INTRODUCTION TO EXTRUSION

In an extruder, a screw turns in a cylinder called the barrel. Sometimes two screws turn in a double barrel, and these screws usually intermesh. Plastic material enters through a feed hopper at one end of the barrel, and is caught by the screw and conveyed through the barrel while it becomes soft and eventually melts (see centerfold diagram).

Plastics for extrusion are thermoplastics -- that means they get soft when heated and harden again on cooling. Heat is generated by the friction of the screw turning in the plastic mass, and most of the energy to melt usually comes from the motor as it turns the screw. Sometimes, more heat is added by barrel heaters, preheated feed, or both.

There is an opening at the output end of an extruder called the die. As the hot, soft plastic emerges, it takes the shape of the hole it passes through: a long slit makes a sheet or flat film, a circular opening makes pipe or tubing, many small holes make filaments, etc. Once out of the die, the plastic is cooled by air, water or contact with metal, and then pulled away to be rolled or cut to desired dimensions.

As the screw turns, it tries to unscrew itself backward out of the barrel full of material. It can't come out because a bearing holds it in place, but its push against the molten material forces that material out the other end.

The head and die assembly act as a resistance. The longer and smaller it is, the more the screw works to push the hot material out. That means more horsepower is required of the motor that turns the screw.

The extruder operator sets the temperatures of the barrel, the head and the die, and sometimes also the temperatures of the screw and the feed -- as well as the screw speed.

The barrel is divided into several zones, each with heating and cooling controls to control its temperature as desired. These temperatures are not the same as those of the plastic inside but are selected as needed in each zone. The rear zone, nearest the feed hopper, is especially important as it affects feed rate and may control production rate. There are heaters and controls on the head and die also, and their temperatures are often closer to that of the plastic inside.

Melt temperature is measured at the end of the screw, just before the plastic enters the die. If too high, there may be cooling problems or some chemical degradation of the plastic. Most melt temperatures are between 350-600 F (175-315 C).

Melt pressure is also measured at the end of the screw, and reflects the resistance of the head and die assembly. Most pressures are between 1000-6000 psi (70-400 atm = 7-40 MPa).

Screw speed is selected usually as high as will still produce a good quality product. Typical screw speeds are 30 to 150 rpm.

The current in the motor (amperes) is measured for safety reasons (avoid damage to motor), and to show surging (thickness variation) and material changes.

DRIVE SYSTEM

Almost all extruders made in the last 30 years are driven by variable-speed DC motors. Regular AC supply is converted to DC as part of the drive package. Changing DC motor speed is easily done by varying the input voltage, and this is how screw speed is changed during operation. DC drives can be linked to thickness measuring devices and computers, either for closed-loop control or just to record speed and current.

DC motors are normally not totally enclosed, which means possible trouble in dusty areas. There is a fan that blows filtered air through the motor, and carbon "brushes" that need inspection and changing from time to time. Recently, brushless DC motors have been introduced.

Some magnetic-clutch AC drives are still in operation. They work best at or near their top speed, as at low speeds they need much cooling.

All these motors run much faster than typical screw speeds, so there must be reduction to bring motor speed (1750-2000 maximum rpm) down to extrusion range (100-200 maximum rpm). Reduction is usually in two stages and may be either all gears or a combination of pulleys and gears. In many systems, top screw speed can be changed by changing gears or pulley diameters. This allows operation as close to top motor speed as possible, and thus makes more horsepower available.

The speed reduction ends in a large "bull gear" into which the screw fits with keyways or splines. The backward thrust produced by the screw is taken by a large bearing called the thrust bearing. Its life can be estimated as follows:

$$\text{B-10 Life} = \left[\frac{C}{P \times A}\right]^{\frac{10}{3}} \times \frac{16{,}667}{N}$$

B-10 life = hours after which 10% of a group of similar bearings will fail
C = basic dynamic capacity, lb or Kg, data from bearing maker
N = screw speed in rpm
P x A = pressure at screw tip x cross-section area there = thrust (use same units as C)

The life of a thrust bearing is shortened by high speed and especially high pressure. Also, failure to inspect and lubricate properly is a major cause of failure. It is good to know what bearing is in an extruder (maker and model), expected life, its cost, and where to get a replacement.

There is also a radial bearing or bushing that supports and aligns the screw, but it is normally not highly loaded and should not cause trouble if it is properly maintained.

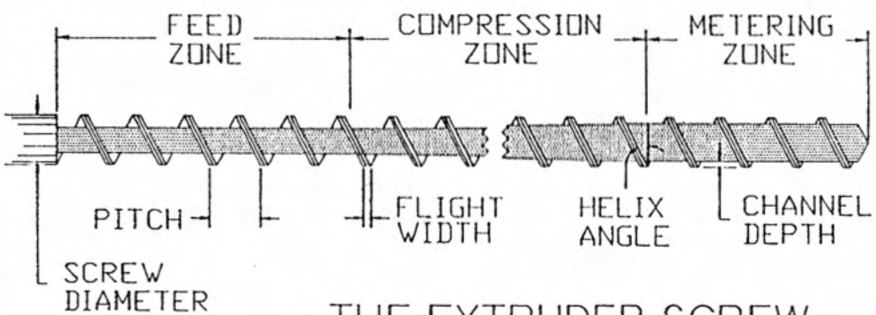
Centerlines of most extruders are around 40 inches or one meter from the floor, which places the die and head at a convenient working level. For film, a "low-boy" extruder is common, with centerline as low as 12" (30 cm) off the floor. This gives more height for cooling; also the die and air ring are lower for easier access.

Many extruders have their motors located under the barrel (tuck-under), saving floor space but limiting access. Others have the motor set to one side.

SCREWS AND BARRELS

About 90% of the extrusion industry in North America is single-screw extrusion, which means one screw in one round barrel. We express the length of this system as the length-to-diameter ratio, or the L/D. Many extruders have an L/D of 24:1, some are shorter at 20:1, and a few are extra-long at 30:1 or even more. More length may mean more output where heating, melting or mixing are output limits. Most of the very long screws have one or two vents in the barrel, which are holes from which moisture, air or other volatile matter can be drawn out by vacuum.

Most screws are square pitch, which means that the pitch (the distance from one flight to the next) is the same as the diameter. This makes it easy to count L/D by just counting turns. The portion under the feed opening is not included in the L/D because there is no full barrel there.



THE EXTRUDER SCREW

The compression ratio of a screw is the ratio of the volumes of the first and last flights and is usually between 2 and 4. It is useful, but not enough to properly describe a screw unless at least one channel depth is known.

Flight thickness is around 10% of barrel diameter. Any more would waste screw length and possibly develop excess heat in the clearances to the wall, while thinner flights would risk breakage and excess backflow in the clearances. A few screws have thicker flights at the feed end, some have tapered sides (trapezoid profile) and a few have a slight bevel on the outer (top) surface to reduce heat development in the clearances.

The surfaces of the flights closest to the barrel are treated to prevent wear. Flame-hardening is enough for light usage, such as in a laboratory, but the preferred treatment is a cap of very hard metal on these surfaces. The entire screw may also be hardened by nitriding or carbiding.

The barrels are steel cylinders lined with a wear-resistant metal. Some barrels, especially for twin screws, are nitrided rather than lined; this is normally not as good as lining, but there are some exceptions.

The clearance between the screw flights and the barrel wall on new screws is approximately 0.005" or 0.1 mm. A tighter fit would be difficult to make and would develop too much heat. Greater clearance is common as the screw wears down. Some worn screws can produce as much or more than when they were new, so be sure there is a real problem before rebuilding or replacing a screw. Rebuilt screws cost around 50-75% of a new screw of comparable quality and design.

Chrome-plating of a screw is said to promote slip and prevent corrosion, but isn't necessary for most plastics. PVDC and some fluoropolymers need special metals throughout the system, as ferrous materials will corrode and plating isn't good enough.

Many screws have a hole drilled through them from the back, through which a cooling fluid is passed. Water may be used to cool the output end of the screw to improve mixing there.

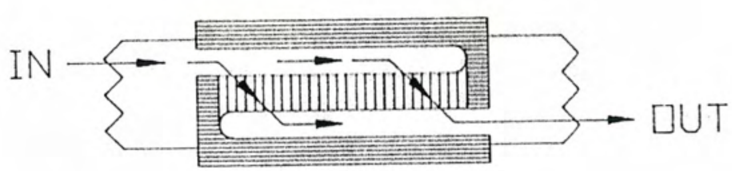
Oil may be used with rigid PVC to keep the screw tip around 300 F/150 C, so that the PVC doesn't degrade there.

A standard screw has three zones: a feed zone, a compression zone and a metering zone. In the feed zone the depth is constant and deep enough to take in the plastic particles. In the compression zone the depth gets shallower -- as if the walls were closing in on the plastic -- and that builds up pressure and thus prevents the air between the particles from continuing down the barrel.

As the plastic enters the metering zone, it should be nearly all melted and ready to be homogenized and pumped out through the die. This zone has a constant depth, but much shallower than the feed.

