Injection Molding

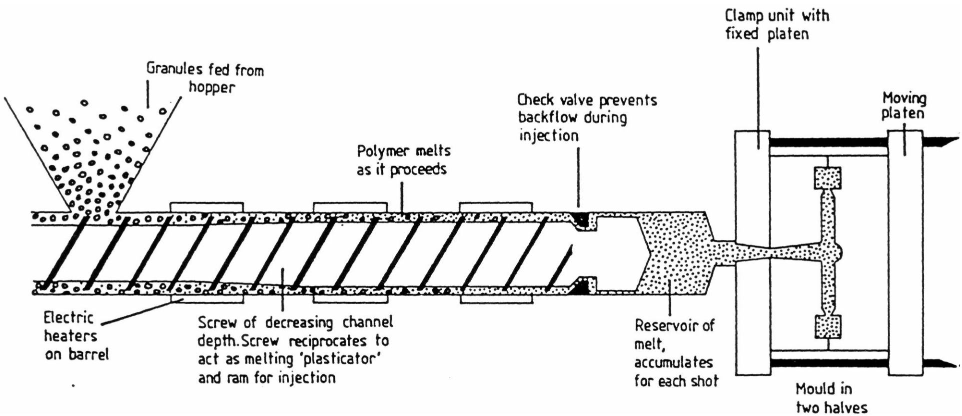
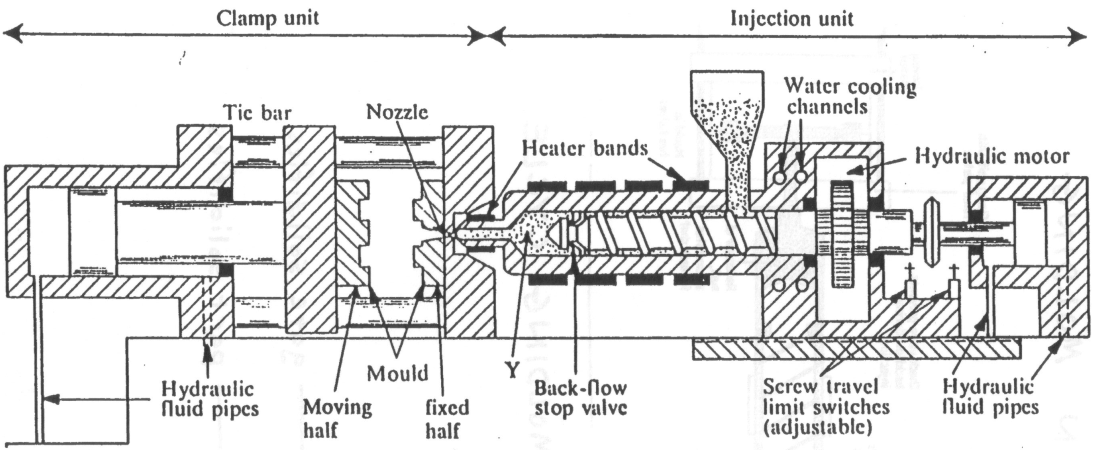


Figure 1: Principles of injection molding.

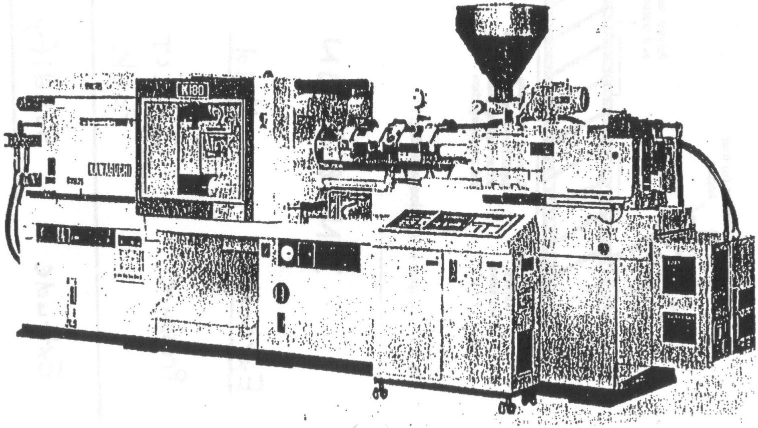
Injection molding cycle:

Extruder	***Mold***	
Pressure	Inject	
	Pack	gate solidifies
Extrude	Solidify	
		part solidifies
	Open Mold	
	Eject Part	
	Close Mold	

Injection Molding



180 Ton Machine



Injection Molding ECONOMICS

Injection molding machine is expensive.

