Injection Molding

2.810

T. Gutowski

Diagram of a typical injection molding process. (Image taken from the OSHA Technical Manual.)
V-6 air intake manifold

Water control valve
Brass Vs injection mold

www.mnrubber.com
Short history of plastics

1866 Celluloid
1891 Rayon
1907 Bakelite
1913 Cellophane
1926 PVC
1933 Polyethylene
1938 Teflon
1939 Nylon stockings
1957 Velcro
1967 “The Graduate”
1970 Earth Day recycling
TABLE 7.2

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_g$ (°C)</th>
<th>$T_m$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nylon 6,6</td>
<td>57</td>
<td>265</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>150</td>
<td>265</td>
</tr>
<tr>
<td>Polyester</td>
<td>73</td>
<td>263</td>
</tr>
<tr>
<td>Polyethylene</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High density</td>
<td>−90</td>
<td>137</td>
</tr>
<tr>
<td>Low density</td>
<td>−110</td>
<td>115</td>
</tr>
<tr>
<td>Polymethylmethacrylate</td>
<td>105</td>
<td>176</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>−14</td>
<td>176</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>100</td>
<td>239</td>
</tr>
<tr>
<td>Polytetrafluoroethylene</td>
<td>−90</td>
<td>327</td>
</tr>
<tr>
<td>Polyvinyl chloride</td>
<td>87</td>
<td>212</td>
</tr>
<tr>
<td>Rubber</td>
<td>−73</td>
<td></td>
</tr>
</tbody>
</table>

4.21 Dependence of the shear modulus on temperature for three representative engineering polymers: natural rubber (cross-linked); PVC (essentially amorphous and not cross-linked); and nylon 6 (crystalline). The temperatures at which these polymers are used in technology are indicated (after Wolf).
Outline

- Basic operation
- Cycle time and heat transfer
- Flow and solidification
- Part design
- Tooling
- New developments
- Environment
30 ton, 1.5 fl oz (45 cm³) Engel

Injection Molding Machine
for wheel fabrication
Process & machine schematics

Schematic of thermoplastic Injection molding machine

* Source: [http://www.idsa-mp.org/proc/plastic/injection/injection_process.htm](http://www.idsa-mp.org/proc/plastic/injection/injection_process.htm)
Process Operation

- Temperature: barrel zones, tool, die zone
- Pressures: injection max, hold
- Times: injection, hold, tool opening
- Shot size: screw travel
Typical pressure/temperature cycle

Cooling time generally dominates cycle time

\[ t_{cool} = \frac{\text{(half thickness)}^2}{\alpha} \]

\[ \alpha = 10^{-3} \frac{cm^2}{sec} \text{ for polymer} \]

* Source: [http://islnotes.cps.msu.edu/trp/inj/inj_time.html](http://islnotes.cps.msu.edu/trp/inj/inj_time.html)
Calculate clamp force, & shot size

\[ F = P \times A = 420 \text{ tons} \]

3.8 lbs = 2245 cm\(^3\) = 75 oz

Actual ; 2 cavity 800 ton
Clamp force and machine cost

Figure 8.9  National average injection molding machine rates.

Boothroyd/Busch
Heat transfer

Note; $\alpha_{\text{Tool}} \geq \alpha_{\text{polymer}}$

1-dimensional heat conduction equation:

$q_x \rightarrow q_x + \Delta q_x$

Fourier’s law

$$\frac{\partial}{\partial t} (\rho \cdot c \cdot T) \Delta x \Delta y = - \frac{\partial q_x}{\partial x} \Delta x \Delta y$$

$$q_x = -k \frac{\partial T}{\partial x}$$

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \quad \text{or} \quad \frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

Boundary Conditions:

1st kind

$$T(x = x') = \text{constant}$$

2nd kind

$$-k \frac{\partial T}{\partial x} (x = x') = \text{constant}$$

3rd kind

$$-k \frac{\partial T}{\partial x} (x = x') = h(T - T_\infty)$$

The boundary condition of 1st kind applies to injection molding since the tool is often maintained at a constant temperature.
Heat transfer

Let $L_{ch} = H/2$ (half thickness) = $L$ ; $t_{ch} = L^2/\alpha$ ; $\Delta T_{ch} = T_i - T_W$ (initial temp. – wall temp.)

