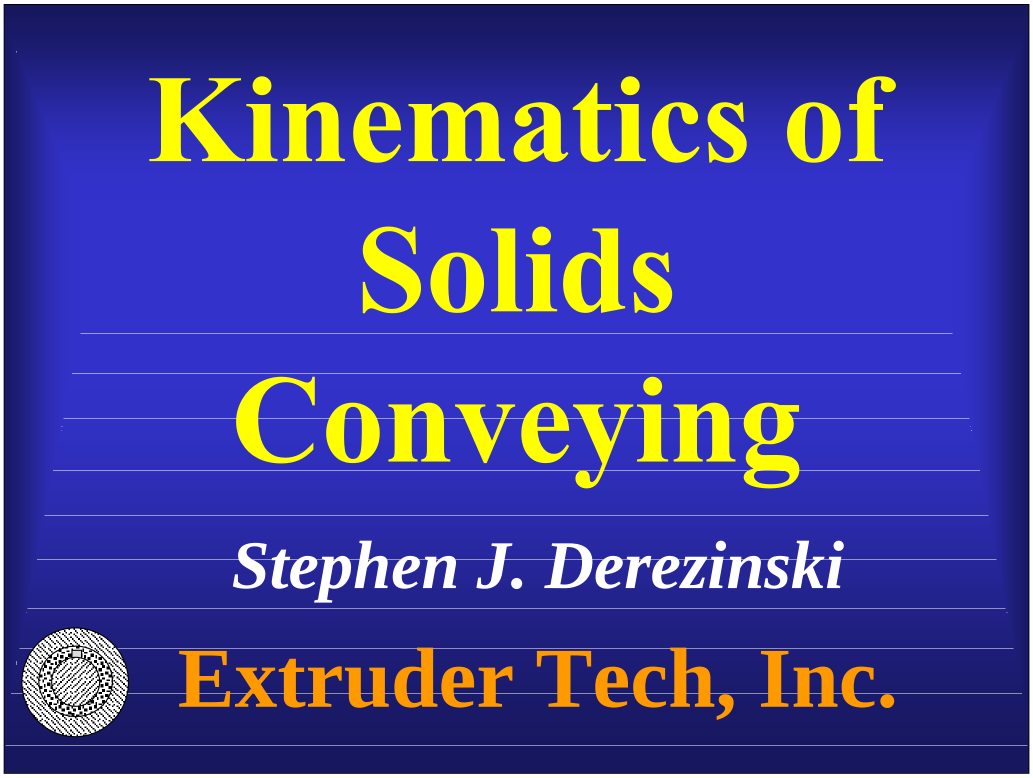
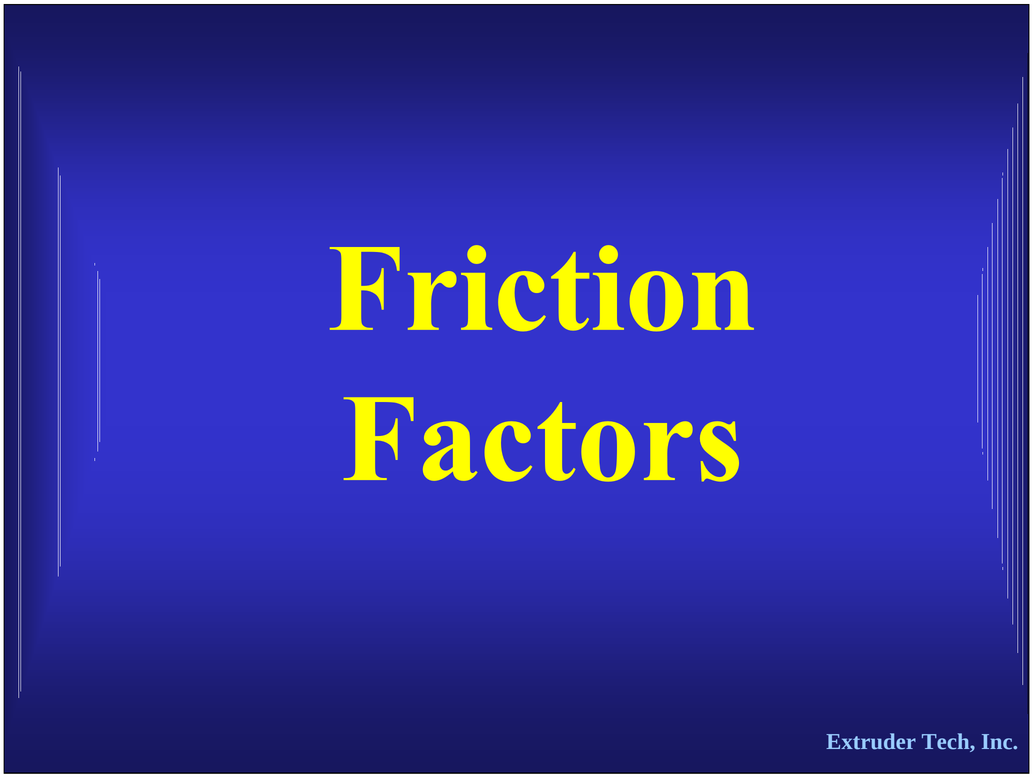
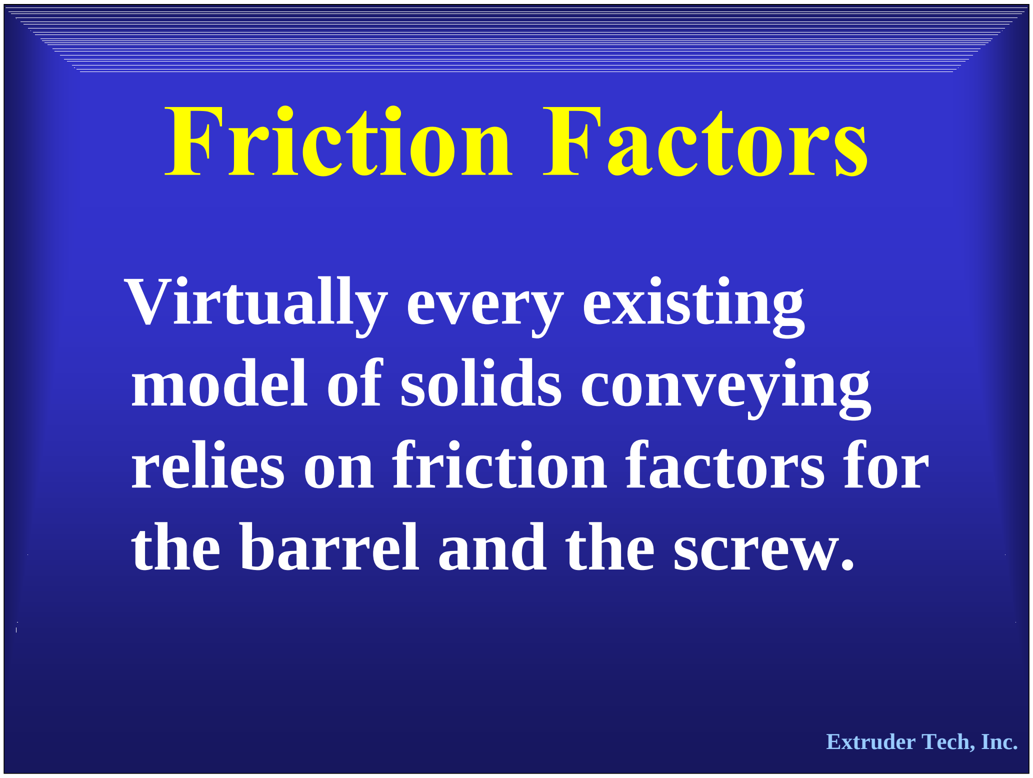


Traditionally, understanding and modeling of solids conveying is approached with a complete statement of the physical laws and worked forward, hopefully, to an accurate prediction of solids conveying flow. Numerous models have been developed using the conservation of mass, torque balance, force balance, and in some cases energy balance, to predict solids flow in an extruder. All have varying degrees of success in consistently hitting the answer.

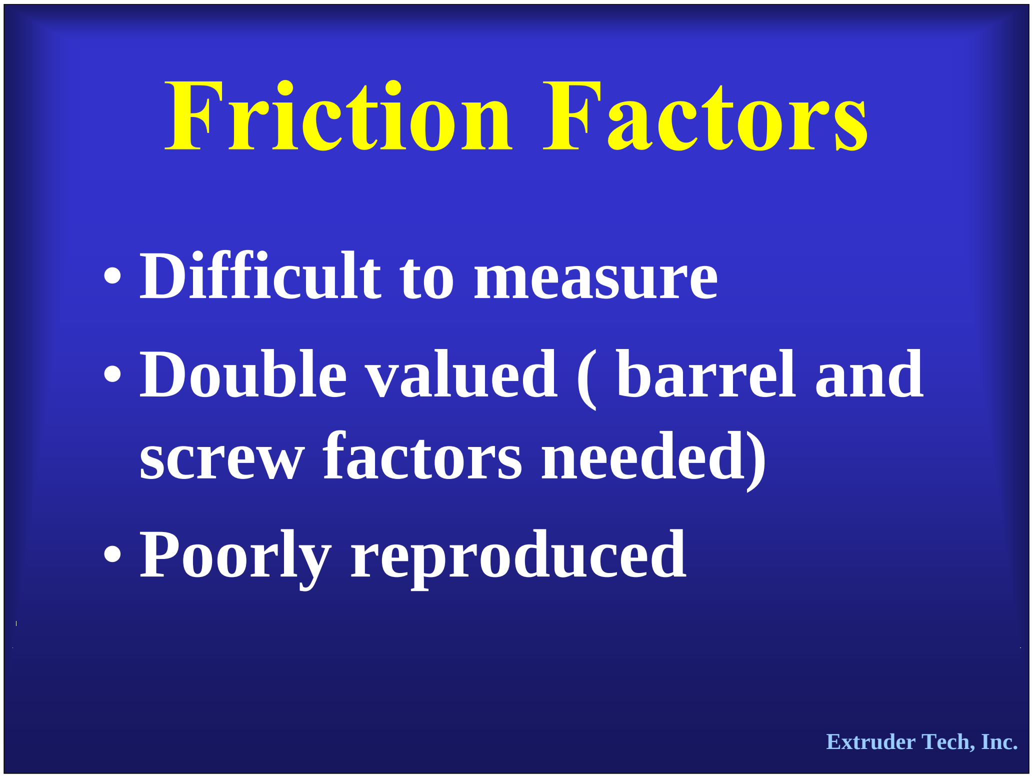
The approach here is philosophically different. It starts with the conservation of mass to describe the kinematics of the process, or just the motion of the solids plug. Then, *it jumps to the answer and works in reverse* with machine data to link the answer to the kinematics. The data provide the information needed to capture the remaining physics through understanding and correlation of an empirical factor, the *solids conveying angle*. A complete model of solids conveying results based on kinematics and the solids conveying angle.