Mold itself is expensive - Need **mass production** to justify these costs.

$$N = \text{total number of parts}$$

$$n = \text{number of parts molded in one shot}$$

$$t = \text{cycle time}$$

$$\begin{aligned} \text{Production Cost (\$/part)} &= \text{Material Cost} \\ &+ \text{Mold Cost}/N \\ &+ \text{Molding Machine Cost (\$/hr)} * t/n \end{aligned}$$

Injection Molding
EJECTION

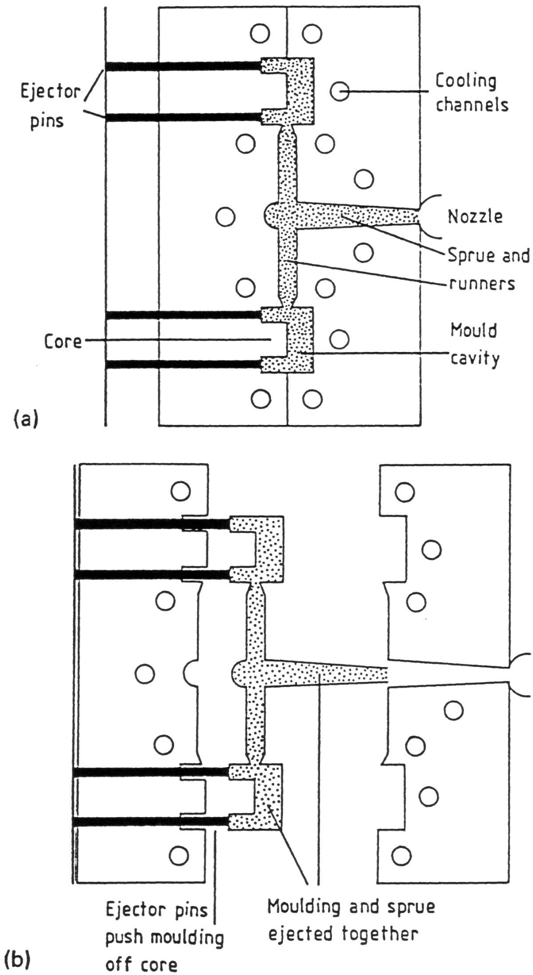
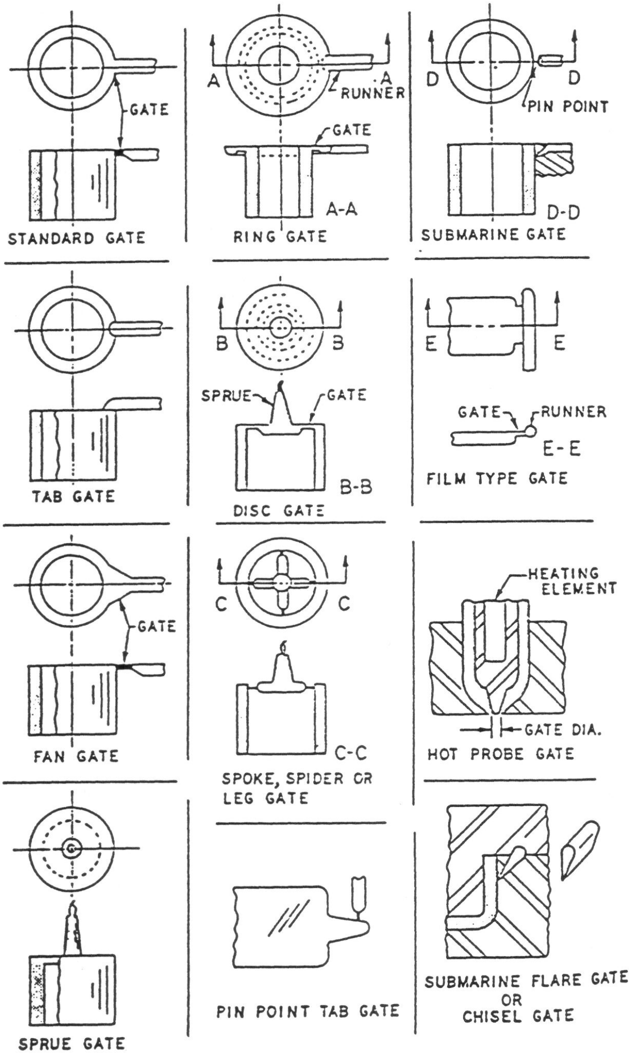


