step of method: regression and extrapolation to zero Delta T



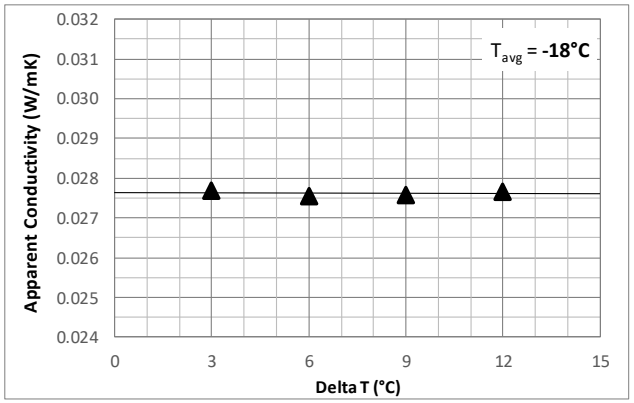
2 pt Linear



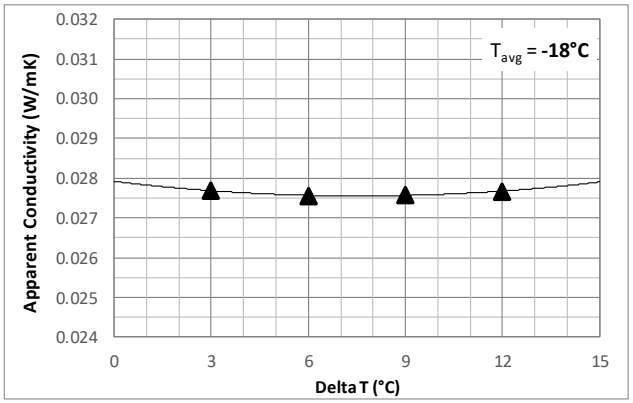
3 pt Linear (short)



3 pt Linear (Long)