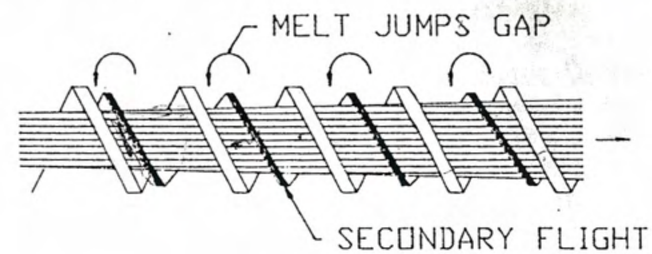
SPECIAL SCREW DESIGNS

1. A Maddock section is a length of screw around two diameters long, normally placed just a few turns before the end of the screw, with large grooves (flutes) parallel to the screw axis, instead of flights. Each inlet flute has a corresponding outlet flute, with a barrier ridge between them. The clearance to the barrel over this barrier is around 0.020-0.030" or 0.50-0.75 mm. The melt enters the inlets, jumps the barrier through this clearance, and leaves through the outlets. Unmelted pellets can't pass over whole, but are sheared and flattened as they finally pass through. This device keeps unmelted material out of the die, and thus provides a more uniform melt.



MADDOCK SECTION

2. A barrier screw is a standard screw with an extra flight in the melting (compression) zone that divides it into two channels, one for melt and one for pellets. The new flight is not full diameter so there is a gap (e.g., 0.060" = 1.5 mm) over which the melt can pass into its channel. The pellets remain in the main channel but are drained of excess melt which might overlubricate them, and can rub and melt more efficiently. As the plastic moves down the screw, the pellet channel gets smaller and the melt channel gets bigger. At the end of this section the pellet channel ends and a single flight continues into the metering zone. The barrier section in the following diagram is only 4 diameters long, but was shortened for clarity. Usual length is at least 10 diameters.



BARRIER SCREW

3. Mixing pins are rings of studs projecting from the screw root to disrupt streamlined flow, thus improving mixing. Usually they are set in the last quarter of screw length.

4. Grooved barrels have axial or helical grooves in the feed section to improve the intake of slippery, hard plastics like high-density polyethylene. A screw with a shallower feed and deep metering zone is needed, often with no compression at all. Because a deep metering zone gives poor mixing, an extra mixing section is needed at the output end.

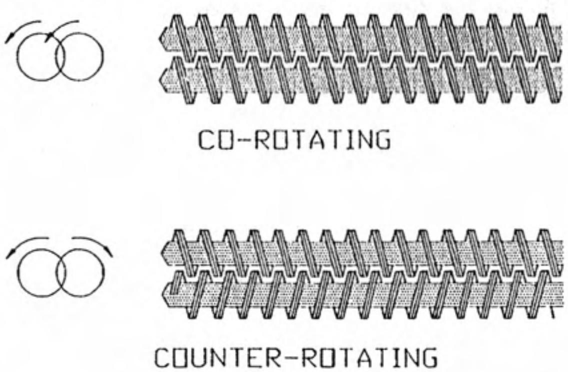
5. For vented (two-stage) extrusion, a very long screw is needed, as all the material must be melted in the first 70%. This first portion is a normal 3-zone screw, but at its end the channel suddenly gets deep again, reducing melt pressure so that a vacuum can be applied through a hole in the barrel (the vent) to draw off moisture, air or volatiles. The melt is then recompressed, passes through a final metering and mixing section, and then goes out through the die.

Additives can be added through a vent -- notably glass fiber, which is much less abrasive if added to hot, molten material rather than mixed with hard, solid feed particles.

In a vented screw, the front stage must take away what the rear stage puts into the vent zone, so the front channel depth must be greater. Otherwise, material will come up the vent, which is what happens when the screens get clogged or the feed intake suddenly improves. The ratio of front to rear metering depths is between 1.5 and 2.0. However, deep channels can't pump well against high pressures, so a vented screw can only work against a maximum of around 2500 psi = 170 Kg/cm resistance of screens, head and die combined. For higher resistance, only a gear pump will allow venting.

6. In <u>double-flighted screws</u>, there are two parallel paths in part or all of the screw length. In the metering zone, this helps heat transfer so it is sometimes used for extrusion-coating where very high temperatures are desired. The two paths are claimed to give smoother feed (less pulsing) and less bending of the screw at the end of the compression zone but it is seldom used for these reasons. A barrier screw is double-flighted in its barrier section but the two paths are not equal, while a wave screw has a double-flighted section where melt is passed back and forth from one channel to the other, thus improving mixing.

7. <u>Twin-screw extruders</u> are used in about 10% of all extrusion. There are two screws turning in a "figure-8" barrel, usually intermeshing:



TWIN-SCREW EXTRUDERS

The screws may both turn in the same direction (co-rotating) or in opposite directions (counter-rotating).

Some twins have slow-moving, counter-rotating, deep-channel conical screws in a matching barrel; the diverging axes allow bigger bearings which can take more die resistance, as needed for rigid PVC pipe/profiles. Fast co-rotating parallel screws are still preferred for compounding, the other big use for twins. They have shallower channels and may need intensive cooling. They may have ports for additives and venting, and some are even used as continuous chemical reaction vessels.

Twin-screws mix by splitting the streams where the flights of each screw come together rather than by the less-effective parallel-plane shear of the single-screw systems. There is intense shear in the nip between the two screws, but much less elsewhere, so that the <u>total</u> shear energy input is low. This means lower melt temperature, which is why twins are used for heat-sensitive plastics like rigid PVC. Lower melt temperature can reduce PVC material cost (less stabilizer), making up for the higher machine cost per unit output.

Twins give a more positive bite (intake) for easy entry of powders, and are often fed by volumetric or weigh feeders which control production rate.

THE HEAD ZONE

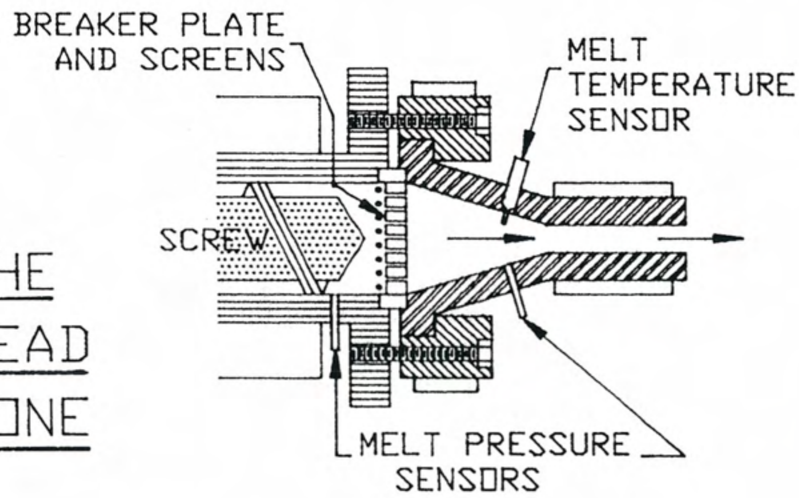
After the material reaches the end of the screw, it passes through the head. First it goes through woven-wire <u>screens</u> which trap contaminants such as bits of paper, wood, or decomposed plastic. A pack of two to four screens fits in a recess on the screw side of a heavy metal disc called the <u>breaker plate.</u> The coarsest screen goes up against the plate and the finest screen faces the screw tip. The thickness of the plate is around 20% of its diameter. It has many holes drilled through it, and can be thought of as a very coarse screen. In addition to supporting the real screens, the breaker plate is the sealing gasket between the head and the body of the extruder. All mating surfaces must be clean and smooth to avoid leakage.

A typical screen pack might be 20-40-60 square mesh (the numbers refer to wires per inch). There are sandwich packs (e.g., 20-40-60-40-20) to prevent anyone from putting the pack in backward -- i.e., with the finest screen up against the breaker plate. In such a case, the pressure of the melt would blow the fine screen through the breaker plate, with bits of contamination and screen in the product and possible scratching of expensive polished die and roll surfaces.

The screens are commonly thought to raise pressure in the extruder and thus improve mixing, but it is really the contamination that blocks the openings and raises pressure. Screens may, indeed, improve mixing, but pressure keeps rising as contamination increases. Therefore, using screens to improve mixing should be a last resort, a temporary technique only, except perhaps with a very clean material.

The pressure entering the screens is the pressure at the tip of the screw, and reflects the combined resistance of the screens, head and die. It may be very high, but the screens may not blow through because it is the pressure <u>differential</u> across the screens that blows them, not the absolute value.

THE HEAD ZONE



Usually the pressure buildup is slow because contamination enters slowly, and can be monitored by reading the pressure gauge or connecting a recorder.

Sometimes, however, a lot of contamination enters rapidly, such as paper, polyester tape or perhaps a handful of stones or gravel. In such a case, we say the screen is blinded; pressure rises rapidly and there is danger of the head and die separating from (blowing off) the extruder. This is dangerous, as hot plastic may shoot out and injure people, or the equipment can be damaged, or both.

To avoid this problem, some lines use rupture discs at the screw tip which will relieve the melt pressure if it gets too high. Others have shear pins in the gate bolts which are designed to fail under stress and thus allow harmless leakage of the blocked material. Pressure gauges can be connected to an alarm to alert operators or even to shut down the extruder if necessary. Everyone working around an extruder should know the pressure limits, what safeguards exist and whether they work properly.

Screens are thrown away after use. They can be cleaned, but this is too much work and mess for the value recovered, and they may tear during removal or cleaning. Also, such re-use risks putting them in backward (with the surface that faced the screw now facing the die), in which case the extrusion pressure will push out particles embedded in the wires and contaminate the first product.

Screen changers are devices which allow changing screens without taking the head apart. This saves time and makes less scrap. With the simplest ones, the line is stopped, the head loosened, and the clean plate with screens is pushed into place -- thus pushing out the old one with its dirty screens. Better models have a sealing system which allows the line to keep running during screen changes. Some even have a prefill position where the new plate and screens are filled with hot plastic just before entering the head, thus minimizing the disruption of the system -- even then, the sudden pressure change may affect product dimensions.

