injection machine rheology. This is why we Universal molders prefer rheology by power.

If we substitute the definition of relative shear stress ($\tau_R = P_H \times R_i$) and relative shear rate ($\dot{\delta}_R = 1/T$) into the equation for viscosity ($\tau = \mu\dot{\delta}$), we get:

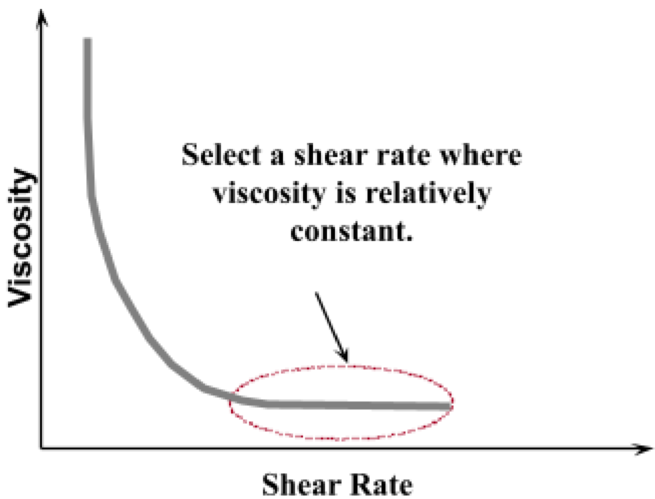
$$\mu_R = P_H R_i T$$

According to this equation, relative viscosity μ_R is simply determined by reading the hydraulic pressure and the injection time; then multiplying both by the intensification ratio.

Remember, if the injection unit reads plastic pressure and not oil (hydraulic) pressure, the equation would be:

$$\mu_R = P_P T$$

We then create a graph of viscosity versus shear rate and select a shear rate where the corresponding viscosity is relatively constant.



VII-9. Zone where the change in relative viscosity is minimal

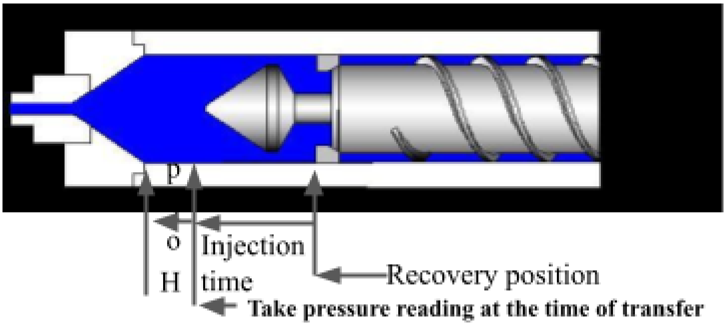
The idea is to select an injection time in which the melt is at its lowest viscosity and relatively constant. The lower the viscosity the easier the melt flows and, as a result, the more efficient the fill.

Notes:

- These viscosity and shear rate equations should only be used in rheology for injection molding machines. Do not use these values for other calculations or other scientific work.
- If the injection unit provides the melt pressure, shear stress τ_R is equal to the pressure reading of the plastic melt, or $R_i = 1.0$.
- Although these equations do not represent the effects of viscosity and shear rate, they have standardized the determination of injection time. If you are not comfortable with these equations, use rheology by power.

Reading the values

Pressure is read at the time of transfer (change from injection to hold), and time is equal to the duration of the injection stage.



VII-10. Readings of transfer pressure and injection time

We use transfer pressure for convenience. The average pressure would be more representative; however, very few machines provide that reading.

These graphs are traditionally created by injecting at various injection speeds. For each injection speed, injection time and injection pressure readings are taken at the time of transfer. Then their corresponding coordinates are calculated.

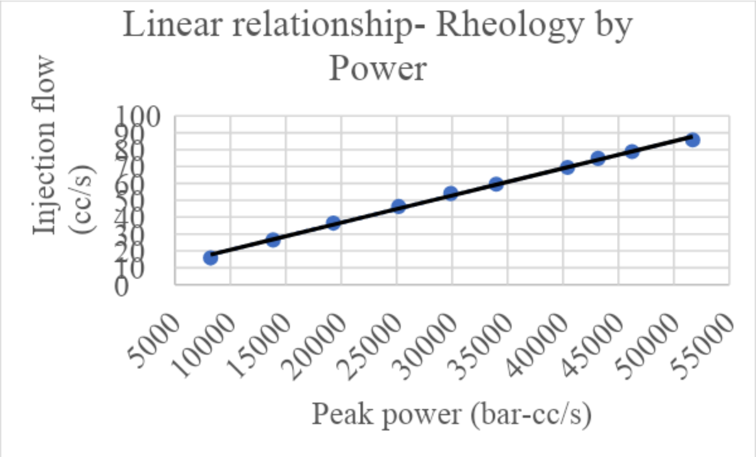
During the development of ***Universal Molding***^{TM}, it was established that the determination of the injection process parameters would have standardized procedures and corroborated equations. The next chapter will discuss the recommended procedures in detail.