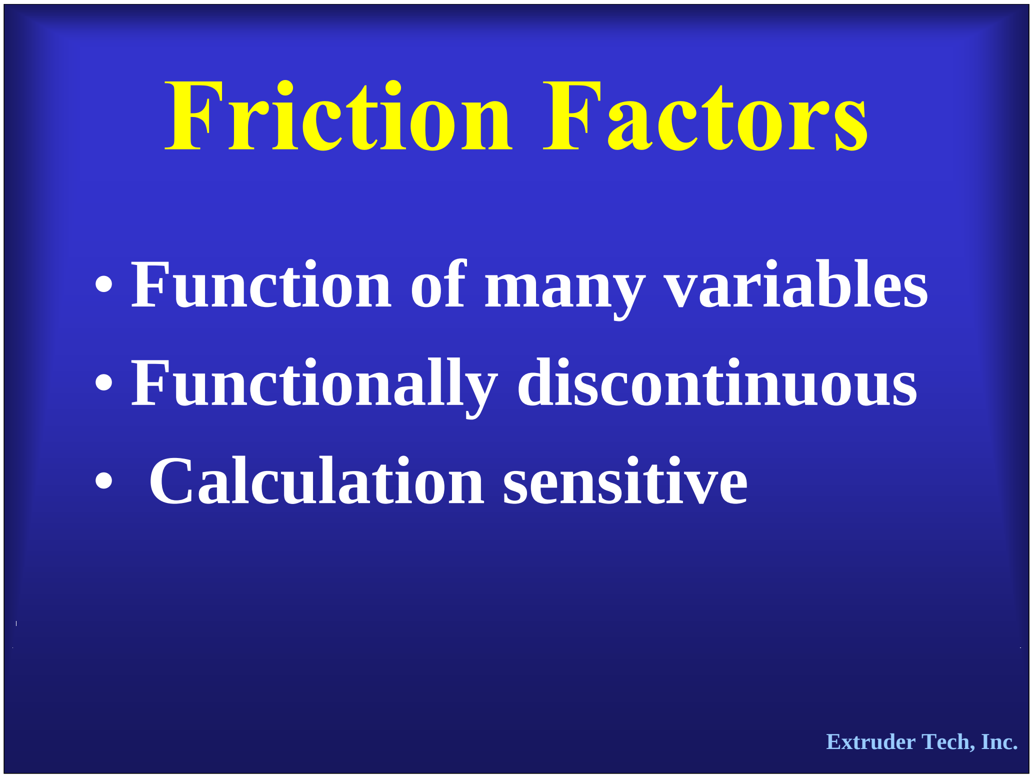
We start with an indictment of friction factors for solids conveying.



Solids conveying has been modeled by numerous investigators in an effort to accurately capture the solids conveying flow. Darnell and Mol were the first to establish a model, and many others have followed with improvements or slightly different approaches. However, there is a “disconnect” between models and actual solids conveying. The models are much more sensitive to slight changes in friction factor than actual performance typically demonstrates.



Friction factors are wrought with difficulties.

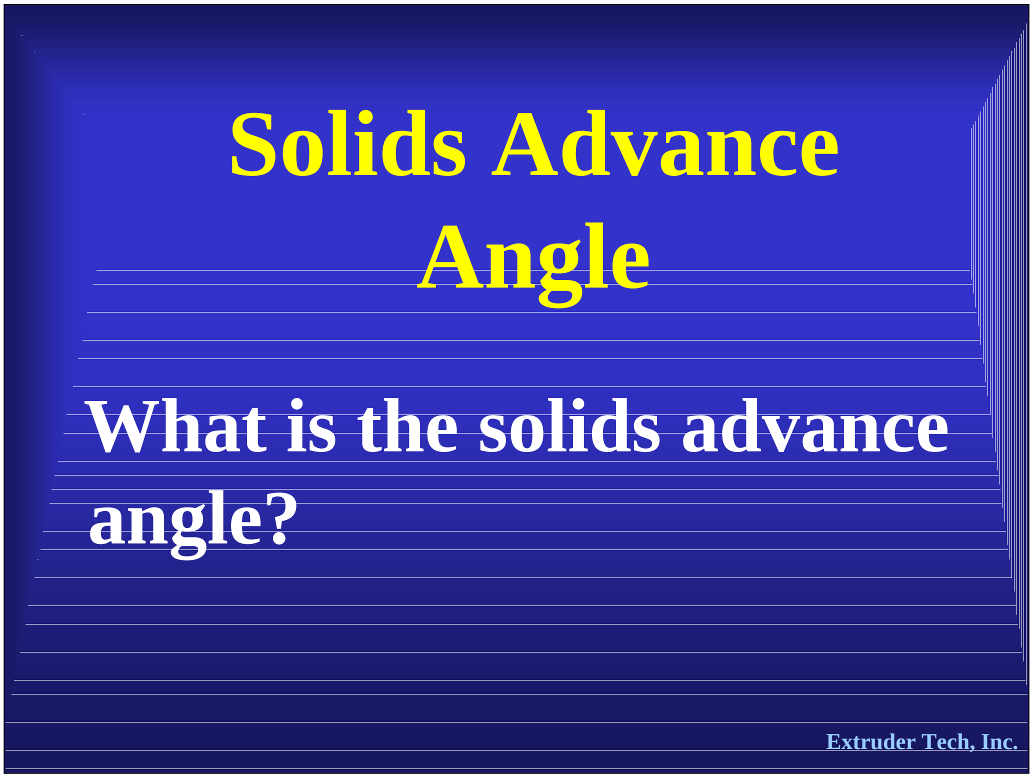


Friction factors are extremely difficult to use for any model.

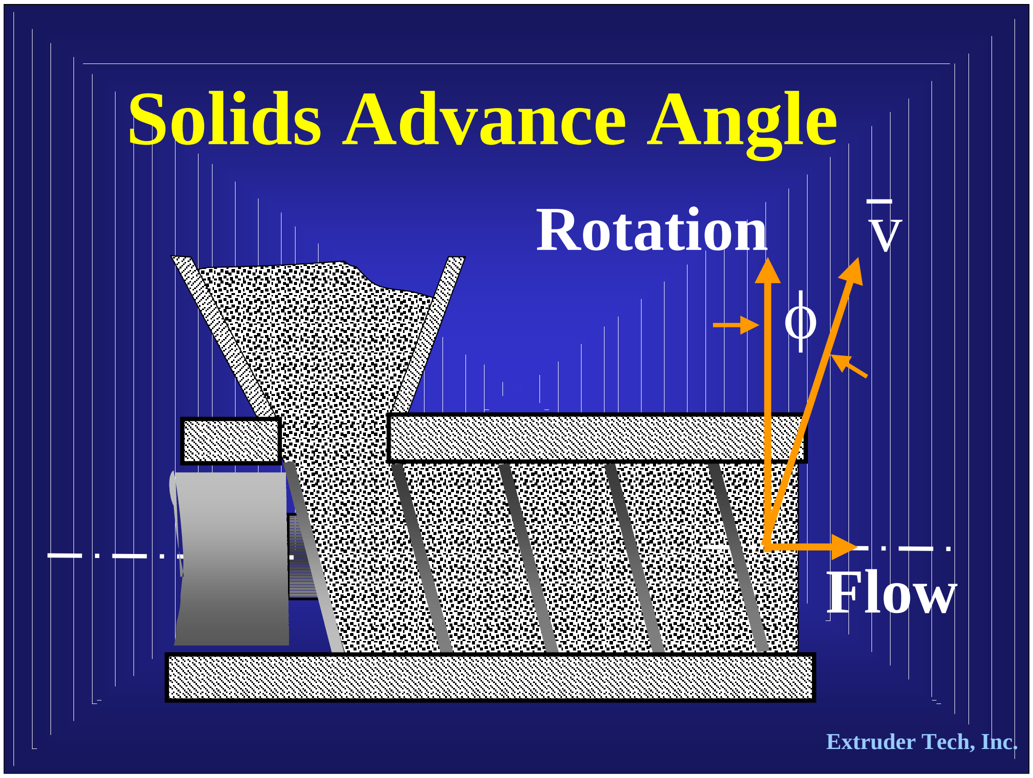
Kinematics of Solids Conveying:
The Solids Advance Angle

Extruder Tech, Inc.

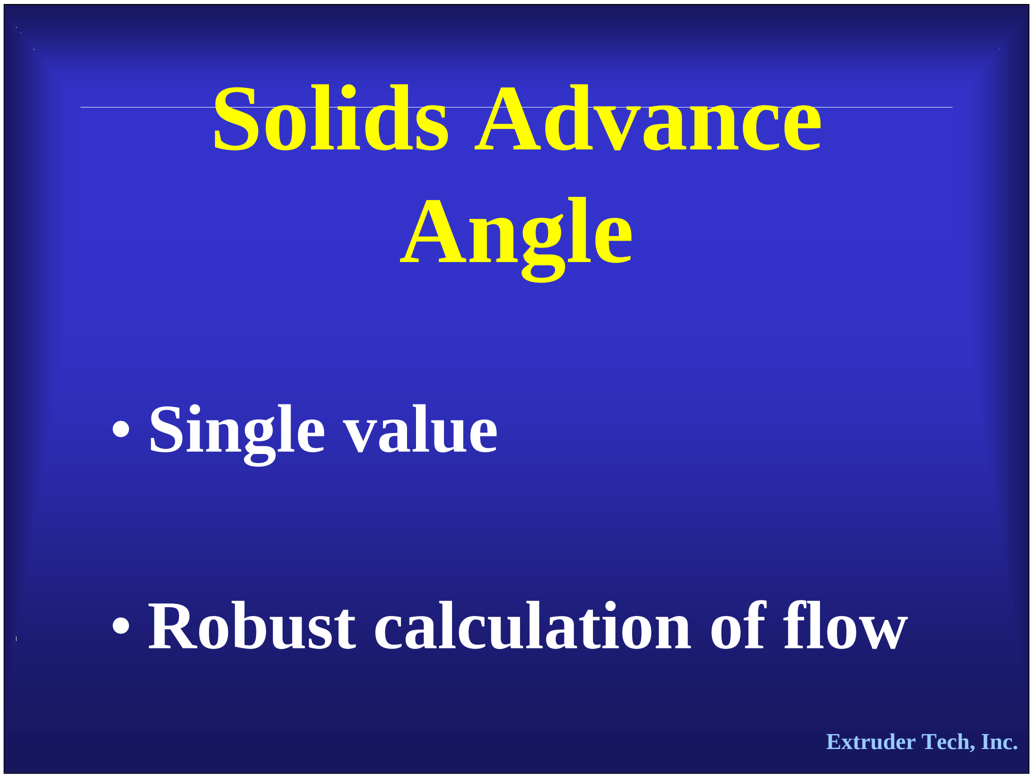
A kinematics model of solids conveying illustrates that the solids angle is an empirical factor for understanding and calculating solids conveying.



First, the solids advance angle is defined.

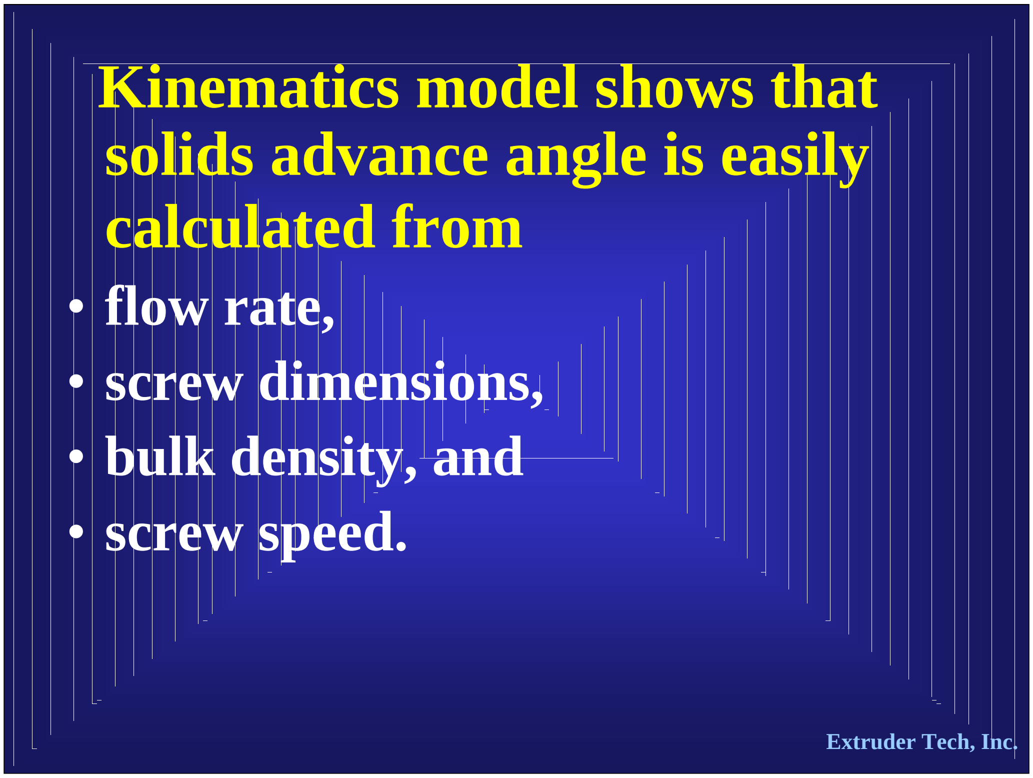


The solids advance angle is the angle formed between the velocity vector for the solids plug motion and a line perpendicular to the axis of the screw. For this work it is defined at the end of the solids conveying portion of the process.