Non-dimensionalize: $\theta = \frac{T - T_W}{T_i - T_W}$ ; $\xi = \frac{x}{L} + 1$; $F_o = \frac{\alpha \cdot t}{L^2}$

Dimensionless equation:

$$\frac{\partial \theta}{\partial F_o} = \frac{\partial^2 \theta}{\partial \xi^2}$$

Initial condition

$F_0 = 0 \quad \theta = 1$

Boundary condition

$\xi = 0 \quad \theta = 0$

$\xi = 2 \quad \theta = 0$

Separation of variables ; matching B.C.; matching I.C.

$$\theta(\xi, F_o) = \sum f(F_o)g(\xi)$$
Temperature in a slab

Centerline, $\theta = 0.1$, $F_o = \alpha t/L^2 = 1$

See Heat Transfer Text
By Lienhard on line

$Bi^{-1} = k/hL$
Reynolds Number

Reynolds Number:

\[ Re = \frac{\frac{pV^2}{\mu}}{\frac{V}{L^2}} \]

For typical injection molding

\[ \rho = 1 \, g/cm^3 = 10^3 \, N/m^4/s^2; \quad L_Z = 10^{-3} \, m \quad \text{thickness} \]

\[ V \approx \frac{\text{Part length}}{\text{Fill time}} = \frac{10^{-1}}{1s}; \quad \mu = 10^3 \, N \cdot s/m^2 \]

For Die casting

\[ Re \approx \frac{3 \cdot 10^3 \cdot 10^{-1} \cdot 10^{-3}}{10^{-3}} = 300 \]

* Source: [http://www.idsa-mp.org/proc/plastic/injection/injection_process.htm](http://www.idsa-mp.org/proc/plastic/injection/injection_process.htm)
Viscous Shearing of Fluids

Generalization: \( \tau = \mu \cdot \dot{\gamma} \); \( \dot{\gamma} = \text{shear rate} \)

Typical shear rate for Polymer processes (sec\(^{-1}\))

- Extrusion: \(10^2 \sim 10^3\)
- Calendering: \(10 \sim 10^2\)
- Injection molding: \(10^3 \sim 10^4\)
- Comp. Molding: \(1 \sim 10\)
Viscous Heating

Rate of Heating
= Rate of Viscous Work

\[
\frac{P}{Vol} = \frac{F \cdot v}{Vol} = \frac{F}{A} \cdot \frac{v}{h} : \mu \left( \frac{v}{h} \right)^2
\]

Rate of Temperature rise

\[
\rho \cdot c \cdot \frac{dT}{dt} = \mu \left( \frac{v}{h} \right)^2 \quad \text{or} \quad \frac{dT}{dt} = \frac{\mu}{\rho \cdot c} \left( \frac{v}{h} \right)^2
\]

Rate of Conduction out

\[
\frac{dT}{dt} = \frac{k}{\rho \cdot c} \frac{d^2T}{dx^2} \sim \frac{k}{\rho \cdot c} \frac{\Delta T}{h^2}
\]

\[
\frac{\text{Viscous heating}}{\text{Conduction}} = \frac{\mu v^2}{k \Delta T}
\]

Brinkman number

For injection molding, order of magnitude \( \sim 0.1 \) to 10
Non-Isothermal Flow

Flow rate: \( \frac{V}{L_x} \)

Heat transfer rate: \( \frac{a}{(L_z/2)^2} \)

\[
\frac{\text{Flow rate}}{\text{Heat xfer rate}} = \frac{V \cdot L_z^2}{4 \alpha \cdot L_x} = \frac{1}{4} \frac{VL_z}{\alpha} \cdot \frac{L_z}{L_x}
\]

For injection molding

\[
\frac{\text{Flow rate}}{\text{Heat xfer rate}} \approx \frac{10 \text{ cm s}^{-1}}{4} \cdot \frac{0.1 \text{ cm}}{10^{-3} \text{ cm}^2 \text{s}^{-1}} \cdot \frac{0.1 \text{ cm}}{10 \text{ cm}} = 2.5
\]