Developing these graphs takes time and resources. We have developed a more efficient method called “approximated rheology”. Students from the University of Puerto Rico at the Mayagüez campus, under the supervision of Dr. Ivan Baigés, were the ones who initiated this simple technique.

Approximated Rheology

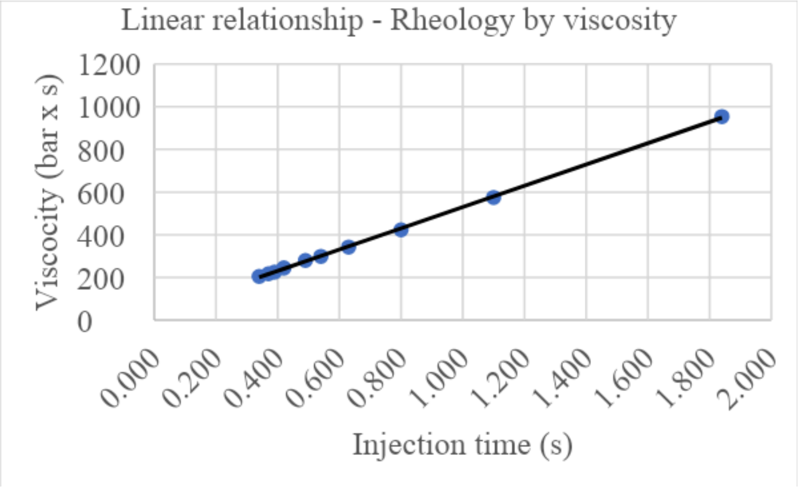
Developing a rheology lab for an injection machine consumes time and resources. With approximated rheology, a mathematical prediction technique, the laboratory is performed in less than a 3rd of the time. Let's see how.

If you work with rheology by power, you will notice that there is a relatively linear relationship between injection flow and peak power.



VII-11. Graph of linear behavior between injection flow and peak power

If you work with rheology by viscosity, there is a linear relationship between relative viscosity and injection time.



VII-12. Graph of linear behavior between relative viscosity and injection time

Both graphs reveal that the intermediate points on the graph can be approximated by the simple function of the equation of a line, $Y = Y_o + MX$. Let me explain, by knowing slope M and the intercept Y_o on the Y axis, we can predict intermediate points.

Example:
In the optimization of a process injecting a volume of 29.17cc, the injection time and transfer pressure readings were obtained at two injection speeds:

Vel (mm/s)	**T_{inj} (s)**	**P_{tran} (bar)**
193	0.34	602.7
19	1.84	518.5

VII-13. Example of injection times and transfer pressures

Using the equations shown above:

$$\text{Average injection flow} = \frac{\text{Injection volume}}{\text{Injection time}}$$

$$\text{Peak power} = \left\{ \text{Average injection flow} \right\} \text{X} \left\{ \text{Pressure at the time of transfer} \right\}$$

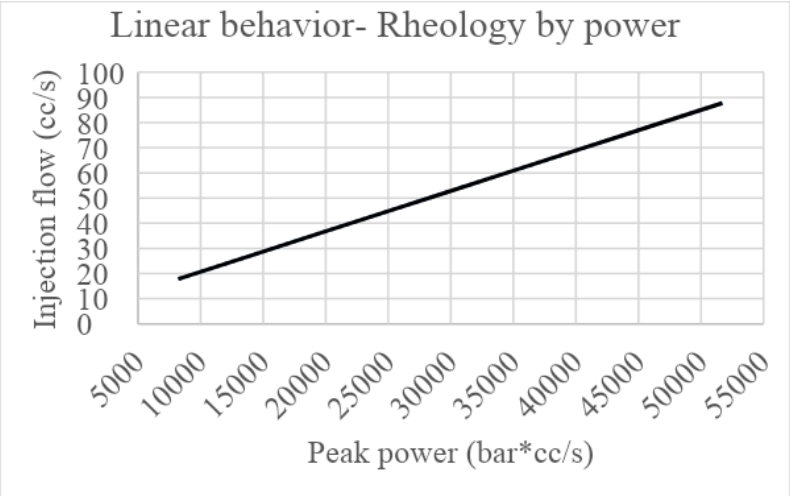
Relative viscosity = Plastic pressure x Injection time

$$\text{Shear rate} = \frac{1}{\text{Injection time}}$$

We calculate and add the values in the following table:

