

# Thermoforming: Art, Science or Both?

**SPE ' 2018 THERMOFORMING  
CONFERENCE,  
Fort Worth, TX, USA**

Amit Dharia  
Transmit Technology Group, LLC  
Irving, TX 75063



# Background

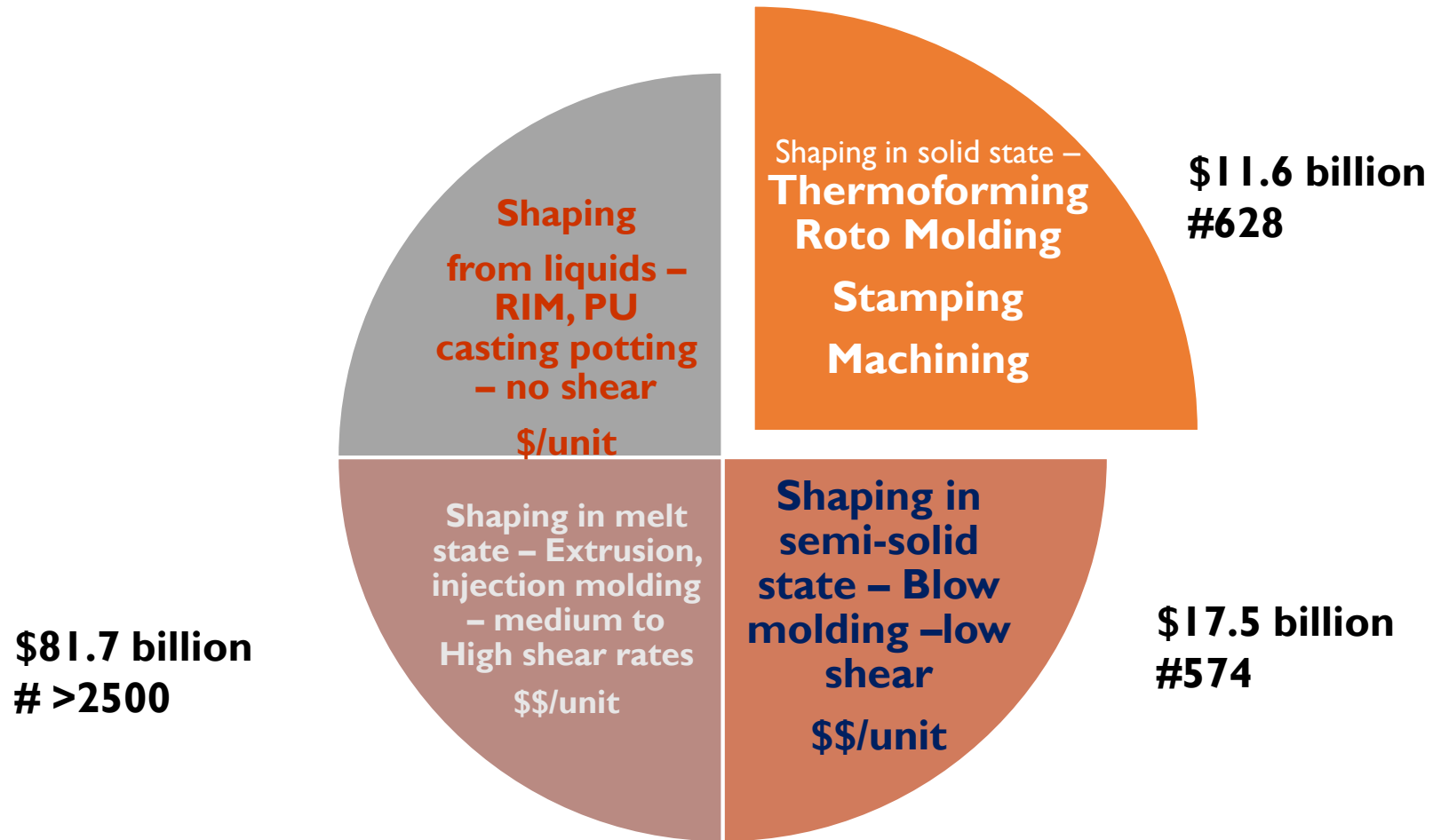
## **How did I get interested in Thermoforming?**

How solid ( $>T_g$ ,  $<T_m$ ) plastics respond to large scale deformation at very high strain rates? What method do we use to capture this response?

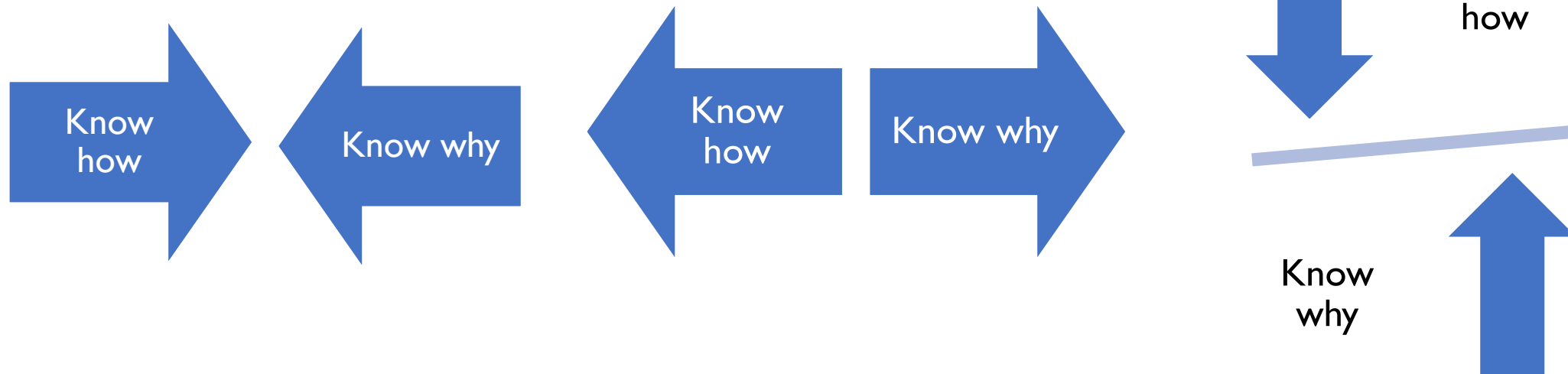
## **Role of Scientific approaches in TF industry.**

QM are not used as widely in TF industry as in IM and Extrusion. Why?

# Plastics Processing Methods



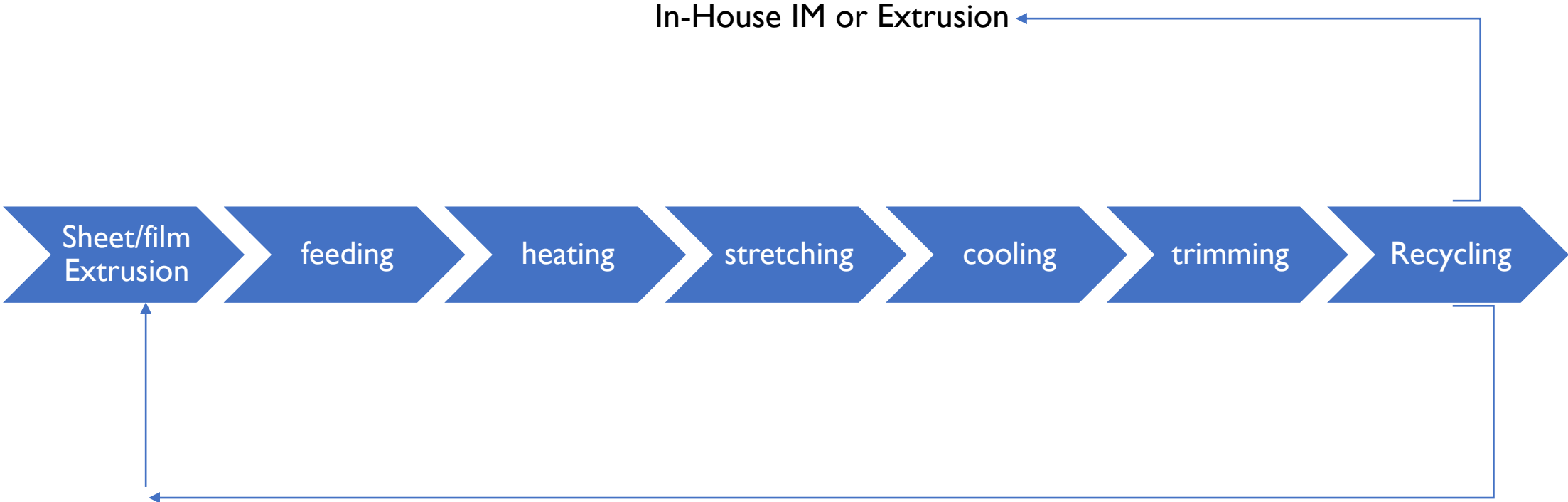
# The Industry Status



# Objectives

- **Outline various unknowns and their significance in TF process.**
- **Demonstrate use of “Technoform” in evaluating thermoformability using small samples and controlled conditions.**
- **Compare various analytical and computational tools**
- **Highlight need and benefits of quantitative measurements in TF.**

# What is Thermoforming?



# What makes Thermoforming different?

- Secondary process starting with an extruded sheet or film.
- Involves solid phase non-linear time dependent viscoelastic deformation
- Large scale deformation at 80-300 mm/s speed –high strain rates)
- Free surface flow –difficult to define boundary conditions
- Very low pressure and stress (80 to 100 psi)
- Partially or fully reversible deformation
- Inherent bi-axial orientation .
- Non-isothermal heat transfer and at slow rates.
- Significant interaction between tool surface and sheet
- Variable wall thickness and only one side is finished.

# Thermoforming

**Thermoforming seems simple but it is not. There are too many unknowns.**

- **What we know** – Sheet thickness, thickness variation, material type, MFR, color, mechanical properties
- **What we do not know** – Composition, composition variation, extrusion history, E-T relationship at various strain rates, Melt strength and melt elasticity, Sag rate, Heating and cooling rates, Forming temp range, % regrind, % moisture or volatiles, type of CC, amount of CC, % orientation, % crystallinity, % crystallinity as function of orientation, friction between surface and tool, shrinkage, and recovery.

# Major Issues with Sheet

- How is it made? Extruded, Cast, or Calendered ?
- Single layer or multi-layer? Same of different materials?
- Composition variations not known to processor-
  - Material mix-ups, change in resin, additives, CC, % regrind, quality of regrind, change in filler particle , moisture, change in gloss, grain
- Sheet overall and individual layer thickness and variation form edge to center
- Different heat history of edges vs. center, top vs. bottom of roll
- Lot to lot variation in frozen in stresses and orientation

**QUESTION – Does mfg.TDS answer any of this? What is the cost of not knowing this?**

# Pre-Heating and Heating - I

## Why heat?

- Lower temperature leads to
  - Higher the stress required to deform, **TOOL COST**
  - Lower temperature – necking
  - Large deformation in solid state (at lower Temp and high speed) induce higher orientation
  - Poor part shape definition and retention

## Methods of heating

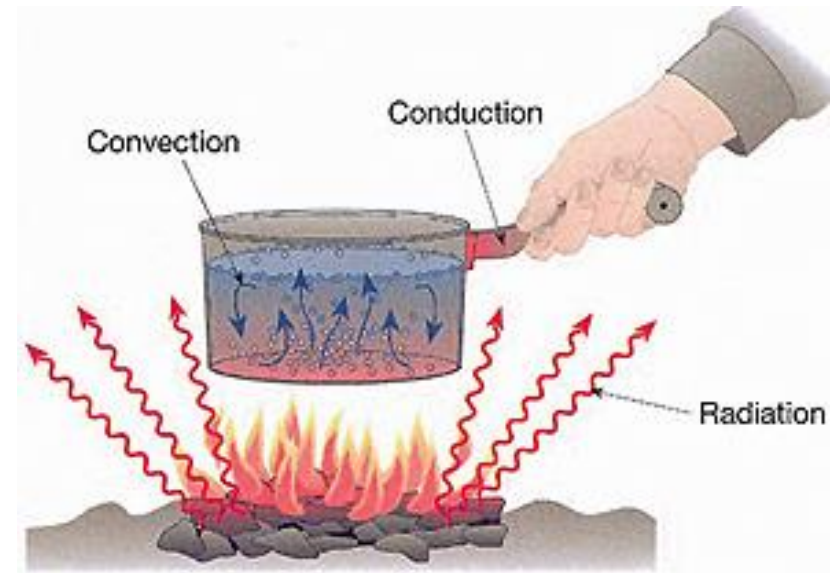
- Radiation >80%
- Convection – Heavy gauge
- Conduction – foils and films
  
