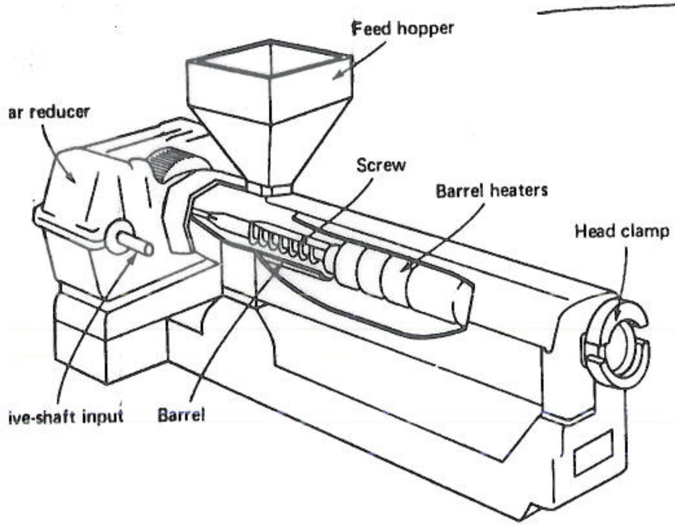
Extrusion



gure 6-1 Cutaway view of a typical single-screw extruder.

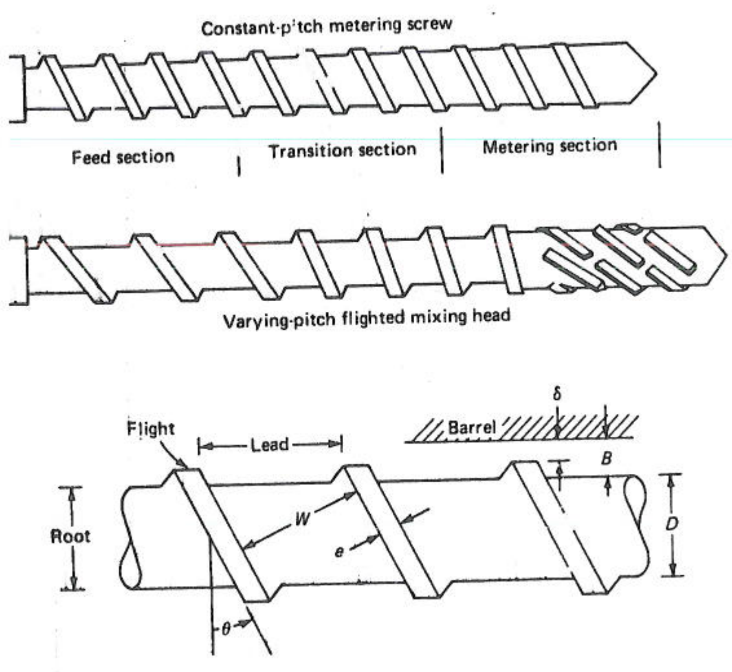


Figure 6-2 Extruder screw geometry.

Part of the versatility of the extruder lies in the design of screws which may be specialized with respect to the function to be served, such as mixing, metering, or removal of volatile solvent. The design of the screw may also vary with the type of plastic resin to be handled. Figure 6-2 shows some typical screw geometries and details which define screw parameters.

In this chapter the analysis of the fluid dynamics of extrusion will be considered. The melting process is not treated here.

6-1 NEWTONIAN ISOTHERMAL ANALYSIS

Under practical circumstances extrusion usually involves a molten polymer flowing under nonisothermal conditions. In developing models of melt extrusion it is useful to begin with the simplest case, namely, isothermal newtonian extrusion. A geometric simplification makes it possible to treat this case analytically, and the resulting "simplified theory" then serves as a basis for comparison of subsequent modifications to the theory.

The geometric simplification begins upon "unwinding" the helical screw channel, as shown in Fig. 6-3. The relative motion of the screw and the barrel becomes equivalent to the steady motion of a plane at an angle θ to the helical axis z. Thus a drag flow is generated with components in the x and z directions.

The dynamic equations in the x and z directions will be written with the assumption that the inertial terms are unimportant, a reasonable assumption in highly viscous fluids. For the steady state we write

$$0 = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2}\right) \tag{6-1}$$

$$0 = -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 u_z}{\partial x^2} + \frac{\partial^2 u_z}{\partial y^2}\right) \tag{6-2}$$

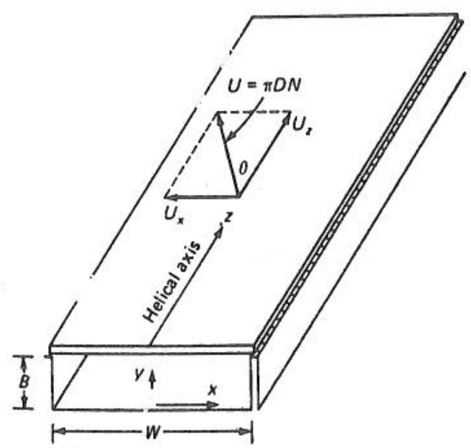


Figure 6-3 Geometry of the "unwound" helical screw channel. The upper surface, representing the barrel, moves at an angle θ to the helical axis and causes flow down the channel (U_z) as well as transverse to it (U_x).

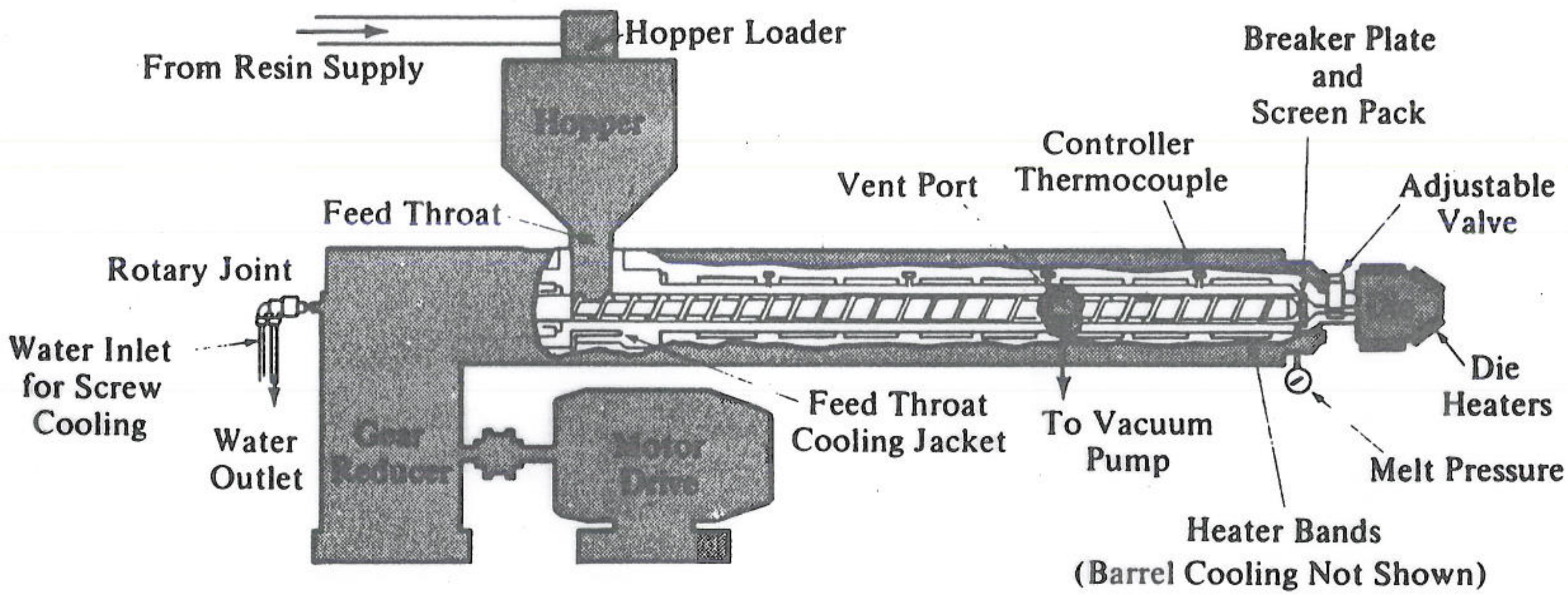


Figure 19.4 Vented extruder. From *Modern Plastics Encyclopedia*, McGraw-Hill, Ne York, 1969–1970 ed.

compression, and metering. The function of the melting section is to convey th solid pellets forward from the hopper and convert them into molten polymer. I analysis involves a combination of fluid and solid mechanics and heat transfe The compression section, in which the depth of the screw flight decreases, designed to compact and mix the molten polymer to provide a more-or-les homogeneous melt to the metering section, the function of which is to pump th

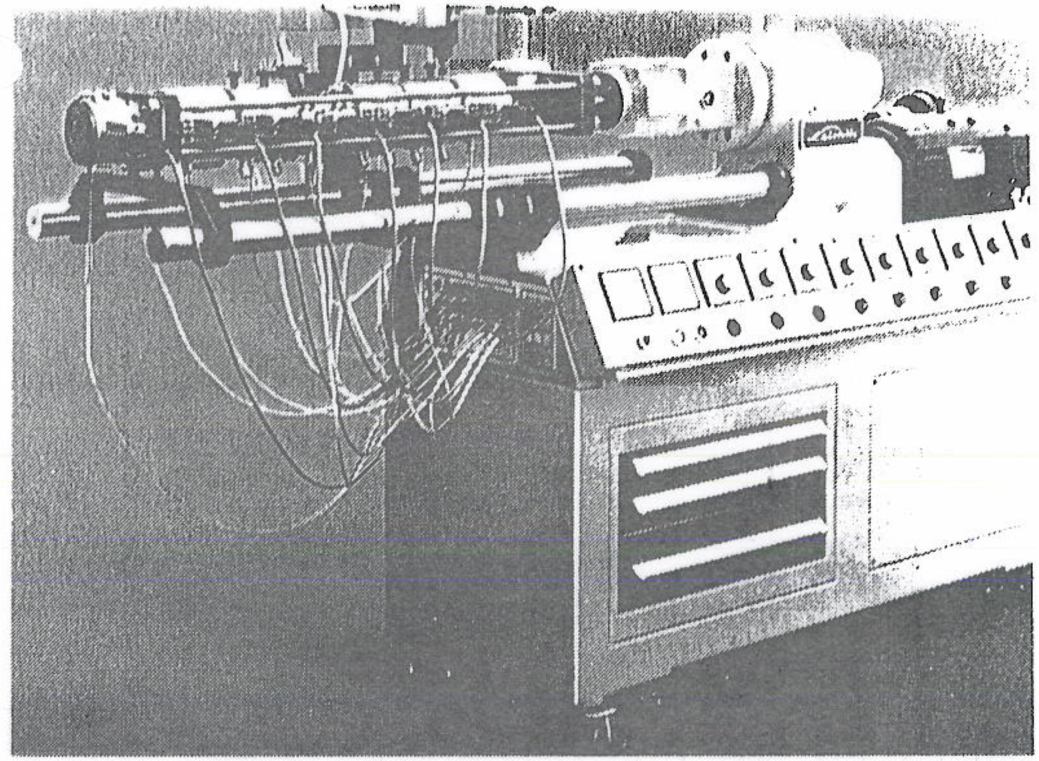


Figure 5.31 • Modular small extruder [LEISTRITZ]

FF]

9[illegible]	220 to 250	200 to 300
120	300 to 350	350 to 450
150	450 to 500	750 to 1000
200	700 to 850	1500 to 1800 *)
225	1000 to 1200	2000 to 2300 *)
250	1300 to 1500	2400 to 2800 *)
300	1700 to 2000	3400 to 4000 *)

*) cascade extruder

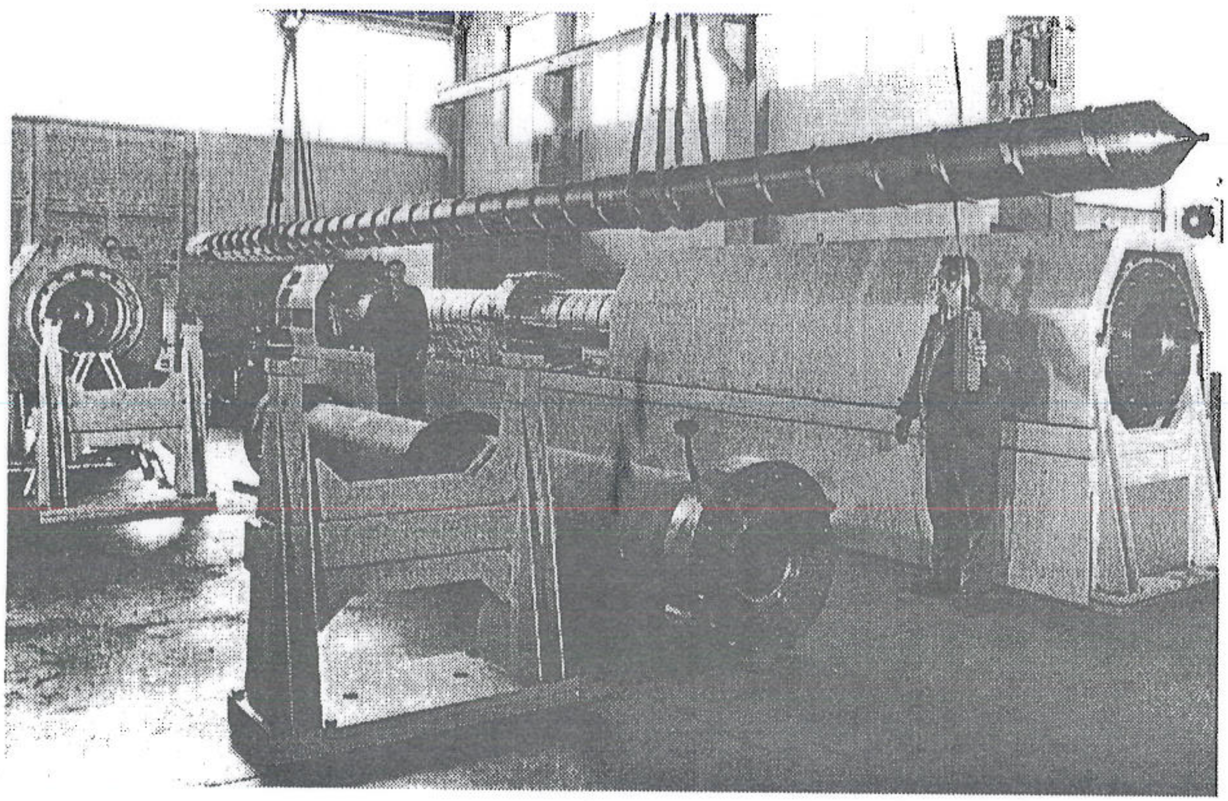


Figure 6. Extrusion unit with melting extruder ($D = 300$ mm, $L = 30$ D) and liquid-fed extruder ($D = 300$ mm, $L = 17$ D) (Photo: Barmag, Remscheid/West Germany)

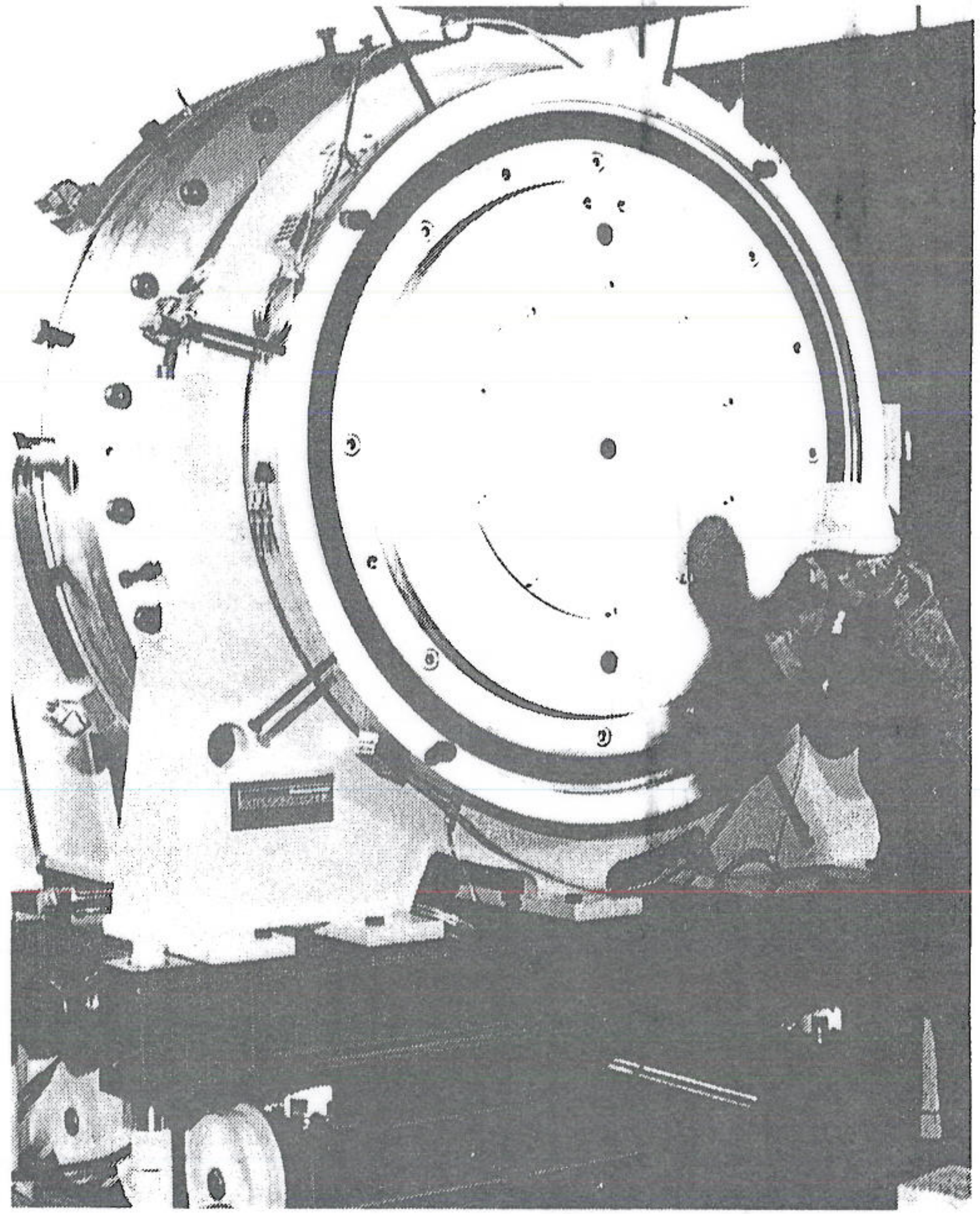


Figure 5.41 · Large tubing die (1400 mm or 55 in. diameter) [BATTENFELD]

piezoelectric actuators to move the flex lip (11).

