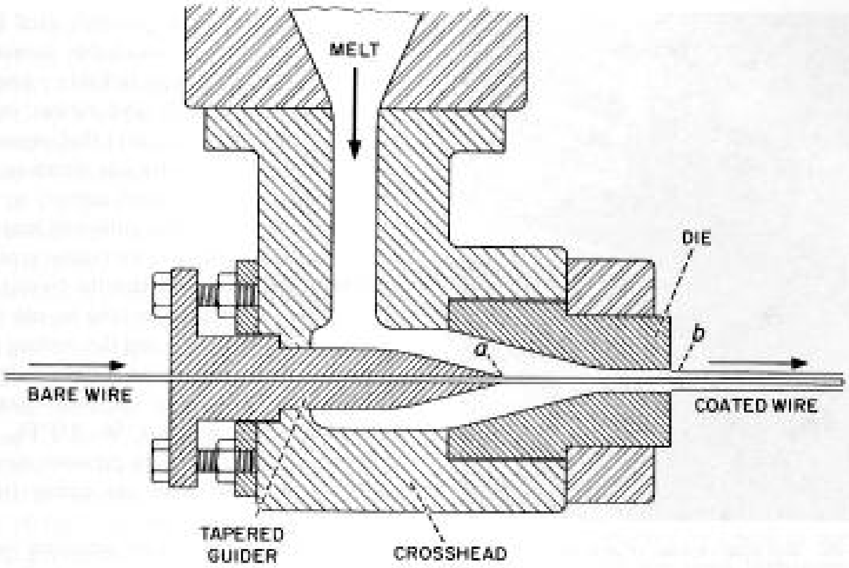

Fig. 4-24. A crosshead holds the wire-coating die and the tapered guider. (*Courtesy Quantum Chemical Corp.*)

changed while the line continues to produce wire at high speeds. (See Fig. 4-27.)

When the coated wire O.D. is measured for quality control, which is quite normal in today's wire coating plants, a gauge is placed after the cooling trough to "look" at the O.D. in both *X* and *Y* axes. Microprocessors allow data gathering for statistical analysis and control and allow accurate "real time" product knowledge for control of the line. The extruder speed and the line speed can be altered automatically by a controller that maintains the wire coating O.D.

Some wire production does not immediately cool the coated wire but involves further heating to a point that causes the special plastic coating to achieve crosslinking of molecules. This crosslinking changes the properties so that reheating to temperatures that normally would melt the thermoplastic wire coating does not soften the material. The main usage of these crosslinked products is in power cables, where high voltage electrical transmission creates high heat levels that the wire must withstand. Some wiring used in automobile engine compartments must be crosslinked to handle the high

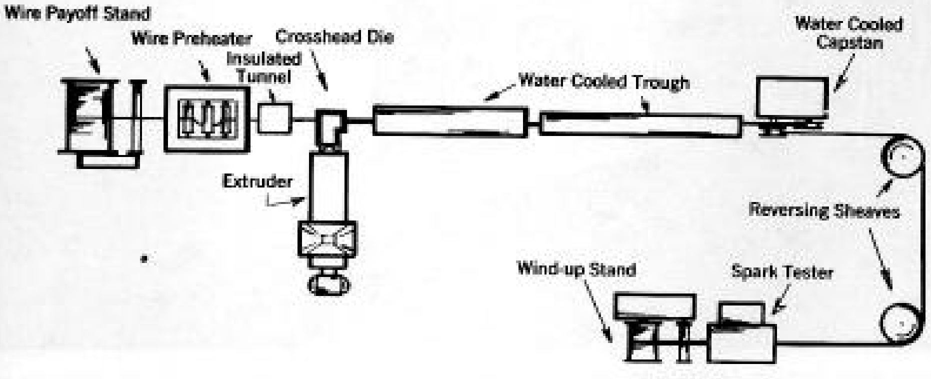

Fig. 4-25. Schematic of flow line for wire coating, showing preheater between payoff and die. (*Courtesy Solvay America*)

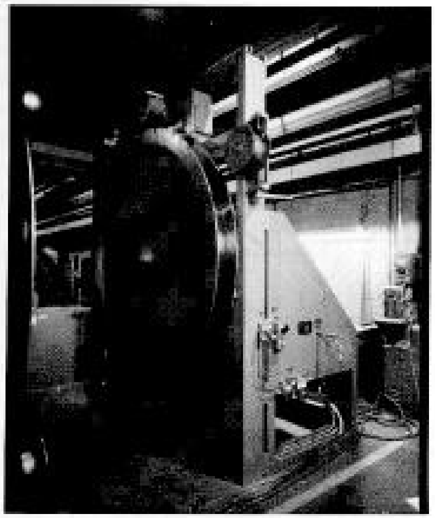

Fig. 4-26. Belt wrap capstan. (*Courtesy Davis-Standard*)

heat levels. The major materials used in these cable products are crosslinkable polyethylene (XLPE) and various crosslinkable rubber compounds. These XPLEs and rubber materials contain peroxides (typically) that permanently alter the material's molecular structure from a thermoplastic (or noncured rubber) to a thermoset type material, after sufficient heating and residence time. The heat for curing typically is supplied by a steam tube that the freshly coated cable passes through. The tube is split into the heating portion (steam) and the cooling portion (water). The tube is sealed at both ends for the steam setup, because of the pressurization of high-temperature steam (250–300°F). An alternative to the use of high pressure steam is to utilize high temperature gas curing (nitrogen typically).

A process getting more attention over the past several years involves producing crosslinked cable without the peroxide and heat