- Goal – Uniform temperature distribution

# What we do not know about heating?

- What “forming temperature” to use?
- How long will it take to heat?
- What method of heating to use?
- When to heat at faster rate and when to heat at the slower rate?
- What is the temperature gradient between surface and core?
- Would sample heat fast enough to avoid scorching of surface?
- What is ‘actual’ surface temperature?
- Sag rate during heating

# Basic Heat Transfer

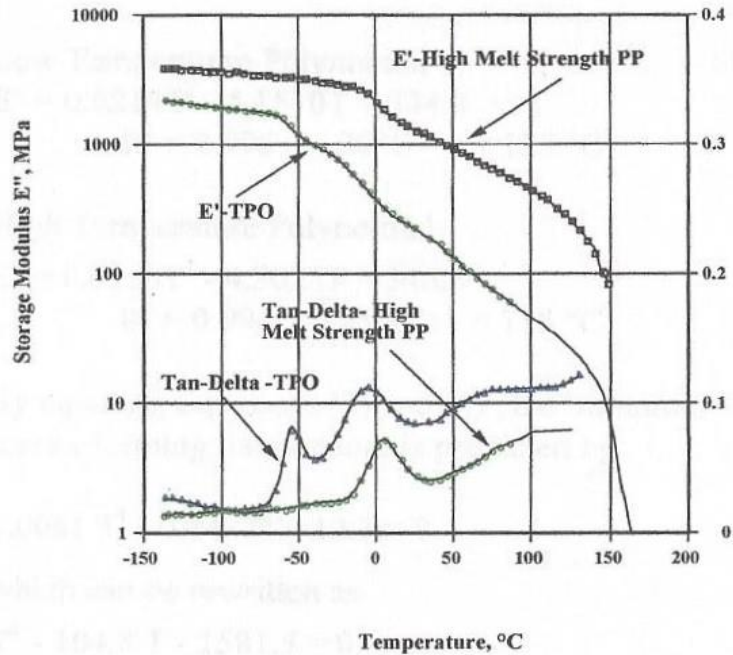
- Heat  $Q = m \cdot C_p \cdot \Delta T$
- Radiation  $Q_R = \epsilon (T_1^4 - T_2^4)$
- Convection  $Q_h = h_a \Delta T$
- Conduction  $Q_c = k \Delta T / dX$



- **Time to heat =  $A \cdot \text{Thickness} \cdot \text{Rho} \cdot C_p \cdot \Delta T / \epsilon \cdot \text{Wattage}$**
- Crystalline material will take lot longer to heat but will initially heat at faster rate. HDPE 2X to ABS
- Metalized Mylar foil (low  $\epsilon$ ) will read much lower temperature than Mylar..

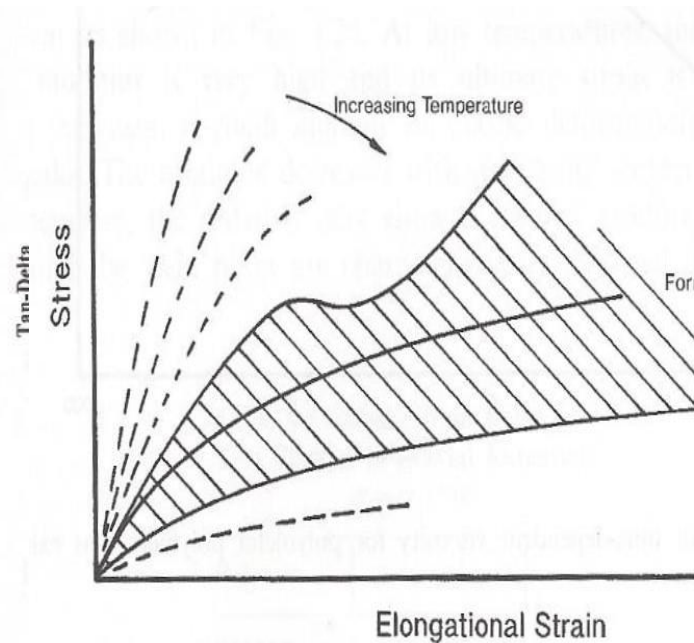
# What is the Right Temperature Range?

## DMTA

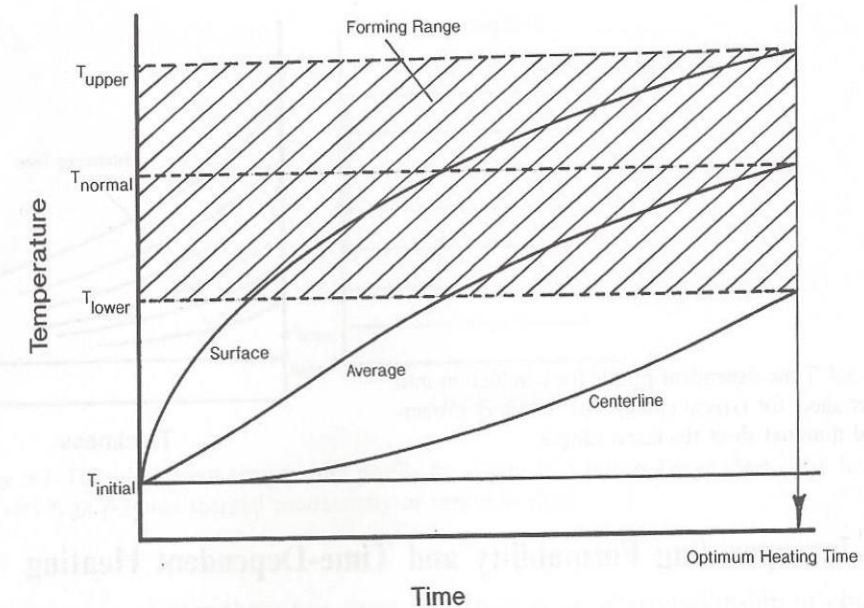


Thomas C. Yu, ANTEC

## Thermoforming Temperature Window



Technology of Thermoforming, Hanser, J.L. Throne



# What Will Affect Heating Rate?

## Material

Material

Radio opacity

Thickness

Density, Specific heat, conductivity, diffusivity, emissivity

Crystallinity

Inorganic fillers

Gloss

Color

Sag rate

## Process

Heater Power (Watts )

Heater temperature

Heater efficiency

View factor

Distance from heaters

Ambient air temperature and flow rate

# What happens during heating?

- Absorption of heat at the surface (fast)
- Conduction of heat to core \*\* Jim's new model\*\*
- Thermal Expansion – Bulging
- First Sag – Weight / Gravity
- Touting
- “Swimming”
- Sag due to loss of hot strength
- Scorching of surface
- Dripping and burning

# What Temperature are we Measuring, Monitoring and Controlling?

- $T_{\text{heater}} = 2897 \text{ K} / \lambda$  (Wien's law)
- Different polymers absorb heat at different frequencies (C-H in  $3.5 \mu\text{M}$  and N-H in  $6 \mu\text{M}$ ).
- Most IR pyrometer are spectral and emits radiation at  $3.5 \mu\text{M}$ .
- Both IR probe and sheet receives radiation reflected from oven surfaces. Measured values can be much higher than actual and should be corrected.
- $T_{\text{actual}} = [(T_i^4 - (T_0^4 - T_a^4))]^{0.25}$
- At what depth we are measuring ?  
Temperature varies across thickness.  
Absorption varies with thickness.

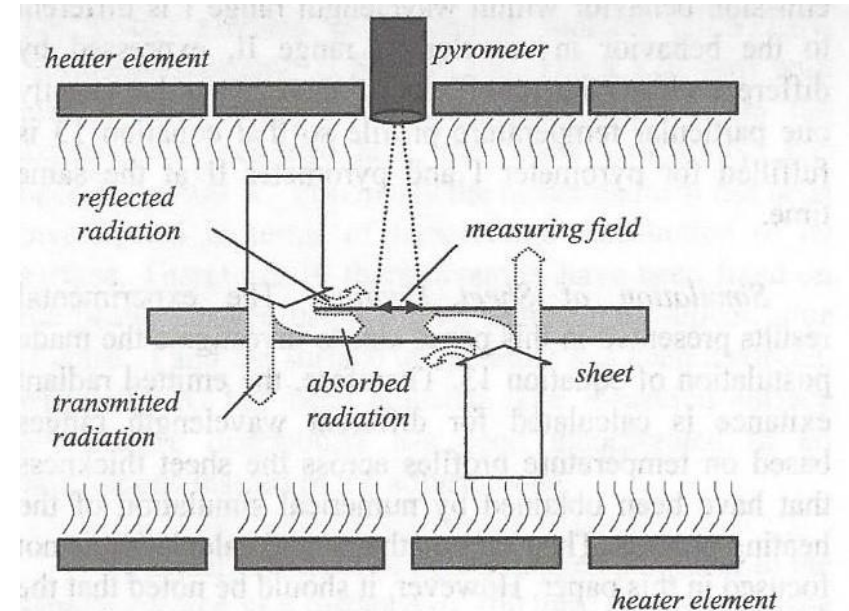
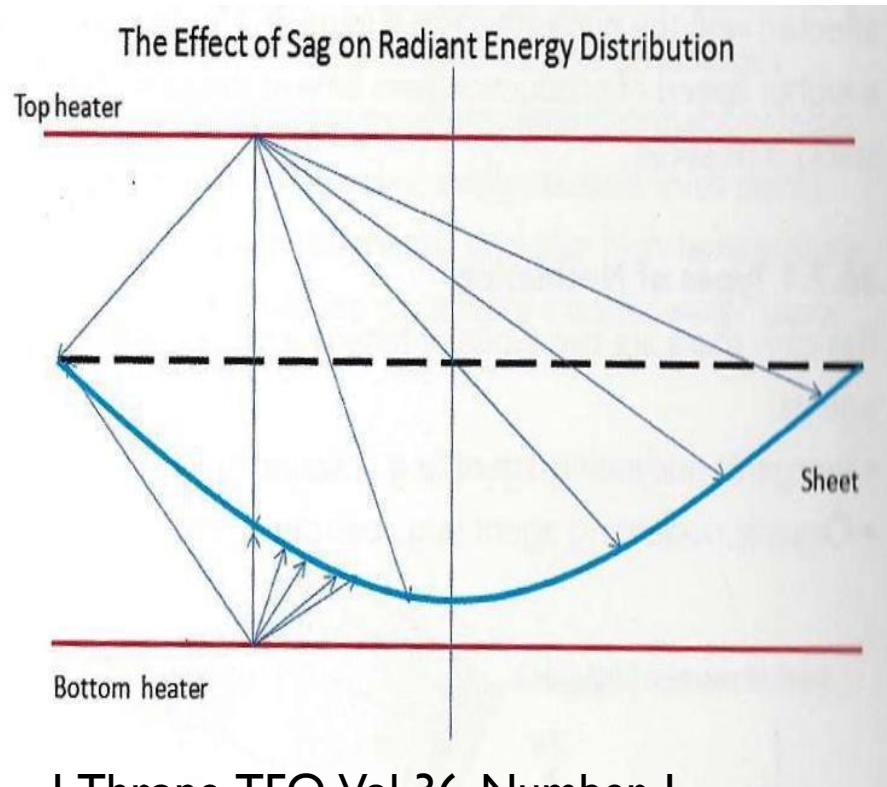


Figure 3. Contents of radiation in measuring the sheet temperature during heating.