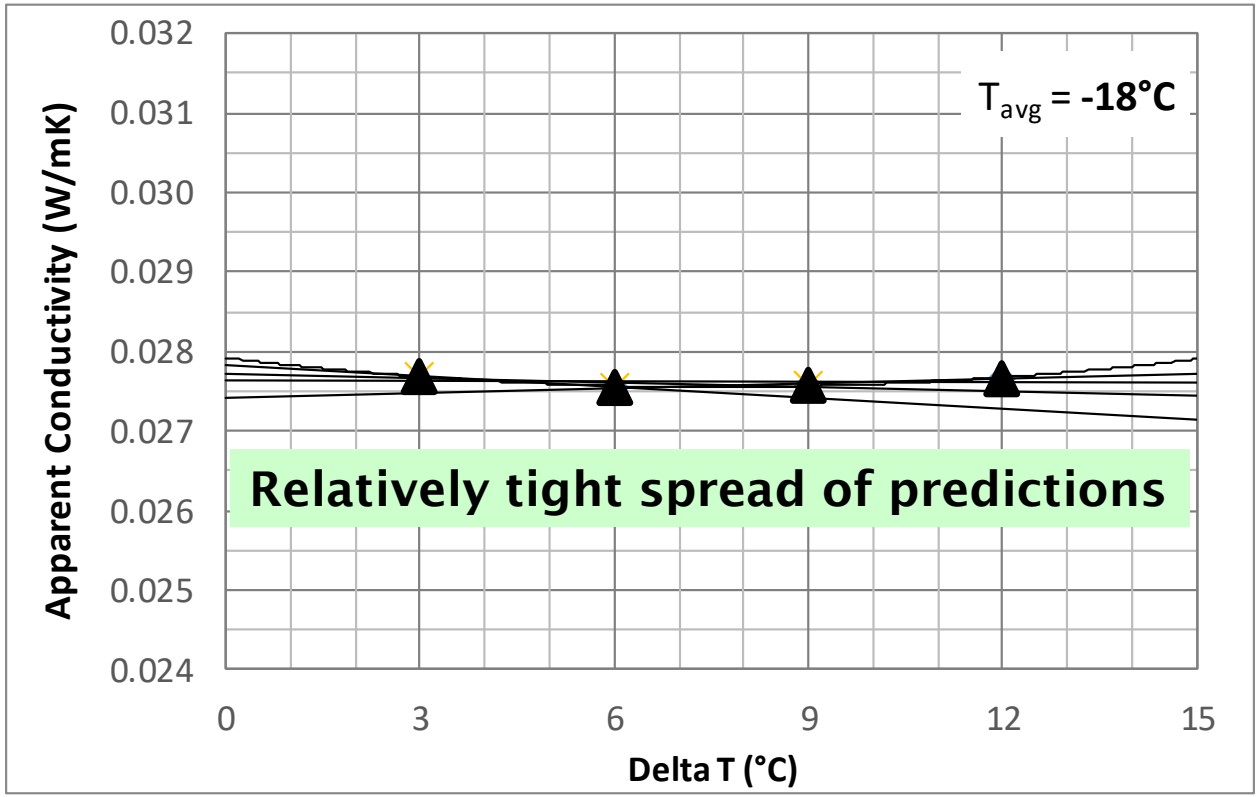
4 pt Linear



4 pt Quadratic

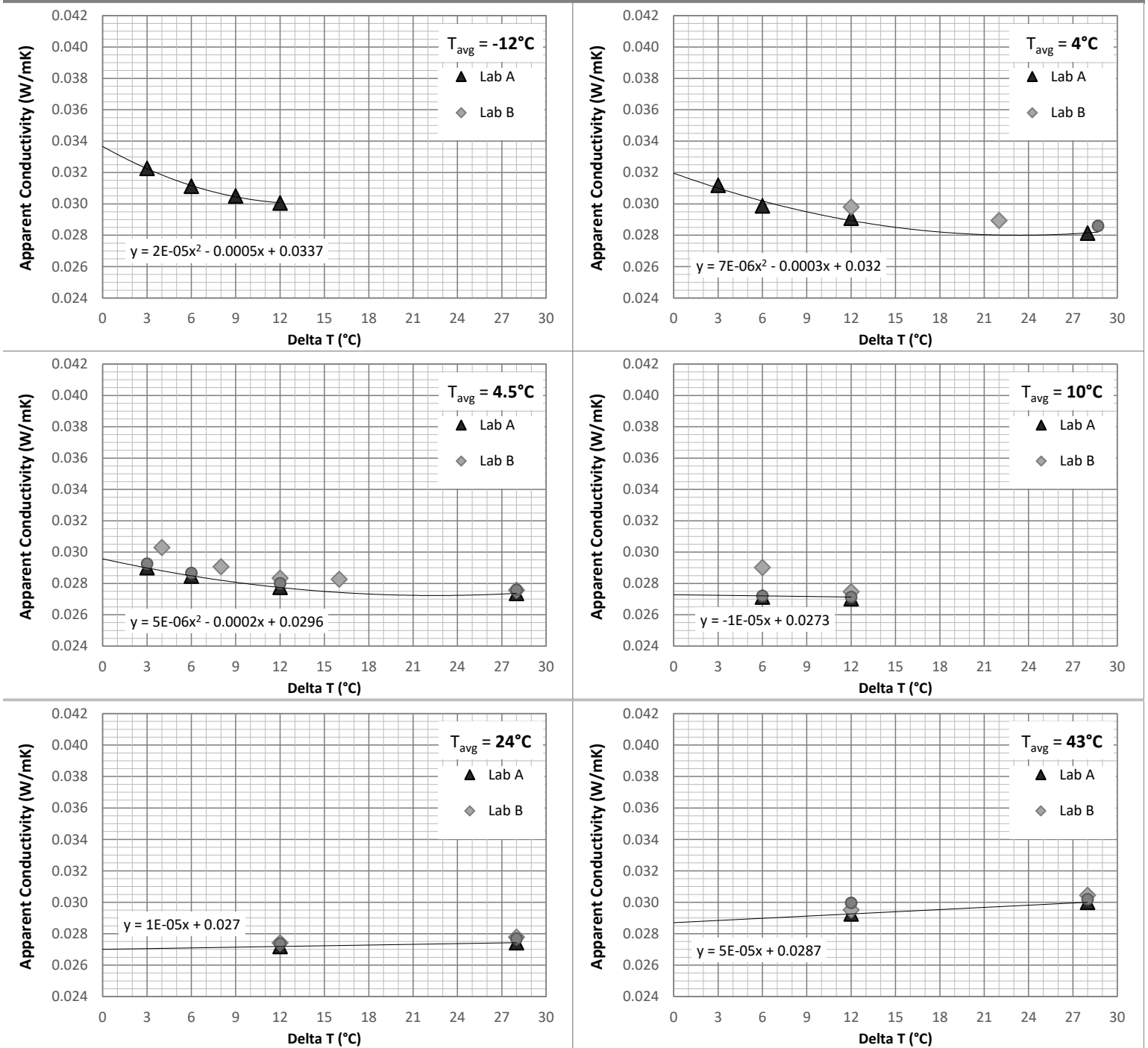
Estimate Conductivity as Delta T → 0
Prediction Intervals

		Prediction Interval @dT=0		% diff v Avg	
	k @ dT=0	Min	Max	Min	Max
Expected	0.02762	R-5.2/in			
2 pt Lin	0.02783	NA	NA	NA	NA
3 pt Lin Shrt	0.02772	0.02611	0.02933	-5.49	6.17
3 pt Lin Long	0.02742	0.02667	0.02817	-3.45	1.99
4 pt Lin	0.02763	0.02706	0.02820	-2.02	2.08
4 pt Quad	0.02792	0.02742	0.02841	-0.72	2.86



