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Economics in Optical Design, Analysis, and Production

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Abstract

There are indications that we are entering an era wherein economics will play an increasing role in the optical design and production process. Economics has always been a factor in the competition between commercial ventures in the product arena. Now, we may begin to see competition between different technologies for the scarce resources of the society, including money. A proper design approach begins with a thorough examination and refinement of the requirements from the top down. The interrelationships of the various components must be properly understood and balanced. The specifications must be clear, complete, and realistic. Improper or incomplete system design can cause an extensive waste of resources. The detail optical design to meet the performance requirements has sometimes been the only part of the process that the designer has considered his own responsibility. The final optimization should also consider economic related factors: the cost of tolerances, the available tools, test plates, materials, and test equipment. In the preliminary design stage, he should have decided which alignment and test methods are most appropriate to the system. The distribution of tolerances in an optical/mechanical system is a frequently neglected opportunity to reduce cost. We have reported previously on our work in this area, and expand further on it in the context of this paper. The designer now has an opportunity to generate better designs at a lower cost that are more economical to produce. The watchword for the 1980's may become the one found in the assembly automation industry: "more, better, for less".

Introduction

We believe that we have entered an era where economics are taking on a new importance that has not been seen in several decades. We expect this to have a significant influence on the field of optical design as it will in many other aspects of our lives. The period of the 1950's and 60's was characterized by a drive to achieve new capabilities which had not been previously possible or practical. We view this as similar to the period when the first airplanes were being developed. After the capabilities were achieved, the thrust changed to the economic application of the capability for the benefit of society and those who provided the capability for a price. Optical system development and production seems to be entering such a phase where competition within the field and with other fields is becoming more keen. This operation of the free market sharpens and strengthens the participants and provides the user with increased benefits for his expenditures. For example, witness the progress in the electronic and computer industries from which we lens designers benefit. We will discuss this area in more detail under the section"tools and data for the designer".

The nature of the progression of this process is to ultimately provide "more, better, for less". We discuss why we believe that the optical designer can make or break the organization for which he works and we plan to show ways in which he can help make his organization, and thereby himself, more "failsafe. We review the overall process whereby optical systems are developed and are put into production, and then the detail design processes, and tools and data which the designer uses. Ways by which these can be used more economically and creatively are examined.

Overall Process

If the detail design and analysis is not properly done with an eye to economics, no amount of skill or economy in the processes that follow can recover the loss of potential performance in the technical or economic arena. Figure 1 shows some of the key elements of the overall process to develop and produce a new optical product. The figure indicates our estimate of the approximate weight of the potential impact on product economics of each element of the process. The preliminary optical design and the detail design and analysis dominate the economics and will be the principal subject of the rest of this paper.

The overall process begins with the identification of a need which is to be satisfied and a definition of all of the requirements which must be met to satisfy that need. This is a very critical phase when it comes to actually solving the problem. It is necessary to get to the heart of the real need and requirments to be sure that the problem is well stated for the system designers or system engineers. There are few things more wasteful than solving the wrong problem; the resources are expended and the right problem is still unsolved.