Model based Temp. measurements for TF applications

# Effect of Sheet Sag on Measured Temperatures

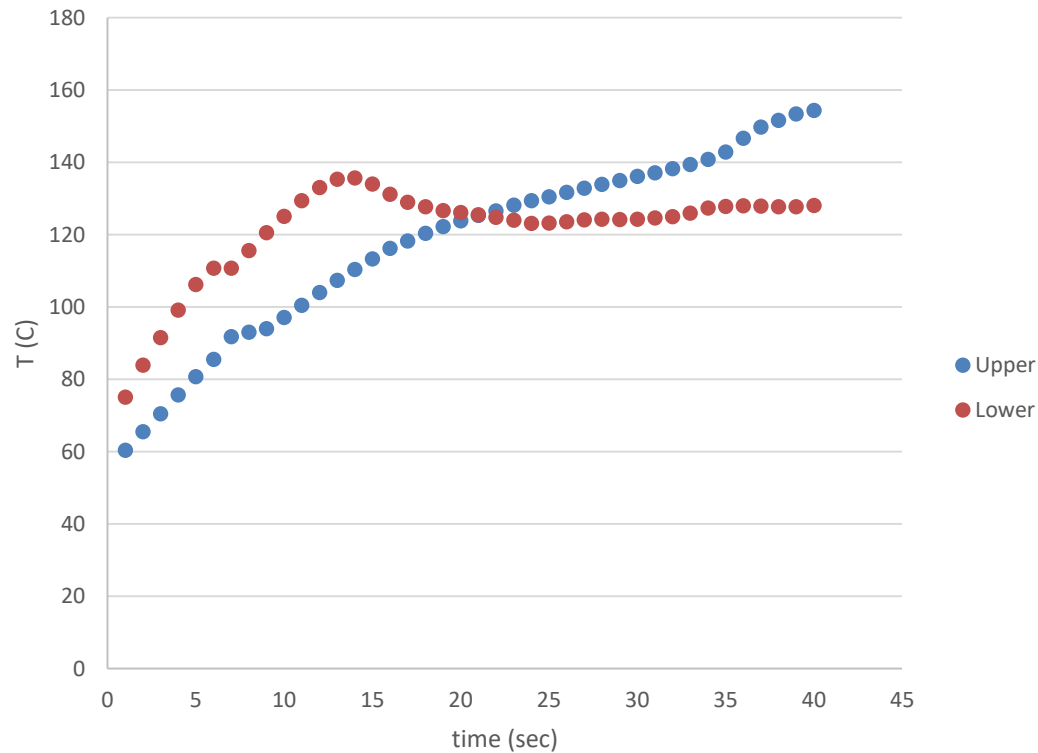


J. Throne, TFQ, Vol 36, Number 1

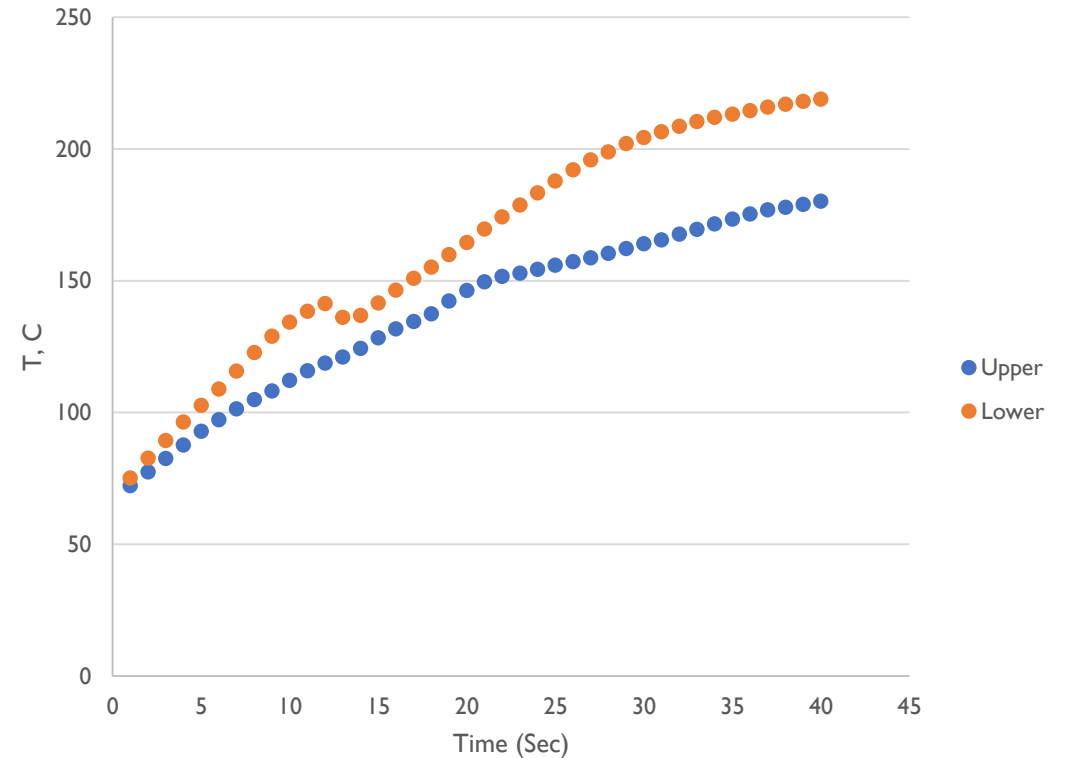
- As sheet sags, the lower surface gets more energy and upper surface get less energy.
- The lower surface temperature will be higher than the upper surface temperature.
- Overall energy input is not affected.
- Analytical solution either not available or do not account for increase in surface area due to sag.

# Lower and Upper Surface Temperatures (25 -30 mil thin sheets)

Surface Temp. Vs. Time  
GPPS



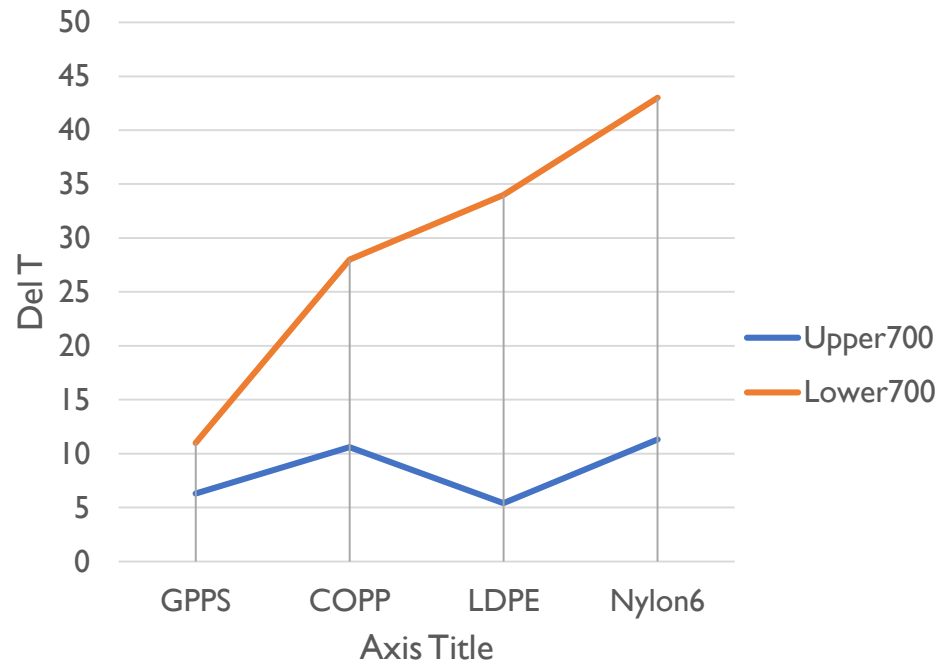
Surface Temperature vs time.  
Filled Brown COPP



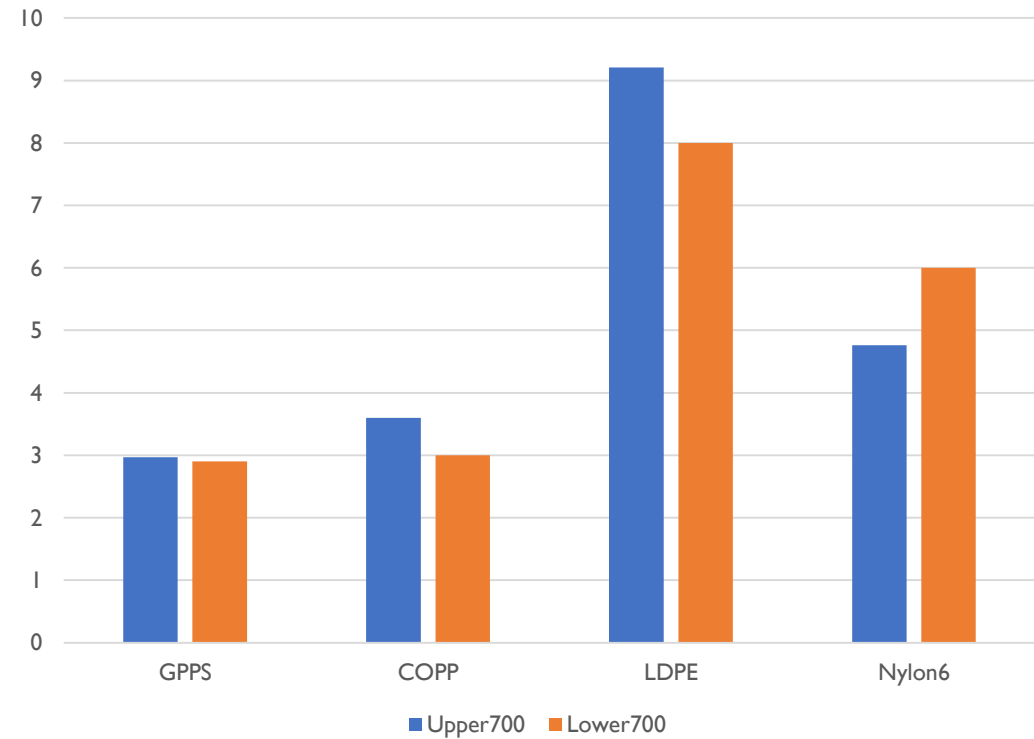
1000 watt/mt2 heaters at 650 C placed at 100 mm from each surface

# Surface temperature difference (Heater at 700 C)

## Surface Temperature difference



## Sag

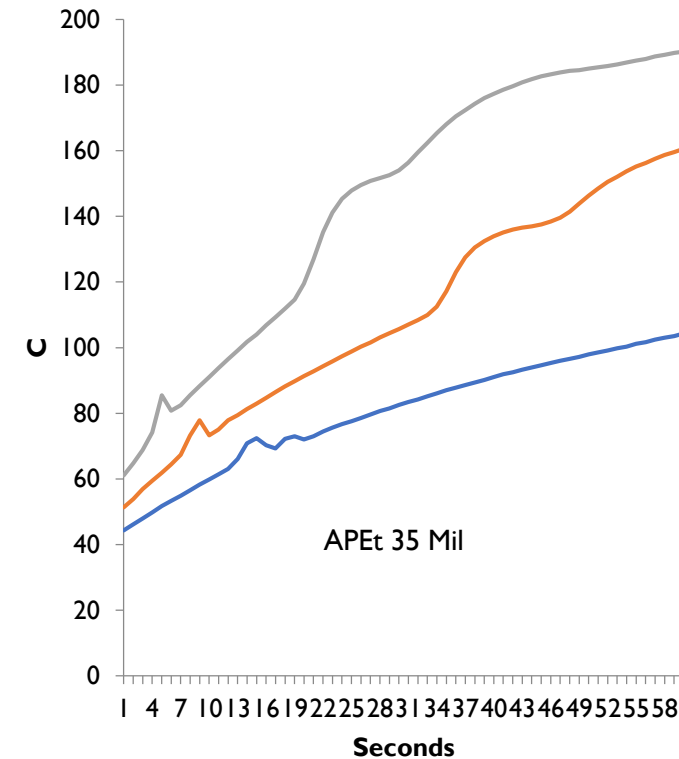
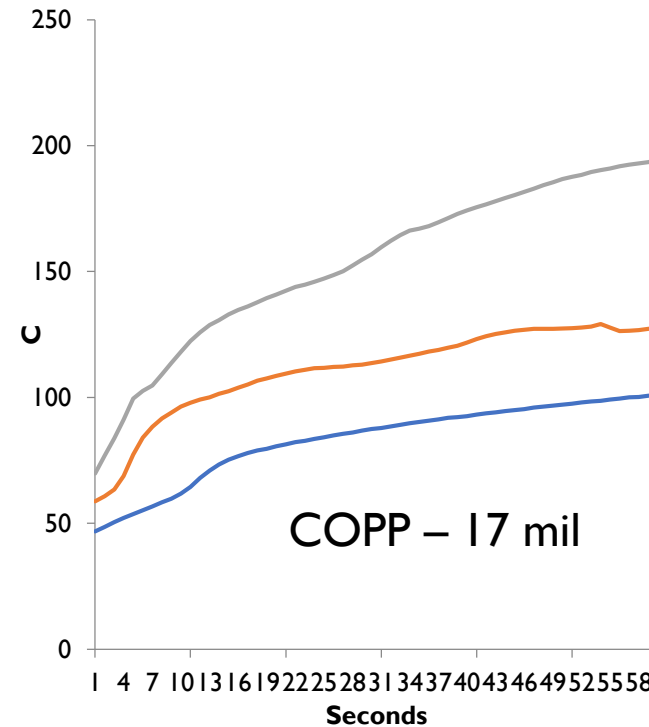
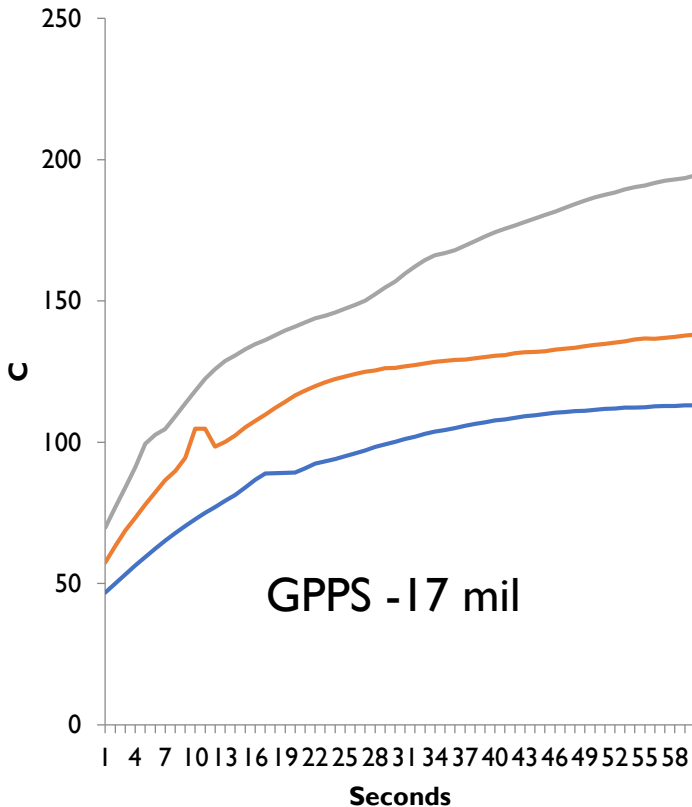