Applying the Decreasing Delta T Method to a Polyiso sample

Sample 2


T_{avg} = -12°C
Lab A
Lab B
y = 2E-05x² - 0.0005x + 0.0337
T_{avg} = 4°C
y = 7E-06x² - 0.0003x + 0.032
T_{avg} = 4.5°C
y = 5E-06x² - 0.0002x + 0.0296
T_{avg} = 10°C
y = -1E-05x + 0.0273
T_{avg} = 24°C
y = 1E-05x + 0.027
T_{avg} = 43°C
y = 5E-05x + 0.0287
Apparent Conductivity (W/mK)
Delta T (°C)
0.042
0.040
0.038
0.036
0.034
0.032
0.030
0.028
0.026
0.024
0 3 6 9 12 15 18 21 24 27 30

Compare results between methods

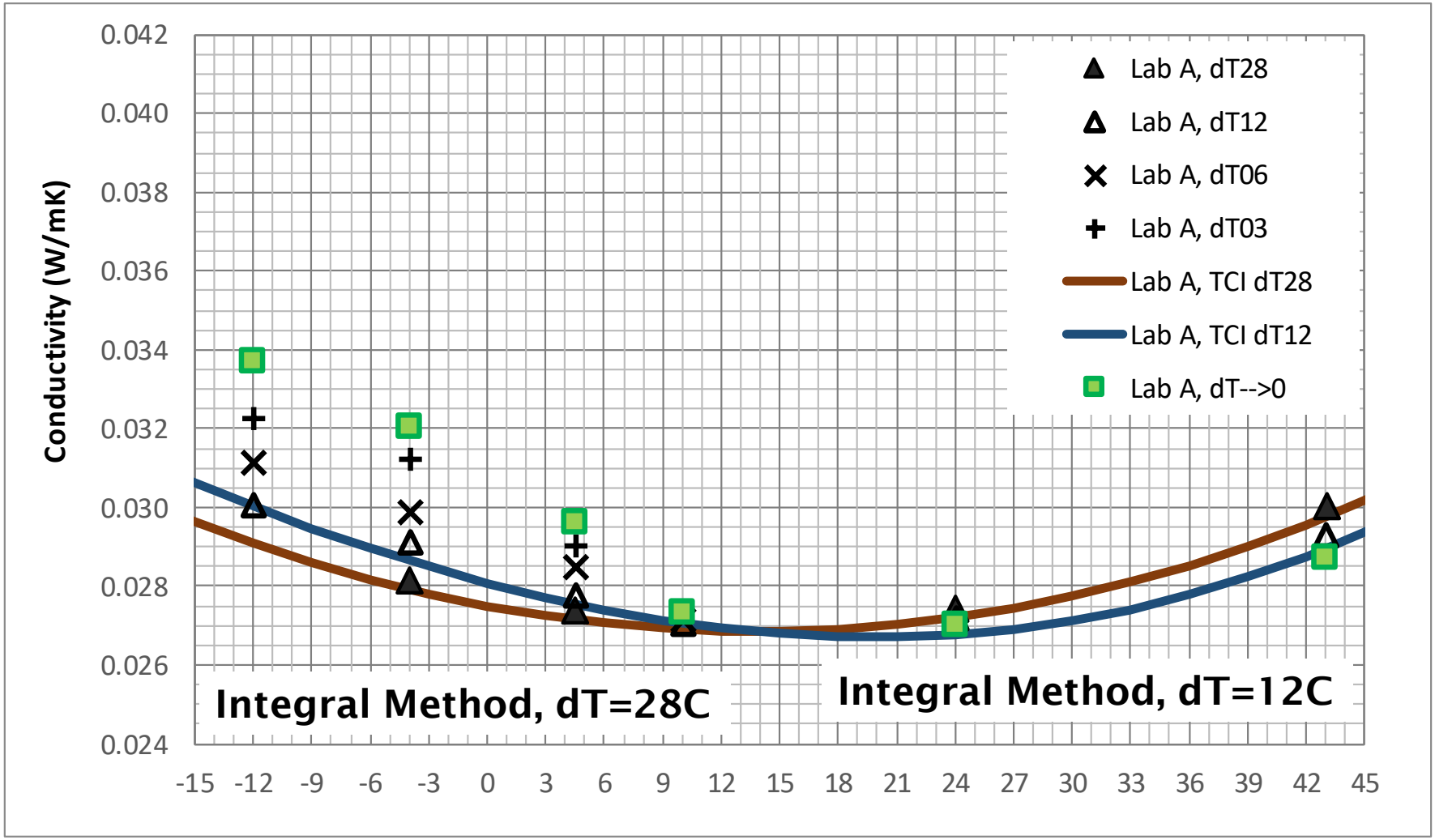
→Two methods give quite different results