Continuous screeners move a strip of screen or a series of screen pieces continuously across the flow path. Unlike the screen changers, they can keep pressure at the screw tip relatively constant by speeding up for more contamination and slowing down for less.

The gate is a thick steel piece which clamps the head and die assembly onto the end of the extruder barrel. The standard gate has four bolts at the corners which must be tightened evenly to avoid leakage. The bolts are attached to the barrel and swing out when their nuts are loosened. The nuts should stay on the bolts to avoid their loss.

Quick-opening gates have only one or two bolts holding the segments of the gate together. This is especially useful for PVC where cleanup must be fast to avoid decomposition.

Many gates are hinged on one side for easy screen changing. The hinge pin should be on the side away from the operator, and should come out completely to allow removal of the gate while still attached to the die. This is needed for big dies which have their own supports. Gates may be heated at start-up and to make up radiation loss, but they are seldom insulated (which would be a good idea) and never cooled.

The adapter is the connecting piece through which the plastic flows, between the extruder barrel and the die.

Temperature measurement of the head and die is done with thermocouples for each zone set deep into the metal walls. These signals are sent to controllers which regulate the corresponding heaters. Also, a melt thermocouple projects around 0.25 inch (6 mm) into the plastic stream, usually in the adapter after the screens and breaker plate but before the die. It is not used for feedback control, but it does show steady operation and may also signal possible degradation or cooling problems. If there is no melt thermocouple, one can get an idea of melt temperature by sticking a needle pyrometer into the emerging melt or aiming an infra-red device at it.

Melt pressure is measured at the tip of the screw, just before the screens, where the pressure shows both the contamination on the screens and the resistance of the head and die. This pressure, too, is the one that reflects melt temperature, affects the mixing and stresses the thrust bearing. A second pressure gauge may be set in the adapter after the screens; its pressure shows up surges (thickness changes), and the differential pressure across the two gauges (hence across the screen pack) can be used to actuate an automatic screen change.

To measure pressure, a thin metal disc is set flush with the inner wall and transmits pressure to an indicator through a solid rod or a tube filled with liquid such as mercury. It can generate an electrical signal for closed-loop control.

The first pressure gauges were grease-filled tubes open to the plastic flow path. These can work if set on the underside of the adapter so that the grease doesn't leak into the plastic stream, but they are still troublesome and have been almost all replaced by sealed disc-based devices.

A valve is an adjustable barrier to flow which can raise pressure without clogging, unlike screens. The valve is often a steel rod with a spherical end, threaded into the adapter, and moved up and down by hand or a controlled device. Valves are often seen on vented extruders, but are quite rare on others.

Static mixers are flow-diverting devices set between the extruder and the die which divide and redivide the melt as it is pushed through by the extruder, thus achieving better dispersion and mixing. As a static mixer is part of the head resistance, there is some pressure drop across it which may raise melt temperature. Some mixers are jacketed to provide more heat or cooling as needed. Some are easier to purge and clean than others, and all increase the need for a die support because they lengthen the neck between the extruder and the die.

Dynamic mixers are like static mixers but are driven by their own motors, or else are extensions of the screw.

A gear pump (sometimes called a melt pump) may be set between the gate and die, and takes over the job of pushing the melt through the die. A pair of intermeshing gears turn in a closed chamber and the melt is carried around in the spaces between the gear teeth and the chamber walls. If a precise drive is used, it gives very uniform output and thus eliminates the effect of surging in the extruder. It also takes some of the load off the extruder motor, which may reduce the pressure at the end of the screw, and possibly the melt temperature. If these were production limitations, the gear pump may allow a higher output rate.

Gear pumps are self-lubricated with molten polymer, so they must never run empty. Pressure control at the pump entry, fed back to the extruder drive, prevents this. The first pumps were oil-heated, but electric heating is standard now.

A coextrusion feedblock is another device sometimes found in the head, just before the die. Coextrusion is the combination of two or more molten streams of plastic so that they exit from a single die to give a multilayered or striped or other multi-material product. The flows must be similar to get uniform layers, and adhesive layers may be needed to bond incompatible plastics. The passages inside a feedblock are designed like traffic intersections for the smooth and gradual joining of materials in a common stream.

EXTRUSION DIES

The die is a steel block at the output end of the extruder with a passage through it that ends in one or more openings that form the final shape. Dies vary widely in size, from tiny wire-coating dies to huge paper-coaters eight feet or more across.

Heating of a die is done with electrical resistance, either mica- or ceramic-insulated heaters that clamp or bolt to outside surfaces, or cartridge heaters that fit into holes drilled in the die block.

Die heaters are needed for several reasons:

1. To allow safe start-up. Cold starts can cause substantial equipment damage and are a serious safety hazard, too.

2. To make up for radiation loss during operation. Insulation can serve the same purpose, and some heaters also provide this function.

3. To control die temperature, either to keep it uniform, or to vary it to get differential flow.

4. To reduce resistance by reducing viscosity at the inner metal surfaces (hot-lips method).

5. To heat the emerging surface to gain more gloss, less swell and less chance of melt roughness.

Most dies are made of steel, but lips and inserts for holes may be hardened to reduce wear, and a few dies have low-friction internal surfaces of porous metal impregnated with a fluoroplastic.

The formulation of the material to be extruded may also reduce the friction in the die. Especially for linear low-density polyethylene, there are additives which reduce the friction and thus reduce the melt temperature. This, in turn, means easier cooling and consequent higher production rate. These additives also help production by raising the critical speed above which melt roughness would occur.

Brass adjusting bolts may be used in steel dies; they don't rust, there is less turning friction, and if they seize or otherwise lock, they fail before they distort or damage the rest of the die. Chrome-plated interior contact surfaces may avoid corrosion (with PVC) and reduce friction, but must be a thick and adherent layer (no "flash" chrome). With good purging and cleaning, chrome plating may not be needed, even for rigid PVC. However, PVDC and a few fluoroplastics need special anticorrosive metals, not only for dies but for screws and barrels as well.

WHAT HAPPENS INSIDE THE BARREL

A. Feed Zone

In most cases, free-flowing pellets from the hopper fall by gravity into the screw, through a hole in the barrel called the feed throat. This section is sometimes cooled with water to prevent bridging and sticking to its walls. Don't confuse this vertical entry passage with the feed zone, which is the first section of the screw itself.

The feed zone in the barrel occupies the first three to ten turns of the screw, the channel depth is constant, and pellets that drop in it are grabbed and pushed forward by the flights of the screw. The pellets should ideally stick to the barrel wall and slip on the screw root.

If they stuck to the screw they would build up on the screw root surface, reduce the input and eventually cause some obstruction and slowing down or stopping of production. The usual cause of sticking to the screw root is stopping of the machine for a few minutes while the feed zone is still full of material. The entering plastic is really the main cooling agent of the system, because it is coming in at room temperature. The rest of the system is up at the extrusion temperature and the new material absorbs all heat produced in that system by the motor and the heaters. Stop the feed -- in other words, stop the coolant -- and you risk sintering and sticking to the screw root.

The material must stick to the barrel wall in the feed zone so that it can be caught by the flights of the screw and pushed forward. As the cold pellets touch the hot barrel wall, they melt at the points of contact. These pellets then roll around and touch and stick to other pellets, beginning to form what will eventually be called the solid bed of pellets moving forward in the compression zone.

At this point we want pellets to stick to one another and interlock so that when a few of them are pushed forward by the moving flight, others will follow. The ability of the first flight to take in pellets is called the bite. This bite

depends on the shape of the particles, how big they are, how regular they are, and also how slippery, because if pellets are slippery they won't stick to one another as easily.

The bite also depends on the interaction between the feed and wall temperatures. The more the pellets stick to the barrel wall, the more the feed flights will grab them and push them forward.

The real quantity that enters is always much less than the perfect bite (100% displacement) because the pellets are rolling around and sliding on one another; they don't move forward as an integral mass yet. However, calculating the perfect bite is a useful starting point:

6.13 (D-h)DhNB lb/hr, if D and h are in inches
0.17 (D-h)DhNB Kg/hr, if D and h are in cm (not mm)

D = barrel diameter	N = screw RPM
h = channel depth	B = bulk density, g/cc

The bulk density is an important variable here because it tells how fluffy or how dense the feed is. Fluffy feed, of course, will feed at a lower rate than dense feed. Bulk density is simple to measure: fill a cup with plastic and weigh it. Then take out the plastic, fill the cup with water, and weigh it again. Since the density of water is one gram/cc, the ratio of the weights (plastic to water) is the bulk density in grams/cc. (Remember to subtract the weight of the cup in each case.)

When you calculate perfect bite, the result is very high, perhaps 750 lb/hr for a 2.5-inch extruder or 2000 lb/hr for a 3.5-inch extruder. These, of course, are unrealistic rates because we don't get perfect bite. What we do get varies from as low as 20% of perfect bite (hard, slippery pellets) to 40% or more (softer, more rubbery materials).

At very low barrel temperatures there is little sticking to the barrel and the bite is therefore lower. As rear-barrel temperature increases, sticking increases and bite is better.

However, as temperature rises further, the melted layer lubricates the pellets (ice-skater's effect) and thus opposes sticking. Therefore, there is one temperature at which the sticking is highest and at that temperature the grab or the bite will be best.

