

INJECTION MOLDING OF PLASTICS

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ADVANTAGES AND DISADVANTAGES

OF

HIGH INJECTION RATES

by

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What are high injection rates? There really is no hard and fast definition. With the typical reciprocating screw injection molding machines in use today, the injection rate capability varies with the machine size; particularly with the size of the injection unit shot size.

The larger shot size machines have greater injection rate capacity. This is required as larger machines have larger platen areas for larger molds with increasing projected areas and melt flow lengths. If injection rate did not increase with injection unit shot size, large parts would have to have even thicker walls to enable the cavity to be completely filled before melt freeze-off in the area near the gate. Typical injection rates specifications for standard machines of today are 8 to 16 cubic inches per second for a 150 ton machine with 6 to 12 ounce shot capacity, 25 to 45 cubic inches per second for a 500 ton machine with 48 to 76 ounce shot capacity, and on up to 70 to 90 cubic inches per second for a 1000 ton machine with a 160 to 180 ounce shot capacity. The injection rate capacity of the machine is a direct function of the hydraulic pumping capacity of the machine. Hydraulic flow rate in GPM determines the injection rate, and hydraulic pressure controls the injection pressure.

The first step normally taken to increase the injection rate capacity of the machine is to add additional hydraulic pumping capacity, either by replacing existing motors and pumps with larger ones, or by adding an additional motor and hydraulic pumps. This option is available from most machine builders and is commonly called a power pack. Typical power pack options may increase the machine's injection rate capacity by 20 to 30 per cent, depending on the size of the added pumps. For a 500 ton machine with 48 to 76 ounce shot size, this means the injection rate would go up from 25 to 45 cubic inches per second to about 35 to 60 cubic inches per second.

To be energy efficient, the machine sequence can be arranged to utilize this additional pumping capacity only as needed during the injection step. For parts with longer cycles and lower injection rate requirements, the additional motor and pumps can be turned off to save energy and reduce molded part cost.

In the past few years, the need for still higher injection rate capacity in the molding process has become more widely recognized. A review of alternate methods to accommodate this need, to find the best way to significantly increase the hydraulic flow capacity on the molding machine indicated that simply adding more pumping capacity to the machine was not the best alternative. The hydraulic accumulator is a more attractive and energy efficient method.

The accumulator is really nothing more than a device that can store up hydraulic energy, as its name implies, and then release it in a very short time. An accumulator can supply instantaneous flow rates well in excess of 1000 GPM for periods of a few seconds which makes it an ideal power source for high injection rate capacity machines. A small pump is then employed to recharge the accumulator during the balance of the machine cycle. Often this small pump is a pressure compensated pump to further reduce energy requirements.

An accumulator is constructed much like a hydraulic cylinder without any piston rods. It has a large port at the bottom end for entry and exit of the hydraulic oil, and a piston inside which is free to move up and down inside the body. The space above the piston is filled with pressurized nitrogen and acts exactly like a spring.

As one might expect, there are some compromises associated with the use of accumulators. As an accumulator discharges the gas, pressure drops off reducing the output hydraulic pressure. This can be a particular problem if the accumulator is not large enough for the application, as the injection pressure into the mold is directly proportional to the hydraulic pressure at the accumulator, less the flow pressure drop in the hydraulic system. This rate of pressure loss can be reduced by adding a remote nitrogen storage tank to the system increasing the volume of pressurized nitrogen above the accumulator piston. This feature is available on some accumulator equipped machines.

Another requirement for an accumulator machine is the need to have a suitable nitrogen supply available for initial precharging and maintenance of proper precharge pressure. If gas pressure varies, injection rates can change resulting in part variations. Good design practices for nitrogen piping systems minimize the need for maintenance, but can't totally eliminate it.