→Warmer temps show better consistency

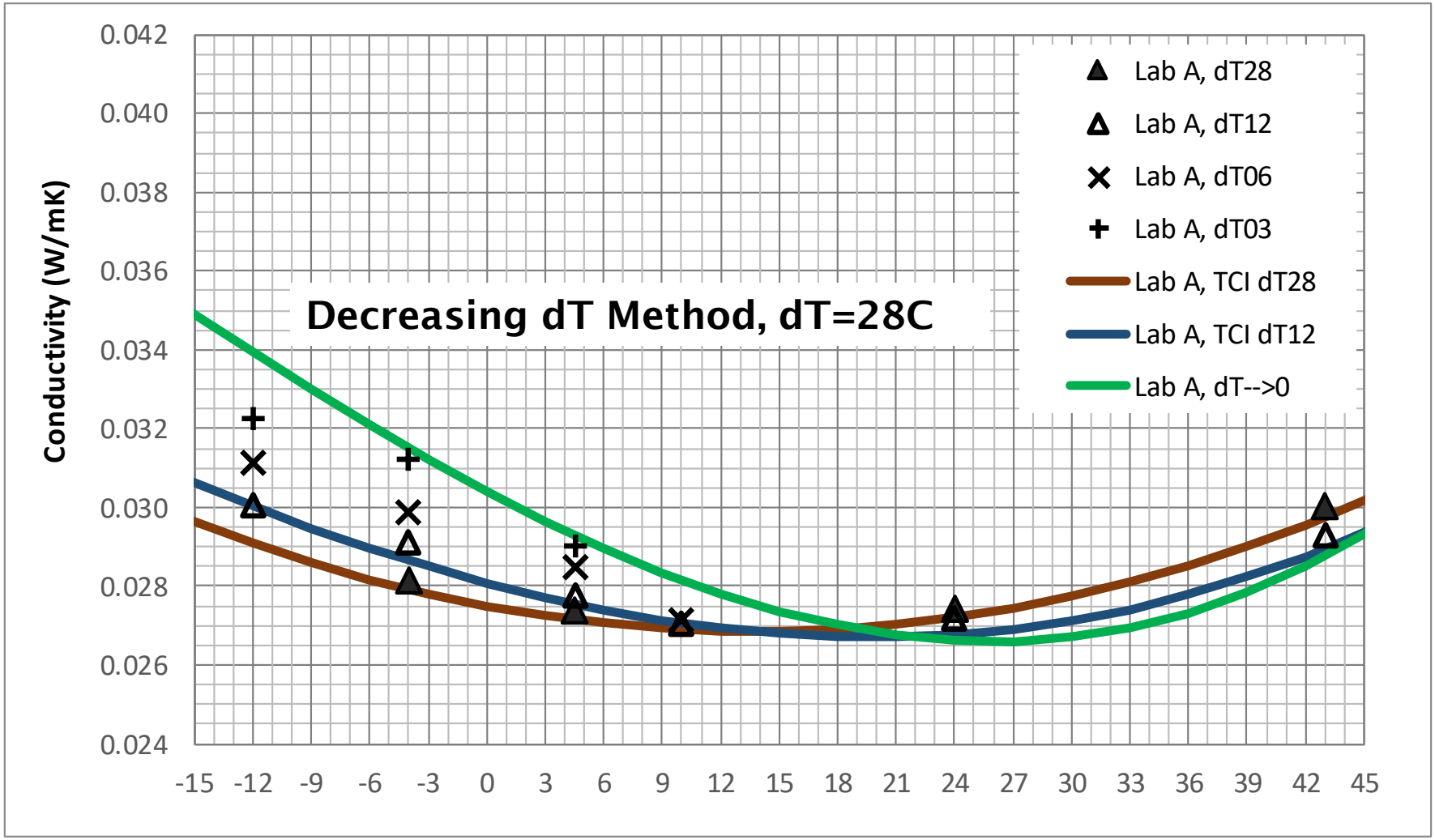
Tmean	k dT->0	k Integ	% Diff
-12	0.0337	0.02909	-15.9
-4	0.0320	0.02793	-14.6
4.5	0.0296	0.02715	-9.0
10	0.0273	0.02691	-1.5
24	0.0270	0.02721	0.8
43	0.0287	0.02977	3.6

→k(T), estimated from Decreasing Delta T Method, doesn't converge with k(T) from the Integral Method

k(T) estimated using both methods



k(T) estimated from Decreasing Delta T



1. **Integral method, gives different answers for different dT's**
2. **The two methods give different answers**

What does it all mean? "Conclusions"

→ Insulation exhibits temperature effects

- → These are in the order of 10% of heat flow
- → ASTM standard in place to manage this

→ Polyiso (and some other products) show **non-linear** effects

- → Heat flow can be 10-25% higher at cold temperatures
- → R-6/inch is not a reliable design value (R-5? R5.5?)

→ Two methods: integral and decreasing DeltaT are both supported by ASTM and history

- → But neither is able to accurately predict low-temperature polyiso performance
- → Difficult to understand why!