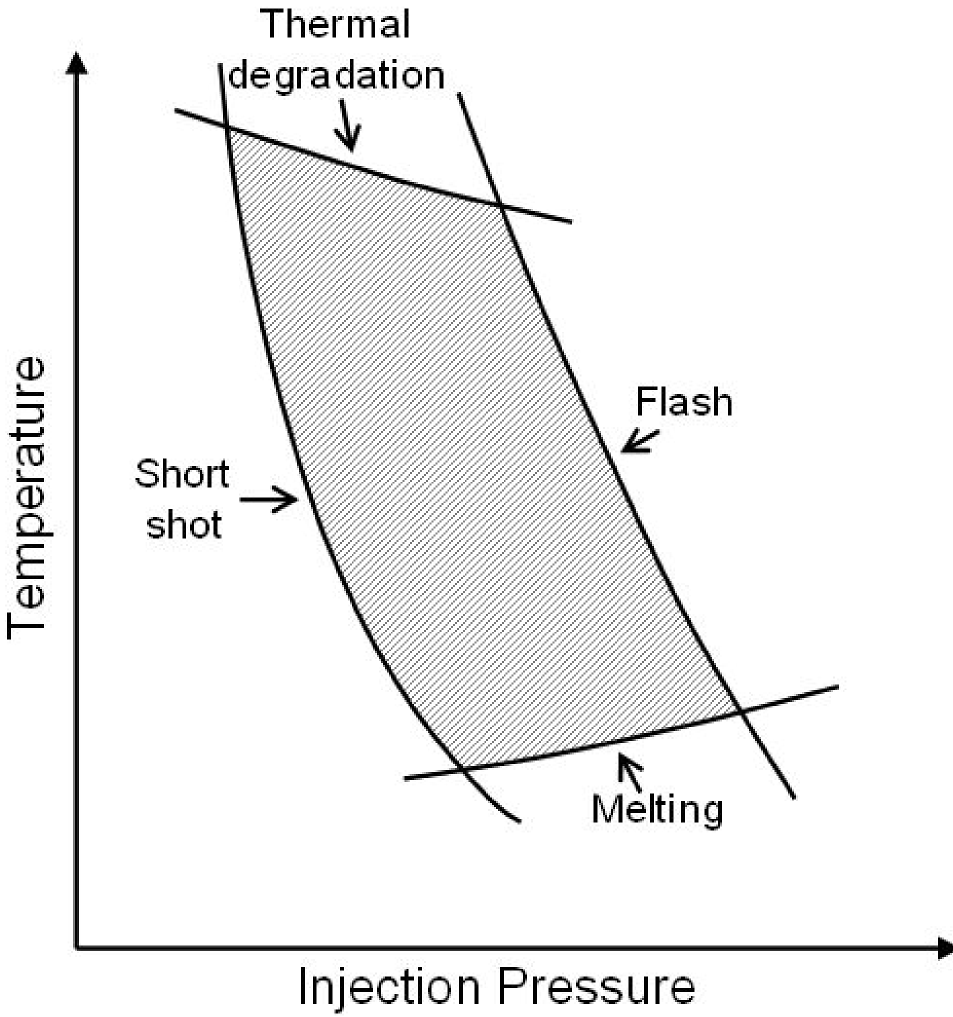
Figure 2: The molded part **cannot** have any enclosed curves or the part will not eject from the mold!

Injection Molding
TYPES OF GATES



Injection Molding

THE INJECTION MOLDING WINDOW



Injection Molding
CENTER-GATED DISK

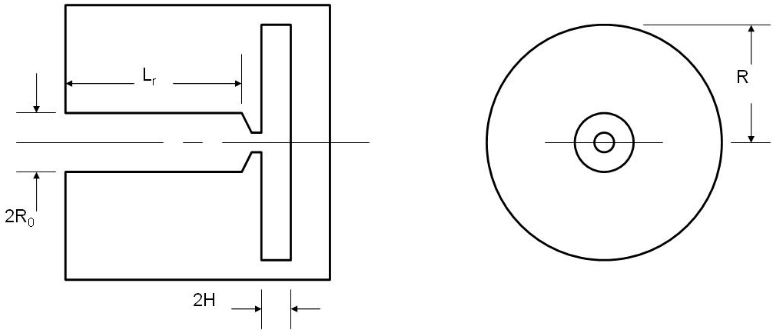


Figure 3: Mold used in conjunction with a constant volumetric flow rate Q.