Horseshoe for narrower webs

Flow non-uniformities from changes in power law index can be largely eliminated in a die with a horseshoe shape manifold. This manifold was developed by Winter and Fritz (12). The die is designed such that the shear rate anywhere in the manifold region is constant. If the ratio of channel width W to channel depth H is larger than about 10, the shape factor becomes independent of the power law index. For a manifold with constant channel width W, the squared ratio of the channel depth H(x) to the depth of the preland region h equals half width b minus distance x divided by the width of the manifold W. The squared ratio of land length y(x) at distance x to twice the manifold width equals half width b minus distance x divided by the manifold W minus one.

This geometry has been applied to fan gates in injection molding, to annular dies in blow molding, to profile dies with flat sections, as well as film and sheet dies. A drawback of the horseshoe die is that the preland length, also called manifold drop, y(0), becomes rather large for wide sheet dies. This makes the die more susceptible to clamshelling.

Calculating clamshelling

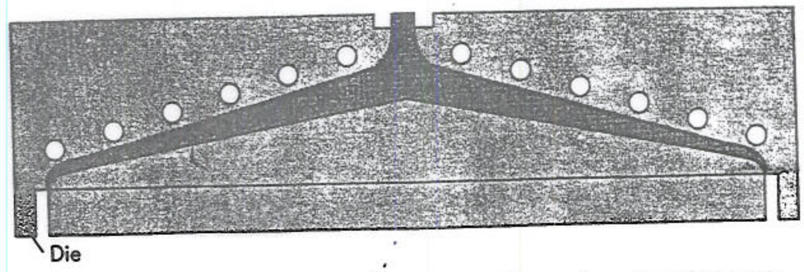
Clamshelling is simply the mechanical deformation of the sheet die by the pressure of the plastic melt. Since the die is clamped together at the edges of the die but not in the center, the largest deflection occurs in the center of the die. As a result, more material will tend to flow through the center than through the side regions. If the clamshelling is not too severe the flex lip or choker bar can be adjusted to compensate for clamshelling. Such an adjustment, however, is throughput dependent and has to change when the throughput is increased or decreased.

Proper calculation of clamshelling requires numerical techniques to determine the deformation at various points in the dies. Finite element programs are well suited for these types of calculations. A much simplified method was proposed by Michaeli (13). The method involves calculation of the die lip deflection due to bending and shear in the cross section through the center of the die and perpendicular to the manifold. As an example, for a die with a total land length of 6 inches, each die half 4 inches high, maximum pressure of 3,000 psi, the total deflection is 0.0042 inch. This assumes an elastic modulus of the steel of 30 million psi and a Poisson's ratio of 1/3.

The total land length has the strongest effect on clamshelling because the deflection increases with land length to the fourth power. If the land length in the example is reduced from 6 inches to 4 inches the total deflection reduces from 0.0042 inch to 0.0011 inch. Thus, a reduction in the land length by 33% reduces the total deflection by almost a factor of four. □

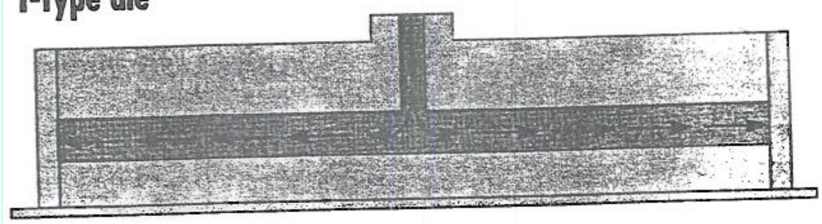
Melt distribution varies with die geometry

Fishtail die



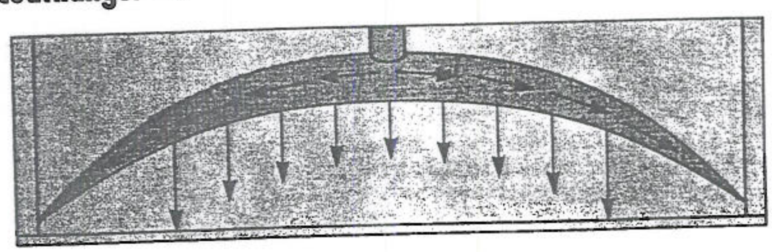
In fishtail dies, the land restriction reduces with distance from the center. This type of internal geometry makes it difficult to obtain uniform melt distribution.

T-type die



You won't get uniform-melt distribution with a T-type die, so don't use them for high-viscosity materials. But this design has found a niche in high-temperature coating applications, where viscosity is low and flow distribution is acceptable.

Coathanger die



Coathanger dies are common in cast film and sheet, and can be designed to give uniform melt distribution. However, high machining costs make this type of die more expensive than others.

lose togeter and the film thickness is up to about 200 µm.

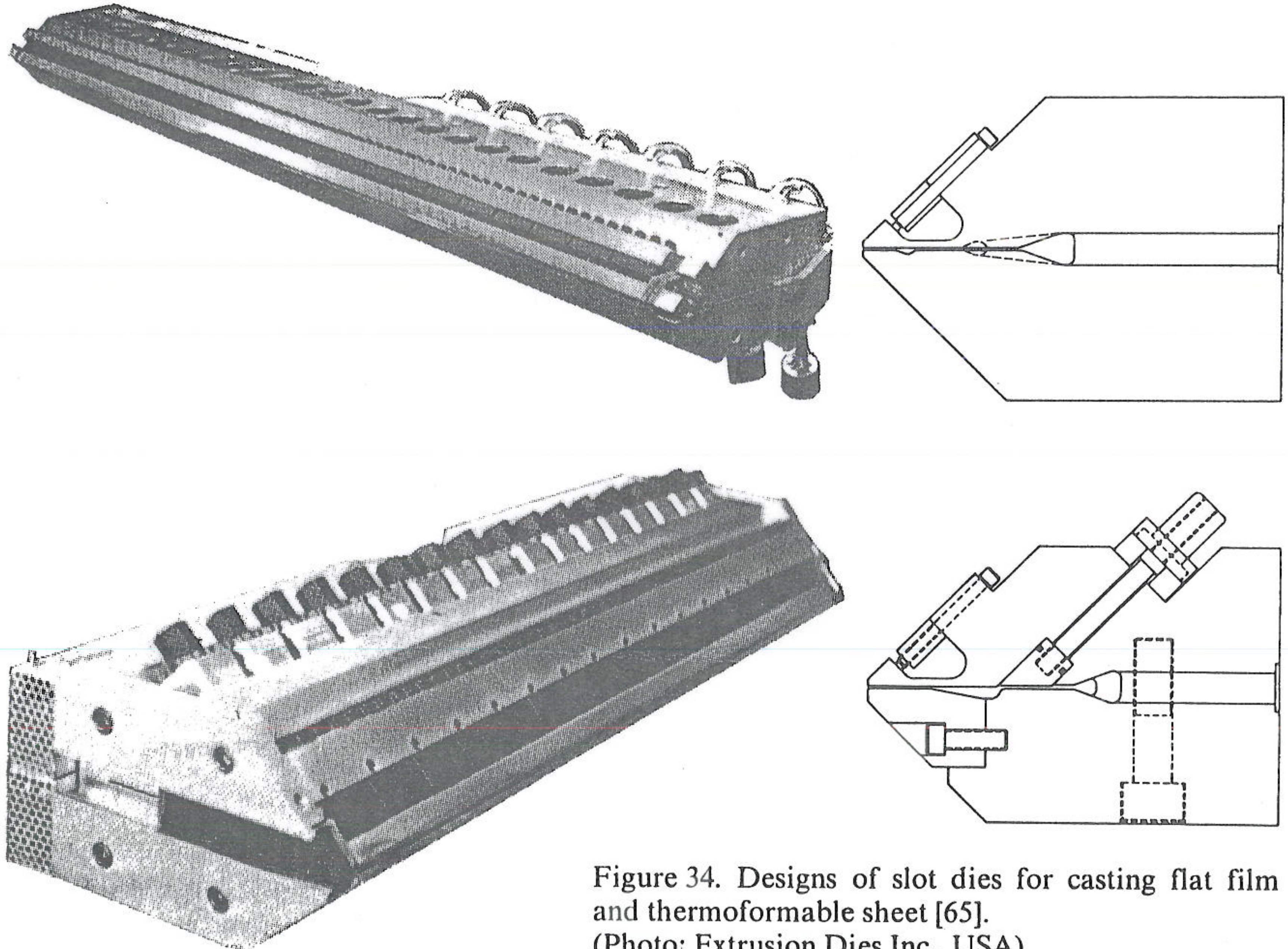


Figure 34. Designs of slot dies for casting flat film and thermoformable sheet [65].
(Photo: Extrusion Dies Inc., USA)

ne die-half is designed with a flexible lip to allow the die gap to be sensitively adjusted
y push screws or push/pull bolts with differential threads. The melt-contact surfaces are

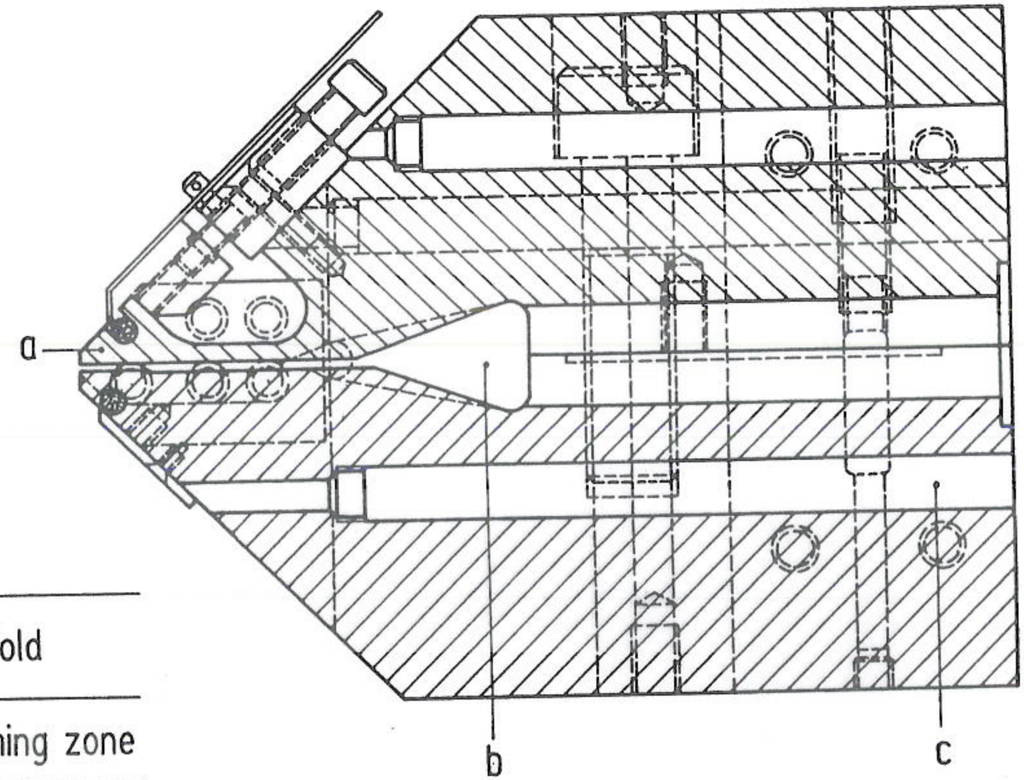


Figure 4. Slot die
a flexible, adjustable die lip, *b* distribution manifold, *c* cartridge heater

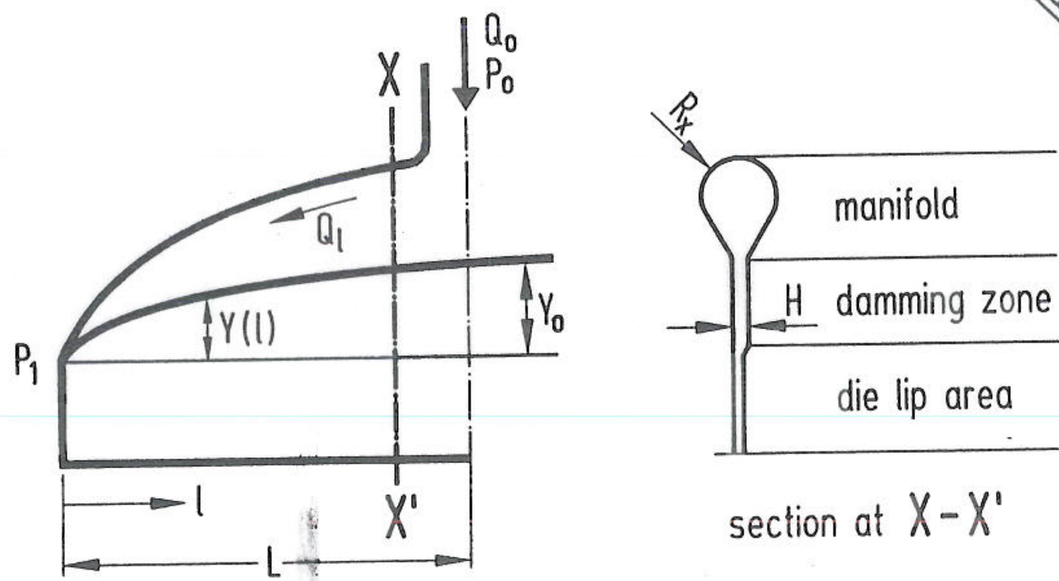


Figure 5. Diagram of the melt distributor system (manifold)
Q_0 throughput at die inlet, P_0 pressure at die inlet, Y_0 max. island length, $Y_{(l)}$ island length as function of width coordinates, l width coordinate, L half die width, H gap, Q_1 throughput as function of width coordinate, P_1 pressure in die lip area

constant throughput across the die width for all flow paths, with a uniform pressure drop from the die inlet to the die outlet.