Because the application of accumulators to injection molding machines is relatively new, no standard method of machine testing has been established to adequately define actual injection rates on accumulator-equipped machines. This results in considerable difficulty for machine builders to establish meaningful injection rate specifications, and for molders in selecting a specific machine to handle a given molding task. Predicting actual injection rates on accumulator machines is at best difficult. The basic problem stems from the fact that the hydraulic discharge rate out of an accumulator is totally dependent on the actual flow pressure losses in the entire injection system. This includes the dynamic pressure losses in the hydraulic system,

through the control valves, manifolds, piping, hoses, and injection cylinder ports and throughout the melt flow system from the machine nozzle through the mold sprue, runners, gates, mold cavity to the extreme ends of the melt flow paths, and even the size and efficiency of the mold vents.

Until such standards are established and uniformly accepted and adopted, it will be necessary for molders to work closely with machine builders to properly apply accumulator machines and to take full advantage of the high injection rate capability offered by accumulator machines. Based on this lack of uniform standards of testing, only a very few machine builders have published injection rate specifications data for accumulator machines, although many are offering accumulator option packages or machines designed specifically with accumulators. Stated theoretical injection rates range from 100 to over 200 cubic inches per second. On a typical 500 ton machine, this is 2 to 4 times the injection rate of a standard machine, even with a power pack.

Very high hydraulic flow rates are common on accumulator machines. For an injection rate of 200 cubic inches per second with a maximum injection pressure rating of 20,000 PSI, a hydraulic flow rate of about 350 GPM is required. In order to minimize the pressure drop through the hydraulic system at this high flow rate, very large control valves, piping, manifold drillings, and hoses are needed. Some machine builders are using large conventional spool type directional valves, while the majority are using cartridge type valves. The cartridge valve is a simple two port valve with a very high flow capacity and low pressure losses. It also has a very fast shift time, is quite insensitive to dirt and has a positive shutoff seat with considerably less leakage compared to a spool type directional valve. Stroke limiters are also available for certain types of cartridge valves enabling them to be used as flow controlling valves to yield variable injection velocity settings below the wide open position.

Some types of cartridge valves can be used in a servo valve type mode using feedback loops for pressure control, according to valve manufacturers, and some European injection molding machine builders are now offering this capability.

Although testing is now going on, no U.S. machine builder is currently offering injection pressure control during the first or fill stage injection step on an accumulator machine using cartridge valves, in that the basic objective is to fill the mold as rapidly as possible. During the second stage of injection, hold pressure control capability is provided as on non-accumulator machines.

Some U.S. machine builders are offering machines with increased injection rate capacity by incorporating accumulator hydraulic systems on conventional machines with single stage reciprocating screw injection units. Others are going to two stage units. Some offer both. The basic two stage design is certainly not new, as it was first used decades ago on plunger machines. The two stage machines being offered today; however, are really hybrid machines and do offer some advantages compared to single stage units when used for high injection rate applications.

In a reciprocating screw machine, the screw serves two purposes; both to plasticize the melt, and to serve as the injection plunger. In a two stage machine, the plasticating and injection functions are separated. The typical injection unit arrangement locates the plasticating screw in a horizontal position directly above the injection plunger assembly. The plasticating screw may be either a stationary non-reciprocating extruder type screw or a reciprocating screw, depending upon the machine builder. Melt is transferred from the end of the plasticating cylinder down into the melt accumulator through a transfer tube or cross-over assembly. The melt accumulator, or shot cylinder, serves only to inject melt into the mold under controlled velocities and pressures. Some type of shutoff nozzle or flow direction valve is used to enable recovery of the melt accumulator.

Some of the advantages of a two stage unit over a single stage reciprocating screw injection unit for high injection rates, are as follows: On a two stage unit, the total mass of moving parts for the injection function is typically less than that on a reciprocating screw unit. This results in better shot size control, particularly with large shots. On two stage units with non-reciprocating plastication screws, the melt is homogeneous throughout the shot as the length to diameter ratio does not change during the recovery step.

