Injection Molding

2.810

T. Gutowski

Diagram of a typical injection molding process. (Image taken from the OSHA Technical Manual.)

D. Roylance
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
Ref Kalpakjian and Schmid

**FIGURE 7.2** Molecular structure of various polymers. These are examples of the basic building blocks for plastics.

**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>265</td>
</tr>
<tr>
<td>Polyethylene High density</td>
<td>-90</td>
<td>137</td>
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<td>Polyethylene Low density</td>
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<td>115</td>
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<tr>
<td>Polymethylmethacrylate</td>
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<td>—</td>
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<tr>
<td>Polypolyolefin</td>
<td>-14</td>
<td>176</td>
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<tr>
<td>Polystyrene</td>
<td>100</td>
<td>239</td>
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<tr>
<td>Polytetrafluoroethylene</td>
<td>-90</td>
<td>327</td>
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<tr>
<td>Polyvinyl chloride</td>
<td>87</td>
<td>212</td>
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<tr>
<td>Rubber</td>
<td>-73</td>
<td>—</td>
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</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
Schematic of thermoplastic Injection molding machine

* Source: 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**

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

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

* 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

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

\[
3.8 \text{ lbs} = 2245 \text{ cm}^3 = 75 \text{ oz}
\]

Actual; 2 cavity 800 ton
Clamp force and machine cost

Figure 8.9 National average injection molding machine rates.
Heat transfer

1-dimensional heat conduction equation:

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

Fourier’s law

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

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

Boundary Conditions:

1st kind \hspace{1cm} T(x = x') = \text{constant}

2nd kind \hspace{1cm} -k \frac{\partial T}{\partial x} (x = x') = \text{constant}

3rd kind \hspace{1cm} -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

\( F_O = 0 \quad \theta = 1 \)

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:

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

For typical injection molding

\[ \rho = 1 \text{ g/cm}^3 = 10^3 \text{ N/m}^4/\text{s}^2; \quad L_z = 10^{-3} \text{ m} \quad \text{thickness} \]
\[ V \approx \frac{\text{Part length}}{\text{Fill time}} = \frac{10^{-1}}{1 \text{s}}; \quad \mu = 10^3 \text{ N} \cdot \text{s/m}^2 \]

Reynolds Number: \( Re \approx 3 \cdot 10^3 \times 10^{-1} \times 10^{-3} \\ = 300 \]

For Die casting

* 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

Newtonian Viscosity

Generalization: \[ \tau = \mu \dot{\gamma} \] \( \dot{\gamma} \): shear rate

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

- Extrusion: \(10^2\sim10^3\)
- Calendering: \(10\sim10^2\)
- Injection molding: \(10^3\sim10^4\)
- Comp. Molding: \(1\sim10\)
Viscous Heating

Rate of Heating

$$\frac{P}{Vol} = \frac{F \cdot v}{Vol} = \frac{F}{A} \cdot \frac{v}{h} \sim \mu \left( \frac{v}{h} \right)^2$$

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

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

Viscous heating \( \frac{\mu v^2}{\text{Conduction}} \)

Brinkman number

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

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

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

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

For injection molding

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

For Die casting of aluminum

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

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

Flow rate: \( 1/t \sim V/L_x \)

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

\[
\begin{align*}
\text{Flow rate} & \sim \frac{V \cdot L^2_z}{4 \alpha \cdot L_x} \\
\text{Heat xfer rate} & \sim \frac{1}{4} \frac{VL_z}{\alpha L_x} \cdot \frac{L_z}{L_x}
\end{align*}
\]

For injection molding

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

For Die casting of aluminum

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

Very small value for aluminum requires thicker runners
Injection mold  
die cast mold
Fountain Flow

* Source: http://islnotes.cps.msu.edu/trp/inj/flw_froz.html ; ** Z. Tadmor and C. Gogos, “Principles of Polymer Processing”
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
2.0
60°

Direction of flow – 0.020 in/in
Perpendicular to flow – 0.012

Shrinkage

Before shrinkage

1.96
60.32°

After shrinkage

1.976

Air entrapment

Gate

2.0
Effects of mold temperature and pressure on shrinkage
Where would you gate this part?
Weld line, Sink mark

Basic rules in designing ribs to minimize sink marks

* Source: http://www.idsa-mp.org/proc/plastic/injection/injection_design_7.htm
Mold Flow Analysis by Peter Jones

CORD-WINDER™ DESIGN
- Modified version of duplex outlet wall plates.
- Cord-winder has the following advantages:
  - Eliminates cord tripping hazard.
  - Better wire organizing.
  - Easy to spot with personalized color choices.
  - Good thermal & electrical properties.
  - May comply with building and electrical codes.

