PLASTIC OPTICS

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INTRODUCTION

We will limit this discussion to optical systems making use of plastic components instead of or in conjunction with conventional glass elements; we will not explore Fresnel optics, lenticular arrays, or multiple lens arrays, which *must* be produced in plastic. We will examine the various production techniques in current use and list and describe suitable molding materials. We will then discuss some of the advantages and disadvantages of conventional plastic optical elements and systems. Finally, we will attempt to show how their design and manufacture differ from the design and manufacture of their glass counterparts. We will conclude by presenting approximate cost figures, which you may find useful in deciding whether or not to use injection-molded plastic optics.

Bear in mind that I am speaking from the point of view of a designer and a high-volume producer of optical systems to satisfy cost-effective performance requirements.

MANUFACTURING TECHNOLOGY

Plastic optics can be fabricated by casting, molding, or machining. Molding is the preferred method for high-volume production.

Casting

Casting is used for prototypes or unusually large pieces, but it is generally unsuited for production because of the cost of the large number of molds and the environmentally controlled curing space required to achieve significant through-put while avoiding the introduction of strains and/or distortion during curing. The ophthalmic industry does cast and/or grind and polish spectacle lenses from PPG's CR-39 (allyl diglycol carbonate). Surprisingly enough, the best study of cast plastic optics is still the 1945 report, *Optical Plastic Material, Synthesis, Fabrication, and Instrument Design* (Contract Number OEM-SR-70), summarizing work undertaken at Polaroid during the Second World War.

Machining

Most plastics are quite easily single point machined with diamond tools. With the advent of precise, numerically controlled contour millers, it is approaching feasibility to single point machine optical surfaces. Polishing is another matter. Most plastics are more difficult to polish than glasses. People know how to do this; however, one can buy good-

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quality ground and polished acrylics optics. CR-39 is also ground and polished in moderate production quantities.

Molding

There are two molding processes used in high-volume production. These are compression and injection molding.

Compression Molding In compression molding, the molding plastic in either powder or sheet form is pressed between heated dies in a vertical flatbed press. Since the dies generally have to be temperature cycled during each pressing, the cycle time is relatively long, from 5 to 20 minutes. However, the dies can make multiple impressions, and often several dies can be pressed at once, so that the machine time per part can be quite acceptable. This process is routinely used for Fresnel lenses and lenticular arrays. I believe it could be adapted for thin lenses. The dies are generally made by electroforming, a well-controlled nickel-plating process. Compression molding has been developed to a fine art by the phonograph-record industry, which routinely reproduces detail much smaller than optical wavelengths in high volume.

Injection Molding The majority of optical elements in high-volume production are injection molded in conventional molding machines (Figure 1). In this process, the molding powder is liquified by heat and mechanical work in a barrel containing a rotating screw. After the material is up to temperature, it is injected at high pressure (in the order of 10,000 psi) into a temperature-controlled mold. The plastic solidifies in the mold, the mold is opened, and the piece is removed. Since the mold maintains more or less constant temperature throughout the cycle and injection takes place repidly, molding cycles can be short, as low as 30 seconds in some cases. Through the use of multicavity molds, each