For Die casting of aluminum

\[
\frac{\text{Flow rate}}{\text{Heat xfer rate}} \approx \frac{10 \text{ cm s}^{-1}}{4} \cdot \frac{0.1 \text{ cm}}{0.3 \text{ cm}^2 \text{s}^{-1}} \cdot \frac{0.1 \text{ cm}}{10 \text{ cm}} = 10^{-2}
\]

* Very small, therefore it requires thick runners
Non-Isothermal Flow

Flow rate: \( \frac{1}{t} \sim \frac{V}{L_x} \)

Heat transfer rate: \( \frac{1}{t} \sim \frac{a}{(L_z/2)^2} \)

\[
\frac{\text{Flow rate}}{\text{Heat xfer rate}} = \frac{V \cdot L_z^2}{4\alpha \cdot L_x} = \frac{1}{4} \frac{VL_z}{\alpha} \cdot \frac{L_z}{L_x}
\]

For injection molding

\[
\frac{\text{Flow rate}}{\text{Heat xfer rate}} \sim \frac{1}{4} \frac{10 \text{ cm/s} \cdot 0.1 \text{ cm}}{10^{-3} \frac{\text{cm}^2}{\text{s}}} \cdot \frac{0.1 \text{ cm}}{10 \text{ cm}} = 2.5
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\]

Very small value for aluminum requires thicker runners
Injection mold  

die cast mold  

Single-cavity die  

Multiple-cavity die  

Combination die  

Unit die
Fountain Flow

Shrinkage distributions

* Source: G. Menges and W. Wubken, “Influence of processing conditions on Molecular Orientation in Injection Molds”
Gate Location and Warping

- **Center gate:** radial flow – severe distortion
- **Diagonal gate:** radial flow – twisting
- **End gates:** linear flow – minimum warping
- **Sprue:** 2.0
- **Air entrapment:** 1.96
- **Before shrinkage:** 2.0
- **After shrinkage:** 1.976
- **Shrinkage:**
  - Direction of flow: 0.020 in/in
  - Perpendicular to flow: 0.012
Effects of mold temperature and pressure on shrinkage
Where would you gate this part?
Design Features

* Source: [http://www.idsa-mp.org/proc/plastic/injection/injection_design_2.htm](http://www.idsa-mp.org/proc/plastic/injection/injection_design_2.htm)
Weld line, Sink mark

Mold Filling

Solidified part

Sink mark

Weld line

Basic rules in designing ribs to minimize sink marks

* Source: http://www.idsa-mp.org/proc/plastic/injection/injection_design_7.htm
**DESIGN SUGGESTIONS**

1. Thick bosses can cause sink on the other side of part.
2. Knit lines may form downstream of through-holes.
3. Thinner sections may not fill and can cause surface flaws.
4. Thicker features can sink, have voids or cause warp.
5. Thick ribs can cause sink on the other side of the part.
6. Surface finishes:
   - **SPI-A2**: High polish, no tool marks (suitable for many applications but not for precision imaging).
   - **SPI-B1**: Finished with 600 grit paper, no tool marks.
   - **SPI-C1**: Finished with a 600 grit stone, no tool marks.
   - **PM-FO**: As-machined or to Protomold discretion (default B-side finish).
   - **PM-F1**: Mostly SPI-C1, but evidence of underlying tool marks may still be noticeable in some areas (default A-side finish).
   - **PM-T1**: SPI-C1 followed by light bead blast.
   - **PM-T2**: SPI-C1 followed by medium bead blast.
7. If you incorporate the boss into the wall, do so without undesirable thicker sections.
8. Design bosses and ribs to be 40–60% of the wall thickness. Bosses can be strengthened with gussets rather than using thicker walls.
9. Tie bosses to walls with short ribs.
10. Create undercut features that can be molded using sliding shut-off in straight-pull molds. Maintain 3 degree minimum draft on shut-offs.
11. Core out thick sections.
12. Living hinges add functionality but parts can be difficult to fill. They work best in polyethylene or polypropylene.
13. Side action cams can create features perpendicular to the main direction of pull. These include holes, hooks, text, texture on side walls, and much more.