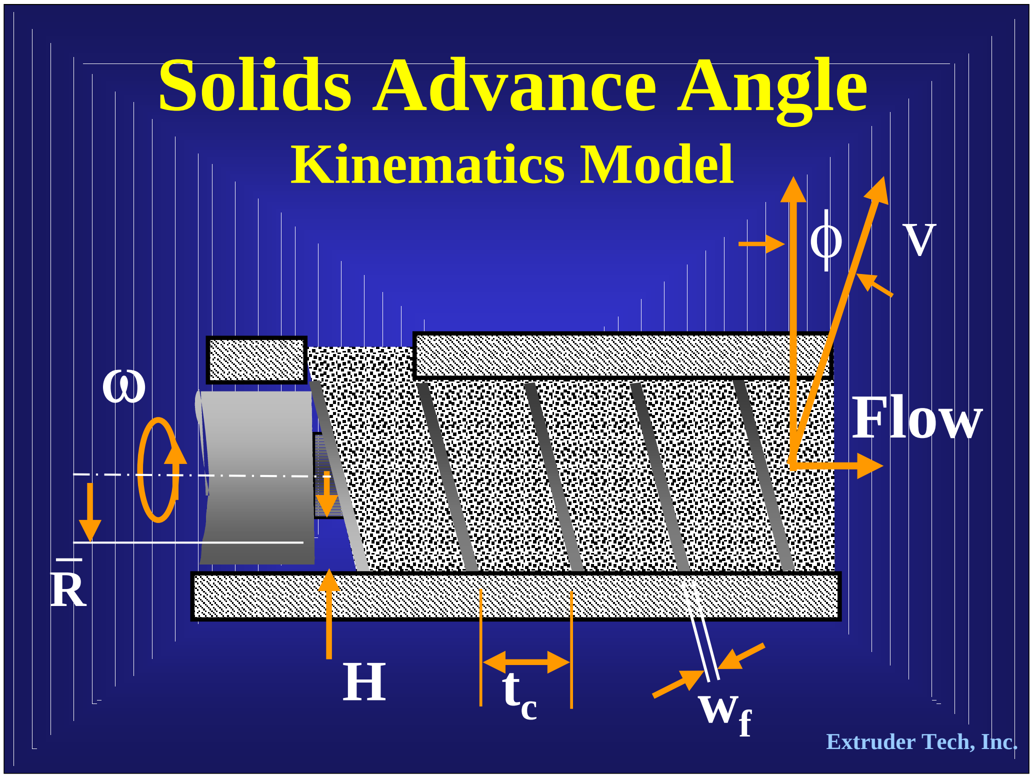


The solids advance angle is a single empirical value that affects the flow as opposed to two friction factors (barrel and screw.)

The calculation of the flow rate with the kinematics model and the solids conveying angle is computationally stable. I.e., small change in solids angle will not create large changes in the calculation. For the typical friction-factor based model, a small change in friction factor often has an inordinately large affect on the flow.



The calculation of the solids angle depends on factors that are easily and accurately measured. Other than bulk density, they are commonly known for any operational machine. Bulk density is widely reported in the literature, or it can be measured with the most fundamental instruments.



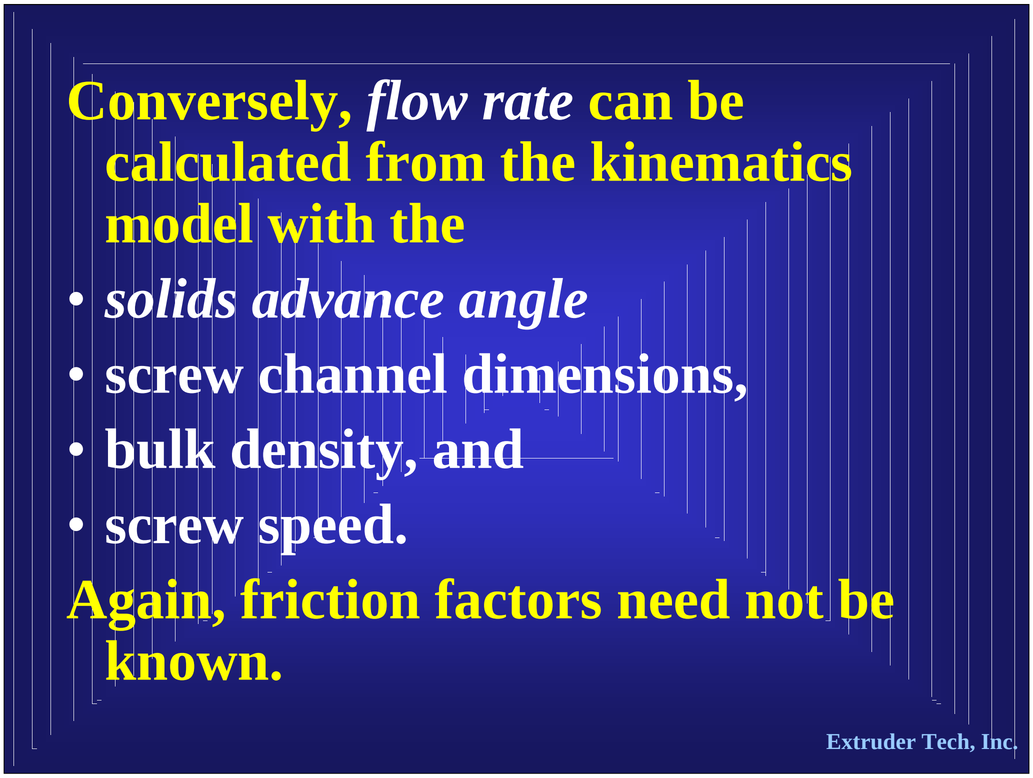
Here are the geometrical factors that are used in the kinematics model to calculate the solids advance angle. Screw speed and flow rate are also needed, as shown. Bulk density is also needed, but not shown.

Solids Advance Angle

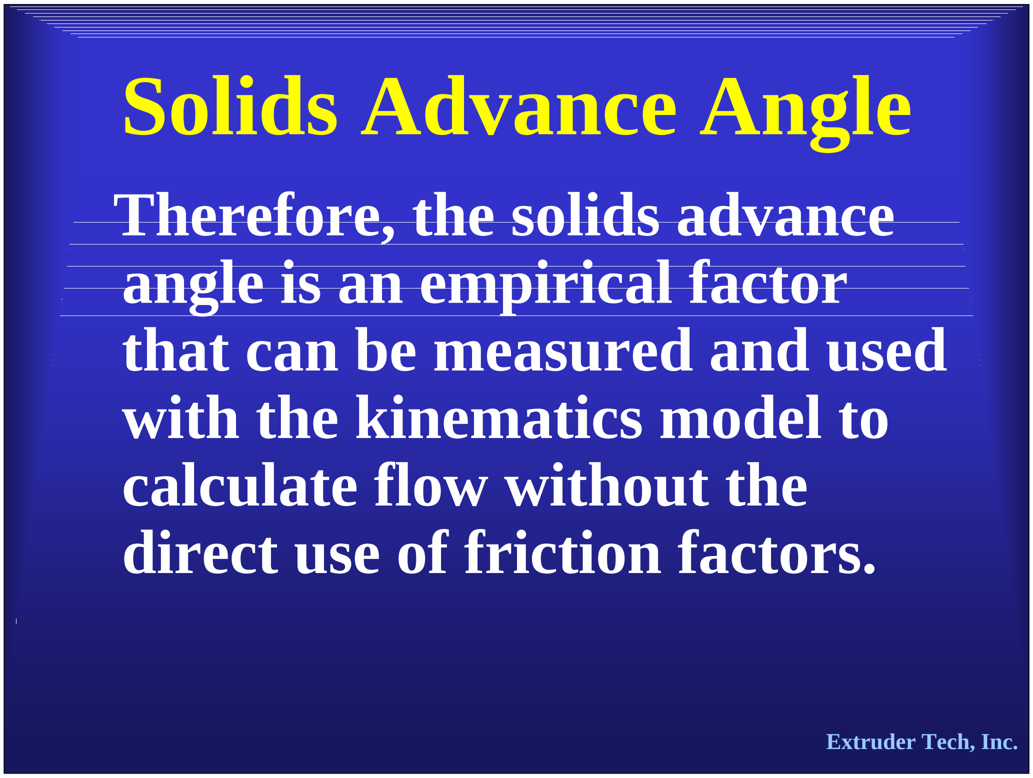
Friction factors need not be known for the calculation of solids angle from flow rate with the kinematics model.

Extruder Tech, Inc.

Friction factors are not evaluated, but they are implied.

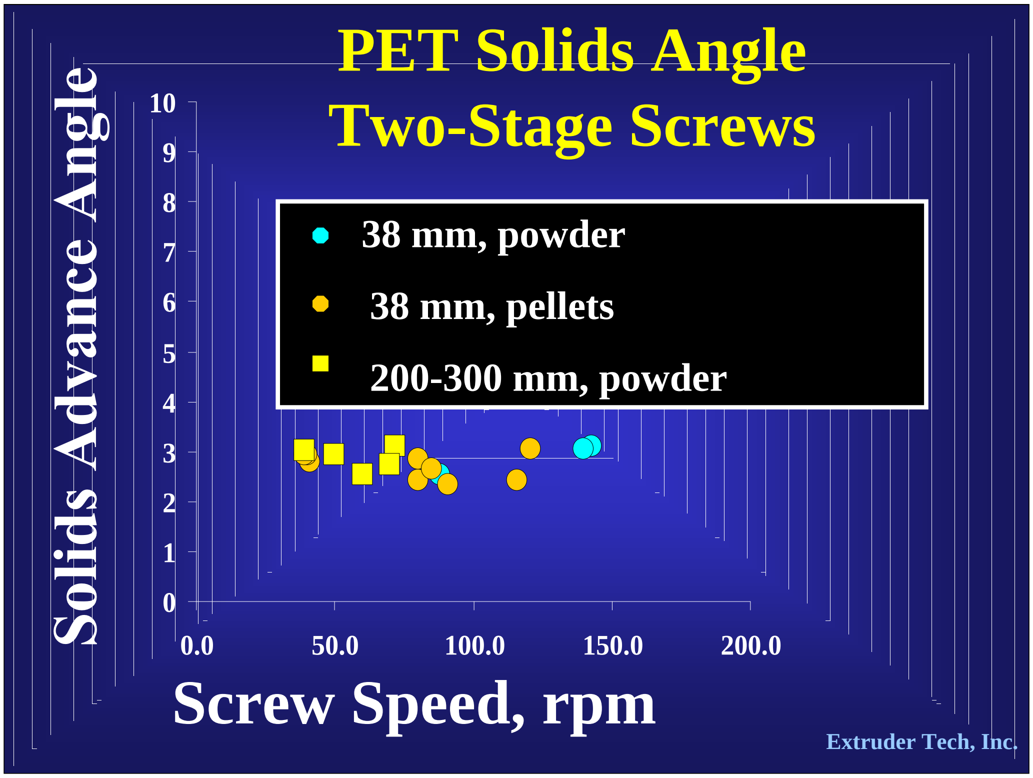


It is important to note that the converse is possible. One can use the kinematics model to calculate the flow rate if the solids angle is known. Therefore, once the solids angle is predictable for a given polymer, it can be used to size and design extruder screws for proper solids conveying flow.