Different materials often differ considerably in their rheological behavior. So-called

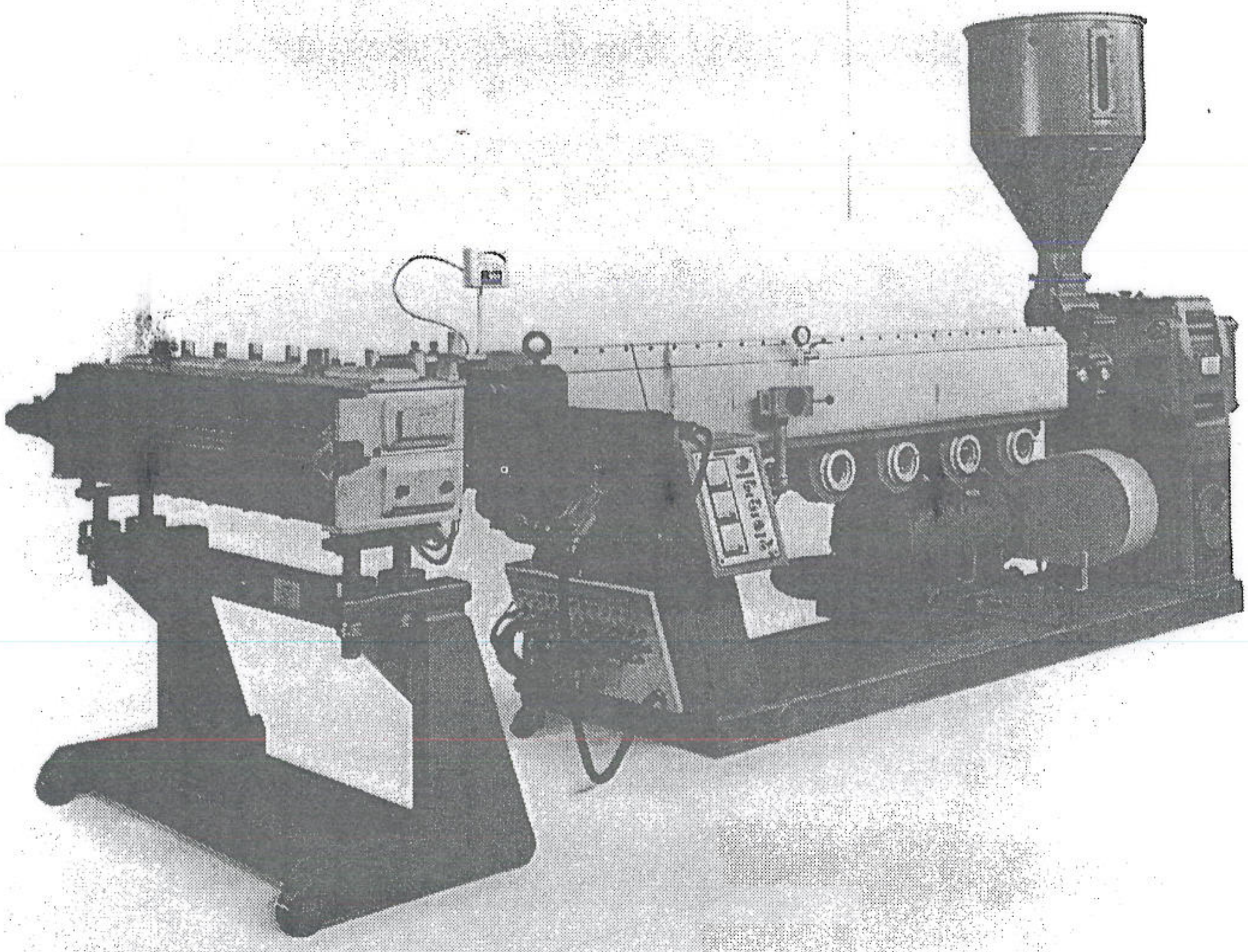
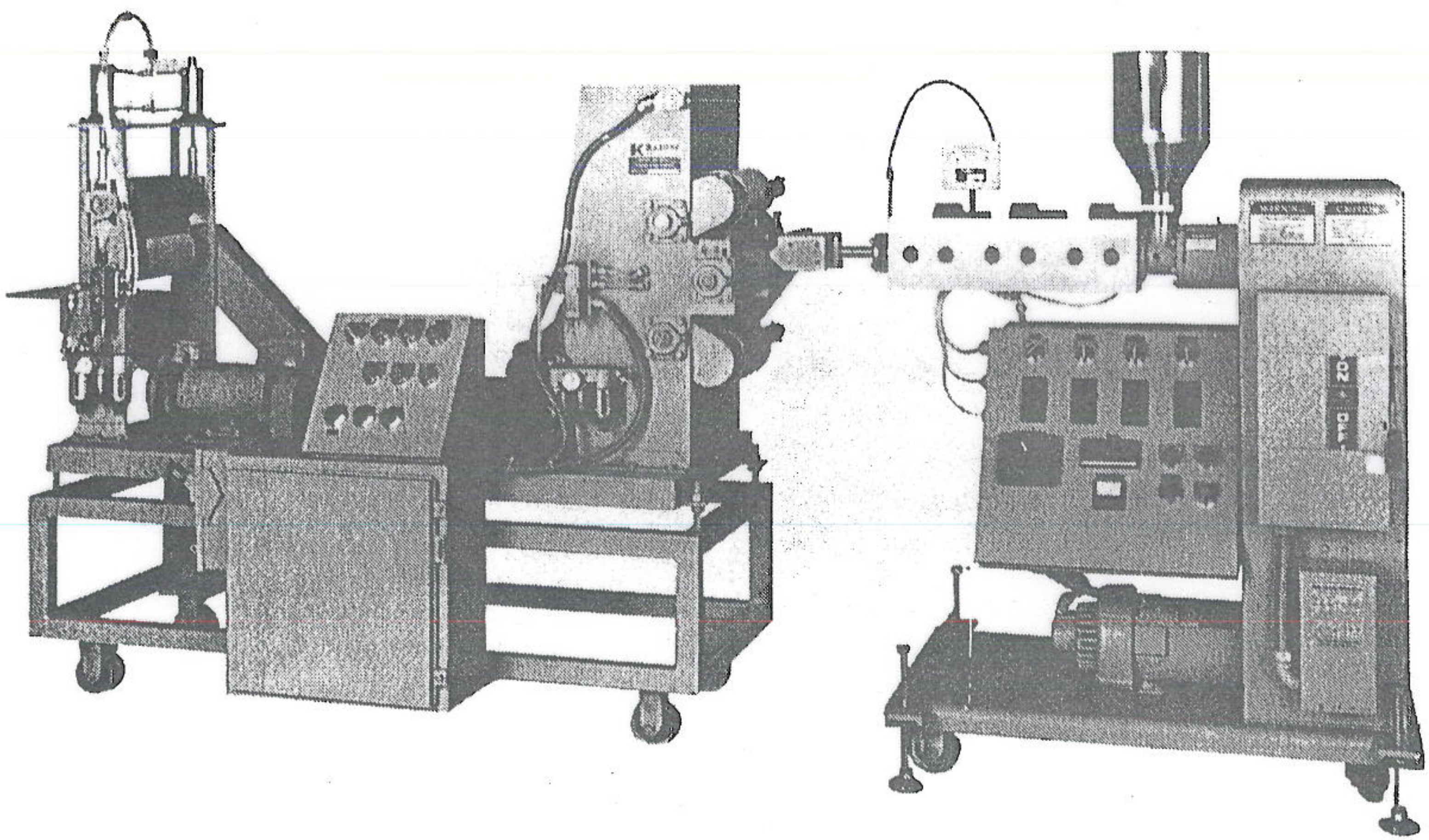


Figure 5.33 · Sheet die with single screw extruder (90 mm or 3.5 in.) [OMIPA]



gure 5.32 · Laboratory sheet line [KILLION]

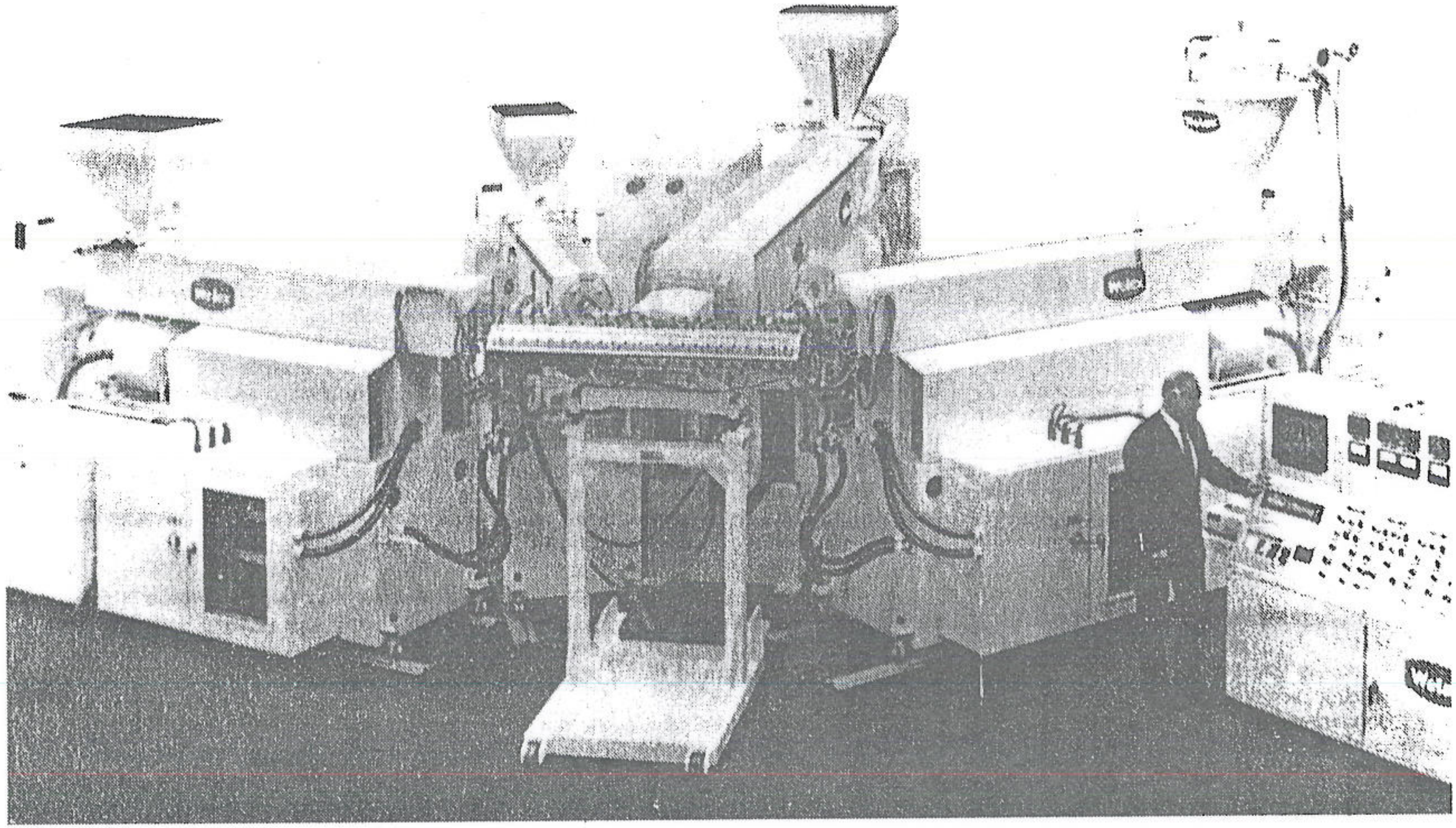


Figure 5.36 • Large sheet coextrusion set-up (one 6 in., two 3.5 in. and one 2.5 in. extruders; 5 or 150 mm wide die) [WELEX]

Injection Molding

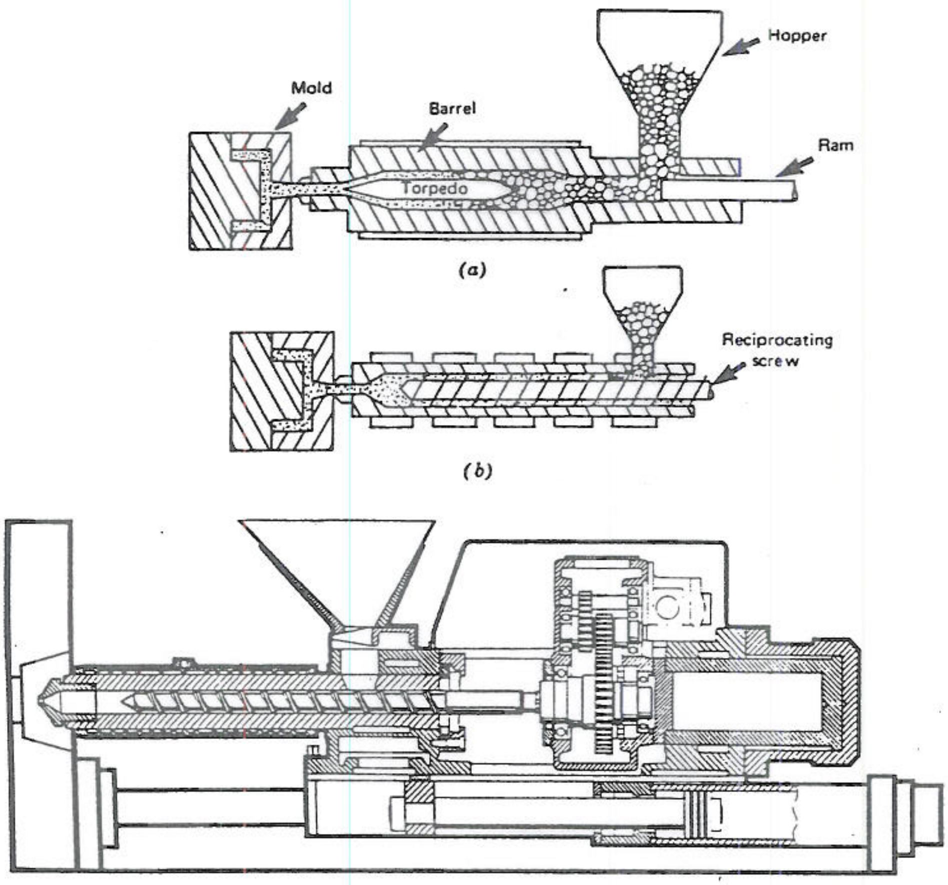


Fig. 1.12 Schematic view of conventional injection molding machines. (*a*) Ram-fed injection molding machine. (*b*) Screw-fed injection molding machine. (*c*) Layout of a typical screw injection molding machine. (*a* and *b*, reprinted with permission from W. A. Holmes-Walker, *Polymer Conversion*, Halsted Press, London, 1975; (*c*) courtesy of Werner & Pfleiderer, Waldwick, N.J.)

Figure 1.13 depicts the injection molding cycle. The screw moves forward and fills the mold with melt and maintains the injected melt under high pressure, during what is called the "hold" time. (A no-return valve at the end of the screw prevents the polymer from flowing back onto the screw.) During hold time additional melt is injected, offsetting contraction due to cooling and solidification. Later, the "gate," which is a narrow entrance to the mold, freezes, thus isolating the mold from the injection unit. The melt within the mold is still at high pressure. As the melt cools and solidifies, pressure drops to a level that is high enough to ensure the absence of sinkmarks, but not so high that it becomes difficult to remove parts. After gate freezing, screw rotation commences. The "extruded" melt is accommodated in the increasing cylindrical space in front of the screw created by its backward axial motion. Flow rate is maintained by controlling the back pressure (i.e., the hydraulic pressure exerted on the screw), which in turn determines the pressure in the melt

generated in f
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melt by heat co
time. Meanwhi
the next shot.
without any n
computer contr
from part to pa
The mold fi
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complex geome
discusses all the
of recent inten
design remains l
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Fig. 1.13 The inje
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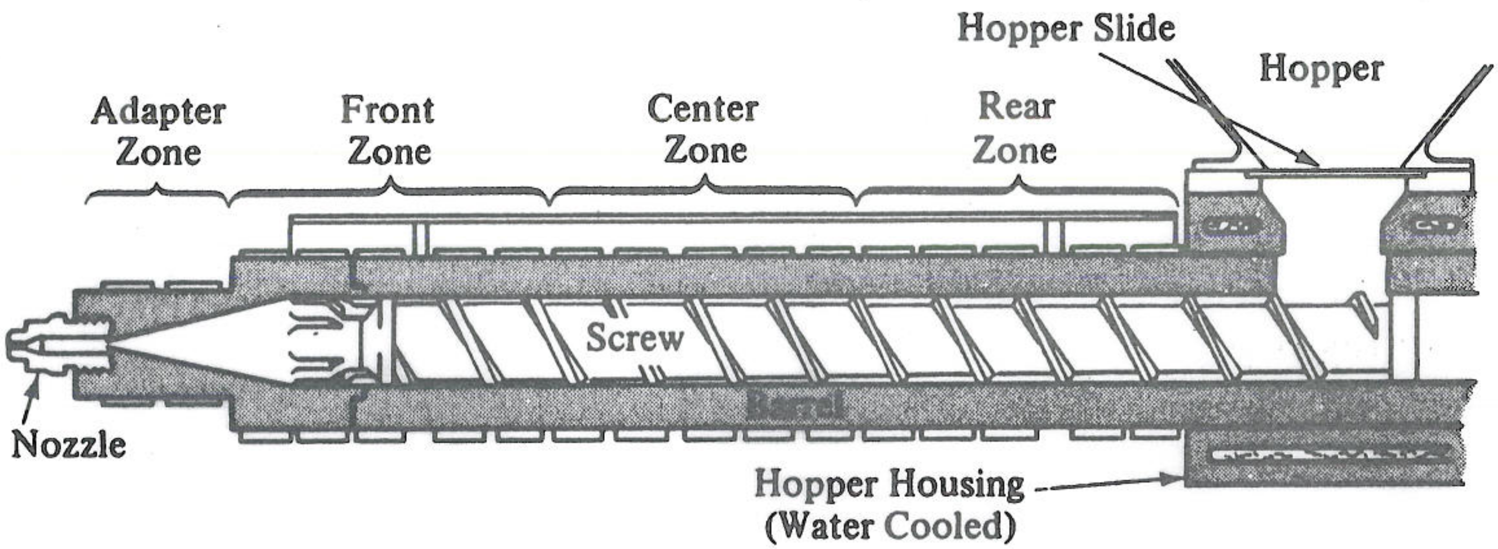


Figure 19.1 Injection molding machine. From *Modern Plastics Encyclopedia*, McGraw-Hill, New York, 1969–1970 ed.

very poor. This resulted in low plasticizing (melting) rates, and a thermally nonuniform melt. The screw generates heat *within* the material and provides some mixing, thereby increasing plasticizing rates and giving a more uniform melt temperature.