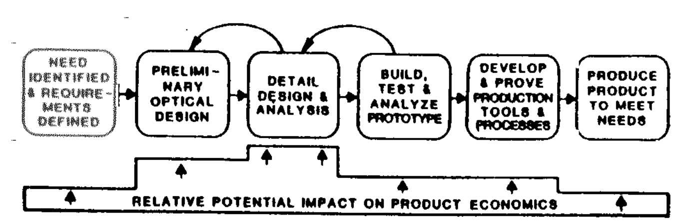

FIGURE 1. OVERALL PROCESS TO DEVELOP AND PRODUCE A NEW OPTICAL PRODUCT

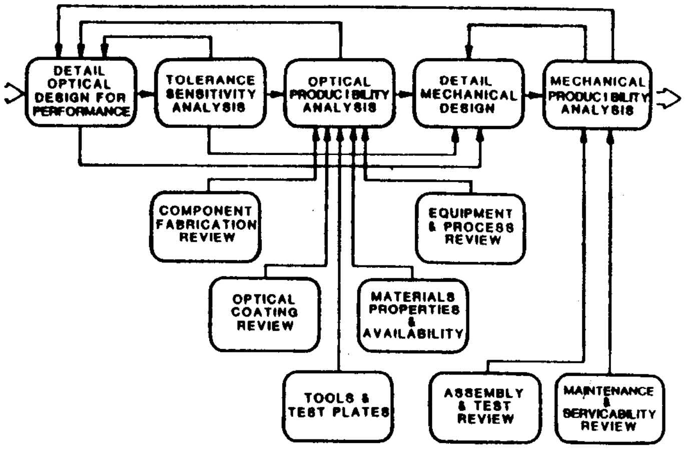

FIGURE 2. DETAIL DESIGN AND ANALYSIS PROCESS OF AN OPTICAL PRODUCT

The preliminary optical design would generally proceed with a (hopefully) creative examination of the possible ways to meet the requirements. This might be referred to as the morphological examination of the possibilities. This part of the process is where the good designer can really shine, and we don't believe he will ever be replaced by a computer program. Computers free the designer to devote more of his efforts to being creative and thorough in this area. Once he has collected all the ways that he can think of, the best candidates are selected and evaluated. The evaluation proceeds to eliminate the candidates or determine the potential value of a detail design evaluation of some of them.

It is not too early at this stage to get feedback from those who will be called upon to fabricate the optics and apply the coatings. Potential problems may be avoided and opportunities discovered at this stage. The system engineer must keep economic performance in perspective as well as technical performance. Incomplete system engineering can be the downfall of both. When this is accomplished, the process moves on to the detail design and analysis phase, but that phase may feed back into the preliminary design phase if the results are significantly better or worse than expected.

We will examine the design phase in more detail in the next section, but we will first complete our discussion of the overall process. Once the detail design is complete, a prototype system should be built, tested, and the results analysed. This usually generates feedback which leads to some revisions of the detail design work. Even with the sophistications of present design tools, many systems find refinements desirable after the first unit of a new design has been tested. We certainly know a great deal more about a new design before it is built than would have been known in the past when computations were more difficult; but we also have escalated the sophistication of many of the designs to a correspondingly higher level. Therefore, the old need for a prototype is still there, it just appears now in much more complex systems.

Once the design and prototype phases have yielded a design which is suitable for production, it is necessary to develop and prove out production tools and processes. This is also an area where there are opportunities for some creativity and economic impact, but no amount of creativity in the production phase can overcome the impact of a poor design.

When all of the foregoing phases have been accomplished, the production can proceed to fill the needs which started the overall process. Even this last phase may generate creative ideas that improve the economic production, but they cannot generally overcome problems left over from the design stages.

It is clear that each process must look ahead to the next processes and be sensitive to feedback from those areas. No part has any independent value without the others and can only be truly successful through proper interdependence and communication. When the overall process is well tuned and operating, a product will be produced which has the required performance at the most economical cost practical. This requires careful orchestration and conduction by the organization's leadership. Above all, it requires each player to understand and listen to how the other parts harmonize with his own.

Detail Design and Analysis

Some of the key elements of the detail design and analysis process are shown in Figure 2. The detail optical design to meet the performance requirements is the first step. Unfortunately, some designers have considered this the only task of the optical designer. This by itself is nothing more than an academic exercise for the student. All of the rest of the details shown in Figure 2 must be addressed before a useful product can be produced.