Inj. Vol. = 29.17 cc			**Rheo. by Power**		**Rheo. with Viscosity**	
Vel. (mm/s)	T_{inj} (s)	P_{Tran} (bar)	Flow (cc/s)	Power (bar*cc/s)	V_{shear} (1/s)	Visc. (bar*s)
193	0.34	602.7	85.79	51708	2.94	204.9
19	1.84	518.5	15.85	8220	0.54	954.0

VII-14. Examples of rheology values

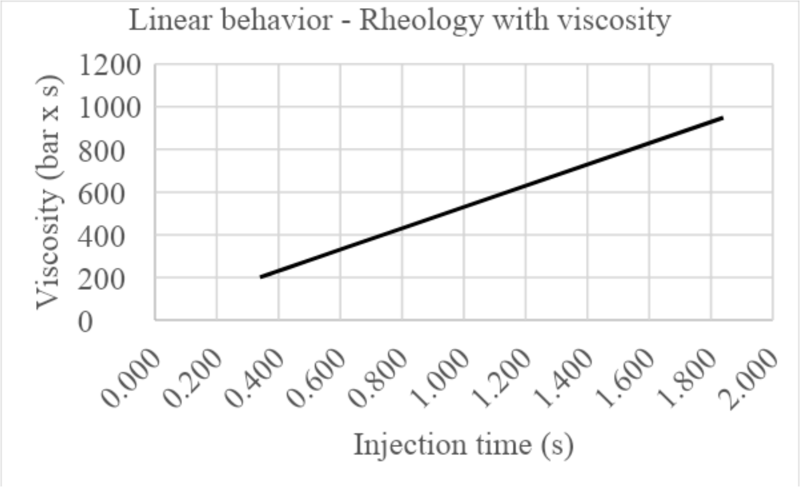


VII-15. Graph of the linear effect between average injection flow and peak power

The linear equation of rheology by power would be:

$$\text{Flow} = 0.0016 \times (\text{Power}) + 4.5962$$
or
$$\text{Power} = (\text{Flow} - 4.5962) / 0.0016$$

Now let's look at the linear equation of rheology with viscosity:



VII-16. Graph of the linear effect between relative viscosity and injection time

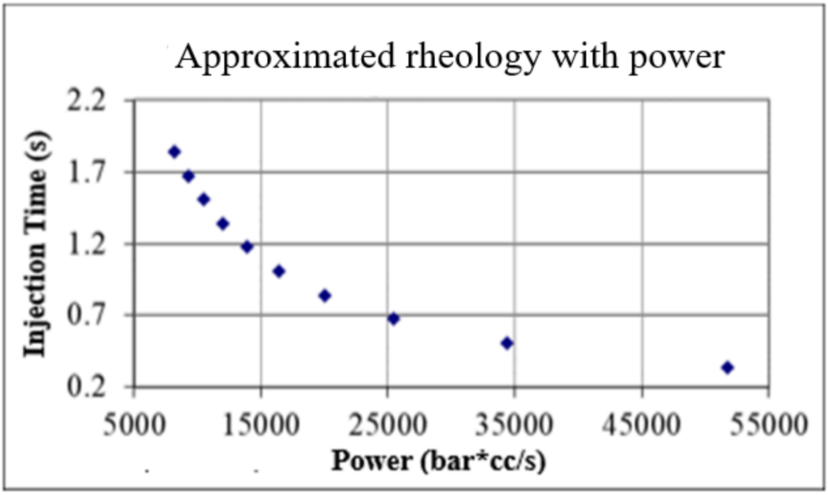
The equation would be:

$$\text{Viscosity} = 498.8 \times (\text{Injection time}) + 31.322$$

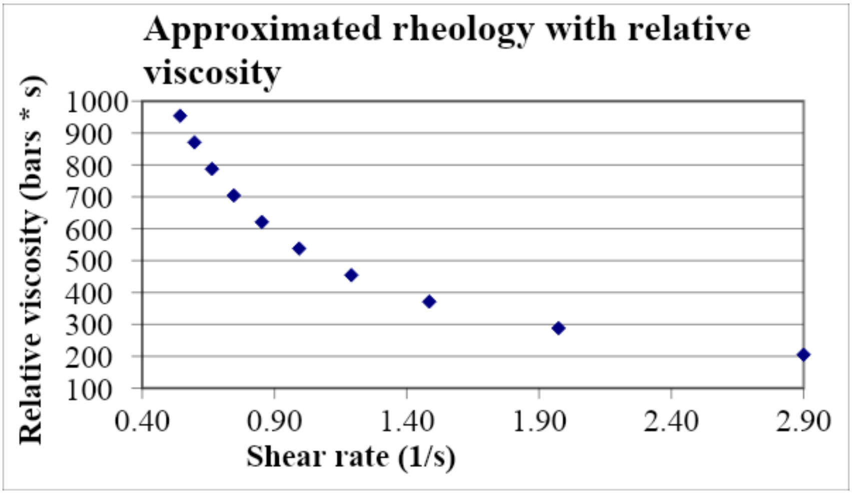
The next step is to determine eight injection times equidistant between the existing times, T_{inj}. Then complete the calculation of the corresponding average injection flow and changing rate for each injection time added.