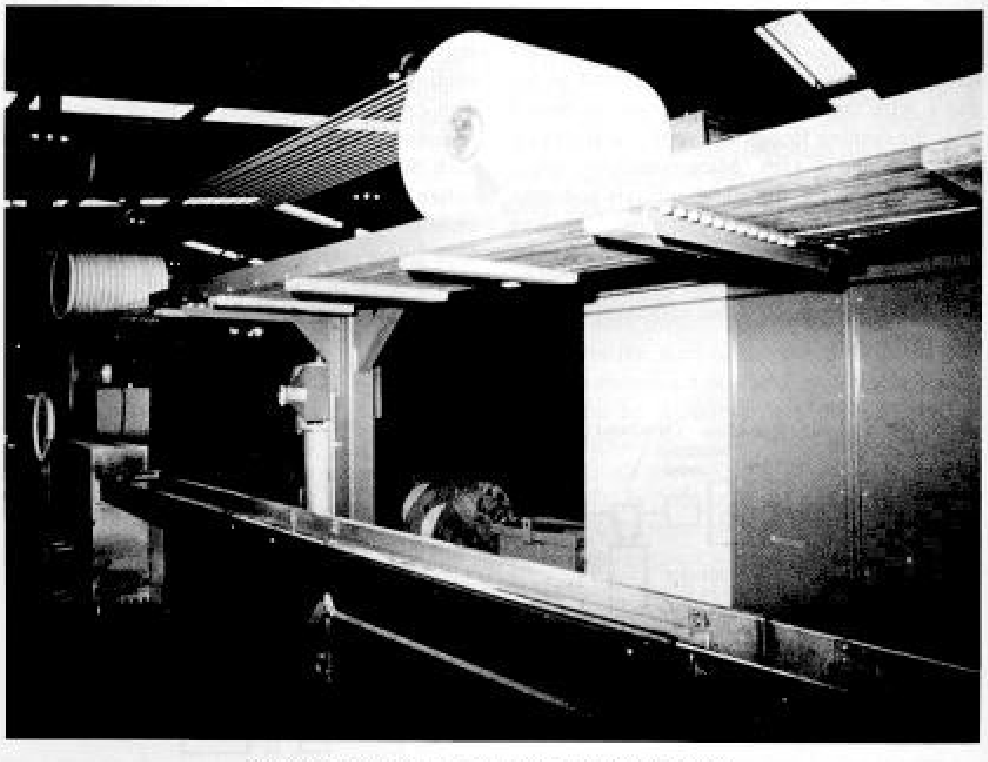

Fig. 4-27. Wire accumulator. (*Courtesy Davis-Standard*)

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Carbi
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method. A special additive is introduced to the polyethylene in the extruder hopper (a silane material and a catalyst developed by the Union Carbide Corp.), and the cable insulation is extruded and cooled as normally done for thermoplastic wire coating. The finished cable is placed in a high-humidity atmosphere for a time, which reacts the silane and crosslinks the coating material.

Coextrusion is popular in wire and cable production to allow the efficient production of many wire constructions. (See Fig. 4-28.) Previously, many multilayered coatings were made by passing the cable through an independent crosshead for each layer. The development of coextrusion crossheads allowed the extrusion of several insulation layers at one time and cooling of the "assembly" on one extrusion line. The production of many different colors on a single extrusion setup often uses special coextrusion dies to allow switching of the layers, to bring a given layer to the outside of the insulation and hide the previous color inside the wire coating. The alternative for a color change is to change the material in the coating extruder, which takes longer and wastes wire and coating material.

Some of the many materials seen in the coating of wire and cables include rubber, polyethylene, polypropylene, nylon, fluoropolymers, and PVC.

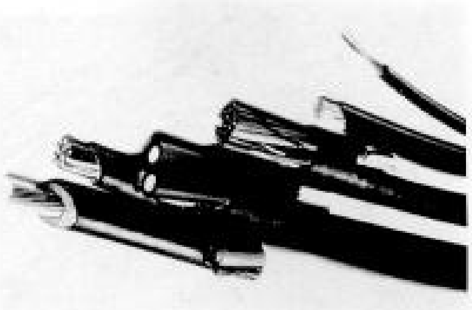

Fig. 4-28. Wire and cable configurations. *(Courtesy Davis-Standard)*

Fiber

Fibers have been produced from thermoplastics for some time. The materials used in normal fiber spinning operations are of lower viscosity than their blow molding, profile, or blown film counterparts. The polymers are extruded at fairly high melt temperatures into a piping manifold with a series of melt pumps. Each melt pump feeds a spinnerette, which is a die with many small circular orifices. The fine melt strands produced are pulled from the die and cool rapidly. As the fibers are pulled farther downstream, they are oriented in the machine direction to impart good tensile strength. The orientation is performed by a series of rolls that are wrapped by the fibers and have successively faster speeds. The increase in speed pulls the fiber and elongates the strands, imparting orientation in the machine direction. The many strands then are spooled on a rack of many rotating cores. Were the same higher-viscosity materials as seen in blown film and blow molding used in the traditional fiber operations, the pressure resulting from the small-diameter die openings would be prohibitive, and the drawdown ability of the fibers would be reduced.

Some fiber operations use a wide slit die (15 to 30 inches) and cut the strip into numerous narrow ribbons, which subsequently are drawn down and oriented into a coarse fiber (tape yarn). This method uses somewhat higher viscosity materials than the spinnerette process and operates at lower temperatures—more like a sheet operation than a traditional fiber process.

Materials commonly used for making fibers include polypropylene, nylon, and polyesters.

EXTRUDER SCREWS

Extruder Screws (General)

This section will present some ideas about selecting screws for specific situations and the design considerations that lead to a screw's selection. (See Fig. 4-29.) Screw design is a blend of some basic engineering, some theory, and a good amount of experience with the material and process in question. Many factors are involved in design selection to define a screw's overall performance, and most of these factors

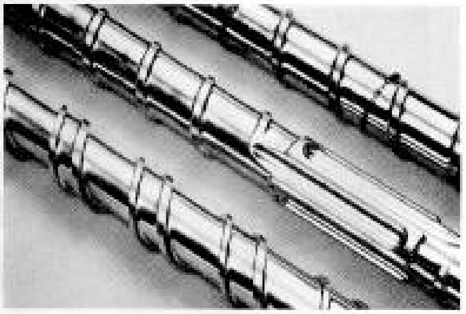

Fig. 4-29. Three extrusion screws. *(Courtesy Davis-Standard)*

must be defined to set the goals of the screw design selection process.

The main performance goals are listed below:

1. *Output rate requirements:* The amount of material a screw must deliver usually is defined as the maximum that the process can handle when sizing and cooling the melt into the final product. This is defined in well-known terms of lbs/hr, ft/min of product, lbs/hr/rpm, etc. The use of lbs/hr/rpm is the least precise because of the nonlinearity of this number as screw speed changes or as die pressure levels change. The other two measurements of output are well defined by common terms.
2. *Output stability (screw pumping consistency):* This parameter often is assumed by the purchaser of a screw to be ensured by the screw designer. The product dimensional consistency required leads to the levels of pumping consistency necessary. This parameter is easily measured through the use of a pressure transducer at the end of the barrel or in the die adaptor system. A chart recorder or data acquisition system can be utilized to allow long-term stability to be recorded. A good measure of pressure variation at the screw tip or in the die system for most processes would be 0–2.0% (±1% or less). A pressure variation level in the range of 2.5–3.5% would be judged as fair, with some measurable product variation expected, and a variation of 4% or higher is above the acceptable limits for most product variation allowances. The output variation can be up to three times as large as the pressure variation, depending on the degree that the material acts like a Newtonian fluid in the melt phase, but typically the above ranges are accepted, based on much accumulated extrusion experience. An exception to low output variations would include some pelletizing operations, where a 20–40% variation of pellet dimension may be totally acceptable.
3. *Melt temperature level:* Melt temperature is often the limiting factor to an extruder's output performance. The limit usually is due to a melt-handling limitation, as the viscosity is reduced by increasing the melt temperature or when a temperature is reached that will start to degrade the extruded material. The method by which this parameter is measured is critical to its usefulness in defining a screw's limitations or comparing one screw to another. (More information on the measurement of melt temperature is given below.)
4. *Melt temperature consistency:* This parameter is best measured on a chart recorder or with a data acquisition system so that long-term variation can be accurately defined. The variation measured is a good indicator of the homogeneity of the screw's melt and the degree of distributive mixing that has occurred. A good melt temperature variation level for most situations would be 2°F or lower (±1°F). This would be measured with a probe protruding an adequate distance into the melt stream.
5. *Melt quality level:* The appearance of the final product usually is defined for the screw designer. This can be based on a product smoothness specification, the surface finish (gloss vs. dull), or some other aesthetic concern.
6. *Mixing efficiency:* Sometimes colors or the blending of other additives is necessary; so some minimum mixing level

must be reached. If the mixing specification is visible, the evaluation can be simple. If a nonvisible ingredient must be blended, product properties may need to be evaluated to determine if the screw has performed sufficient mixing.

The selection of the final screw design usually must fulfill specifications defined in terms of most or all of the above parameters. A good understanding of their measurement and evaluation is necessary to good screw definition. One of the most elusive quantities to define is the melt temperature. The use of a thermocouple placed in the die adaptor system is a reasonable method, but if the tip of the thermocouple is not protruding at least one-third of the way into the melt stream, an inconsistent temperature is recorded. Flush thermocouples, as seen with pressure transducer/melt thermocouple combination devices, thus are not true indicators of melt temperature. Just like melt temperature, the other screw design parameters must be well understood to ensure that any values used to compare one screw's performance to another's are measured consistently.

Screw Types

Many screw designs have been utilized over the years for the various extrusion processes and materials. A few of these designs are seen in Fig. 4-30. The best-known screws can be loosely separated into two categories—conventional screws and barrier screws. Conventional screws usually are single flighted designs with the flight lead (or flight pitch) equal to the screw's nominal diameter. This type is termed a square-pitched screw, and when no mixing devices are present, it usually is referred to as a metering screw. Barrier screws are seen in many design configurations used in the extrusion industry, depending upon the designer. These screws have a second flight, which acts as a melt/solid separator designed to enhance output stability and allow higher usable output performance levels. Like conventional screws, barrier screws must be well designed to ensure that optimized performance is reached and that screw design parameters are successfully met.

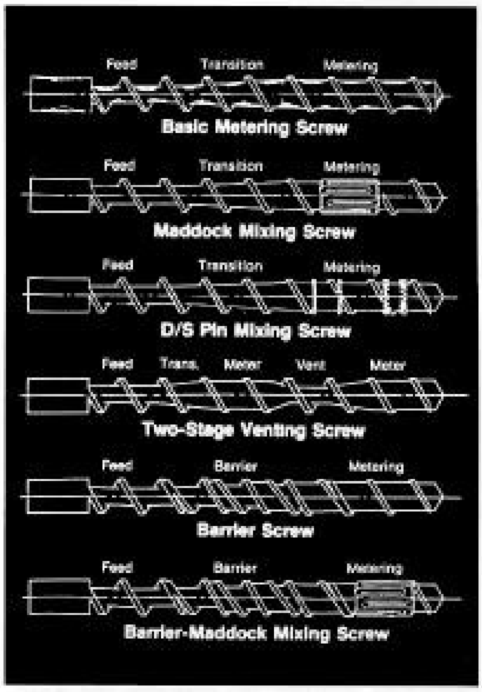

Fig. 4-30. Six screw configurations. (*Courtesy Davis-Standard Co.*)

A poorly designed barrier screw can yield worse performance than a well-designed conventional screw. Either screw can give improved performance with the addition of a mixing section of minimized shear levels for the particular material and processing conditions being utilized. (Such mixing devices will be discussed in a later part of this section.) The type of screw selected will depend on the performance required and the extruder size selected. When the extruder is large for a required output level, a simple screw usually is adequate (conventional metering or mixing design). Most extruders are not large for the process involved, so maximum output rates and/or minimum melt temperatures are required from the screw. This means maximizing screw depths to generate a high output rate at low screw speeds and low melt temperatures. Maximizing screw depths while maintaining good output stability and melt quality is typically best done on barrier screws because of their better melting performance. One exception to the general practice of minimizing melt temperatures at moderate or high screw speeds occurs when extrusion coating or cast film is being produced. These cases require high melt temperatures to allow adherence of the melt to some substrate being passed through the cooling roll nip point or just to produce a low viscosity melt to allow very thin sheet gauges. In general, in the majority of cases the extruder should minimize the melt temperature.

Conventional Screws (Metering and Mixing). These screws usually include a constant-depth feed section, a constant-depth metering section at the output end of the screw, and a varying-depth transition section connecting the feed and metering sections (see Fig. 4-31). The lengths and depths of the sections are varied to alter the performance of the screw to meet given performance goals. There are numerous schools of thought about the optimum screw for a given processing situation, but measuring the different screws' performance parameters indicates the strengths and weaknesses of each design. There has been much extrusion experience with metering and mixing screws with most materials, due to the long history of their usage; so a good design starting point usually is determined when conventional screw designs are desired. Low or moderate output performance usually is certain with these designs; but as the extruder is asked to yield higher and higher output rates, work is needed to select a design that will ensure the output rate, the output stability, an acceptable melt temperature, and good melt quality (and possibly other important design parameters). As screw speeds are increased, the melting performance along the screw becomes quite chaotic compared to that defined in the earlier section on melting, and the conventional screw typically presents problems in output stability and perhaps melt quality parameters. The years of optimizations performed with these designs have led to an array of screw designs for various situations, with the higher output screws usually containing mixing devices and fairly long metering sections to control as much as possible, the melting situations that cause quality and instability problems. This long metering section design can only be taken to the point where the shortened feed section and transition will adequately convey the solids and early melt and ensure completely filled metering flights. Some materials (polyethylenes, flexible PVCs, etc.) will process successfully with a 3–5-diameter feed section length and a 3–5-diameter transition section length, thus allowing a long metering section (12–17 diameters). The longer metering section gives higher shear in the channels, but that factor is offset by deepening the channel for maximized output rates. Screw channel depths also vary widely, depending on the material extruded, the length of screw section, and the output performance required from a given extruder size. Usually, metering section depth is based on the screw's output requirement. This can be roughly calculated by the melt pumping equations (drag and pressure flow equations) given previously. The feed section depth then is chosen, based on a factor called the compression ratio, typically in the range 2 : 1 to 4 : 1. The specific value has been determined for most materials from the expe-