GATE LOCATION (TO MINIMIZE FILL TIME)
- Side Gate: Time to reach ejection temp: 11 sec
- Top Gate: Time to reach ejection temp: 10.5 sec

GATE LOCATION (TO MINIMIZE WELD LINES)
- Side Gate: Faster fill
- Top Gate: 2 weird lines around screw through-hole

MOLD FILLING ANALYSIS WITH RUNNER/GATE
- No filling issues expected
- Fill Time: 1.2 s
- EOF Pressure: 38 MPa
- V-P Pressure: 48 MPa
Injection Molding

* 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)
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.
Tooling Basics

Basic mould consisting of cavity and core plate

Sprue
Nozzle
Cavity Plate
Core Plate
Cavity
Moulding
Core
Gate
Runner
Melt Delivery
Tooling for a plastic cup

- Nozzle
- Runner
- Part
- Cavity
- Core
- Stripper plate
- Knob
Tooling for a plastic cup
Toy tooling example from Protomold

part

Side pull

Side pull in position
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 \( \sim 0.025 \text{ in} \)
- 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
Micro embossing

Replacing serial processes with parallel processes at small scales

h) Side view of wire EDM stainless steel micro well embossing insert

i) Micro well embossing insert (top view)  j) HDPE embossed micro wells

k) Hexagonal micro well embossing insert (Mezzo Systems Inc.) and HDPE embossed hexagonal micro wells

B. Kim UMass
Conformal Cooling Channels

Tooling built using Additive Manufacturing

Innomis.cz
Environmental issues

- Energy
  - Polymer production
  - Compounding
  - Machine types

- Recycling
## Polymer Production

**Largest Player in the Injection Molding LCI**

What is a polymer:

![Polymer Structure]

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>
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<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>
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</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>
<td>121.18</td>
<td>136.07</td>
<td>126.07</td>
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<td>Energieweb</td>
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<td>68.00</td>
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<td>84.00</td>
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<td>81.00</td>
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</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
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-electrics have very low fixed energy costs (small idling power). SEC is constant as throughput increases.

\[ SEC \approx p_v \]

![Graph showing SEC vs. Throughput for All-Electric and Hydraulic systems.](image)

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

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

Does not account for the electric grid. 

Source: [Thiriez]
The hydraulic plot would be even higher than the hybrid curve.

Source: [Thiriez]
Driers

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

\[
\frac{P}{m} = \frac{E}{m} = SEC = \frac{P_0}{m} + k
\]

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>Consumed</th>
<th>Inj. Molded</th>
<th>PC</th>
<th>PET</th>
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<tbody>
<tr>
<td><strong>avg</strong></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>
<td>95.7</td>
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<tr>
<td><strong>low</strong></td>
<td>77.9</td>
<td>79.7</td>
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<td>52.4</td>
<td>70.8</td>
<td>69.7</td>
<td>62.8</td>
<td>78.2</td>
<td>59.4</td>
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<tr>
<td><strong>high</strong></td>
<td>111.5</td>
<td>79.7</td>
<td>92.0</td>
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<td>79.5</td>
<td>118.0</td>
<td>102.7</td>
<td>97.6</td>
<td>117.4</td>
<td>96.0</td>
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</tbody>
</table>

**Polymer Delivery**

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<tr>
<td><strong>avg</strong></td>
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<td><strong>low</strong></td>
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**Compounder**

<table>
<thead>
<tr>
<th></th>
<th>Internal Transport</th>
<th>Drying</th>
<th>Extrusion</th>
<th>Pelletizing</th>
<th>Building (lights, heating, ect..)</th>
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<tbody>
<tr>
<td><strong>avg</strong></td>
<td>0.09</td>
<td>0.70</td>
<td>3.57</td>
<td>0.16</td>
<td>0.99</td>
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<td><strong>low</strong></td>
<td>-----</td>
<td>0.30</td>
<td>1.82</td>
<td>0.06</td>
<td>-----</td>
</tr>
<tr>
<td><strong>high</strong></td>
<td>-----</td>
<td>1.62</td>
<td>5.00</td>
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**Subtotal**

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## Injection Molder

<table>
<thead>
<tr>
<th></th>
<th>Drying</th>
<th>Injection Molding (look below)</th>
<th>Scrap (Granulating)</th>
<th>Building (lights, heating, etc..)</th>
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<tr>
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<td>0.30</td>
<td>0.03</td>
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<tr>
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<td>-----</td>
<td>1.62</td>
<td>0.12</td>
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### Injection Molding - Choose One

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

### Subtotal

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<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td><strong>avg</strong></td>
<td>13.08</td>
<td>7.35</td>
<td>6.68</td>
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<tr>
<td><strong>low</strong></td>
<td>5.35</td>
<td>4.47</td>
<td>3.17</td>
</tr>
<tr>
<td><strong>high</strong></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><strong>avg</strong></td>
<td>93.60</td>
<td>87.87</td>
<td>87.20</td>
</tr>
<tr>
<td><strong>low</strong></td>
<td>71.65</td>
<td>70.77</td>
<td>69.46</td>
</tr>
<tr>
<td><strong>high</strong></td>
<td>178.68</td>
<td>117.34</td>
<td>124.18</td>
</tr>
</tbody>
</table>

### TOTAL w/o Polymer Prod

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>avg</strong></td>
<td>18.97</td>
<td>13.24</td>
<td>12.57</td>
</tr>
<tr>
<td><strong>low</strong></td>
<td>8.84</td>
<td>7.96</td>
<td>6.66</td>
</tr>
<tr>
<td><strong>high</strong></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 order 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 scarp rate of 10% is assumed.

Source: [Thiriez]
Do Polymers get recycled?

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)