We can't always say whether more or less heat on the barrel zone or a hotter or cooler feed will give more bite, as it can go either way. It is usually easiest and most reliable to find out by running different rear barrel temperatures to see the effect on the output rate.

With bite, more isn't always better. There can be too much, and the extruder can in effect bite off more than it can chew. This happens when the rear zone wants to take in more than the front zone wants to pump out. Of course, a compromise is reached, as what goes in must come out, but too much "overbite" in the rear zone may lead to overheating and possible material degradation, usually at the entrance to the metering zone, about 3/4 of the way down the extruder.

Too little bite is also possible; the front end of the screw is capable of pumping a lot but the rear end can't keep the front end satisfied. That happens where the feed zone is too shallow or narrow or, even more likely, when feed is too fluffy. Scrap filament and scrap foam, for example, might not be able to fill the channel enough to keep up with what the front end wants to put out. In such cases, force-feeding with a screw or stuffer in the throat sometimes helps.

With such light feeds, a screw made for pellets may feed poorly at low, uneven rates. There are several ways around this, in addition to the force-feeding just mentioned:

(a) use a screw with longer or deeper channels in the feed zone. With deeper channels, the screw root becomes smaller, and there is greater danger of its twisting and breaking. A front-end drive allows deeper feed channels. Some machines even have a dual diameter -- a fatter screw at the feed end for greater intake capacity with less danger of its breakage.

(b) compress the feed in the hopper, or pass it through a separate densifying process where it is spun in a high speed mixer until it shrinks and balls up into little particles. These, when cooled at the right time with air or water, make a flowable mass.

(c) densify the feed in a machine which compresses the light material into tablets or similar form. If the bulk density can get up to at least two-thirds of the original pellets, it should be able to flow in a hopper.

(d) pass the feed through another extruder which makes pellets that can be fed by conventional means.

(e) feed the material directly into the extruder from a roll or bobbin (film or monofilaments), saving the step of chopping and the problem of feeding a bulky, fluffy mass.

Starve feeding is another method for getting poorly-flowing material into the extruder. In starve feeding, the hopper is empty; in fact, the hopper may not be a hopper at all, but may be just a chute through which material is dropped. The screw runs so fast that whatever falls in is taken away, and the feeder controls the input, hence the output.

Starve feeding is sometimes used where there is no feed problem, but there is some controversy regarding such use. It is alleged to aggravate surging and certainly loses some melting and mixing capacity. Much depends on the quality and precision of the feeding device. Starve-feeding can be used to avoid a pre-mixing operation: two or more hoppers drop materials through a chute directly into the feed zone of the extruder screw.

Grooved barrels have already been mentioned as a method for improving the input per rpm. They greatly improve the bite, claiming up to 75% of perfect and much more than any smooth-barrel system. The result is that lower rpm can be used for the same or even greater output. This means lower melt temperature, which, in turn, enables higher production rate for blown film, and explains why they are virtually standard for high-density polyethylene blown film lines.

With grooves, good control of rear barrel temperature is critical and special metals are needed to avoid excessive wear of the grooves and feed flights. Since the screw is run at lower rpm, this means more torque and possible drive overload or a broken screw. Therefore, altering an existing smooth-bore machine is not recommended although it may be technically possible. In any case, a new screw is needed.

Obstructions in the feed zone sometimes occur for no apparent reason. There are no feed bridges, but the pellets just roll around in the first flights and very few move on. Sometimes a hotter feed or barrel wall may help in the first zone and even in the second zone. If plastic is sticking to the screw root, try a cooler feed temperature, or cool the screw in that region as a last resort. Purging with chopped scrap or special purge compounds may also help. Sometimes, poking in the feed zone with a flexible steel strip works. Remember that most screw root buildup in the feed zone is a result of temporary stoppage, not wrong conditions. To avoid this situation, don't stop a full screw for more than a few seconds.

B. Compression Zone

In this zone, the channels get smaller as the solids compress and condense into a continuous melt. Only with grooved barrels do we find little or no compression, as there is such good bite in the feed zone that a substantial compression would be too much restriction. Output rate would drop, and pressure and temperature would become excessive.

Screws for smooth barrels, on the other hand, start to compress around the point where substantial melting begins, and most of the melting actually takes place in this zone. Heat enters the advancing particles from the barrel wall and the screw root, which conduct heat backward from the hotter front end. Most important of all, as the motor turns the screw in the viscous mass, its electrical energy is changed to frictional heat, especially in the melt-filled clearances between the screw flights and the barrel wall. The barrel may get even more heat from its external heaters if needed.

Much of this melted material collects on the pushing surface of the flights as they scrape the barrel walls. Some melt will leak back over the flights into the preceding channels, and some will infiltrate the unmelted particles and help to heat them up. The air between the particles can't move forward -- it has no place to go, as the pressure is greater ahead of it -- while the solids and melt are pushed forward by the flights against this higher pressure.

The mass of solids, called the <u>solid bed</u>, acts like logs in a river. It may break up erratically and thus cause sudden changes in pressure, amperage and output rate. This is one cause of surging, the name given to cyclical change in the output rate. Another related cause is the loss of tacky (high-friction) contact of the unmelted pellets with the hot wall. This may occur if the mass isn't yet soft enough to compress and the shrinking channel volume forces the first melt up into the spaces between the still-hard particles.

Use the ammeter to spot surges. Watch for at least half a minute and record the high and low marks. A band of 2% is good, a band of 5% may be OK, but 10% or more is too much for most products. Sometimes, surging can be relieved by a change in feed or rear-barrel temperature, or anything else that might change bite. In extreme cases, only a gear pump between the extruder and the die can iron out surges.

C. Metering Zone

By the end of the compression zone the plastic should be entirely melted, air-free and ready to pump out. However, a few more flights, called the metering zone, are needed to do the final mixing and homogenizing to get thermal as well as material uniformity. In the metering zone, the channels are once again uniform in depth, as they were in the feed zone. However, unlike the feed zone, we now have a melt which is assumed to stick to all surfaces. The screw motion drags the plastic around so that the flights will push it forward to overcome the resistance of the head and die.

Sometimes this push of the flights is helped by an overbite in the feed zone. The entrance to the metering zone is where the compromise is made between overbite, if there is any, and pumping capacity of the metering zone. This entrance is like a toll booth on a highway which limits the amount of material that can enter the metering zone. If the rear is pushing harder than the front wants to pump out (considering the head/die resistance) a pressure peak will occur at this point, where pressure is even higher than that in the die or at the end of the screw.

The desire of the metering zone to pump out material against zero resistance (no die, no screens) is the drag flow:

$2.64\ D^2hNp$ lb/hr, if D and h are in inches
$0.073\ D^2hNp$ Kg/hr, if D and h are in cm (not mm)

D = diameter	N = screw speed, RPM
h = channel depth	p = melt density, g/cc

Note the use of melt density, which must be used for all calculations of flow in the metering zone and die because the plastic there is fully melted. There is a great difference between melt and solid density -- as much as 20% for the polyolefins and at least 5% for most other plastics. This difference represents the expansion of the solid material as it becomes a melt. Low-density polyethylene, for example, with a solid density of 0.92 grams per cc, expands to a melt density of 0.76 g/cc. Materials like PVC and polystyrene are amorphous -- that means they don't have a crystalline structure -- and therefore have less expansion on heating and less shrinkage later on, when cooled.

Melt densities for some common plastics in typical unfilled formulations, at reasonable pressures and temperatures, are:

ABS --------------------	1.00	Polyester PET ----------	1.21
Acetal -----------------	1.16	Polyethylene HD ------	0.78
Acrylic PMMA -------	1.12	Polyethylene LD ------	0.76
Cellulose Ac-Butyrate	1.05	Polypropylene --------	0.73
Nylon 6 or 66 -------	0.98	Polystyrene ------------	0.99
Polycarbonate --------	1.11	PVC Unplasticized ---	1.27

Melt density depends on temperature. It is around 0.5% to 0.7% lower for each 10 C rise in temperature; polyethylenes change the most, polystyrenes the least. Molten plastics are also slightly compressible, so that a melt has a higher density inside the extruder than at atmospheric pressure. The difference is around 0.5% per 1000 psi. Both of these temperature and pressure variations can be neglected when using the above drag flow equation, but must be considered for more precise work.

Calculating the drag flow can be useful in identifying extrusion problems. If the real output is near the drag flow, or even above it, there is an overbite, which means probable overheating at the entry to the metering zone (the toll booth), a pressure peak there and maybe wear of the flights there. The corresponding temperature control zone is likely to override, and when the screw is removed from the barrel it often has a blue color at this point. This "blue screw syndrome" means that the rear end is taking in more than the front end wants to put out, or "biting off more that the machine can chew."

This isn't necessarily bad; in fact, it may give more output and make screw wear irrelevant. However, it may also mean that the melt temperature is too high, and if this causes problems the overbite must be reduced.

If the real output is very much below the drag flow -- for example, over 20% -- this means there is a very high die resistance, or a problem in feeding or solids conveying in the feed zone, or both.

The drag flow is normally calculated using original screw dimensions, with the usual 0.005" or 0.1 mm clearance from flight to barrel wall. However, if the screw is worn in the metering zone (which is usually due to misalignment) there is less pushing surface, and less pumping capacity. More melt "leaks" backward over the flight clearances and the screw must turn faster for a given output, with consequent possible higher melt temperature. With overbite, the reverse is true, as the wear reduces the resistance to the high push from the rear and may actually increase output.