Two stage units do have some disadvantages compared to reciprocating screw single stage units. Typically, the residence time of the melt in the injection unit is slightly longer with the two stage unit. There is also a slight amount of melt leakage past the shot cylinder piston. With good melt accumulator and piston design, this is not a problem. Another consideration is possible contamination in a two stage unit. With good clean melt flow path design, this is not a problem and complete purging of material during color changes can be accomplished without too much difficulty.

In general, the two stage design does offer high injection rate capability with extremely precise shot size control. During some initial testing at Beloit we molded a polypropylene refrigerator tray. The part weight was about 500 grams. The machine shot capacity was 25 pounds. Even with a shot size less than 5% of the total shot capacity of the unit, the part weight

only varied about 1/2 of 1% when ten consecutive parts were weighed. The resin used for the test was a 22 melt index general purpose polypropylene homopolymer.

When tested in the structural foam molding mode, similar results were achieved. In this test the part weight was about nine pounds, and the shot capacity of the injection unit was 25 pounds. Again, the part weight variation was less than 1/2 of 1% when ten consecutive parts were weighed. The resin used for this test was Noryl with a chemical blowing agent. This consistent part weight was achieved at about 5% below the target weight for the part as currently molded on other structural foam equipment. The parts also had excellent cell structure.

There are three primary advantages when using high injection rates: reduced part weight, shorter cycle times, and improved part quality and dimensional stability.

With increased injection rates in standard injection molding applications, the final packing pressure required to fill the cavity is typically reduced, resulting in lower residual stress levels and better dimensional stability.

The present market thrust for high injection rate accumulator machines is in the plastic container molding industry, utilizing the typical plastics packaging resins, styrenes, polyolefins, particularly high density polyethylene, for rigid thin wall parts in high volumes.

This includes food containers of all types, drinking tumblers, housewares, such as: wastebaskets, laundry baskets, trash cans, dishpans, pails, and other market areas such as medical disposables. Any part with long flow lengths that has thicker walls than are actually needed to afford required stiffness and strength for proper function, is a candidate for molding at increased injection rate. Certain resins that are highly shear sensitive and susceptible to thermal degradation are not candidates for high injection rates (ref. PVC, polycarbonate, acetal). Some machinery manufacturers are advocating part weight reductions up to 25%, with similar reductions in cycle times. The reduced part weight results from thinner walls and the cycle time savings from less shot recovery time and injection time per part and shorter cooling time due to thinner walls. These savings are predicated on the part and mold design being optimized to take full advantage of the increased injection rate capacity of an accumulator equipped two stage injection molding machine.

lubricants are additives which affect the speed and the quality of the molding operation. The definition of lubrication might be broken down into two categories.

INTERNAL LUBRICANTS - which break down into two categories: 1. which break down into two categories: 2. which break down into two categories.

LUBRICATION FOR PVC INJECTION MOLDING

by

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LUBRICATION FOR PVC INJECTION MOLDING

Lubricants are additives, which effect the speed and the quality of the molding operation. For definition, lubrication might be broken down into two categories.

1. INTERNAL LUBRICANTS - which break down intermolecular tractions and allow one molecule to flow over another, thereby promoting polymer melt flow.
2. EXTERNAL LUBRICANTS - which form monomolecular films between the polymer melt and the metal processing equipment. This monomolecular films allows for release from metal surfaces.

Lubricants can effect the processing of the polymer or the physical properties of the finished product, either negatively or positively.

Internal lubricants promote flow and increase the molding speed while minimizing the effect of shear burning, as they allow one molecule to flow over another. They reduce mechanical rebound in the polymer as it cools. Therefore, sink is minimized in finished molded articles. Since internal lubricants do not form strong filamentous coatings of the products, they do not adversely effect weld line knit or paintability of the finished product. One must, however, caution that overuse of these materials will cause a decrease in heat distortion temperature and, in some cases, a decrease in izod impact.