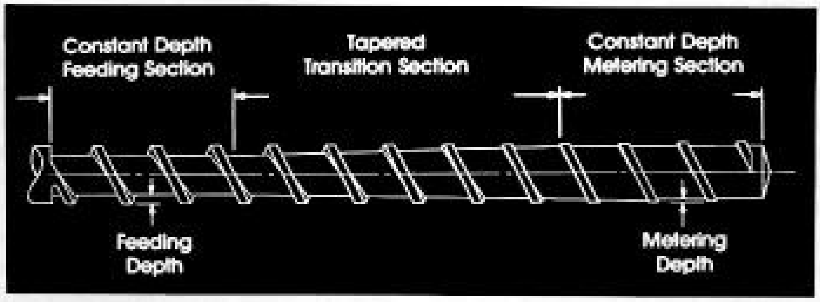

Fig. 4-31. Metering screw design. (*Courtesy Davis-Standard Co.*)

rience of polymer manufacturers and/or screw manufacturers.

True metering screws (no mixing elements) usually are used where low or moderate output rates are required from an extruder; mixing screws are used in high output situations, or where added mixing is desired at lower output levels. A fairly shallow design (shallow channel depths) can be made to perform well up to the screw speed where a melt temperature limit is reached. Deepening this design to improve output rates usually leads to deterioration in output stability (and usually melt quality) as screw speeds are increased for increased output requirements. There are some rare exceptions to this phenomenon in processing areas where the material is unusually easy to fuse into extrudable form, such as most true rubber compounds and some highly filled polymers.

Offering specific screw designs for a given material is always of questionable value because several screws will process a material successfully over a range of conditions. Optimum screw design depends upon the conditions on a given extrusion line and the performance goals (extruder size and length, extruder cooling/heating available, die pressures reached, materials extruded, melt temperature levels allowable, etc.).

Table 4-1 shows some designs that may be obtained from various screw suppliers for a given material. These are four screws that might be specified by various suppliers for processing LDPE, depending on the conditions required on the 2.5" 24:1 extruder. The first screw is a simple metering screw with reasonable results at low to moderate screw speeds (20–50 rpm). The second screw will operate at higher screw speeds (75–150 rpm) with acceptable quality and usually reasonable output stability, up to the point where the melt temperature limit is reached. The third screw, which may or may not be specified with a mixer, would also be a modest output performer and would have a slightly higher but less stable output than screw A. The 8*D*-8*D*-8*D* length setup is a typical design offered by numerous material suppliers and screw suppliers as a "generic" screw of modest output performance for small extruders (2.5" and smaller) but is not an exceptional performer compared to the other three screws under most conditions. As die pressures increase (processes with restrictive dies, such as blown film and some small wire coating applications), the simpler screws usually exhibit improved output stability. If die pressures are quite high (6000–8000 psi), melt temperature limitations often are reached at low screw speeds (10–40 rpm), depending on the materials utilized, and a simple metering screw may do an acceptable job.

Barrier Screws. In applications where extruders must improve output rate, maximize output stability, and minimize melt temperature levels while maintaining acceptable melt quality, barrier screw designs are enjoying increased usage (see Fig. 4-32). Barrier screws are more difficult to design and are more expensive than conventional screws, but potential performance benefits in production under most conditions usually justify their use. When properly understood and properly designed, these screws make it possible to maintain good output stability over wide screw speed ranges and thus allow deeper channels and better out-

Table 4-1. Four possible screw designs for a material (extruder: 2.5" (63.5 mm) 24:1 *L*/*D*; material: LDPE, 2.0 melt index).

	Screw A	*Screw B*	*Screw C*	*Screw D*
Feed section length (dias.):	4*D*	5*D*	8*D*	5*D*
Feed depth:	.330"	.450"	.390"	.480"
Transition:	8*D*	3*D*	8*D*	11*D* (Barrier sect.)
Meter section:	12*D*	16*D*	8*D*	8*D*
Meter depth:	.110"	.150"	.130"	.190"
Mixing sect.:	No	Yes	Yes	Yes

Fig. 4-32. Example of barrier screw. (*Courtesy Davis-Standard*)

put rates at a given screw speed. When the output rate for a given screw speed is maximized, the screw speed necessary to deliver the output rate requirement is reduced, thus reducing melt temperature levels. Alternately, the higher output rate at a given speed can be achieved at similar melt temperatures to those of the lower-output design. Therefore the barrier screw typically offers lower melt temperatures or higher output rates or a combination of the two parameters. Barrier screws have a feed section and a metering section, as with conventional screws, but there is also a barrier section made up of a second flight designed to separate the solid bed from the melt pool and maintain this configuration until all (or most) of the material has melted. The placement of the barrier flight, barrier section design (width of solids and melt channels), depth and length of feed and metering sections, solids channel depth, melt channel depth, and clearance of barrier flight all affect the screw's performance. Whether a mixer will be present and how to design the mixer's clearances (shear levels) are also important design considerations.

There are many barrier screws on the market that are available to the extrusion plants. The barrier screw is a more complex design to manufacture, and it requires a better understanding of polymer melting performance to achieve optimum results. The extrusion operator needs to be fully assured of successful operation when contemplating the purchase of a relatively expensive barrier screw in an effort to improve performance. Unless the screw is reasonably well optimized prior to delivery, there is some chance that a rework for improved performance will not be possible because of the barrier design; for example, if the barrier flight is not properly located on the screw. Also, a poor design cannot be easily analyzed on most production lines because of a lack of proper instrumentation. A random attempt at extrusion with a ''standard'' barrier screw can lead to disappointment and wasted production time.