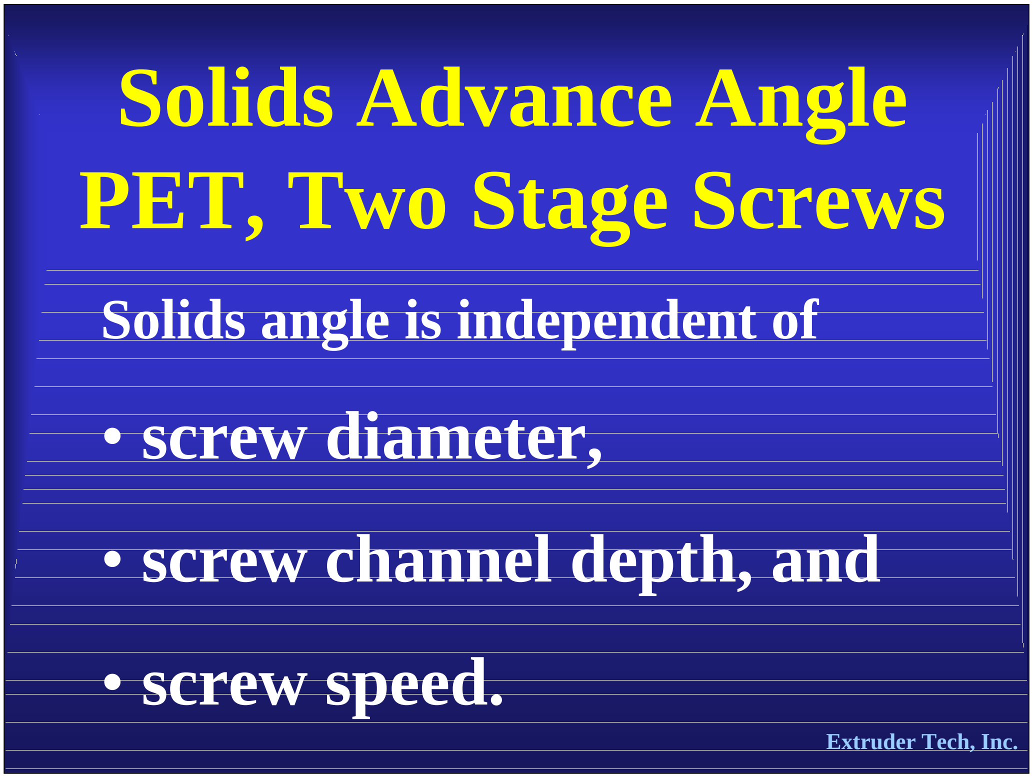


The effect of process variables and screw design on the solids angle must be determined in order to have it be used with the kinematics model for calculating solids conveying flow.

In order to correlate the the actual flow to the kinematics, the solids advance angle is determined from operational data. To start, flow data for several screws for PET were compiled. First are data for two-stage screws.

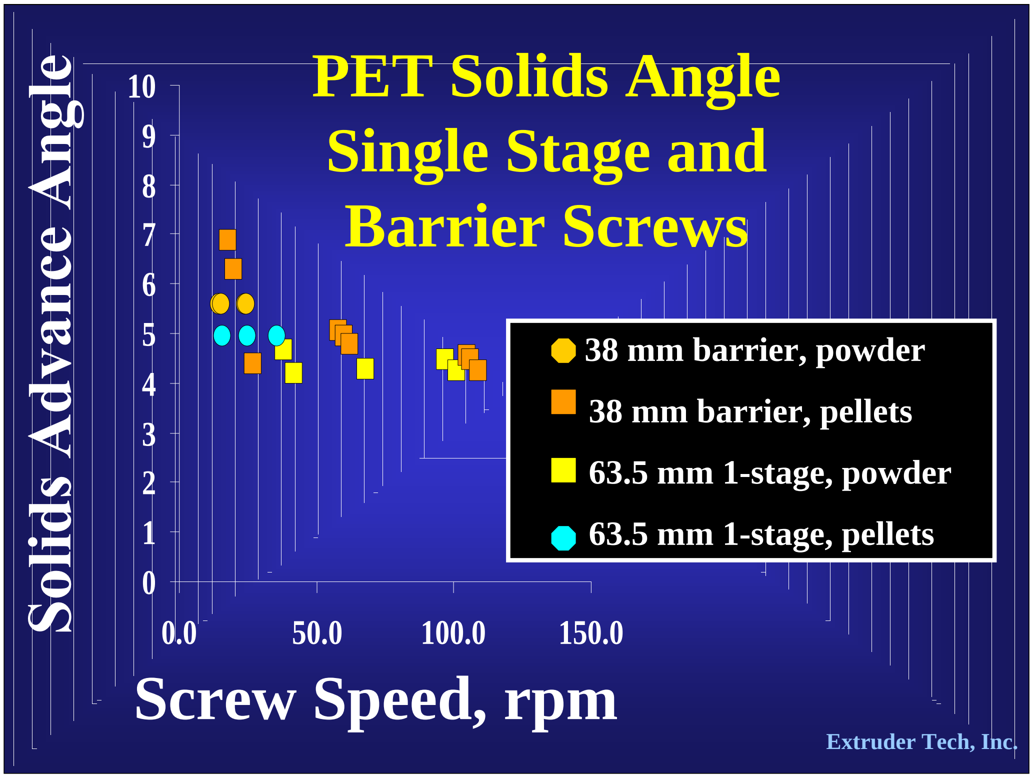


Solids advance angle is plotted versus screw speed. PET powder and pellets were used in two-stage screws. Diameters and channel depths cover a large range. The lead lengths were square pitched for the most part, but some slight variation in that was also included. As can be seen, little variation in solids advance angle exists.



So, the solids advance angle for PET is shown to be independent of screw diameter, channel depth, and screw speed. In operational two-stage screws it has an average value of 2.8 degrees.

Barrel zone temperature was always the about the same, too.



A change to barrier screws and single stage screws for PET shows a change in solids advance angle. It now has a constant value of about 4.5 degrees. However, low speed operation shows that the solids angle is significantly higher.

PET, Single Stage and Barrier Screws

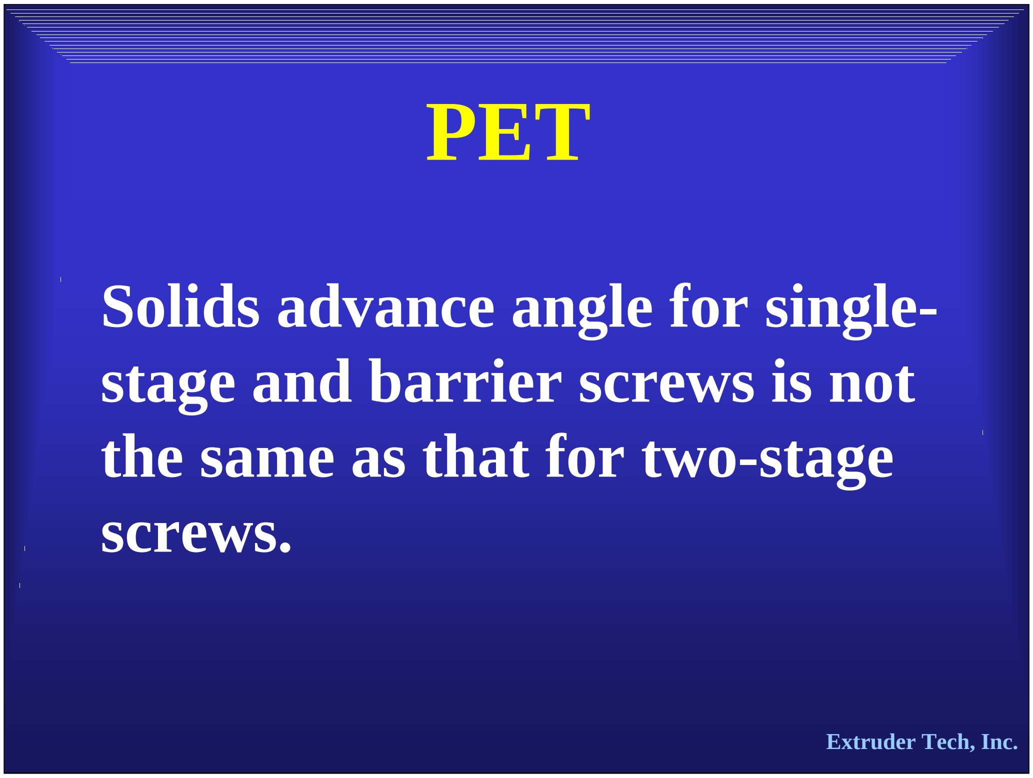
Solids advance angle is

- **independent of pellets or powder, and**
- **independent of barrier or single stage screw.**

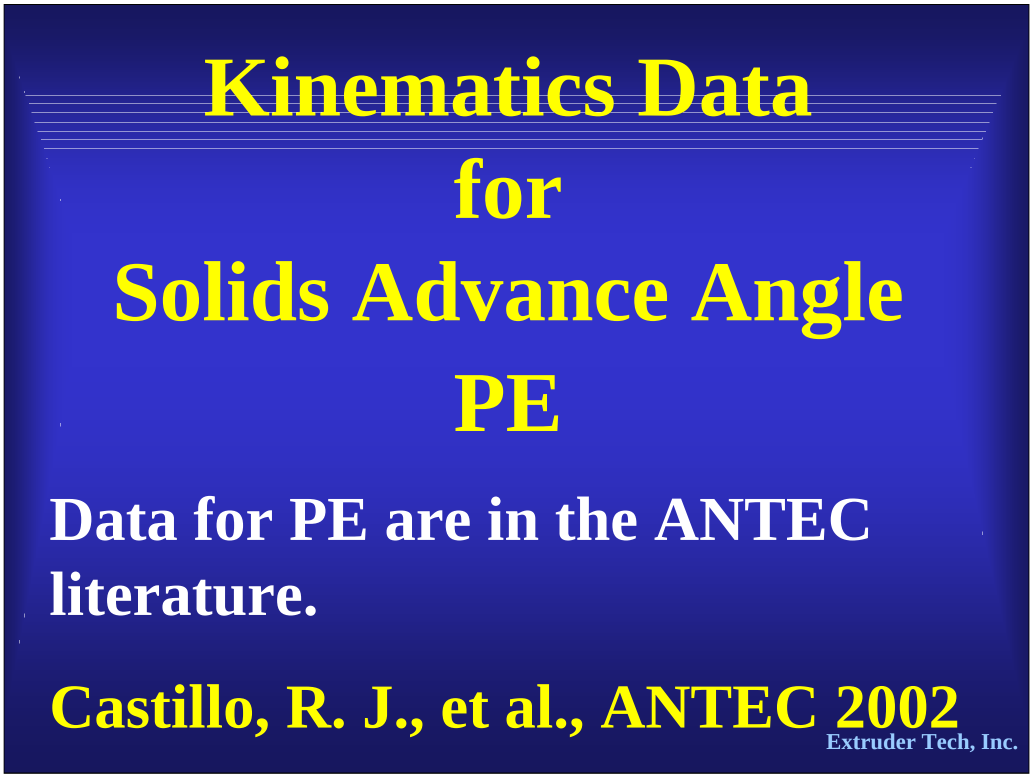
Extruder Tech, Inc.