→ More research needed in this area

Discussion + Questions

FOR FURTHER INFORMATION PLEASE VISIT

→ www.rdh.com

→ www.buildingsciencelabs.com

OR CONTACT US AT

→ cschumacher@rdh.com

Bogdan et. al., 2005

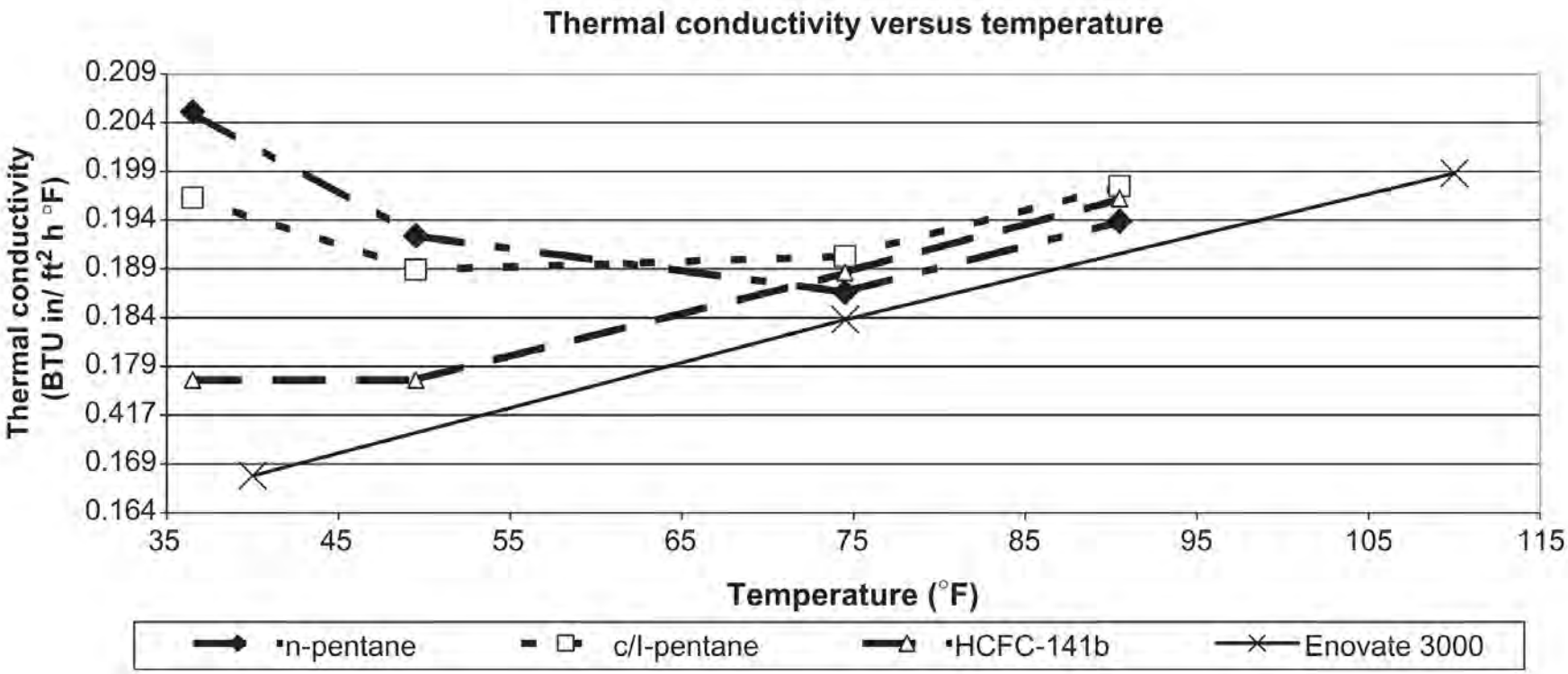


Figure 6. Thermal conductivity vs temperature at 100 days – 1.5 in. core samples.