The sensitivity of the design parameters to each tolerance should be determined. Our previous paper[1] goes into some detail and examples of this phase of the process and the benefits to be derived from a careful treatment of tolerances versus costs. We will discuss this subject further in the next section also. The need for an optical producibility analysis is expressed or implied. If the designer does not institute it himself, it will be brought home to him by the shop which has to produce the system, either directly or by the excessive costs which result. The designer does well to review the component details with the fabricator to determine feasibility and possible compromises which could ease the process. This can reduce the cost or prevent potential failures. A similar interaction should be undertaken with the coating designer-fabricator. Once these basic factors have been moved as near to consensus as practical, the designer should examine the availability of tools, test plates, test equipment, and materials. When some or all of these items are available, the cost and time to produce can be significantly reduced. It has been common industry practice for the designer to take lists of test plates and tools available, find the nearest ones to his nominal design, and use these as fixed values in an adjustment of the design. It is usually possible to reestablish the required performance with a reasonable selection of test plates. One or two may need to be changed to the next available plate, and in a rare case a new radius must be used. The spacings and thicknesses can also be adjusted for fine tuning of the design. A similar process can be pursued when the actual melt data for the glasses become available. Sometimes the glasses may be available from a stock at hand and thus reduce delays considerably. The modern use of laser interferometers somewhat changes the test plate picture, but the same principles still apply.

At the preliminary optical design phase and the detail design phase, the use of adjustments or compensators to remove the effects of tolerance buildups needs to be analysed and selected. Effects on focal length and plane, and even image quality can usually be compensated. It may even be worth considering a relaxed tolerance on surface figure with a compensation of figuring one surface of an assembly to remove residual spherical aberration. This is most apt to be practical when all of the surfaces contributing to figure error are near the surface to be corrected. In some cases, an aspheric surface of significant deviation from a sphere can be used instead of two or more spherical elements. This can reduce light losses and weight and size, but it is generally at an additional economic cost. The opposite tack can be taken to eliminate an expensive aspheric by adding spherical optics if the number of elements is not serious from a light loss or weight point of view.

Once the results of the producibility analysis have been incorporated into the detail design and a possible reiteration of the tolerance sensitivity, the mechanical design can be detailed. A similar mechanical producibility analysis then needs to be performed. This should be subjected to an assembly and test review and a maintenance and servicability review. These may cause feedback to and modification of the mechanical design and even the optical design in some cases.

One admonition that we would like to make is that the testing schemes should be screened to insure that they are necessary and sufficient to insure that the system will meet the performance requirements. We have seen examples where tests which are unrelated to system performance tend to creep into the processes. Much expensive and unnecessarily elaborate equipment has been wasted on systems which do not need it.

Tools and Data for the Designer

We will now address the principle area of this paper, some of the tools and data which can help the designer to be more economic in his work and the impact of his work on the overall process. This could be called "the sermon on the amount". The subject leans heavily on cost: the cost of the designer, the cost of his computing, and the cost of his tolerances.

The cost of the designer can have an extensive range. His direct salary may range from $10/hour to over $30/hour, but the overhead of his organization might add as much as 300% to this directly or indirectly. This implies that there might be a ratio of almost 10:1 in cost for designer time on an hourly basis. The question of cost, as in most things, is much more easily determined than the question of value. Value can only be determined by comparison to other alternatives, and it also is somewhat like beauty, it is in the eye of the beholder. However, the most important and indirect cost or value of the designer can lie in the end effect of his design on the product over its life cycle. If he saves or loses $10 on a product which is sold in 100,000 quantities, he has saved or cost one million dollars on that design alone. Let us say for fairness sake, on the other hand, that the designer should be careful not to expend more design cost trying to save production cost than he can recoup in production. The quantity to be produced is the primary guide in this area. These are areas where foresight, business sense, and wisdom are needed. Creativity and thoroughness are appropriate characteristics of a good designer. The combination is not commonly found, but it can be developed in many cases. The cost and value of the designer's work are critical, we will now discuss ways to reduce the costs and increase the value of his work.