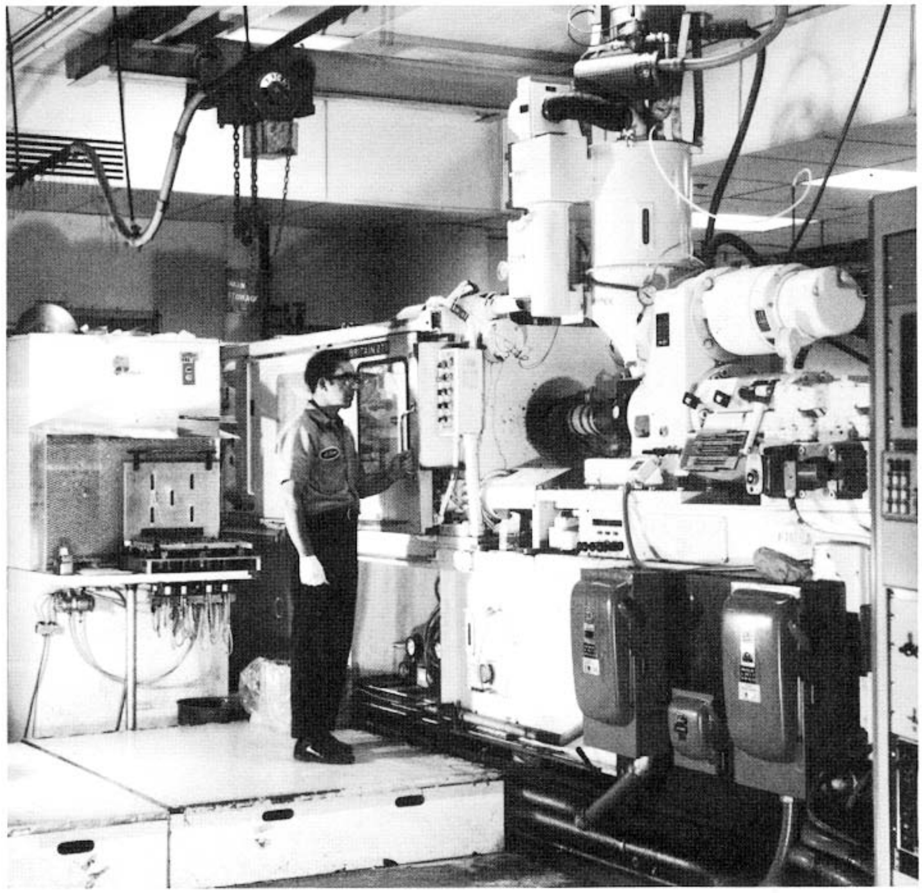

Figure 1. A 275-ton clamp, 6-ounce horizontal injection molding machine set up to produce optical elements.

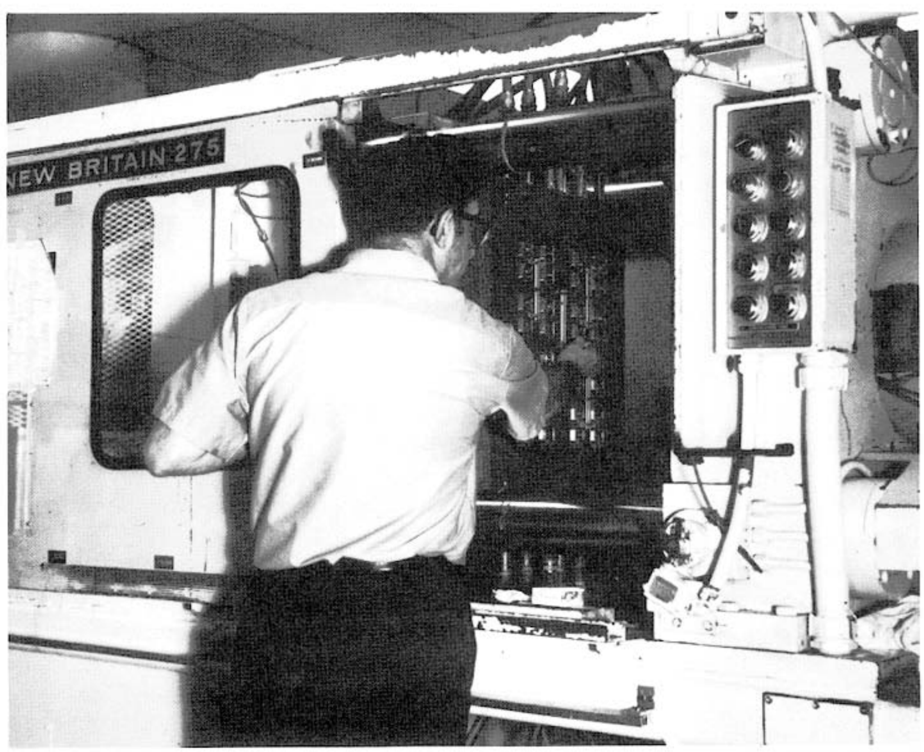

Figure 2. Machine operator removing "shot" from a 32-cavity optical component mold.

injection or "shot" can produce 32 or even 48 pieces, which are removed and handled as a unit (Figure 2).