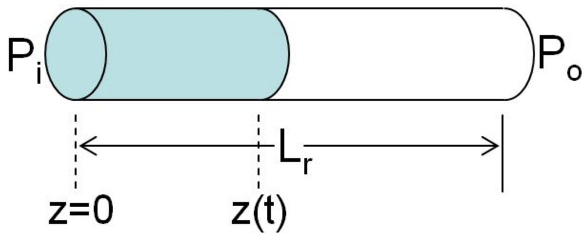


Figure 4: Position of an advancing flow front.

Part 1 - Flow in the Runner

$$Q = \pi R_0^2 \frac{dz(t)}{dt}$$

$$z(t) = \frac{Q}{\pi R_0^2} t$$

Pressure builds during filling of the runner, given by the Hagen-Poiseuille Law:

$$P_i(t) = \frac{8\mu Q}{\pi R_0^4} z(t) = \frac{8\mu Q^2}{\pi^2 R_0^6} t$$

Injection Molding
CENTER-GATED DISK

At $t = t_0$, the runner is filled ($z = L_r$)

$$t_0 = \frac{\pi R_0^2 L_r}{Q} \qquad P_i(t_0) = \frac{8\mu Q L_r}{\pi R_0^4}$$

For $t > t_0$, the runner is full and the pressure drop along the runner is always constant:

$$\Delta P_r = P_i - P_0 = \frac{8\mu Q L_r}{\pi R_0^4}$$

Part 2 - Flow in the disk cavity

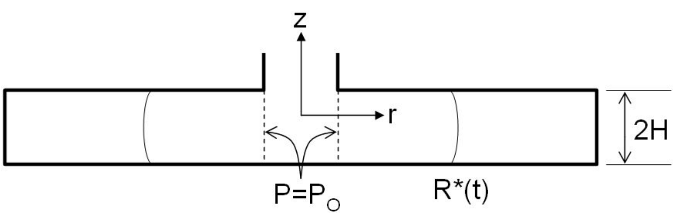


Figure 5: Position of the advancing front in the disk indicated by $R^*(t)$.

$$Q = 2H * 2\pi R^* \frac{dR^*}{dt} \qquad R^*(t_0) = R_0$$

$$R^{*2} - R_0^2 = \frac{Q}{2\pi H}(t - t_0)$$

$$\text{Filling time} \qquad t^* - t_0 = \frac{V}{Q} = \frac{2\pi H}{Q}(R^{*2} - R_0^2)$$

$$v_z = v_\theta = 0$$

Injection Molding
CENTER-GATED DISK

$$\text{Continuity: } \frac{1}{r}\frac{d}{dr}(rv_r) = 0$$

$$\therefore v_r = \frac{C(z,t)}{r}$$

$$\text{N-S: } \frac{dP}{dr} = \mu\frac{d^2 v_r}{dz^2} = \frac{\mu}{r}\frac{d^2 C}{dz^2}$$

$$\frac{dP}{dz} = \frac{dP}{d\theta} = 0$$

$$\frac{r}{\mu}\frac{dP}{dr} = \frac{d^2 C}{dz^2} = A(t)$$

$$\text{at } z = \pm H \qquad v_r = 0$$

$$\text{at } r = R_0 \qquad P = P_0(t)$$

$$v_r(r,z,t) = -\frac{A(t)H^2}{2r}\left[1 - \left(\frac{z}{H}\right)^2\right]$$

$$\text{Volumetric Flow Rate } Q = 4\pi \int_0^H r v_r dz$$

$$A = -\frac{3Q}{4\pi H^3} \qquad \text{constant } Q \qquad \therefore \text{ constant } A$$

$$r\frac{dP}{dr} = A\mu = -\frac{3\mu Q}{4\pi H^3}$$

$$P_0 - P = \frac{3\mu Q}{4\pi H^3}\ln(r/R_0)$$

Injection Molding
CENTER-GATED DISK

The pressure drop is logarithmic

$$P \sim \ln(1/r)$$

B.C. at $r = R^*$ $\quad P = 0$

$$P_0 = \frac{3\mu Q}{4\pi H^3} \ln(R^*/R_0)$$

can plug in previous result for R^* to get $P_0(t)$
Combine with pressure drop in runner to find

$$P_i = P_0 + \Delta P_r = \frac{3\mu Q}{4\pi H^3} \ln\left(\frac{R^*(t)}{R_0}\right) + \frac{8\mu Q L_r}{\pi R_0^4} \qquad \text{for } t_0 < t < t^*$$