# Effect of Heater Temperatures

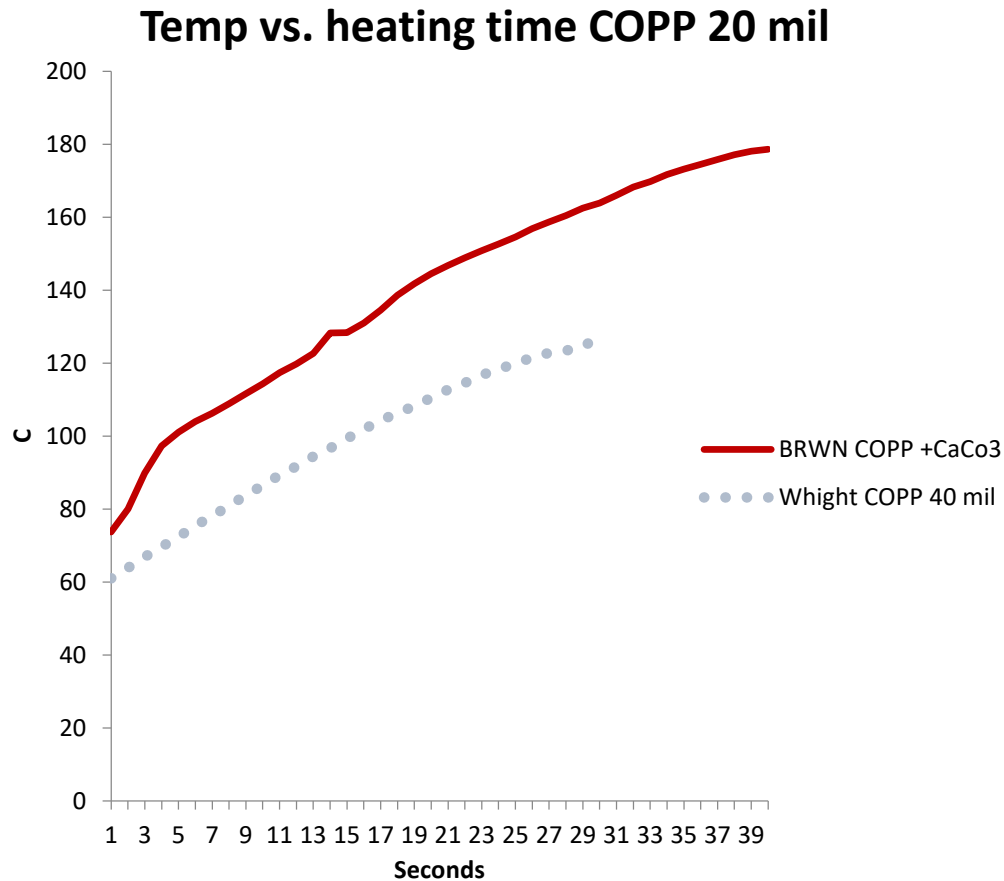
	450 C	550	650
C/sec	3.5	5	7

C	450	550	650
C/sec	2	4.6	6.83

C	450	550	650	
C/sec	2	3	6	



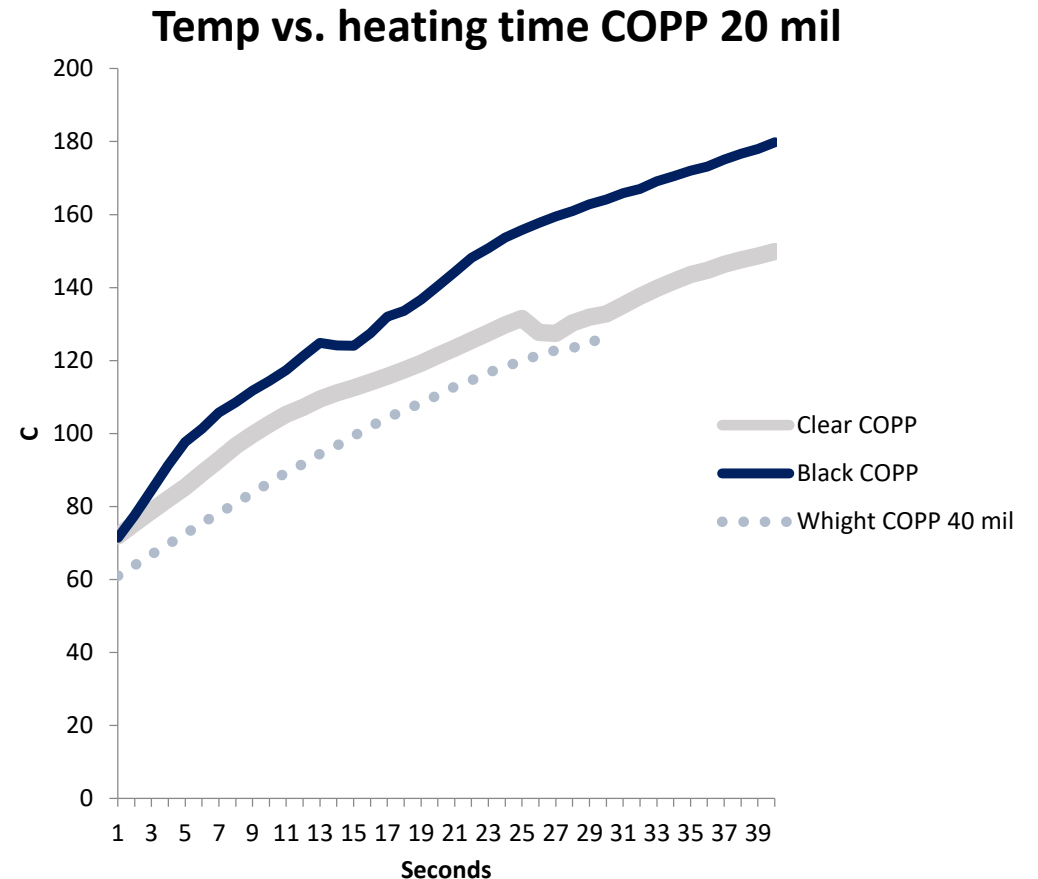
# Effect of Filler on Heating Rate



- $Q = \rho C_p \Delta T$
- The energy required to heat filled plastics is higher due to higher Sp. Gravity.
- $P$ ,  $C_p$  and  $k$  all increase with % Volume fraction.
- Surface heating rate increases with % filler.
- The overall temperature is lower than the surface temperature due to rapid conduction.

# Effect of Color on Heating Rate

- In visible range(0.38-0.71  $\mu\text{m}$ , color does not affect heat transfer.
- Inorganic pigments blocks visible light and increase IR absorptivity.
- Heat is not emitted or absorbed at one wavelength but at many frequencies.
- In Infrared range, inorganic pigments changes thermal properties.



# Multi-layer film heating

	PE	Nylon	Nylon Top	PE Top	N-P-N	P-N-P
					77	84
PE	95 C	115	101 C	96		
	128 C	158	161 C	160.1	151	146
PA						
90 Sec						
	650 C	650 C	650 C	650 C	650 C	650 C
Sag	8.5 mm	5.9	10.2	5.5	5.4	7.3

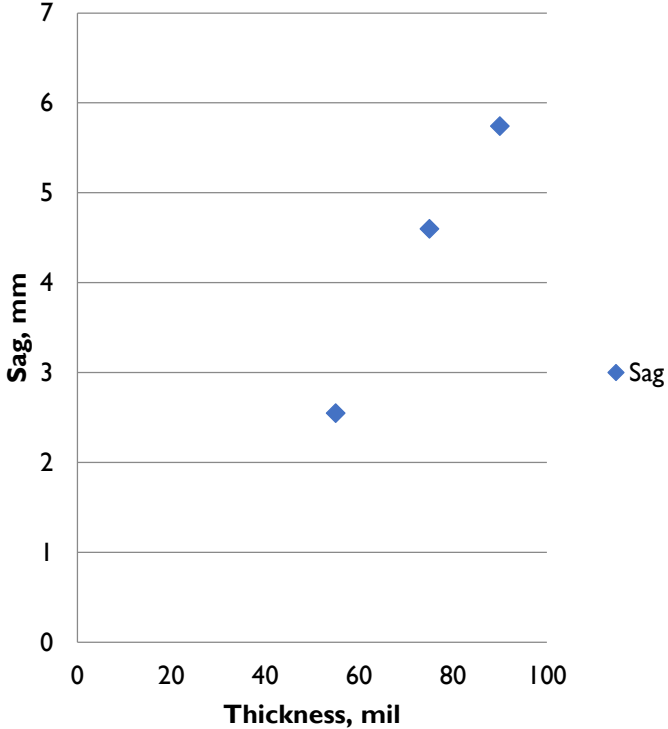
# Sag

- **Most commonly used indicator in industry –Easy to use, direct test, simple, scalable**
- **Sag rate = Sag distance / time**
- **Sag = f (temperature, sheet geometry, clamping mechanism, heating mechanism)**
- **Sag = f (E(T)) = f (% crystallinity, density)**
- **For disk sample of diameter d, Sag  $y = \frac{3 q d^4 (5+v)}{(1-v) 16 E(T) h^3}$**
- **Isothermal Constant temperature, time to sag by certain distance)**
- **Variable temperature ( Heat from T1 to T2, measure sag and time)**

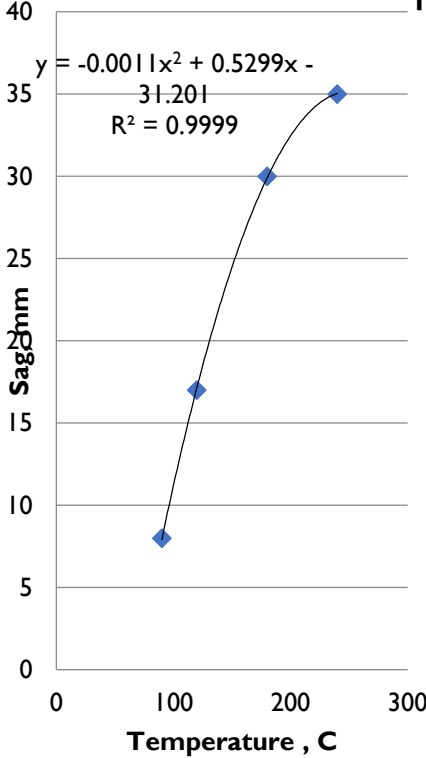
# Sag – Effect of sheet thickness and Temperature

$$\text{Sag } y = 3 q d^4 (5+v) / (1- v) 16 E(T) h^3$$

**Sag vs. Sheet Thickness at 180 C**



**Sag vs. pre-heat Temperature**

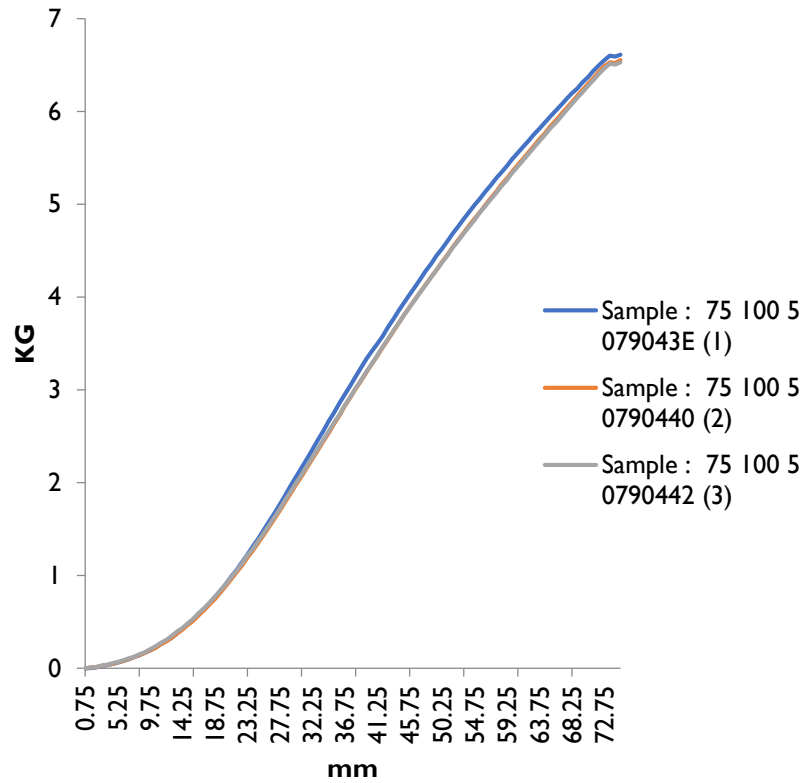


Measured Sag 10" D sample, 45 Mil TPU	72.63 mm
Predicted using Technoform 4"D sample	68.6
% error	5.4%