Pellets or powder had little affect on solids advance angle for any of the three screw types for PET.

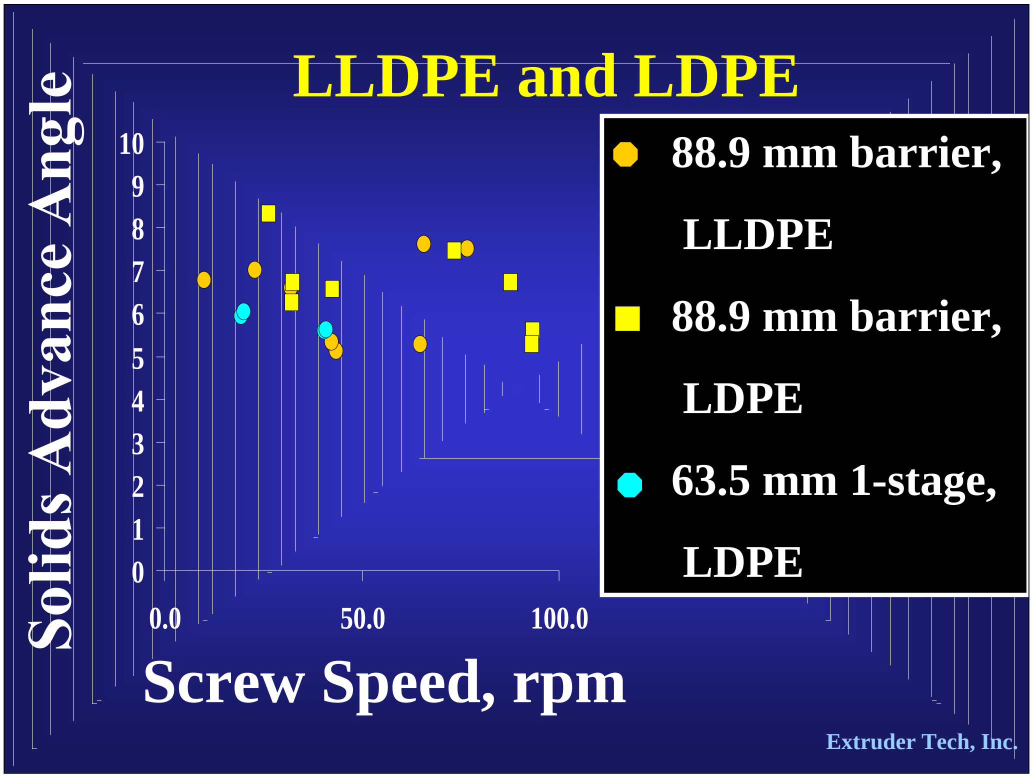
Barrier and single-stage screws performed similarly.



However, the solids advance angle for two-stage screws is smaller (2.8 degrees) than that for single-stage and barrier screws (4.5 degrees.)

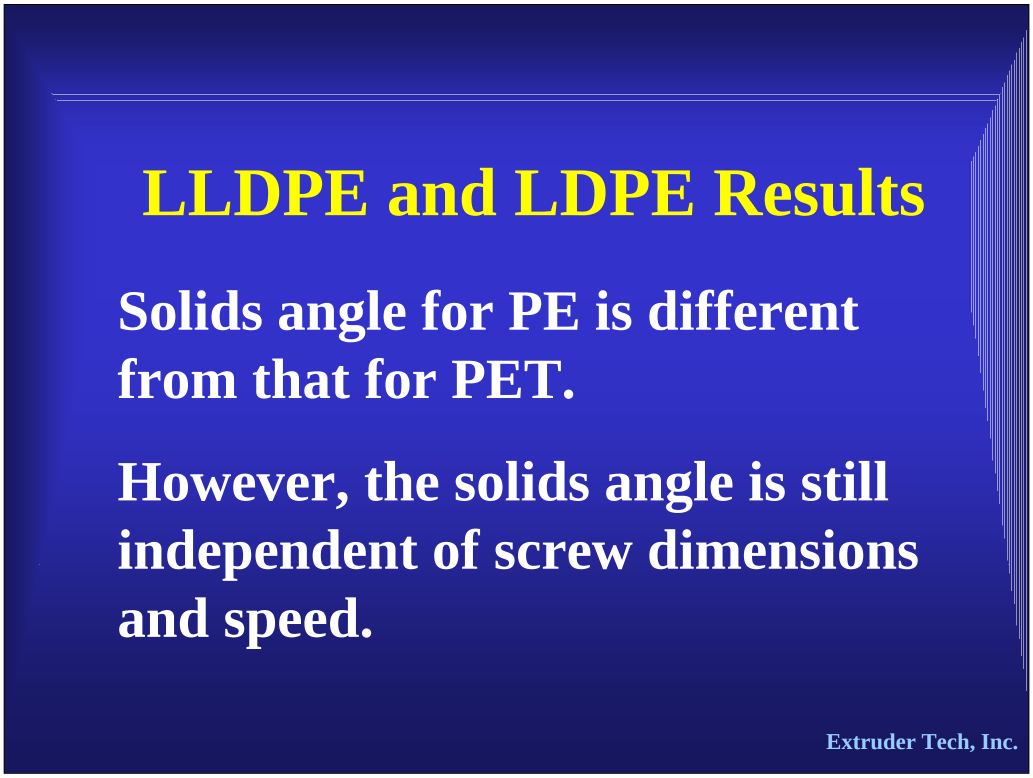


Now to change polymer. Polyethylene data are used from literature as well as my own measurements.



LLDPE and LDPE data show some scatter as compared to the previous PET data.

The scatter may be a result of the various lengths of the solids conveying sections or these screws. It ranged from 4.5 to 6.5 L/D, whereas the screws for PET all had L/D of about 9 to 10.



However, the effects of screw geometry, size, or speed are still not a significant factor.

Solids Advance Angle

What about the effect of pressure on solids advance angle?

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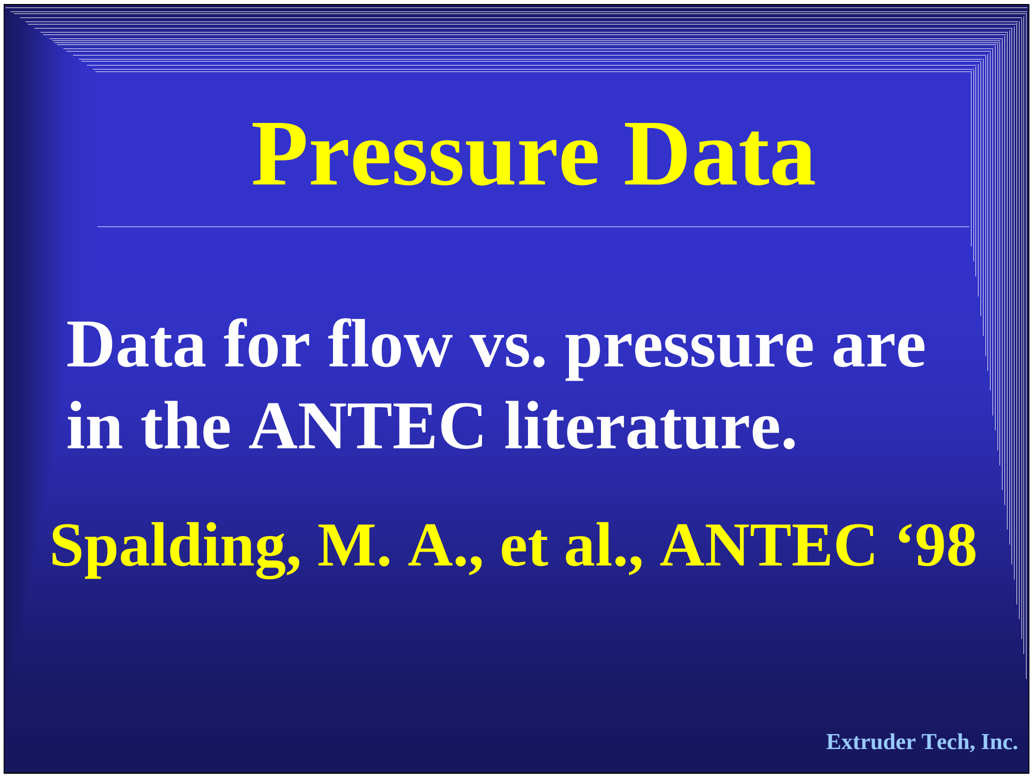
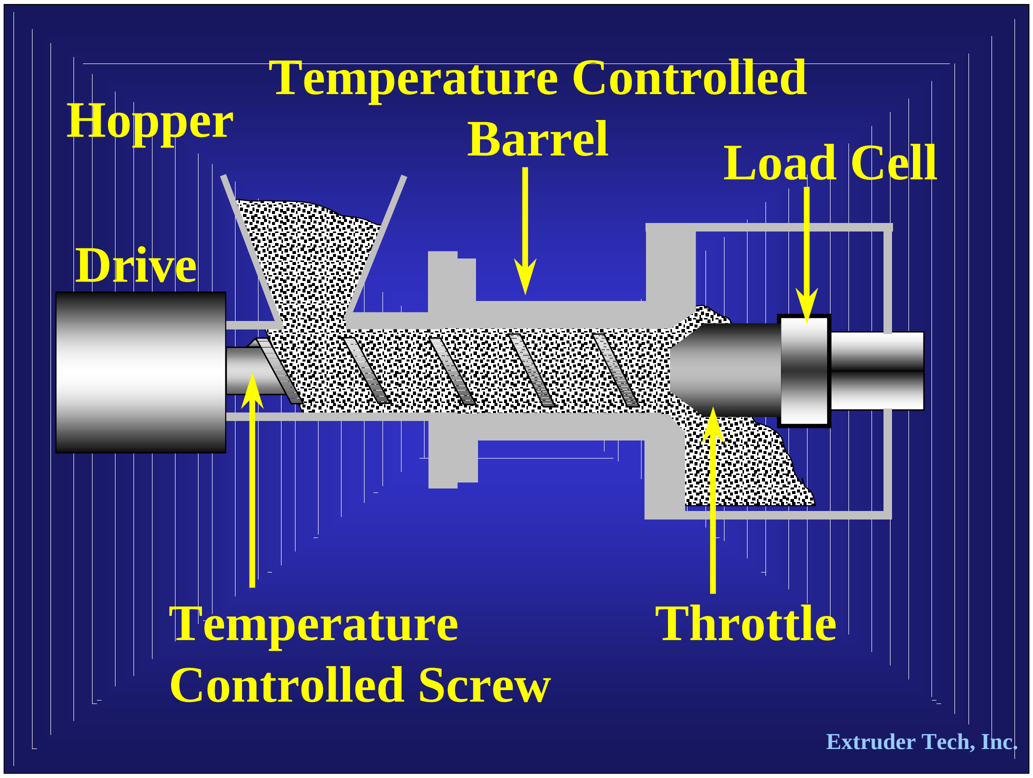
Up to now, pressure has been assumed to be that needed for proper operation of the process. That is, all the data are from stably operating machines. Therefore, the proper pressure must be developed to produce stable melting. This pressure is likely to be relatively constant.