Melt pressure is normally measured at the end of the metering zone. The variation will reflect surging and will show as thickness variation in the product, but not necessarily in direct proportion. The 1-2-3 rule is sometimes useful: a band of 1% (+/- 0.5%) is very good, a band of 2% (+/- 1%) may be acceptable and a band of 3% (+/- 1.5%) or more may mean trouble in controlling thickness. If the pressure gauge is in the adapter or the die, it is easy to read and apply this rule. However, most gauges read pressure at the screw tip, which is good for knowing when the screens need changing, but is hard to read because of screw beat, the cycling of pressure with the turning of the screw.

Screw beat comes from the difference in pressure across the channel, from front to back. The most recent digital pressure gauges have the ability to eliminate this problem; although it still occurs, the gauge shows a single value.

The 1-2-3 rule for pressure and the 2-5-10 rule for amperes mentioned earlier are useful starting points. However, they shouldn't be followed too closely, because each product has different tolerances for what is acceptable, and the appropriate variation should be determined in each case.

WHAT HAPPENS IN THE HEAD AND DIE

The head and die comprise the resistance that must be overcome by the forward push of the extruder, and its magnitude is shown by the pressure at the screw tip, sometimes called back pressure. This resistance is one of the main demands for drive power, along with resistance of the plastic to the screw's rotation within the barrel.

Changes in die resistance have a big effect on the process. In general, a higher resistance will produce a higher melt temperature, as the motor must work harder to push the material through. Higher resistance will mean less output per horsepower, but better mixing. Conversely, lower resistance will yield lower melt temperature and more output per horsepower, but mixing may suffer.

Die lip opening is one of the most important contributors to head resistance. This is fortunate, as it is sometimes adjustable, both by gap size and lip temperature. Tiny gaps mean very high resistance, as resistance is generated in inverse proportion to the square of the gap, or the cube of the radius if the product is round.

The screens produce high resistance only if very fine (80 mesh or more) or if they are badly clogged. A static mixer can add to the resistance, as can a valve, or any die (such as a spiral-mandrel film die) with long, constricted paths leading to the die lips.

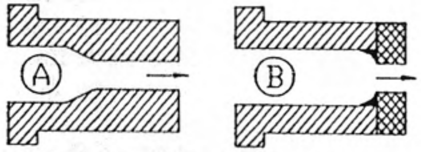
A gear pump can take over the job of pumping through the die and any static mixer in the line, but not the screens, which must stay where they usually are in order to protect the gear pump. The pump can't change the head resistance, but does shield the extruder from its effect, and thus can lower back pressure if desired.

Streamlining the flow path through the head and the die reduces the resistance, and is especially needed to avoid corners and other places where the plastic doesn't flow well. Stagnation in such places will make material and color changes take longer, and will promote degradation of the plastic there -- yellowing, making unmeltable particles that end up as product contaminants and, in severe cases, actual blackening of the plastic and corrosion of internal die surfaces. This is sometimes called "burning," although there is no fire or flame. Charring or cooking describe it better. With PVC, such degradation is self-catalyzed -- once it starts, it gets worse very fast and all production must stop.

In addition to contaminating the product, bits of degraded plastic may lodge ("hang up") in the die, causing permanent streaks on the product called die lines.

A completely aerodynamic passage is not needed, but gentle angles of change are preferred. As in die A, 30 degrees or less is often enough. In die B, hang-up is likely, resistance is increased by the sharp directional changes, and the melt temperature may even be higher. Dies like B, called plate dies, are sometimes made for low-cost or trial production.

FLOW PATHS IN DIES



Heaters are used at startup and to maintain the desired melt temperature through the head and die (see pp 14-15 for more on die heaters). In large extruders with small dies, head and die heating has little effect on melt temperature as the melt is moving fast and residence time is low. With small extruders and large dies, however, the situation is reversed and head/die heating is an important factor in achieving final melt temperature. In all cases, hotter dies mean less extruder pressure (less resistance).

Heaters may help thickness control by directing flow toward or away from certain die areas (but beware on-off heater pulses, which will themselves cause thickness changes). In some flat film/sheet dies (and a few for tubular film), die heaters control the thickness across the product: an on-line measuring device feeds signals back to these heaters which either heat the lips in the appropriate areas, or expand bolts which in turn change the gap in those areas.

Further dimension control is usually needed because what comes out of the die is never just like the opening. Corners and thin projections shrink more than thicker parts, but the internal flow paths are designed to compensate. There may be centering or other manual adjustment combined with the downstream cooling system to give final thickness control.

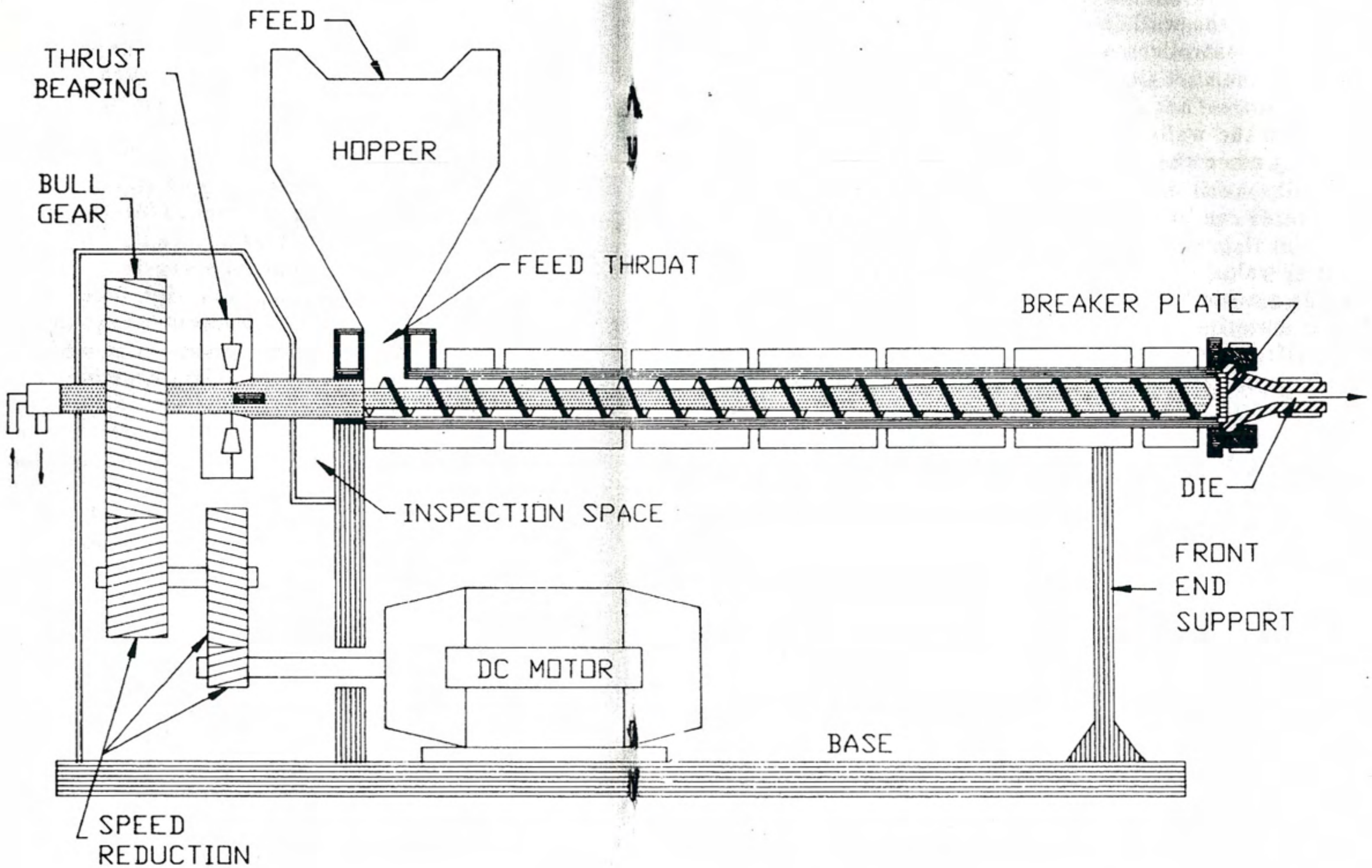
Swelling takes place when any plastic leaves a die. The amount (in transverse direction) may vary from near zero to as much as 75%, with polyolefins giving the highest values. Swell decreases with hotter melt, and also with longer, more streamlined dies. Drawdown compensates for swelling, and can be controlled manually or automatically by varying the puller speed. Dies are designed by experience with these things in mind, and there is still much trial and change. Computers can help, but cannot yet be relied on entirely.

Orientation is a strengthening of the product by stretching it while warm. The maximum effect occurs at temperatures well below those of extrusion -- e.g., polypropylene orients well at 110 C/230 F, but its extrusion requires at least 200 C/390 F. Therefore, such high-level orientation cannot be done directly at the extrusion die; instead, specialized cooling and reheating equipment is needed for products like filaments and tapes (monoaxial, stretch in one direction) or film (biaxial, both directions).

For other products, some low-level orientation is always introduced by the pull of the takeoff, even at extrusion temperature. This is usually unwanted, as although the pulling direction is strengthened, the cross direction is correspondingly weakened.

To minimize low-level orientation, keep the die gap as small as possible, don't pull down too much, and keep melt temperature high, consistent with cooling and degradation limits. An exception is tubular (blown) film, where low-level orientation makes a stronger film, but blow-up ratio and drawdown must be balanced to give equal properties in all directions.