Tooling

From here on, we will concentrate on injection molding, because in most applications it is the most efficient production technique. Aside from common mechanical inspection gages, drop indicators, etc., and the ubiquitous test plates, virtually all of the tooling for plastic optics is in the molds. Let us define terms. The mold consists of a mold base containing cooling passages, the sprue bushing to mate with the injection nozzle, and various movable plates to actuate ejector pins, etc. The actual cavity used to form the components contains two types of parts: receivers, containing nonoptical detail of the part, and polished inserts defining the optical surface. Figure 3 shows the components of a multicavity optical mold before assembly. Clearly, if the receivers and inserts are changed, the same mold base can be used to produce a variety of components.

Most manufacturers use 420F or 440C hardenable chromium stainless steels for both receivers and inserts. This choice seems to rest on a good compromise among factors of hardness, corrosion resistance, and machinability. The principal drawback of 420F is an unpredictable tendence toward carbon inclusions in some ingots. Often it is worthwhile to rough in the optical surfaces, shine them up, and inspect them for carbon inclusions before going through the trouble and expense of finishing the optical surface. The inserts are usually placed in close-fitting polishing holders and ground and polished by conventional glass-working techniques in bowl polishers. Spherical curves are finished to specific tolerances for power and irregularity.

It is important to note that, unlike other segments of the molding industry, optical components production is not practical from "soft" or temporary tooling. The soft tooling of plastics would be equivalent to generating and polishing a short run of glass optics on pitch pads by using cast iron laps and loose abrasives, as opposed to spot blocks and diamond tools. Because of this, a plastic prototype tends to be prohibitively expensive. If you need optical prototypes, it is often simpler to make them of glass with appropriate tweaking of radii. K-10 can be used for acrylics, TiF-5 or TiF-6 for SAN, NAS, polycarbonate, and styrene. TiF-6 is soft as glass goes, and is a little hard to work.

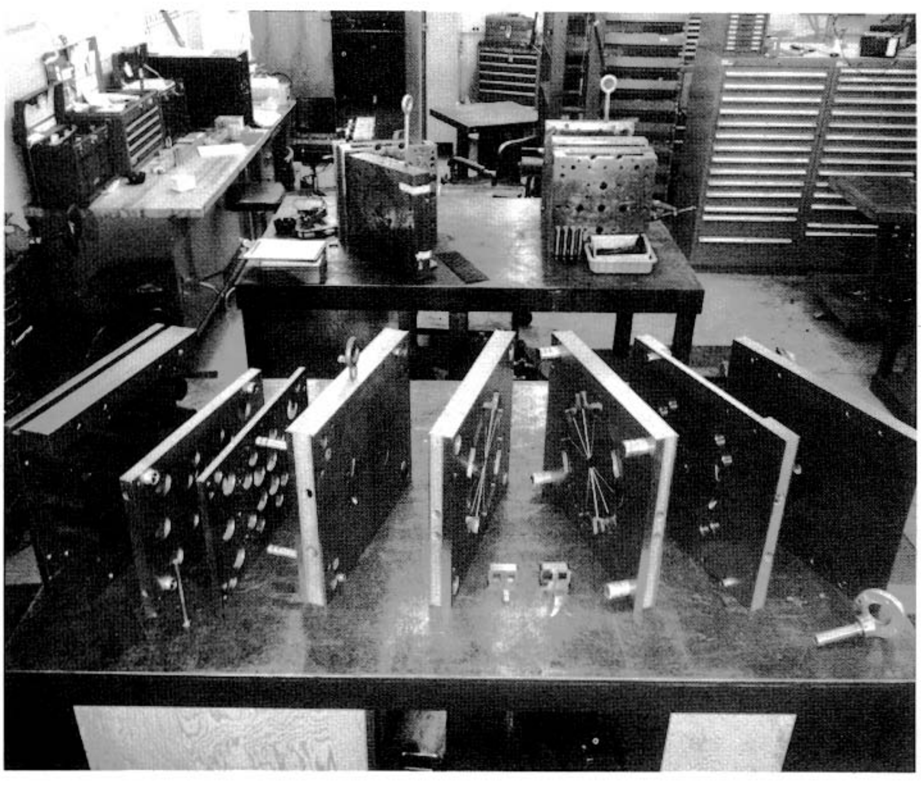

Figure 3. A disassembled 16-cavity lens mold awaiting assembly in the mold shop.