However, the complete picture of the solids angle must include the influence of pressure if it is to be used for calculations and design purposes.



Accurate data for flow versus pressure is not available from operational machines. It must be determined by special experimental means. Such data are available in the literature for LDPE.



The lab device to measure the flow versus pressure for solids conveying is schematically shown. Features are:

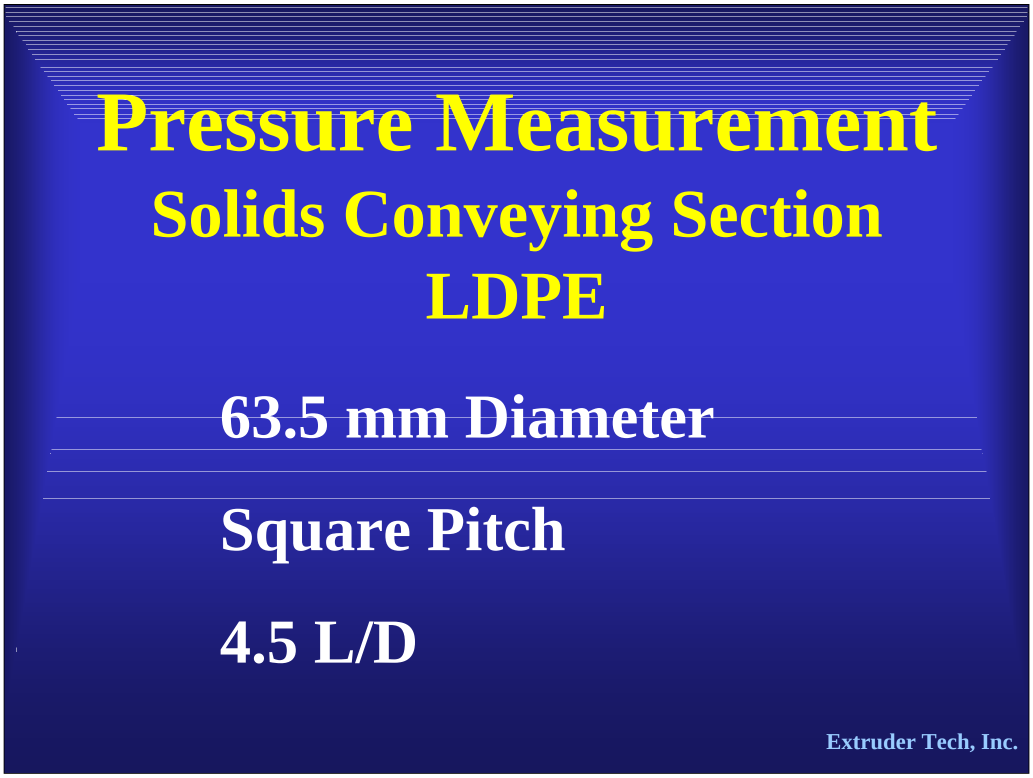
•Temperature controlled barrel

•Temperature controlled screw

• Speed controlled drive

•Throttle to restrict flow

•Load cell to measure force and pressure at the exit



Several factors are constant for the test device.

Pressure Measurement

Four Temperature Combinations

	Barrel	Screw
A	125 ^{o}C	50 ^{o}C
B	125 ^{o}C	100 ^{o}C
C	100 ^{o}C	50 ^{o}C
D	100 ^{o}C	100 ^{o}C

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Four combinations of barrel and screw temperatures are used.

Pressure Measurement LDPE Data

	Channel Depth	Screw Speed
⯃	8.9 mm	50 rpm
■	8.9 mm	80 rpm
▲	11.1 mm	50 rpm
◆	11.1 mm	80 rpm

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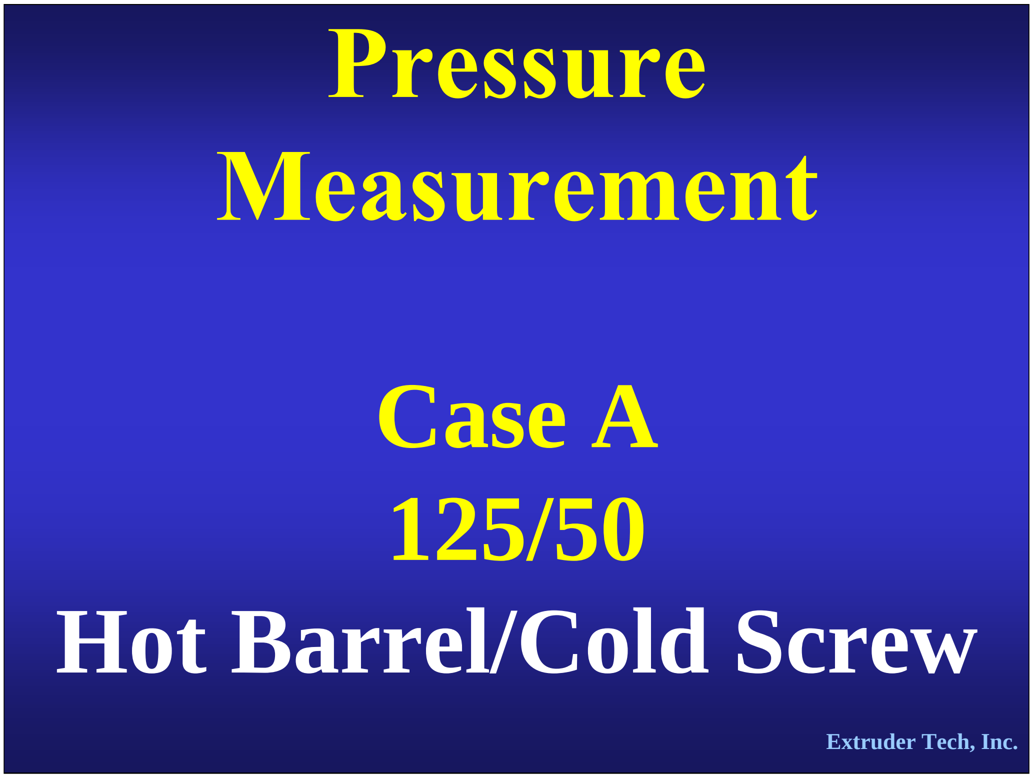
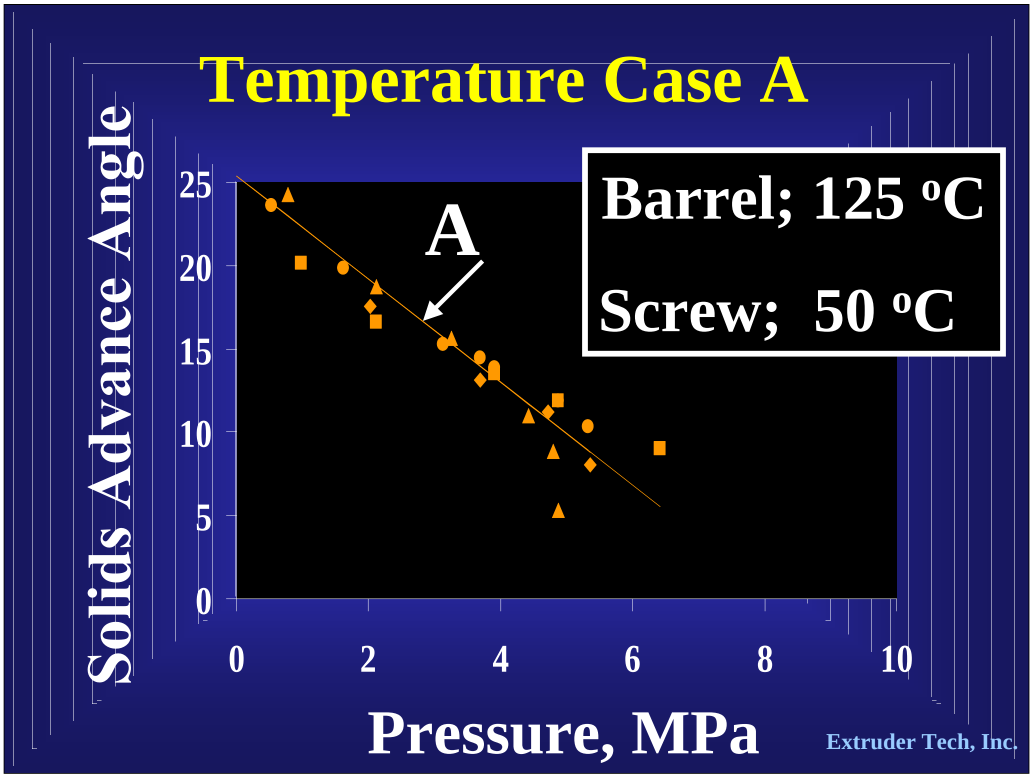
Four combinations of screw channel depth and screw speed are used.



This is the base case, and the best conditions for flow.



The hot barrel and cold screw data show the independence of the solids angle to channel depth and screw speed. A linear relationship is evident for angle versus pressure.

Pressure Measurement

The effect of speed or channel depth is *not* a significant factor on solids advance angle under pressure.

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Just as for PET and PE of operational screws, channel depth and screw speed had little significant affect on the solids advance angle.