Inj. Vol. 29.17 cc			**Rheo. by power**		**Rheo. with viscosity**	
Vel (mm/s)	**T_{inj} (s)**	**P_{Tran} (bar)**	**Flow (cc/s)**	**Power (bar*cc/s)**	**V_{shear} (1/s)**	**Visc. (bar*s)**
193	0.34	602.7	85.79	51708	2.94	204.9
	0.51		57.57	34337	1.97	284.0
	0.67		43.32	25430	1.49	367.2
	0.84		34.73	20058	1.19	450.3
	1.01		28.98	16465	0.99	533.4
	1.17		24.86	13892	0.85	616.6
	1.34		21.77	11960	0.75	699.7
	1.51		19.36	10455	0.66	782.8
	1.67		17.43	9249	0.60	866.0
19	1.84	518.5	15.85	8220	0.54	954.0

VII-17. Table with 8 equidistant injection times

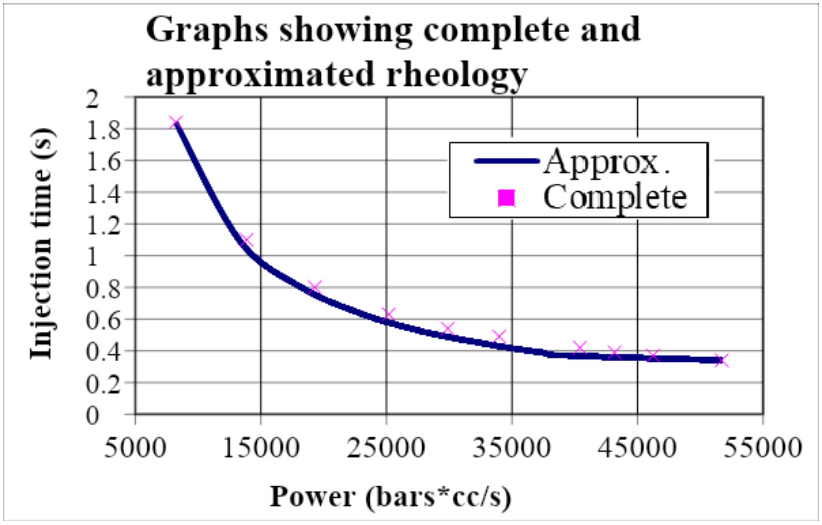


VII-18. Graph of approximated rheology by power



VII-19. Graph of approximated rheology using relative viscosity and shear rate

Now let's superimpose the graph of an approximated (two-point) rheology with the graph showing a complete (ten-point) rheology.



VII-20. Superimposed graphs of complete and approximated reology

This graph shows that approximated rheology is very close to complete (ten-point) rheology, which makes it a timesaving, beneficial option.

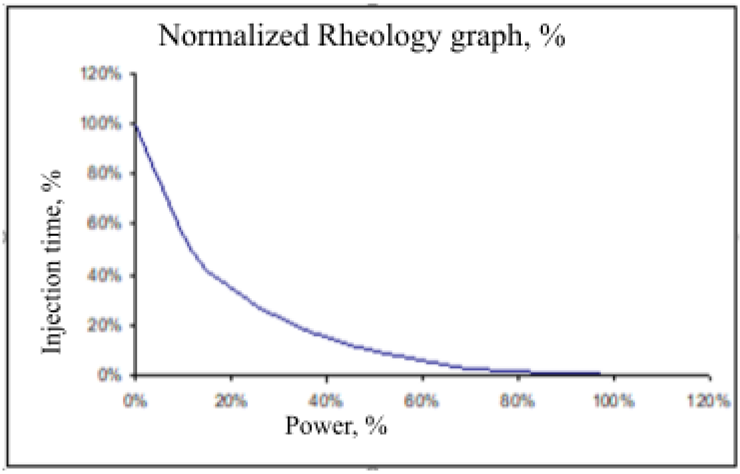
Again, we Universal molders prefer rheology by power because definitions describe the effect with more conviction. You can use the method which makes you feel more comfortable; both rheologies lead to good results.

Equation to Predict Injection Time.

During the development of ***MU***^{TM} it was established that all parameters must be determined by clear procedures and equations. This was done in order to ensure similar results between molders.

If the selection of injection time depended on an individual's criterion, then it would be impossible to obtain similar results between molders. Using the criteria of multiple molders, who have a clear understanding of machine rheology, this situation was resolved. With rheology graphs with their coordinates normalized in percentages and simple statistics, the selection trend of some Universal molders was determined.