Visit www.protomold.com/designinguidelines for more tips on design.
Where is injection molding?

Controlled by shrinkage and warping. Hence, polymer, fillers, mold geometry and processing conditions can all influence the final tolerance.

Shrinkage is of order 10-100/1000 for unfilled and 1-10/1000 for filled across the thickness.
Where is injection molding?
Controlled by shrinkage and warping. Hence, polymer, fillers, mold geometry and processing conditions can all influence the final tolerance.

Shrinkage is of order 10-100/1000 for unfilled and 1-10/1000 for filled across the thickness.

**TABLE 8.7** Percentage Increases for Tolerance

<table>
<thead>
<tr>
<th>Tolerance level</th>
<th>Description of tolerances</th>
<th>Percentage increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>All greater than ±0.5 mm</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>Most approx. ±0.35 mm</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Several approx. ±0.25 mm</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Most approx. ±0.25 mm</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Several approx. ±0.05 mm</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>Most approx. ±0.05 mm</td>
<td>30</td>
</tr>
</tbody>
</table>

*From Boothroyd et al*
Tooling Basics

Basic mould consisting of cavity and core plate

Melt Delivery

Sprue
Nozzle
Cavity Plate
Core Plate
Moulding
Core
Cavity
Gate
Runner
Tooling for a plastic cup
Tooling for a plastic cup
Toy tooling example from Protomold
Tooling

* Source: http://www.idsa-mp.org/proc/plastic/injection/; ** http://www.hzs.co.jp/english/products/e_trainer/mold/basic/basic.htm (E-trainer by HZS Co.,Ltd.)
Tooling Alternatives

**FIGURE 19.11** Types of molds used in injection molding.

*Kalpakjian & Schmid*
Undercut features to hold tape on
Evidence of tooling feature
Part design rules

- Simple shapes to reduce tooling cost
  - No undercuts, etc.
- Draft angle to remove part
  - In some cases, small angles (1/4°) will do
  - Problem for gears
- Even wall thickness
- Minimum wall thickness ~ 0.025 in
- Avoid sharp corners
- Hide weld lines
  - Holes may be molded 2/3 of the way through the wall only, with final drilling to eliminate weld lines
Novel development- Gas assisted injection molding
Novel development; injection molding with cores

Injection Molded Housing

Cores used in Injection Molding

Cores and Part Molded in Clear Plastic
Micro injection molding
Conformal Cooling Channels

Tooling built using Additive Manufacturing
Environmental issues

- Energy
  - Polymer production
  - Compounding
  - Machine types

- Recycling
Polymer Production
Largest Player in the Injection Molding LCI

What is a polymer:

\[
\begin{array}{cccccccccccc}
 & H & H & H & H & H & H & H & H & H & H & H \\
 & H & Cl & H & Cl & H & Cl & H & Cl & H & Cl & Cl \\
\end{array}
\]

How much energy does it take to make 1 kg of polymer = a lot !!!

<table>
<thead>
<tr>
<th>Sources</th>
<th>HDPE</th>
<th>LLDPE</th>
<th>LDPE</th>
<th>PP</th>
<th>PVC</th>
<th>PS</th>
<th>PC</th>
<th>PET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boustead</td>
<td>76.56</td>
<td>77.79</td>
<td>73.55</td>
<td>72.49</td>
<td>58.41</td>
<td>86.46</td>
<td>115.45</td>
<td>77.14</td>
</tr>
<tr>
<td>Ashby</td>
<td>111.50</td>
<td></td>
<td>92.00</td>
<td>111.50</td>
<td>79.50</td>
<td>118.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patel</td>
<td></td>
<td></td>
<td>64.60</td>
<td></td>
<td>53.20</td>
<td>70.80</td>
<td>80.30</td>
<td>59.40</td>
</tr>
<tr>
<td>Kindler,Nickles [Patel 1999]</td>
<td></td>
<td></td>
<td>71.00</td>
<td></td>
<td>53.00</td>
<td>81.00</td>
<td>107.00</td>
<td>96.00</td>
</tr>
<tr>
<td>Worrell et al. [Patel 1999]</td>
<td></td>
<td></td>
<td>67.80</td>
<td></td>
<td>52.40</td>
<td>82.70</td>
<td>78.20</td>
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<tr>
<td>E³ Handbook [OIT 1997]</td>
<td>131.65</td>
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<td>126.07</td>
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<td>Energieweb</td>
<td>80.00</td>
<td>68.00</td>
<td>64.00</td>
<td>57.00</td>
<td>84.00</td>
<td></td>
<td></td>
<td>81.00</td>
</tr>
</tbody>
</table>