MATERIALS

The sad estate of affairs in moldable optical plastics is illustrated by the "glass map" (Figure 4), which plots index of refraction vertically and dispersion horizontally. Each black dot represents an optical glass. The circles represent potentially useful plastics. The scarcity of circles represents a severe limitation in designing high-performance systems. I have listed the more useful optical plastics in Table 1.

Methyl methacrylate (acrylic) is the workhorse of the optical plastics industry. It is readily moldable, can be polished, has good stability, and is relatively inexpensive.

If acrylic is the crown of the plastic world, styrene is the flint. Styrene has higher index, is readily moldable, is somewhat less stable, and is prone to absorb more water than acrylics.

Styrene acrylonitrile (SAN) can be used in place of styrene. It has a tendency to be yellow but molds well and is quite stable.

NAS, a copolymer of styrene and acrylic, has nearly the same optical properties as SAN but has the advantage of being clear.

Polycarbonate (Lexan) is also quite close to styrene on the glass map. When compared with styrene, it has better high-temperature stability, is stronger, is more difficult to mold, and is less stable. Unfortunately, it also can be easily scratched.

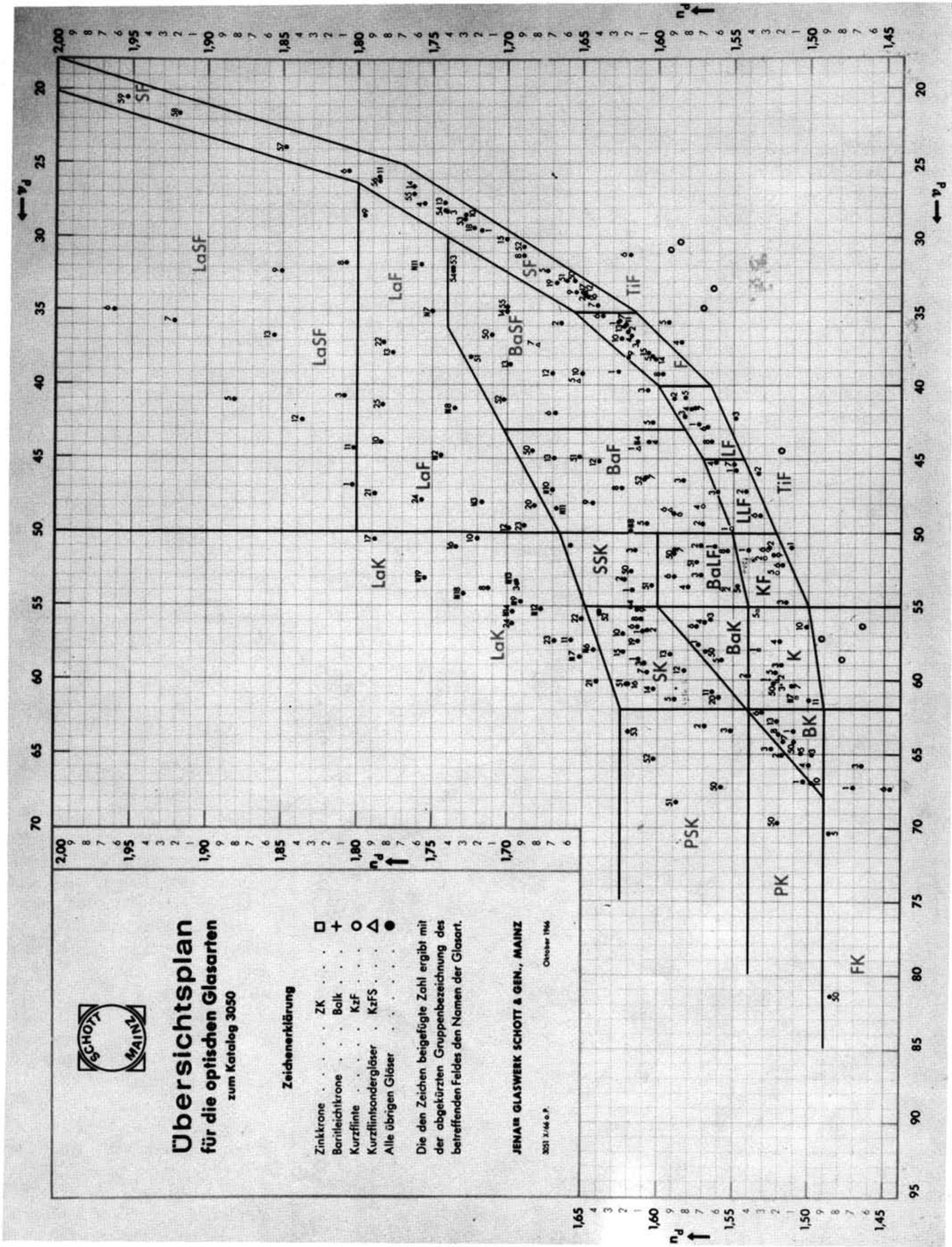

Figure 4. The standard Schott glass map with circles indicating the optical constants of the generally used moldable plastics.