The cost and value of computing have changed radically over the past two or more decades. Since optical design and analysis are very computation intensive, this has had a major impact on the way we design lenses. Figure 3 shows roughly the changes in cost over two decades. A computer in the early 1960's cost on the order of one million dollars. Today we can do nearly the same work on a thousand dollar "home" computer. The cost of memory is a good measure and is shown on the graph. It has had a major trend change with the advent of semiconductor memory. This factor has caused about three orders of magnitude drop in the cost of fast memory. It may be of interest to note that the cost of most lens design software was over $100,000 two decades ago. We are surprised to find that some packages are aparently still at those levels. However, there are now serious optical design packages for less than $1000 that do most of the key functions of the older programs which cost hundreds of times more. The gamut of software that is now available is almost as great as the staggering number of options possible in hardware. The most efficient combination for any particular type of work will depend on the nature of the work and the personality of the designer. One should examine such factors as the amount of computation really necessary for solution, the cost and availability of the hardware and software, the use and cost of the designer's time, etc.

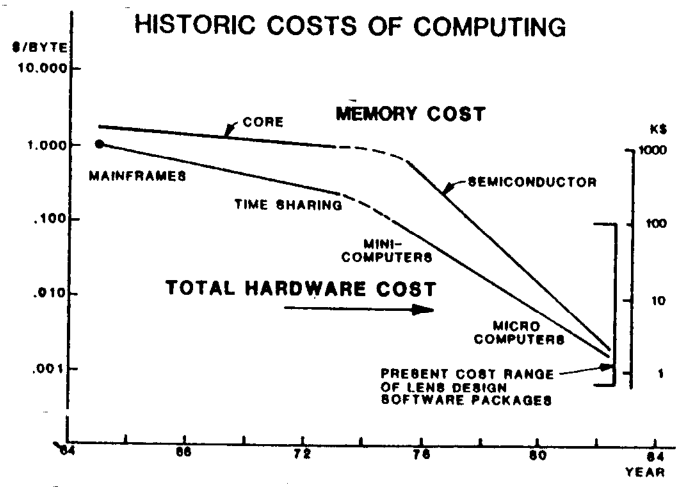

FIGURE 3. RECENT HISTORY OF FACTORS AFFECTING COSTS OF OPTICAL COMPUTATIONS

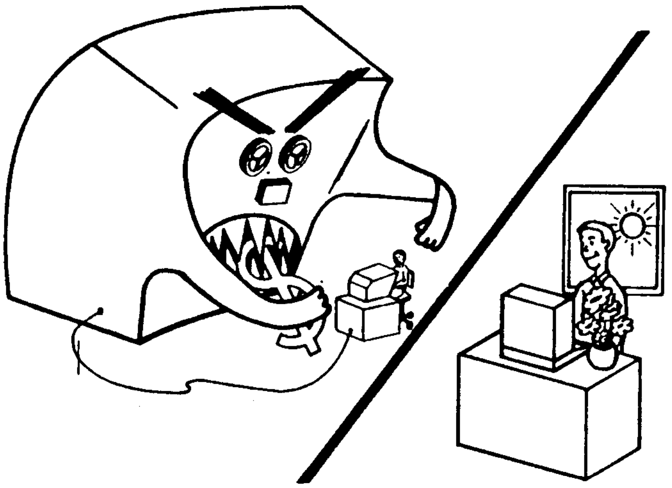

FIGURE 4. BIG NUMBER CRUNCHERS MUST BE USED JUDICIOUSLY TO AVOID STIFLING CREATIVITY THROUGH INTIMIDATION

R. E. Hopkins recently made an observation[2] with which we tend to agree. He expressed his preference for the big number crunchers (and dollar munchers) only for optimization of the last fine tuning of a design. Up to that point, the design is developed on smaller, friendlier computers of negligible cost. Figure 4 shows our view of the intimidation factor of a big, expensive system on the designer. He tends to be driven by the machine. It can drive him to the poor house if it is not carefully monitored and directed. It is easy to make very expensive mistakes which lie hidden in piles of paper and billions of computations. The small, inexpensive system, on the other hand, cannot run too far away without the designer catching it. This and other "friendly" factors remove the intimidation and free the designer to be more creative while still having more computational and analytical capability than he can usually put to use. As in many things, it is important to ask the right question in order to get a right answer. The small system is probably the best place to formulate the question, even if the final answer is best provided by more extensive computation on the large system.