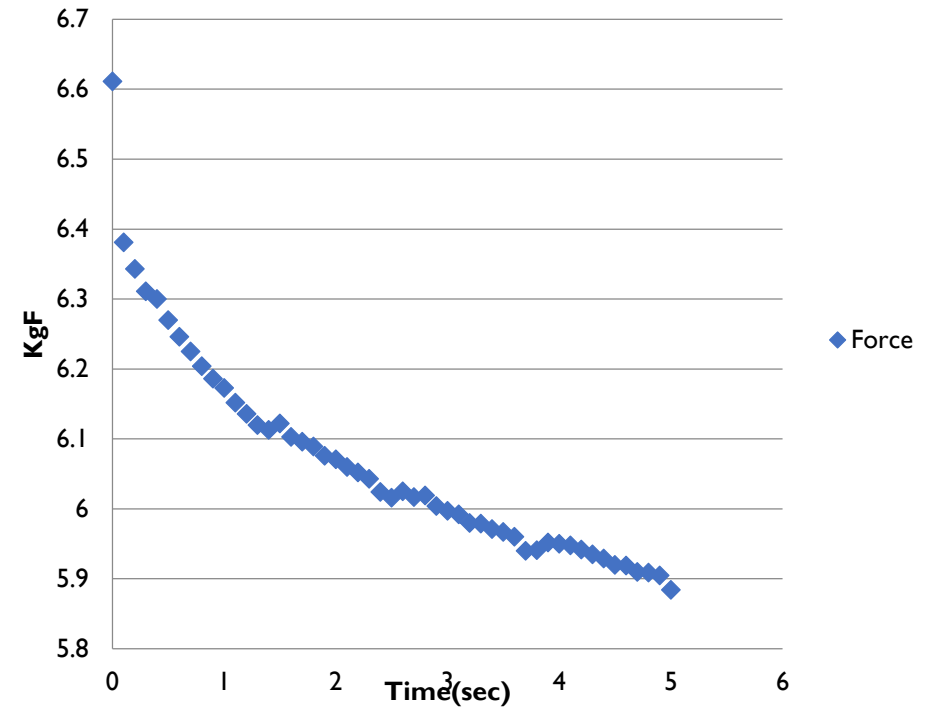
# Stretching a Rubber Balloon

@ 30 C 17 mil, 100 mm/sec

## Force v Distance



## Force vs. time (dwell)



# Stretching - what we do not know!

- What forming speed to use?
- How far to stretch before applying vacuum?
- What is the maximum area draw down ratio?
- How would hot sheet interact with plug (stick, slip, stick-slip)?
- How much would it shrink upon cooling?
- What would be the crystallinity?
- What would be the thickness distribution?

# Stretching - Force (stress) vs. Draw Depth (strain)

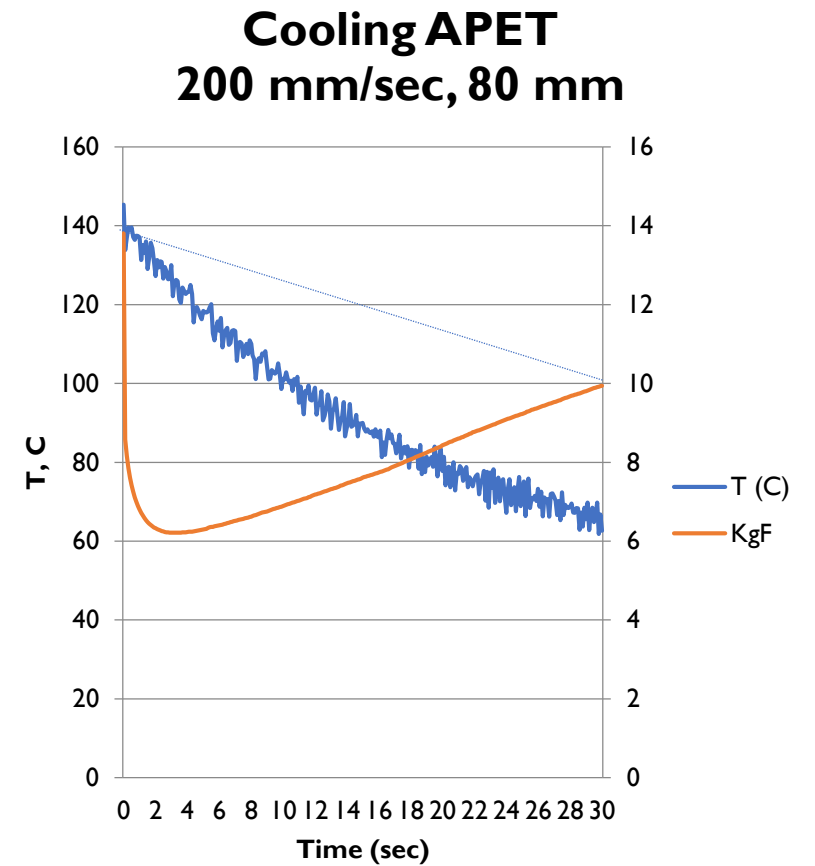
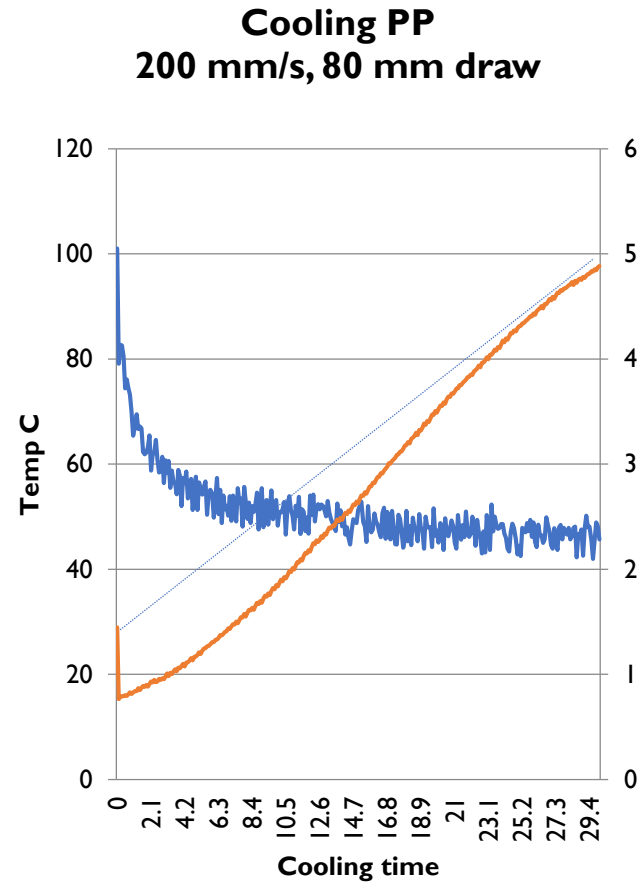
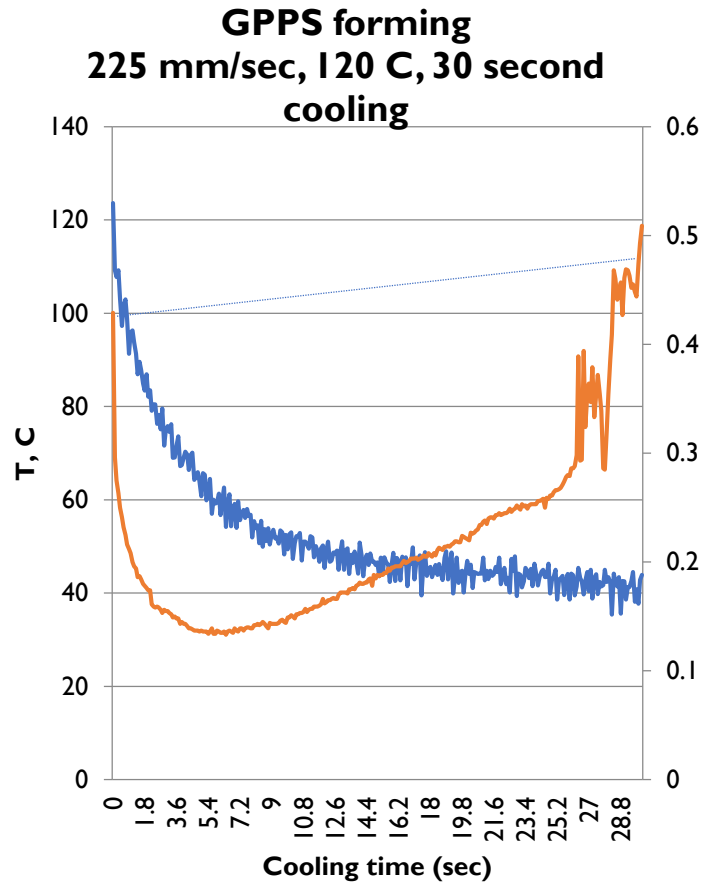
## At low draw depth

- Effect of raw material characteristics (Melt strength)
- Modulus  $E(T)$
- Effect of frozen in stresses (CLT,  $\Delta T$ )
- Mw Degradation

## At high draw depth

- Effect of melt elasticity
- $M_c$  (crosslinking or entanglement)
- Strain hardening
- Orientation (Extrusion speed and output rate)
- Plug –material interactions
- Cooling

# What Happens as Sample Cools?



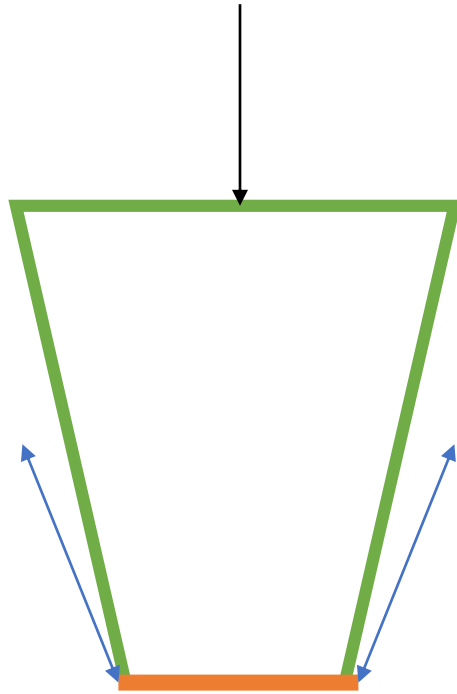
# Interaction Between plug, mold & Heated Sheet

- Contact between plug and heated sheet – f(plug geometry, speed, method of forming, draw depth,. Sheet thickness)
- Mechanical interaction between plug and sheet
  - Slips - portion which slips stretches –thinner wall
  - Sticks - surface which sticks does not stretch –thicker wall
  - Slip and stick – very high plug speeds
- Heat Transfer
  - Sheet in contact with plug cools heat via convection and conduction
  - Sheet not in contact with plug cools only via convection.
  - Sheet which comes in contact first cools first and stretches less
  - Continuous heat transfer to plug raises plug temperature
  - Chilled or water cooled plug will cause inner surface to cool faster causing shrinkage and poor release.