External lubricants, on the other hand, promote the release of the parts from the mold to prevent hangups. Again, overuse can have its detrimental effects. Overuse may promote splay or denomination around the spew of the injection molded part. Since it forms a filamentous coating of the part, poor weld line strengths and poor paintability or printability may result.

In more simple terms, internal lubricants are essentially plasticizers which are functional only at high temperatures, but non-functional at room temperature. External lubricants are materials, which are incompatible and come to the surface and allow for release of the part.

The next question we may ask is how does molecular structure influence functionality. If we refer to Figure 1 of the Appendix, one can see that this is a schematic diagram of the structure of various glycerol esters. One can see, that as esterification is more completely attained in a glycerol ester, as one goes from glycerol monostearate to glycerol distearate to glycerol tristearate, the polar density of the molecule is decreased, as the aliphatic nature of the molecule increases. This trend tends to make the molecule less plasticizing and more incompatible. Therefore, it becomes more externally lubricating in its properties.

On the other hand, if one is to maintain the same degree of esterification, for instance, a di-ester of glycerin, and increase the aliphatic chain length from C-14 through C-18 to C-20 or higher, the aliphatic nature of the molecule is increased, as the chain length increases. Therefore, the molecule becomes more incompatible and more externally lubricating in its functionality as chain length increases.

Now that we have defined the subject and we have some knowledge of the theoretical situation, we should develop tests in which to evaluate various candidates.

The first test which we might apply here would be the standard Brabender, Fusion and Stability Test described in Figure 2 of the Appendix.

Figure 3 of the Appendix is a diagram of a typical Brabender plasticorder torque curve. The fusion time here, that is the time between the loading peak and the maximum torque on the curve, represents the fusion delay properties which external lubricants characteristically impart to powder compound. This test lends itself to powder compounds only. One can theorize that the strength of the lubricant film, as it coats particle to particle, is proportional to that which separates particle from metal surfaces and as the resin becomes hotter and hotter and tackier and tackier, it eventually overcomes this lubricant film in order to fuse or coalesce.

As the material is subjected to shear, it begins to thermally degrade and at the end of the stability time, the polymer begins to crosslink. One should caution that crosslinking time is not the only barometer of stability; that color is also important. If the product is discolored, it is also unacceptable and, therefore, one might take samples every five minutes and display them for color evaluation.

It is important to recognize that the shear developed from the Brabender mixing bowl is far less than that attained through the nozzle of an injection molder and, therefore, it does not represent the flowability of the material, at least where lubricant evaluations are being considered. It is obvious then that we must go to another test in order to be able to evaluate the flow characteristics of the compounds as influenced by internal lubricants. See Figure 4.

The Extrusograph, which is a 3/4" Brabender extruded attachment with rheometric die is one such apparatus where pressure drop through orifice, which simulates the nozzle of the injection molder, can be evaluated. By use of the Poiseuille's equations, one can then calculate the shear rate versus melt viscosity, as the melt is extruded through a small orifice. This test gives numerical values, but is not quite as practical as other tests might be.

A spiral flow mold test using the spiral flow mold as attached to a (Fig5) small injection molding machine, is probably the most practical methods available to evaluate melt viscosity and flow. When the pressure in the ram and the time for the screw to be allowed to move forward is kept constant, the length of the amount of material injected into the spiral flow mold is proportional to the melt viscosity. This is a rather accurate method of being able to predict moldability of PVC compounds.

By keeping the shot weight constant and increasing the speed in which the screw is allowed to move forward and observing the parts, the degree of shear burn and splay can be evaluated. As lubricants have a tendency to effect the physical properties of the finished article, it is also necessary for us to evaluate the heat distortion temperature and the impact property of articles made from compounds containing lubricants to determine if they have exhibited too adversely an effect on the finished article.

Now the next question we can ask ourselves is, what other types of materials can be used as lubricants.