The author's opinions do not necessarily represent those of Martin Marietta or any of the other designers there, but are expressed here in the hopes that they may be of benefit to the reader. The author's preferred approaches to design have evolved over the past 23 years as computers available have evolved. The first efforts were on IBM 704's which were available to the author on an unlimited basis. The objective was to develop programs which automatically optimized optical designs. Having a background in optics but no training in lens design, the advice of several respected experts in the field was sought. Dr. James G. Baker, well known in design for astronomical instrumentation, had the greatest impact on the pursuit. He recommended the recently published work of Dr. Max Herzberger[3] as the basis for a modern attack on optical design. The classical works of Conrady[4] came from an era where the mode of computation was so different and difficult, that it had a limited value for other than academic interests. Herzberger's methods of computation were developed with computational machinery in mind, although only desk calculators at the time. They are efficient and structured to minimize effects of round off errors. They are general and easily accomodate aspherics, toroidal surfaces, tilts, decentration, and vignetting apertures.

The positions taken by the author may seem to be somewhat contrary to those who were students of the old school, but they have survived the test of time and profitability for over two decades. In 1960, the position was that the lowest cost per computation would be achieved on the largest computers available due to the mass production factor of the computing itself. The measure used was the "crisp", which stood for colors x rays traced x optimizing iterations x surfaces in the system x parameters varied. In the early days, the speed of the biggest machines produced a crisp in about 50 milliseconds at a cost of about one cent per crisp. It was not uncommon to spend tens of thousands of dollars on the computer to solve a complex design problem. This implies about a million crisps. For example, one optimization iteration in three colors with 13 rays in a 10 surface system while varying six parameters would cost about $23.40 (crisp = 3x13x1x10x6). One contrary position taken is that third order aberrations are not worth the effort to use them in most systems, and higher order aberration theory is strictly academic. We believe at the present time that first order computations and rigorous ray tracing are the most efficient tools to produce practical designs. We believe that third order leaves so many unanswered questions, that it does not shorten the path to the final design which must be completed by rigorous raytracing. We further have not found the computation of diffraction effects necessary in most of our applications. Most systems are either so far from diffraction limited as to make it inconsequential, or they must be diffraction limited. In the latter case, we design to have all rays well within the airy disk. This approach has served us well in the design of many astronomical instruments[5]. What we have settled upon as the most useful merit function includes what we would call the Hamiltonian aberrations. These include: lack of stigmatism or point imagery of a point, curvature of field, and distortion. For a measure of stigmatism, we use the RMS deviation of the rays from the central ray in the aperture. We have found that the focus where this is a minimum is very close to where the human observer would tend to set the focus. The deviation of such images over the field longitudinally and laterally from the ideal positions will give the other two aberrations. Our approach to color aberrations is to trace a bundle of rays which includes 50% of the rays in the color of the center wavelength of the band and 25% in colors which represent the half power points of the spectral band. The composite image point produced well represents the heterochromatic image effects in a very simple manner. The merit function can therefore be constructed very simply from size and position of the image plus the boundary conditions that the designer chooses to place on the physical dimensions of the design. This minimizes the amount of data to be communicated between the designer and the computer, and promotes intuitive understanding of the progress of the design. It does not tend to bury the designer with data that he cannot assimilate and might obscure what is happening to the design. We believe that as we can simplify our view of problems and our approaches to them, we are able to solve more complex problems.

Our previous work on reducing system cost through improved tolerance distribution[1] has been continuing. We have noted with great interest the article by Plummer and Lagger[6] on cost effective design. We have plotted their data with ours in a new format which we find useful. Figures 5 through 8 show good correlation between Plummer's report and ours. We believe the data should be valuable to cost conscious designers.