Molten material passes through a check valve at the front of the screw, and as it is deposited ahead of the screw, it pushes the screw backward while material

Balancing of Sprue /Runner Systems

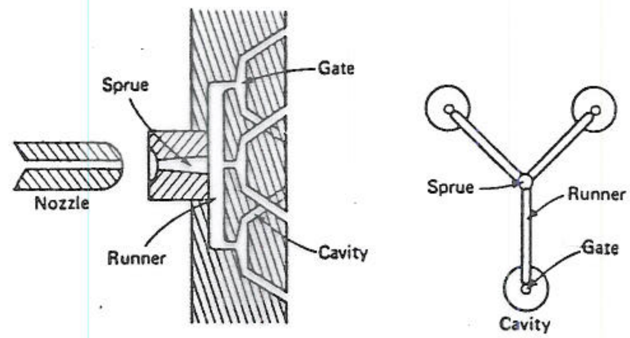


Figure 11-4 Schematic of a three-cavity mold.

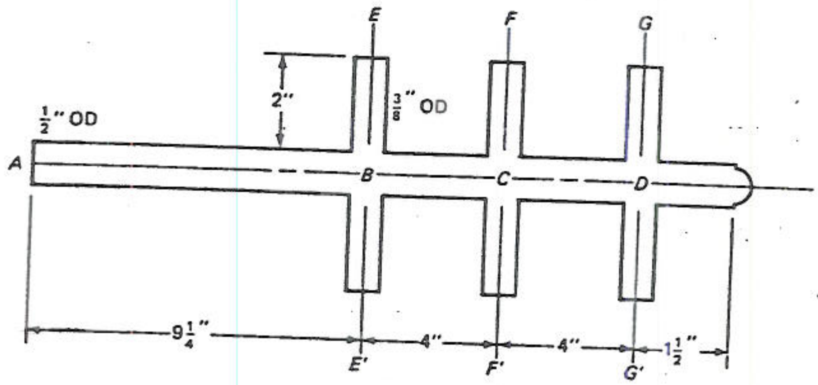


Figure 11-18 Sprue-runner system for a six-cavity telephone-handle molding die.

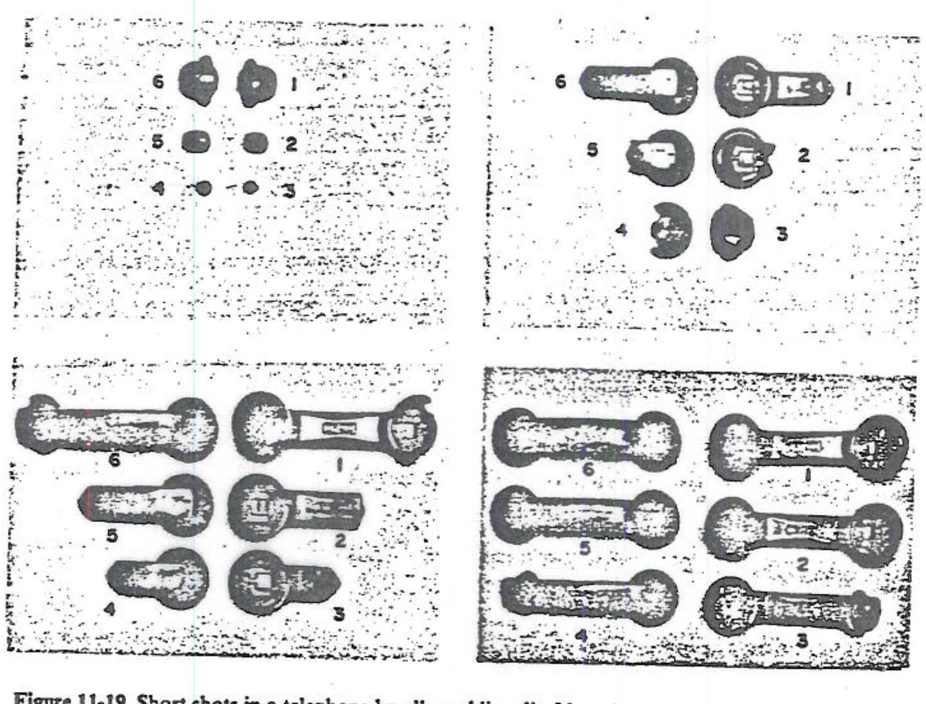
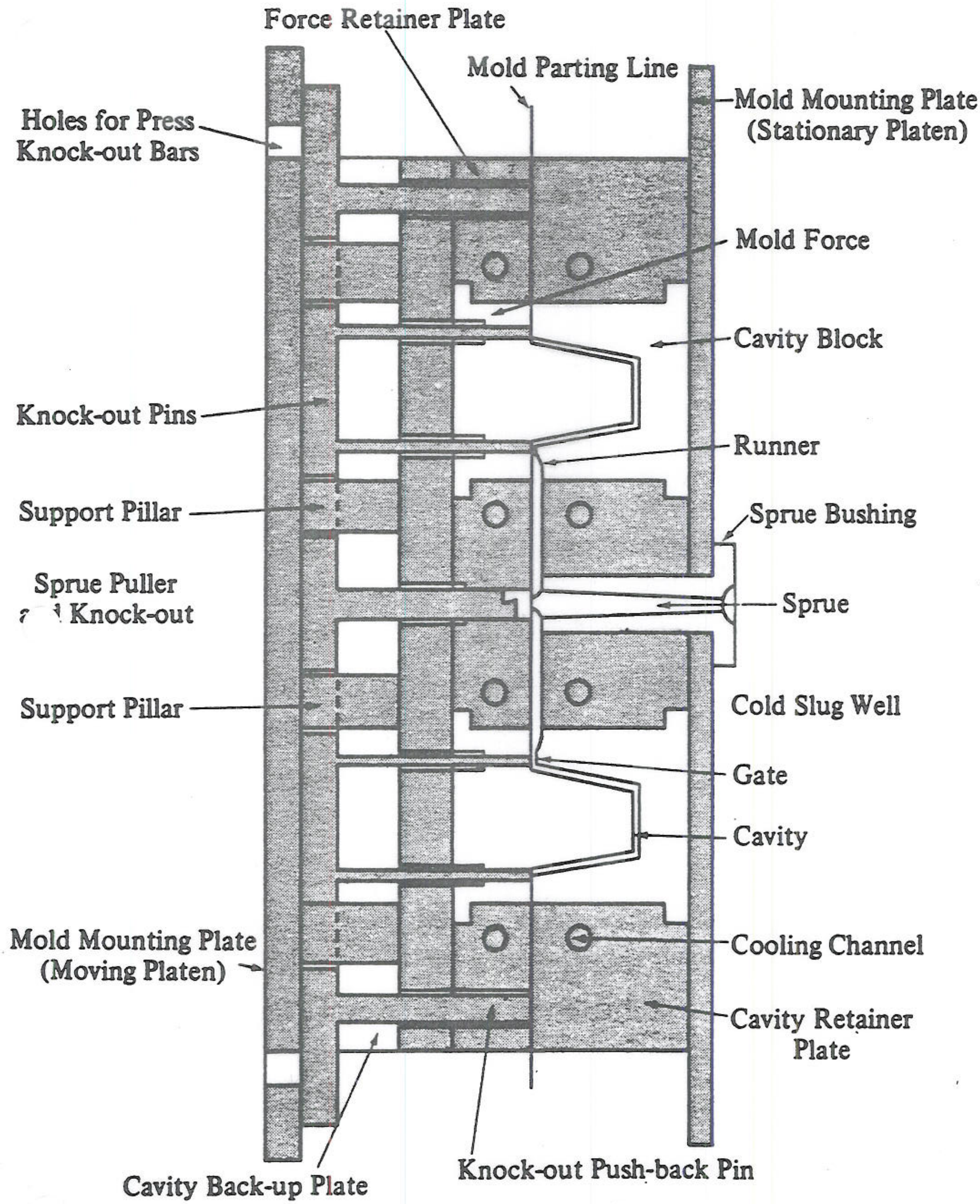


Figure 11-19 Short shots in a telephone-handle molding die. Note the asymmetry, due to unbalanced runners. (*Photo courtesy of G. Williams and H. A. Lord.*)



.2 Two-cavity injection mold. From *Modern Plastics Encyclopedia*, McGraw
York, 1969–1970 ed.

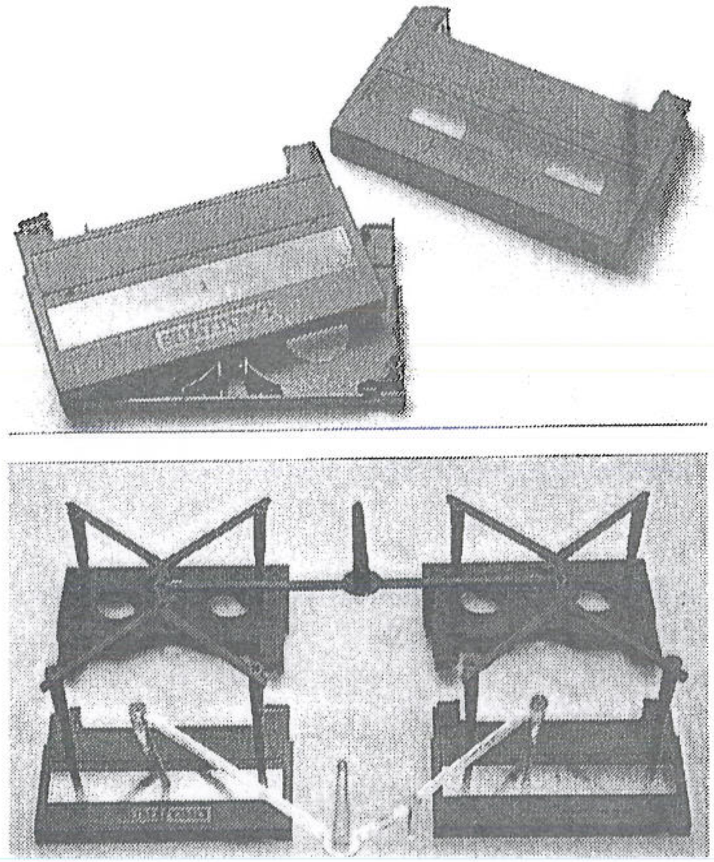


Fig. 5.177

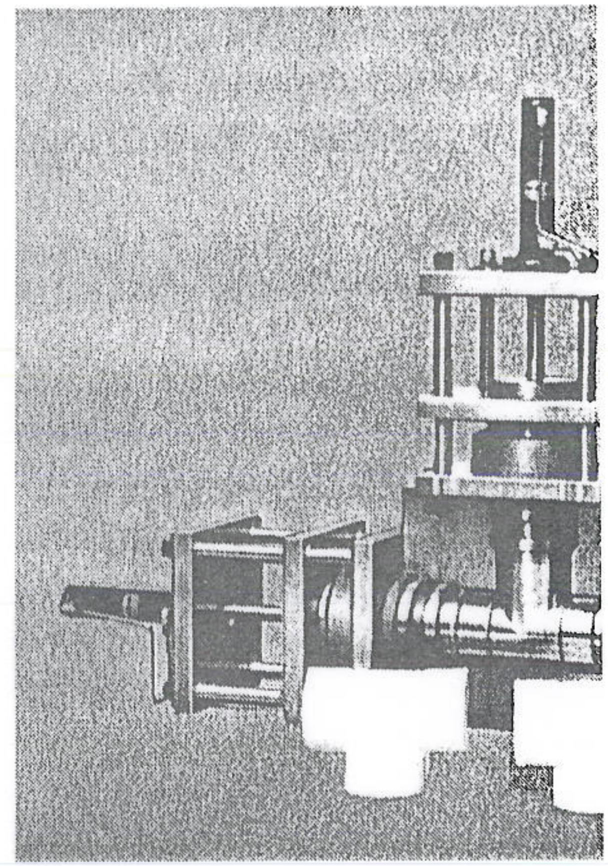
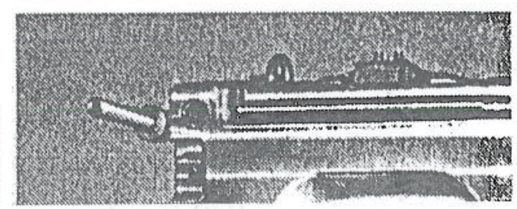
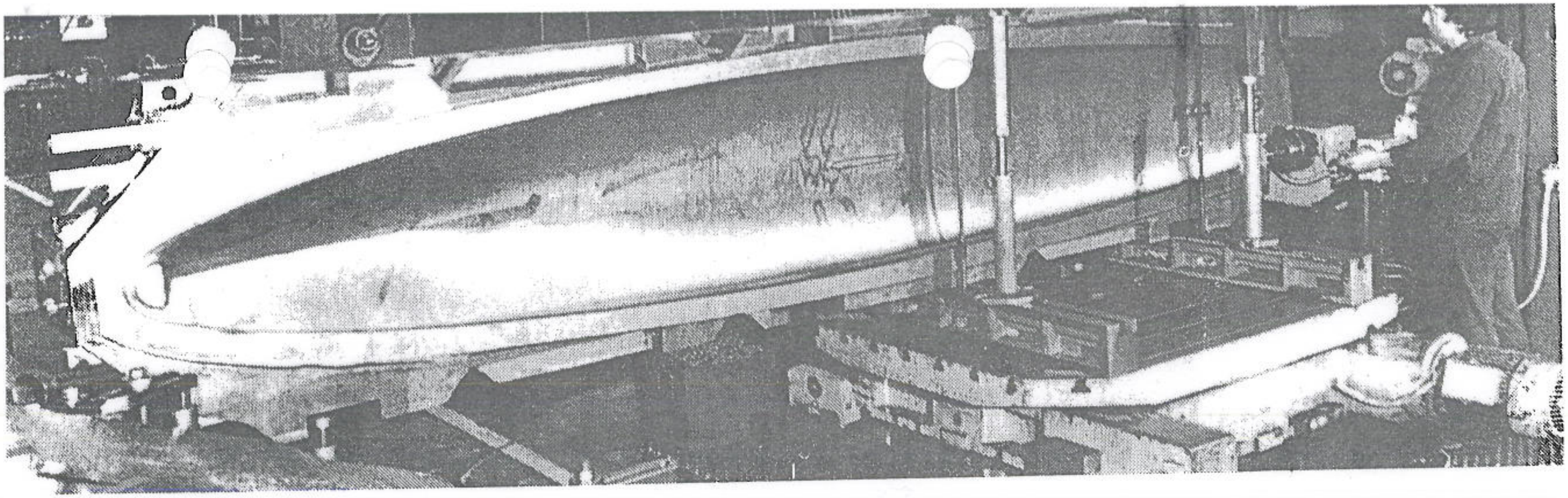


Fig. 5.178

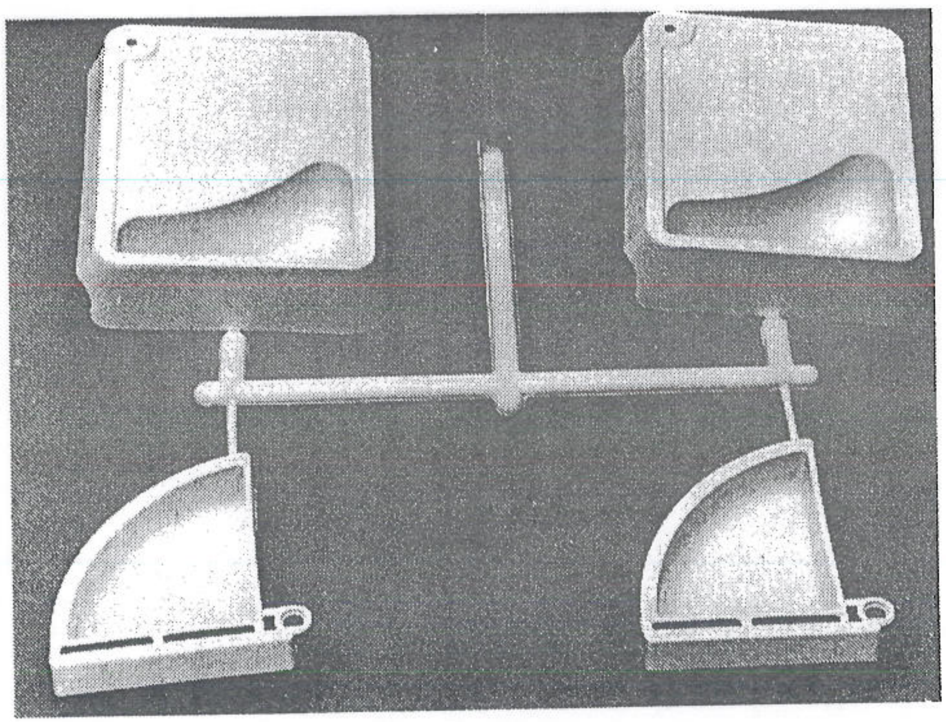
Figure 5.177 · Sequential co-injection of video cassette case (pigmented
in three-plate mold) [SUMITOMO]