The first of these would be the fatty acid esters, which are the most versatile of all lubricants. They range from the highly efficient internals to externals which exhibit a high degree of forgiveness. These are probably the only true internal lubricants. Other groups are the calcium stearates, fatty acid amides, paraffins and the polyethylenes.

The fatty acid esters can be subdivided into the following groups:

- Glycerol Esters
- Simple Esters
- Partial Esters of
 - Polyfunctional Alcohols
- Polyesters of Fatty Acids

The glycerol esters have the advantage of being moderately co-stabilizing and are the lowest cost of the esters. They will also contribute to good clarity. Their disadvantages as compared to the other esters are many. They can contribute to plate-out if not of the highest quality. When one evaluates the partial ester of glycerin, one must be extremely careful that the acid and glycerin content are low. Partial glycerol esters are not completely hydrolytically stable; they may adversely effect the HDT properties; and, the flow is not as good as some of the other esters which are available.

Simple esters, on the other hand, have the advantage of contributing to good flow; they resist plate-out; they are thermally and hydrolytically stable and do not effect HDT as adversely as the glycerol esters; but, they have a disadvantage in that they are not co-stabilizing.

The partial esters of polyfunctional alcohols are the best internal lubricants available. They contribute to superior flow. They have a low threshold of effect, resist plate-out, are thermally and hydrolytically stable, do not adversely effect HDT or impact significantly and are mildly co-stabilizing. See Figures 6 & 7.

The polyesters of polyfunctional alcohols and fatty acids are probably the best external lubricants available on balance of property. They have efficient metal release. They exhibit good processing latitude or forgiveness and are responsible for resistance to delamination in the finished injection molded part. They also contribute to superior clarity in clears.

The next major category would be fatty acid amides. See Figures 8 & 9. These materials have a good balance of lubricating properties. They have reduced effect on HDT & impact, but have very poor thermal stability.

If one looks at Figures 8 & 9, you can readily see that the Brabender stability time for materials containing esters versus amides, is increased by 20% or more and that one can use 25% less stabilizer and achieve the same stability results when esters are substituted for amides.

The third type of material which one can consider are calcium stearates or metal stearates. See Figures 10 & 11. They have a strong co-stabilizing effect and are necessary in many formulations for economic reasons as stabilizer extenders. They can act as processing aids by speeding fusion of compounds containing high calcium stearate, but unfortunately these materials have little or no internal lubricating properties. At high concentrations, they actually will resist flow. If one looks at the Figures 10 & 11, one can observe that compounds in which esters have been substituted for calcium stearates, even though this is not evident in the Brabender test, will produce spiral flow molds of considerably longer length in the spiral flow mold test indicating the improved flow of the ester and the resistance to flow of the high calcium stearate compound.

The fourth group here is paraffins. They have good metal release and low cost. Unfortunately, they have poor processing latitude and their over-use can readily result in splay or delamination.

The last group is the polyethylenes, which have excellent release; but, they are very concentration sensitive, which may lead to poor processing latitude and again delamination problems with the finished articles.

A typical rigid injection molding formulation for pipe fittings would be as follows: See Figure 12.

PVC Resin K (56 - 60)	100.0
TiO ₂	1.5
Impact Modifier (Dow CPE 3615) (Acryloid KM 611)	3 to 5
CaCO ₃ Filler (Superflex 200)	3 to 5
Process Aid (Acrolloid K120N)	2.5 to 1.5
Tin Stab. (Butyl.) Mat#T137	1.5*
Cardinal 101FC	
Ca Stearate	.7 to 1.0

It would be of interest for us to note here that it is our opinion that the CPE gives better flow properties and lends itself to pelletizing before production into fittings.

The KM611 speeds fusion more than the 3615 and is more adaptable to manufacture of finished articles directly from powder. Although, these general statements can be counteracted by the fact that if one uses more process aid with the CPE, one can achieve similar results. Also, if one needs to use less process aid with the KM611 and can obtain also similar results. Therefore, process aid Acrolloid K120N concentrations we would recommend, would be 2.5 to 1.5.