With several graphs such as the one illustrated, the following question was asked: Where does the plateau begin?



VII-21. Graph of standardized rheology in %

The average of this entire population was evaluated, and the following formula was obtained:

$$\mathbf{T_{plateau}} = T_{min} + (T_{max} - T_{min}) / 9$$

Where:

- $\mathbf{T_{min}}$ - Injection time corresponding to the maximum injection speed
- $\mathbf{T_{max}}$ - Injection time corresponding to the minimum injection speed
- $\mathbf{T_{plateau}}$ - Injection time where the plateau starts on the graph

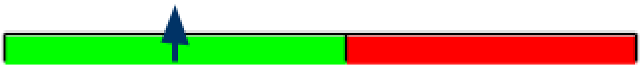
This equation calculates injection time, where the rheology curve begins to be relatively constant. Based on this simple calculation, we determine that the ideal injection time should be less than that obtained by the equation.

$$T_{\mathbf{Ideal}} < T_{min} + (T_{max} - T_{min}) / 9$$

The ideal injection time will depend on the type of industry. Conventional molding industries should select an ideal injection time in the center of the plateau. Industries that mold materials sensitive to friction as a result of high injection rates, such as the rigid PVC fittings industry, should be close to $T_{plateau}$. High-volume injection industries, such as cap manufacturers, should be close to $T_{min.}$

Let's take a closer look:

Conventional molding industries – Select an ideal injection time between $T_{plateau}$ and T_{min}.

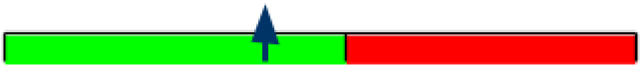


T_{min}
T_{max}
$T_{plateau}$

$$T_{\mathbf{intermediate}} = (T_{plateau} + T_{min}) / 2$$

VII-22. Injection time for conventional molding industries

Industries that mold friction-sensitive materials (such as manufacturers of rigid PVC fittings) - For materials that degrade at high speeds, select an ideal injection time near $T_{plateau.}$

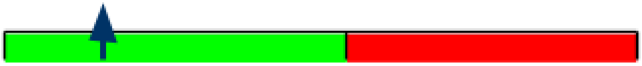


T_{min}
T_{max}
$T_{plateau}$

$$\mathbf{T_{sensitive}} = T_{min} + \tfrac{3}{4} (T_{plateau} - T_{min})$$

VII-23. Injection time for industries that mold friction-sensitive materials

High-volume injection industries (such as cap manufacturers) - Select an ideal injection time near T_{min}.



T_{min}
T_{max}
$T_{plateau}$

$$\mathbf{T_{fast}} = T_{min} + \tfrac{1}{4}\,(T_{plateau} - T_{min})$$

VII-24. Injection time for high-volume injection industries

If we replace the definition of the plateau time ($\mathbf{T_{plateau}} = T_{min} + (T_{max} - T_{min}) / 9$) within each of the three previous equations and simplify, we get:

Conventional molding industries

$$\mathbf{T_{intermediate}} = T_{min} + (T_{max} - T_{min}) / 18$$

Industries that mold sensitive materials

$$\mathbf{T_{sensitive}} = T_{min} + (T_{max} - T_{min}) / 12$$

High-volume injection industries

$$\mathbf{T_{fast}} = T_{min} + (T_{max} - T_{min}) / 36$$

After selecting the application type, select the corresponding equation, replace the values of T_{min} and T_{max}, and determine the ideal injection time.

Example: Using the calculated rheology for a $T_{min} = 0.24$ seconds and a $T_{max} = 1.58$ seconds, the corresponding injection times would be:

Average application:

$$\mathbf{T_{intermediate}} = T_{min} + (T_{max} - T_{min}) / 18 = 0.24 + (1.58 - 0.24) / 18$$
$$= 0.31 \text{ seconds}$$

Application of sensitive material:

$$\mathbf{T_{sensitive}} = T_{min} + (T_{max} - T_{min}) / 12 = 0.24 + (1.58 - 0.24) /12$$

$$= 0.35 \text{ seconds}$$

High volume application:

$$\mathbf{T_{fast}} = T_{min} + (T_{max} - T_{min}) / 36 = 0.24 + (1.58 - 0.24) / 36$$
$$= 0.28 \text{ seconds}$$

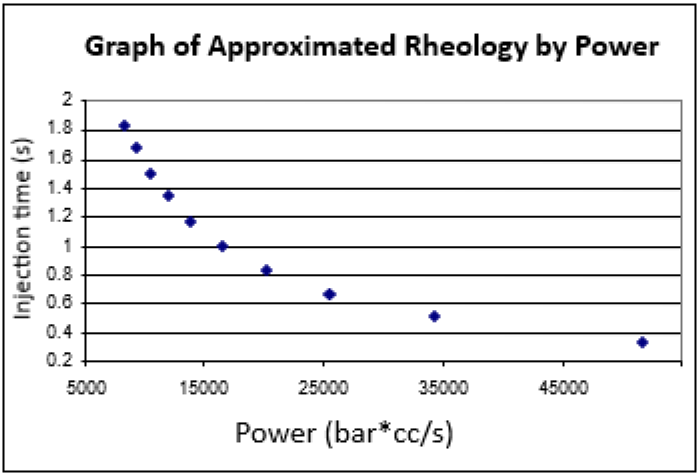
Procedures for obtaining these minimum and maximum injection times will be discussed later.