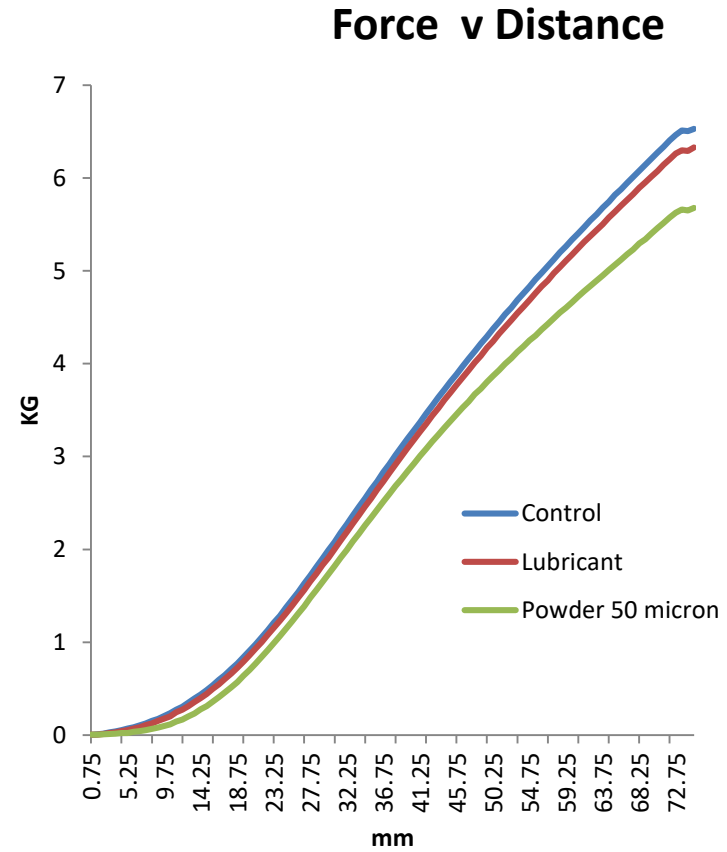
# Coefficient of Friction

- Not affected by speed
- Affected mainly by temperature. As  $T$  approaches to forming window, COF increases rapidly.
- Low COF (Slip) would result in thinner but uniform walls.
- High COF (stick) will result in thin walls and thick bottoms.
- The force to form will increase with increase in COF.

# Plug-Material Interaction

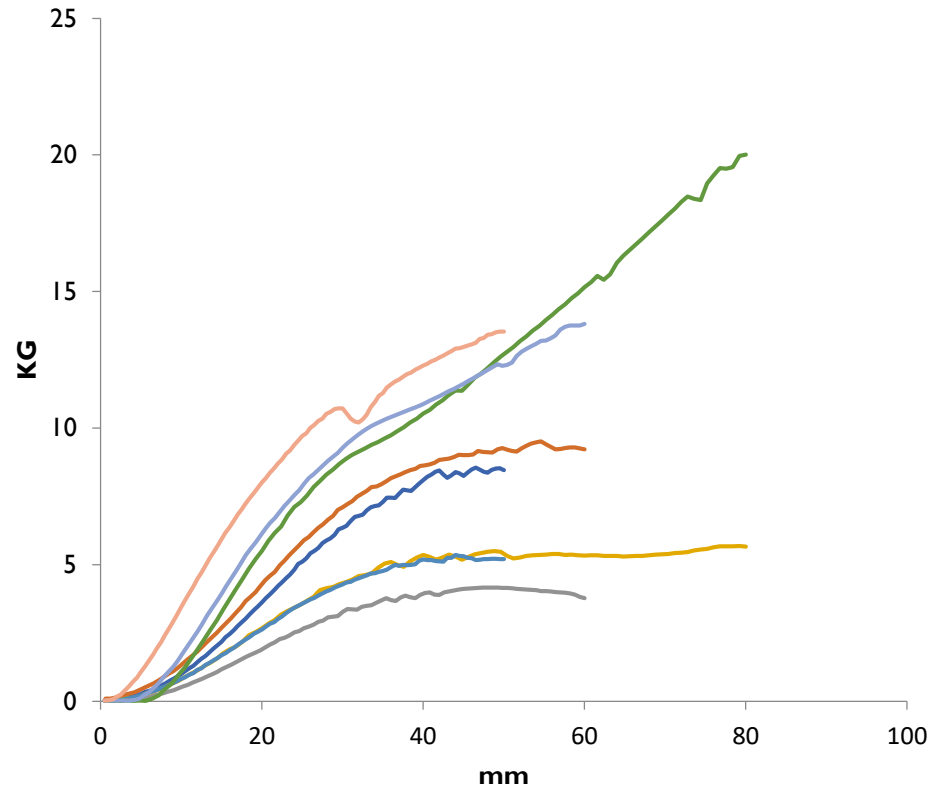


$$\tan \theta = \mu = F_R / F_N$$

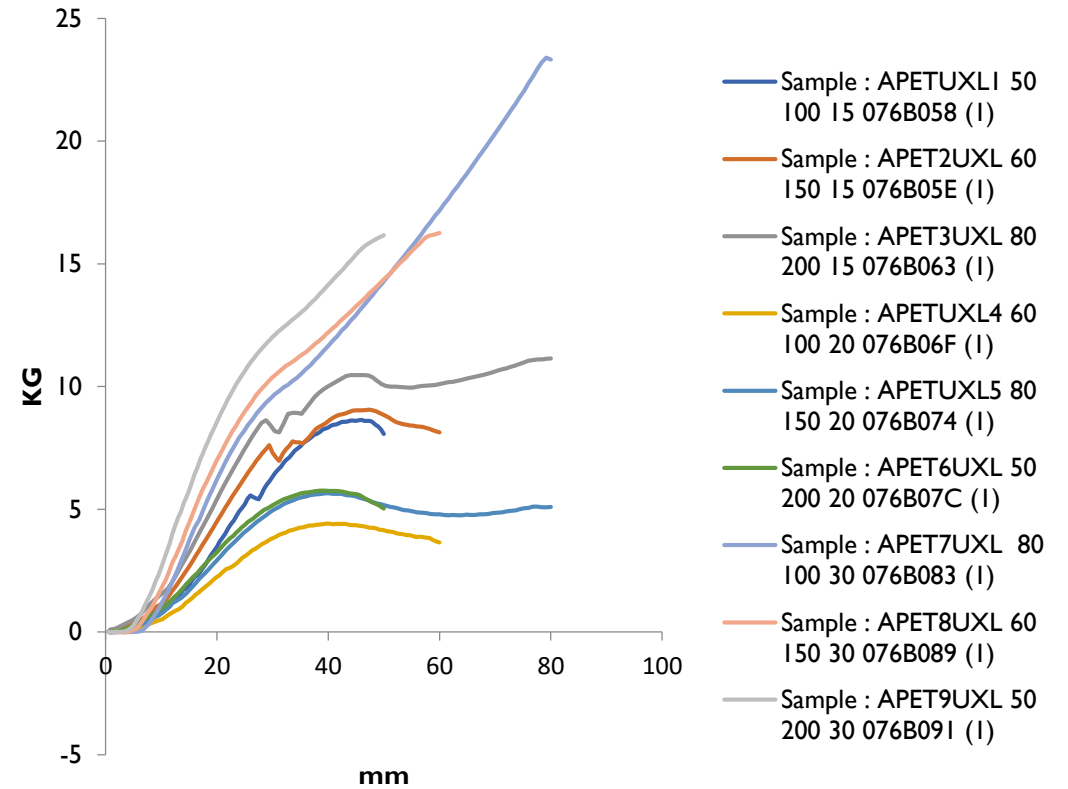


# Effect of Different Plug Materials

## APET Plug HYTAC BIX I



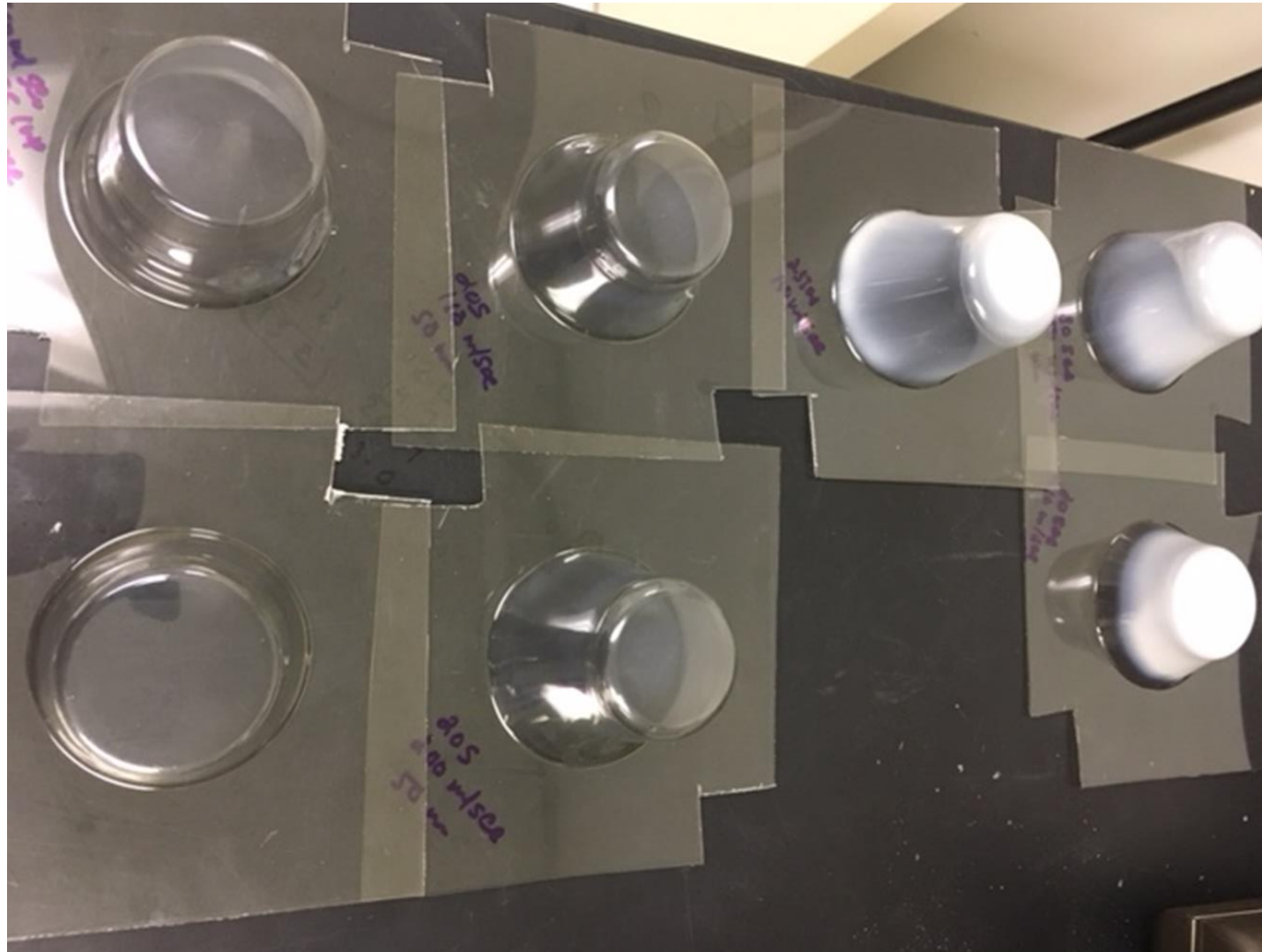
## APET Plug New High k material



# Effect of processing on the crystallinity of APET

	Speed	Plug	Heat ET	Th,C	Hm1	Hm2	Tm1	Tm2	Tg		net	Appearance	
	mm/s		sec		J/g	J/g	C	C	C		Hm	% Crystallinity	
APET	150	CMT	20.01	135	-30.90	40.60	126.40	249.00	72.90	0.31	9.70	6.87	clear
APET	200	CMT	20.01	135	-28.80	40.70	126.10	250.00	71.90	0.26	11.90	8.43	clear
APET	150	CMT	25.01	150	-17.30	38.90	120.20	249.60	78.80	0.00	21.60	15.31	SemiOpac
APET	150	SS	20.02	135	-27.70	43.60	124.30	248.20	72.40	0.17	15.90	11.27	Clear
APET	200	SS	20.01	135	-15.50	44.80	115.60	249.40	74.50	0.25	29.30	20.77	Clear
APET	150	CMT	30		0.00	40.30	nA	250.70	110.10	0.45	40.30	28.56	Opaque
PET	250	CMT	30.01	155	-2.26	37.30		252.20	NA	NA	35.04	24.83	Opaque
APET ctrl	0				-27.90	40.00	128.80	251.00	70.20	0.31	12.10	8.58	Clear