Two Stage (Venting) Screws. When it is determined that a vented extruder is required, the screw design requires some special considerations, whether a conventional screw or a barrier screw design is selected. A vented screw usually is defined by the number of stages on the screw. A two-stage screw (see Fig. 4-30) has initial feed, transition (or barrier section), and meter sections that define the screw's first stage. There then is a rapid deepening of the screw flights to form a secondary feed section, also called the vent section. This is the area where the barrel has an opening to the atmosphere or to a vacuum source for removing moisture, air, and/or other volatiles. The screw then has a second transition and a final metering section. The vent section, second transition, and second metering section make up the second stage. The screw operates like two single-stage screws connected in tandem, which operate at the same screw speed. The first stage must operate like a typical single-stage screw, although full melting to an extrudable melt quality usually need not be reached. The first stage typically must perform 50–90% of the full melting, depending on the material involved and the extent of the volatile removal. For example, most of the powder fed materials, which only require air removal at the vent, do not need much more than 50–70% melting at the vent for the air removal to be successfully performed. This air removal often can be done with no need to use a vacuum system on the vent. On the other hand, when moisture or some internal volatiles must be removed, a fuller melt usually is necessary to ensure that the majority of the volatiles will be removed by the vent vacuum system. These volatiles will boil out of the melted material more easily at lower pressures (under vacuum), but if a substantial amount of the material passing by the vent is not adequately melted, the volatiles will not be removed and may show in the final product as voids.

A goal of increasing output rates and decreasing melt temperature would lead to deepening the first stage as much as possible and allowing as much partial melt to pass the vent opening as the venting efficiency (and final melt quality) of the process permitted. Should the screw be designed for full melting at the vent section, the shear contributed by the second stage would generate a sizable melt temperature increase. The particular material being processed will determine how complete the melting must be at the end of the first stage for a successful extrusion (i.e., void-free and of sufficient melt quality). A screw with two barrel vent openings would be a three-stage screw. The single-vent setup is the most popular choice by a wide margin, but the second vent of the three-stage design sometimes is believed desirable for more complete volatiles removal in some compounding operations. Single-screw processing would be limited for practical reasons to a double-vent setup, but some specialized twin-screw compounding extruders can be designed to have four or five barrel openings, used for venting or additive introduction to the screw.

One of the most difficult screw designs, used to provide good output stability, is the vented design. The "two screws" placed together in tandem to make up a two-stage screw design must operate at a reasonable output balance to ensure output stability. On the other hand, one could see vent flow from a poor screw "balance." The first stage is doing the majority of the melting and is setting the output rate of the process. The second stage must take away the material from the first stage and produce enough pressure pumping capability to push the material through the die system and avoid the occurrence of vent flow. Should the second stage have too much pressure pumping ability under an attempted extrusion condition, the second stage would operate with a low channel fill percentage, which usually results in a surging condition (product dimension variation). Two-stage screws typically can be designed to operate with 1.5 to 3% pressure variation at the end of the screw under a specific condition, that is, a specific material, a given screw speed, and a given die system resistance (pressure). Many two-stage screws must operate with some variation of conditions caused by product ranges (different die pressures) and alternative materials, and must operate over a screw speed range. These variations cause the screw design to be difficult because, inherently, there is limited versatility in two-stage screws. The use of an adjustable valve in the die adaptor system can offer some die pressure correction if the second stage is designed with too much pressure pumping ability; the valve can increase the pressure to improve the screw's balance. This is limited to cases where the die pressure is low or modest and where non-degrading materials are being extruded. When die pressures are high, due to thin product dimensions or restrictive die systems for some other reasons, the vent must be located as far from the screw tip as possible to allow a long second stage for pumping. High-pressure die systems (3000–

5000 psi) require a 12–15-diameter second stage length, whereas low-pressure dies (500–2000 psi) may require only an 8–10-diameter second stage. If there is an easily justifiable place for a melt pump in extrusion to enhance stability and reduce extrusion pressure from the screw, it is with vented screws. Most single-stage screws (especially barrier screws) can be designed to produce good extrusion pumping stability, but two-stage screws are not easily guaranteed to yield good extrusion consistency. Three-stage screws are even more difficult to design for good extrusion stability and to avoid vent flow over any modest range of processing conditions.

The need for adequate pressure pumping capacity against moderate or high die resistance causes the typical vented screw to be longer than 24 : 1 *L/D*. The typical length of a vented extruder of reasonable output capacity is 30 : 1 minimum, with 34 : 1 or longer also typically utilized.

Screw Cooling

Most screws have a core hole drilled from the rear (gearcase shank) end for some distance. Some cores are full, that is, they extend to within about 1 inch of the screw's tip, whereas other core holes are drilled to some shorter length. Today's screws are typically designed to operate "neutral," that is, with no cooling circulation, because that situation ensures maximum output rate with most polymer materials. Cooling reduces the screw's ability to convey material, and the colder the cooling fluid is, the lower the resultant output rate. Some older metering screw designs require screw cooling to allow acceptable melt quality on a screw that is too deep or one that has too short a metering section. Most conventional screw designs now contain some mixing section and/or a long enough metering section to provide adequate melting without retarding the output rate by screw cooling. Properly designed barrier screws also ensure adequate melting and so can avoid the full screw cooling mode. Most screws today are cored for a short distance, which reaches the exit side of the feed throat plus perhaps one to two diameters farther. This drilling allows cooling of the feed area, which is necessary under some conditions where the material tends to stick to the root of the screw (e.g., adhesives or nylon materials).

When a screw is fully cored today, that is done either because the screw will process a degradable material (such as some PVCs) where stagnation at the screw tip is avoided by cooling. The tip cooling setup typically utilizes oil rather than water as the medium to avoid freezing melted material to the end of the screw, where the slowest-moving material resides. A double cooling pipe is popular, where the outer pipe threads into the rear of a removable screw tip (which has a smaller core than the main screw with a pipe tap), and the feed tube runs inside the outer pipe. The return flow does not directly touch the screw core and therefore will not adversely affect the output rate. Oil cooling usually is performed at temperatures in the 200 to 300°F range.