TABLE 1 Optical Plastics

Chemical Name	Common Name	Trade Names	Nd[a]	ν	Cost/Lb. ($)
Methyl Methacrylate	Acrylic	Lucite Plexiglas	1.491	57.2	0.50 – 0.60
Polystyrene	Styrene	Lustrex	1.590	30.9	0.20 – 0.30
Polycarbonate	Lexan	Lexan	1.586	34.7	1.00 – 1.30
Styrene Acrylonitrile	SAN	Lustran Tyril	1.571	35.3	0.40 – 0.50
Methyl Methacrylate – Styrene Copolymer	NAS	NAS	1.562	35.	0.40 – 0.50
Methylpentene Polymer	TPX	TPX	1.466	56.4	

[a]The accuracy of the third place decimal is questionable.

TPX is closer to the acrylics in optical properties but has superior temperature resistance and is reputed to have a much higher shrinkage than the acrylics. It is not in general use.

PROS AND CONS

I will try to list the advantages and disadvantages of plastic optical components when compared with glass.

Pros

Inexpensive Individual optical elements are less expensive than the equivalent ground and polished glass units; the cost of plastic parts typically ranges from 1/20 to 1/3 the cost of glass elements.

Aspherics Since the mold components can produce hundreds of thousands of replications, one can afford to generate and figure aspheric surfaces on the inserts, thereby making aspheric components economically feasible.

Simplified Mounting and Handling It is often possible to include mounting flanges, spacers, staking tenons, etc., in the optical part, thereby simplifying the mounting and handling of the component in assembly.

Weight Plastic components usually weigh less than glass ones.

Design Flexibility Since the cost of finishing mold inserts is a small part of the cost of plastic optical components, steep curves, which would be blocked one per spindle in glass and would therefore be expensive, are no more costly than shallower curves in plastic.

Breakage Plastic components are much less fragile and likely to chip than glass. This often simplifies packaging and handling.

Cons

Expensive Tooling Plastic elements can be economical only in large volumes. Prototypes or small production runs are often relatively expensive.

Thermal Stability Plastics are less stable than most glasses. At temperatures above 93.3°C, many useful materials will deform under their own weight. The index of refraction of plastics changes more with temperature than does the index of glass.

Hardness Plastics are softer and more easily scratched than glass.

Coating While virtually all of the optical plastics can be anti-reflective coated, to do so requires more care than with glass. The chemical reaction that takes place when glass is coated hot does not happen with plastics; the coatings on plastics are therefore soft.

Material Selection There are too few optical plastics. This places severe restriction on the lens designer, especially when more-complex systems are undertaken.

Optical Data Unfortunately, the major consumers of molding powders are concerned with the mechanical rather than the optical properties of these materials. The material manufacturers, therefore, have little incentive to document the optical properties of their products. The total tonnage of molding powder used by the optics industry is insignificant compared with that consumed in other uses, so that we have little hope of changing the situation. Reliable optical data are therefore hard to come by. This in turn limits the complexity of designs that we can attempt.

QUALITY

I have purposely not mentioned the pros and cons of quality because they are worthy of separate attention. Let me summarize my feelings:

Plastic optical components can be, and often are, figured to the same tolerances as are their glass counterparts. The perfection achieved is, as in the case of glass, a question of economics and skill.

When proper attention is paid to thermal considerations, plastic optical systems can be designed and manufactured to outperform more-costly glass systems.

As with glass components, the level of system performance achieved in high-volume production is largely dependent on the tolerances adopted, the effectiveness of our process control, and elegance of our assembly operation. When we are careful, we produce really fine systems; if we are sloppy, we produce junk.