Figure 5.178 · Piping T-mold (three retractable cores)





:e 5.175 • Machining of cavity block for injection molded sailboard hull [SMTP]



... detergent holding set)

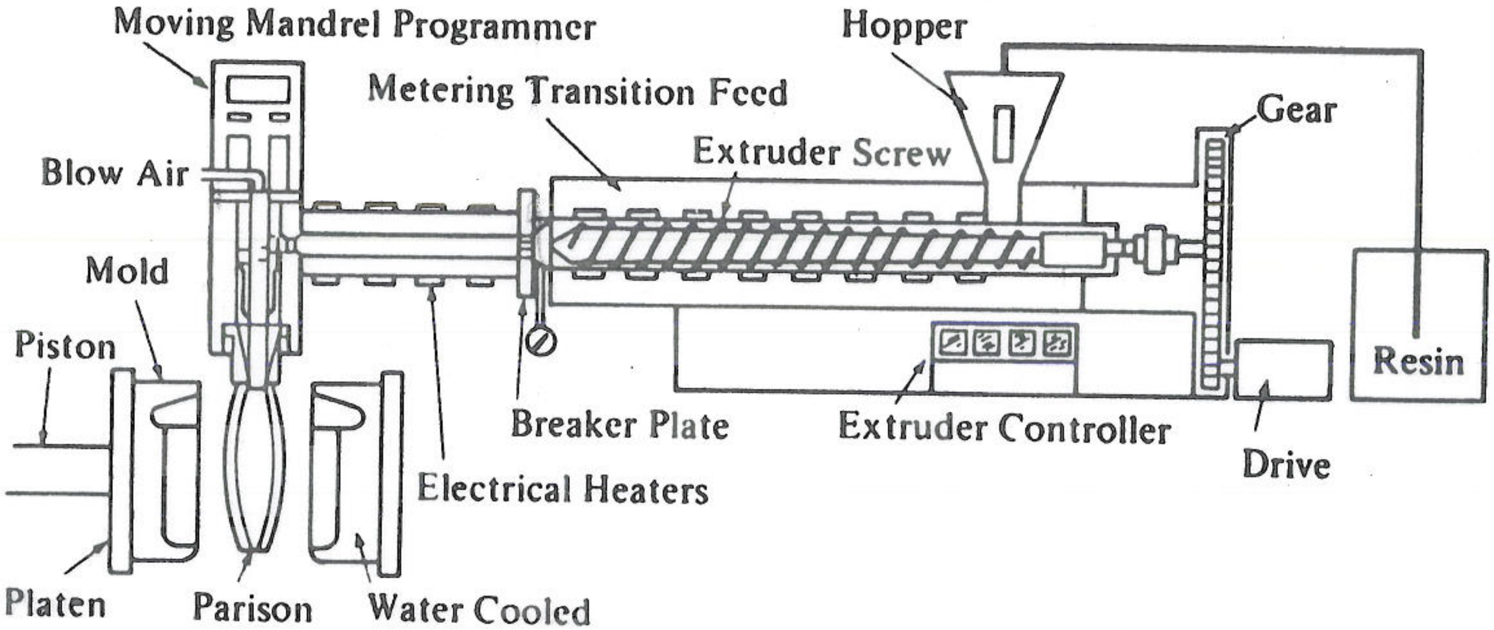


Figure 19.6 Extrusion blow molding. From *Modern Plastics Encyclopedia*, McGraw-Hill, New York, 1969–1970 ed.

Many blow-molding extruders are equipped with *parison programmers*, which vary the orifice diameter as the parison is being extruded, minimizing variations in wall thickness in the blown product. The parisons may be "ovalized" to reduce variations in wall thickness in objects of noncircular cross section.

Extrusion blow molding has passed well beyond the bottle-production stage. It is now being used to produce large items such as drums (to replace the familiar light weight and great design flexibility.

In *injection blow molding*, the parison is formed by injection molding rather than extrusion. A variation known as *stretch* (or *orientation*) *blow molding* is responsible for the now ubiquitous plastic soda-pop bottle. In this process, parisons (often called *preforms* in this case) are injection molded with the bottom end closed and the threads and neck molded on the open top. They are allowed to cool to room temperature. Prior to blowing, they are reheated in a radiant-

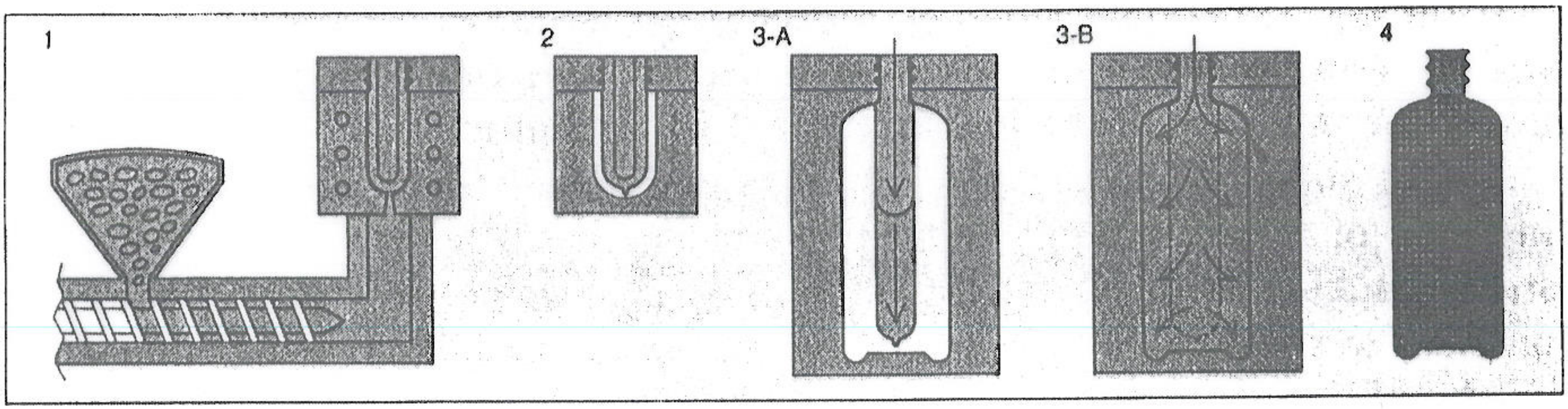


Figure 19.7 Stretch blow molding: 1, parison injection molded; 2, parison is reheated; 3-A, a rod stretches the parison, imparting axial orientation; 3-B, air expands parison against mold walls, imparting tangential orientation; 4, finished bottle ejected from mold. From *Modern Plastics* 55(10), 22 (1978).

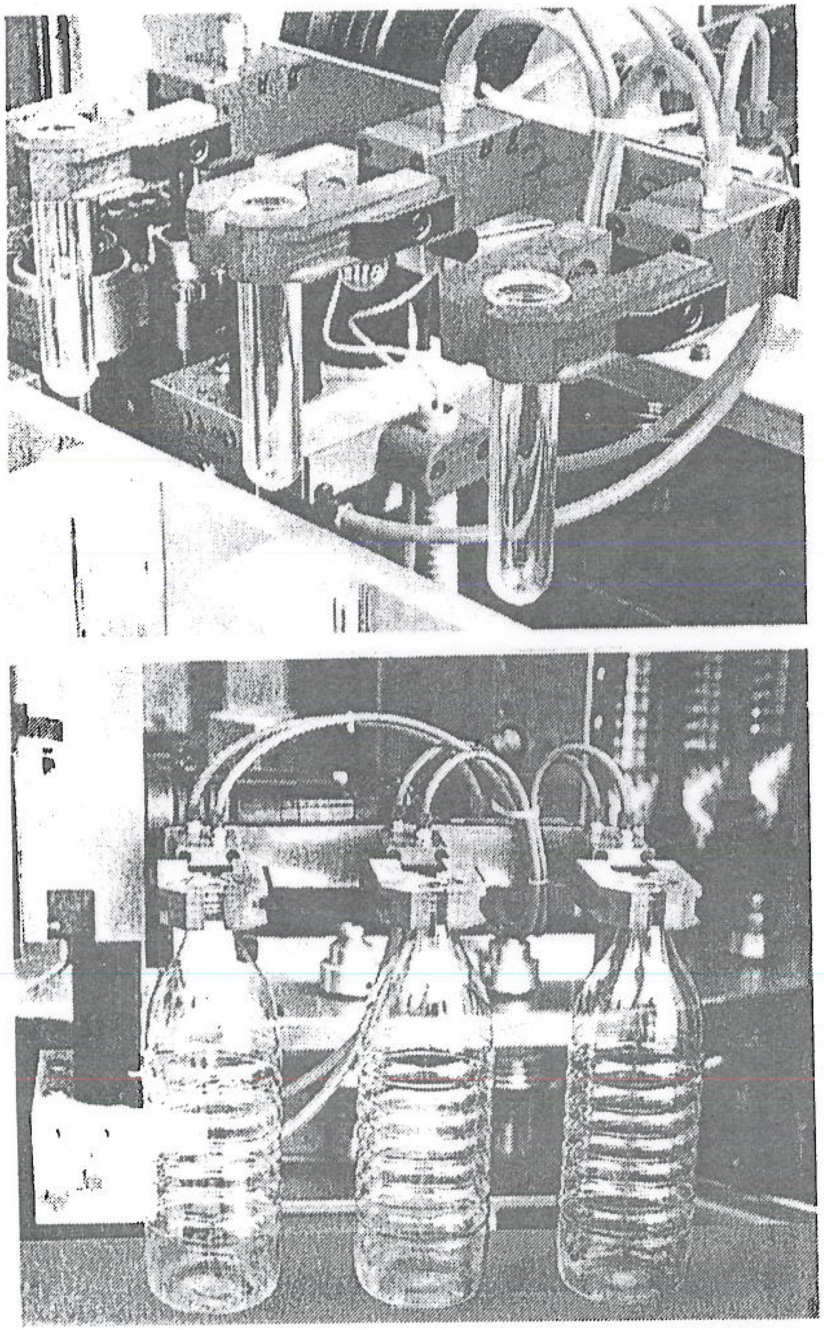


Fig. 5.105

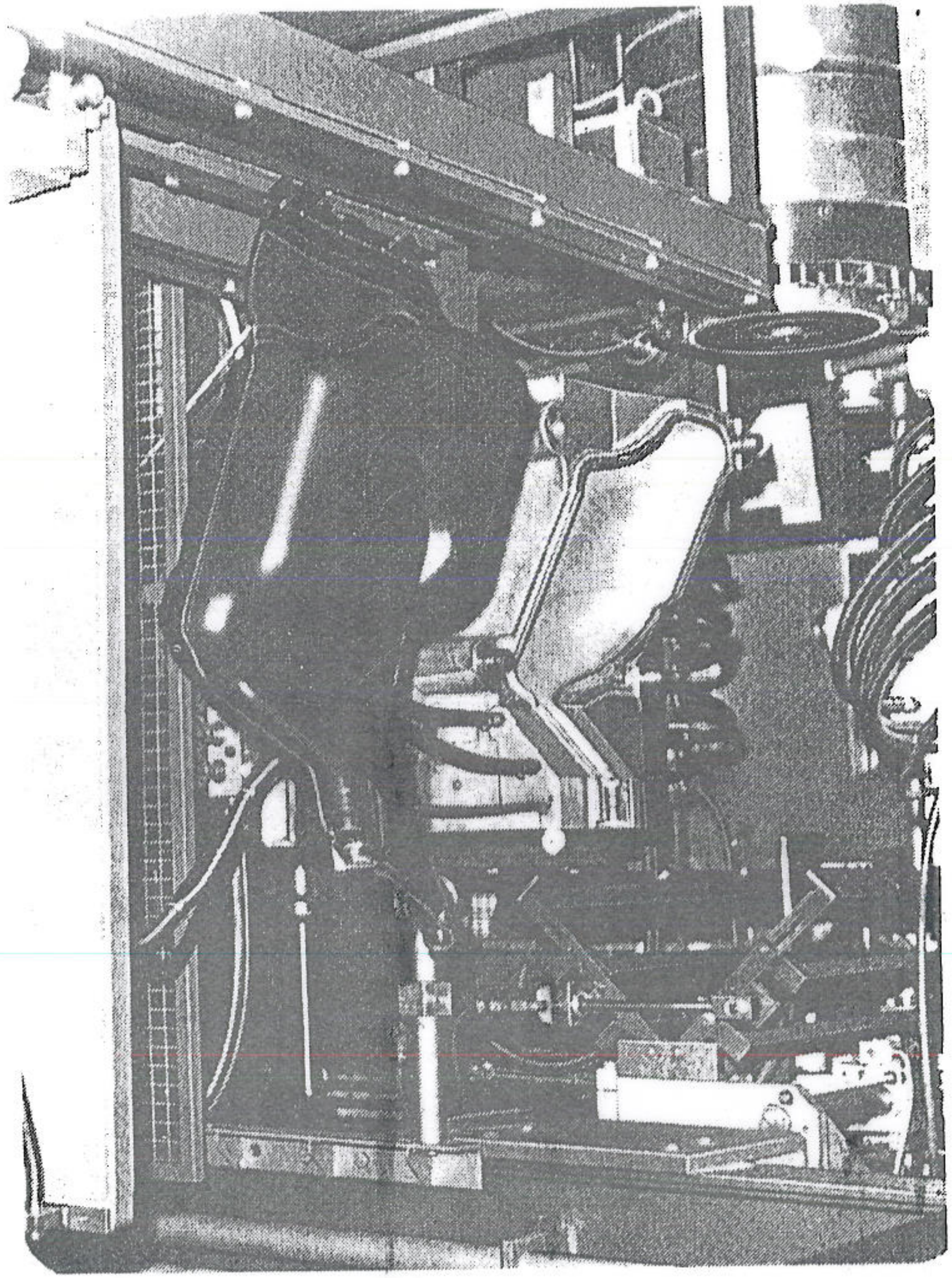


Fig. 5.106

Figure 5.105 · Injection-stretch blow molding of PET bottles (preforms and finished products) [BATTENFELD]

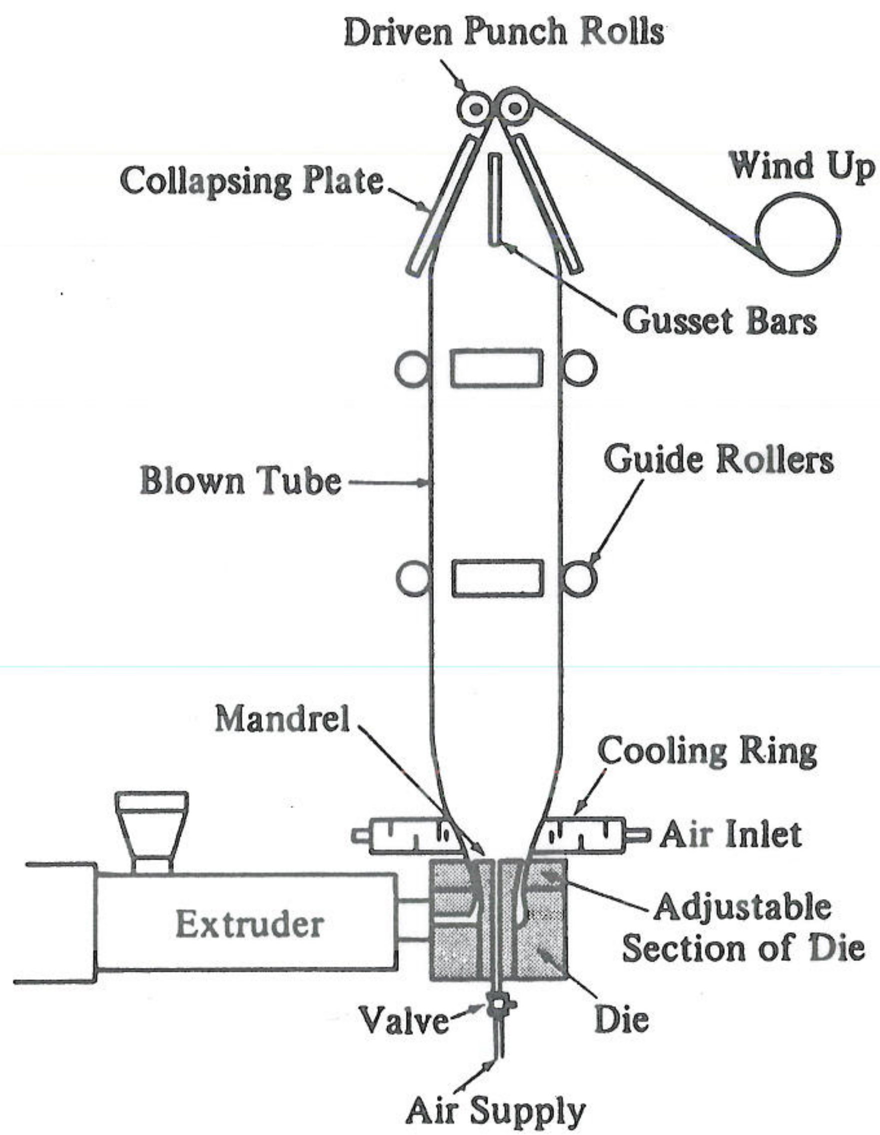


Figure 19.5 Blow extrusion film line. From *Modern Plastics Encyclopedia*, McGraw-