Questions

1) Using calculated rheology, you can determine the ideal injection time without having to create a graph. For example, depending on the type of industry, the injection time should be less than $T_{min} + (T_{max} - T_{min})/9$. For a T_{min} of 0.24 seconds and a T_{max} of 1.58 seconds, the ideal injection time should be
   a. Shear rate = 0.24+ (1.58 – 0.24)/9
   b. $T_{ideal} < 0.24 + (1.58 – 0.24)/9$
   c. 4 seconds

2) For a process with a total cycle of 3.5 seconds, we use the approximated rheology equation
   a. $T_{intermediate} = T_{min} + (T_{max} - T_{min})/18$
   b. $T_{sensitive} = T_{min} + (T_{max} - T_{min})/12$
   c. $T_{fast} = T_{min} + (T_{max} - T_{min})/36$

3) In the graph of approximated rheology by power shown, an ideal injection time would be
   a. 1 second.
   b. greater than 1 second.
   c. 0.4 seconds.



4) Universal molders prefer machine rheology by power,
   a. because shear rate is graphed against injection power.
   b. because it is graphed with parameters that truly describe the effect being measured, injection time against peak power.
   c. because viscosity versus injection power is graphed here.

5) Peak power
   a. is calculated by multiplying average injection time by the pressure at the time of transfer.
   b. is the maximum plastic pressure reached by the injection unit, usually at the time of transfer.
   c. is obtained by multiplying the average injection flow by the pressure at the time of transfer.

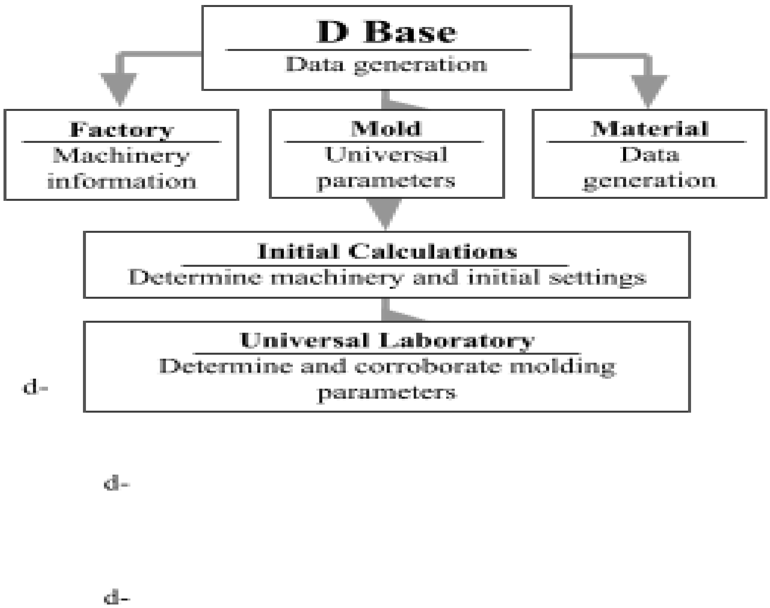
6) Average injection flow
   a. is a function of injection time and the volume of melt filled in the injection stage.
   b. is the maximum plastic pressure reached by the injection unit, usually at the time of transfer.
   c. is obtained by multiplying the average injection flow by the pressure at the time of transfer.

7) The injection volume represents the volume filled from the recovery position to the transfer position.
   a. True
   b. False

VIII. Determining Injection Speed

- **Laboratory I - Understanding Fill and Its Limitations, Determining Minimum Injection Time and Injection Pressure Limit**
- **Laboratory II - Procedure for Determining Minimum Injection Time and Injection Pressure Limit**
- **Laboratory III – Determining Injection Time and Injection Speed**
- **Laboratory IV - Graph of Rheology and Determination of Ideal Injection Time and Speed**
- **Laboratory V - Approximated Graph**
- **Laboratory VI - Injection Time Prediction**

In order to maximize the use of this molding discipline, you must have a clear understanding of the fundamentals of ***Universal Molding***™ and "Molding from the Desk". Understand and identify the needs of your process, and address those needs with well thought-out solutions. ***Universal Molding***™ is a discipline that promotes a structure of organized events.