Mixing Considerations and Mixing Devices

Mixing devices are used for several reasons on single-screw extruders and come in numerous designs. (See Figs. 4-33 and 4-34.) The mixing contributed by these devices can ensure improved melt quality and melt temperature uniformity and/or can perform some distributive mixing for color blending, polymer blending, and additive blending. The typical goal is to achieve the desired mixing quality level while inducing the minimum amount of shear and thus minimizing the rise in melt temperature. These devices can be placed on the screw, attached to the screw tip, or placed after the screw (in the die adaptor). The most common mixers utilized on the screw include fluted mixers (credited to Maddock of the Union Carbide Corp.; see Fig. 4-33) and mixing pins. Mixing pins are arranged in rings around the screw and can be of various sizes and shapes to break down and hold back any solids that have reached the ring position. This action reduces the possibility of unmelted polymer reaching the die system. The rings typically are placed along the metering section of the screw to offer successive blocks to solids moving along the screw channel. Placing multiple rings in close

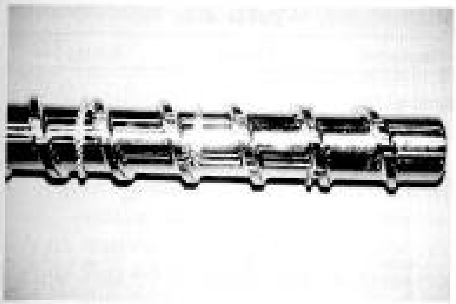

Fig. 4-33. Maddock mixing device. *(Courtesy Davis-Standard)*

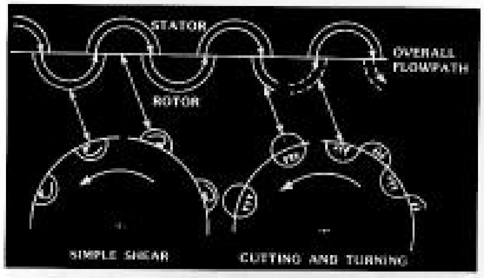

Fig. 4-35. Cutaway of cavity transfer mixer. *(Courtesy Davis-Standard)*

approximation to one another creates a more restrictive situation. Multiple rings are used occasionally in low-viscosity-material applications, where blocking and breaking down the soft solids is difficult unless fairly tight restrictions exist. The fluted (Maddock) mixing section creates several dam sections as the material enters the flutes on the feed end of the device, and the material then is forced over the dam, enters the exit flutes, and is forced into the following screw section. The dams of this mixer create a blockage to the remaining solids, breaking them down to ensure improved melt uniformity. Altering the shear input of this design is accomplished by changing the dam clearance or altering the dam widths. There are many other variations of these mixing devices, but the performances are similar to the basic designs discussed.

When simple mixers on the screw cannot give a high enough degree of distributive mixing (as with low amounts of a color additive, 0.25–1.5%), there are some advanced dynamic mixer designs that attach to the screw tip and noticeably improve mixing. An example of this type of mixer is the cavity transfer mixer or CTM (see Figs. 4-35 and 4-36). The spherical "pockets" on the stator and rotor are misaligned by half a pocket length to allow material to pass from the stator to the rotor and back while moving toward the die system. The melt is split as it moves from stator to rotor, and with the rotation of the screw, the number of "splits" grows rapidly (exponentially) with increasing rows of pockets. Even a CTM with four or five rows does a noticeably better distributive mixing job, compared with mixers on the screw.

Mixers installed in the die adaptor system are of the static variety. Several manufacturers produce these mixers and the amount of mixing depends on the length of the mixing elements selected. These devices split the stream, like dynamic mixers, but without rotation they require longer devices to do a comparable job. The pressure drop across any of these mixers obviously increases with element length and must be taken into account in the design of the device because pressure affects melt temperature levels. The biggest volume usage of the static mixers has occurred where long adaptor pipes are necessary between the extruder and the final die. This condition leads to tempera-

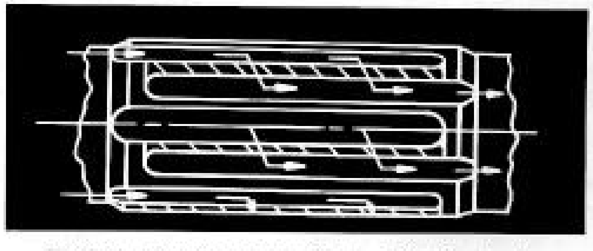

Fig. 4-34. Pin mixing device. *(Courtesy Davis-Standard)*

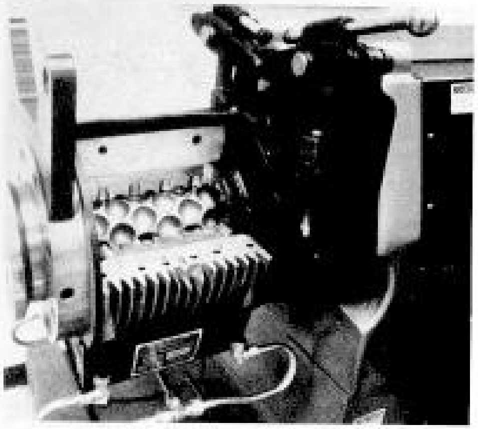

Fig. 4-36. Cavity transfer mixer—anticipated mixing. (*Courtesy Davis-Standard*)

ture gradients forming along the long pipe system, which are corrected with static mixers at the exit end of the piping, just before the die. The melt entering the die thus is assured of having a uniform melt temperature throughout. Systems with short adaptor pipes (2 or 3 feet or less) are not typically fitted with static mixers because the screw-type mixers can ensure a uniform melt into the die system.

Scaling Screw Design and Extruder Performance

When the performance is known for a given extruder size, it is sometimes necessary to predict the performance on a different-size machine using the same material. Some mathematical relationships have been developed to perform this function, as summarized in Table 4-2. The output rate is scaled by using the square of the diameter ratio, which relates to the barrel surface area and, hence, the melting capacity. The goal of a scaleup or scaledown exercise is to predict the equivalent extrusion performance at similar melt temperature conditions. The shear created on different-diameter extruders at similar screw speeds is different; thus for equal melt temperatures, a larger extruder must run at slower screw speeds. The scaled output rate is therefore delivered at a different screw speed. Drive power usage is scaled similarly to the output rate because it is assumed that the scaled condition uses equal lb/hr/hp. In scaling from a smaller to a larger extruder, it is difficult to achieve accurate results because of the melt temperature difference usually seen. A good practice when using the scaling equations is to keep the distance of scale as small as possible. The scale from a 3.5-inch-diameter extruder to a 4.5-inch machine is reasonably accurate, while a 1.5-inch scaled to a 4.5-inch extruder is quite risky and will not give good confidence that the scaled numbers will closely match reality. The use of a very small lab extruder ($\frac{3}{4}$ or 1 inch) thus will not allow good data to be used to predict production-sized extruder results. As long as the scaling laws are used with this limitation in mind, a reasonable result can be achieved.

Table 4-2.