Fig : 5.57 · Blown film extrusion line (70 m extruder) [REIFENHAUSER-VAN DORN] ·

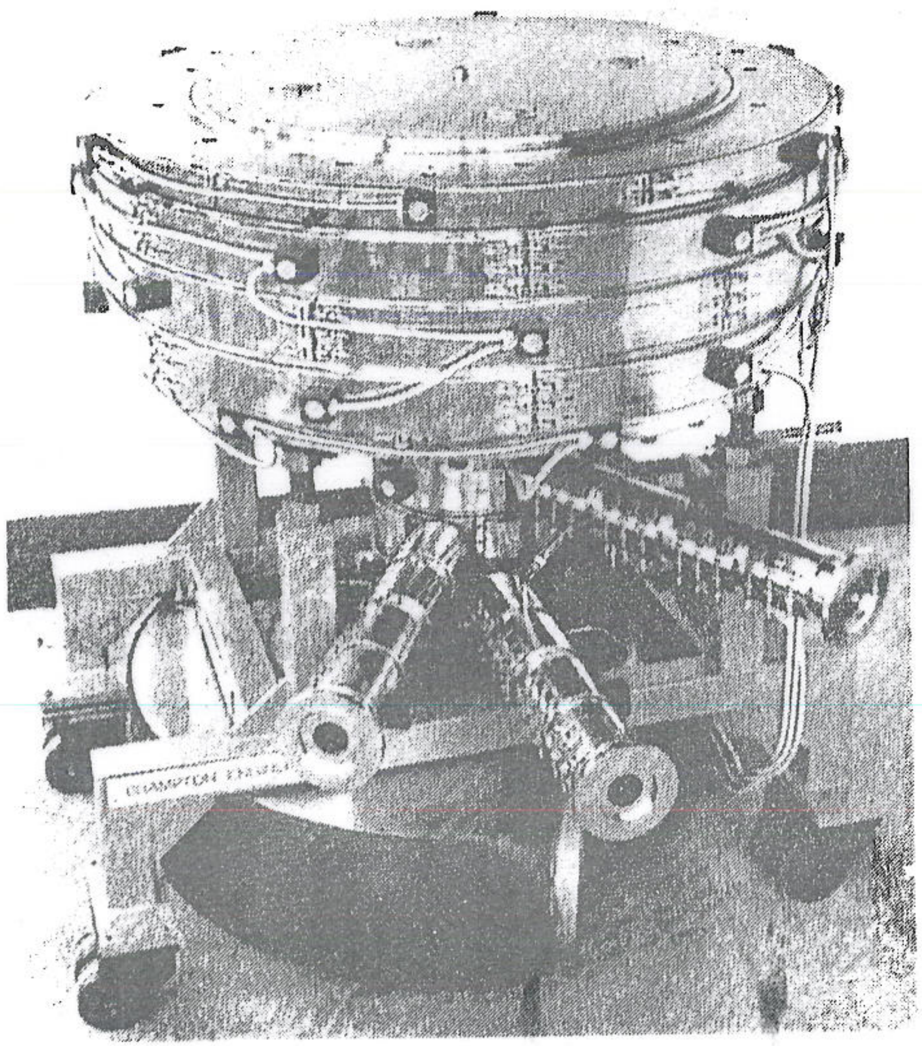


Figure 5.58 · Multilayer film blowing die (three materials, fiver layers) [BRAMPTON]

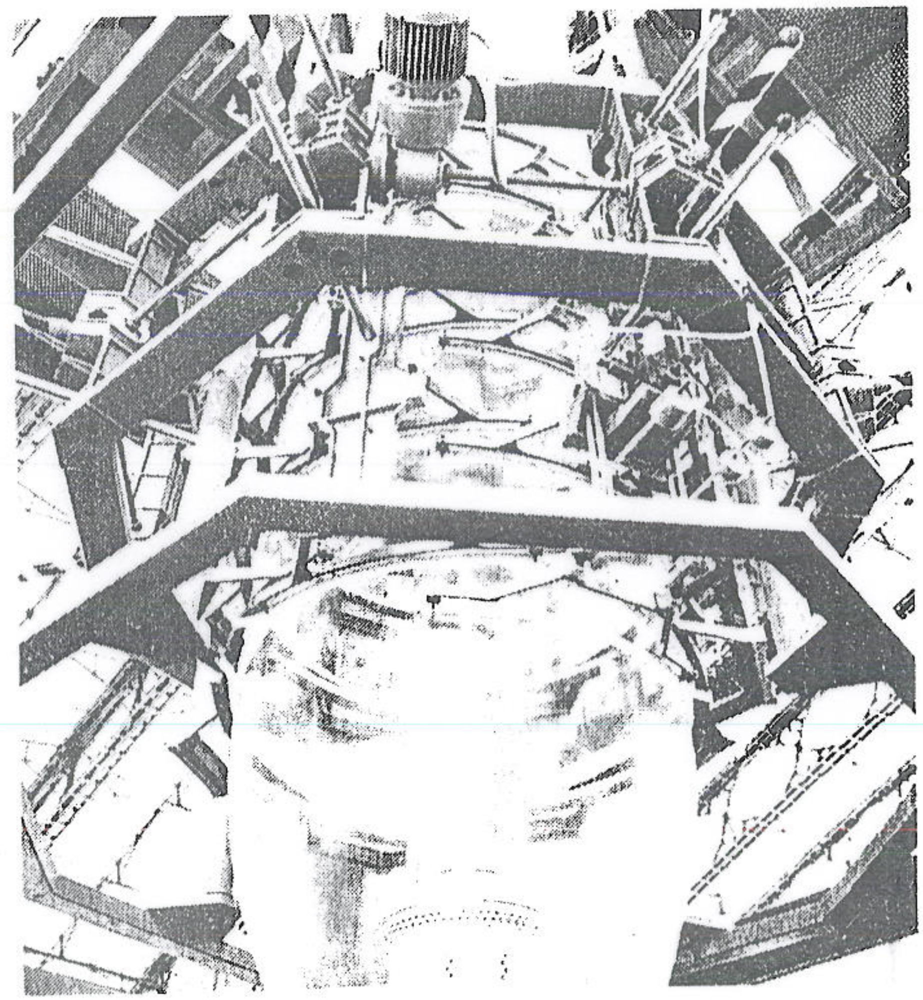


Figure 5.59 · External and internal calibration/cooling of film blowing bubble [DOLCI]

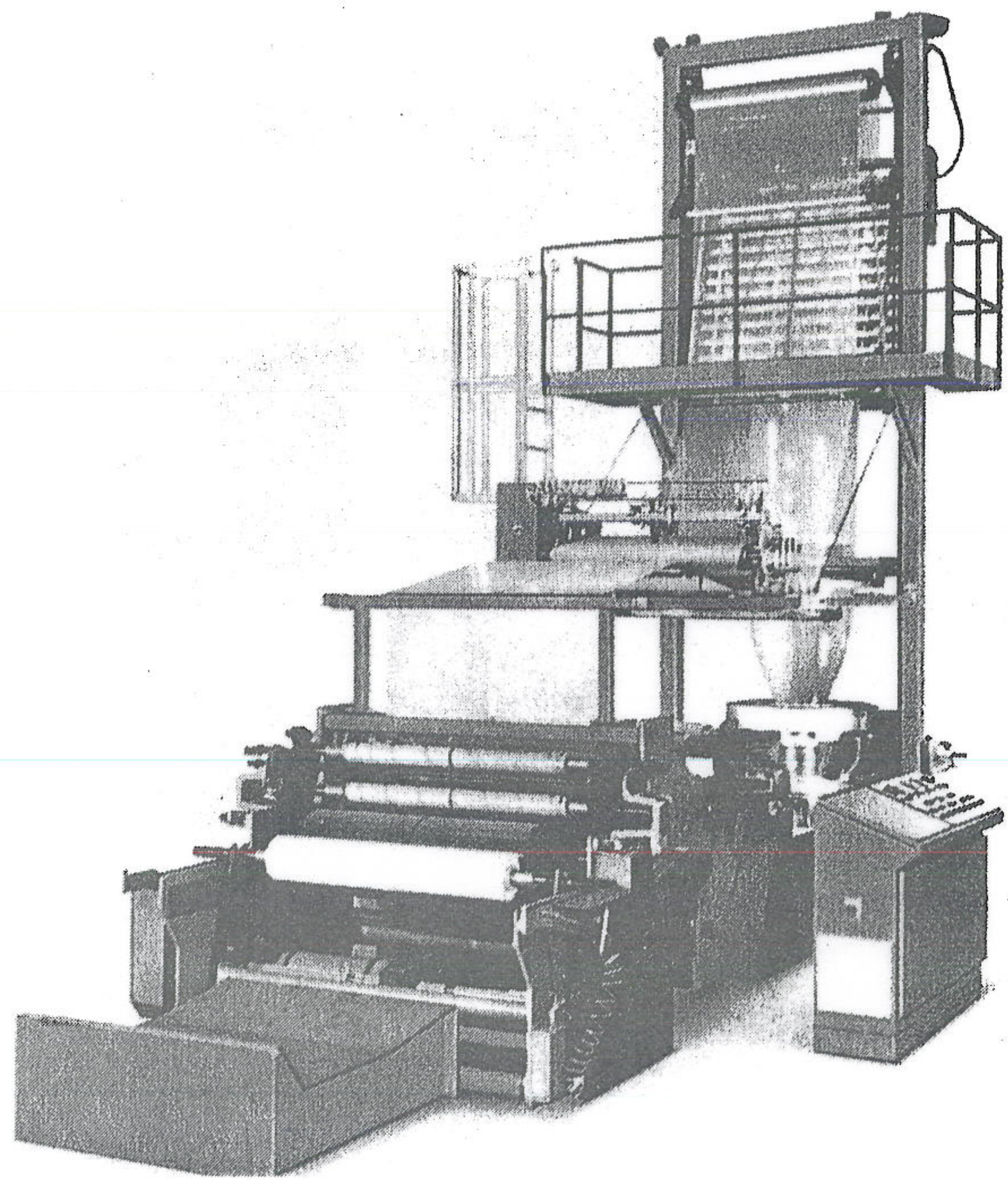


Figure 5.57 · Blown film extrusion line (70 mm extruder) [REIFENHAUSER-VAN DORN]

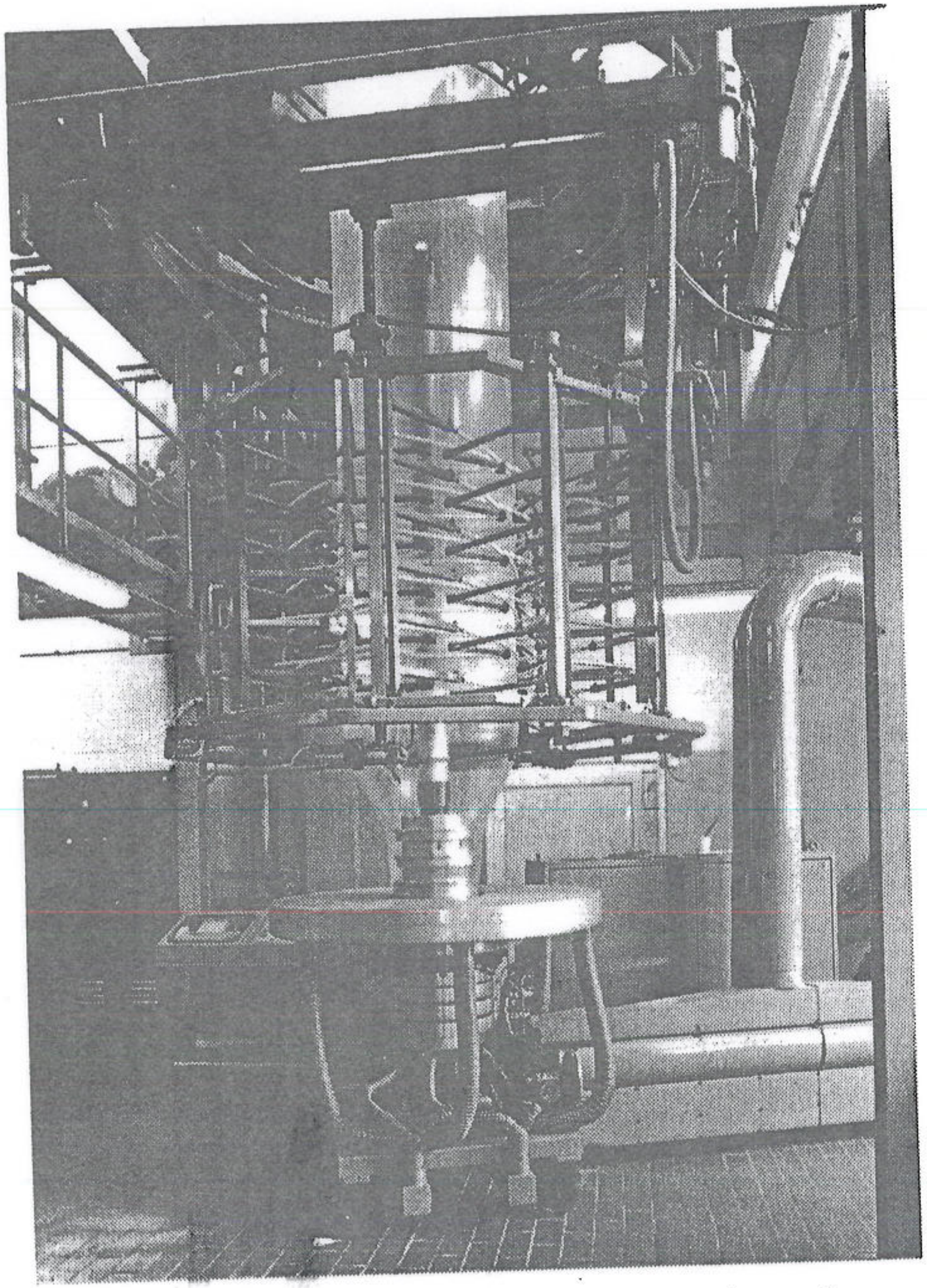


Figure 11. Blowing head with internal air exchange, calibration and external rotating IR thickness