Next is calcium carbonate filler. We might suggest a super flex 200 or some other very finely divided coated filler. Although, we have obtained fittings which pass the PPI specifications by using up to 20 parts of this particular one.

Next would be a tin stabilizer, possibly most often butyl tin, M & T T137 or Cardinal 101FC. As for lubricant packages, we would recommend calcium stearate .7 to a maximum of 1.0. We have found that over 1.0, the calcium stearate begins to retard the flow of the compound, but the stabilizer extending effect of calcium stearate up to 1.0 is most desirable for economics. As the lubricant systems here, they must be selected with the type of compounding equipment, as well as the type of conveying equipment and the demands of the injection molding process, in mind.

Lubricant system A and B are the old standby simple ester, polyester combination. Formulation C is a lower cost system, which lends itself to beading and demands of the automatic powder weighing and conveying systems to the compounding apparatus.

Formulation D contains no calcium stearate and is a powder system, which has good dry flow, which has superior flow properties, as calcium stearate is absent, but may require more stabilizer to attain the same stability.

Formulation System E contains the complex ester and a partial ester of polyfunctional alcohols. This is probably the best economical system with the best processing latitude available.

Formulation F is an alternative which we see on the world market.

Formulation G is a liquid system, which also contains no calcium stearate, which gives you superior flow, which is automatable into pre-mixes with stabilizer and automated liquid dispensing systems into the mixing equipment.

Formulation H is also a liquid system which compares equivalently to the B & E formulations in processing properties.

Formulation I is a low cost system which lends itself to powder conveying, which consists of the paraffin and a partial ester of polyfunctional alcohols. It has less processing latitudes, but cost is a factor here. This also lends itself to automated powder conveying systems.

For clear rigid injection molding, the typical formulation would be:
See Figure 13.

PVC 56 to 58 K Value	100.0
Impact Modifier, possibly Acrolid KM641	10.0
Processing Aid, possibly Acrolid K120ND	1.5
Tin Stabilizer, Octyl Tin or Butyl Tin for GP	2.0

As for lubricant packages here, one would use a co-stabilizing ester and a polyester external for the best possible flow.

Formulation A is the old standby, which offers good co-stabilizing effect and good flow.

Formulation B would be a system tailored for FDA use and C likewise.