# APET Cups formed at different conditions



# What processors wants to know?

- How well a new material will thermoform?
- How consistently it will thermoform? With-in-Lot variations – same location
- Is sheet uniform ? – Residual stresses, orientation, thickness variation, recycled content, moisture, material mix-up?
- How does it compare to other materials (Lot to lot or material to material variations)
- What is the optimum process temperature window?
- How will material interact with mold/plug material (friction, slip, cooling)
- How long will it take to heat material? To cool material ? Overall Cycle time
- How well material demolds ?
- How well shape is retained ? Grain is retained?
- What is the effect of additives ? Blooming, migration, fogging

# “Thermof ormability”

- Material’s ability to be shaped via thermoforming in a functional part with a desired shape under specific process conditions and using a specific tool.
- For a given tool shape and tool material,
  - Force (t, d, T, v) = f (material + extrusion)

# Test Methods

## Direct

- Sag
- Inflation of heated sheet
- Funnel test
- Thermoforming simulation tests
  - **IKP (isothermal)**
  - **Technoform (non-isothermal)**

## Indirect Indicators

- DSC (% Crystallinity)
- DMTA ( $T, E^*, E'/E'' = \tan \delta$ , torsional)
- Hot Tensile test  $E(T, \epsilon)$
- Hot compression or creep test
- Rheolgy (Viscosity, relaxation time)
- MFR ratio (I10/I2)
- Rheotan
- HDT
- **Simulation models (heating, stretching)**

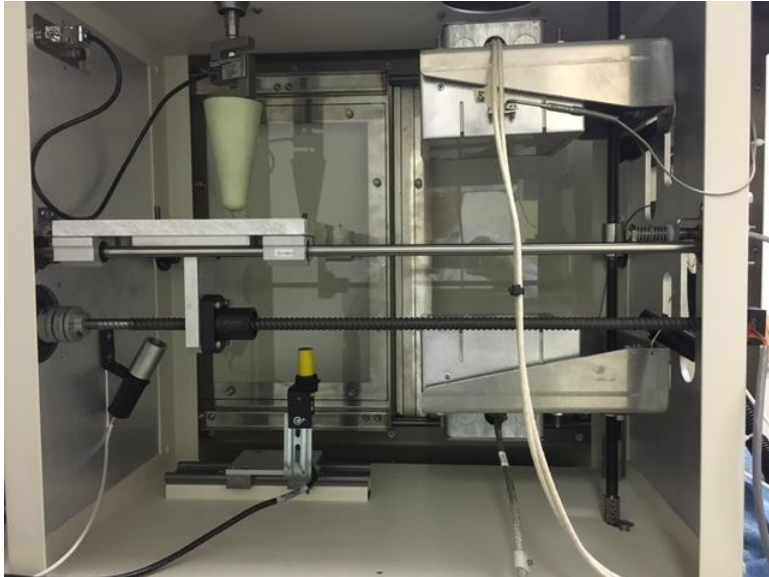
# Current Test Methods-I

Method	Advantages	Disadvantages	Cost	Fee/sample
Melt Index	Easy to perform Repeatability, pellets	>T <sub>m</sub> , Single point, Mw	\$10K-20K	\$150
Tensile Test	Common equipment Pellets or sheet	Inconsistent, sample clamping, necking, Long heat times Secondary crystallization, decomposition	\$18K-\$30K	\$300
Rheotan	Melt elasticity, melt Strength	Special equipment, >T <sub>m</sub> , single point,	\$50K-\$60K	\$1,500
Log (MT) =A+B Log(MI)	Pellets , very few labs have it Set up required	>T <sub>m</sub> , Single point, Mw effect of cooling		
In -oven sag	Most common, east to set up Sheet or film Sag number can be scaled	Geometry dependent, no load, long times Measures hot strength, Inconsistent Potential for annealing and secondary crystallization	<\$10-\$15K	
DMTA	T-t dependent properties	Measures melt strength (E'), recovery	\$25-\$30K	\$300-\$600
@ 1Hz log E vs. T	Temperature range Precision and repeatability	Conducted in LVR , Sample size must fit to fixture TE does not occur in LVR		

# Current Test Methods-II

Method	Advantages	Disadvantages	Cost	Fee/test
Thermoformability Index	Performed on sheet, repeatability	Constant stress test at low speeds	\$25-30K	\$250-500
viscosity x Je	Rheometer Small sample, pellets or sheet	>Tm, single layer 1-2 hour per test		\$250-500
DSC	Tonset- Tc, % Crystallinity, Heat Capacity, rate, stress induced crystallization	Limited to crystalline materials 2-3 hour per test	\$15-25K	\$500
Lab Thermoformers	Direct testing (T, t displacement) Sheet or film or compression molded	Qualitative, 12"x12" samples	\$17K-30K	
Technoform	plaques 1-3 minute per test, Small sample size F-T-V data for material	New Method Higher initial cost	\$50K-60K	< \$10

# Technoform – Direct Testing Equipment



# Technoform – Plug and play Test Equipment

## Input

- Thickness, color, plug type, plug geometry
- Upper heater temperature
- Lower heater temperature
- Plug temperature
- Distance between heater and sample
- Plug mode
  - Preheat temperature or time
  - Plug speed
  - Draw depth
  - Cooling time
- Vacuum Mode
  - Vacuum level
  - Vacuum time
  - Cooling time

## Output

- Upper surface temperature
- Lower surface temperature
- Sag Distance
- Force vs. draw depth during forming
- Force vs. time during cooling
- Temperature vs. time during forming and cooling
- Distance vs. time (Vacuum)

## What is measured?

Surface Temp. vs. time  
During heating

Sag distance after heating

Force (stress) vs. draw depth (Strain)  
as function of speed and Temperature  
and plug material during forming

Fstart - F End

T start-T end

Thickness (post forming)

## What does it means?

Heating rate,  $DT/Dt$   
Material mix ups (inflection points)  
Additive blooming and moisture

Sag resistance - scalable

Initial slope - Hot modulus,  $E(T)$   
Yield length - elasticity  
Data for BKZ model (F,D,V,T)

Shrinkage, orientation

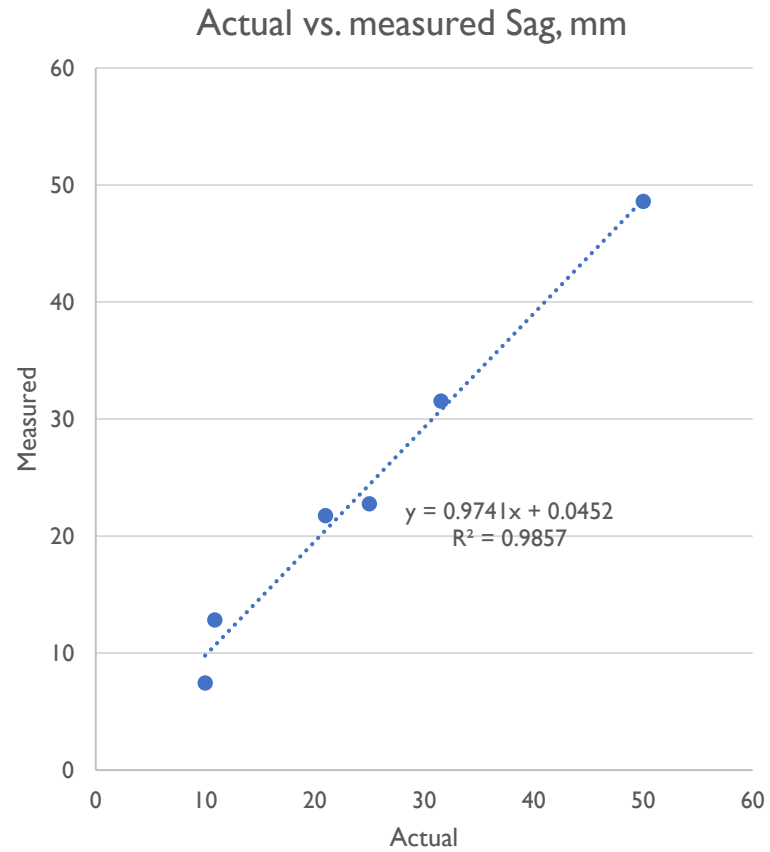
Heat retention, rate of cooling

Thickness Distribution

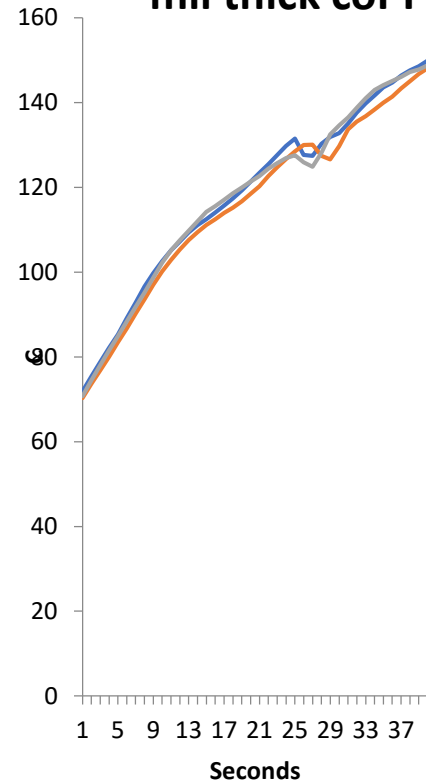
# Advantages of Technoform Thermoformability Test

- Mimics actual thermoforming conditions and uses similar terminology
- Performed on single layer or multiplayer sheets or films
- Flexibility of changing, controlling, and monitoring key variables
- Provides multiple indicators in a single test (material mix-ups, heating rates, issues with non-uniform sheet quality, sag, forming characteristics, effect of cooling rates, plug materials, geometry)
- Rapid and requires far less material and time than lab thermoforming tests
- Easy to perform full scale DOEs for process and material optimization as well go / No –go decisions.