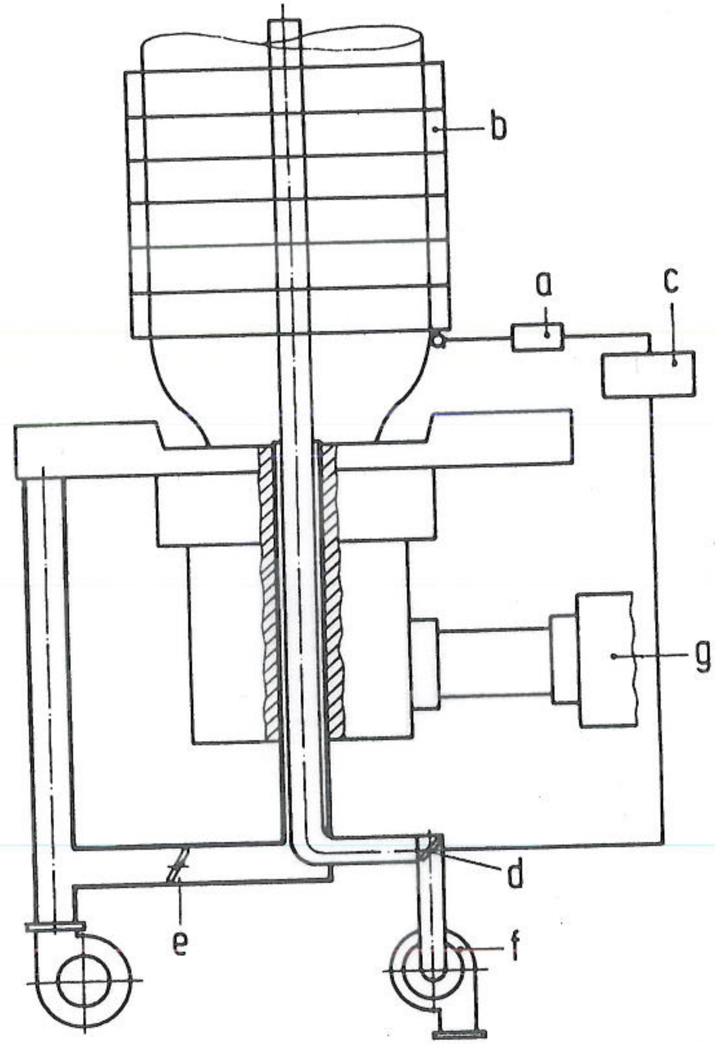


Figure 12. Schematic diagram of control system for bubble diameter and degree o basket filling

a value monitor,
b calibrating basket,
c regulator,
d throttle valve,

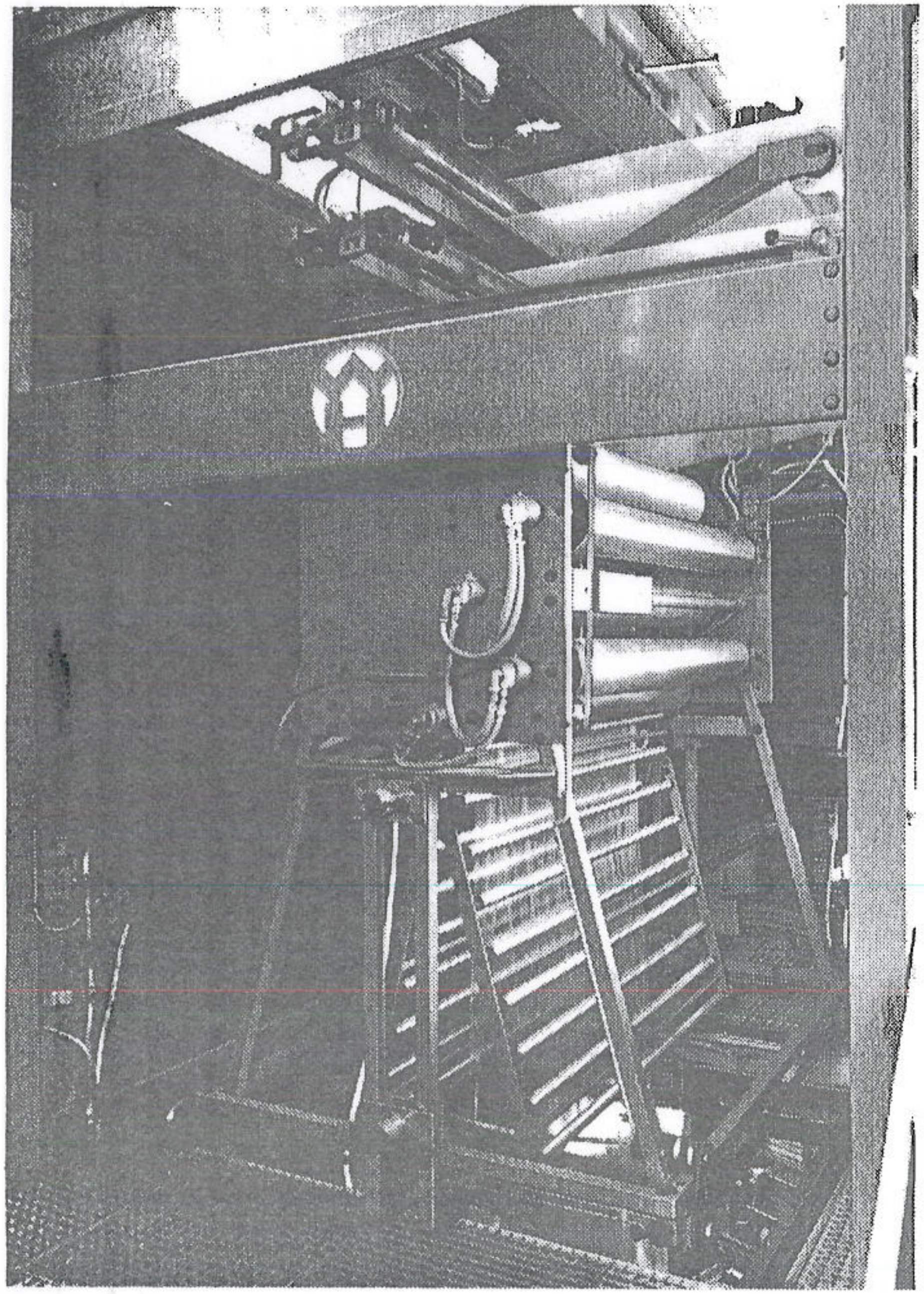


Figure 13. Haul-off unit consisting of collapsing rolls, cooling rolls, haul-off rolls and reversing turning bar system. (Photo: Windmöller und Hölscher, Lengerich, West Germany)

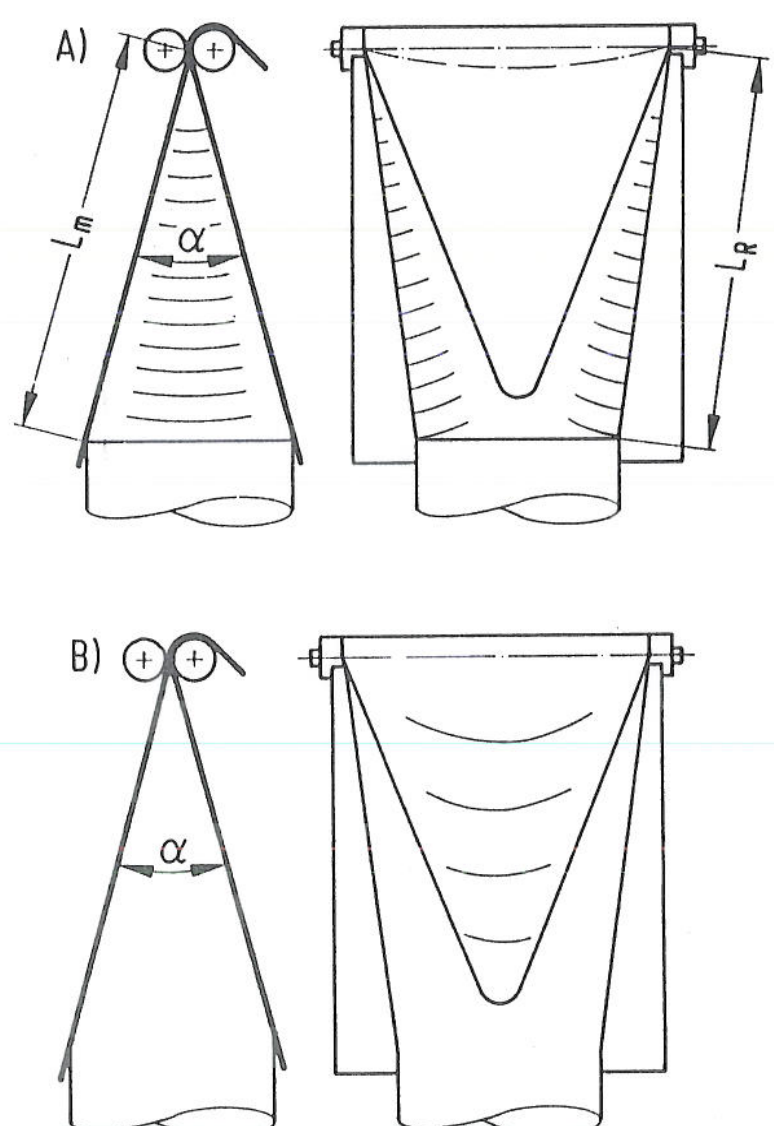


Figure 14. Creasing during bubble collapse because of:
A) length difference, B) frictional resistance

tion rates (up to 100 yards/min). The polymer may be laminated to a layer of fabric between two rolls to give a supported sheeting. The final rolls may also be

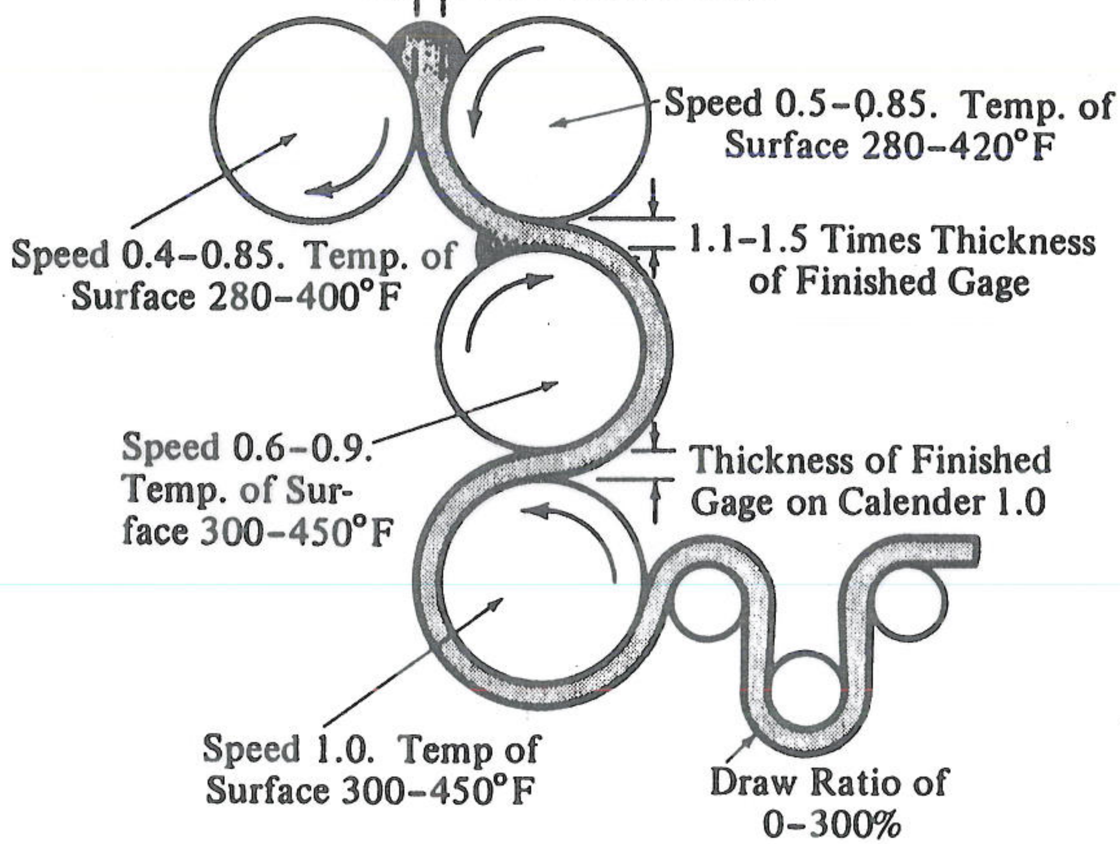


Figure 19.8 Inverted "L" calender, illustrating process variables for the production of PVC sheet. From *Modern Plastics Encyclopedia*, McGraw-Hill, New York, 1969–1970 ed.

C ating

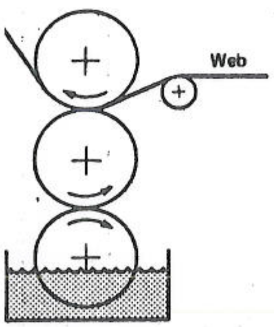


Figure 8-1 Roll coater.

b moves. In some applications the nip separation is controlled; in others the nip essure is controlled.

Similar to the roll coater is the "kiss" coater, shown in Fig. 8-2, in which the b is run over the roll without any backup roll on the other side. The amount of ap around the roll, the tension in the web, and fluid properties control the nount of coating applied to the web. This type of system often has a metering or noothing device downstream to provide more control over the coating thickness.

Figure 8-3 shows the reverse-roll configuration in which the metering roll, the ll that makes the final delivery of fluid to the web, moves in the opposite rection to the web motion. The geometry of roll coating is very similar to that of lendering, and we shall see similarities in the analyses of the two systems.

Figure 8-4 shows blade coating, which can follow a kiss-coating application which can directly meter fluid to the moving web from a "pond" of the coating uid. The blade is usually flexible and acts as a spring. Pressure developed in the ow under the blade determines the precise position of the blade relative to the ackup roll and so determines the coating thickness.

Withdrawal coating is shown in Fig. 8-5. Such a system is normally used hen it is undesirable to contact the coating with another surface such as a blade roll. The coating thickness is largely controlled by the dynamics of the region here the web leaves the pond surface.

Sometimes a coating is applied directly to the web from an extruder, as in g. 8-6. Rolls may be used, in which case this is simply a modified form of roll

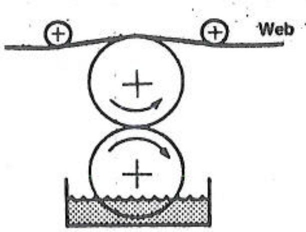


Figure 8-2 Kiss coater.

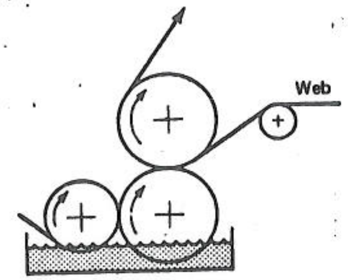


Figure 8-3 Reverse-roll coater.

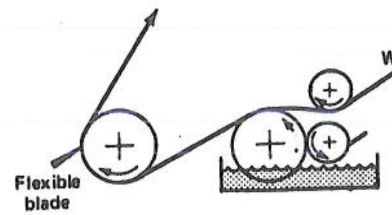


Figure 8-4 Blade coater.

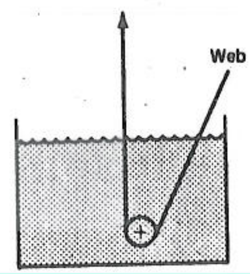


Figure 8-5 Withdrawal coater.

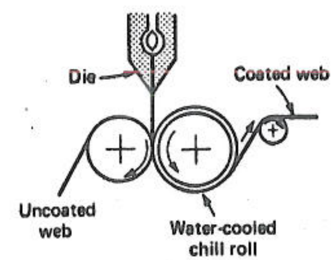


Figure 8-6 Extrusion coater.

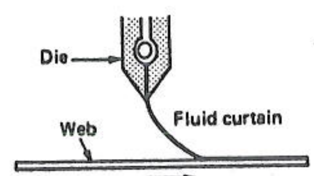


Figure 8-7 Curtain coater.

Fiber Spi[illegible]ing

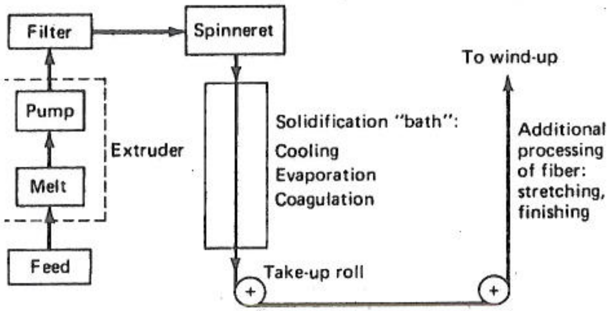


Figure 9-1 Schematic of elements of a fiber-spinning system.

simply by removal of solvent. Often a coagulation step is required which involves contact of the extruded filament with a coagulating bath. Again a very complex mass transfer process occurs in the postextrusion region.

Determination that a fluid is potentially fiber-forming is a necessary, but not sufficient, condition for development of a spinning process. It is often the case that the rheological properties of the extrudate in the postextrusion region are such that a coherent filament cannot be drawn into the quenching or coagulating region. Usually there is an upper limit to the speed of extrusion or a lower limit to the length of the drawing region beyond which the filament "breaks." The word *break* is used loosely here: The liquid stream may be unstable and simply "break" up into a stream of droplets. A principal problem, as yet incompletely solved, is the establishment of criteria which define conditions under which a fiber may be spun.

Fiber spinning is an odd process to analyze in the sense that *if* a stable process is possible, its mechanical description is relatively simple. The principal modeling effort is devoted to the question of stability of the process. In this section we will consider some problems [illegible] stable isothermal melt spinning. In Chap. 13 the problems in which heat and mass transfer interact with the spinning process will be considered. Stability is discussed in Chap. 15.

We will define *melt spinning* as that where the extrudate is a molten polymer or other liquid which does not exchange mass with its surroundings. By contrast, *wet spinning* will be that where the extruded filament enters a liquid bath with which it exchanges material, as in a coagulation process. *Solution dry spinning* will refer to the case where solvent must be removed by evaporation to a surrounding gas phase.