Values are in MJ per kg of polymer produced. Thiriez '06
Gold ~ 250 GJ/kg

**FIGURE 6.8** A bar chart of the embodied energies of materials per unit mass.

Ashby 2009
46
Compounding - extrusion

An extruder is used to mix additives with a polymer base, to bestow the polymer with the required characteristics.

Similar to an injection molding machine, but without a mold and continuous production.

Thus it has a similar energy consumption profile.

Environmentally Unfriendly Additives:

- Fluorinated blowing agents (GHG’s)
- Phalates (some toxic to human liver, kidney and testicles)
- Organotin stabilizers (toxic and damage marine wildlife)
Injection Molding Process

Machine types: Hydraulic, electric, hydro-electric

Source: http://cache.husky.ca/pdf/brochures/br-hylelectric03a.pdf
All-electric vs. hybrid

The hydraulic plot would be even higher than the hybrid curve

Source: [Thiriez]
For Hydraulics and Hybrids as throughput increases, SEC $\rightarrow$ k.

Enthalpy value to melt plastics is just 0.1 to 0.7 MJ/kg !!!

Does not account for the electric grid.

Source: [Thiriez]
All-electrics have very low fixed energy costs (small idling power). SEC is constant as throughput increases.

\[ SEC = \rho_v \]
Driers

- Used to dry internal moisture in hygroscopic polymers and external moisture in non-hygroscopic ones.
- It is done before extruding and injection molding.

\[
\frac{P}{\dot{m}} = \frac{E}{m} = SEC = \frac{P_{aux}}{\dot{m}} + k
\]

Source: [Thiriez]
LCI Summarized Results

### Energy Consumption by Stage in MJ/kg of Shot

#### Thermoplastic Production

<table>
<thead>
<tr>
<th></th>
<th>HDPE</th>
<th>LLDPE</th>
<th>LDPE</th>
<th>PP</th>
<th>PVC</th>
<th>PS</th>
<th>Generic by Amount</th>
<th>Extras</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Consumed Inj. Mld</td>
<td>PC</td>
</tr>
<tr>
<td>avg</td>
<td>89.8</td>
<td>79.7</td>
<td>73.1</td>
<td>83.0</td>
<td>59.2</td>
<td>87.2</td>
<td>81.2</td>
<td>74.6</td>
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<tr>
<td>low</td>
<td>77.9</td>
<td>79.7</td>
<td>64.6</td>
<td>64.0</td>
<td>52.4</td>
<td>70.8</td>
<td>69.7</td>
<td>62.8</td>
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<tr>
<td>high</td>
<td>111.5</td>
<td>79.7</td>
<td>92.0</td>
<td>111.5</td>
<td>79.5</td>
<td>118.0</td>
<td>102.7</td>
<td>97.6</td>
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</table>

#### Polymer Delivery

<table>
<thead>
<tr>
<th></th>
<th>avg</th>
<th>low</th>
<th>high</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.19</td>
<td>0.12</td>
<td>0.24</td>
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</table>

#### Compounder

<table>
<thead>
<tr>
<th>Internal Transport</th>
<th>Drying</th>
<th>Extrusion</th>
<th>Pelletizing</th>
<th>Building (lights, heating, etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>avg</td>
<td>0.09</td>
<td>0.70</td>
<td>3.57</td>
<td>0.16</td>
</tr>
<tr>
<td>low</td>
<td>------</td>
<td>0.30</td>
<td>1.82</td>
<td>0.06</td>
</tr>
<tr>
<td>high</td>
<td>------</td>
<td>1.62</td>
<td>5.00</td>
<td>0.31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subtotal</th>
<th>avg</th>
<th>low</th>
<th>high</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.51</td>
<td>3.25</td>
<td>8.01</td>
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</table>