Pressure Measurement

Case B
125/100
Hot Barrel/Hot Screw

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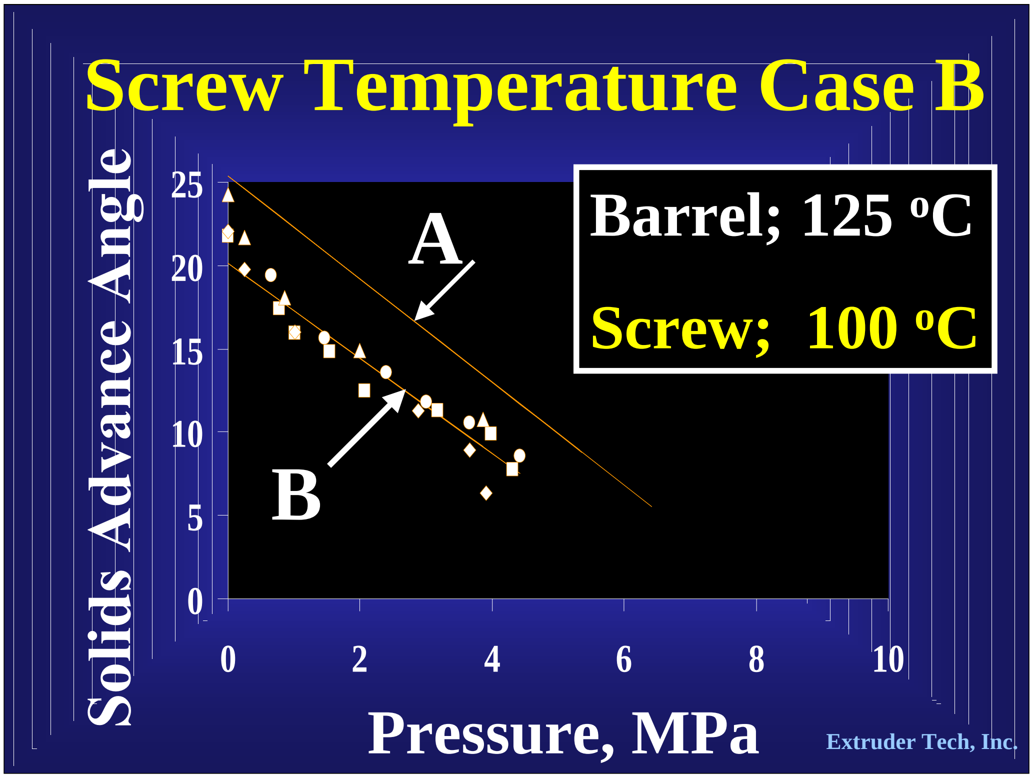
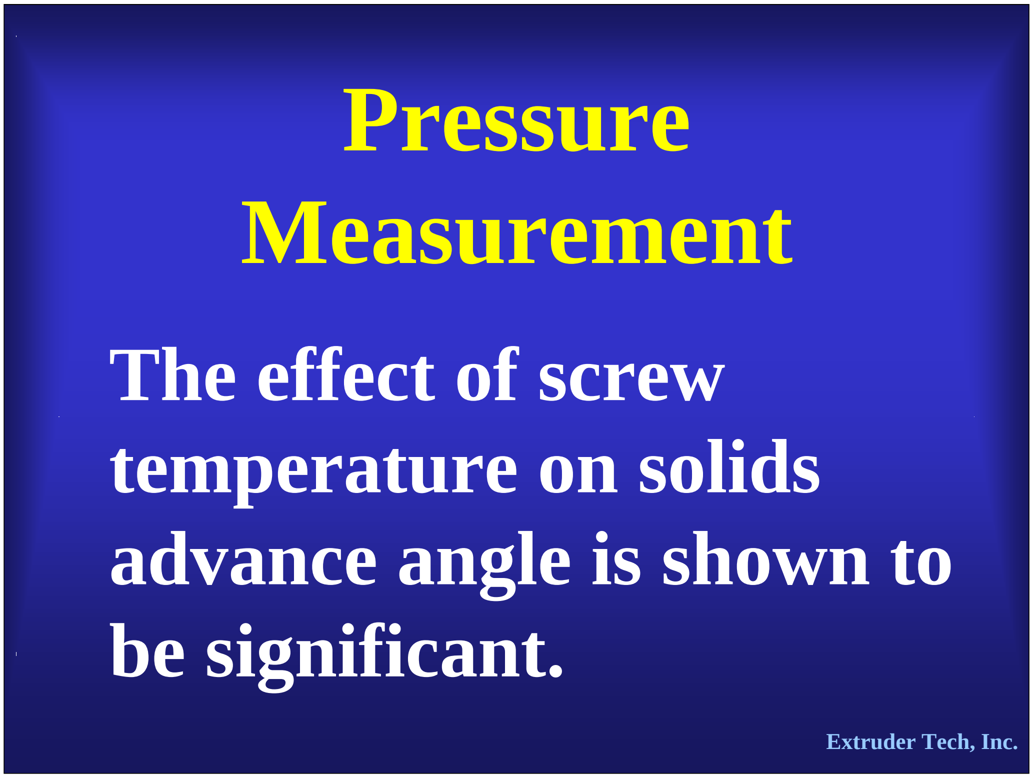
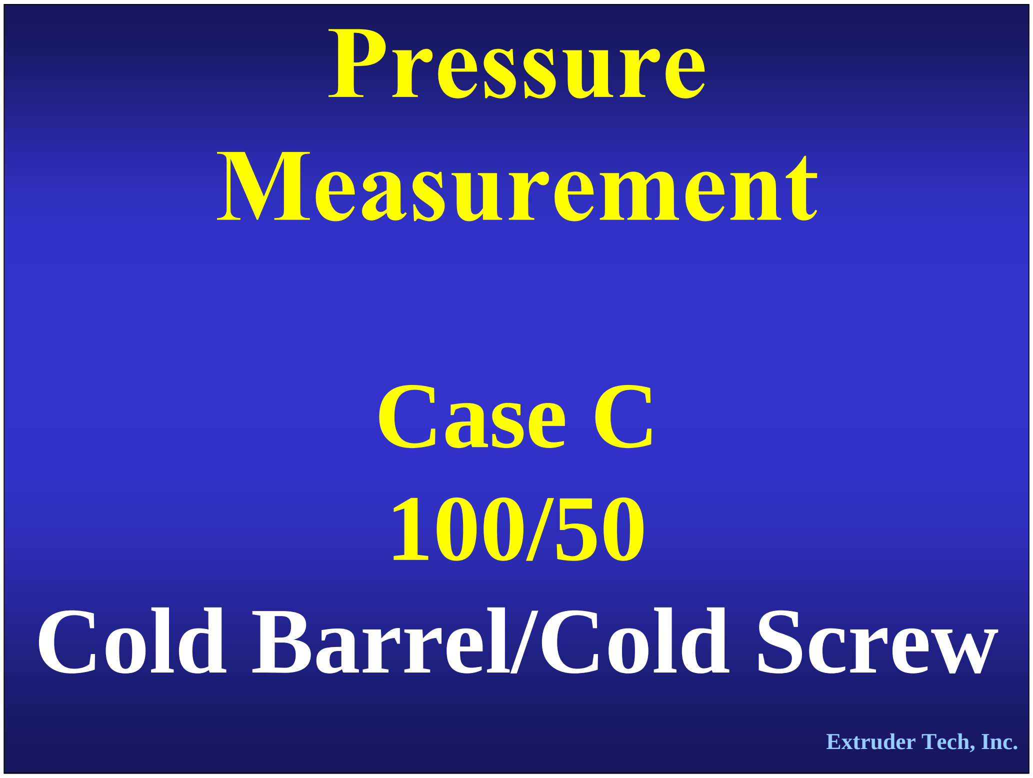
Now for data for a hot screw, but the same barrel temperature.



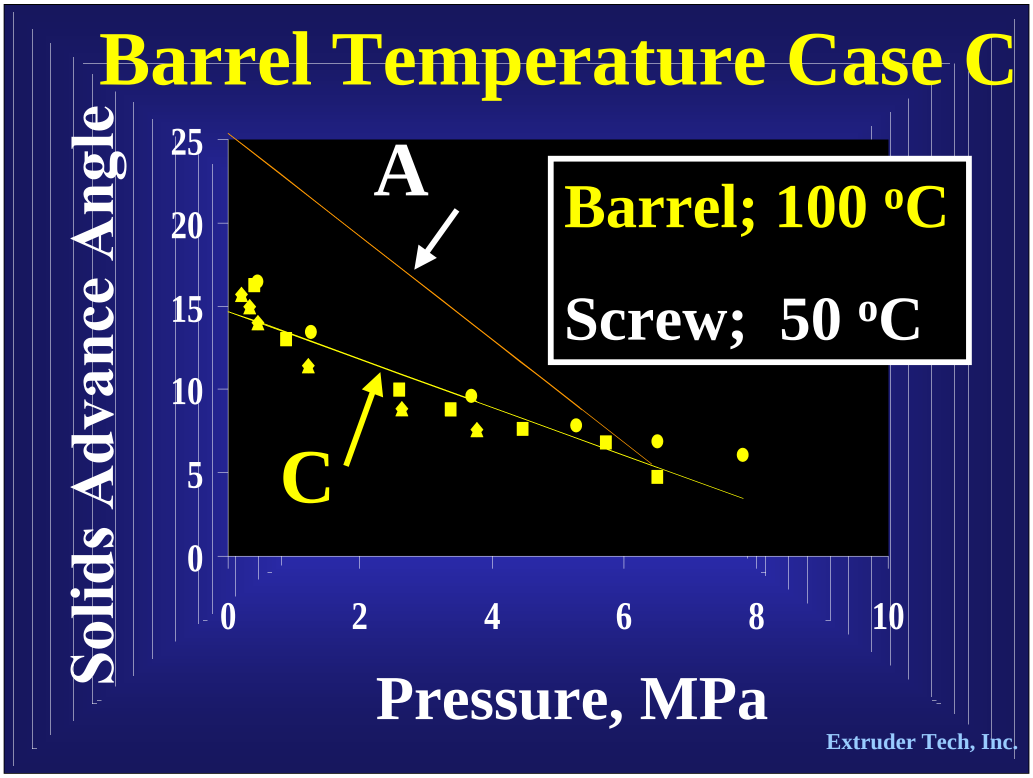
Channel depth and screw speed do not affect the solids angle again. A linear dependence of angle and pressure parallel to that for case A is shown. The solids angle is always lower for the hotter screw.



The data show that screw temperature must be considered in the evaluation of the solids angle.



Now for a cold barrel and cold screw.



A linear relationship of angle to pressure is again evident. Speed and channel depth are not significant. However the slope of the relationship is much lower than that for the hotter barrel.

Pressure Measurement

The effect of barrel temperature on solids advance angle is shown to be very significant.