*VIII-1. Flow chart of **Universal Molding**™ events*

Collect all the information, organize a database, and make that information accessible to everyone in your molding factory.

Include the following:

<u>Molding machine data</u>

- minimum and maximum clamping forces
- ejector pattern
- space between the bars
- minimum and maximum mold width
- maximum mold weight
- injection volume
- maximum injection pressure
- intensification ratio

- special options such as sprues, nozzle valves, etc.

Auxiliary equipment data

- dryer (drying flow, hopper volume, ...)
- TCU (flow, pressure, ...)
- additive feeder
- grinders
- robots
- conveyor belts
- hot runner control, etc.

Mold data

- ejector pattern
- dimensions and opening
- weight
- fill volume
- hot runner
- operational limits
- material or materials to be molded
- mold temperatures
- water flow and pressure drop
- diameter and radius of the sprue bushing, etc.

Data of the material being used

- name of the material and its distributors
- specific melt density
- specific density to environmental conditions
- bulk density of resin
- if hygroscopic, the drying time and temperature
- melt temperature
- suggested barrel temperature profile
- suggested mold temperature
- semi-crystalline or amorphous
- suggested plastic injection pressure, etc.

Once you have all the data of your process, complete your "Molding from the Desk", performing the calculations for drying, the press, the injection unit, cooling, etc.

Finally, determine the optimal molding parameters by performing the ***Universal Molding™*** procedures.

Again, before proceeding with this ***Universal Molding™*** laboratory remember that:

- You must perform the "Molding from the Desk ".
- All auxiliary equipment should be properly installed and operational.
- Temperatures should already have been reached, such as water temperature, injection barrel temperature profile and corresponding melt temperature, hot runner heat zones (if any), etc.
- Barrel adjustments should have been programmed, such as recovery and transfer position, decompression, recovery speed, etc.
- The appropriate nozzle tip must be installed.
- The required clamping force should be adjusted.
- The opening of the platens, their movements, speeds and the mold protection must be carefully and precisely adjusted.
- Extended cooling time must be programmed. Remember that this has to be adjusted longer than is required. To prevent it from interfering with previously determined parameters, it will be optimized at the end.

Important -- only qualified personnel who have read the operational manuals of the equipment and understand the functionality of the equipment should operate and/or adjust them.

Laboratory I. Understanding Fill and Its Limitations, Determining Minimum Injection Time and Injection Pressure Limit

The goal of this lab is to understand the fill's behavior, determining how fast the mold can be filled without causing defects. The maximum speed is determined, its corresponding maximum injection pressure is obtained, and fill limitations, if any, are identified. These fill limitations could be:

- Material degradation or burning as a result of excess speed. For example, PVC tends to burn if the injection speed is high.

- A problem with the vents, such as burns that can occur due to gas combustion, or dieseling. This defect can be corrected by cleaning the vents or, in the worst case, repairing or modifying the mold.
- Equipment limitations, such as an injection unit unable to reach high injection speeds, a limitation that could be a result of an injection unit that is inadequate for the mold.
- etc.

The idea is to identify in advance any defects or limitations that may arise. If any of these defects or limitations occur in the equipment when increasing the injection speed, you must decide whether the modification is simple or complicated. If the remedy is simple, do it. However, if the modification or change is not viable, or is not economically feasible, you will have to carry out the laboratory with that condition. Ideally it would be better to correct the situation before continuing; unfortunately, it is not always possible. For example, in the case of limited injection speed, it would be better to switch to an appropriate injection unit, but if that is economically prohibitive, you will have to work with a limited injection speed.

It is important to understand that not every parameter programmed in the control of the equipment can be reached; therefore, you must ensure that the entered value is being achieved.

The scheduled speed may be limited by an inadequate injection unit, as a result of a low % of utilization. For example, a utilization of 5% might not have the acceleration displacement required by the speed that was entered. Verify that the programmed speed is always being reached.

Procedure for Determining Minimum Injection Time and Injection Pressure Limit

a) Verify that the transfer position from injection to hold was entered. Do you remember how? This procedure was explained in the "Injection Unit Calculations" section.

With machines under 400 metric tons

% of Utilization	35% or less	65% or more	Between 35% and 65%
Transfer	6 mm (0.25 in)	12 mm (0.5 in)	Interpolate

With machines 400 metric tons or larger

% of Utilization	35% or less	65% or higher	Between 35% and 65%
Transfer	12 mm (0.5 in)	25 mm (1.0 in)	Interpolate

VIII-2. Tables to select the injection-to-hold transfer position

b) Turn off the hold stage so that it does not interfere with the determination of the minimum injection time. This could be done by setting the hold pressure to zero. Some injection machines come with the hold stage divided into two, pack and hold. Turn off one of them.

c) Adjust the injection unit to produce parts that are 20% incomplete. This is done to prevent damage to the mold and machine.