#### Polymer Delivery

<table>
<thead>
<tr>
<th></th>
<th>avg</th>
<th>low</th>
<th>high</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.19</td>
<td>0.12</td>
<td>0.24</td>
</tr>
</tbody>
</table>
### Injection Molder

<table>
<thead>
<tr>
<th>Internal Transport</th>
<th>Drying</th>
<th>Injection Molding (look below)</th>
<th>Scrap (Granulating)</th>
<th>Building (lights, heating, etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>avg</td>
<td>0.04</td>
<td></td>
<td>0.05</td>
<td>0.99</td>
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<tr>
<td>low</td>
<td>0.30</td>
<td></td>
<td>0.03</td>
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</tr>
<tr>
<td>high</td>
<td>1.62</td>
<td></td>
<td>0.12</td>
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</table>

### Injection Molding - Choose One

<table>
<thead>
<tr>
<th></th>
<th>Hydraulic</th>
<th>Hybrid</th>
<th>All-Electric</th>
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<tr>
<td>avg</td>
<td>11.29</td>
<td>5.56</td>
<td>4.89</td>
</tr>
<tr>
<td>low</td>
<td>3.99</td>
<td>3.11</td>
<td>1.80</td>
</tr>
<tr>
<td>high</td>
<td>69.79</td>
<td>8.45</td>
<td>15.29</td>
</tr>
</tbody>
</table>

**Subtotal**

<table>
<thead>
<tr>
<th></th>
<th>avg</th>
<th>Hybrid</th>
<th>All-Electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>avg</td>
<td>13.08</td>
<td>7.35</td>
<td>6.68</td>
</tr>
<tr>
<td>low</td>
<td>5.35</td>
<td>4.47</td>
<td>3.17</td>
</tr>
<tr>
<td>high</td>
<td>72.57</td>
<td>11.22</td>
<td>18.06</td>
</tr>
</tbody>
</table>

### TOTAL w/ Generic Inj. Molded Polymer

<table>
<thead>
<tr>
<th></th>
<th>Hydraulic</th>
<th>Hybrid</th>
<th>All-Electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>avg</td>
<td>93.60</td>
<td>87.87</td>
<td>87.20</td>
</tr>
<tr>
<td>low</td>
<td>71.65</td>
<td>70.77</td>
<td>69.46</td>
</tr>
<tr>
<td>high</td>
<td>178.68</td>
<td>117.34</td>
<td>124.18</td>
</tr>
</tbody>
</table>

### TOTAL w/o Polymer Prod

<table>
<thead>
<tr>
<th></th>
<th>Hydraulic</th>
<th>Hybrid</th>
<th>All-Electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>avg</td>
<td>18.97</td>
<td>13.24</td>
<td>12.57</td>
</tr>
<tr>
<td>low</td>
<td>8.84</td>
<td>7.96</td>
<td>6.66</td>
</tr>
<tr>
<td>high</td>
<td>81.04</td>
<td>19.70</td>
<td>26.54</td>
</tr>
</tbody>
</table>

**Notes**

- **Drying** - the values presented assume no knowledge of the materials' hygroscopy. In other words, they are averages between hygroscopic and non-hygroscopic values. For hygroscopic materials such as PC and PET, additional drying energy is needed (0.65 MJ/kg in the case of PC and 0.52 MJ/kg in the case of PET).
- **Pelletizing** - in the case of pelletizing an extra 0.3 MJ/kg is needed for PP.
- **Granulating** - a scrap rate of 10% is assumed.

Source: [Thiriez] 54
Do Polymers get recycled?

FIGURE 6.13 Recycle fraction bar chart.  Ref Ashby 2009
The printer goes in the hopper...
And comes out....
Readings (first 3) & Refs

- Tadmore and Gogos
  - Molding and Casting pp 584 - 610
- Boothroyd Dewhurst
  - Design for Injection Molding pp 319 - 359
- Kalpakjian Ch 7 & 19
- Thiriez et al, "An Environmental Analysis of Injection Molding"
- "Injection Molding Case Study“ (Gas Assist)