Figure 5 plots the relative cost of producing a lens to a given diameter as the tolerance is made more and more restrictive. The tolerance is plotted on a reciprocal scale because the graph tends to be linear per our earlier report. In this example, a diameter with a tolerance of about 100 micrometers would represent something near the base cost. Here base cost is where no additional cost is added by the tolerance above the cost to edge the lens to any diameter. Plummer's data and ours agree amazingly well. They indicate that the cost will be the base cost plus 300% of the base cost divided by the tolerance in micrometers (.000001 meters). For example, a tolerance of .01MM or 10 micrometers would add 30% to the cost where as 5 micrometers would add 60%. In Figure 6, we add some additional data. We have shown the maximum and minimum values from our experiments. This indicates that the base time to produce a polished surface in the case in question varied by about 50% from block to block. The variation became less as the tolerance became the driving force on the time required. Our average data is somewhat different from Plummer's, but we believe this to be primarily due to the fact that our experiment was performed using two of our specialists in this operation rather than an average optician. A good number for industry use is probably more like Plummer's. The upper and lower straight lines show our best estimate of the range of viable values. This implies that a change of figure tolerance from one fringe to 1/4 fringe would add from 39% to 75% to the base cost of a lens polishing operation.

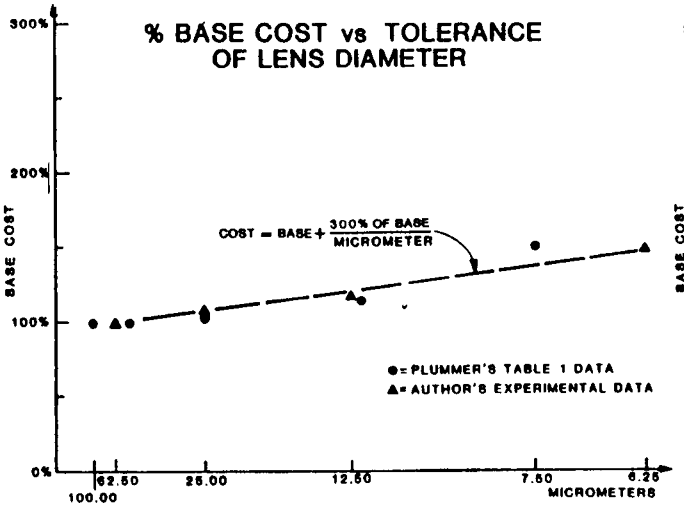

FIGURE 5. LENS DIAMETER TOLERANCE (PLOTTED ON RECIPROCAL SCALE)

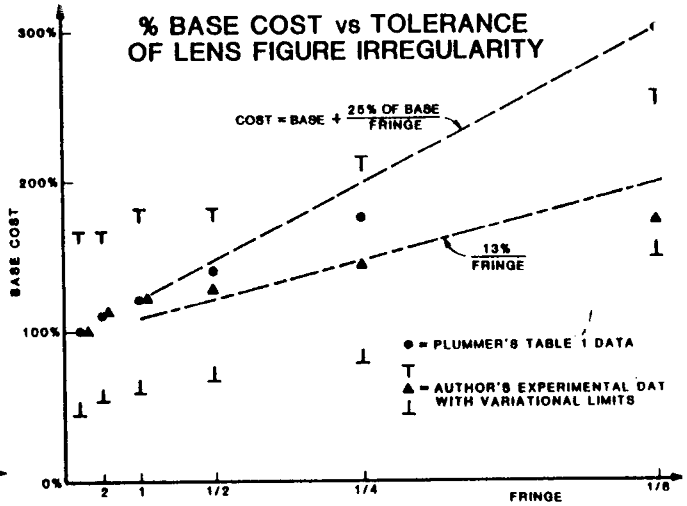

FIGURE 6. IRREGULARITY TOLERANCE ON LENS FIGURE (PLOTTED ON A RECIPROCAL SCALE)