COSTS

It is, of course, impossible to be precise about costs without being very specific about a product. I will try to paint with a very broad brush my experience and that of other people in the business with whom I have discussed this matter. Please realize that there will be specific items that, for very good reasons, will fall outside the cost ranges presented below. For example, plastic aspheric correctors at $50 apiece may well be a bargain when compared with glass units at $500 each.

- Individual elements: single lenses or mirrors or individual elements of a multielement system, from 5¢ to 25¢.
- For coating either: add, per surface, from 1/2¢ to 10¢.

The costs indicated above include material, labor, overhead, general and administrative costs (G&A), and amortization of tooling. These figures assume large enough runs so that the tooling amortization is essentially for the life of the tool. This can be a large number of impressions indeed, up to a million in some cases.

I will try to illustrate some of the economic realities behind these figures. Let us start with the capital expenditures.

Molds

Mold costs include the design costs, the mold base, special machining, inserts, receivers, and assembly labor. Often the same mold base can be used for several products; one simply modifies inserts and receivers.

- Single-cavity molds to produce one piece per shot, from $2000 to $5000.
- Multicavity molds to produce from 2 to 48 pieces per shot, from $10,000 to $75,000.

Molding Machines

These are often big brutes. Injection molders are rated in terms of the number of ounces of material they inject per shot and the clamping pressure they apply to keep the mold closed during injection. Those in general use in optical manufacturing range from 30-ton, 1-ounce vertical machines to 300-ton, 8-ounce horizontal machines.

- Injection molding machines (installed, but without auxiliaries) from $15,000 to $65,000.

Auxiliaries

A number of special controls and sensors are generally fitted to the molding machine to assist the operator to achieve the precise replication of the molds that optical components require. These can be quite expensive.

- Auxiliaries, such as temperature controllers, pressure monitors, and hopper dryers, from $10,000 to $25,000 per machine.

Space and Facilities

In a conventional optical shop, the storage of materials, grinding, polishing, and edging can be performed in different locations with environmental controls suitable for each operation. In molded optics, however, the raw material is transformed into a finished product in a single location. Since plastic scratches easily, this location must have the environmental controls normally associated with an inspection room. This can be expensive.

- Cost of preparing space and facilities per square foot, from $20 to $100.

Typical Component

I will try to complete the picture by pricing out a typical component. I am thinking of a single acrylic element, with some detail in the mounting flange, a power tolerance of four or five rings, and an irregularity tolerance of two or three rings. We will price it two ways, first as an on-going high-volume production run and second as a single run of 200,000 units. These essential characteristics of these two different approaches are tabulated below.

High Volume

Continuous Production, 1 year
  16 cavity mold ($60,000)
  60 second cycle
  3 shifts (22 hours productive)
  90% yield
Production Rate
  = (16) (60) (22) (250) (0.9)
  = 4.752M/year
  = 19K/day

Short Run

200K Total Production
  4 cavity mold ($20,000)
  60 second cycle
  3 shifts (22 hours productive)
  90% yield
Production Rate
  = (4) (60) (22) (0.9)
  = 4.752K/day
  = 42 days to produce 200K units

To make the pricing a little more meaningful, I have listed some assumptions about labor rates, overhead, etc., below. These are more or less pulled out of the air, but I believe they are reasonably representative of current practice. I am fully aware that there are as many different ways to price products as there are people to make them, and I make no claim that this is the best way to do it.

Direct Labor - $4/hour
Overhead - 80% of direct labor
Depreciation:
  Equipment - 12 years
  Tooling - 4 years or length of run
Occupancy - $8/square foot/year
G&A - 15%
Profit, before taxes - 20%
Engineering and engineering overhead - $50/hour