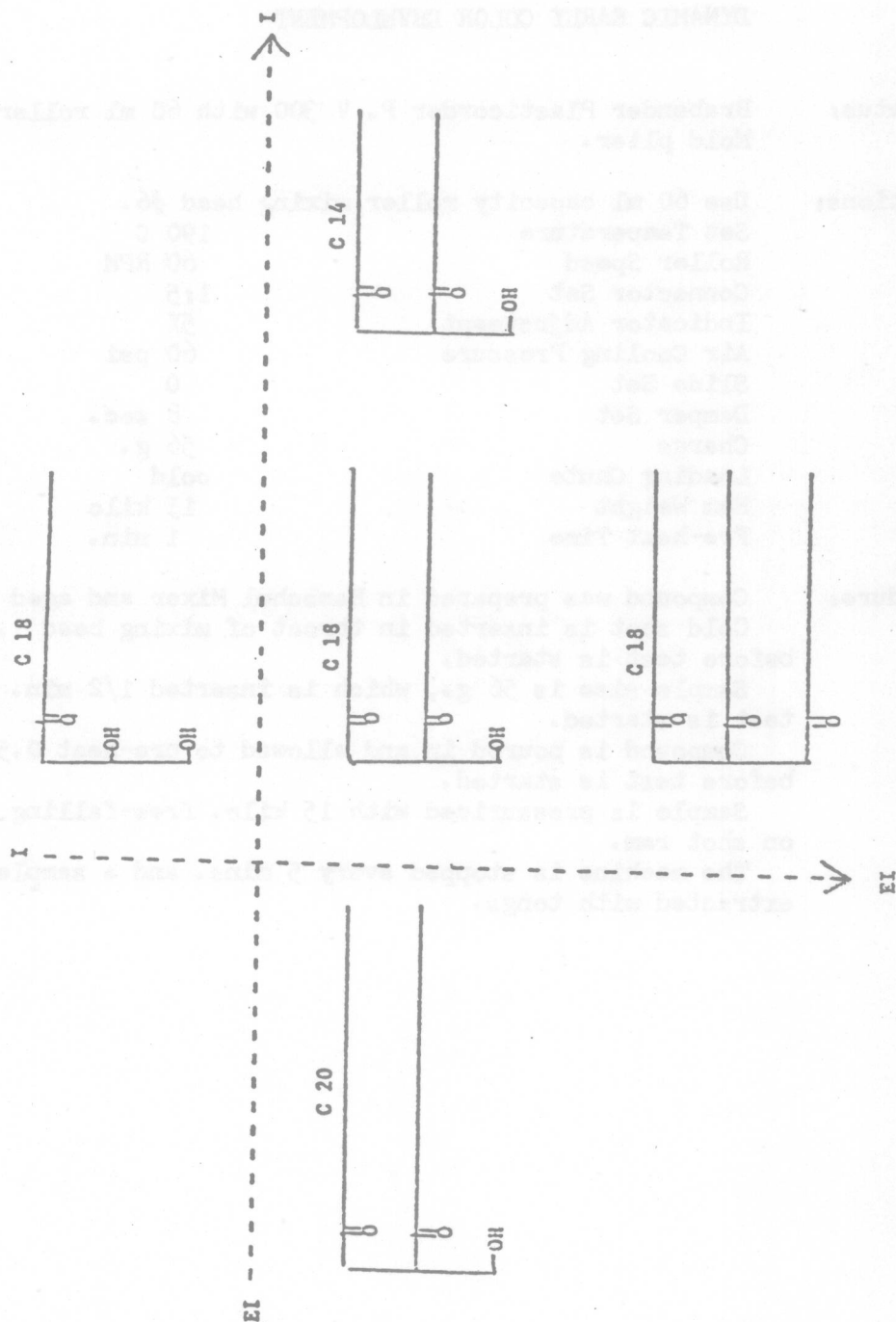
The newest developments in the injection molding field appear to center around attempting to fill PVC compounds to reduce cost. We at Henkel use some lubricant technology in order to effect the flow of these compounds to the point where they will process similarly to unfilled compounds. We have also determined that very finely divided fillers will act as energy absorbing areas and also cause an increase and impact resistance. It has been predicted by Pfizer who gave a paper on this in one of the recent ANTEC. See Figures 14 & 15.

In Figure 14, if one compares Formulation 1 & 2, you can see that the filler content was increased from 3 to 20 parts and the melt viscosity is increased, stability decreases and surprisingly enough, impact is increased, but flow decreases. If one then switches from an acrylic to a CPE which promotes flow, the melt viscosity drops, the stability and the flow returns. If one then doubles the simple esters lubricant, indeed flow is significantly increased to the point where it is an improvement over the unfilled compound, but unfortunately, impact begins to drop off and so does stability somewhat. Unfortunately, we have no explanations why the stability would drop off, but we can say that the lubricant probably coats the filler with a film as the concentrations approach the maximum for compatibility. A decrease in the bond between the filler and the polymer we assume, then results in a loss of impact.

In summary here, we want to point out the fact that we believe that any rigid PVC compound can be processed with the proper lubrication techniques which we hope that we have helped you understand today.

Figure 1

LUBRICANTS FOR PVC VS. STRUCTURE VS. FUNCTION



- A) Effect of Chain Length: As chain increases, the external function increases.
 B) Effect of Ester Function: As esterification and molecular weight increase, the external function increases.