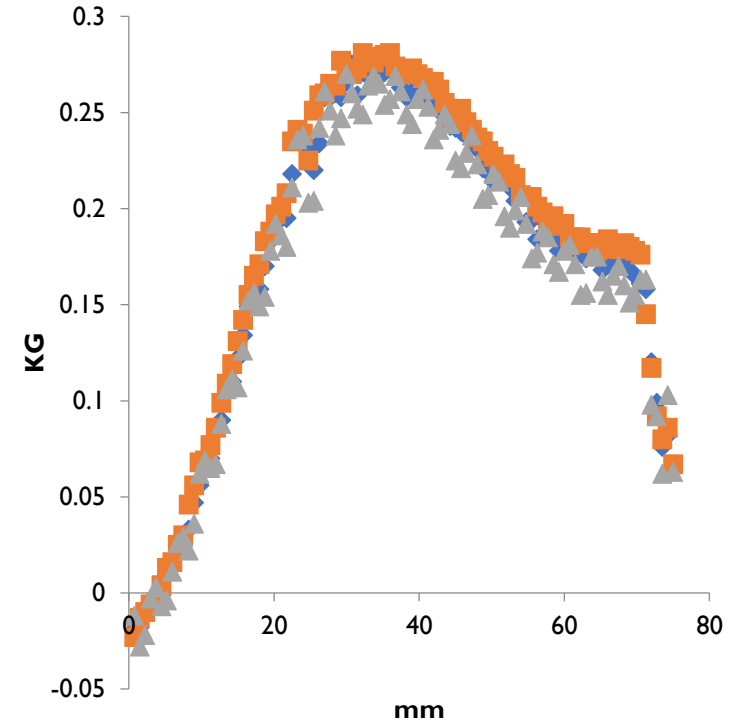
# Repeatability



Temp. vs. time for three 20 mil thick coPP

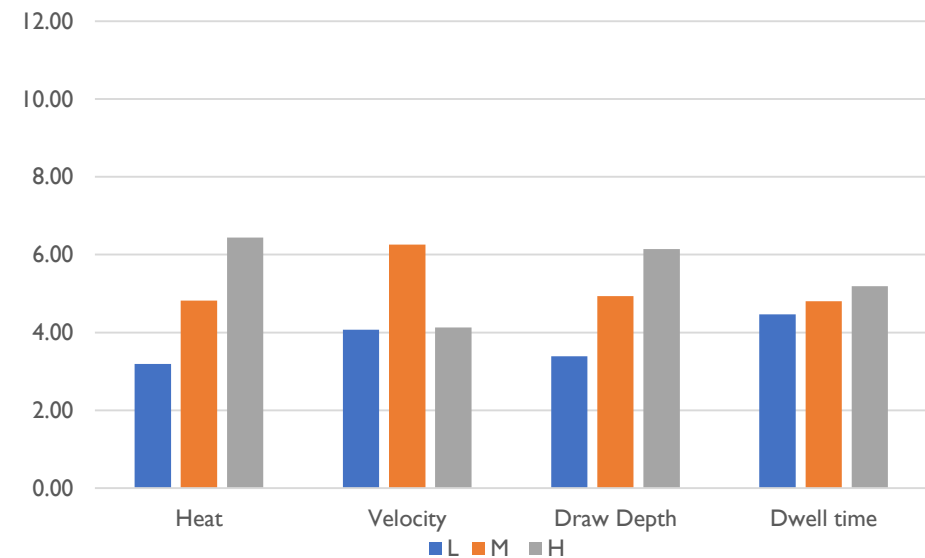
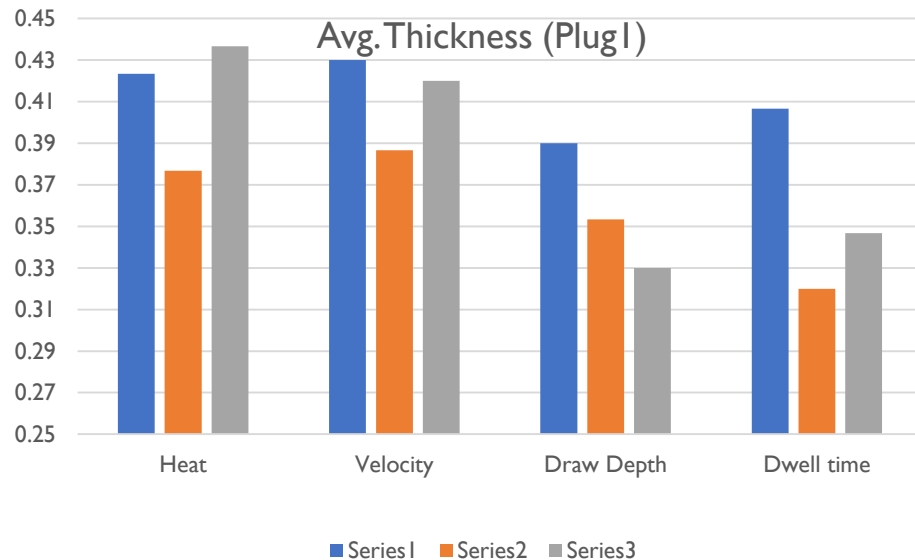


Force v Distance



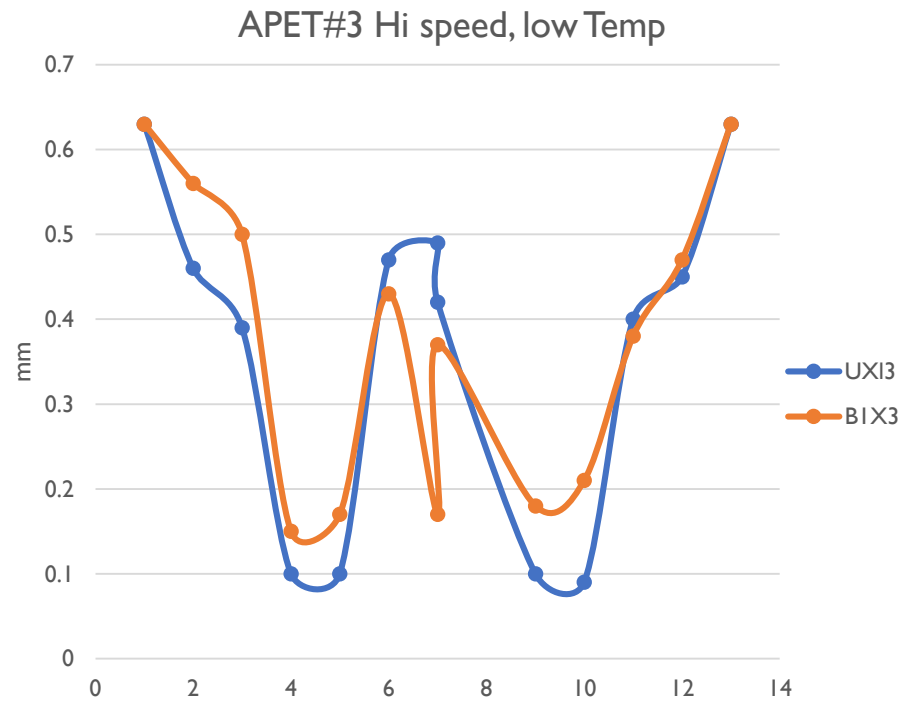
## Thermoforming APET – DOE

Variable	Sag	F, 25 mm	F, 50 mm	T start-T Finish	Del F (forming-cooling)
Temp	+++++	++	++++	++++	+
Plug speed	-	+	+++	++++	+++
Draw Depth	-	-	-	-	-
Dwell time	-	-	-	-	+

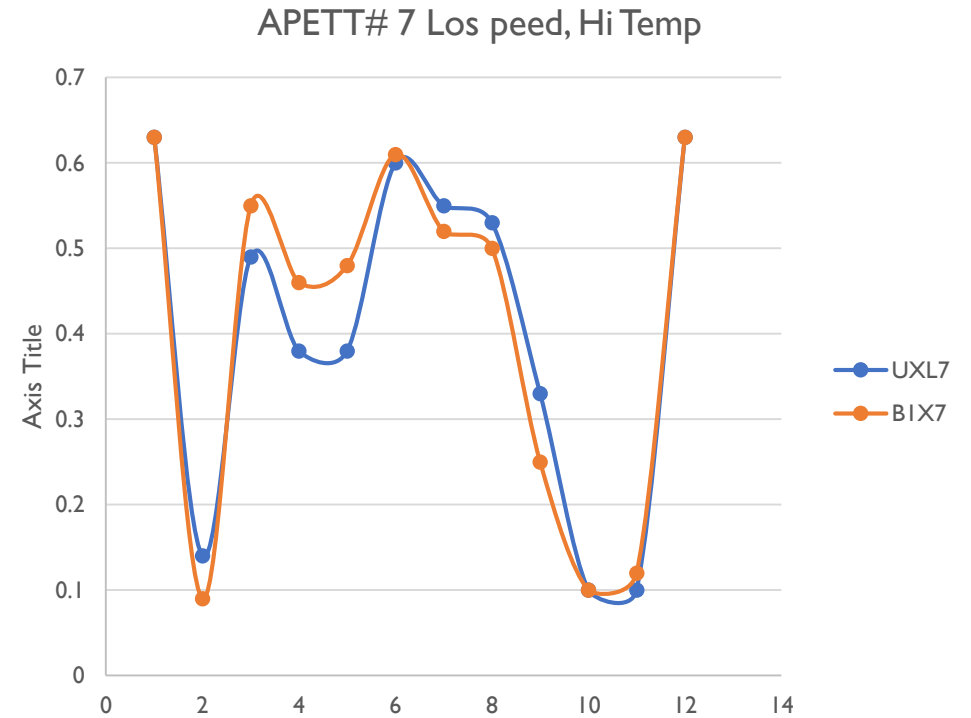


# Thickness Distribution -APET

- Hi Plug speed, Low Temp.

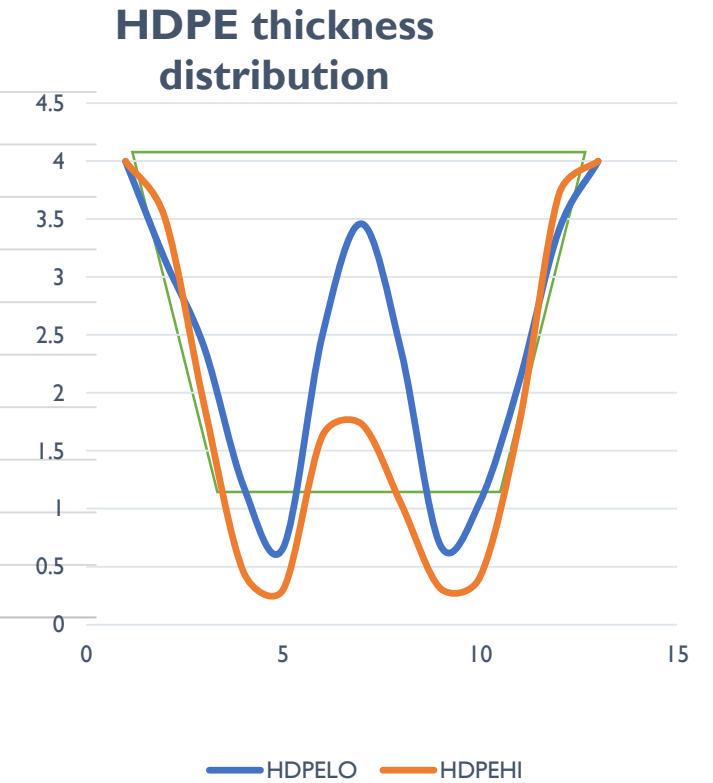
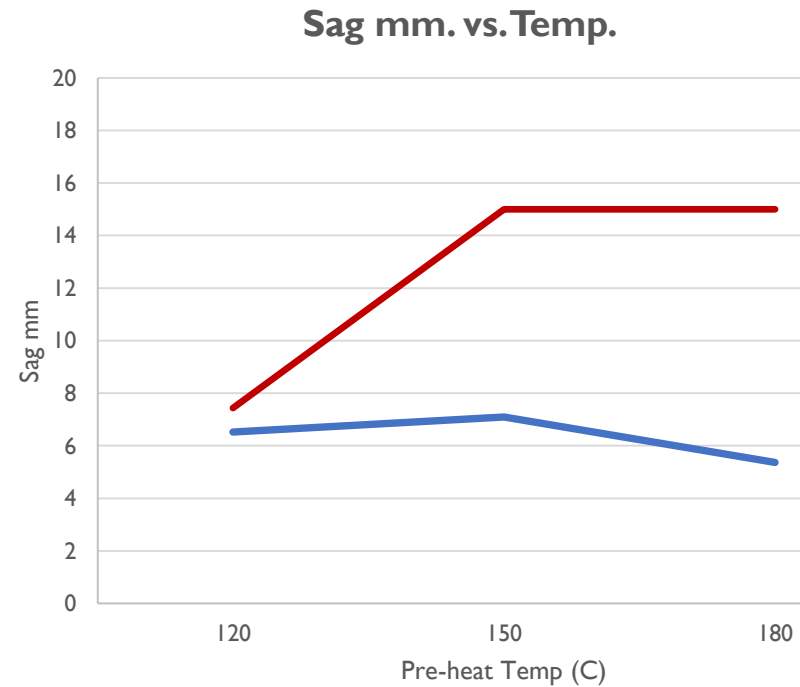
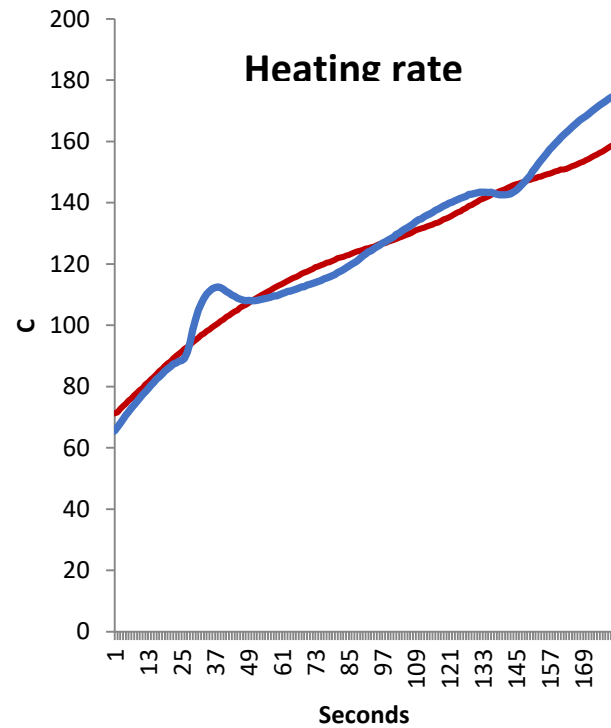


- Low Plug speed, High Temp



# Comparison of HDPE

4 mm, 150 mm/sec, 75 mm



# HDPE forming at 180 C



# Summary

- Thermoforming is a complex process with many unknowns.
- Due to large number of unknowns, complete mathematical modelling is not practical. Empirical measurement is must to use computational models.
- Understanding and empirically measuring effects of significant material and process variables can reduce expensive trials –errors.
- Force to form (F-D) as a function of temperature, tool, and test speed is a good parameter to quantify “Thermoformability”
- TF Industry needs to have a set standardized properties (like MFR is to extrusion and IM) for QC and QA.

# The Innovation Cycle