Recovery position =
transfer position + 80% of injection displacement

Notes:

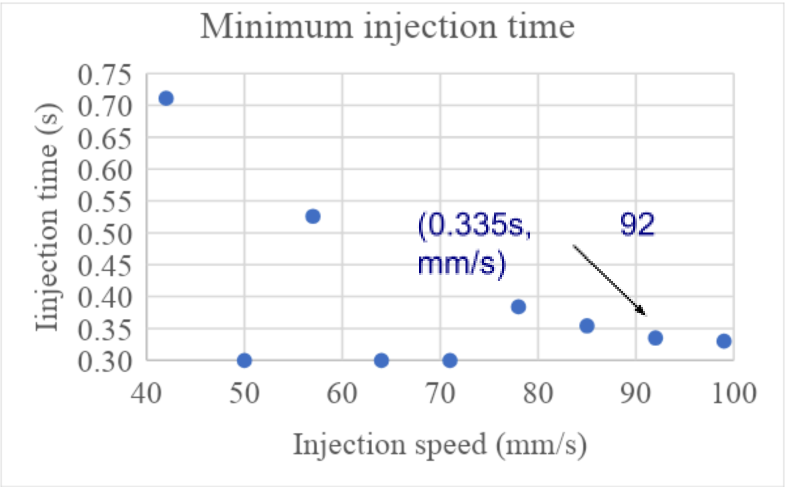
- It is important to maintain a cooling time that is longer than required while determining the minimum injection time.
- You should also be alert during mold closure, to prevent the mold from closing with unreleased parts.
- Turn off alarms that could stop the laboratory, such as the alarm that limits the maximum injection time. Caution: never turn off mold closure protection (mold protect).

d) Find the minimum injection time and maximum injection speed. The idea is to increase the injection speed until the injection time stops decreasing. A safe and practical method is to increase the injection speed and injection pressure limit at the same time, until the injection time stops decreasing. Be cautious and, even if it's easier, don't set the pressure limit to its maximum. It may cause breakage.

During the experiment:

- Verify that parts do not remain trapped in the cavities. You may need to perform this step with the control on semi-automatic.
- If you turned off the hold stage by adjusting the hold time to zero, verify the demolding. If the parts are extremely hot, increase cooling time until the parts demold at a lower temperature.

It is advisable to perform this experiment with a graph of injection time versus injection speed, which will help you determine the minimum injection time. See below.



Pressure (mPa)	Time Inj. (s)	Vel (mm/s)
--------	--------	7
--------	--------	14
--------	--------	21
--------	--------	28
--------	--------	35
151	0.711	42
--------	--------	50
166	0.526	57
--------	--------	64

--------	--------	71
189	0.384	78
196	0.354	85
204	0.335	92
211	0.330	99

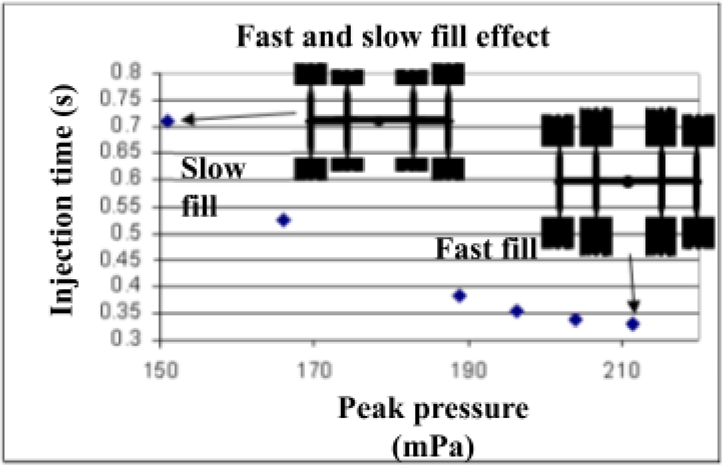
VIII-3. Determination of minimum injection time and maximum injection pressure (example)

The graph of injection time versus injection speed illustrates how, at a pressure of 204 mPa and at 92mm/second, the decrease in time becomes insignificant.

e) Inspect the parts. Although they will be incomplete, make sure you obtain parts free of defects due to degradation.

If the defect requires a simple mold repair, do it and repeat the exercise. However, if the repair is not feasible, the speed at which the defect appeared should be your maximum speed.

Note: the fill of the parts increases with an increase in injection speed.



VIII-4. Effect of injection time on parts fill

This is a normal effect that will not affect the experiment; a slow fill produces incomplete parts and a fast fill will produce parts that might appear to be totally full. Even though the recovery position was adjusted