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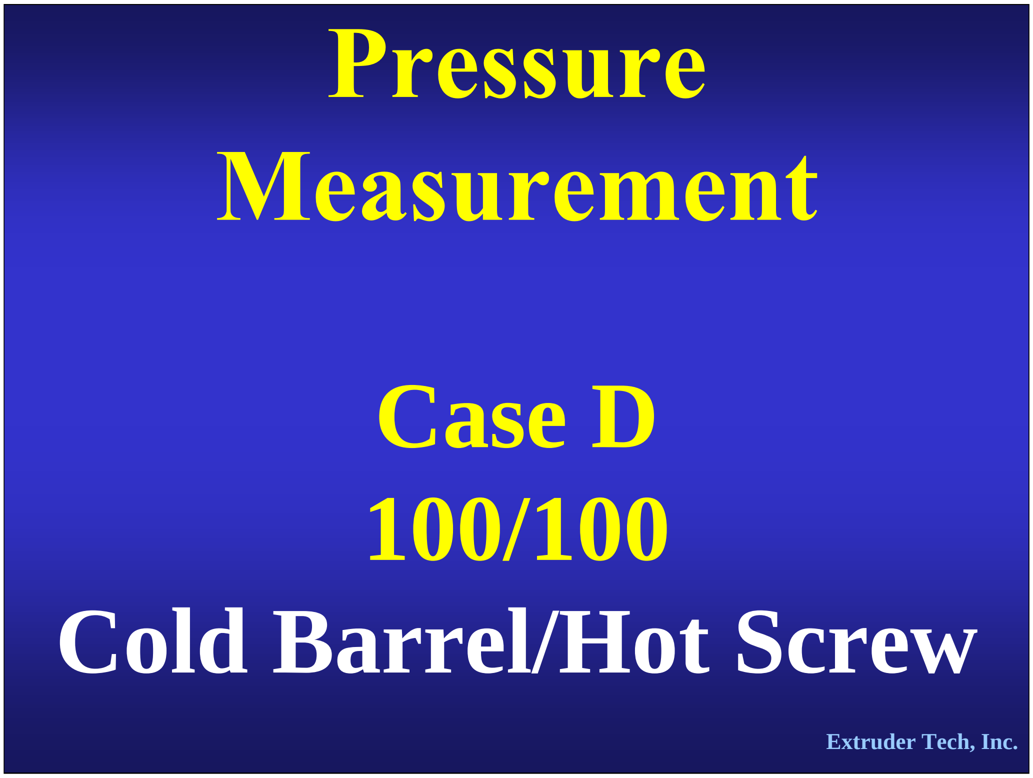
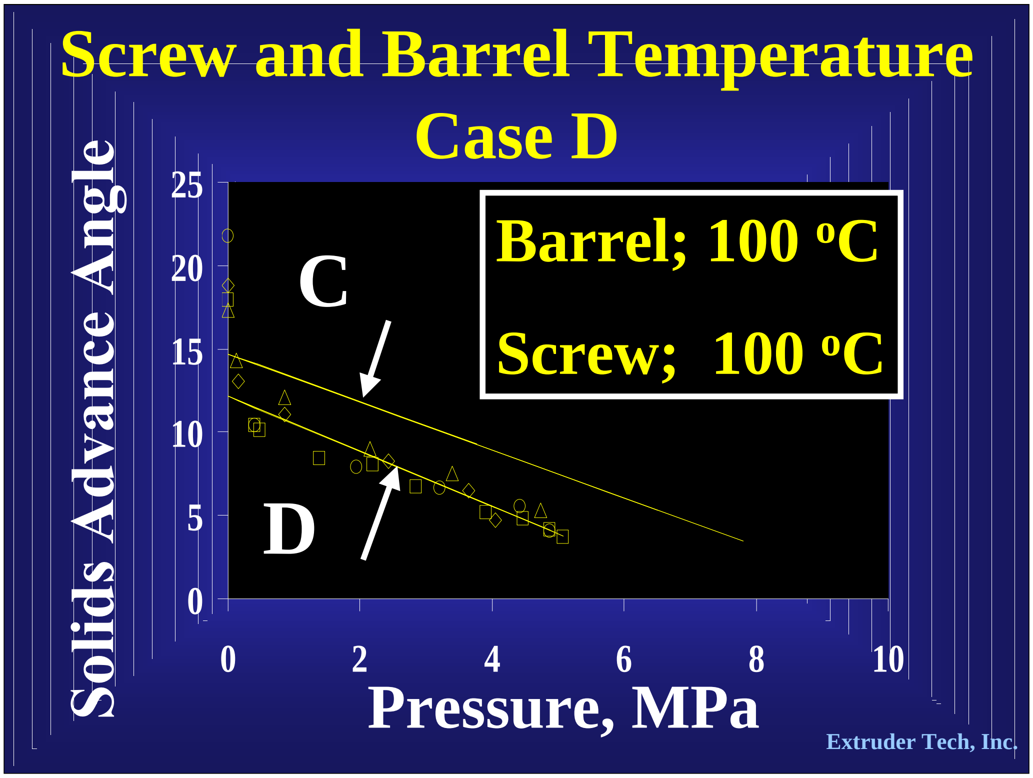
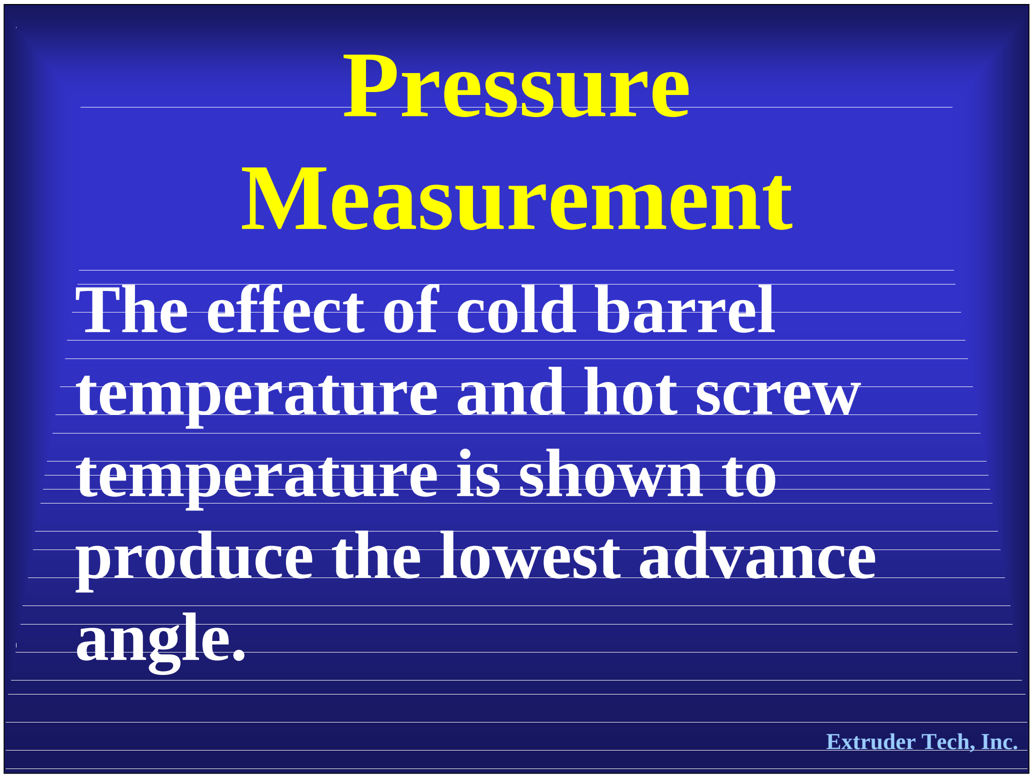
Barrel temperature is very significant because it causes the solids angle to be much lower and to have a much different slope to its linear relationship.



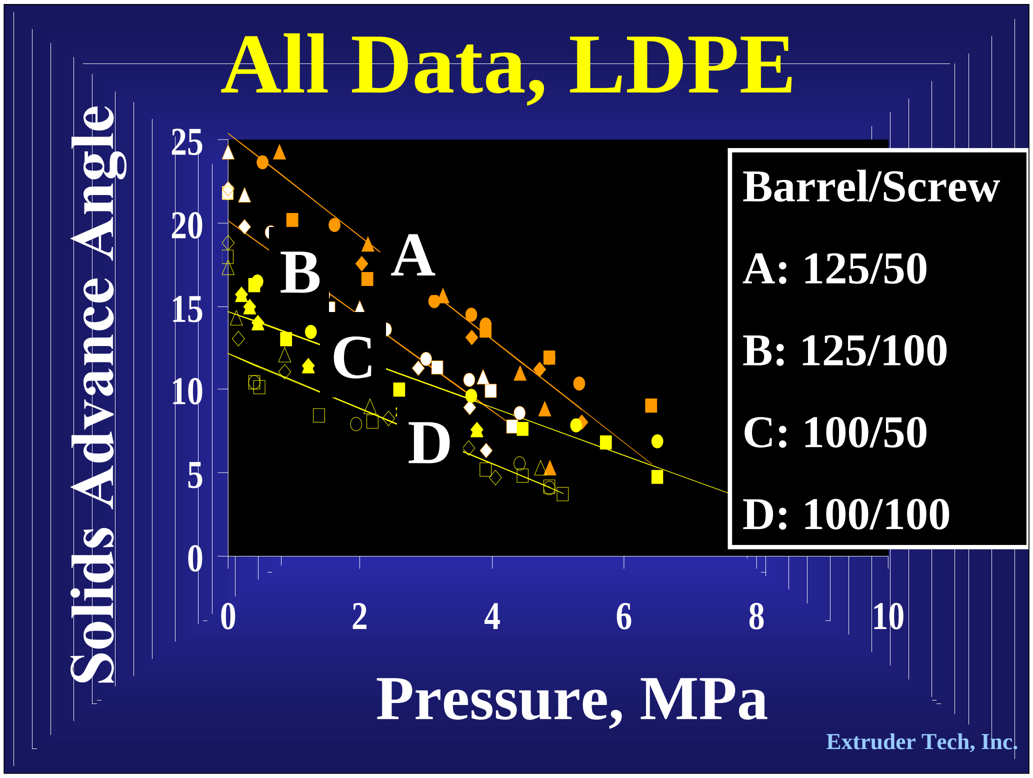
The worst case for solids conveying is the cold barrel and hot screw.



The familiar linear relationship emerges again. The values of solids angle are significantly lower, but the linear relationship is parallel to the case where the barrel was hotter (Case C.)



These conditions are widely known to be detrimental to good solids conveying, and they can lead to plugging or “doughnuts” in the solids conveying section of the screw.

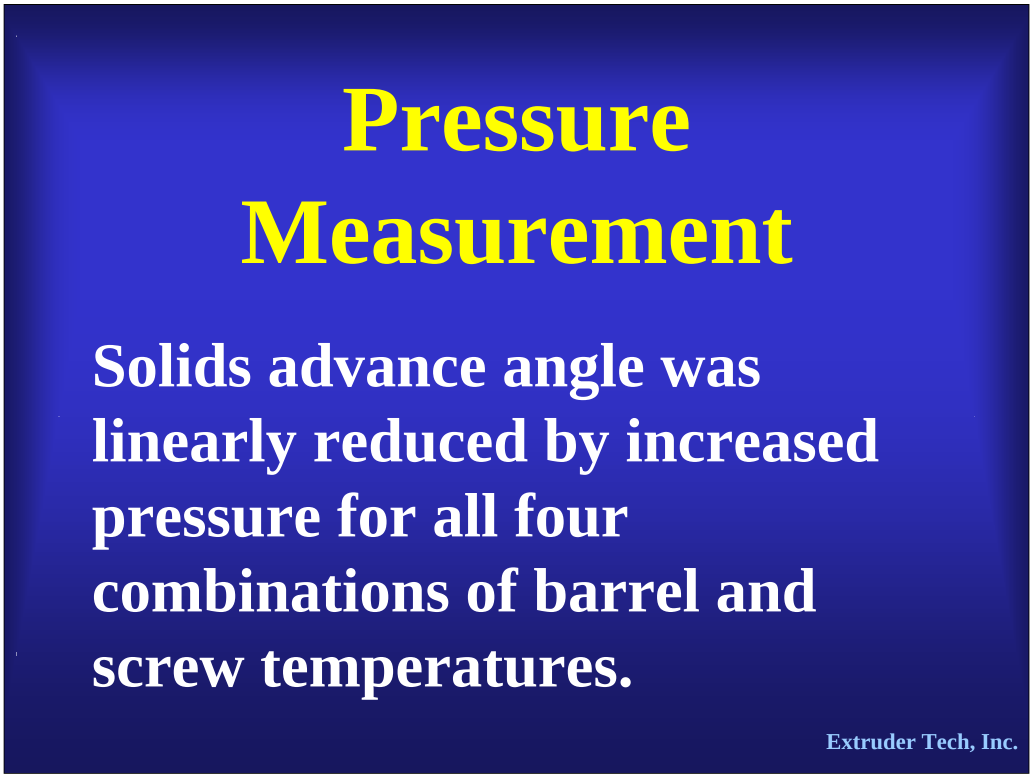


All of the solids angle versus pressure are shown for comparison.

Of note is Case C which has about the same value as case A at about 7 Mpa. Case A was a hot barrel and Case C was a cold barrel. So, if operating at 7 Mpa, one would not see any difference in operation from changing barrel zone temperature setting if the pressure was 7 MPa. However, at lower pressures, barrel zone temperature would cause a change in angle and flow.

Also, at pressures higher than 7 Mpa, Case C would have a higher solids angle (and flow) than Case A. What is optimum barrel temperature at pressures below 7 Mpa, is not optimum pressures above 7 Mpa.

Since it is not apparent from an operating machine what the pressure at the end of the solids conveying portion may be, one cannot tell if a change in barrel temperature will raise or lower the solids angle (and flow), or have not affect at all. A specific barrel temperature for a given polymer will not always provide the optimum performance.



The linear relationship of solids angle to pressure is very easily quantified for use in solids conveying calculations. It does not contain the scatter and discontinuities normally found in friction factors. The resulting kinematics model is robust and easily computed.

Conclusions

Solids advance angle is independent of

- extruder diameter,
- channel depth, and
- screw speed.

Conclusions

Solids advance angle depends on

- **polymer type,**
- **barrel temperature,**
- **screw temperature, and**
- **decreases linearly with pressure.**

Conclusions

The kinematics model with the solids advance angle can be used to calculate solids conveying flow without the direct use of ambiguous friction factors.

Kinematics of Solids Conveying

For more information and spread sheets for calculations with the kinematics model, go to:

www.extrudertech.com

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