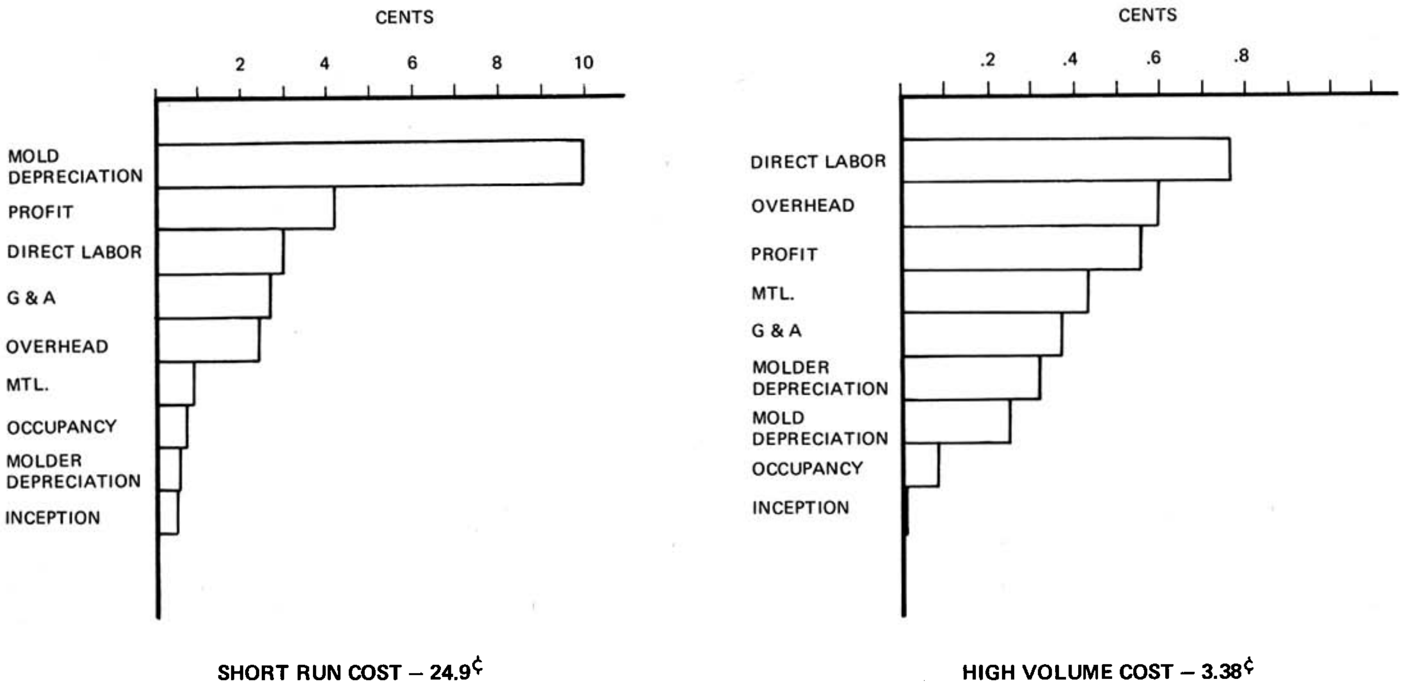

Figure 5. Comparison of the distribution of costs for short-run and high-volume production of the same elements.

Let us see how the same component prices out in the two situations.

High Volume (Yearly Rates)		Short Run (Total Cost, 42 Day Run)	
Direct labor			
4.5 people/day	36K		6.05K
Overhead	28.8K		4.84K
Depreciation			
Molder ($120K)	12K	Molder ($80K)	1.12K
Mold ($60K)	15K	Mold ($20K)	20K
Occupancy			
500 square feet	4K	350 square feet	1.4K
Material at 50¢/lb.			
2 ounces/shot	20.6K	1 ounce/shot	1.73K
Inception		20 hours @ $50/hour	1.K
	$116.4K		$36.14K
G&A @ 15%	17.5K	G&A @ 15%	5.42K
	133.9K		41.56K
Profit @ 20%	26.8K	Profit @ 20%	8.31K
	160.7K		49.87K
4.752M/Yr.	**3.38¢ / EACH**	200K	**24.9¢ / EACH**

There is almost an order-of-magnitude difference in cost. The reason, of course, is that the 200,000-piece run is forced to absorb the cost of the mold. This is more easily illustrated by Figure 5, which shows a distribution of costs in graphical form.

Before scoffing at the 25¢ price of the short tun, remember that it may well represent the equivalent of a 35¢ glass lens and 15¢ worth of metal mounting hardware and assembly labor, so that even at a quarter, it may be a bargain.

SUMMARY

I have attempted to indicate the way the majority of plastic lenses are manufactured and the pros and cons of using plastics, and to indicate in general terms what plastic components are likely to cost. I will consider my article a success if those of you who design, construct, specify, or purchase optical systems will consider the use of plastic components when it makes engineering and economic sense to do so.