Parameter	*Symbol*	*Scaling Law*
Metering depth	h	$\frac{h_1}{h_2} = \left(\frac{D_1}{D_2}\right)^{0.75}$
Screw speed	N	$\frac{N_1}{N_2} = \left(\frac{D_1}{D_2}\right)^{-0.75}$
Output	Q	$\frac{Q_1}{Q_2} = \left(\frac{D_1}{D_2}\right)^{2}$
Power	P	$\frac{P_1}{P_2} = \left(\frac{D_1}{D_2}\right)^{2}$
Torque	Md	$\frac{Md_1}{Md_2} = \left(\frac{D_1}{D_2}\right)^{2.75}$

Simplified extruder scaling laws are illustrated in Table 4-2 for comparing the basic parameters of extruders of diameters D_1 and D_2.

GLOSSARY OF EXTRUSION TERMS

extruder—Basically, a machine that accepts solid particles (pellets or powder) or liquid (molten) feed, conveys it through a surrounding barrel by means of a rotating screw, and pumps it, under pressure, through an orifice. Nomenclature used applies to the barrel, the screw, and other extruder elements.

Nomenclature applicable to the barrel includes:

barrel—A cylindrical housing in which the screw rotates, including a replaceable liner, if used, or an integrally formed special surface material. Nomenclature covers:

- **feed openings**—A hole through the feed section for introduction of the feed material into the barrel. Variations (see Fig. 4-37) include vertical, tangential, side feed openings.
- **feed section**—A separate section, located at the upstream end of the barrel, that contains the feed opening into the barrel.
- **grooved liner** (or barrel)—A liner whose bore is provided with longitudinal grooves.

barrel heaters—The electrical resistance or induction heaters mounted on or around the barrel.

barrel jacket—A jacket surrounding the outside of the barrel for circulation of a heat transfer medium.

barrel heating zone—A portion of barrel length having independent temperature control.

barrel vent—An opening through the barrel wall, intermediate in the extrusion process, to permit the removal of air and volatile matter from the material being processed.

decreasing lead screw—A screw in which the flight lead, or pitch, decreases over the full flighted length (usually of constant depth).

metering type screw (Fig. 4-38)—A simple screw design with a feed section, a transition section, and a metering section.

multiple-flighted screw—A screw having more

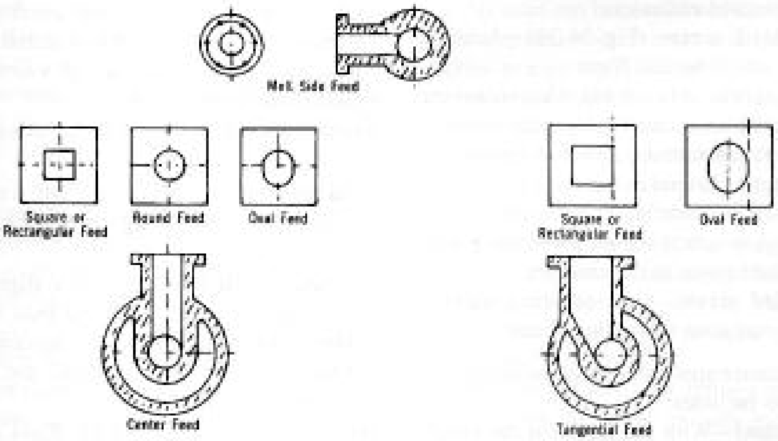

Fig. 4-37. Feed variations.

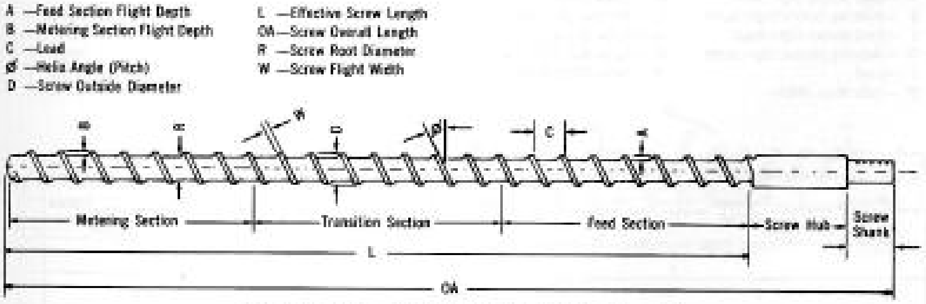

Fig. 4-38. Single flight, single-stage extrusion screw.

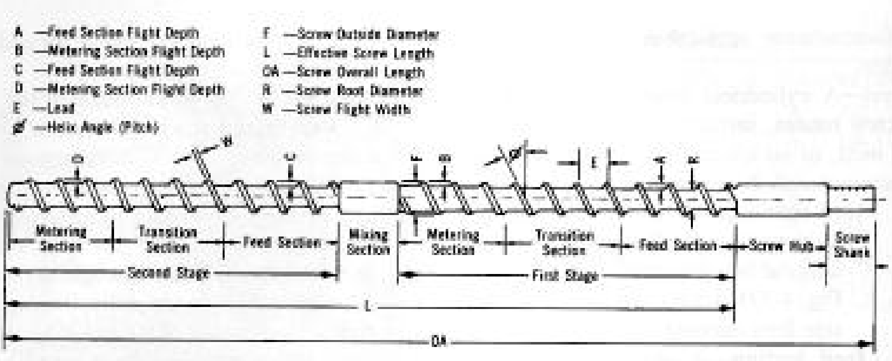

Fig. 4-39. Single flight, two-stage extrusion screw with mixing section.

than one helical flight such as: double flighted, double lead, double thread, or two starts, and triple flighted, etc.

multiple-stage screw (Fig. 4-39)—A two- or more-stage screw with introduction of special mixing sections, choke rings, or torpedoes for vented extrusion.

single-flighted screw (Fig. 4-38)—A screw having a single helical flight.

two-stage screw (Fig. 4-40)—A screw constructed with an initial feed section followed by a restriction section, and then an increase in the flight channel volume to release the pressure on the material while carrying it forward, such as a screw used for venting at an intermediate point in the extruder.

water-cooled screw—A cored screw suitable for the circulation of cooling water.