9-1 ISOTHERMAL MELT SPINNING—NEWTONIAN FLUID

Figure 9-2 shows the extrudate in the postextrusion region. A typical observation is the *die swell* just after extrusion. Die swell is associated with the relaxation of (elastic) normal stresses developed within the fluid by its deformation history

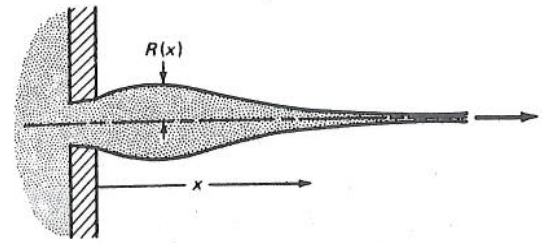


Figure 9-2 Filament in the postextrusion region.

prior to extrusion. The dependence of die swell on rheological properties and on the die inlet geometry is quite complex, and no precise methods exist for accurate a priori prediction of the degree of die swell to be expected under given conditions. This topic is discussed in more detail in Chap. 14, where some methods of estimating die swell are described.

It should suffice here for the reader to recognize that as a consequence of die swell the diameter of the filament near the spinneret is not accurately predictable. The situation is further complicated by the fact that drawing of the filament affects the degree of swelling. Experience suggests that this region of uncertainty lies within a few spinneret diameters of the exit, and that over most of the spinning length the fluid responds to postextrusion, rather than preextrusion, conditions. Analyses of fiber spinning usually take as the initial filament radius the maximum *observed* value and assume that this value is attained right at the spinneret exit.

The simplest analysis neglects any interaction between the filament and the surrounding medium. Thus it is assumed that the filament is isothermal and that no shear or normal stresses act on the filament boundary. Figure 9-3 shows the filament boundary, defined by the local radius $R(x)$ and the unit outward normal vector **n**. The velocity vector is **u**, and the total stress tensor is **T**.

At the free surface no fluid crosses the boundary, and we may express this in vector form as

$$\mathbf{u} \cdot \mathbf{n} = 0 \qquad \text{at } r = R(x) \tag{9-1}$$

The normal vector **n** has components which are easily found to be

$$n_x = -R'(1 + R'^2)^{-1/2} \tag{9-2}$$

$$n_r = (1 + R'^2)^{-1/2} \tag{9-3}$$

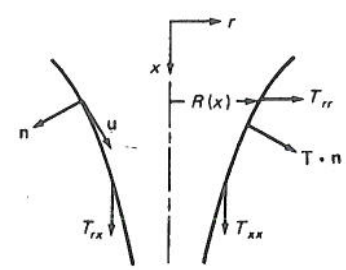
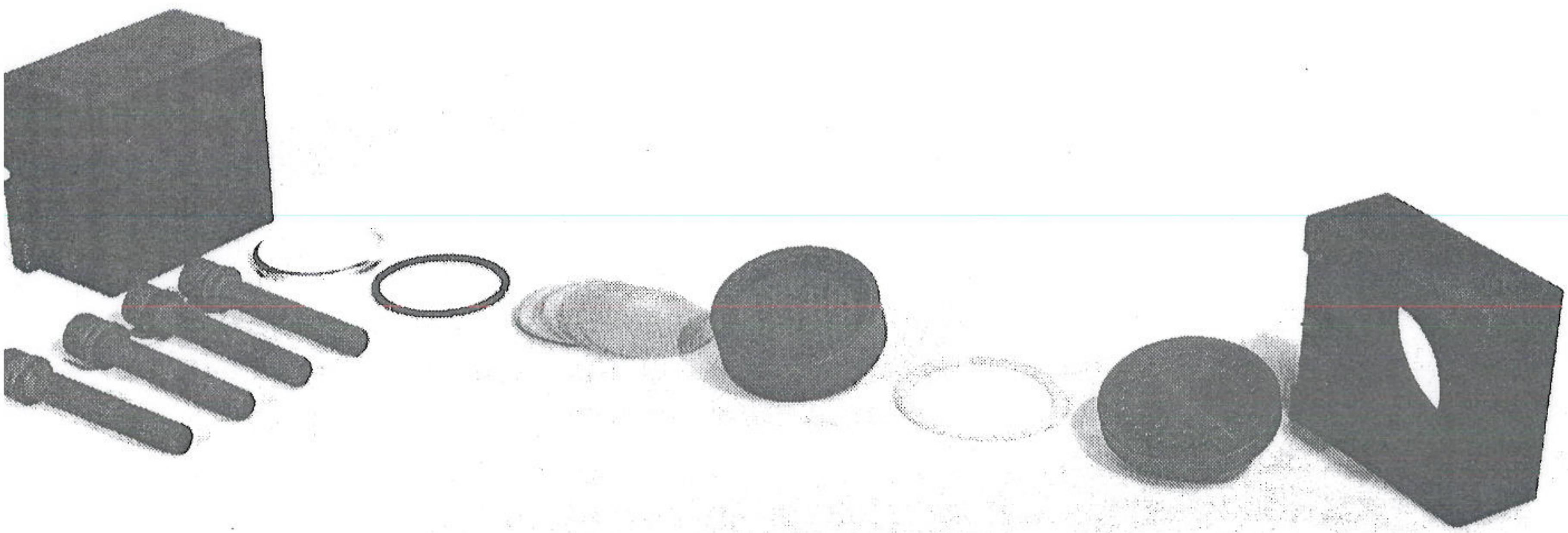


Figure 9-3 Definition sketch for analysis of melt spinning.

r spinning polypropylene, even higher L/d ratios are used, up to approximately 8.
e spinneret holes must have excellent surface quality and, at the outlet, must be flush :h the spinneret plate. If the spinneret plates have undergone frequent cleaning, wear ›ws at the spinneret holes. As a result, the individual filaments no longer emerge with the uired uniformity, and this may lead to filament breaks. Therefore spinneret plates must replaced after a certain length of time.
gure 22 shows a dismantled spin pack. The spinneret plate, the breaker plate, and above he filter, in this case wire mesh, can be seen.



gure 22. Dismantled spin pack. (Photo: Barmag, Remscheid/West Germany)

Mixing in High Viscosity Liquids

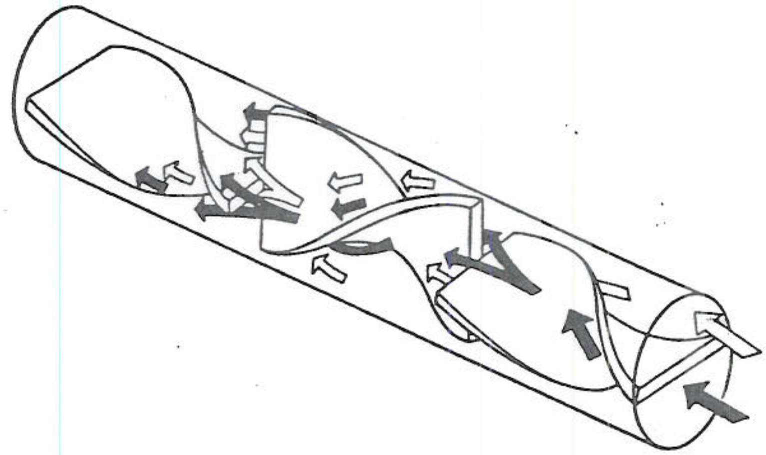


Figure 12-30 Helical elements of a Kenics Static Mixer.

In addition, stream splitting mixes material from one region with that from an adjacent region, thereby providing a degree of radial mixing.

All motionless mixers create strain and cause mixing by that mechanism. The distinguishing feature of commercial motionless mixers is the method whereby stream splitting is achieved. Figure 12-30 shows the design of one popular commercial motionless mixer: the Kenics Static Mixer. This mixer consists of a circular pipe within which are fixed a series of short helical elements of alternating left- and right-hand pitch. The elements are fixed to the pipe wall, and the trailing edge of one element is attached to, and forms a right angle with, the leading edge of the next element.

The helical design of the central element causes a transverse flow to arise in the plane normal to the pipe axis. As a consequence, fluid near the center of the pipe is rotated out toward the circular boundary, and vice versa. Radial mixing is achieved in this manner.

Figure 12-31 suggests what happens to a pair of fluids, initially segregated as they enter a Static Mixer element. To a good approximation the stream is halved each time it passes into a new mixer element. Thus one would anticipate that striation thickness would be reduced by a factor of 2^N, where N is the number of elements in series.

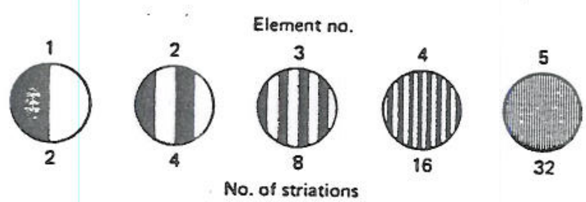


Figure 12-31 Idealization of stream splitting in a Static Mixer.

successively more complex models.

We can begin by considering the pressure drop–flow rate relationship in laminar newtonian flow. One of the simplest models would assume that the flow field is identical to that for flow through a long pipe of semicircular cross secti

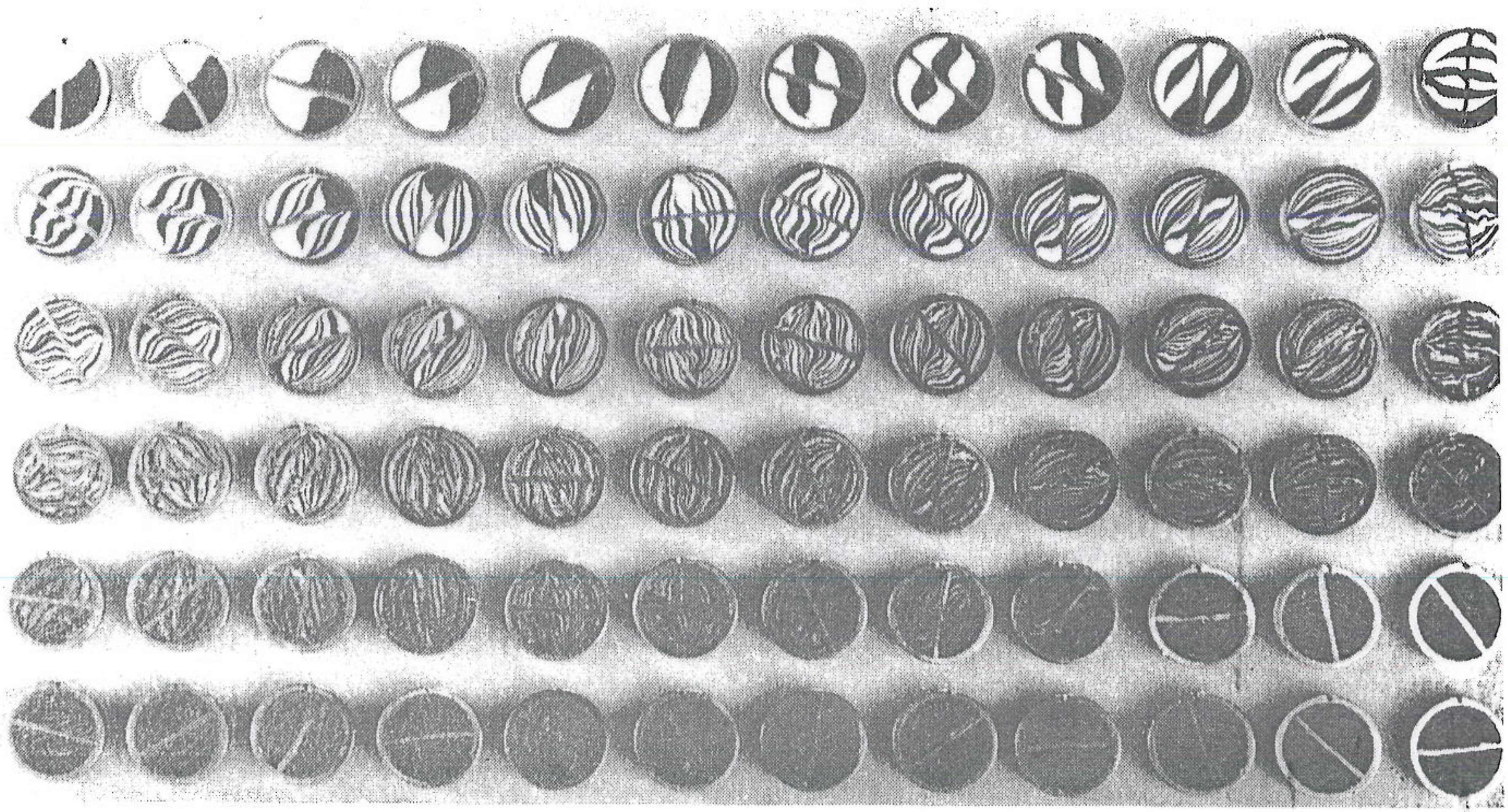
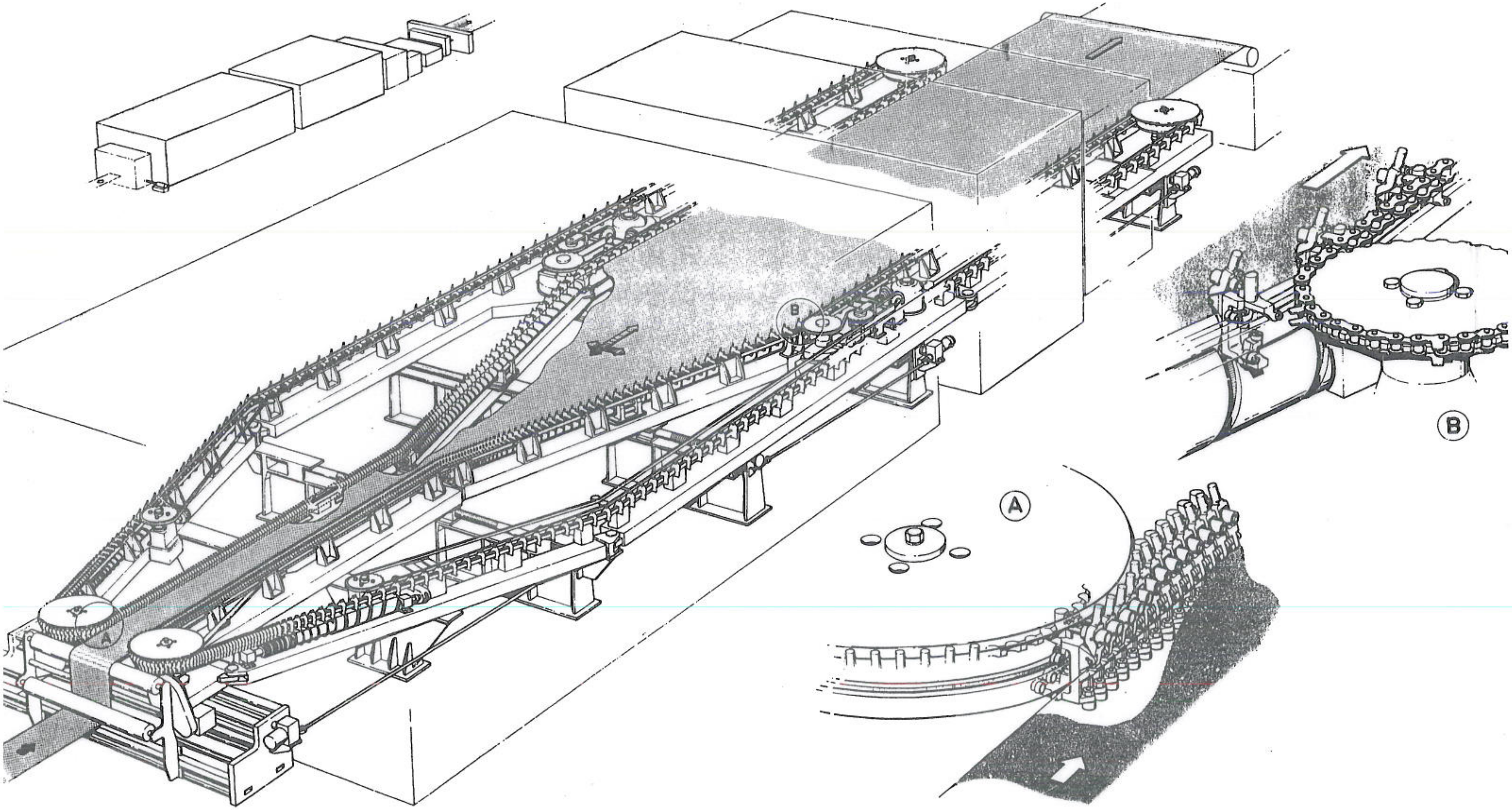


Figure 12-34 Progressive mixing in a Kenics Static Mixer. The two fluids are initially segregat Compare with Fig. 12-33. (*Photo courtesy of Kenics Corporation.*)



13. Unit for simultaneous biaxial stretching. (Photo: Kampf, Bielstein, West Germany)