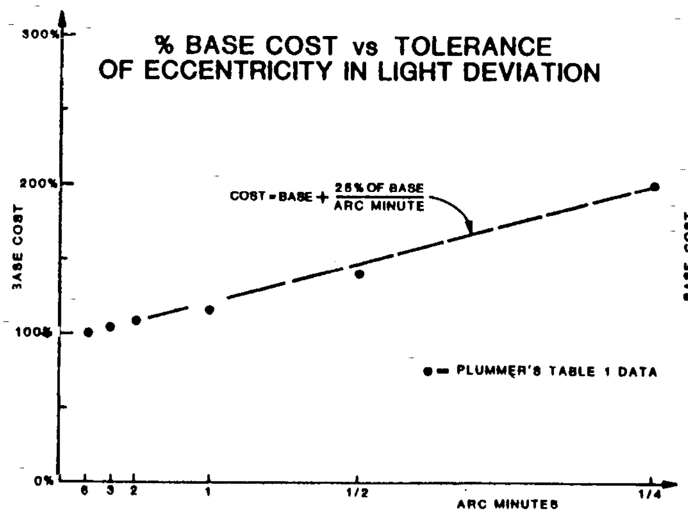

FIGURE 7. ECCENTRICITY TOLERANCE IN LIGHT DEVIATION (PLOTTED ON RECIPROCAL SCALE)

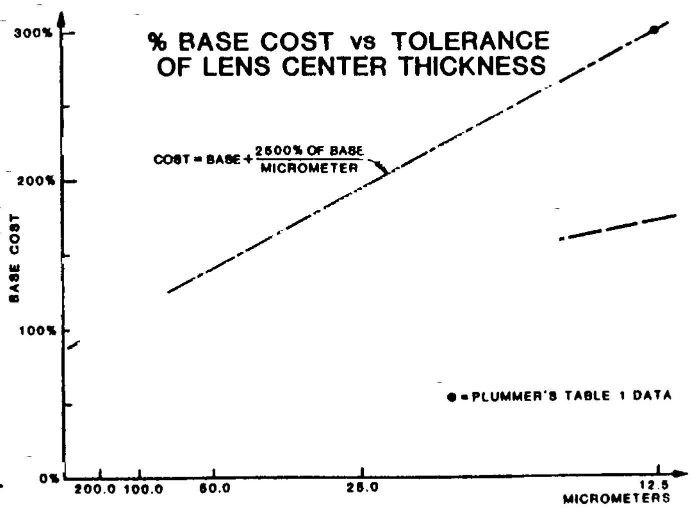

FIGURE 8. LENS C.T. TOLERANCE (PLOTTED ON A RECIPROCAL SCALE)

Figures 7 and 8 plot Plummer's data only. Figure 7 shows centering in arcminutes. Figure 8 shows lens center thickness tolerance. It seems to depart significantly from our hypothetical straight line function. We believe this is due to the fact that beyond a 25 micrometer tolerance on lens thickness, one enters a realm where the result is unpredictable. By this we mean that the operator may have to scrap a large percentage of the parts to get some that pass the requirements. Note that changing a tolerance on axial thickness from 0.2MM to 0.04MM would add 50 % to the cost; and changing to 0.02MM would add 200%.

If one were to pull together all of the various factors of this nature and write a small computer program, it should be practical to make a reliable automatic cost estimating program for Optical Components. This would be useful to the shop doing fabrication and to the designer trying to achieve an economical design. We expect to see such programs and data bases come into use during this decade.

Conclusions

We have shown why we believe that the ultimate cost and value of an optical product is very dependent on the preliminary and detail design processes. No amount of careful or creative work after the design is frozen can make up for lost opportunities in the design phase. The detail design phase must include an adequate tolerance analysis and distribution plus sufficient feedback in the area of producibility from those who will do the production. The designer cannot limit himself, in general, to the consideration of technical performance and exclude questions of economic performance. We believe that designers should serve an internship in the fabrication and production of the kinds of systems that they design. This kind of experience helps them better understand what can and cannot be done economically or at all. They learn the possibilities and the limitations, they learn what they can and cannot "get away with". Knowing what is necessary and sufficient will lead to the best technical and economic performance of any system. The designer should share more of the responsibility and rewards (or penalties) for the success (or failure) of a product from a technical and economic point of view.

The tools and the motivation for economic improvement in the product development process are continually being expanded. The problems are lurking for the inefficient, but the opportunities are waiting for the enterprising. We believe that the free market is the only system that can prevail.

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