Zipfel et. al., 1999

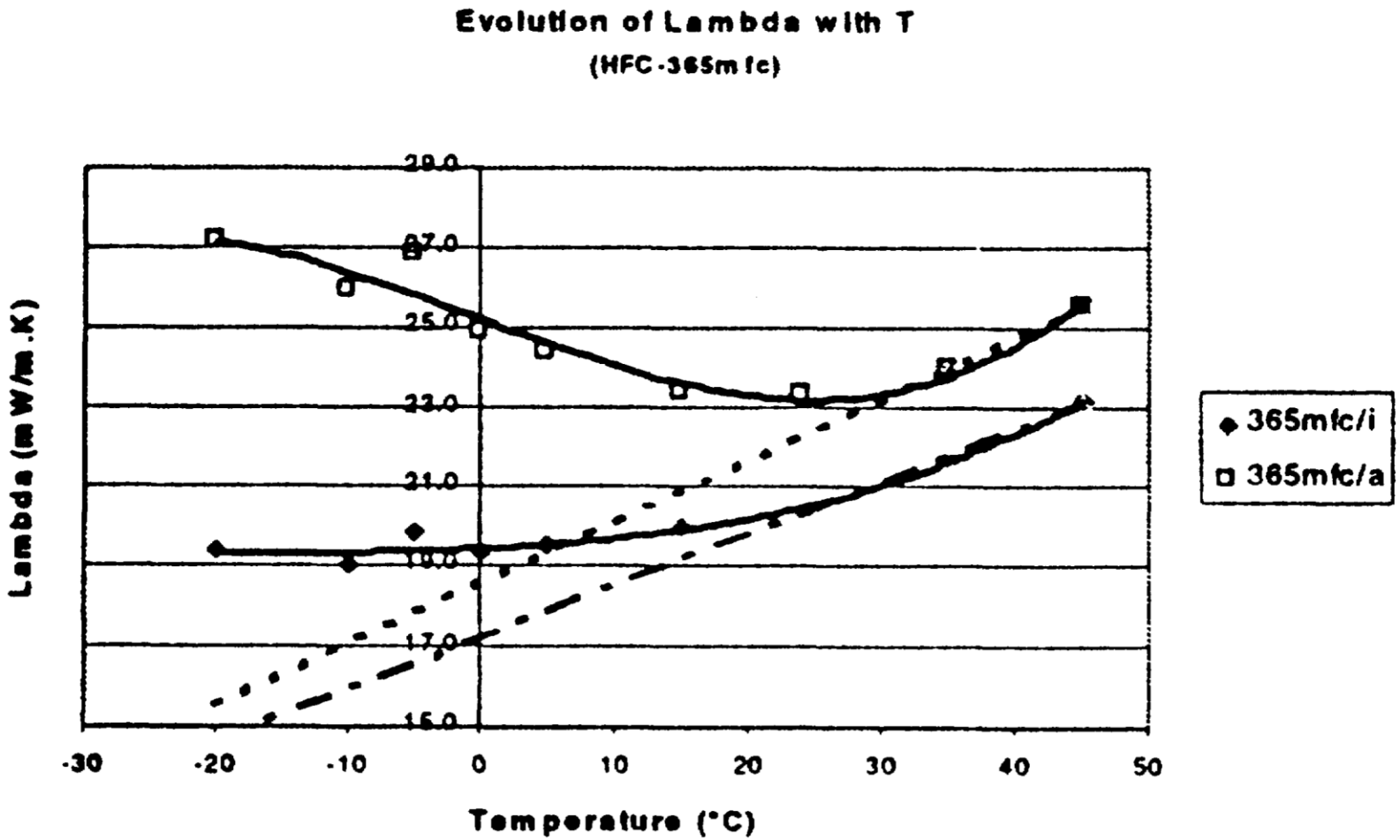
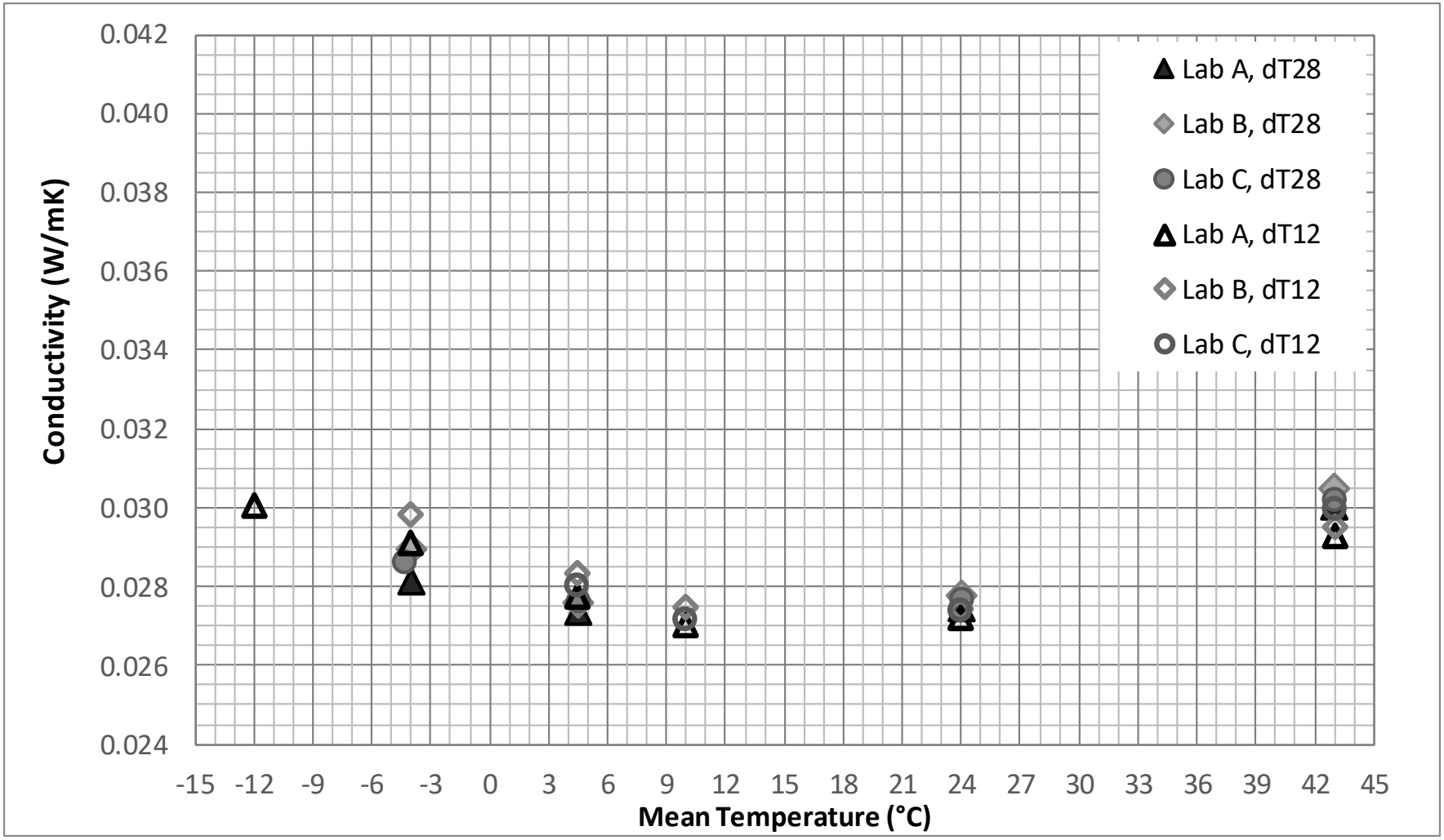