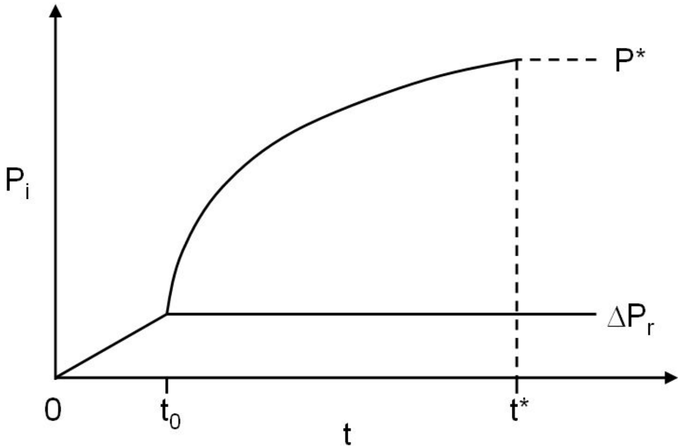


Figure 6: P^* is the pressure required to fill the mold.

Injection Molding
PACKING STAGE

When the mold is full, flow stops, so there is no longer a pressure drop.

Pressure P^* is used to **pack** the mold.

Packing pressure must be maintained until the gate solidifies.

Clamping force to hold mold closed:

$$F = \int_A P^* dA = 2\pi P^* \int_0^R r dr = \pi R^2 P^*$$

General Result $F = P^* A$

Example: Typical packing pressure $P^* = 10^8$ Pa for a total area of $A = 0.1$ m^2. Clamp force $F = P^* A = 10^7$ Nt= 1000 tons.

This is why injection molding machines are so large. They have to keep the mold closed!

Injection Molding
SIZING AN INJECTION MOLDING MACHINE

Packing pressure $\cong 10^8$Pa

Clamping force $F = P^* A$

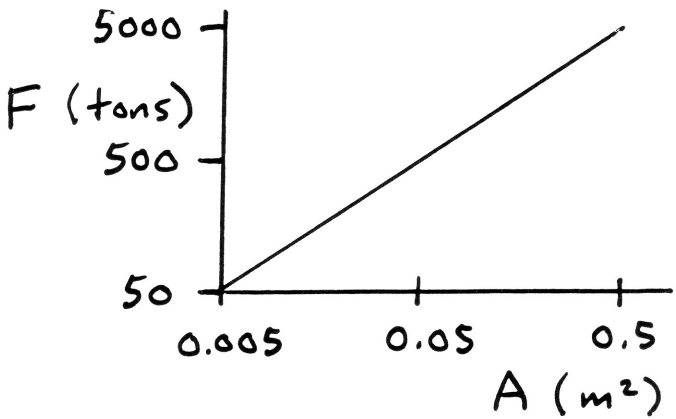


Figure 7: Clamping force as a function of surface area. Note: logarithmic scales.

Mold a single tensile bar - 50 ton machine

Mold a front end of a car - 5000 ton machine

"Typical" sizes are 100-1000 tons

For complicated parts A = projected area

Injection Molding
CRITIQUE OF OUR MOLD-FILLING CALCULATION

Our calculation was fairly nasty, yet we made so many assumptions that the calculation is *useless* quantitatively.

Assumptions:

1. Constant volumetric flow rate - otherwise keep time derivatives in the three Navier-Stokes Equations.

2. Negligible pressure drop in gate

3. Newtonian - Polymer melts are **not** Newtonian! This assumption keeps the three Navier-Stokes Equations linear.

4. **Isothermal** - This is the worst assumption. Actually inject hot polymer into a cold mold to improve cycle time. To include heat transfer, another coupled PDE is needed! The coupling is non-trivial because during injection, a skin of cold polymer forms on the walls of the mold and grows thicker with time.