Nomenclature applicable to screw design and construction includes:

screw channel—With the screw in the barrel, the space bounded by the surfaces of flights, the root of the screw, and the bore of the barrel. This is the space through which the material is conveyed and pumped.

feed section of screw—The portion of a screw that picks up the material at the feed opening (throat) plus an additional portion downstream. Many screws have an initial constant lead and depth section, all of which is considered the feed section.

screw flight—The helical metal thread of the screw.

flight land—The surface at the radial extremity of the flight constituting the periphery or outside diameter of the screw.

hardened flight land—A screw flight having its periphery harder than the base metal by flame hardening, induction hardening, depositing of hard facing metal, etc., for increased screw life.

helix angle—The angle of the flight at its pe-

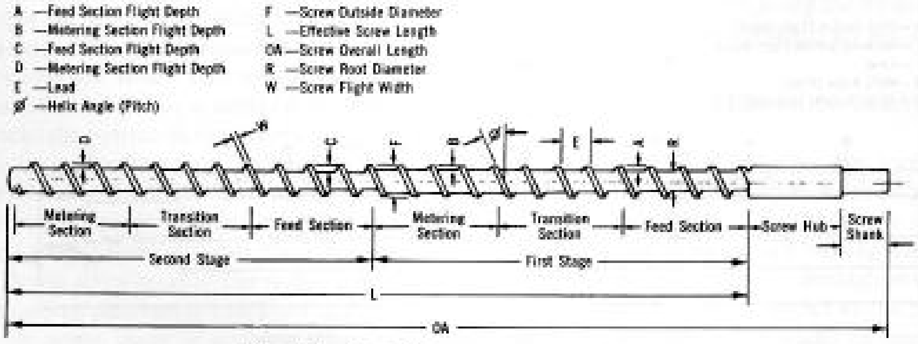

Fig. 4-40. Single flight, two-stage extrusion screw.

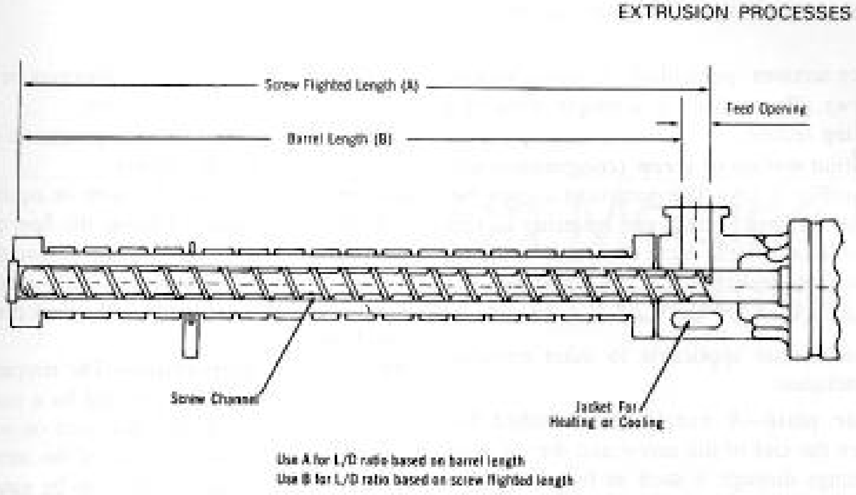

Fig. 4-41. Barrel cross-section.

riphery relative to a plane perpendicular to the screw axis.

screw hub—The portion immediately behind the flight which prevents the escape of the material.

length-to-diameter ratio (*L*/*D* ratio) (Fig. 4-41)—The length to diameter ratio (*L*/*D*) can be expressed in two ways: (a) *L*/*D* ratio based on the barrel-length—the distance from the forward edge of the feed opening to the forward end of the barrel bore divided by the bore diameter and expressed as a ratio wherein the diameter is reduced to 1 such as 20 : 1 or 24 : 1; and (b) *L*/*D* ratio based on the screw flighted length—the distance from the rear edge of the feed opening to the forward end of the barrel bore divided by the bore diameter and expressed as a ratio wherein the diameter is reduced to 1, such as 20 : 1 or 24 : 1. Note: Either definition of the *L*/*D* ratio can be considered correct, but machinery manufacturers should state which applies to a particular extruder.

metering section of screw—A relatively shallow portion of the screw at the discharge end with a constant depth and lead, and having a length of a least one or more turns of the flight.

restriction section or choke ring—An intermediate portion of a screw offering a resistance to the forward flow of material, with the intent to improve extrudate quality and/or output stability.

torpedo (Fig. 4-42)—An unflighted cylindrical portion of the screw usually located at the discharge end, but which can be located in

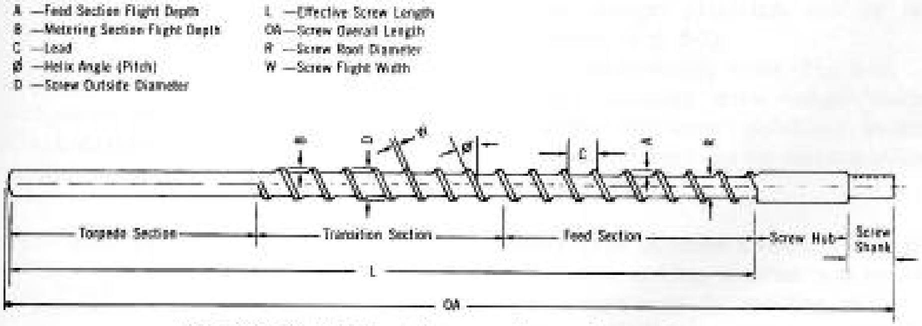

Fig. 4-42. Single flight, single-stage, with torpedo, extrusion screw.

other sections, particularly in multiple-stage screws. The torpedo is a simple form of a mixing section.

transition section of screw (compression section) (Fig. 4-38)—The portion of a screw between the feed section and metering section in which the flight depth decreases in the direction of discharge.

Nomenclature applicable to other extruder parts includes:

breaker plate—A metal plate installed between the end of the screw and the die with openings through it such as holes or slots. Usually used to support a screen pack.

drive—The entire electrical and mechanical system used to supply mechanical energy to the input shaft of gear reducer. This includes the motor, constant or variable speed belt system, flexible couplings, starting equipment, etc.

reduction gear (gear reducer)—The gear device used to reduce speed between the drive motor and the extruder screw. Supplementary speed reduction means also may be used, such as belts and sheaves, etc.

melt extrusion—An extrusion process in which a melt is fed to the extruder.

screens—A woven metal screen or equivalent device that is installed across the flow of material between the tip of the screw and the die and supported by a breaker plate to strain out contaminants or to increase the back pressure or both.

stock or melt temperature—The temperature of the stock or melt as sensed by a stock or melt thermocouple and indicated on a compatible meter. The location of the measurement must be specified for it to be meaningful.

surging—A pronounced fluctuation in output over a short period of time without deliberate change in operating conditions.

thrust bearing—The bearing used to absorb the thrust force exerted by the screw.

thrust—The total axial force exerted by the screw on the thrust bearing (for practical purposes equal to the extrusion pressure times the cross-section area of the bore).