Die flow equations link output, resistance (pressure drop), die dimensions and viscosity. If you know three of these, you can get the fourth. For good results, one needs reliable viscosity data.



THE EXTRUDER AND ITS PARTS

SETTING CONDITIONS

Setting conditions usually means setting the temperatures of the barrel, head and die. There are temperature sensors (thermocouples) in the walls near the moving plastic, which are connected to controllers which work much like home thermostats. (Remember that we control the internal metal surface temperatures, not the plastic.) The controllers turn on heaters when the walls get too cool, and (on the barrel) turn on cooling when the walls get too hot. These controllers are actually much better than any home thermostat, and temperatures can be held very close to desired values.

What are these values, and how do we decide what they should be? Is a normal profile best, with wall temperatures increasing as material moves down the barrel? What about an inverted profile, which is hottest at the rear, or even a camel or hump profile, hottest in the middle?

The actual importance of the temperature profile is often overestimated. It does affect the process, but so do many other things, such as choice of material, scrap percentage, and take-off conditions. Avoid the feeling that all will go well when you find just the right profile. In fact, there is no "best" profile; rather, each zone should be set independent of the others, based on what is happening there.

In the <u>feed zone</u>, rear barrel temperature controls sticking to the barrel walls. Thus, it affects the bite and is often the most important of the conditions. Too much sticking produces overbite, which creates overheating at the end of the compression zone. Too little sticking means underbite, with less output per rpm than otherwise possible. Usually, more heat means more sticking and more bite, but this isn't always true, as some materials self-lubricate at very high temperatures and bite gets worse again. Follow experience, or get it by trying several rear barrel temperatures, and see what happens to melt temperature and output rate.

The first half of the <u>compression zone</u> is where surging often originates. There must be sticking to the barrel wall to keep circulation and avoid plugging.

The second half of the compression zone is the site of excessive pressure and temperature if overbite exists. In such a case, the temperature will override in this zone, the heating is not activated at all, cooling is applied, and the real output will be at or even above the drag flow output. If this happens, feed conditions should be changed to reduce the bite, in addition to (or instead of) cooling the zone that is overriding. The compression zone often needs no added heating, as the heat generated inside the barrel is enough.

Keep in mind that heating a barrel doesn't always make the melt hotter, as it lowers viscosity in the clearances; thus there is less frictional heat generated there. The reverse is true for cooling, which thickens up the melt in these clearances and makes the motor work harder. For these reasons, it is hard to predict what barrel temperatures are best and experience/experiments are often the best guides.

The <u>metering zone</u> doesn't normally need heating either, except for small machines, some special plastics and most extrusion-coating. Use cooling cautiously, as it might be possible to eliminate the origin of the overheating instead. For example, overheating can be due to overbite, or to a plastic with very high viscosity, or to keeping the die too cool (increases resistance), or to a screw that produces too much friction, or simply to a screw speed set too high.

What can be done if conditions have to be developed with no prior experience? In such a case, there must be some knowledge of the type of plastic and its approximate proper extrusion (melt) temperature. Set all the heaters, from the feed zone all the way through to the die, at that value and see what happens. For example, almost all polyolefins and polystyrenes will run at around 200 C or 400 F, so these are adequate starting values. Then, once the material is moving through the system at a reasonable rate, change each heat zone as needed to control bite, overheating, and die flow.

The <u>head and die</u> are always heated but almost never cooled. Heat is needed at start-up to avoid a cold start, which is dangerous to both equipment and personnel. While running, head and die heaters make up for radiation and convection losses, affect gloss and swell, reduce orientation, and sometimes help control thickness by heating certain areas more than others. Despite these useful functions, head and die heaters on many lines are too small, leaving much exposed surface where heat can escape, requiring more time to start up and more heat to make up for the loss, and creating hot and cold areas which may lead to thickness variation.

Die heat may affect flow rate as well as the temperature of the emerging melt. A hotter die usually means a hotter melt and faster flow; however, the hotter die may reduce the resistance so much that less pressure is needed to push the melt through the die, less frictional heat is created by the screw, and the average temperature of the mass is lower.

In addition to the temperature settings, we control one more variable, the screw speed, which is normally set as high as possible, consistent with the manufacture of a good product.

Finally, the melt pressure at the screw tip is controlled in a few cases. With a gear pump, pressure control is used to avoid starving the pump (which controls production rate). The pressure signal is fed back to the screw speed, which changes as needed to ensure that the pump is fed. Selecting pressure input to a gear pump is a balance: lower pressure means lower melt temperature, but higher pressure is better for mixing. The gear pump is, in effect, acting as a valve.

Today, conditions are often controlled by a microprocessor, which is nothing more than a very large memory in which we can record, in advance, the desired barrel, head and die temperatures, and the pressure, too, if that is to be set. The microprocessor display can show all of these settings, plus the dependent variables: the melt pressure, the melt temperature, the current (amperes) passing through the drive motor, and sometimes an indication of the output rate.

The microprocessor allows other levels of process control as well. For example, it takes the place of a man with a clipboard and records all process data. Thus, it can tell us: How much did motor amps vary during the last shift? Was there any slow but steady change in output per rpm over the last few months? In addition to direct process control, data from a microprocessor can be sent to other locations, plotted on charts, analyzed for process improvement and problem solving, or used in plant-wide materials control.

MAINTENANCE

Extruders can last 20 years with good care, and should certainly be producing after 10 years. Proper maintenance means a regular schedule to check the machine. Read the owner's manual carefully; if it is gone, get another copy. Here are some important aspects of extruder maintenance:

BASE -- Everything bolted tight, level and aligned.

MOTOR -- Most DC motors are exposed to the air; the inside must be kept clean and the brushes checked for wear. Make sure the fan is blowing in the right direction; otherwise it will draw dirty air into the motor rather than keep it from entering. The air filter may need replacing. The motor ammeter and the screw speed indicator should be calibrated frequently. The alignment and condition of all couplings, belts and pulleys should be checked.

REDUCTION -- Make sure there is always enough lubricant in the system, and change it at regular intervals. Seals on the shafts should be inspected, leaks observed and repaired if necessary. If there is an oil filter, change it often and inspect the old one to see what is in the oil system -- e.g., metal bits which indicate something wrong inside. Monitor temperature and pressure of lubricant.

THRUST BEARING -- Determine age, model, and replacement procedure, and calculate expected life. While running, look for overheated housing and listen for vibrations and unusual noise; take it apart for inspection if noise, high temperature or metal bits so indicate.

HEATING/COOLING -- Calibrate controllers and thermocouples and check heating and cooling devices for tight contact with the outer barrel surface. Some types of heater do not need close contact, while others do. All electrical contacts and water connections should be tightened. Look for rust; water leaks may not be visible, but rust is good evidence of previous leakage. Replace frayed wiring and guard against future fraying. Flush the cooling system and descale if necessary.

BARREL -- If the screw is pulled, shine a light down the barrel and look for cracks and scores. If wear is suspected, use an accurate instrument to measure diameter from one end to the other. Inspect the powder seal at the feed end. Look at all of the sealing surfaces at the output end, and make gaskets or refinish/replace breaker plates as necessary.

SCREWS -- Measure flights for wear; repair only when justified -- for example, lower output per revolution than when new, combined with overheating. Sometimes wear doesn't make any difference. Keep screw pusher threads clean. If the screw has water cooling, inspect the rotary union for leaks, frayed hoses, rough turning, grease-fitting operation. Make sure the cooling finger which enters the screw bore isn't plugged or otherwise damaged. Keep all screws clean, including spares, which should be wire-brushed clean and anti-rusted when put in storage. When back in the extruder, measure tolerances and concentricity of the screw (remember that it will sag in the barrel, so turn it around a little, then measure, turn, etc.).

HEAD -- Keep breaker plates clean, rustproof them if they are stored, and check their sealing surfaces for smoothness, because nicks and carbonization will mean slow leakage during operation. Calibrate the temperature and pressure gauges. Test the alarms, if any. Lubricate valve threads. Check supply of screens and see that spare shear pins or rupture disks are available when needed.

DIES -- Keep them clean, inspect for damage at the lips and store with protection against damage and rust. See that all bolts are in place and move freely, lubricate if needed. Calibrate controllers and thermocouples. Inspect heaters for damage, poor contact, frayed wires or improper grounding.

TAKEOFFS -- Flush and descale cooling systems, refinish chrome rolls as needed. Rubber rolls are often neglected compared to chrome rolls and may need refinishing if they are glazed, chipped or otherwise slipping. Roll stacks should be kept level. Water tanks should be checked for leaks, especially at hose connections. While running, check all pullers for speed, tension consistency and worn belts.

SPARE PARTS -- Take regular inventory of spare parts; every system needs a different set, so make a list to be sure; e.g., screens, breaker plates, heaters, thermocouples, cooling valves, die bolts, hoses, hose clamps, shear pins, rupture disks, motor brushes and drive belts.

RECORDS -- Maintenance time is a good time to compare the current performance with the past, in output per rpm, average melt temperature and pressure. Include nameplate data in records because the information on the motor and extruder may be needed for replacements, or to accurately analyze the system. Such data include: model and serial numbers, dates of manufacture, horsepower, gear ratios, top speeds, bearing capacities, heater capacities and the like.