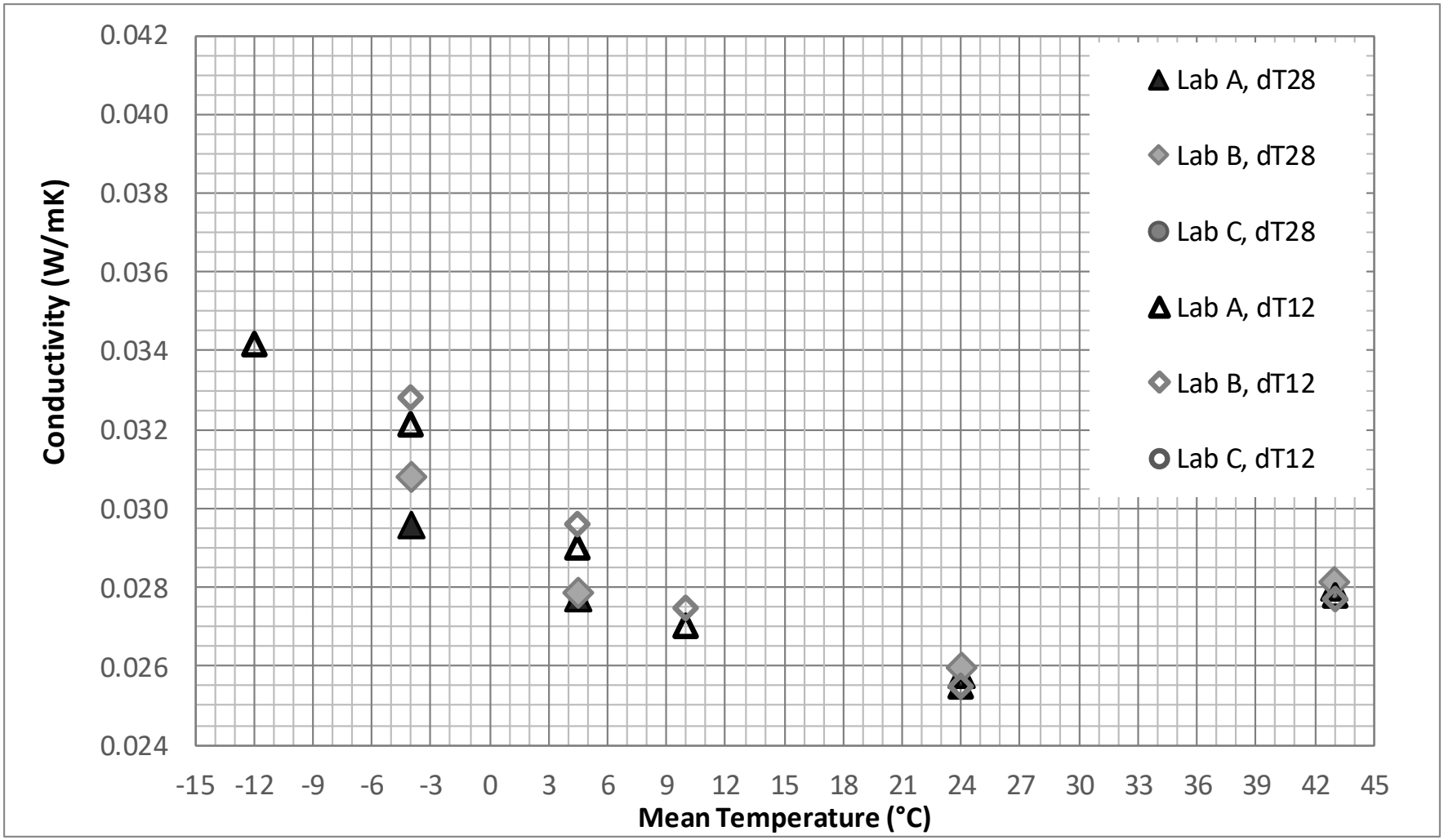
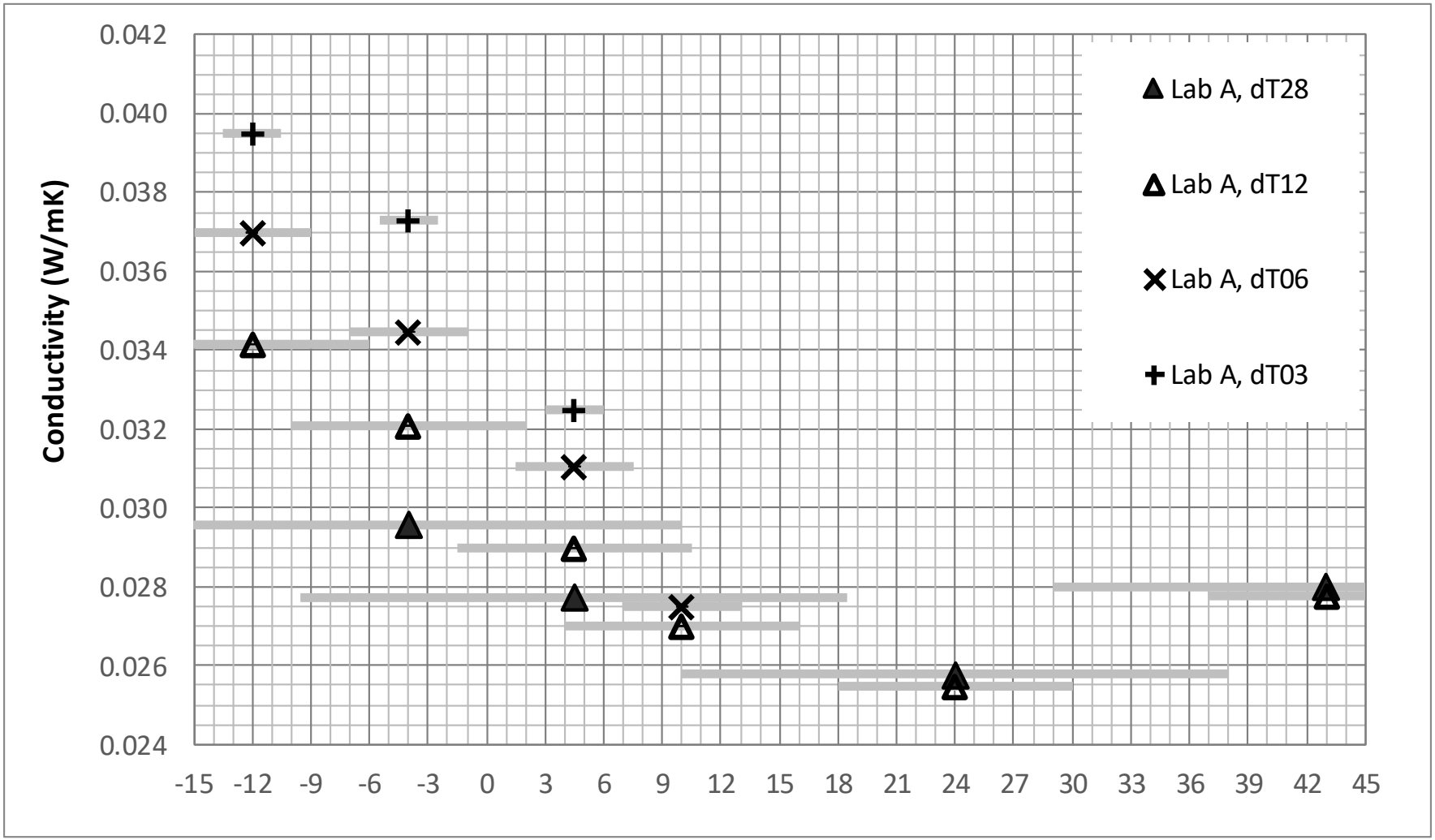
Figure 1. Evolution of the λ value of a HFC-365mfc blown foam before and after aging (1 week at 70°C). Formulation contains 1 pbw of water.

What about Sample 1?

Recall Sample 2 Results, dT = 28˚C and 12˚C



Sample 1 Results, dT = 28˚C and 12˚C



Sample 1 Results, dT = 28˚C and 12˚C