CLEANING SMALL PARTS -- It is sometimes necessary to clean small parts covered with plastic. This is best done while hot and the plastic is still melted. If cold, reheat them in an oven to melt out as much as possible; such heat-soaking is good for hot parts as well. If cleaned manually, steel tools can scratch delicate die lips and flow-path surfaces. Use brass, wood and similar materials instead, especially where a sealing surface is involved, because if these surfaces are damaged, leakage may occur. If a vise is used, avoid vise-grip marks on sealing surfaces. For breaker plates, clamp horizontal rather than vertical, to prevent such marks and make melt-out easier. Direct an air hose at the plastic-metal contact line, which causes shrinkage and clean separation when the plastic is slowly pulled away with long-nose pliers (wear gloves and eye protection).

Burnout with torches may warp or otherwise damage metal parts and is also dangerous. If it must be done, do it slowly and safely. Use solvents with caution, only in ventilated areas and only as a last resort. A solvent soak is effective, but don't put hot parts in solvents and keep containers covered but vented. Molten salt baths are used to clean tiny holes: effective but dangerous.

Hot fluidized beds of alumina particles burn off the plastic with no harm to the part. High-temperature ovens, with or without vacuum, remove plastic from metal parts like a self-cleaning home oven. With all these devices, remember to vent the exhaust safely.

SAFETY

HEAT -- The head and die are hot and seldom insulated, so wear gloves while working with them. Anti-burn materials should be available at all times. A pail of water is useful for burnt hands, but chain it down so no-one throws it on electrical fires. Don't touch molten plastic or metal parts until you are sure they are cool enough to touch. Plastic that has just hardened is especially treacherous, as it may look like the cold product, but can burn just like the melt.

ELECTRICITY -- Keep all wiring protected and repair where needed, including thermocouple leads. Avoid plastic leaks which could push wires together. Guard all heater contacts, ground everything and check the integrity of the grounds from time to time. Fix all water leaks and mop up water spills immediately. Be very careful with high-voltage devices like film treaters and insulation spark testers. If film is being rolled up, watch out for built-up static.

MOVING PARTS -- All roll nips should be shielded and guarded. Check often to see if the safety cords work.

Never wear ties, loose clothes, hanging hair or jewelry near moving parts. Guard all shears and be careful in changing or adjusting slitter blades. Be careful around fast-moving wire, which may be almost invisible. When taking apart a screen changer or anything else hydraulically driven, first relieve any oil pressure in the changing system.

WEIGHT -- Many objects around an extruder are very heavy. Lift them with care and use hoists when necessary. Wear steel-tipped shoes. Keep hands high when rolling a drum and never stack things too high.

INSIDE THE EXTRUDER -- Know the pressure and safety limits of the machine, know what pressure may be expected, and watch out for excess. Avoid plastic leaks in the head area. Never look into a vent when the system is hot without face protection and never stand in front of a hot extruder, even if the screw is not moving, because gases may form in the barrel and suddenly blow melt out the vent or the die. Have a plastic, wood, or brass rod on hand to poke into hoppers and vents; never use your hands.

OUTSIDE THE EXTRUDER -- Keep the workplace clean. Clean the floor often, avoid clutter and hang nothing heavy overhead. Keep ladders and catwalks clean and sturdy with high-friction surfaces. Wear shoes that don't slip even when oily, as there may be oil leaks on the floor. Avoid air hoses, as they can force air into skin breaks and blow dust particles into eyes. Use eye protection, and in some environments, ear protection and even nose-mouth air filter masks. Know where the nearest fire extinguisher is and check it periodically.

START-UP

Is the system full, half-full or empty? Some extruders are started with the whole system full of material, shut down that way to keep air out of the hot breaker plate area. This is common with polyethylene film, to avoid excessive contamination by oxidized plastic in that area. In such a case, the first few feed flights should still be emptied on shutdown to avoid sticking to the screw in the feed zone.

Many lines are started with an empty screw but with plastic in the head and die; if the machine is stopped this way, the screens can be changed and decomposition in the plate/screen area can be avoided without requiring complete disassembly. In a few cases, notably rigid PVC, a clean machine is needed for every start-up, as hot material can't be left in the system even for a few minutes.

In all cases, the system must be preheated before start-up, as otherwise the first material cannot pass through. Cold starts are, in fact, a major cause of equipment damage and personal injury. However, in a well-meant desire to avoid a cold start, sometimes the system is "overcooked" -- heated so long that the plastic starts decomposing inside. This produces hard, discolored bits that contaminate the product and may even produce gases that can blow hot melt out the die. How much heat is enough depends on the mass of the die, the volume of plastic inside, and the wattage of the heaters, as well as the thermal stability of the plastic and the product requirements. Pay close attention to this question of heat-up time; keep it short but keep it safe. And when the extruder looks ready, be careful still: watch the ammeter as the screw starts turning, and don't increase screw speed too fast.

It may help to give extra or early heat (or temporary insulation) to large masses of metal, especially cores of hollow dies, and leave the heat off the low-mass areas such as small dies and connecting tubes, until nearing start-up time. Microprocessors can be programmed to do this.

Some plastics, notably the polyolefins, may shrink away from adapter walls when the line is shut down, and hot plastic from the slower-cooling extruder and die can then be sucked into the voids. Then, on later start-up, if the adapter is reheated too quickly, expansion of its contents may blow the system. Therefore, don't heat adapters and transfer tubes until the rest of the system is already hot.

Don't forget feed preheaters and hopper-dryers; often these are the first things to be turned on as they may take the longest to get up to proper temperature.

Most extruders feed from full hoppers. In such cases, especially for plastics that melt easily, a long preheat time may conduct heat up into the throat and bottom of the hopper and cause sintering and bridging there. This can be avoided by keeping this area free of plastic during preheating, and starting by adding material by hand, little by little, to an empty hopper; this also reduces the danger of overload and cold start. Bridging is also prevented by circulating cold water around the throat.

Head and gate bolts should be tightened on a clean machine when hot, before the motor is started. (On a full machine, there is no need to loosen them, as they should already be tight.) Start the motor slowly and raise the rpm gradually, always watching the ammeter and pressure gauge. Know the safety limits for each of these. The system will normally allow top speed in a minute or less; the usual delay factor is takeoff adjustment to get final product dimensions.

Plastics like PVC decompose easily and cannot be shut down full. Therefore, the system must be cleaned on shutdown, and each start-up is on a clean machine. Because the first material will coat the clean internal surfaces and fill in cracks and slow-moving places, using a highly-stabilized formulation just for start-up can extend the production time possible before another shutdown and disassembly is needed. For all plastics, start-up with uncolored, cheaper material is preferred. Some plants can even recycle their scrap this way, as the first production is also scrap.

Use a threading or stringing aid to get the product moving smoothly, such as a rope, a cloth, or a length of product from a previous run. Remember to open the pulling nips to let the blobs and thick parts through.

When the system is running steadily, again check the "vital signs" -- the melt temperature, the head pressure and the motor amps -- to look for surges and other unusual behavior. Record the conditions and measure the output in weight per hour and weight per rpm.

The final stage of start-up is to get the desired dimensions as soon as possible with the minimum amount of edge trim and other scrap. The actual things to do will vary with the product -- e.g., adjust the inflation pressure on a blown film line, or adjust the die bolts on a sheet die. Always keep the scrap as clean as possible and covered to get full value from its reuse.

MATERIAL CHANGE AND SHUTDOWN

Material changes and shutdowns should be planned as much in advance as possible. For a material change, new material must be made ready and a container must be available for the hopper's existing contents. Follow light colors with dark ones and easy-flow plastics with stiff ones.

Because of production scheduling and sales needs, this isn't always possible. Purge compounds can be used to speed up change and reduce the amount of scrap. They are especially useful in between runs of incompatible materials on large extruders, where mixed scrap has low value and disassembly takes a long time.

Most purge compounds are high-viscosity plastics, perhaps with inorganic filler added for scouring, and highly stabilized to avoid decomposition. Some purges have a solvent action, and one actually reacts chemically to depolymerize whatever is in the system. Many purge compounds can be reused; keep the downstream line going during their use if possible, and grind, cover and label them promptly.

Temperature is important. What resists purging when cool may get soft and be pushed out well when hot, so that just changing temperature alone (e.g., hotter die and front zone, cooler rear) may work without using any special purge.

Water is sometimes used as a purge. The steam softens and blows out the residues, but water alone is very dangerous because the steam may escape from the die or the hopper and scald anyone nearby. Therefore, it is best to use water as absorbed in an appropriate plastic or other material.

Shutdown requires a decision: leave the screw full, or run it dry but leave the system closed and the head and die full, or completely disassemble and clean the head and die. As noted above under "Start-up," the screw may be left full to avoid air going down the screw to the hot breaker-plate and promoting decomposition there. When the screw must be stopped while full, even for just a few minutes, it is best to cut off flow from the hopper with a slide plate and run a few seconds more to clear the first few flights. This will discourage bridging in the throat and sticking to the screw root in the feed zone during cooling and later start-up. When the screw is finally stopped, run on full barrel cooling for several minutes, plus screw cooling if possible.

If contamination with decomposed polymer particles is a serious problem on later start-up, run the screw at low rpm after the heaters are turned off, to get the plastic temperature down and thus discourage chemical change. Be careful doing this; keep an eye on the ammeter and pressure gauge, lest these values rise beyond safe limits. Still another technique occasionally seen is the passage of nitrogen into the screw flights on shutdown to prevent oxygen from reaching the hot, critical area at the end of the screw.

When the head is opened to change screens while leaving the die full and in place, be sure to clean the breaker plate and the matching sealing lines carefully, so that they mate well on reassembly to avoid later leakage.

If the head and die are to be cleaned, do it fast. In all cases the plastic comes away easier when hot, and with PVC, the first 10-15 minutes are critical to prevent degradation. After that, the PVC is too cool to degrade further. As soon as the motor stops, open the head bolts, get the screens and breaker plate out and clean the sealing surfaces, with someone else cleaning the die at the same time.

Cleaning metal surfaces, especially if they have cooled, may require reheating in an oven or a small-parts cleaner such as a fluidized alumina bed, pyrolysis oven or oil or salt bath (see bottom of page 35).

In reassembling a die, the outer face may be coated with a silicone grease to prevent later sticking of plastic to it. When the die is not in use, protect its lips with a non-scratch, non-melting cover such as wood.

Should the screw come out as well? Some extruders never take out the screw, content with occasional purges as they run a material that doesn't require frequent and complete disassembly. Some heat-sensitive materials require screw removal as well as head/die disassembly at every shutdown. And sometimes there is a specific reason to remove the screw, such as to remove material stuck to the root, or to confirm a problem that might be related to screw wear. In such cases, turn the screw at low speed to empty it as much as possible, and follow with a purge or wax to make removal and re-entry easier. Woven copper mesh, added through the hopper after the head has been opened, has the same effect. Push the screw out right away, while the system is still hot. Use a screw pusher and a hoist where needed; avoid a sledgehammer or lift-truck which might bend or otherwise damage the equipment. Once the screw is out of its seat and emerges from the output end of the barrel, it may be pulled from that end as an alternate to more pushing. Pull the screw straight out, and avoid pulling upward too much with a hoist, which might bend the screw and damage the barrel. Keep the screw pusher protected to keep its threads clean.

Once the screw is out, both screw and barrel must be cleaned so that the screw will go back in easily. The screw can be wire-brushed while halfway out, still supported by the barrel, as the output end is already out and is the part that usually needs the most attention. A strap wrench is useful to turn some screws while cleaning them. The barrel can be reamed with a long-shaft wire brush on an electric drill. Wire mesh on a broomstick may also work.

Do not use an air hose to blow material backward down the barrel because particles may lodge in the screw seat and prevent proper seating there. Don't forget to look at this seat, and make sure the keys and key ways are also cleaned and lubricated to get the proper fit on reassembly and make the next removal easier.

COMMON EXTRUSION PROBLEMS

Surging -- Surging is a cyclical variation in product thickness in the direction of extrusion. This wastes material because the thickness aim must be higher. The cycle time is typically between 30 seconds and 3 minutes, and the cause can be inside or outside the extruder.

Outside causes are easier to see and correct. For example, the takeoff pull may be irregular; in this case the screw rpm and ammeter readings remain steady. Sometimes motor speed varies because its regulation is not working properly. This is rare and will show up as unsteady rpm.

Sometimes the feed is uneven because of particle size, light weight, or bridging in the hopper and throat. With very small extruders the feed channel depth is not much bigger than the feed particles, and they may feed erratically for this reason alone.

If none of the preceding outside situations are observed, it is probable that the surging originates inside, typically at the beginning of the compression zone, where the solid bed -- the mass of pellets -- is locking and breaking up irregularly. Screw rpm are steady but the ammeter shows variations of +/- 5% or more. Sometimes this can be cured by increasing the temperature of the feed to promote earlier melting. Raising the rear barrel temperature may help, too. Make big changes, 15-30 C = 25-50 F, and see what happens. Sometimes raising the barrel temperature at the beginning of the compression zone will help by getting better sticking of the pellets to the wall there.

If these actions don't help, try running slower or faster by at least 10%. If the problem still remains serious, consider altering or replacing the screw or installing a gear pump between the extruder and the die.

<u>Poor Mixing</u> -- This often sets the upper limit to output. You can't run the screw any faster because the material is coming out with an applesauce surface, streaks, parabolic ridges or particles of undispersed additive. Screw modifications, such as pins or separate mixing heads, will help but may raise melt temperature. Running more slowly will always help, as it provides more residence time.

A screw with internal cooling mixes better because it has the effect of a shallower channel in the metering zone. The output per rpm drops, sometimes as much as 30%, but may be regained by speeding up the screw, unless melt temperature gets too high or the drive system can't safely run faster.

High pressure is good for mixing. A valve will do this, or a gear pump pressure control can serve as a valve. Cooler dies increase the resistance and thus raise the pressure in the system. Finer screens will raise the pressure, but as they keep clogging, pressure is never constant.

<u>Melt Roughness or Melt Fracture</u> -- This refers to fine ridges or rough surface seen when the melt comes too fast out of a narrow die. It is most common with polyethylene, and can be eliminated by running the melt or the die lips hotter, using a longer or more streamlined die, or trying a different grade or source of material. Additives may help greatly in this regard.

<u>Overheating</u> -- This may limit the rate if the take-off cooling is limited, or it may produce degradation or make dimensional control and sizing difficult. In such a case, stop all barrel heat except in the rear zone as needed for bite (input) control and cool the barrel if necessary. (In a few cases, more barrel heat will yield a cooler melt.)

There is a temperature below which the melt won't go at a given screw speed, even if all the barrel heaters are turned off. See if the controller around 70% down the barrel is overriding. This means overpacking of the metering zone -- overbite -- with much heat generated at the entry to that zone. In that case, reduce the bite by changing the feed temperature, rear barrel temperature or particle size.

Grooved barrels with the appropriate screws will keep the melt temperature lower as they need less rpm to extrude the same output. For all extruders, raw material choice is critical; often, one material will run cooler than another even if properties are similar and they have the same melt index. Test the melt flow at extruder speeds with a small extruder, a melt indexer run at high loads, or a torque rheometer, to show up differences at extrusion shear rates.

<u>Moisture</u> -- Moisture is absorbed by some plastics. It passes through the extruder and boils when the pressure is relieved at the die lips. The result is a pattern of dotted lines, long bubbles, and pits. To remove moisture, the material must be predried, or a vent must be used in the extruder, or both. A moisture level of 0.1% is usually low enough to avoid such visual problems.

Some plastics, such as PET, the nylons and polycarbonate, can degrade and weaken if even a tiny amount of moisture is present when they are melted. For these, dehumidifying dryers are used to get moisture down to 0.01% or less.

<u>Trapped Air</u> -- This is not common with the long extruder barrels of today. However, some old machines had short barrels, and even a long machine can be pushed so fast that the air can't stay back where it belongs. Instead, the air is carried forward into the product. A trapped-air surface shows bubbles and pits, but little, if any, dotted lines. Such a surface will improve if run more slowly, sometimes dramatically so, while moisture will not. A cooler head and die may help. Vents and vacuum hoppers will eliminate trapped air and are essential for powders, where passages between

the particles are much smaller; the air can't escape back through these passages and is carried forward instead.

Contamination of all kinds causes spots or dimples, often called fish-eyes, in an otherwise smooth surface. Test the raw material (see next page) before accusing the supplier, as oxidized or cross-linked bits of plastic may be produced in the extruder itself, in slow-moving or stagnant areas. Use a microscope to detect fibers and colorants. Oxidized bits glow in ultraviolet light. Neither oxidized nor cross-linked particles dissolve in solvents that dissolve plastic.

Another source of contamination is the dust that gets blown around by unfiltered conveyor air or attracted by static electricity. Fibers from sacks of material can get into the product. Don't cut paper bags and dump them, but pull the seam threads off and dump them carefully, clean them off before pouring or, best of all, get the material out of the bags with a vacuum loader. If possible, buy bulk or boxes to avoid bags altogether.

Fine particles may be left in transport lines from silos or in the silos themselves, especially when a silo or transport line is used for two different types of plastic that don't mix when melted (incompatible plastics).

Incompatible plastic dropped in open scrap drums, cigarette butts, ashes, paper cups and other trash, will be shredded in granulators and may end up as contamination.

Finally, bits of undispersed colorant or other additive may look like contamination. Static mixers may help here.

Fine screens -- 100 mesh or more -- can filter out some of the contamination, but they clog quickly and contribute to changing pressure unless there is automation to compensate. Continuous screeners can keep pressure constant while using very fine screens. Crosslinked polymer (gels) are particularly difficult as they are elastic and can get through most screen openings.

MATERIALS FOR EXTRUSION

Material is by far the biggest cost factor in extrusion -- at least 60% and often much more. Therefore, selecting the right material and re-use of scrap are very important.

Melt index = MI (melt flow index = MFI) is a common way of specifying material. This is really viscosity at standard conditions, and relates to strength and flow behavior; high MI means easier flow but less strength as it reflects shorter polymer chains. The test is usually done at flow rates well below those of extrusion, and thus it can be quite misleading. Testing at several flow rates is needed if a reliable comparison is to be made.

Extrusion uses lower MIs than injection molding, where the easy flow is needed to fill the cold molds. When MI gets too low even for extrusion, there may be overheating or not enough horsepower available. In blending, try to mix resins whose viscosities (MI if high-rate value unavailable) are in the same proportion as the components themselves.

Here are a few convenient tests for incoming raw material:

1. Bulk density -- weigh the contents of a known-volume container filled with the plastic in question (see page 17).

2. Solid density -- density column or water displacement (Archimedes), useful to identify unmarked material.

3. Surface friction -- drop a rod with graded marks into a container of the plastic to see how deep it goes.

4. Melt flow -- Use melt indexer at several stresses/rates or a small extruder with rod die. A torque rheometer is even better but needs experience to read and understand.

5. Contamination and color -- use a lab extruder to blow a simple film or thin sheet, or squeeze pellets between hot metal or glass plates, and inspect.